



Conceptual Site Model Re-Development and Discrete Fracture Network Modelling at a Contaminated Fractured Bedrock Site

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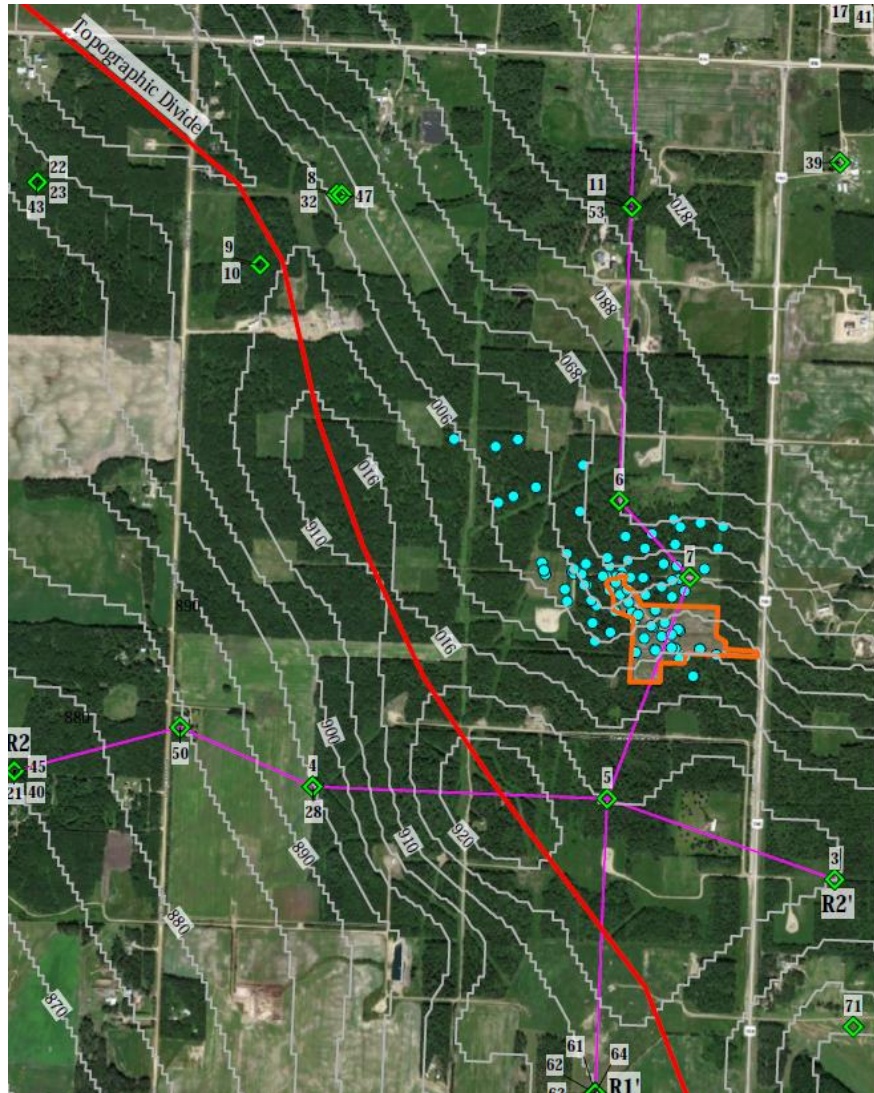
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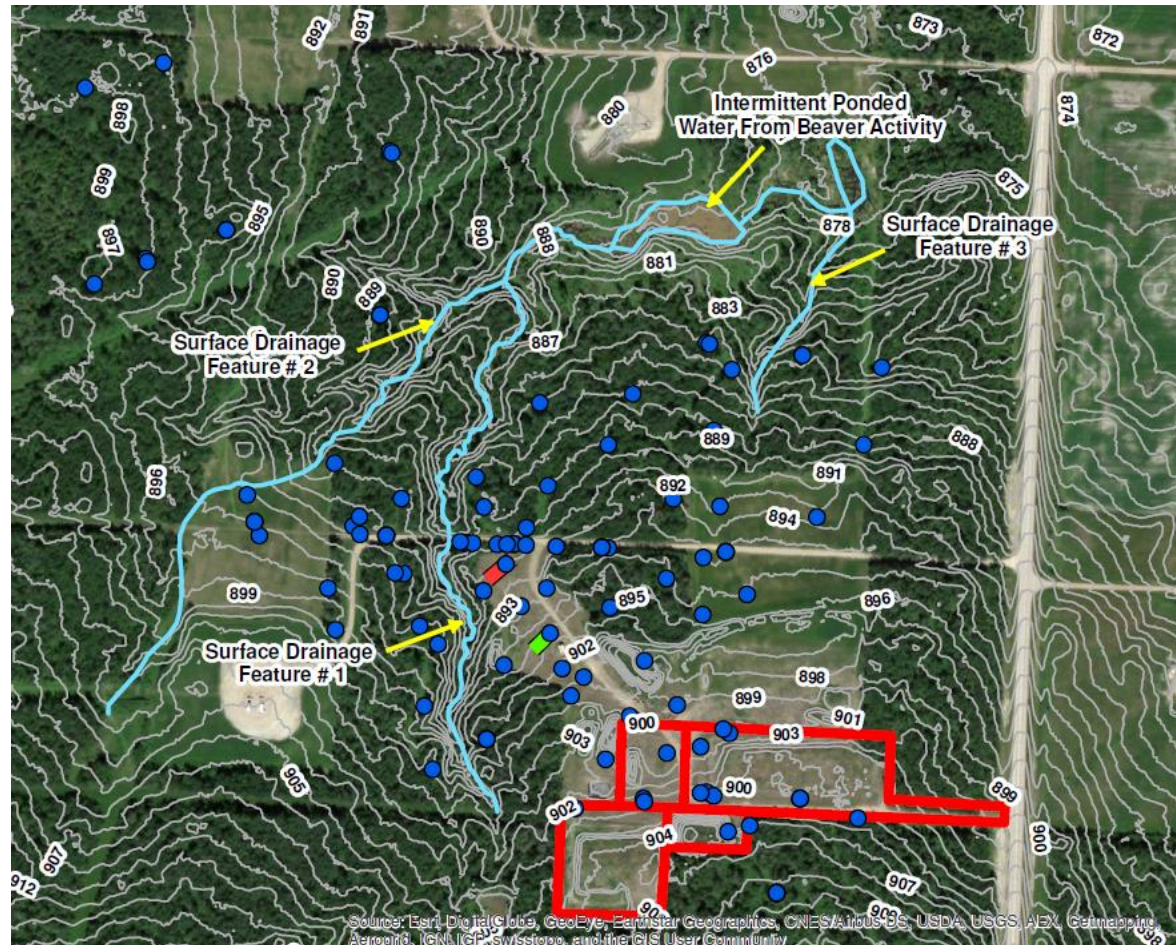
Overview

- Site Physical Setting
- Source Areas and Current Distribution of Impacts
- Evolution of Conceptual Site Model (CSM) and Implications
- Remediation Action Plan and Path Forward

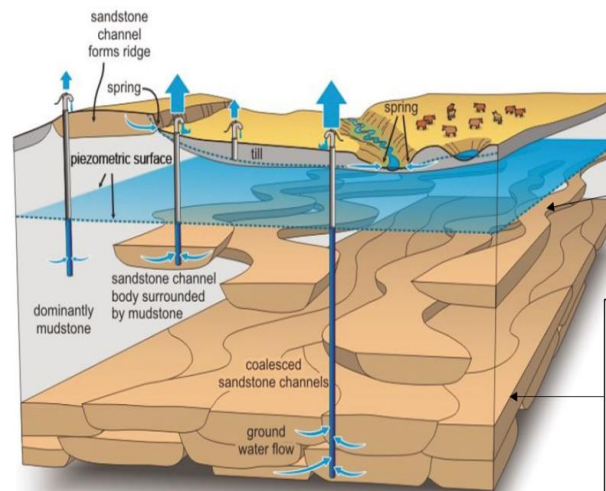
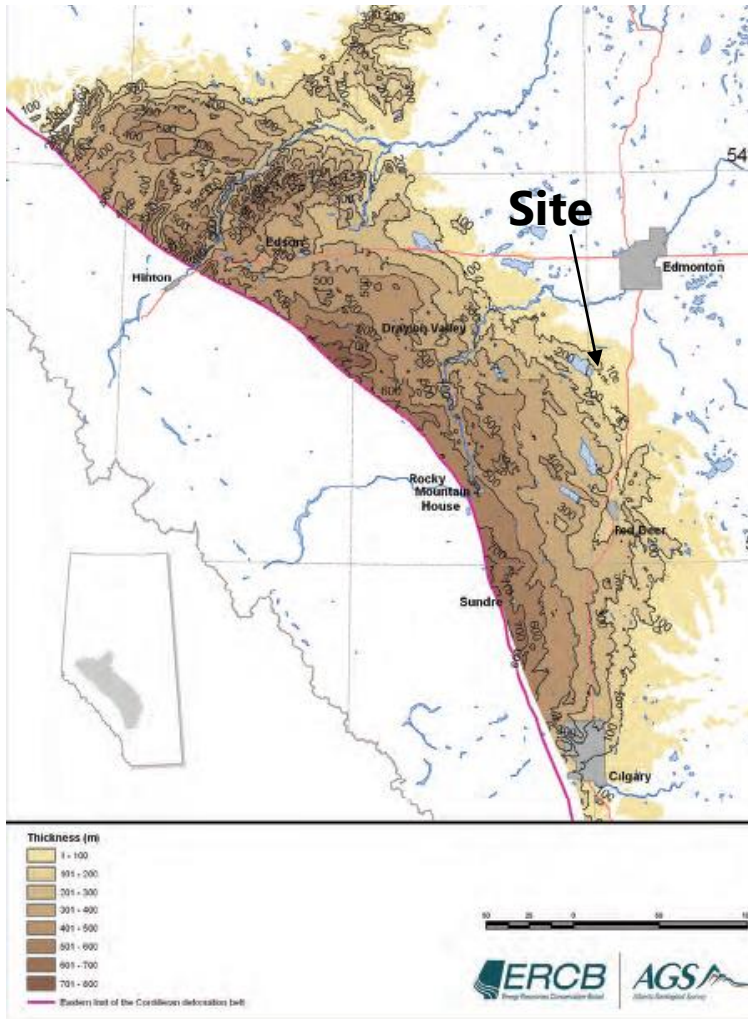
Site Physical Setting – Topography and Drainage



