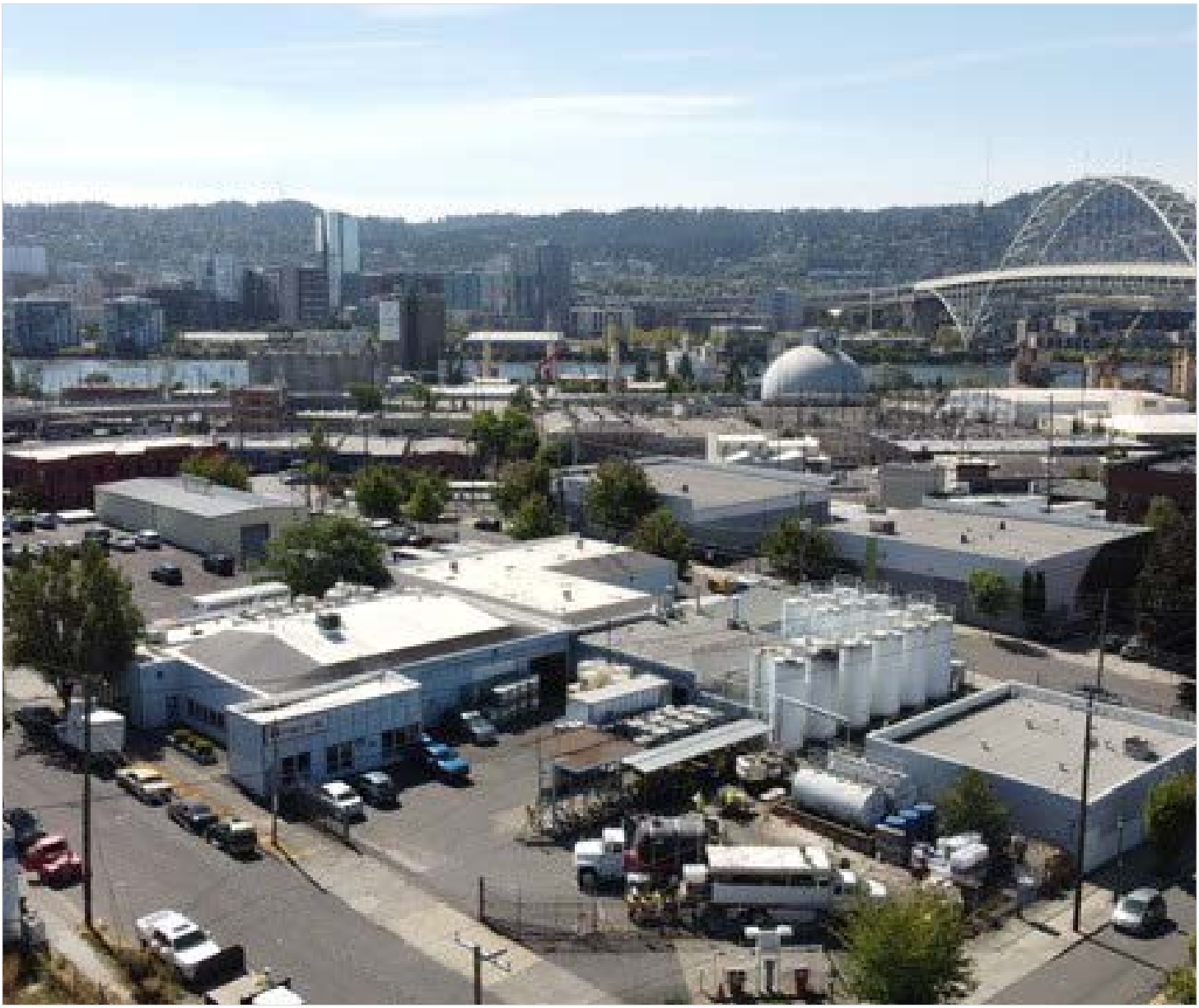
Long-Term cVOC Reduction Downgradient of an S-MicroZVI Barrier

Monitoring documented sustained cVOC reductions at near- and farther-downgradient wells more than five years after barrier installation.



Project Overview

A chlorinated solvent plume at a former industrial facility in the Pacific Northwest contained elevated concentrations of chlorinated volatile organic compounds (cVOCs), primarily including tetrachloroethene (PCE), trichloroethene (TCE), cis-1,2-dichloroethene (cis-1,2-DCE), and vinyl chloride (VC). The plume extended more than 2,000 feet through a predominantly sandy aquifer toward a nearby river, with targeted groundwater treatment extending to depths of approximately 90 feet below ground surface.

The remedial program combined source-mass control with a multibarrier approach to intercept and treat contaminants migrating along the plume core. Injections were completed in late 2020 within three principal treatment areas extending from the source area through downgradient portions of the plume. Selected zones received PlumeStop® in combination with S-MicroZVI®. The intermediate barrier received S-MicroZVI alone and was designed to destroy chlorinated contaminants migrating between the source-area and farther-downgradient PlumeStop treatment zones.

This bulletin focuses on the intermediate S-MicroZVI-only barrier and the subsequent monitoring record at MW-20, approximately 30 feet downgradient; MW-8, approximately 190 feet downgradient; and MW-7, approximately 220 feet in a downgradient but laterally offset position.

REGENESIS originally designed the S-MicroZVI barriers for 3 to 5 years of treatment longevity. Monitoring through March 2026—5.5 years after application—documented substantial long-term declines in parent compounds and transformation products following initial post-application concentration increases and subsequent periods of variability. Initial increases may reflect desorption following the injection program, together with formation and transport of transformation products. S-MicroZVI promotes abiotic reduction while creating conditions favorable for biological reductive dechlorination. Concentration reductions persisted despite changing bulk groundwater geochemistry, including a return to less reducing conditions at some monitoring wells. The monitoring record illustrates why S-MicroZVI performance should be evaluated using multiple lines of evidence, including contaminant trends, transformation products, spatial relationships, and geochemistry.

