Managing Chlorinated Solvent Impacts in Fractured Sedimentary Rocks Using Novel Field and Numerical Modeling Approaches

Huyen Nguyen, Daron Abbey – *Montrose Environmental*

Dr. Beth Parker – *University of Guelph*

Dr. Jessica Meyer – *University of Iowa*

Tom Miazga, Mike Noel, Negar Shahsavar, Ken Walton, Jessica Bulova, Laura Weaver, Chris Gabriel, Anna Best

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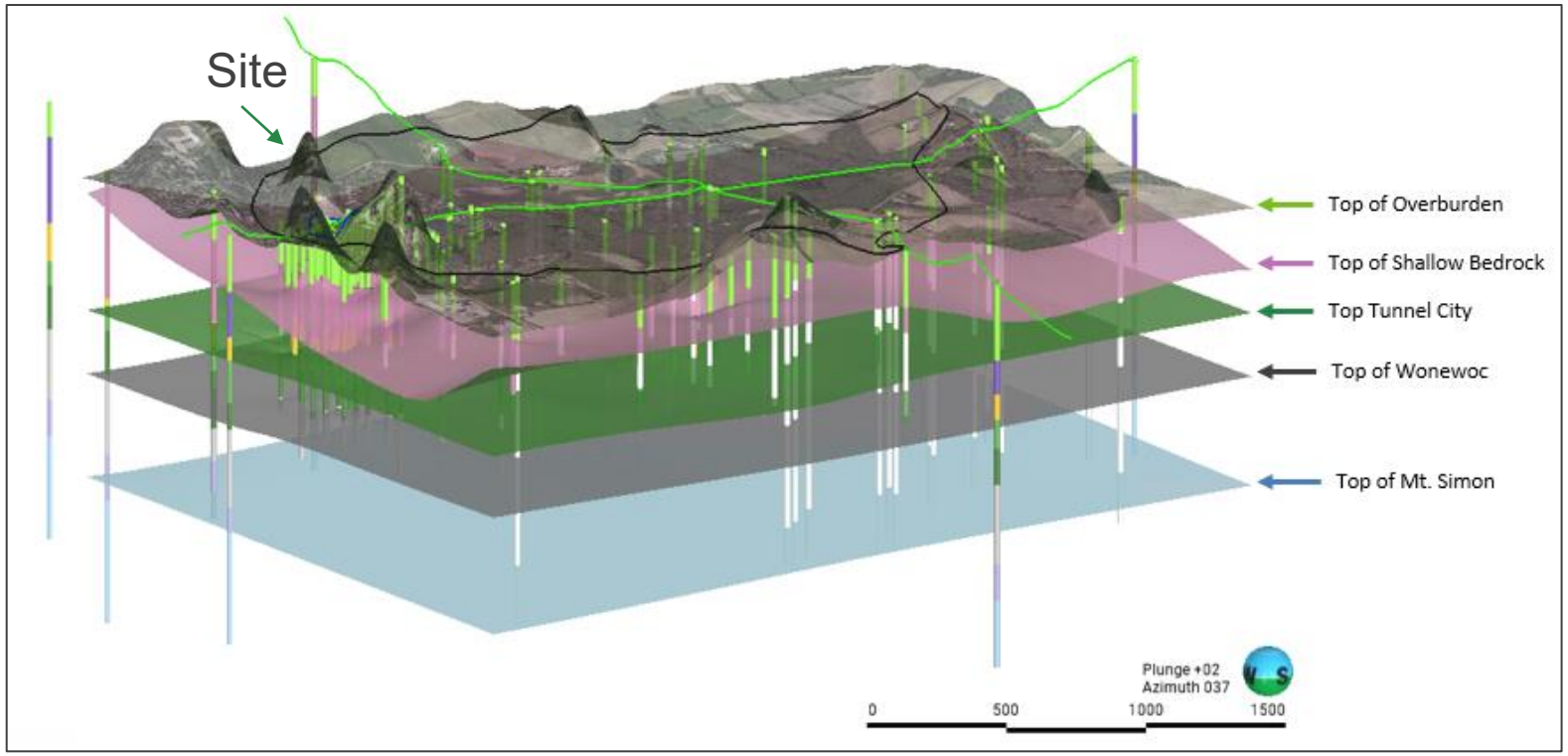
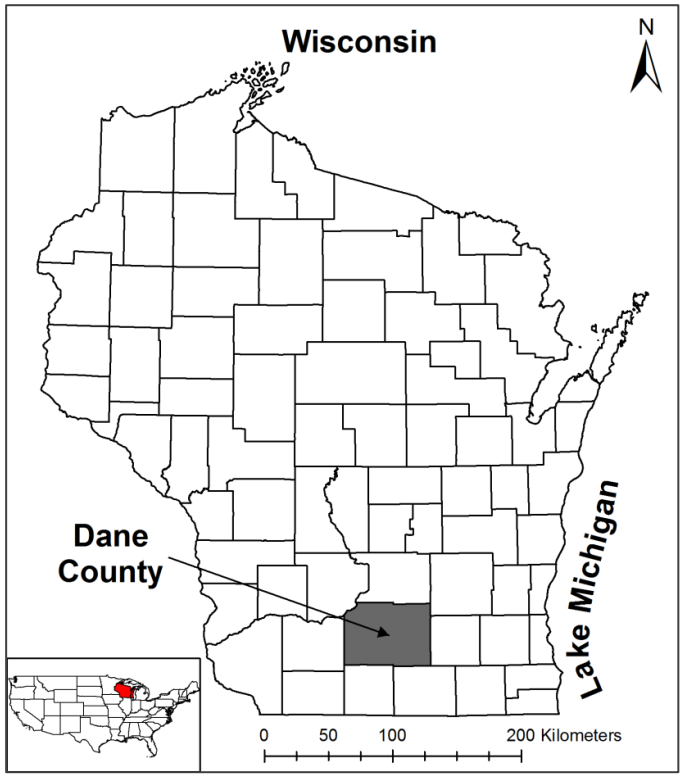
Site Descriptions

- The Site in Dane County, Wisconsin, formerly owned by a chemical company.
- From 1950 to 1970 a **mixed DNAPL** composed of chlorinated solvents, ketones, and aromatics was released into the subsurface.
- Site geology consists primarily of fractured sedimentary bedrocks overlain by unconsolidated deposits. Four thin and laterally continuous aquitards are identified at the site scale.
- Three out of four aquitards correspond to maximum flooding intervals.