Site Physical Setting – Topography and Drainage



Site Physical Setting – Paskapoo Formation Geology



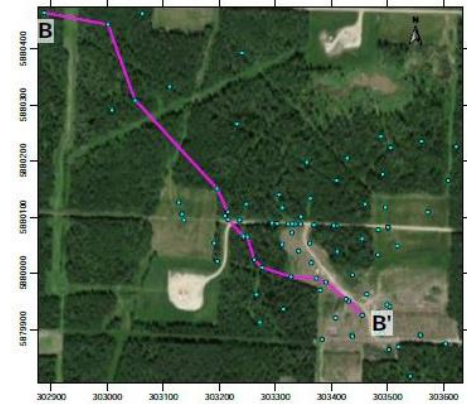
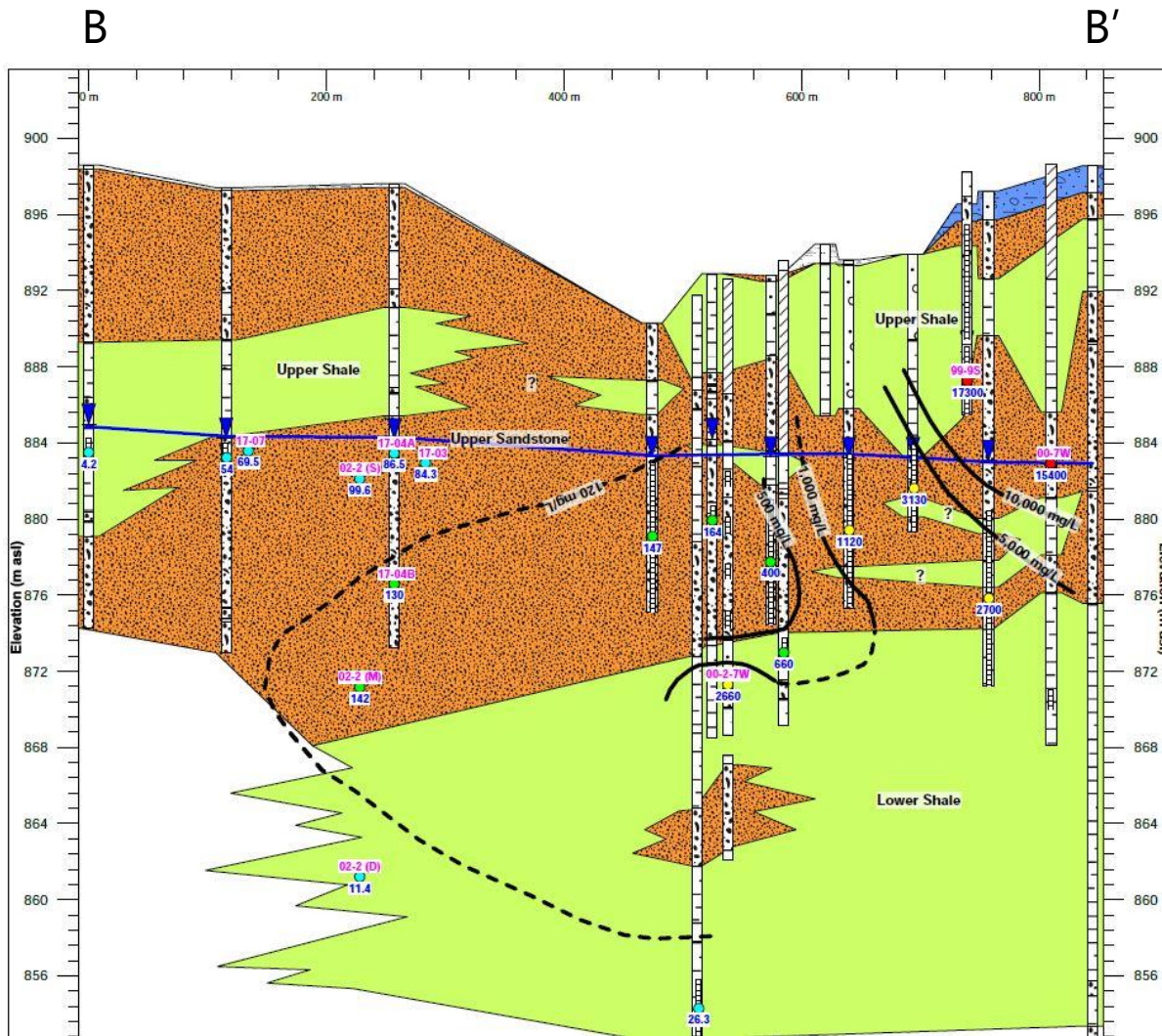
Lacombe Member as exists at the Site. May provide good production, if fractured. Storage could be quickly depleted if overstressed.

Haynes Member - laterally continuous due to fluvial sandstone channels joined together. Provides large permeable storage volume, and production to deep wells, if fractured. Not present beneath Site as per Lyster and Andriashek (2012).

Primary Source Areas and Pre-Excavation Impacts



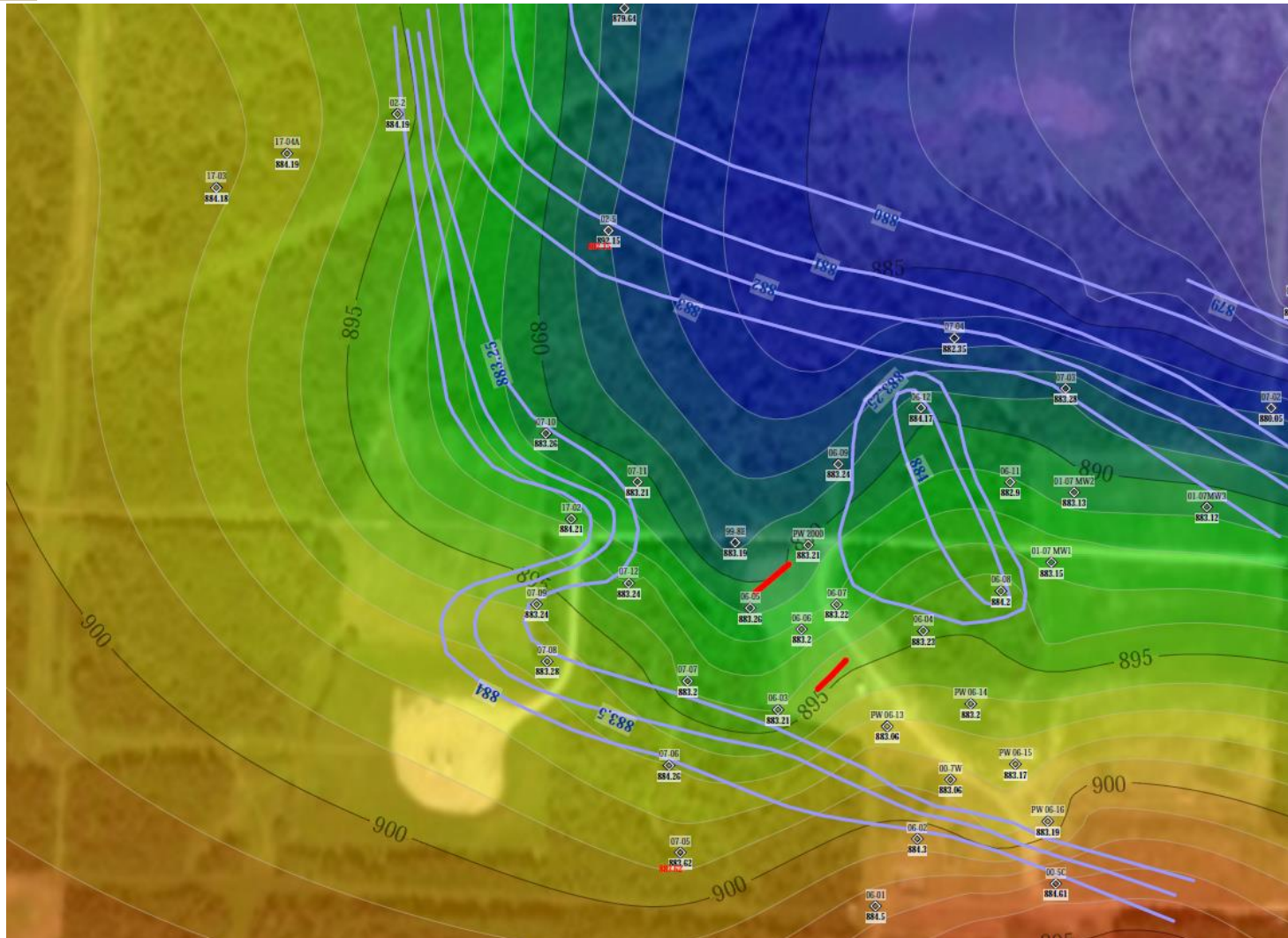
Hydrostratigraphy and Chloride Concentrations