Performance Highlights

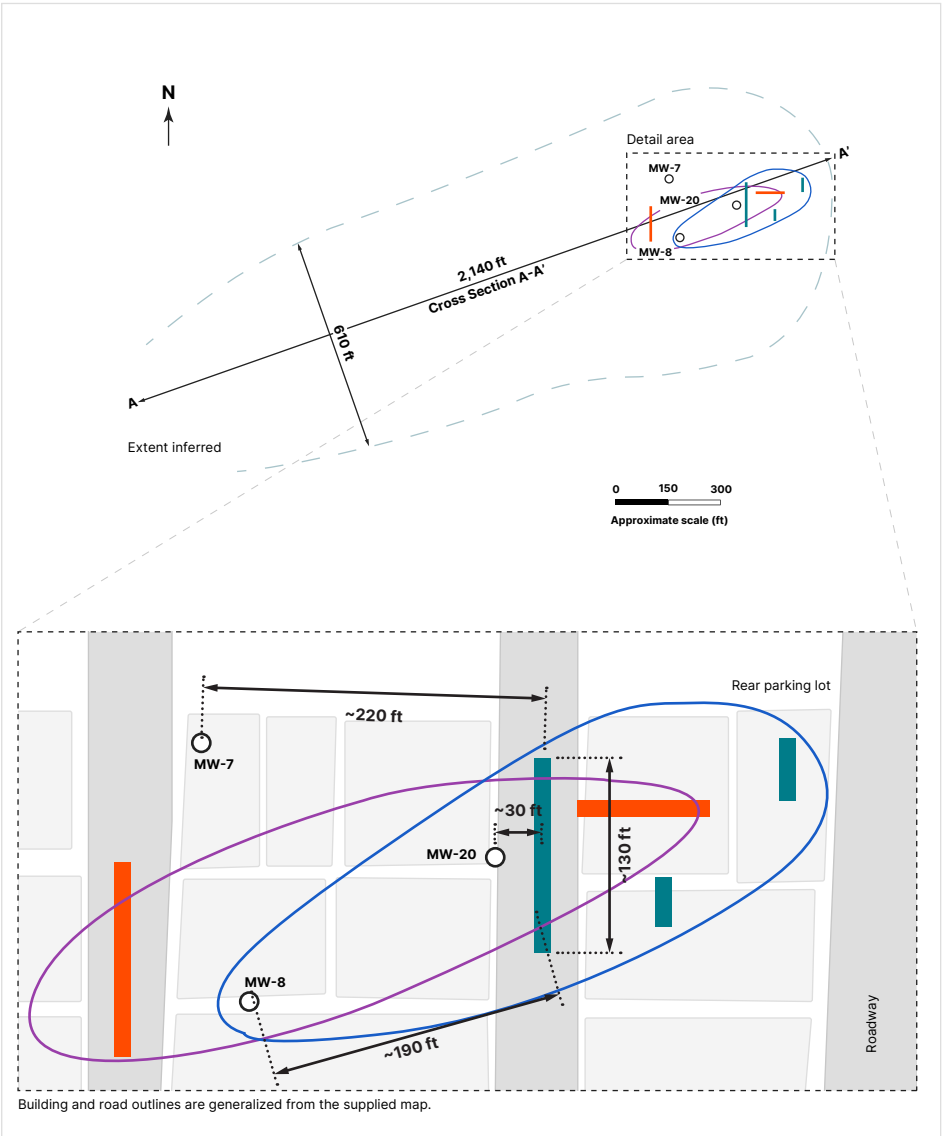
- Five and a half years of post-application groundwater monitoring.
- Sequential PCE, TCE, cis-1,2-DCE, and VC responses at near-downgradient well MW-20, followed by reductions of approximately 98.5% to 99.4% from their respective post-application peak concentrations.
- Reductions of approximately 83% to 94% from post-application peak

concentrations at MW-8, approximately 190 feet downgradient of the S-MicroZVI-only barrier, providing the principal longer-distance performance record.

- PCE, TCE, and cis-1,2-DCE concentrations at laterally offset downgradient well MW-7 remained approximately 78% to 86% below their August 2020 concentrations in March 2026.
- Sustained cVOC reductions despite variable groundwater geochemistry and a return to less reducing bulk groundwater conditions.

Figure 1 Treatment Layout and Historical Plume Contours

The overview shows the historical plume extent and treatment areas. The detail distinguishes the source-area treatment zones, the intermediate S-MicroZVI-only barrier, and the downstream PlumeStop and S-MicroZVI barrier. Source-area zones received either PlumeStop and S-MicroZVI or S-MicroZVI alone. Wells MW-20 and MW-8 are downgradient of the intermediate barrier; MW-7 is downgradient but laterally offset. Well-to-barrier distances are rounded to the nearest 10 ft. Building and road outlines are generalized; contours show historical conditions rather than the current plume extent.



Site Conditions

Site History and Plume Conditions

Historical operations at the former industrial facility included solvent and fuel storage, drum handling, and activities within several warehouse and process areas. Releases from these operations produced multiple source areas containing chlorinated volatile organic compounds in soil, soil vapor, and groundwater.