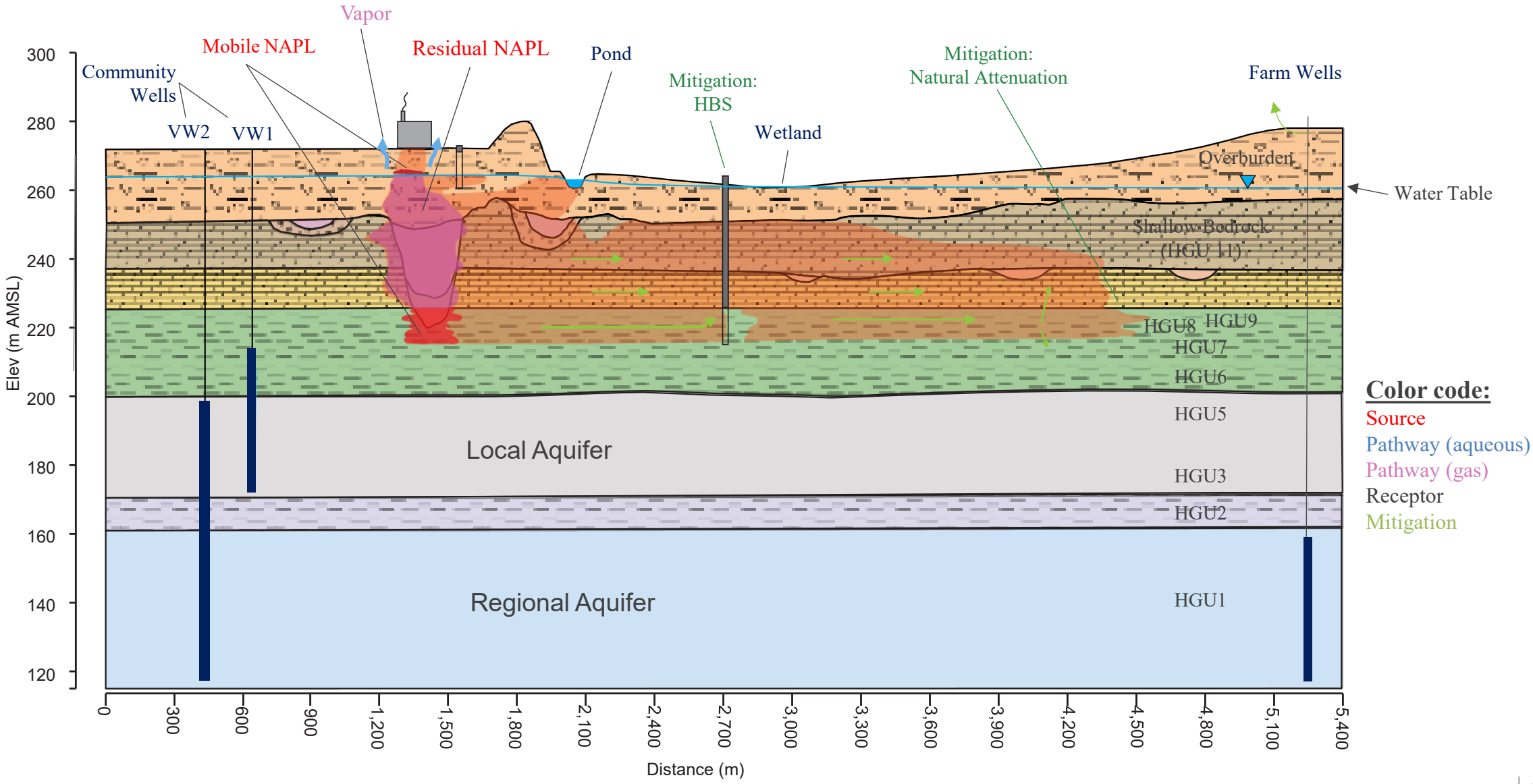


3D Hydro-geologic Units (HGU) at site scale



Site Location

Source-Pathway-Receptor Diagram

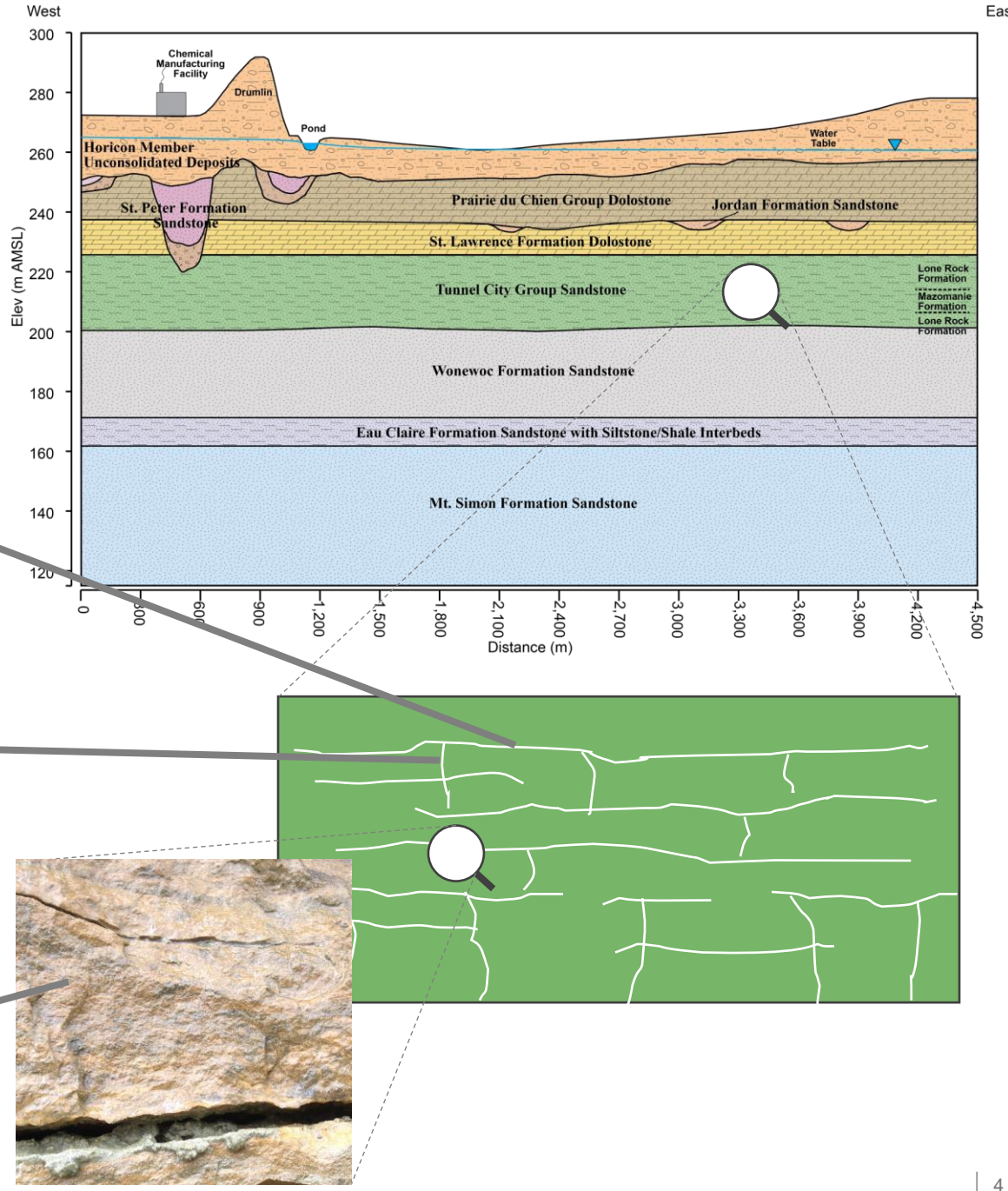


Fractured Sedimentary Rock Characteristics

The fracture network is a systematic arrangement of bedding parallel fractures and nearly vertical joints

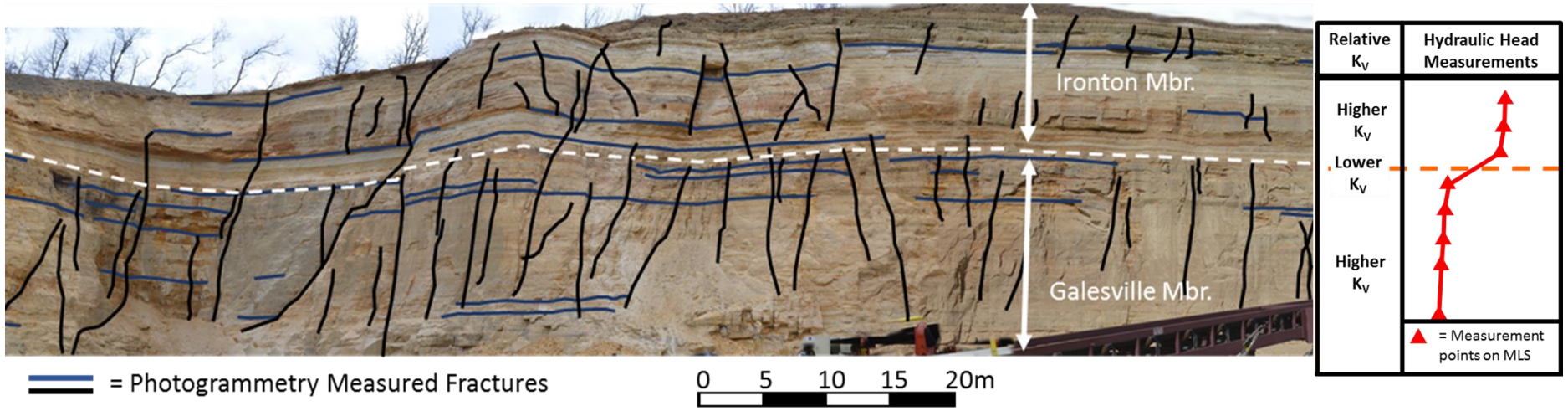
- High angle fractures (or vertical fractures) control the bulk vertical hydraulic conductivity (Kv) of the bedrock units;
- Termination/alignment of high angle fractures across specific stratigraphic horizons controls vertical connectivity.