Bulk Hydraulic Conductivities

- Shale - 7.4×10^{-6} m/s
- Sandstone - 5.6×10^{-5} m/s

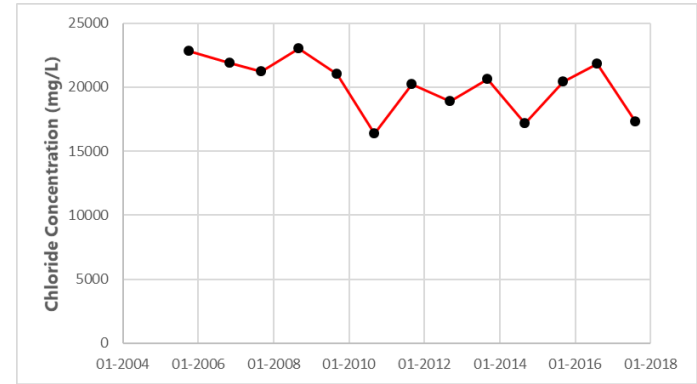
Groundwater Elevations - 2017



Evolution of Conceptual Site Model (CSM)

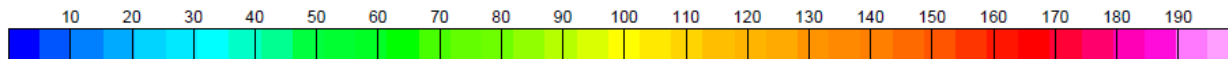
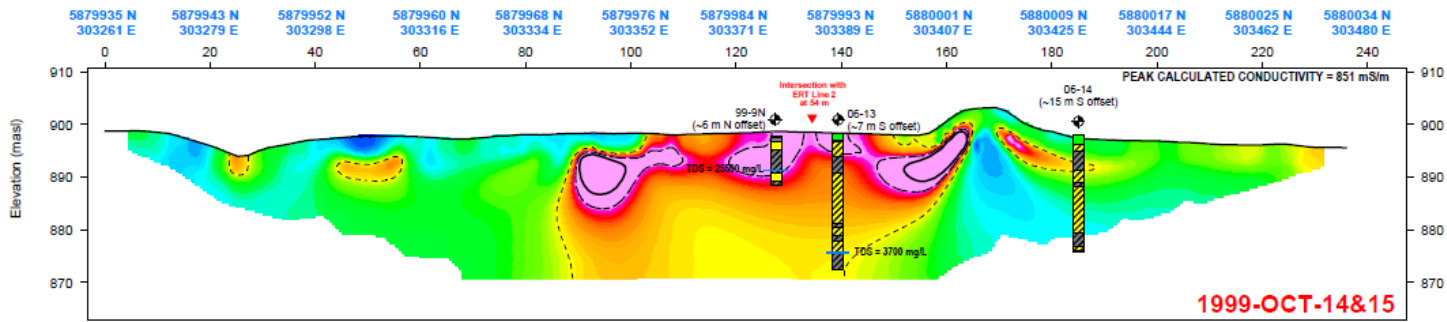
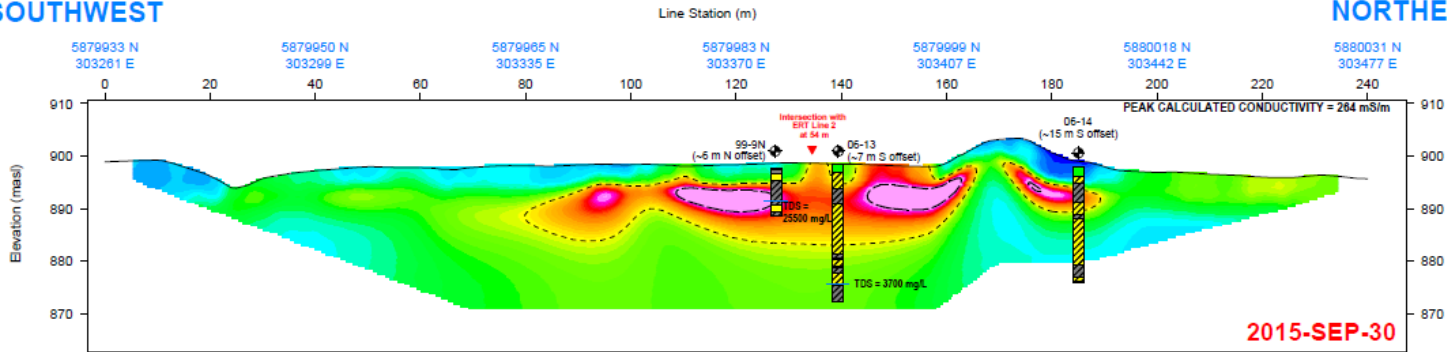
- **Pre-2015 investigation/monitoring**
 - general understanding of the geological and hydrogeological characteristics, plume delineation and partial source removal and containment
- **Post-2015 investigation/monitoring**
 - updated conceptual hydrogeologic model based on groundwater flow and solute transport in a fractured bedrock system
 - Based on direct and indirect lines of evidence:
 - Chloride plume evolution
 - Pumping test results
 - Fracture mapping
 - Numerical groundwater flow and transport modelling

(In)effectiveness of Pumping

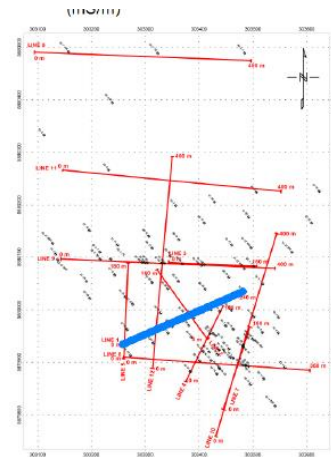


SOUTHWEST

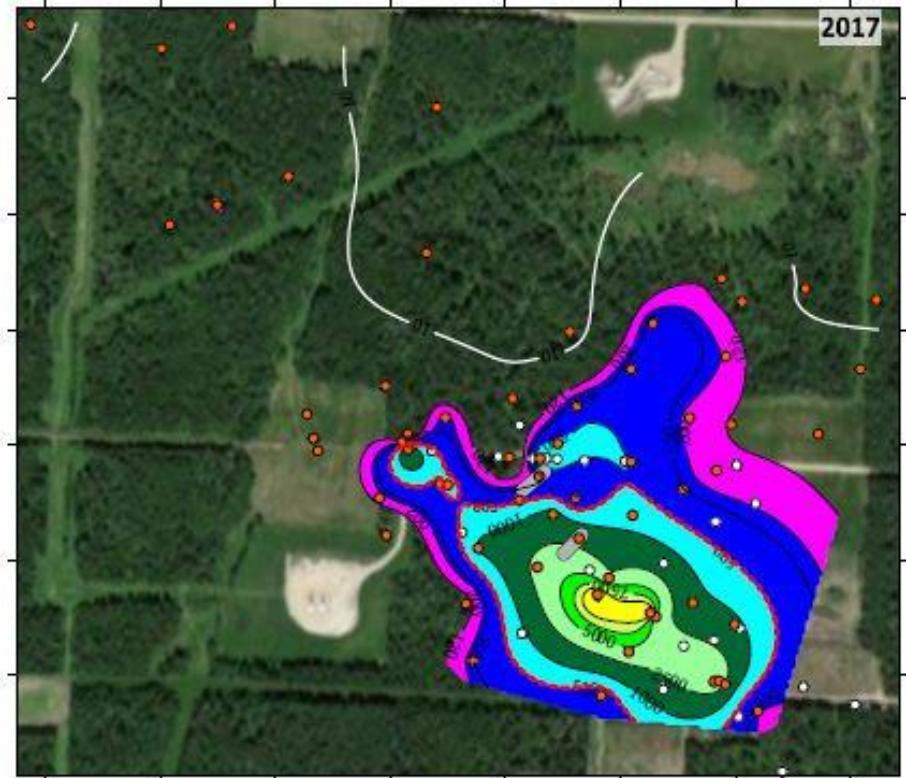
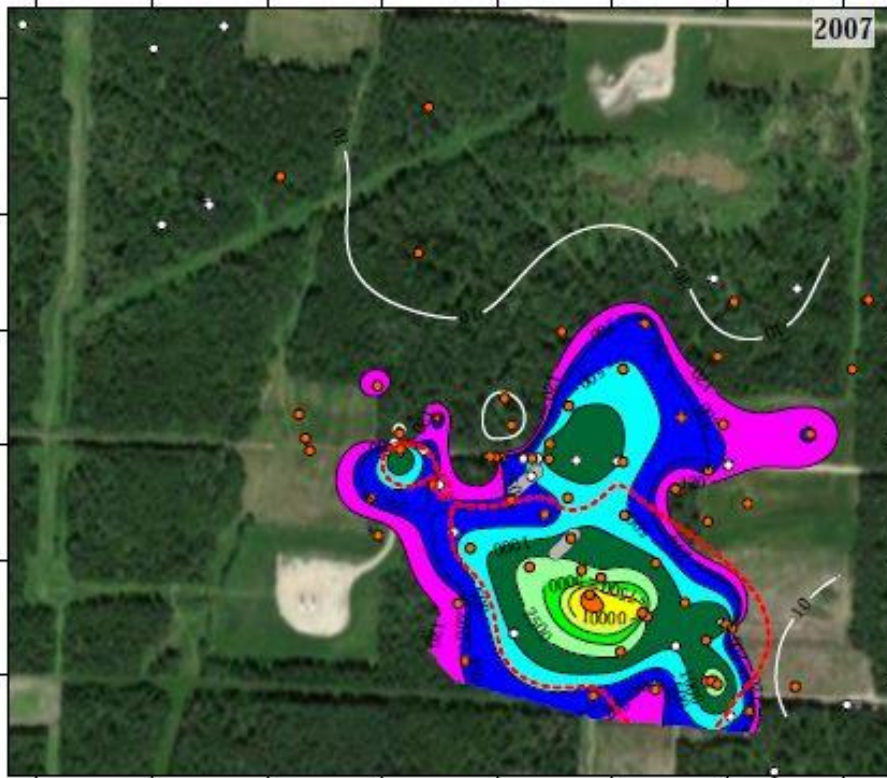
NORTHEAST



