**Time-series depiction of cross contamination and rock-matrix diffusion in an open bedrock borehole**

Authors: Philip T. Harte, USGS; William C. Brandon, U.S. EPA; Cynthia M. Frickle, U.S. EPA

**Abstract:**

This animation shows the progression of subsurface contamination from a hypothetical dense nonaqueous phase liquid (DNAPL) source and the resulting dissolved groundwater contaminant plume within a system of overburden and fractured, sedimentary rock. It illustrates the drilling of an open borehole well nearby, which penetrates the dissolved plume in overburden and bedrock. This results in cross-contamination of previously unconnected fractures, altering fracture flow and exposing new sections of rock to contamination. Over time, the source and dissolved plume evolve, in concert with a complex series of interactions with the fractures and the rock matrix. This can have unintended consequences, such as creating new contaminant pathways which may result in new contaminant receptors. The implications are that these unintended connections may result in longer timeframes to decontamination of the groundwater.

**Transcript:**

This animation will show the progression of subsurface contamination from a hypothetical dense nonaqueous phase liquid--or DNAPL--source to a dissolved-phase plume with matrix diffusion. Drilling an open borehole through a plume and into fractured bedrock can have unintended consequences, such as creating new contaminant pathways and cross contamination of previously uncontaminated fractures. These pathways are created by the differences in the hydraulic head of the individual open fractures. Part of the creation of new pathways is the contamination of previously unexposed rock, through “matrix diffusion,” a process whereby dissolved-phase contaminants chemically diffuse into the unfractured rock matrix.

In this example, there are unconsolidated sediments, also called “overburden,” sitting atop a sedimentary bedrock unit, with three fractures--F1, F2, and F3--along bedding planes. The rock matrix has limited porosity and groundwater flow on the site scale is from right to left.

Leaky drums release strings of residual DNAPL called “ganglia” Into the overburden. As groundwater flows through this area, a dissolved contaminant plume emanates from the DNAPL zone. Additionally, a DNAPL pool forms on the bedrock surface.

A second dissolved plume forms as DNAPL reaches the upper fracture, F1, and moves downgradient with decreasing hydraulic head toward the left.

At this time, the source input has decreased, but there are still two active dissolved contaminant plumes. A halo of contamination diffuses into the rock matrix around the DNAPL pool and along F1. Note that contamination is *not* present in fractures F2 or F3 because they don’t intersect with F1 or the contaminated overburden.

To the right, the image represents a cross section where a future borehole will intersect. Prior to drilling, no contamination is present. Watch this space to see a close-up view of what happens in the borehole over time.

Site remediation begins and the leaky drums are removed, so the source is no longer contributing to the DNAPL pool.

As a borehole is drilled for groundwater monitoring, it passes through the contaminated overburden and fracture F1, and the dissolved plume enters the borehole. This introduces contaminant to new areas and the borehole now has the potential to contaminate to greater depths with further drilling. The borehole itself creates a conduit between previously unconnected fractures and can alter groundwater flow direction based on the hydrogeology of any new fractures it encounters.

In this simplified scenario, the highest hydraulic head exists in F1, and head decreases with depth in successively deeper fractures. This vertical gradient would not be apparent before drilling an open borehole, and the hydraulic head in the borehole will be altered each time the borehole encounters a hydraulically active fracture. As the borehole is drilled deeper and intersects fracture F2, the higher hydraulic head in fracture F1 forces contaminated groundwater to move into and down the borehole, and out into fracture F2. The hydraulic head of the borehole is now a weighted average of the heads in fractures F1 and F2. This results in contamination of a previously unconnected fracture, altering fracture flow and exposing new sections of rock to contamination. At this point, fracture F3 is still uncontaminated.

The hydraulic head of F3 is lower than in fractures F2 or F1. As the borehole intersects F3, contaminated water from the borehole flows into F3. The hydraulic head of the borehole is now an average across all three fractures. Fracture F2 now exhibits cross-flow, meaning uncontaminated water flows into the borehole, mixes with the contaminated groundwater, and then flows out downgradient in F2.

Based on this complex flow interaction, the dissolved plume shows very distinct concentration patterns. The concentration of groundwater in a fracture depends on the position of the fracture relative to the DNAPL source. The contaminant concentration of borehole water is predominantly a flow-weighted average of the water from fractures going into the borehole but can also be controlled by the location of inflowing and outflowing fractures. Where the flow is moving outward from the borehole, the concentration is like the water within the borehole.

During this early stage of borehole construction, we see in the cross section at the right that the freshly exposed rock matrix around the borehole contains limited contaminant mass compared to the weathered zone around fracture F1. This represents the **early** stage of borehole contamination, and we will watch what happens over time.