- The rock **matrix porosity** provided by interconnected pores **is large;**
- The bulk **fracture porosity is extremely small.**

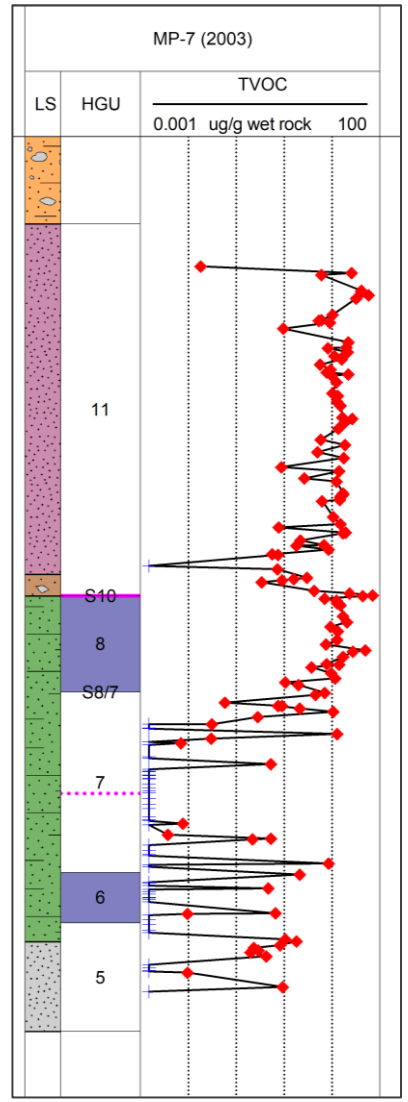


High Angle Fractures Control Groundwater Flow Vertically

Morgan, MS, 2019, Meyer et al. 2023, Journal of Hydrogeology



Head profiles inflect at fracture termination horizons

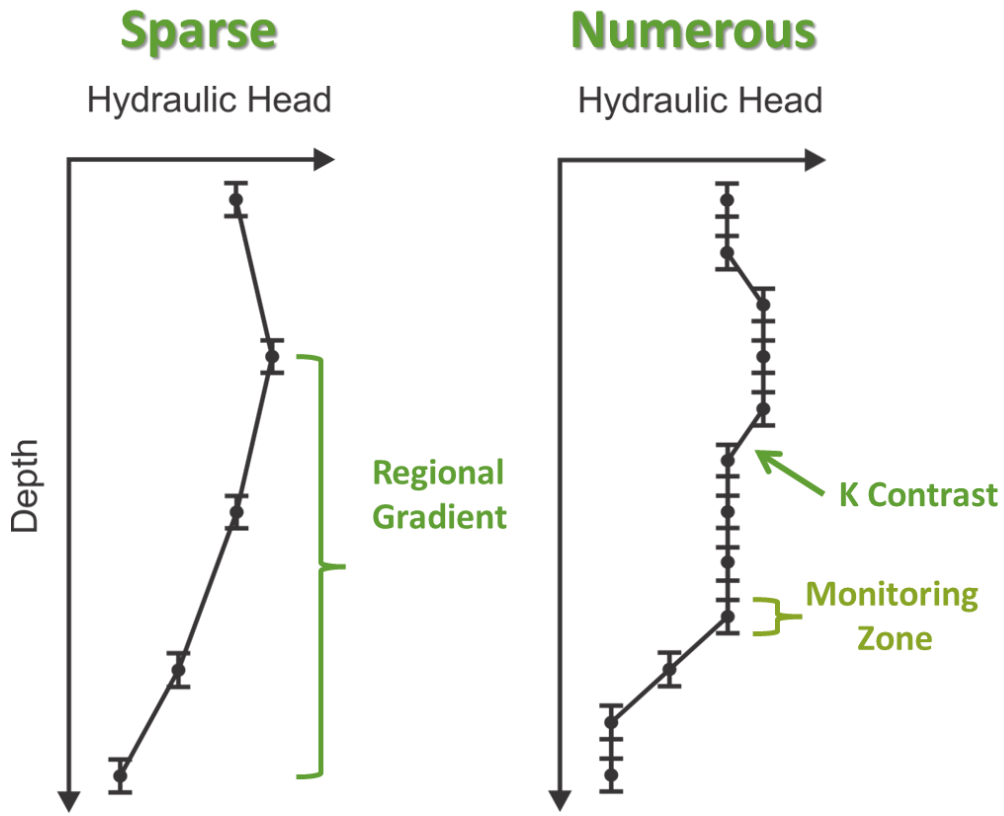


Facture termination horizon contributed to stopping downward DNAPL migration

Austin, MS, 2005, Meyer et al. 2023, JOH

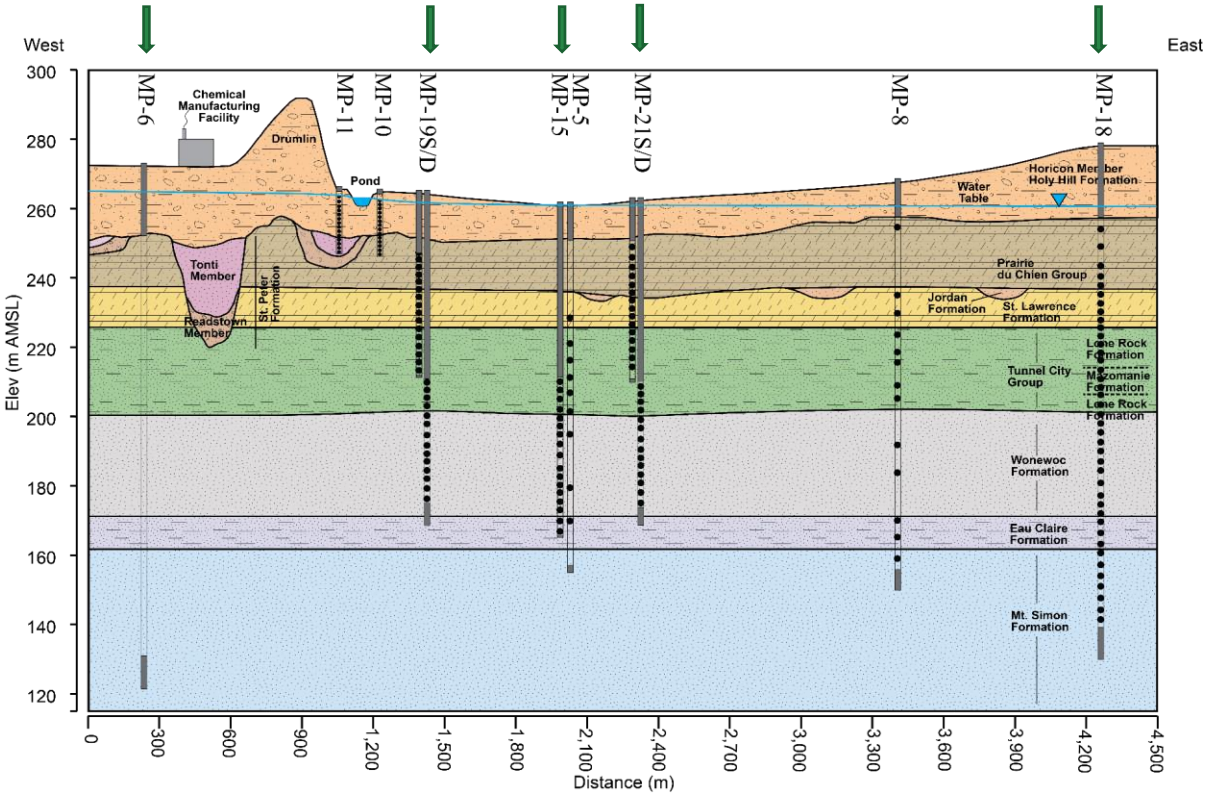
High- vs. Low-Resolution Monitoring Systems