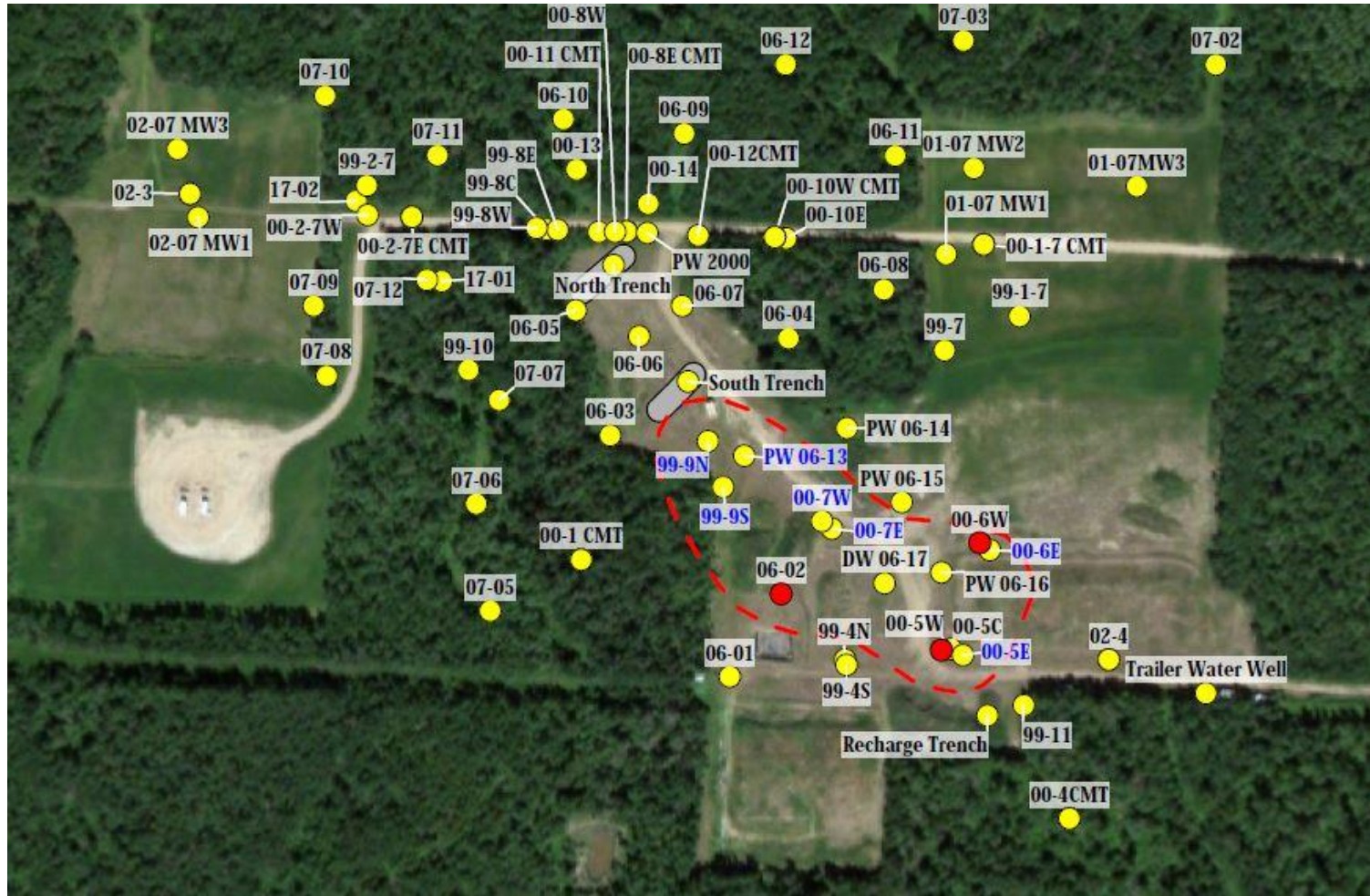
DRAFT



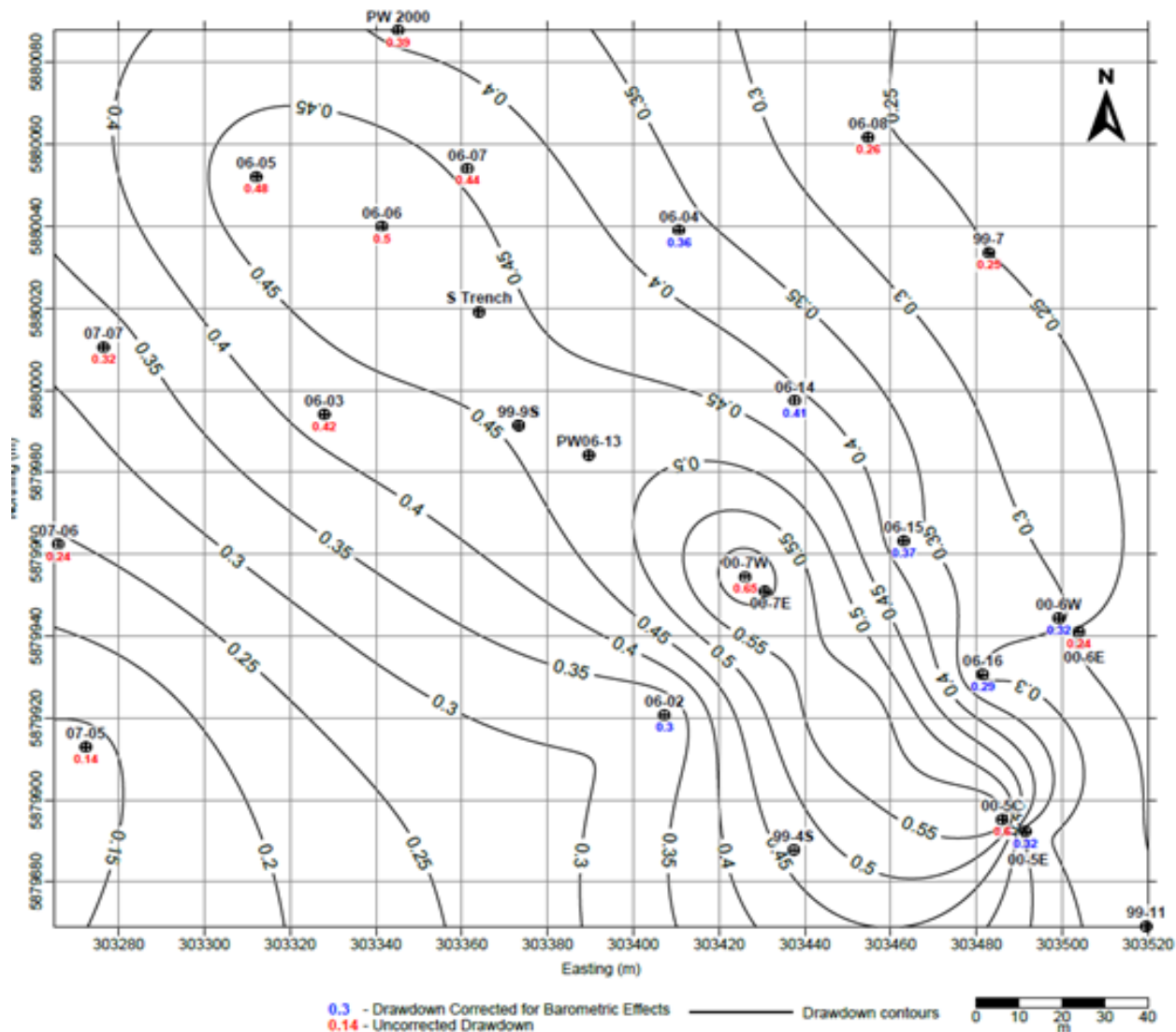
Plan View – 2007 and 2017 Chloride Concentrations