Matrix diffusion begins along the walls of the borehole and the additional fractures that now receive contaminated water from the borehole. In general, contaminant mass can diffuse more readily into the rock along fractures than into freshly-drilled rock surfaces. In particular, highly weathered fractures have more surface area for contaminant adsorption.

Again, in the borehole cross section, matrix diffusion continues from the borehole water into the surrounding rock.

As time goes by, there may be significant changes in the source and distribution of contaminants.

Over a span of months to years following borehole drilling, the rock matrix adjacent to the borehole and the borehole water come to a quasi-equilibrium state, meaning the contaminant concentrations in the rock and adjacent borehole water are similar at any location. This represents the **middle** stage of borehole contamination.

Seen in the borehole cross section, the borehole water and the adjacent rock matrix come to equilibrium.

As the plume attenuates and DNAPL is no longer contributing dissolved contaminants to the plume, the borehole water is now less contaminated than the surrounding rock. At this stage, backward diffusion begins: contaminants now diffuse from the rock matrix into the borehole water.

Dissipation of the DNAPL pool represents the **late** stage of borehole contamination. This may take decades. In this phase, groundwater contamination persists as contaminants desorb from fracture surfaces and back diffuse from the rock matrix. This continuing contaminant source can add years to remediation efforts.

The late stage of borehole contamination may persist for decades before reaching a condition of **negligible back diffusion**. During this time, external factors such as climate, land development or new pumping wells drilled nearby may also impact groundwater flow dynamics. These changes can result in unexpected consequences such as altering hydraulic gradients, creating new contaminant pathways, or changing subsurface chemistry in a manner that exacerbates or prolongs contaminant release. However, by understanding matrix diffusion and fracture flow both conceptually and systematically in the context of real-world site scenarios, remediation professionals can design more effective remedial solutions and monitoring networks.

**Assumptions:**

This simplified animation depicts many nuances related to borehole and fracture flow, but other factors may affect contaminant distribution and diffusion:

* The presence of an extensive weathered rock zone can serve as an additional source of contamination, further complicating contaminant transport.
* Stagnant flow zones in a borehole may exhibit much higher diffusion than in active flow zones.
* If contaminants volatilize in the well casing, the borehole water concentration will be affected.

**Acknowledgements**:

Charlena Bowling, EPA Office of Research & Development

William C. Brandon, EPA Office of Land and Emergency Management

Lucila Dunnington, EPA Office of Superfund Remediation & Technology Innovation

Cynthia M. Frickle, EPA Office of Superfund Remediation & Technology Innovation

Edward J. Gilbert, EPA Office of Superfund Remediation & Technology Innovation

Philip T. Harte, U.S. Geological Survey, New England Water Science Center

Andrew Schmidt, Remedial Project Manager, EPA Region 8

Chris Vallone; Remedial Project Manager, EPA Region 3

Rick Wilkin, EPA Office of Research & Development

**References**:

Allen-King, R. M., Kiekhaefer, R.L., Goode, D.J., Hsieh, P.A., Lorah, M.M., and Imbrigiotta, T.E., 2022, A Borehole Test for Chlorinated Solvent Diffusion and Degradation Rates in Sedimentary Rock: Ground Water Monitoring and Remediation. at doi: 10.1111/gwmr.12495.

Environment Agency, 2003, DNAPL Handbook: Environment Agency, R&D Publication 133, Bristol, United Kingdom, 67 p.

Huling, S.G., and Weaver, J.W., 1991, Dense Nonaqueous Phase Liquids: Environmental Protection Agency: Ground Water Issue, EPA/540/4-91-002, 21 p.

Harte, P.T., and Brandon, W.C., 2020, Borehole-Scale Testing of Matrix Diffusion for Contaminated-Rock Aquifers: Journal of Remediation, V. 30, Issue 2, p. 37-53.

Harte, P.T., 2002, Comparison of Temporal Trends in VOCs as Measured with PDB Samplers and Low-Flow Sampling Methods: Ground Water Monitoring and Remediation, V.33, No. 6, p. 45-47.

Imbrigiotta, Thomas and Harte, P.T., 2020, Passive Sampling of Groundwater Chemistry in Wells: U.S. Geological Survey Techniques and Methods Report, No. TM 1-D8, Book 1; Collection of Water Data by Direct Measurement, Section D, Water Quality, Chapter 8.

Ji, Sung-Hoon, Yeo, In Wook, and Lee, Kang-Kun, 2003, Influence of Ambient Groundwater Flow on DNAPL Migration in a Fracture Network: Geophysical Research Letters, V. 30, No. 10.