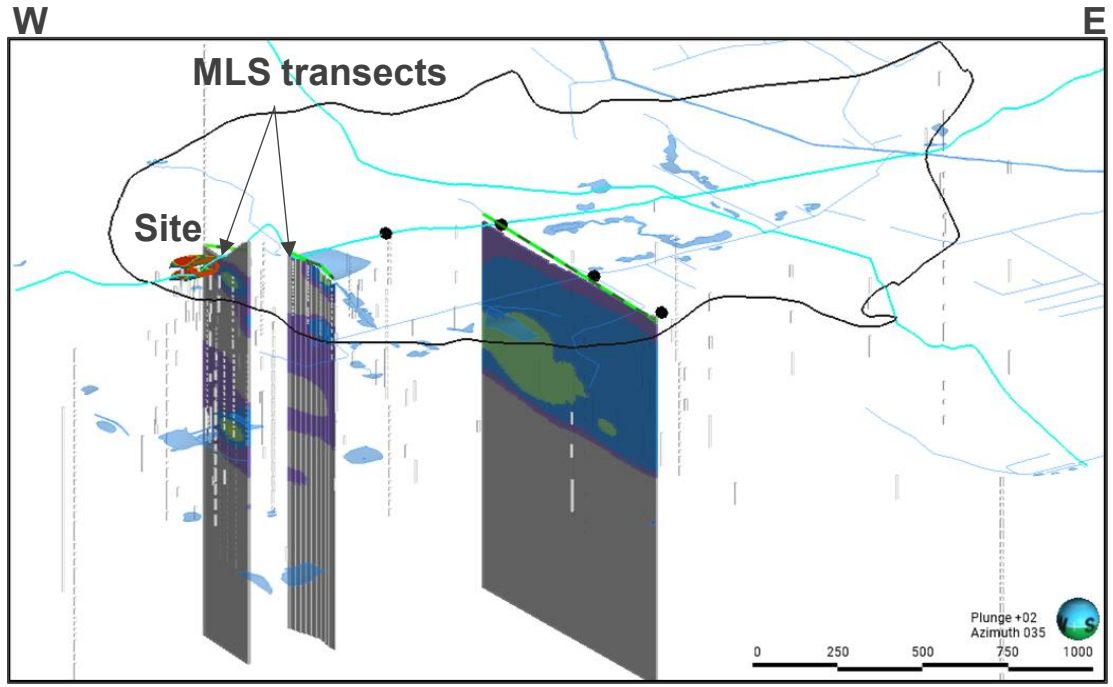
- High resolution MLS includes between 3 and 5 monitoring zones per 10 meters of borehole.
- Westbay MLS has been used for decades in geotechnical applications to assess slope stability, pore water pressure, and seepage within dam structures.
- In sparse monitoring intervals, we are missing details in vertical heterogeneity of system.
- In numerous monitoring intervals, uncertainty is reduced when sampling datasets adequately represent heterogeneity at the scale of the problem.



High-Resolution 3D/4D Data Provides Transient GW Flux and Contaminant Flux

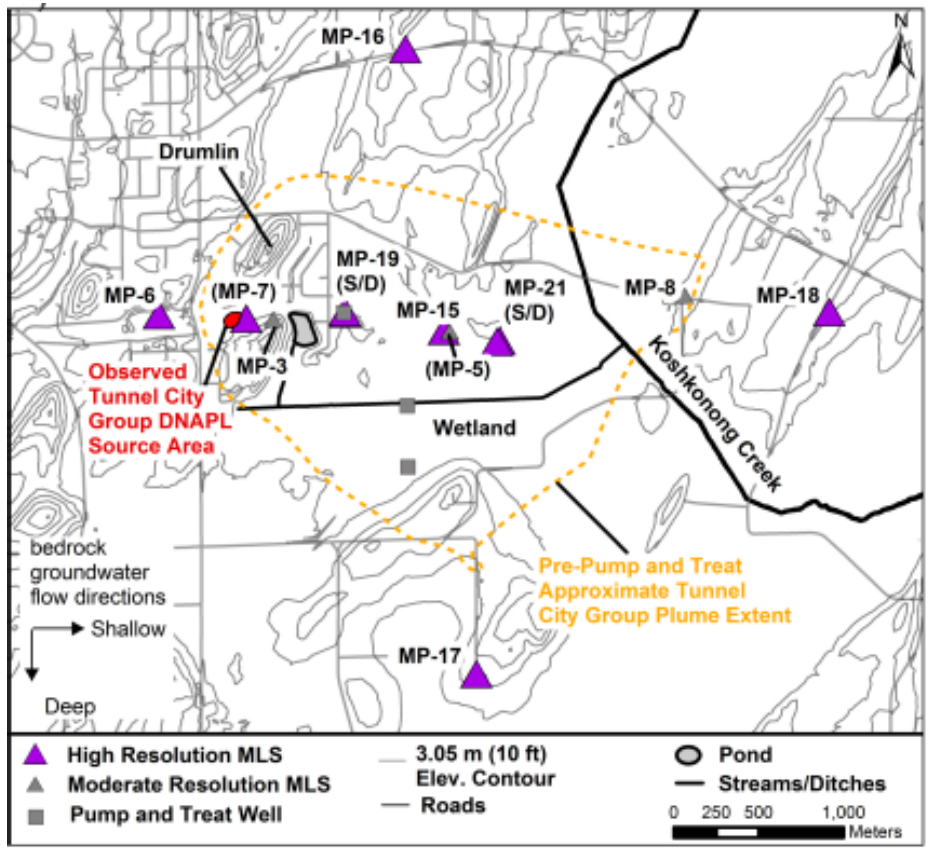
- Vertical head and contaminant profiles over multiple time periods:
  - *Hydrogeologic unit delineation, includes fracture vertical connectivity*
  - *Estimate fluxes through transects of MLS (groundwater and contaminants)*
- **Transient monitoring** provides flux with time and better understanding of units contributing to mine inflow or dewatering flow.

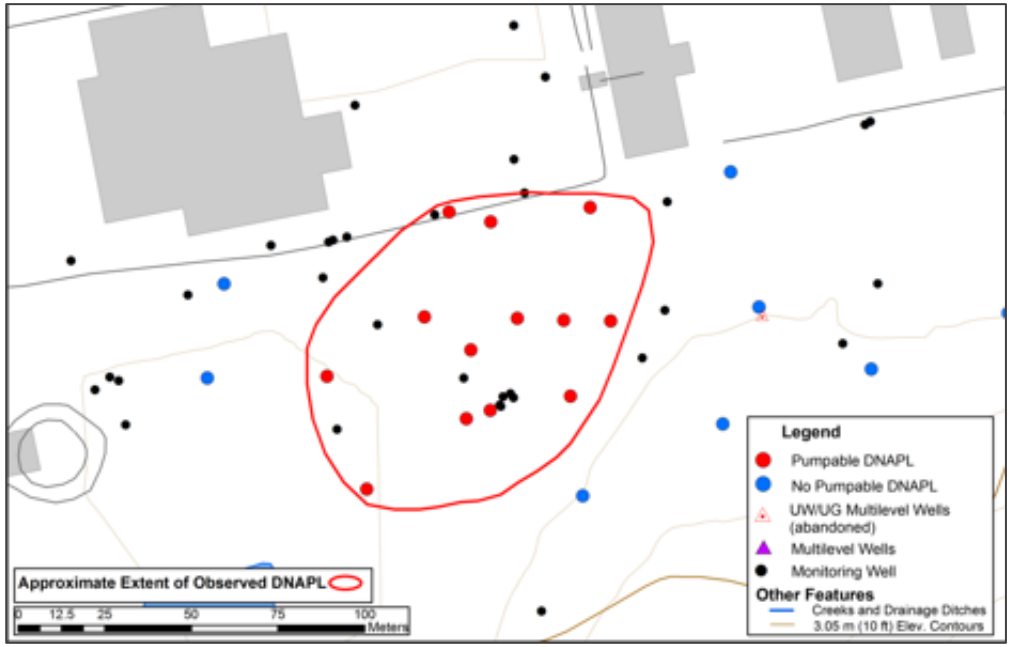




Field Remedial Activities

- 1997 – 2000: Air sparging/soil vapor extraction
- 1998 – 2001: DNAPL pumping from the Tunnel City Group. Pumped 9,000 gallons of DNAPL (164 drums)
- 2001 – 2002: Private wells decommissioned in the Tunnel City Aquifer and replaced by wells screened in the deeper aquifer
- 2003 – Present: Hydraulic Barrier System (HBS) pumping in the Tunnel City.





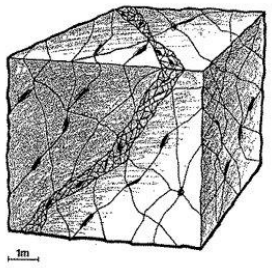
Pumped DNAPL locations

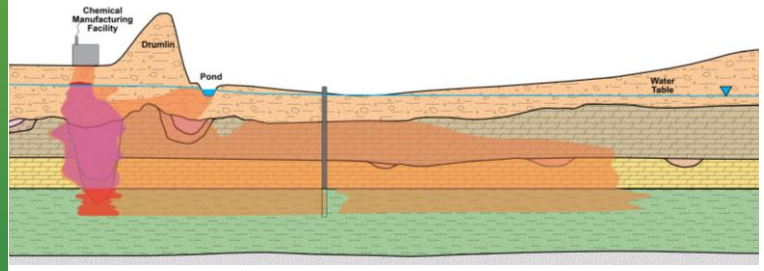
Dual-porosity Modeling to Represent Two Domains in the System

- The model is the tool that represents the conceptual model quantitatively.
- It allows us to interpret data and apply it to predict future behavior of the system.