The primary groundwater contaminants of concern were PCE and TCE. Other detected chlorinated compounds included cis-1,2-DCE, VC, 1,1-dichloroethane, 1,2-dichloroethane, methylene chloride, and chloroform. In the portion of the plume evaluated in this bulletin, pre-application PCE and TCE concentrations ranged from hundreds to thousands of micrograms per liter. The groundwater plume extended approximately 2,000 feet toward a nearby river, making control of contaminant migration along the plume core a principal remedial objective.

A state-approved remedy was established through a 2017 record of decision and consent order. The selected groundwater remedy combined targeted in situ treatment with monitored natural attenuation. Separate soil-vapor collection and extraction systems addressed the vapor-intrusion pathway.

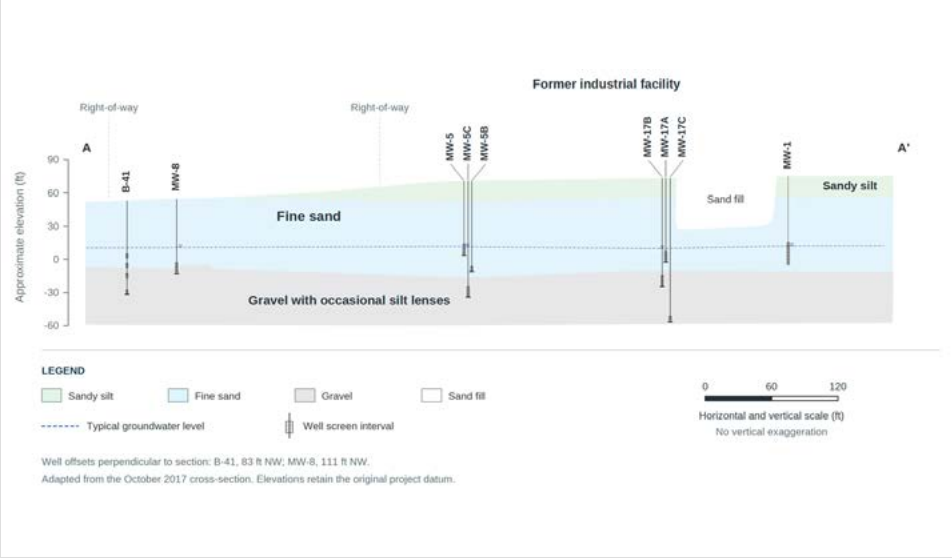
Geology and Hydrogeology

The site is underlain by unconsolidated flood deposits consisting primarily of sandy silt and fine sand over a deeper, gravel-dominated formation. Sandy silt extends from the ground surface to approximately 18 feet below ground surface near the former facility and pinches out downgradient. Beneath this unit, fine sand extends to the underlying gravel formation, which occurs at approximately 85 feet below ground surface near the facility and becomes shallower toward the downgradient surface-water receptor.

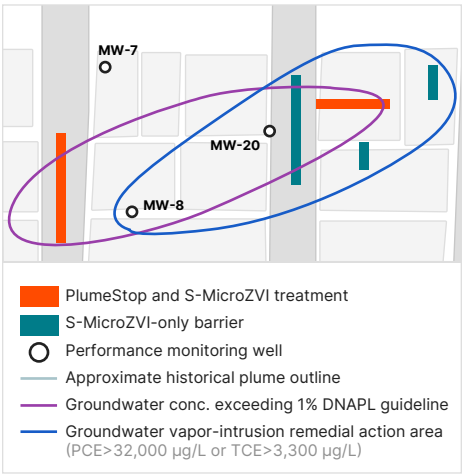
The unconsolidated deposits form an unconfined sand-and-silt aquifer above a deeper gravel aquifer. Depth to groundwater ranges from approximately 60 feet below ground surface near the former facility to approximately 30 feet below ground surface farther downgradient. Groundwater flows, and dissolved contaminants migrate, generally west-southwest toward a nearby river.

Figure 2 Generalized Geologic Cross Section

Generalized geologic cross section A-A' through the plume centerline.



Passive flux meter (PFM) measurements indicated groundwater velocities of approximately 400 to 500 feet per year within some contaminant-transport pathways. These conditions emphasized the importance of intercepting dissolved contaminant mass along the plume core. The intermediate S-MicroZVI-only barrier targeted groundwater at depths of approximately 60 to 90 feet below ground surface.



Treatment layout detail from Figure 1

Remedial Strategy and Objectives

The coordinated remedy targeted mass-flux reduction within the plume core through the treatment zones shown in the accompanying detail from Figure 1. Within the source area, one treatment subzone received PlumeStop and S-MicroZVI, while a second subzone received S-MicroZVI alone. An intermediate S-MicroZVI-only barrier was installed within the closest downgradient right-of-way. A second barrier incorporating PlumeStop and S-MicroZVI was installed approximately 280 feet farther downgradient.

PlumeStop provided engineered contaminant sorption and a biomatrix supporting biodegradation, while S-MicroZVI promoted abiotic contaminant reduction and reducing conditions favorable for reductive dechlorination. Together, the treatment zones were intended to reduce contaminant mass near the source and intercept mass flux migrating through the plume core.

The two downgradient barriers were positioned across portions of the plume where dissolved PCE or TCE concentrations met or exceeded 1% of the compounds' aqueous solubility. This criterion is used as a screening indicator for the potential presence of dense nonaqueous-phase liquid (DNAPL), rather than definitive evidence of its presence.[1]

[1] U.S. Environmental Protection Agency. 2004. Site Characterization Technologies for DNAPL Investigations. EPA 542-R-04-017.

S-MicroZVI Barrier Design and Installation

The intermediate S-MicroZVI-only barrier installation consisted of a single row of direct-push injection points extending across the cVOC plume core and the vertical extent of the principal mass-flux pathway. Combined membrane interface probe and hydraulic profiling tool (MiHPT) data and PFM measurements were used together to identify the targeted contaminant-transport pathways and guide amendment placement.