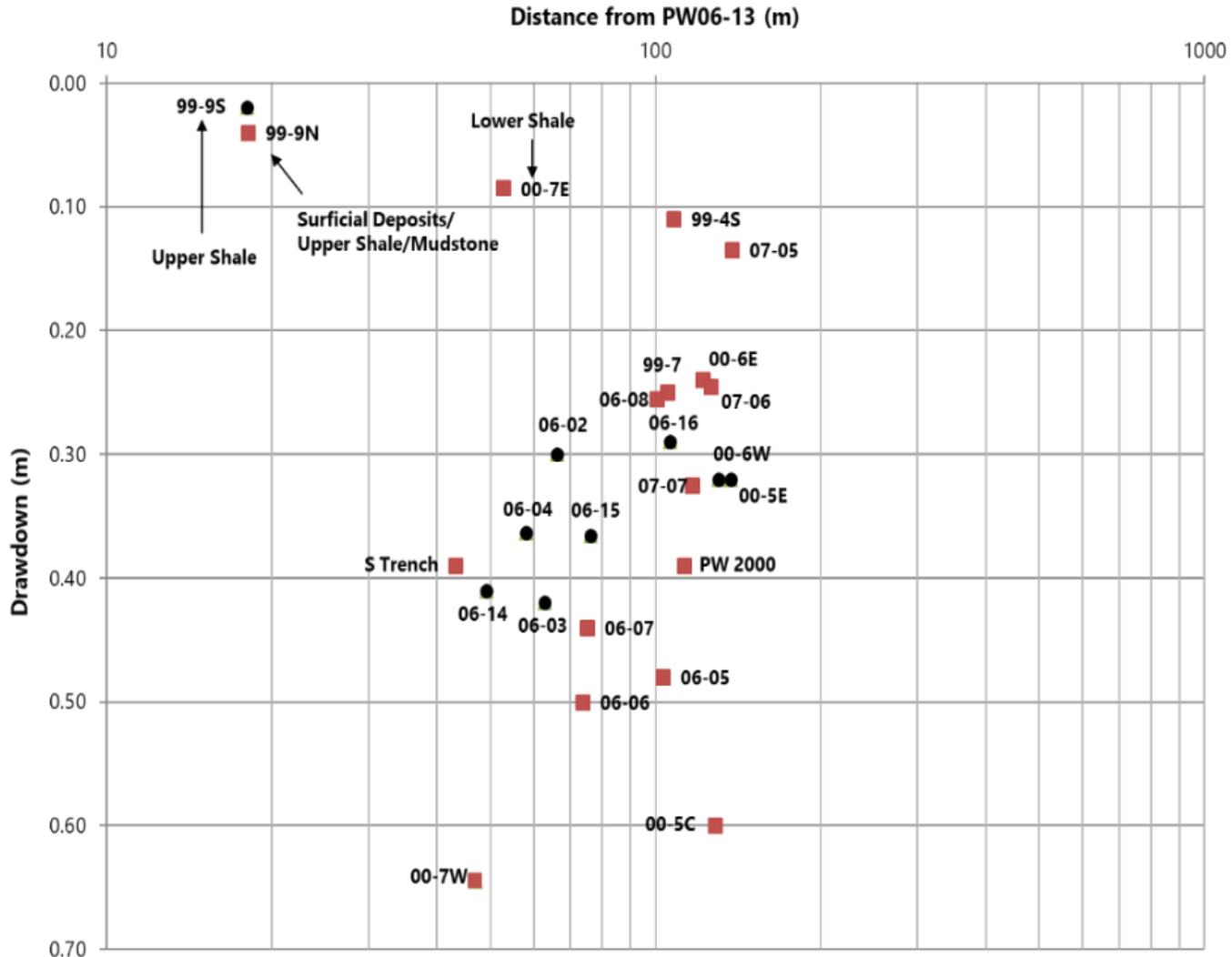
Plan View – 2017 Petroleum Hydrocarbons



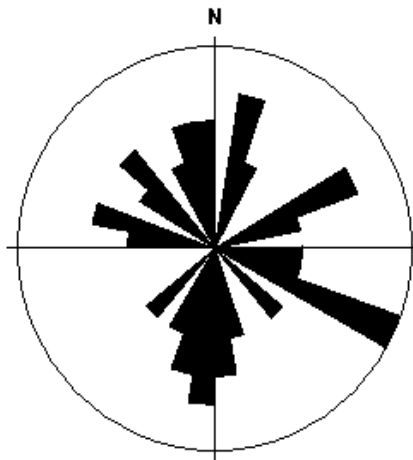
Pumping Test – Hydraulic Response



Pumping Test – Hydraulic Response



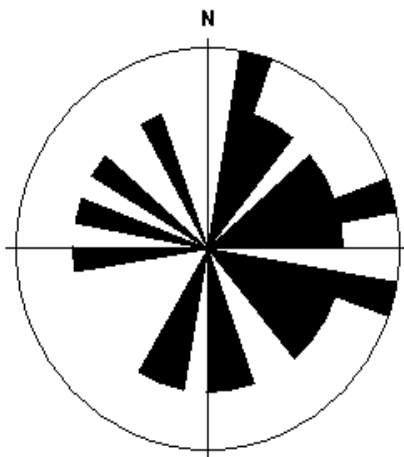
Paskapoo Fm. Fracture Mapping - Regional



Data from : Overbank Fractures Pask

Formation: Paskapoo Formation
Location: Red Deer River, AB
Section: Various Locations
Feature: Fracture Ovbk (n=37)
N: 37
Vector mean: 83.8
S.D.: 75.8
95% C.I. : 25.7
Mag. var.: 0
Circle = 13 %
Petal arc: 10 deg.
Binning from: 0 deg.

Non-linear



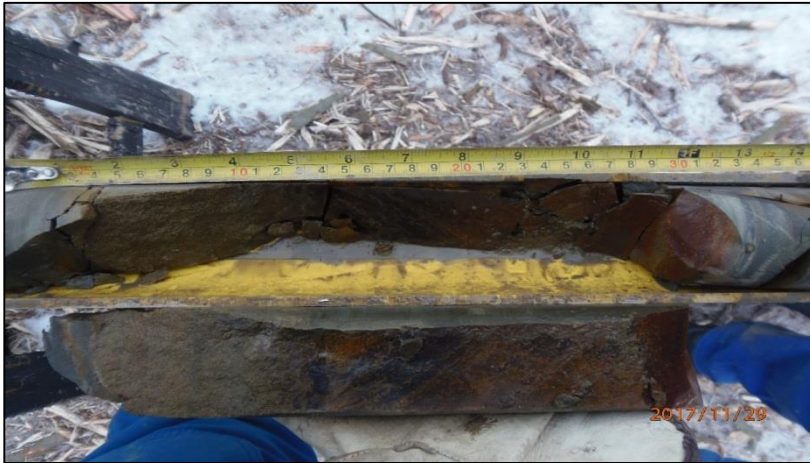
Data from : Channel Fractures Paska

Formation: Paskapoo Fm
Location: Red Deer River, AB
Section: Various Locations
Feature: Fracture Chnl (n=22)
N: 22
Vector mean: 77.5
S.D.: 66.9
95% C.I. : 30.3
Mag. var.: 0
Circle = 9 %
Petal arc: 10 deg.
Binning from: 0 deg.