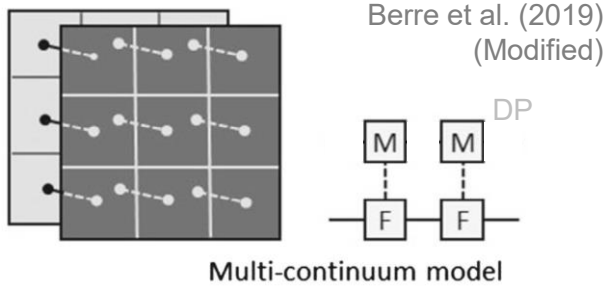
Site Data
& Physical Process Knowledge

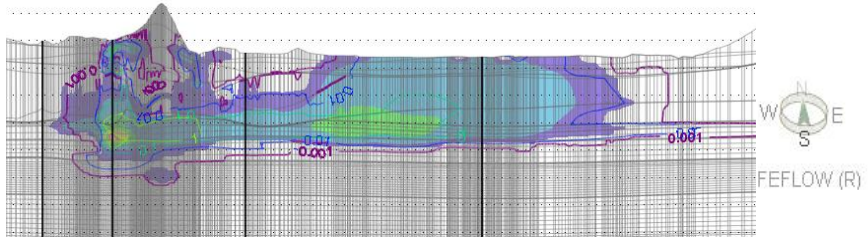
Numerical Model Suite
Simulated 3D Flow + Transport



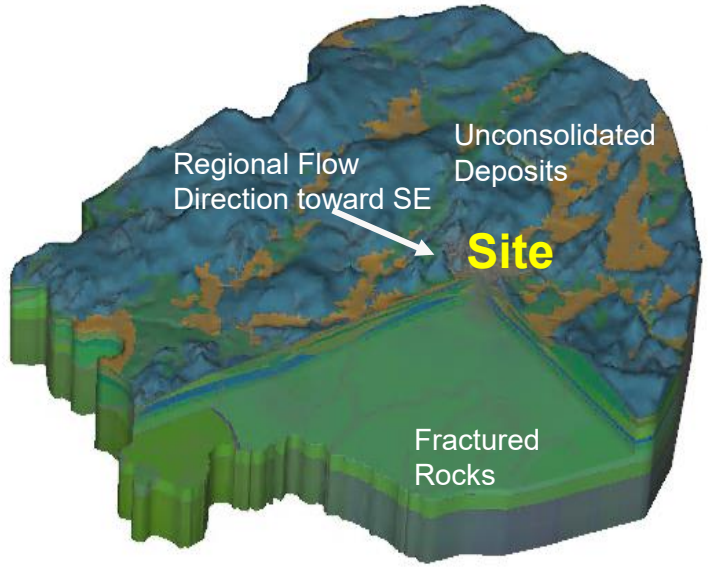


Discrete Fracture Network-Matrix (DFN-M) Model using **HydroGeoSphere** to determine matrix block sizes.





Dual Porosity model using **FEFLOW** to simulate groundwater flow, fate and transport.



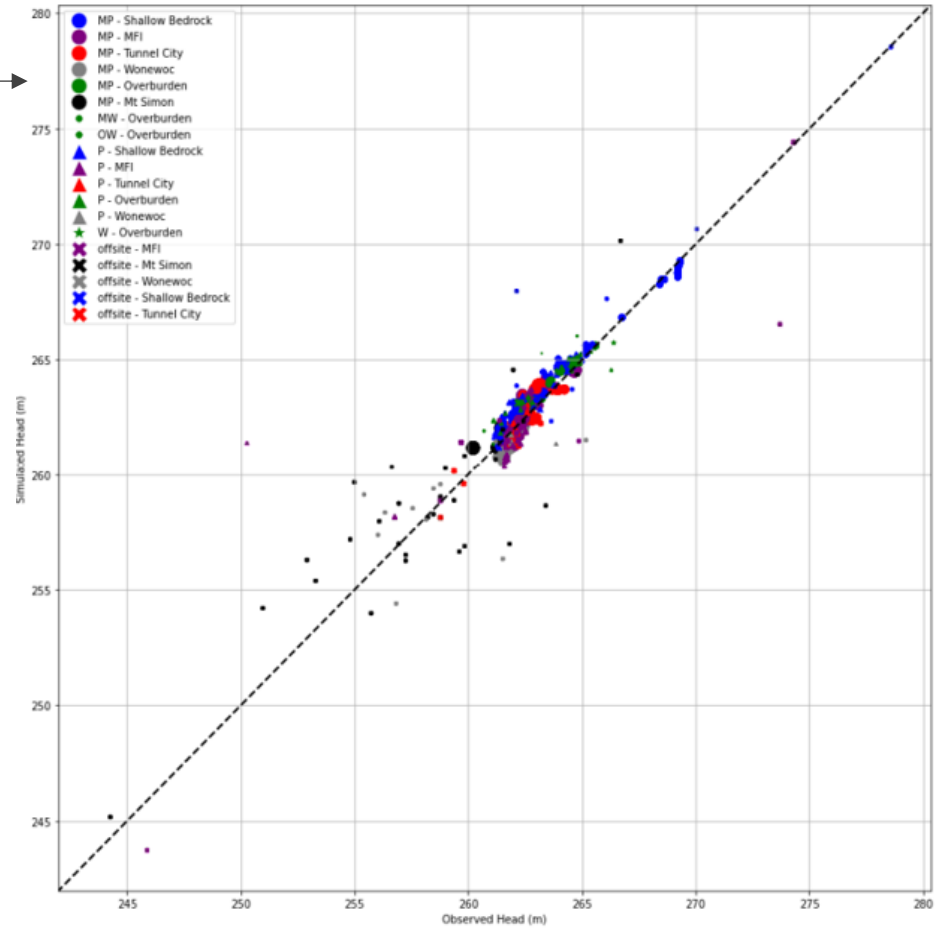
Model dimension: 240 km^2
W×H×D = 19 km × 18 km × 160 m

3D Model

Vertical Head Profiles Help Constrain Parameters in Flow Model History-Matching

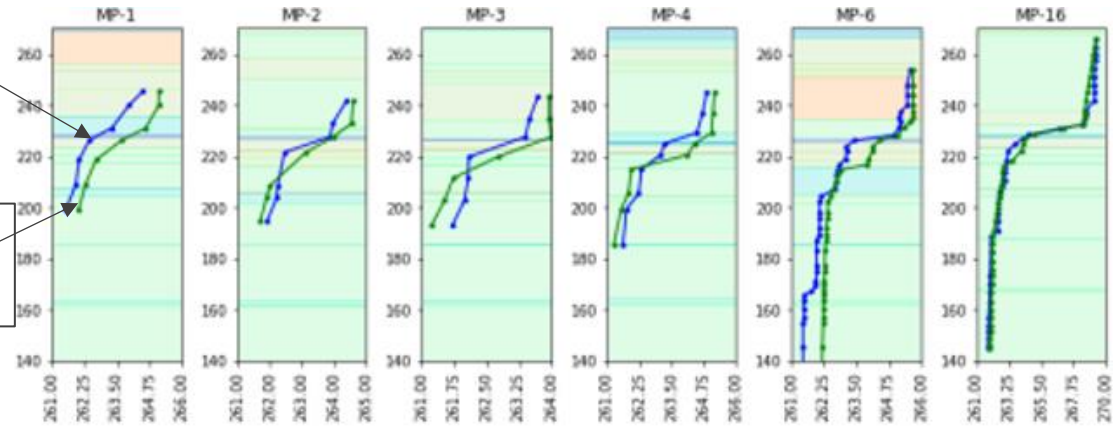
- Typically, model history-matching relies on single data measurements of hydraulic head from single-piezometer boreholes, represented as a 1:1 plot for steady-state heads.
- Vertical head profiles delineate the impact of pumping on the flow system and enhance the accuracy of simulated heads at locations with MLS monitoring wells.