S-MicroZVI dosing was determined using a corrosion-based model that accounted for contaminant mass flux and competing electron acceptors, including dissolved oxygen and nitrate, over the intended treatment period. Groundwater velocities derived from PFM measurements provided a key input for estimating contaminant and electron-acceptor loading, amendment requirements, and the timing of downgradient responses. The original design projected 3 to 5 years of treatment longevity under site-specific loading assumptions.

The amendment was delivered using a direct-push rig with injection point spacing designed to provide sufficient overlap between points. Installation details are summarized below.

Injection Design Details	Value
Barrier length	128 ft
Treatment interval	60 to 90 ft bgs
Injection points	17
Point spacing	6-10 ft
S-MicroZVI applied	12,000 lb
Total injection volume	46,460 gal
Installation date	September 2020

Monitoring Approach

Groundwater monitoring included PCE, TCE, cis-1,2-DCE, and VC, together with field parameters and selected geochemical indicators, including dissolved oxygen, oxidation-reduction potential, ferrous iron, methane, ethane, and ethene.

MW-20, approximately 30 feet downgradient of the S-MicroZVI-only barrier, provides the principal near-downgradient record. Because MW-20 is also downgradient of a separate source-area treatment zone, its response is interpreted within the context of the coordinated remedy.

MW-8, approximately 190 feet downgradient of the S-MicroZVI-only barrier and upgradient of the next treatment barrier, provides the principal farther-downgradient performance record. MW-7, approximately 220 feet downgradient but laterally offset from the S-MicroZVI-only barrier, provides a comparison point for evaluating the broader plume response.

Groundwater Performance

Groundwater performance was evaluated using concentration trends, compound-specific response timing, monitoring-well position, transformation products, degradation gases, and bulk groundwater geochemistry. Initial concentration increases following the source-area and barrier injections may reflect desorption of contaminants from aquifer solids, together with formation and transport of transformation products. Performance was therefore evaluated relative to both pre-application concentrations and subsequent post-application peaks.

Near-Downgradient Transformation at MW-20

MW-20, approximately 30 feet downgradient of the S-MicroZVI-only barrier, exhibited the clearest sequential cVOC response. Following barrier installation, PCE peaked first in February 2021, followed by TCE in August 2021 and later by cis-1,2-DCE and VC in August 2022. This progression is consistent with sequential reductive dechlorination. In addition to promoting abiotic reduction, S-MicroZVI creates reducing conditions favorable for biological reductive dechlorination. The monitoring record does not establish the relative contributions of these pathways.

After reaching their respective peaks, all four compounds declined substantially. By March 2026, reductions from post-application peaks ranged from approximately 98.5% to 99.4%. PCE, TCE, and cis-1,2-DCE were also approximately 85% to 96% below their August 2020 concentrations. VC remained above its pre-application concentration but had decreased from 1,270 to 7.15 µg/L, a reduction of approximately 99.4% from its August 2022 peak.

PCE and TCE temporarily rebounded in 2024 before resuming their downward trends. This variability may reflect changing flow paths, continuing release of stored contaminant mass from lower-permeability materials, or variable contaminant loading entering the treatment zone.

Repeated detections of ethene and ethane at MW-20 provide additional evidence of complete transformation to non-chlorinated products.

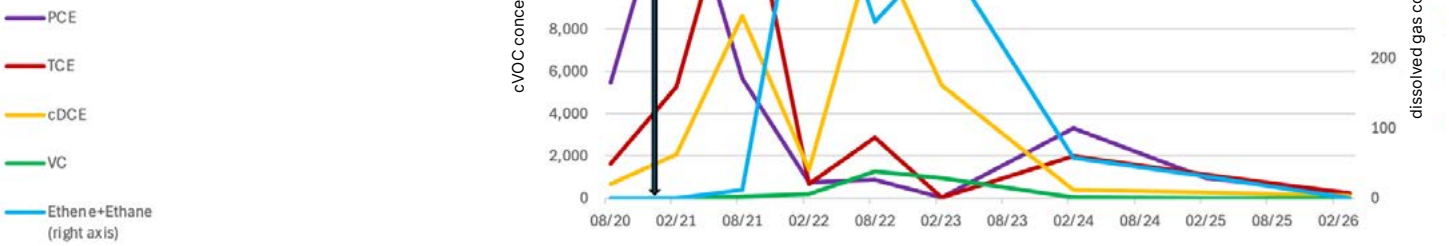
Table 1 Concentrations and Reductions

Pre-application, post-application peak, and March 2026 cVOC concentrations at MW-20 (µg/L), with reductions calculated from each compound-specific peak.

Compound	Aug 2020	Post-application peak	Mar 2026	Reduction from peak
PCE	5,480	16,200 (Feb. 2021)	233	98.6%
TCE	1,630	16,300 (Aug. 2021)	243	98.5%
cis-1,2-DCE	673	12,300 (Aug. 2022)	101	99.2%
VC	0.725	1,270 (Aug. 2022)	7.15	99.4%

Figure 3 Concentration Trends at MW-20

cVOC and combined ethene and ethane concentration trends at MW-20, approximately 30 feet downgradient of the S-MicroZVI-only barrier. cVOC concentrations use the left axis. Combined ethene and ethane concentrations use the right axis. Ethene and ethane were not detected above the 13 µg/L reporting limit in March 2026 sampling.



Farther-Downgradient Response at MW-8

MW-8 is approximately 190 feet downgradient of the S-MicroZVI-only barrier and upgradient of the next treatment barrier. Its location provides the principal longer-distance monitoring record for groundwater passing downgradient of the intermediate barrier.