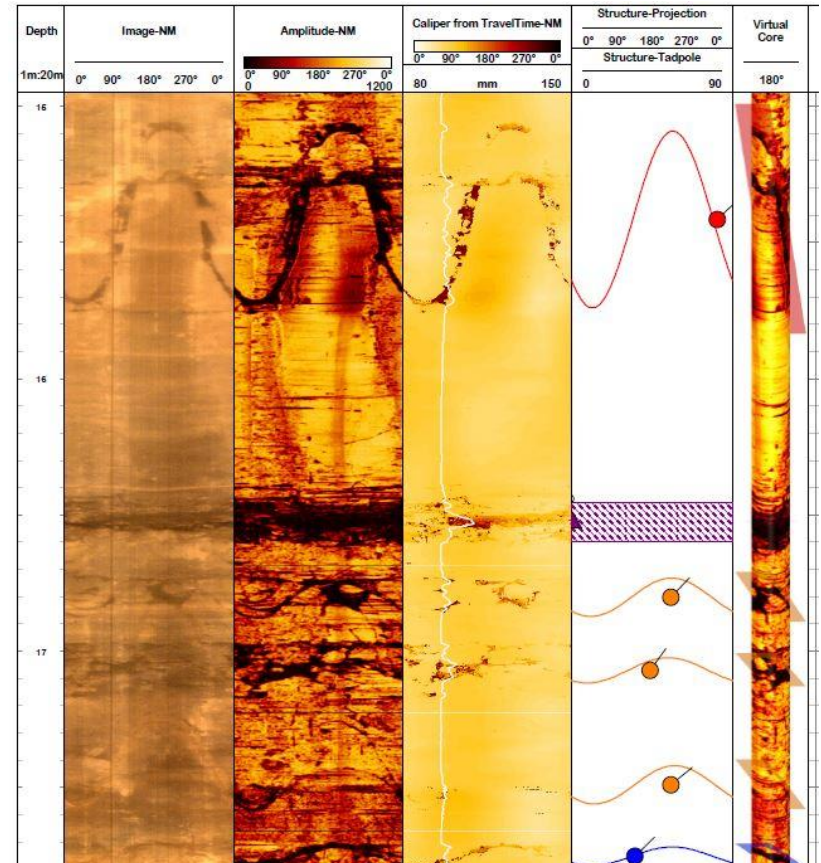
Non-linear



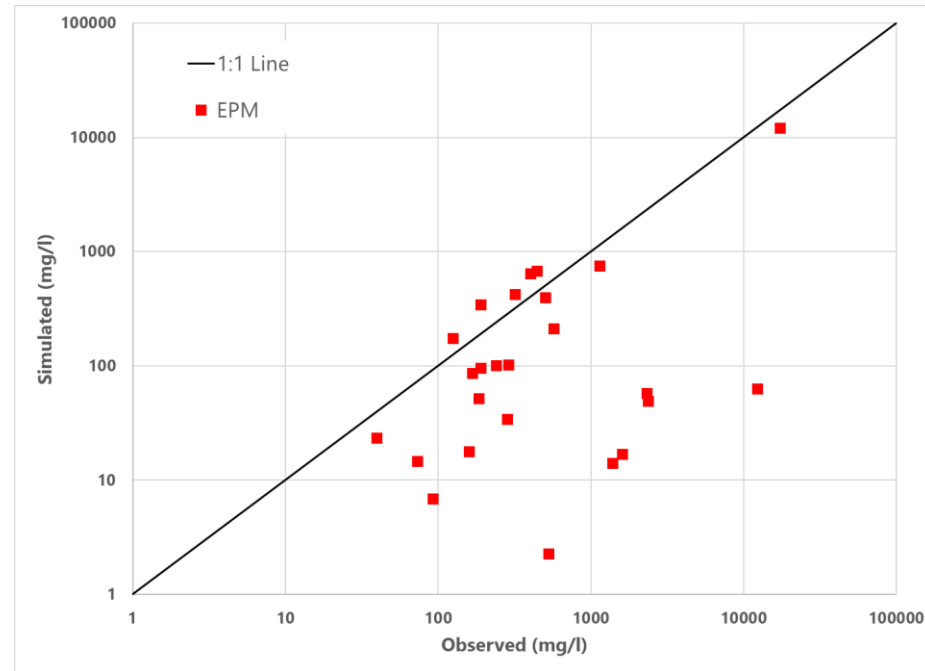
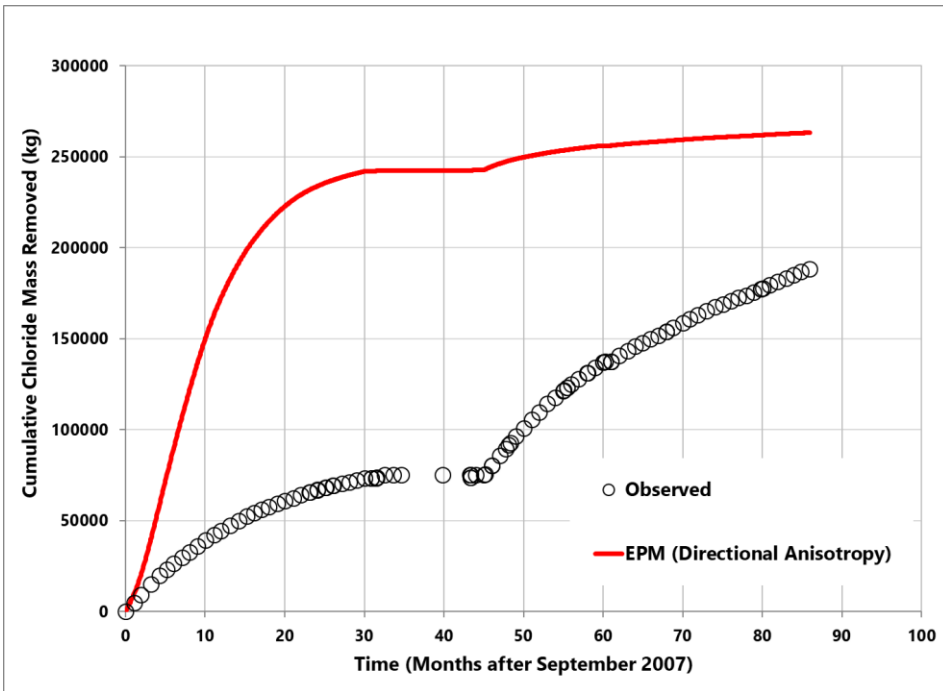
Paskapoo Fm. Fracture Mapping – Local



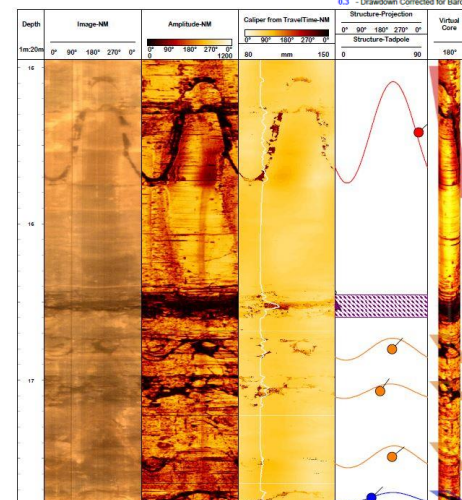
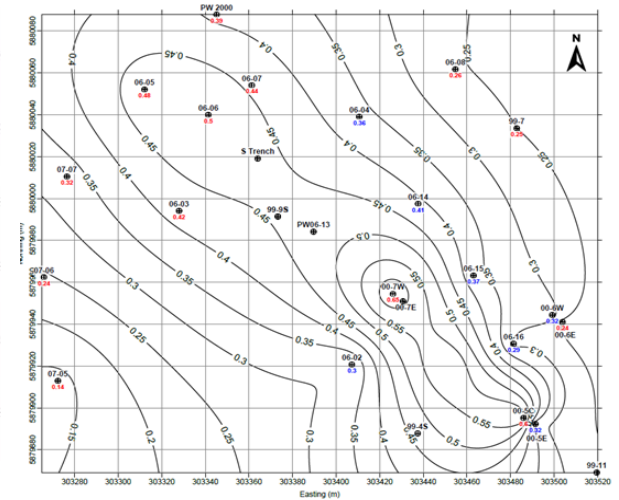
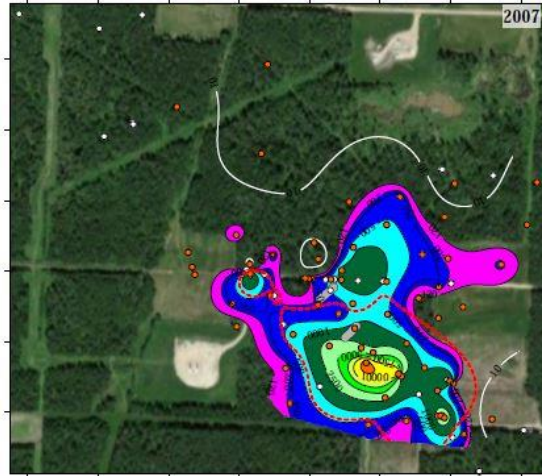
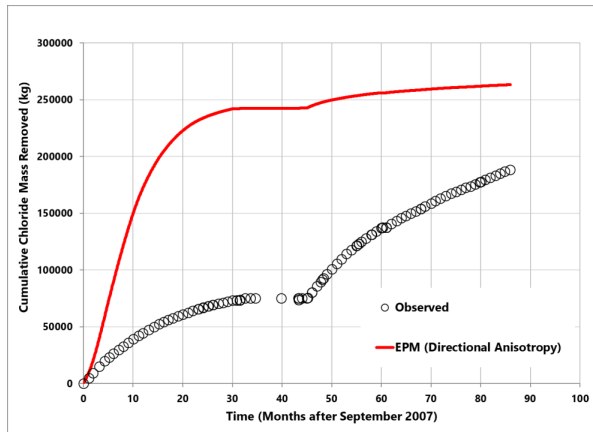
- cycles of coarser grained sand/sandstone and clay/shale arranged into fining upward grain size trends
- fractures occur in both lithological types either singularly or grouped into a fracture zone