Simulated vs. Observed Steady-State Heads



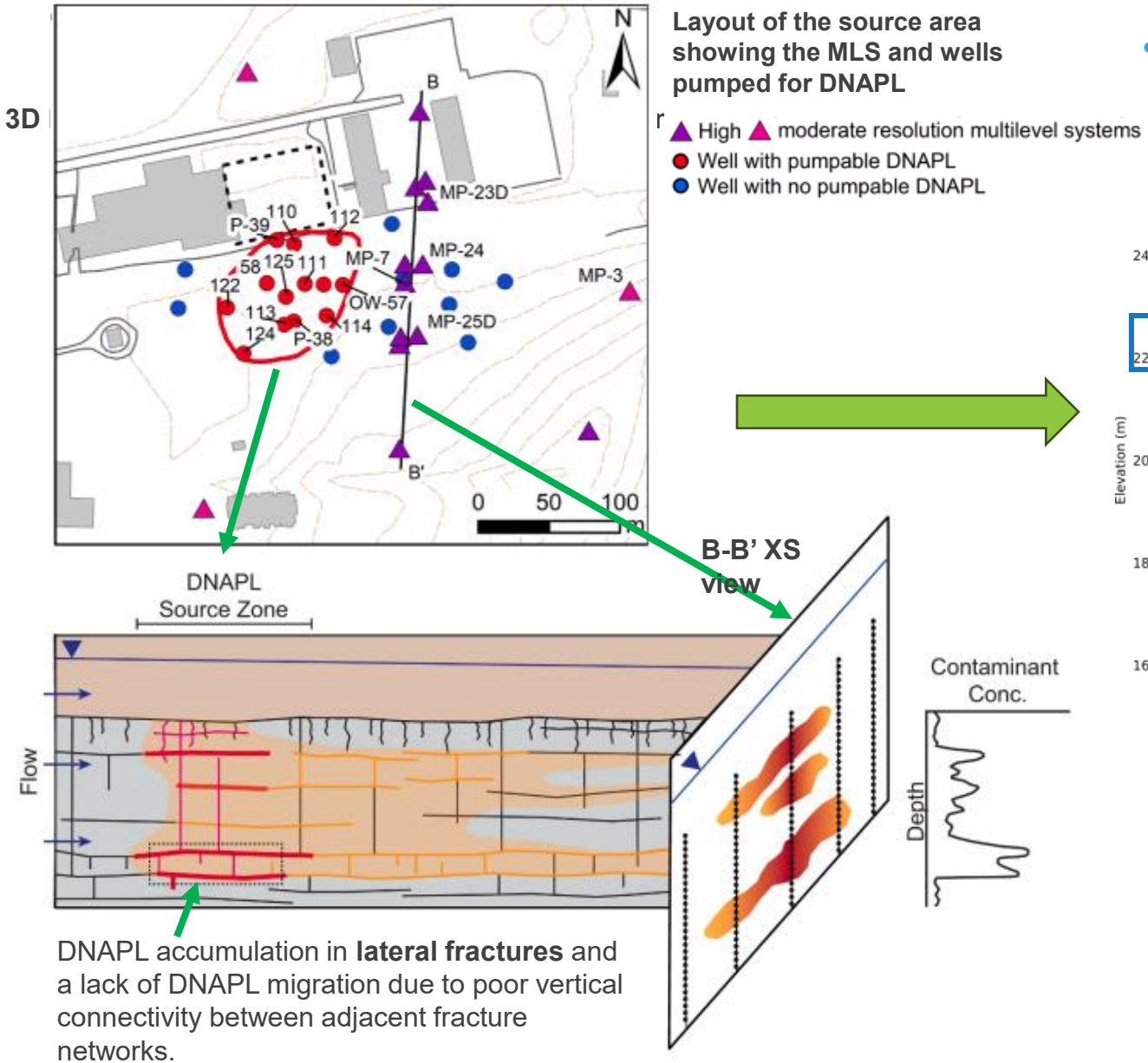
Observed MLS heads

Simulated MLS heads

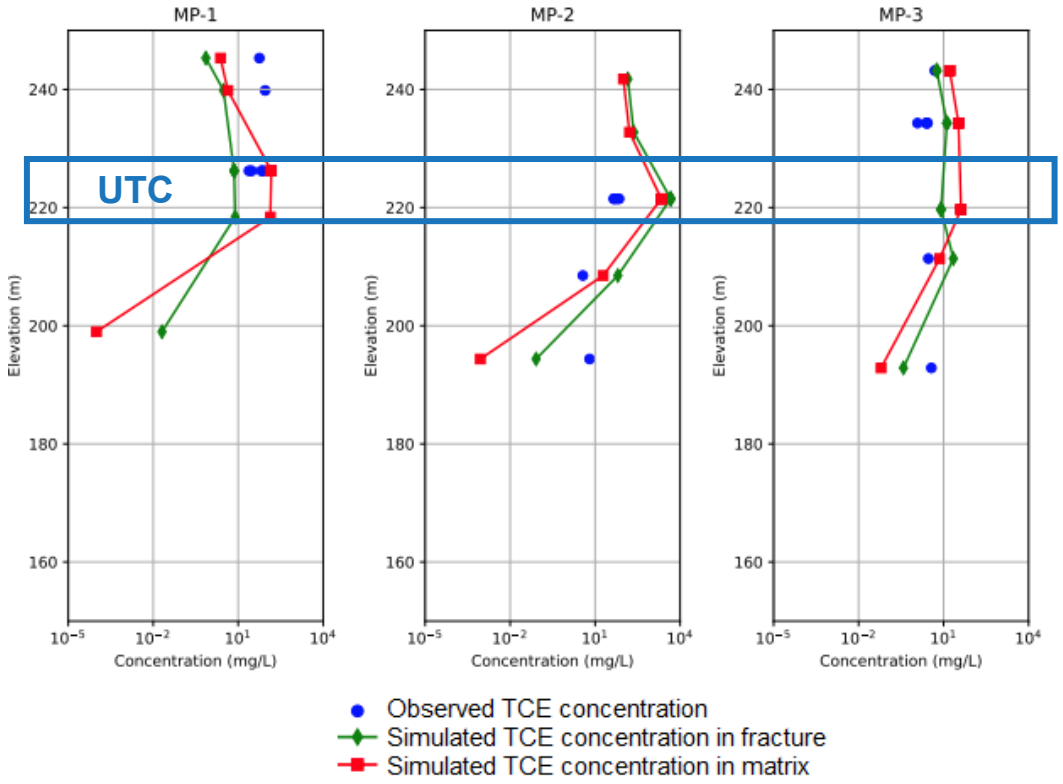


Simulated vs. Observed Vertical Head Profiles during pumping

Vertical Contaminant Profiles delineated by MLS and Transport Model History-Matching



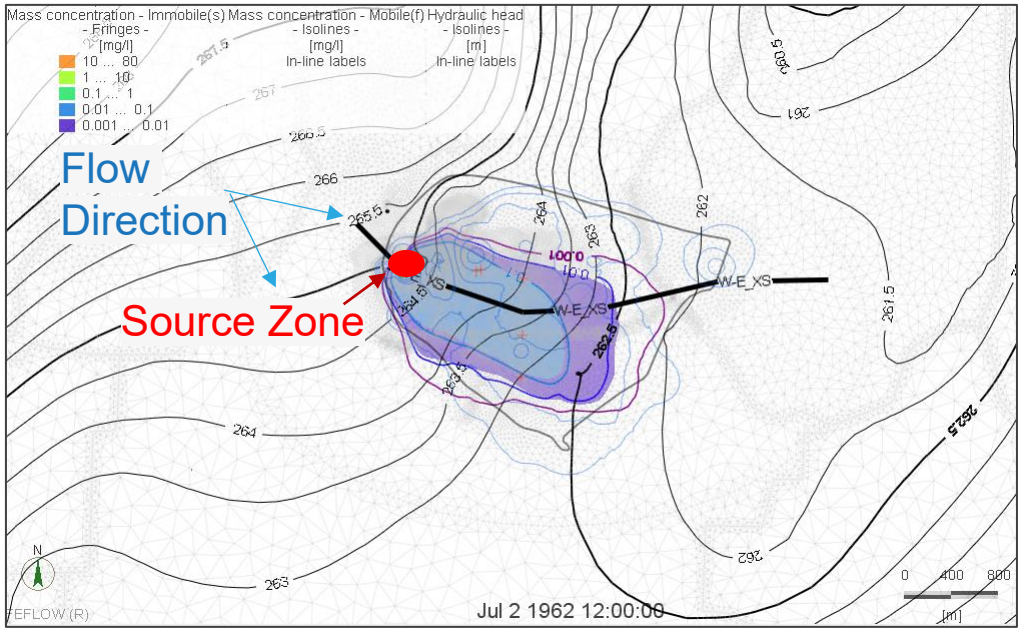
- Transport model was simulated using dual-porosity model representing fracture and matrix.