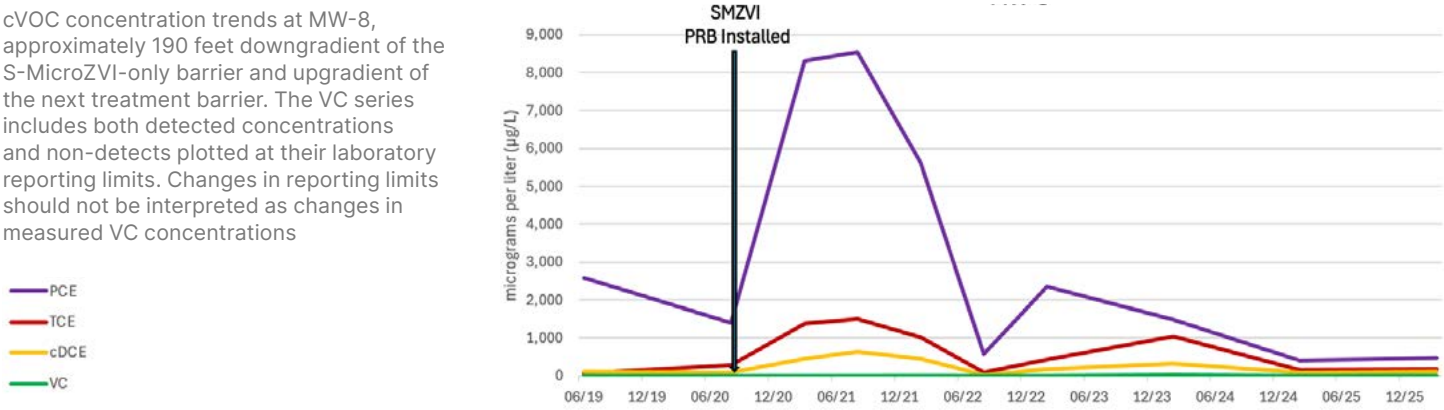
PCE, TCE, and cis-1,2-DCE increased following application and reached their highest measured concentrations in August 2021. These increases may reflect temporary increases in dissolved contaminant loading associated with desorption following the upgradient injection program, together with formation and transport of transformation products. Concentrations declined markedly in 2022, rebounded during 2023 and 2024, decreased substantially in 2025, and increased modestly in March 2026 while remaining well below their August 2021 peaks.

For PCE, TCE, and cis-1,2-DCE, the March 2026 primary and duplicate sample results were approximately 83% to 94% from their respective August 2021 peaks. PCE and TCE were also below their August 2020 concentrations, while cis-1,2-DCE was near its August 2020 concentration.

VC was detected intermittently at MW-8, with a maximum measured concentration of 13 µg/L in February 2024. Several other VC results were non-detects with changing reporting limits and should not be interpreted as measured concentrations.

Figure 4 Concentration Trends at MW-8

cVOC concentration trends at MW-8, approximately 190 feet downgradient of the S-MicroZVI-only barrier and upgradient of the next treatment barrier. The VC series includes both detected concentrations and non-detects plotted at their laboratory reporting limits. Changes in reporting limits should not be interpreted as changes in measured VC concentrations



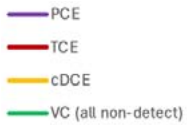
Laterally Offset Downgradient Response at MW-7

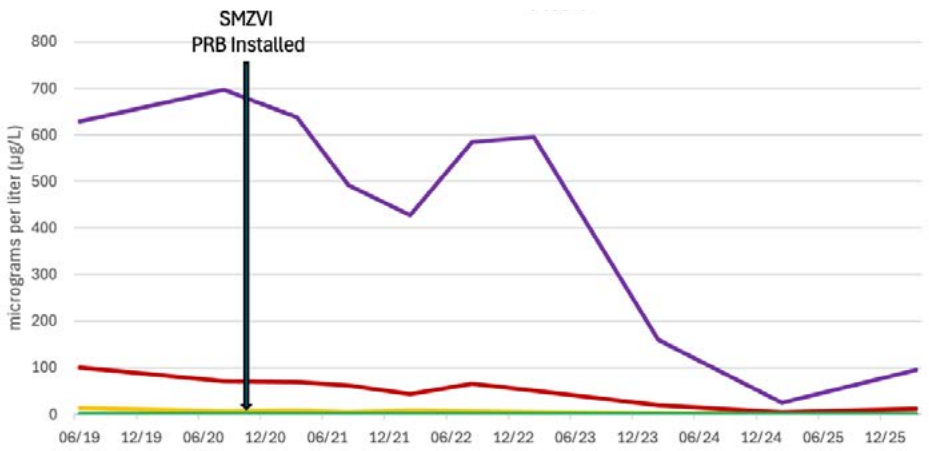
MW-7 is approximately 220 feet downgradient but laterally offset from the S-MicroZVI-only barrier. PCE, TCE, and cis-1,2-DCE concentrations changed relatively gradually through 2023 before declining sharply in 2024 and 2025. Concentrations rebounded in 2026 but remained approximately 78% to 86% below their August 2020 concentrations.

VC, ethene, and ethane were not detected at MW-7. The well's laterally offset position and more oxidizing conditions distinguish its response from the pronounced sequential transformation observed at MW-20. Its concentration declines are consistent with broader plume improvement following implementation of the coordinated remedy, but do not establish direct treatment by the intermediate barrier.

Figure 5 Concentration Trends at MW-7

cVOC concentration trends at MW-7, approximately 220 feet downgradient but laterally offset from the S-MicroZVI-only barrier. VC was not detected above the reporting limit in any sample.