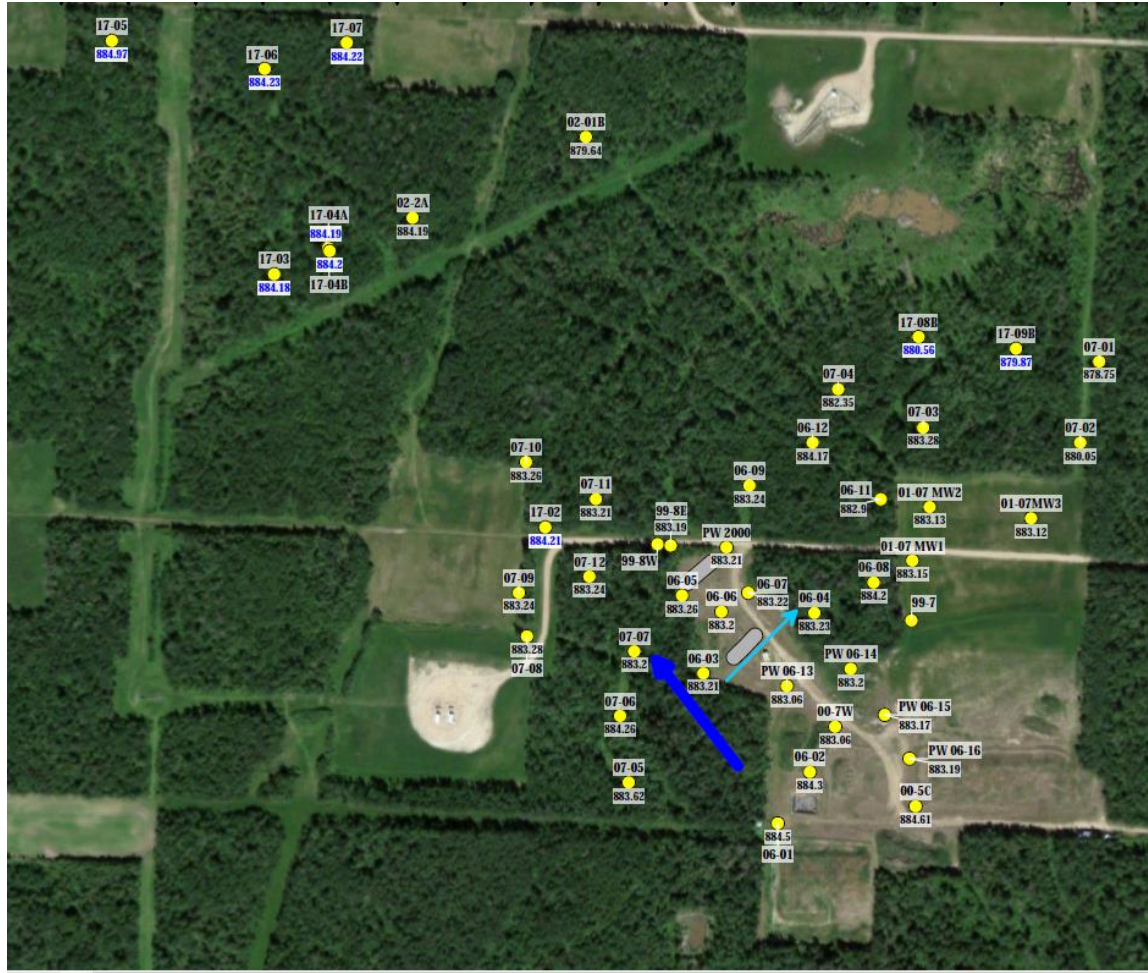
EPM Numerical Model Results



Evidence of Fracturing



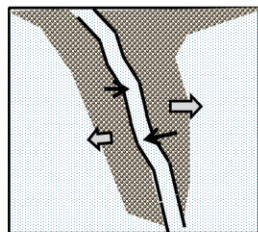
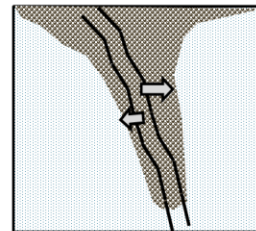
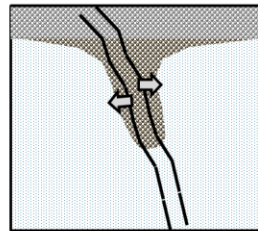
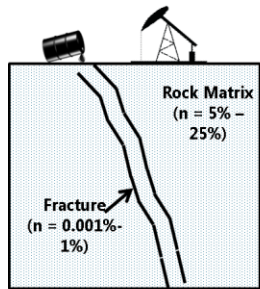
Inferred Groundwater Flow and Transport Directions



Groundwater Flow and Transport Modelling

- Two approaches undertaken to simulate groundwater flow and chloride transport:
 1. Equivalent porous medium (EPM) approach
 - Fracture flow and transport are approximated as a continuum (i.e., assume that at a large enough scale, will behave as a porous medium)
 2. Discrete fracture network (DFN) approach
 - Fracture properties and geometries are explicitly incorporated into model in order to more rigorously investigate their influence on flow and transport
- The results of initial mass intrusion from an analytical model was used to successfully calibrate a 3D DFN numerical model

Groundwater Flow and Solute Transport Mechanism in Fractured Bedrock



Diffusion: movement of solute from area of higher concentration to area of lower concentration (as long as a concentration gradient exists).

n = porosity

⇒ Diffusion from fracture to matrix

← Back diffusion

- Stage 1: solutes enter open fractures.
- Stage 2: rapid movement of solute along fracture and slow diffusion of solutes into initially clean rock matrix under concentration gradients.
- Stage 3: further expansion and maturation of solute plume over time along the fracture network and continued diffusion from fracture to the rock matrix.

Stage 4: fracture networks are being flushed during remediation phase. Fractures mostly carry fresh groundwater, but there is slow back diffusion from matrix, becoming a persistent long-term source due to the relatively low matrix hydraulic conductivity.

Analytical Modelling

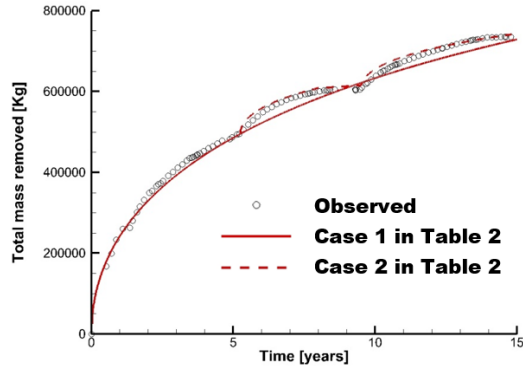
$$J_I(t) = -2nD_e \left. \frac{\partial C(x,t)}{\partial x} \right|_{x=0} = 2nC_0 \sqrt{\frac{RD_e}{\pi t}} \quad \text{Eq (3)}$$

$$M_I(t) = \int_0^t J_D(0, \tau) d\tau = 4nC_0 \sqrt{\frac{RD_e t}{\pi}} \quad \text{Eq (4)}$$

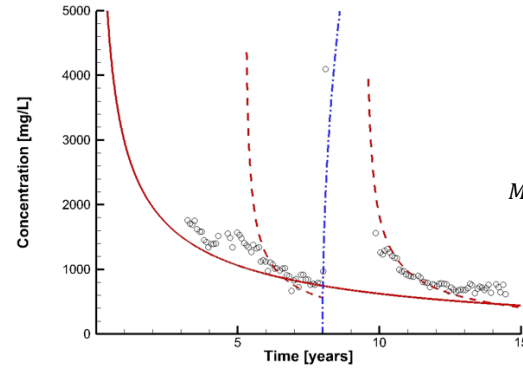
$$C_R(x, t \geq T_R) = C_0 \operatorname{erfc} \left[\frac{x}{\sqrt{4D_e t/R}} \right] - C_0 \operatorname{erfc} \left[\frac{x}{\sqrt{4D_e (t-T_R)/R}} \right] \quad \text{Eq (7)}$$

$$M_R(t > T_R) = \int_T^t J_{RD}(\tau) d\tau = 4nC_0 \left[\frac{RD_e}{\pi} \right]^{1/2} (\sqrt{T_R} + \sqrt{t-T_R} - \sqrt{t}) \quad \text{Eq (9)}$$

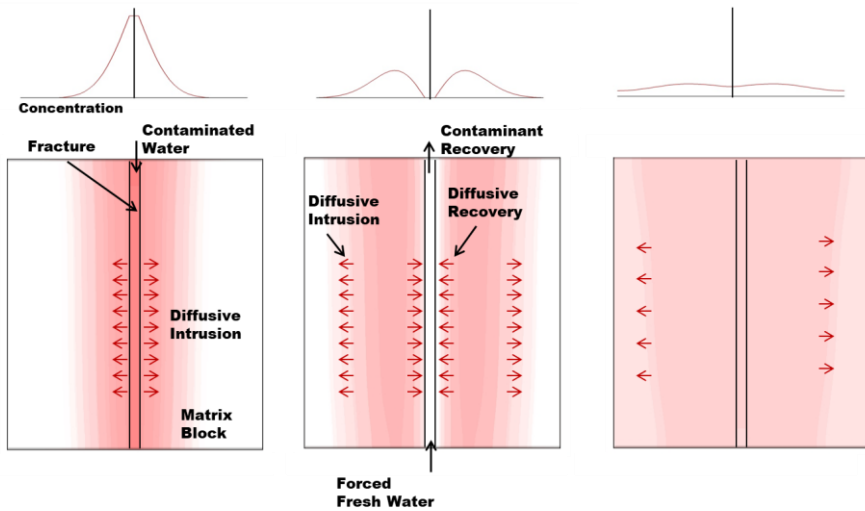
$$C_B(x=0, t > T_B > T_R) = \frac{2C_0}{\pi} \left[\tan^{-1} \sqrt{\frac{t-T_B}{T_B-T_R}} - \tan^{-1} \sqrt{\frac{t-T_B}{T_B}} \right] \quad \text{Eq (12)}$$



(a)



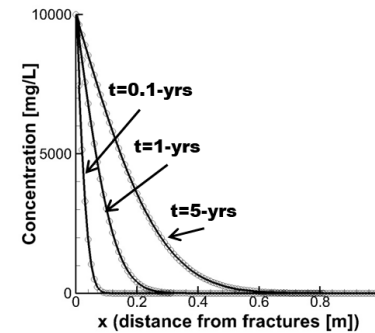
(b)