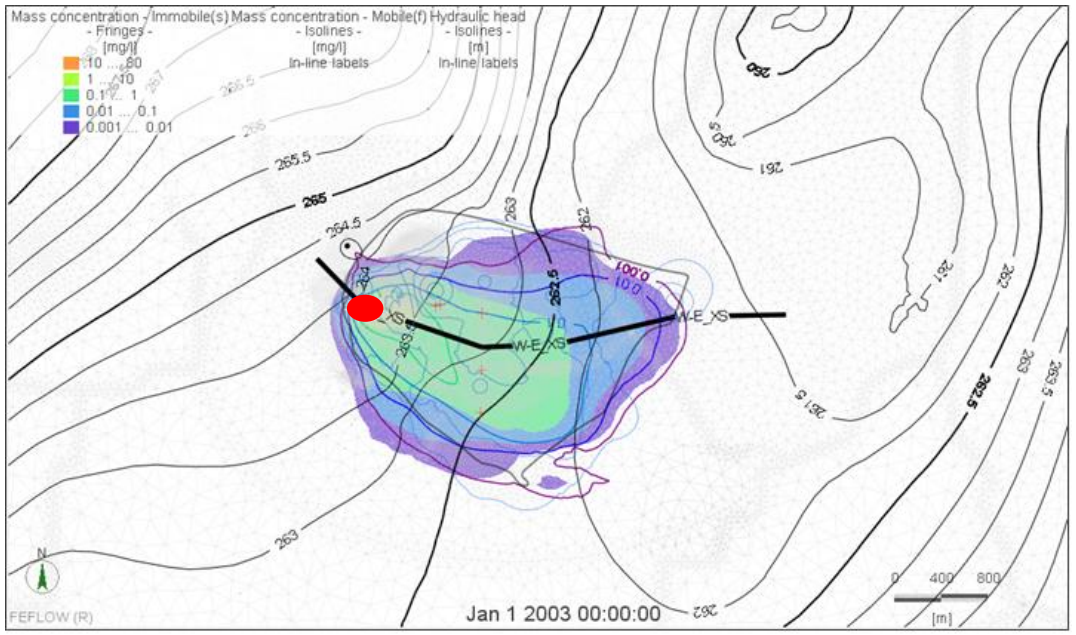
Transport Model Results – TCE Plume Evolution

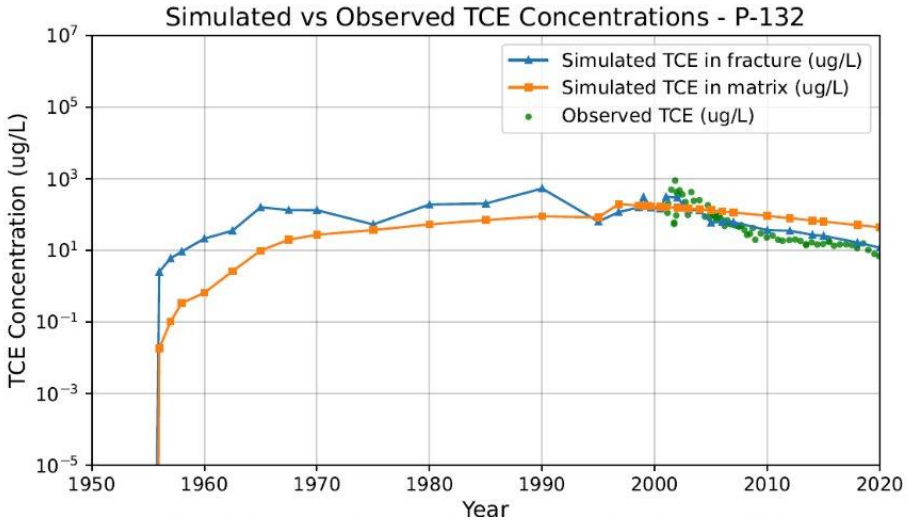
***1955:** DNAPL release at the Site. **2003:** Pre-Hydraulic Barrier System installation.*

Plan view - 1962

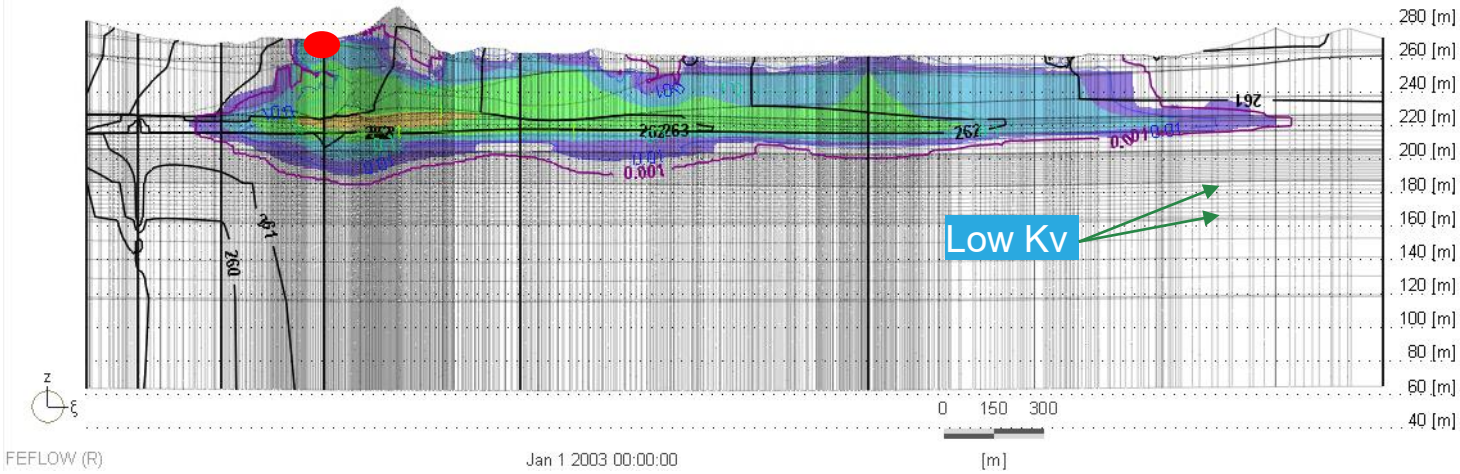


Plan view - 2003

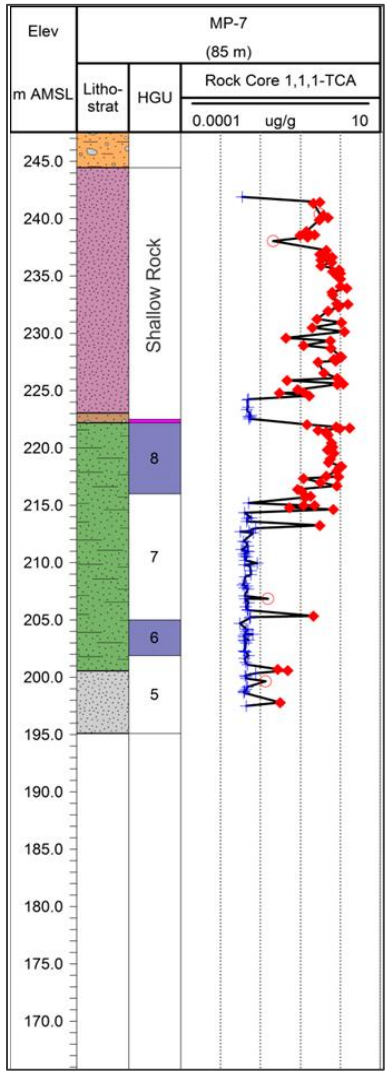




W-E Cross-section view - 2003



Dissolved mass mostly resides in the matrix



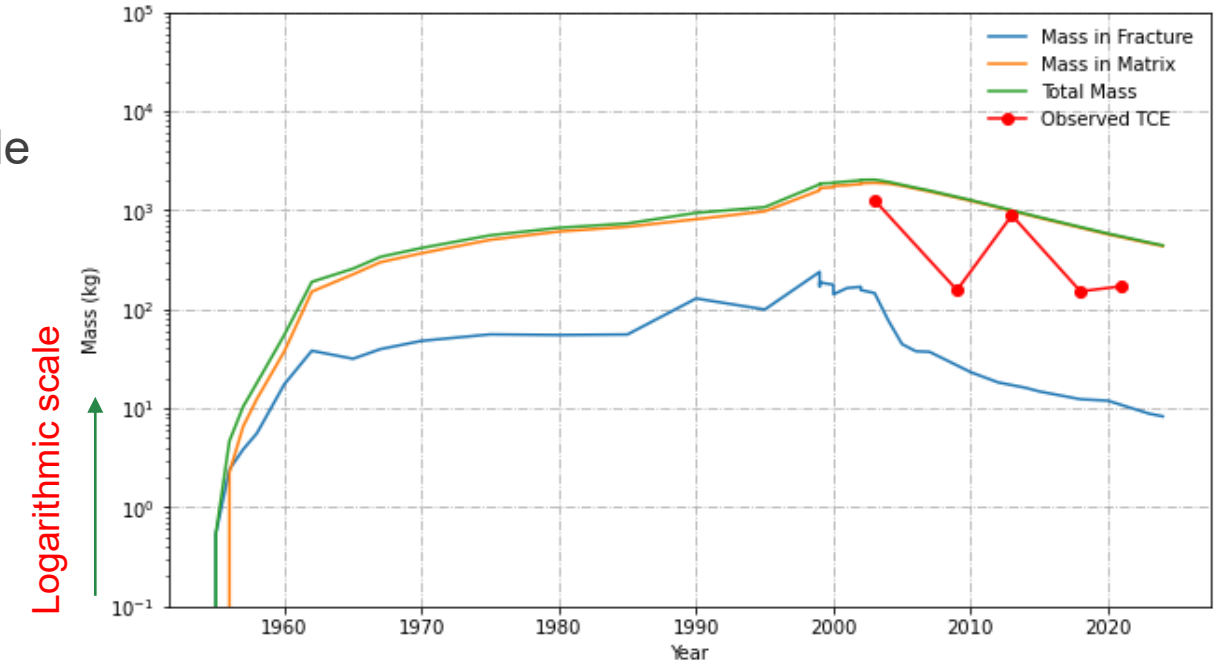
VOC Rock Core Data:

- Strong matrix diffusion fluxes over decades, and
- Large mass storage in the matrix porosity.

→ Majority of the mass in the dissolved phase plume to reside in the lower permeability rock matrix.

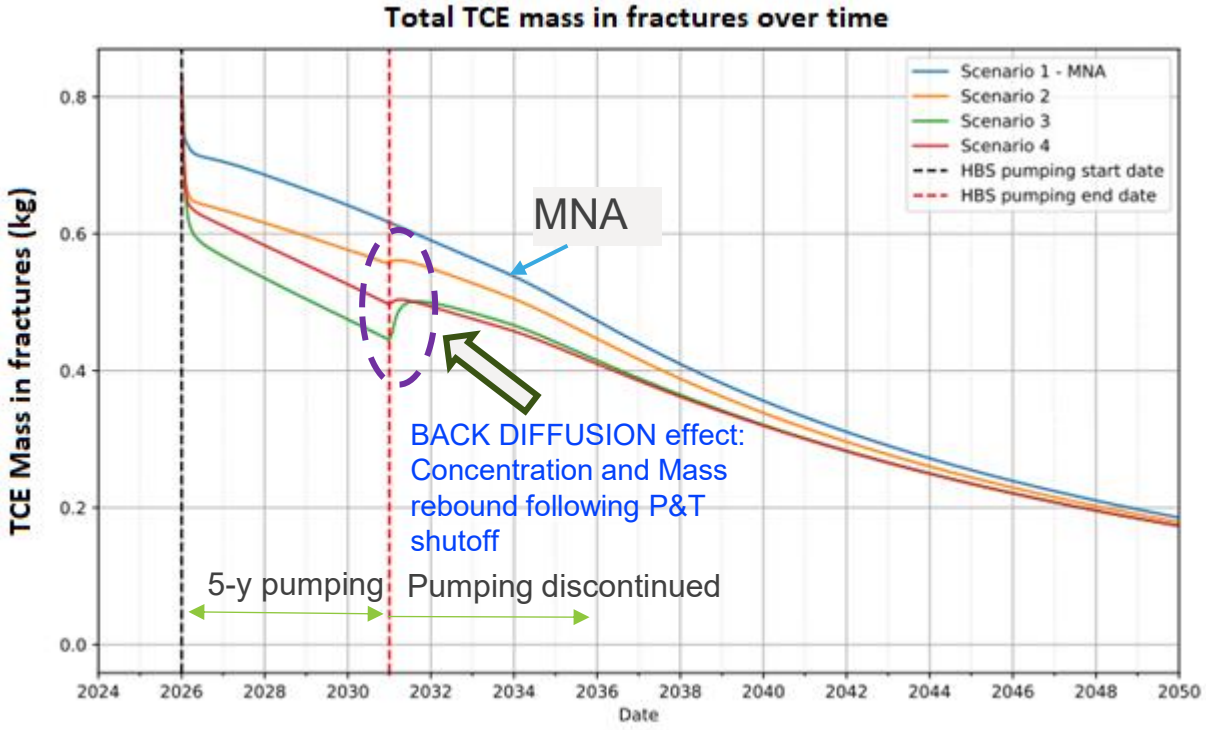
Model Results:

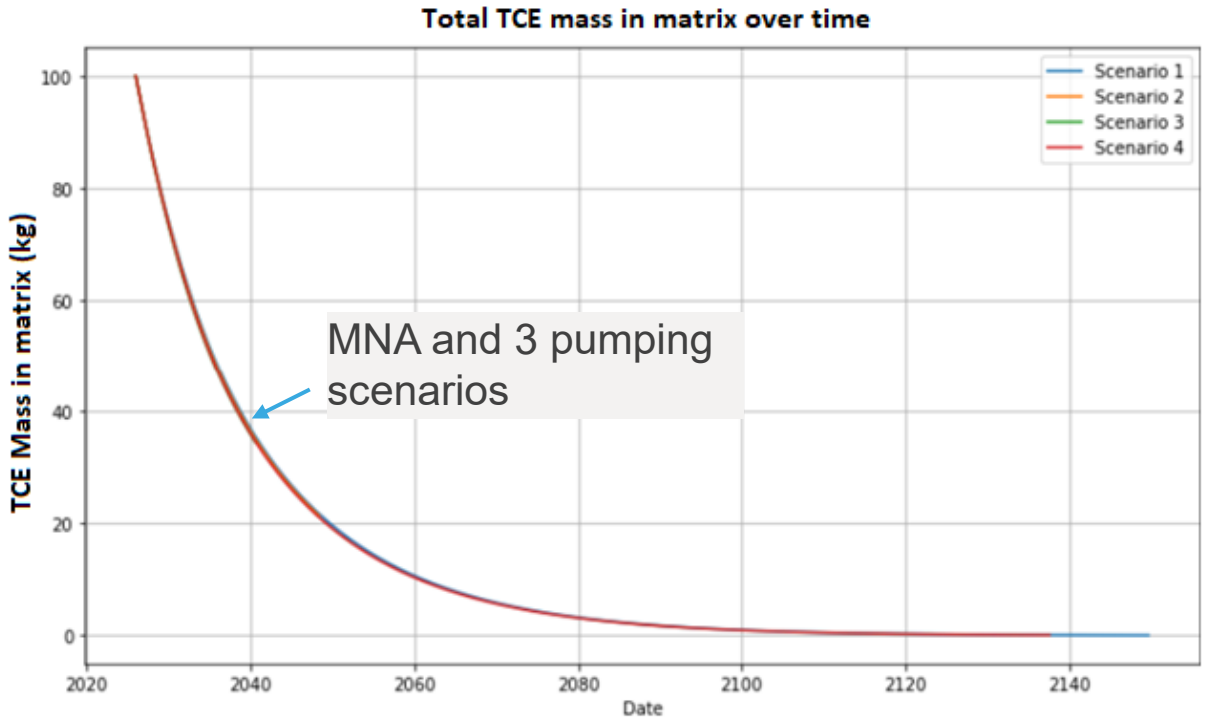
- Over 98% of the mass resides in the matrix in 2020.
- Red lines are observed mass in the system.



Corrective Measures Study: Back-diffusion does not enhance pumping effectiveness

- Evaluate the **pump-and-treat (P&T)** effectiveness: One MNA scenario and three pumping scenarios.
- Left plot shows mass reduction in fractures; right plot shows mass reduction in matrix.
- **Back diffusion** contributes only less than **0.5%** of the total mass transferred from the matrix to fractures and therefore has limited impact on mass removal rates and remediation timeframes.





Summary and Conclusions

- High-Resolution monitoring data can:
  - Increase confidence in hydrostratigraphy, structures, connectivity, and water quality variations.
  - Reduce uncertainty, benefits water management costs, remediation and closure costs, including monitoring programs.
- All studies can benefit from at least one high resolution multi-level system to characterize the levels of heterogeneity at the site.
- Numerical modelling reproduced plume evolution in a dual-porosity system, showing matrix back-diffusion has limited impact on overall mass removal and remediation timeframe.

Thank you!

- **Huyen Nguyen** – Senior Hydrogeological Engineer: hnguyen@montrose-env.ca
- **Daron Abbey** – Technical Director: dabbey@montrose-env.ca
- **Beth Parker** – Professor: bparker@uoguelph.ca
- **Jessica Meyer** – Assistant Professor: jessica-meyer@uiowa.edu