Performance Interpretation

Multiple Lines of Evidence

At the near barrier well MW-20, the sequential parent- and daughter-compound response, substantial subsequent concentration declines, and repeated detection of ethene and ethane provide complementary evidence of reductive transformation. Together, these observations support contaminant transformation, rather than concentration reduction by attenuation alone.

MW-8 provides complementary spatial evidence approximately 190 feet downgradient of the intermediate barrier and upgradient of the next treatment barrier. Its substantial long-term concentration reductions support improvement along the plume core following implementation of the coordinated remedy. Both MW-20 and MW-8 are also downgradient of source-area treatment, so their long-term responses cannot be attributed exclusively to the intermediate barrier.

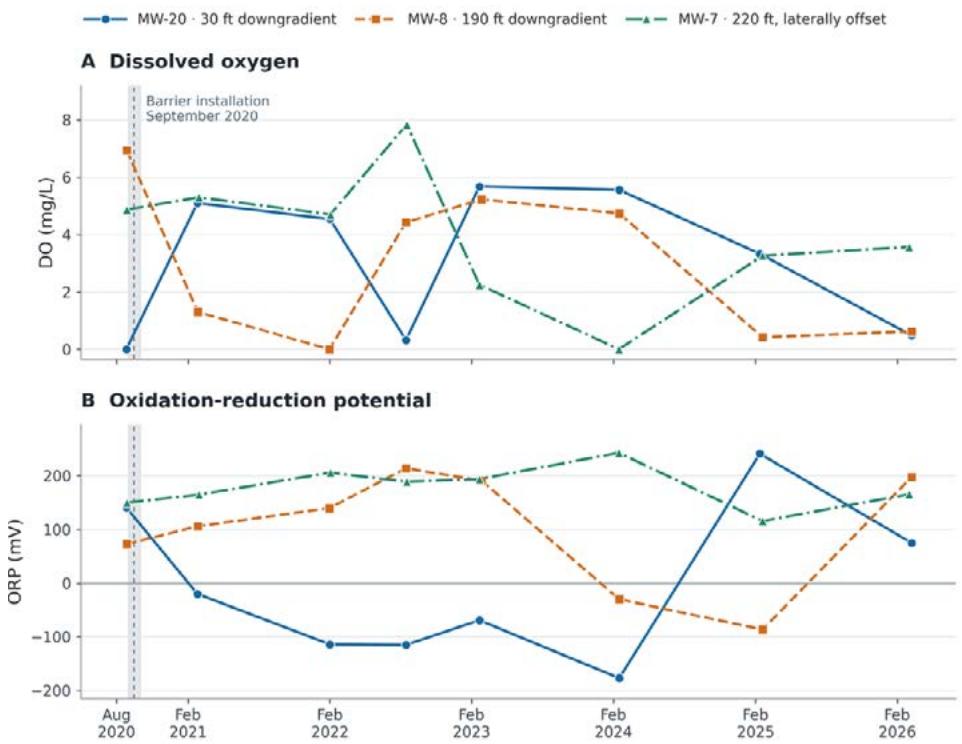
Concentrations fluctuated during the monitoring period. PCE and TCE rebounded at MW-20 in 2024, concentrations at MW-8 increased during 2023 and 2024, and the three principal cVOCs rebounded at MW-7 in 2026. Nevertheless, concentrations remained substantially below their respective post-application peaks at MW-20 and MW-8 and below baseline concentrations at MW-7. At MW-20, the renewed declines following the 2024 rebound, together with repeated ethene and ethane detections through February 2025, support a sustained treatment response within the coordinated remedy. The temporary increases did not reverse the substantial long-term improvement.

Geochemistry and Longer-Term Response

An S-MicroZVI barrier treats groundwater as it passes through the iron-amended zone, where reducing conditions develop and contaminant transformation occurs at reactive iron surfaces. Treatment is concentrated within this zone, while groundwater and dissolved reaction products move downgradient. Mixing with surrounding groundwater and subsequent reactions can alter indicators such as dissolved oxygen (DO), oxidation-reduction potential (ORP), and sulfate. Downgradient wells may therefore reflect local aquifer conditions that differ from conditions within the barrier. By reducing contaminant loading leaving the treatment zone, the barrier can support sustained downgradient concentration reductions without reducing conditions extending throughout the aquifer.

Figure 6 Groundwater Geochemistry at Performance Wells

Dissolved oxygen (DO) and oxidation-reduction potential (ORP) at MW-20, MW-8, and MW-7 from August 2020 through March 2026. The shaded band marks installation of the intermediate S-MicroZVI-only barrier in September 2020.



MW-20

- **Dissolved oxygen and ORP:** Pre-application measurements in August 2020 included an ORP of +141 mV and a reported dissolved oxygen concentration of 0 mg/L.
- ORP subsequently became negative, ranging from −20 to −177 mV during reported monitoring events from February 2021 through February 2024. Dissolved oxygen varied and did not consistently track the ORP response.
- ORP returned to positive values in 2025 and 2026. By March 2026, ORP was +75 mV and dissolved oxygen was 0.48 mg/L, while cVOC concentrations remained substantially below their post-application peaks.
- **Other geochemical indicators:** Sulfate decreased from 20.6 mg/L before application to below 1 mg/L in February 2023.
- Nitrate decreased from 2.54 mg/L in February 2021, the first available post-application measurement, to below 0.25 mg/L during three monitoring events in 2022 and 2023.
- **Transformation products:** Ethene and ethane were detected at every monitoring event from August 2021 through February 2025, supporting transformation to non-chlorinated products.
- Pre-application dissolved-gas results were unavailable in the compiled table.
- Neither compound was detected in March 2026, when reporting limits increased from 1 to 13 µg/L per compound, limiting comparison with earlier low-level results.

MW-8

- **Dissolved oxygen:** Decreased from 6.95 mg/L before application to 0.62 mg/L in March 2026, with substantial intervening variability.
- **ORP:** Baseline ORP was +73 mV. Subsequent measurements included approximately −30 mV in 2024 and −86 mV in 2025, followed by +198 mV in March 2026.
- **Dissolved gases:** Methane was detected during multiple monitoring events, while ethene and ethane were detected intermittently at comparatively low concentrations.
- **Interpretation:** These results document a variable geochemical response at the farther-downgradient well alongside substantial long-term cVOC reductions.

MW-7

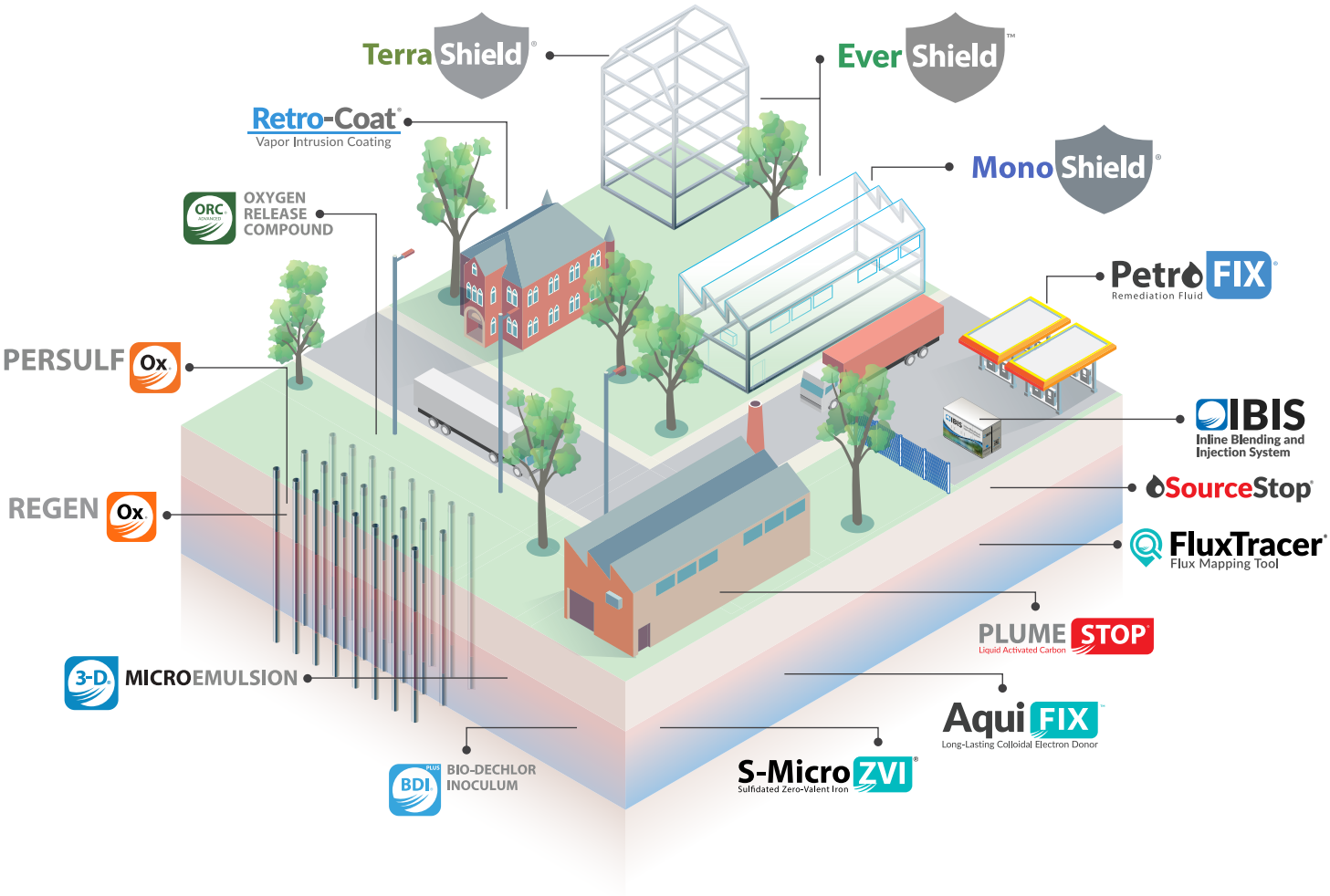
- **Dissolved oxygen:** Baseline dissolved oxygen was 4.87 mg/L, compared with 3.57 mg/L in March 2026. Concentrations were generally elevated but variable.
- **ORP:** Baseline ORP was +150 mV, compared with approximately +166 mV in March 2026. ORP remained positive throughout the monitoring record.
- **Transformation products:** Ethene and ethane were not detected.
- **Interpretation:** Together with the well's laterally offset position, these observations support interpreting its cVOC declines as evidence of broader plume improvement.

Technical Implications

This case study documents substantial cVOC concentration reductions over five and a half years downgradient of an S-MicroZVI-only barrier installed as part of a coordinated site remedy. The long-term monitoring record supports the following technical implications:

- MW-20 and MW-8 recorded substantial reductions approximately 30 and 190 feet downgradient, respectively, of the intermediate S-MicroZVI-only barrier. MW-7, approximately 220 feet from the barrier in a downgradient but laterally offset position, also recorded substantial reductions, indicating plume improvement following remediation.
- Initial concentration increases and subsequent rebounds should be interpreted within the complete monitoring record. At this site, sequential daughter-product responses, detections of non-chlorinated end products, and substantial subsequent concentration declines provide complementary evidence of a sustained treatment response within the coordinated remedy.
- Downgradient monitoring wells may reflect local aquifer conditions that differ from those within the iron-amended treatment zone. Treatment within the barrier can reduce contaminant loading to downgradient groundwater without reducing conditions extending throughout the aquifer. Concentration trends, transformation products, geochemistry, and hydraulic relationships should therefore be evaluated together to assess treatment effectiveness.
- The original design projected 3 to 5 years of treatment longevity under site-specific loading assumptions. Sustained concentration reductions remained evident approximately 5.5 years after application, beyond the original projected period. Continued monitoring will evaluate whether these long-term reductions are maintained.

The monitoring results support the remedy's objectives of source-mass control and long-term sustained concentration reductions along the plume core.



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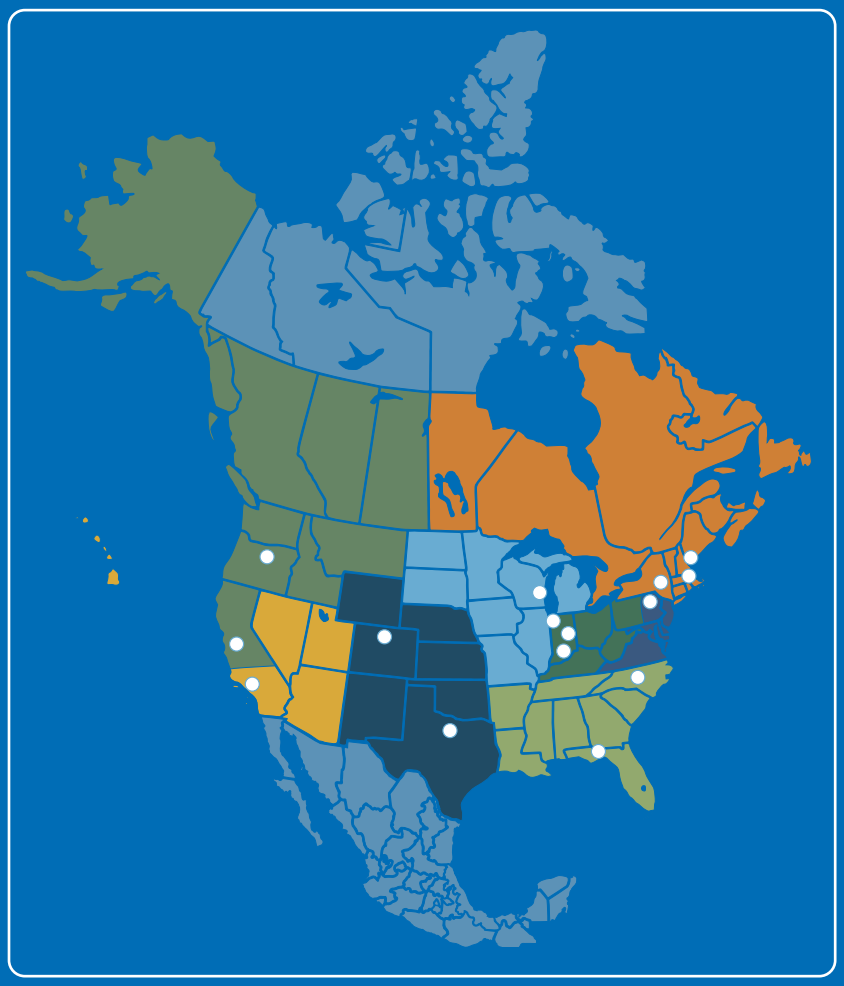
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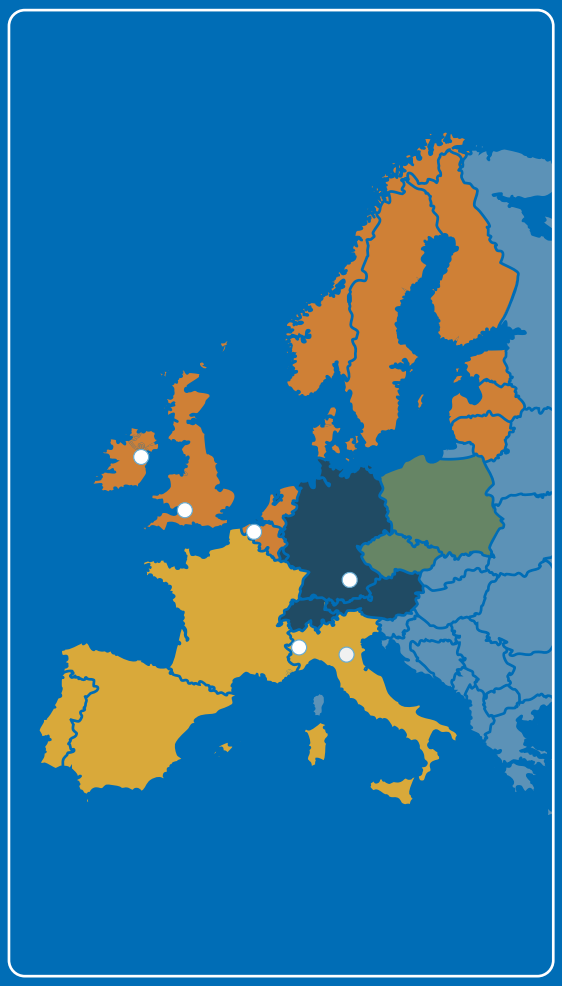
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