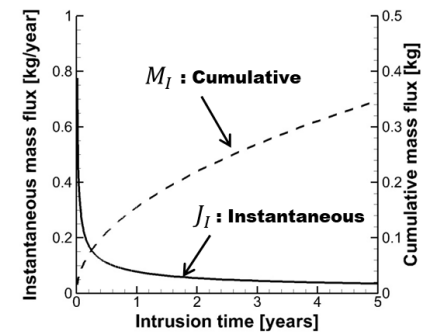
(a) Intrusion Phase

(b) Recovery Phase

(c) Bounce-Back Phase

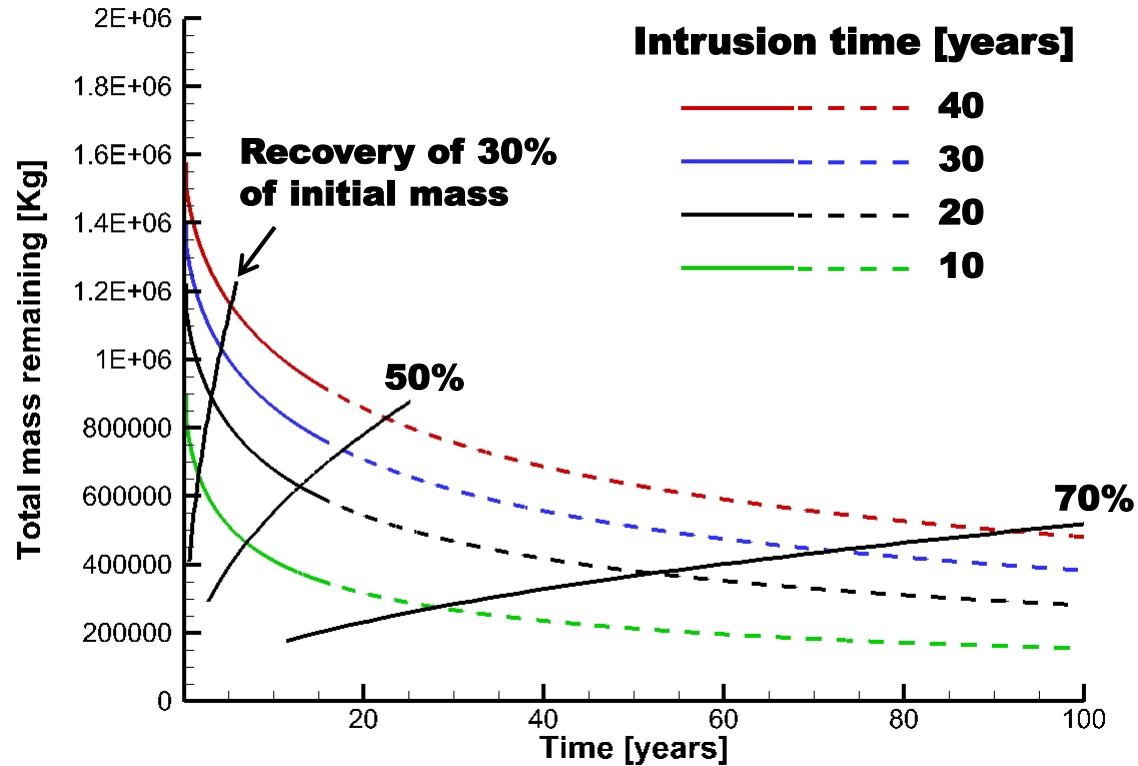


(a)

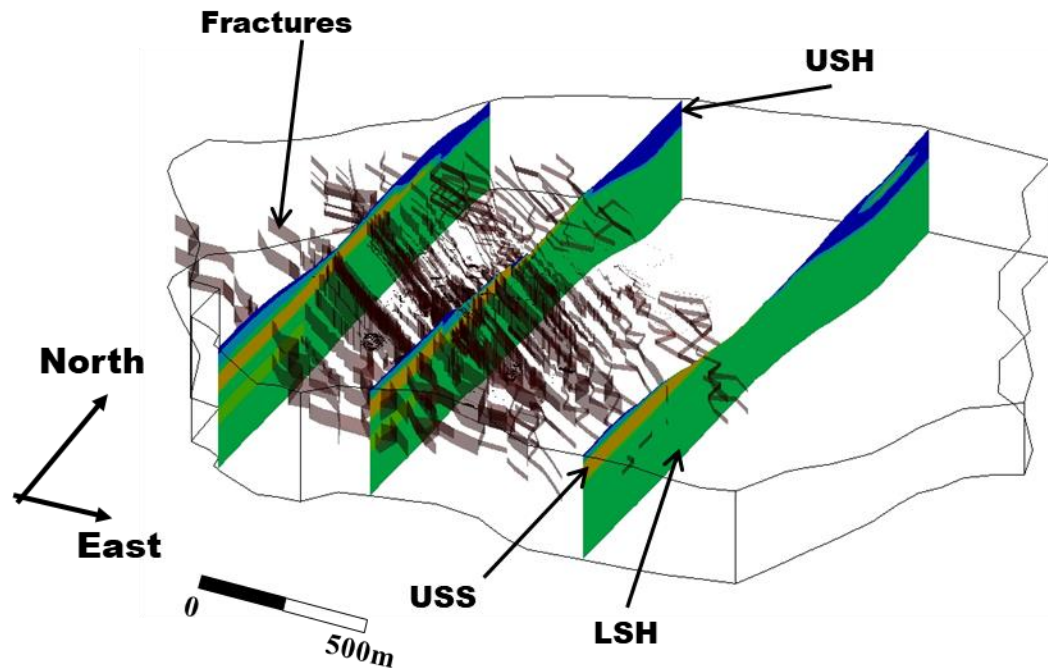


(b)

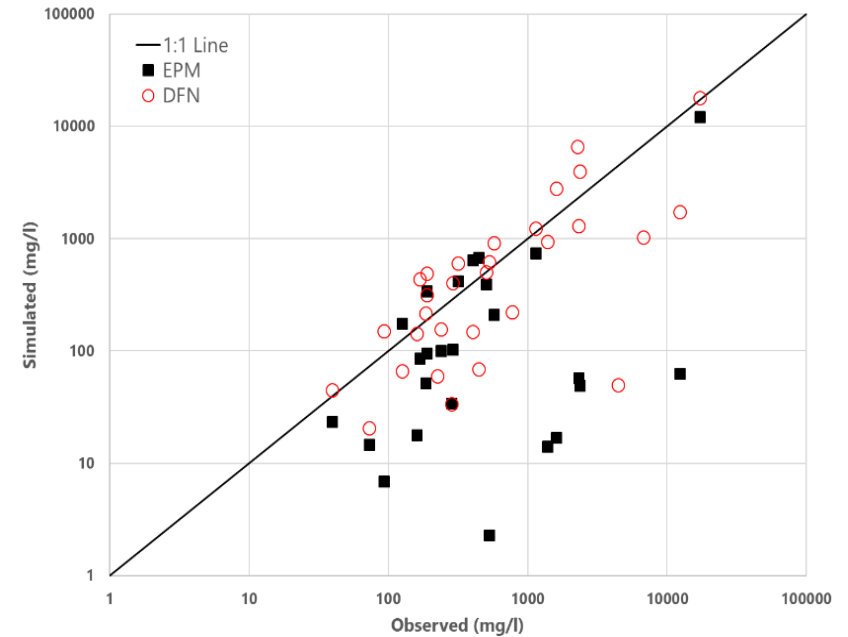
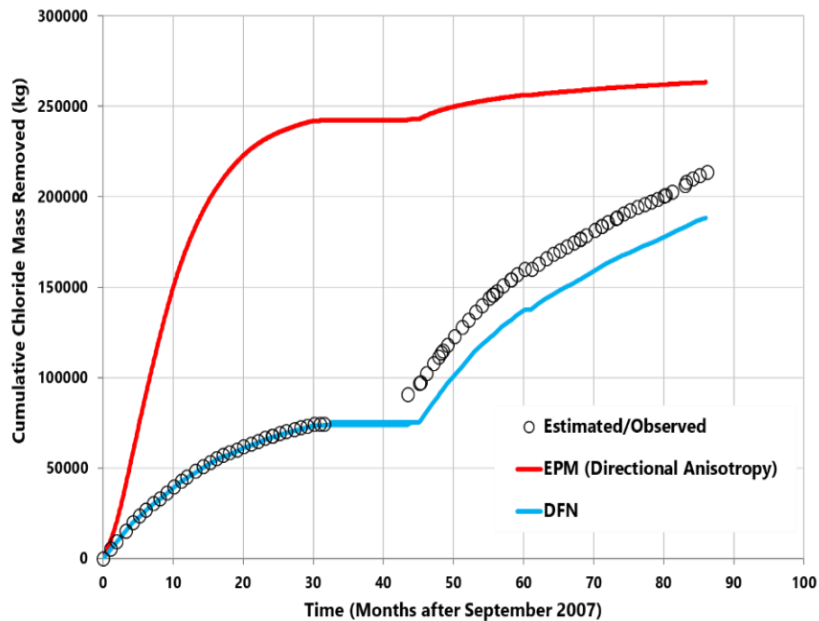
Analytical Modelling



DFN Numerical Modelling



Numerical Groundwater Flow and Transport Modelling Results



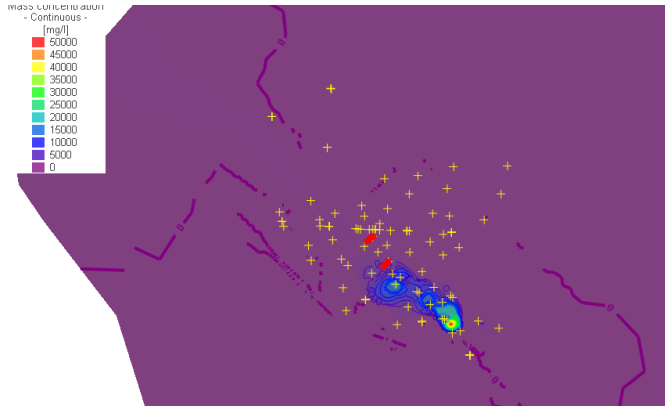
Screening Level Assessment of Remediation Options

Remediation Option	Feasible?	Achieve Endpoints?
1. No further active pumping	Y	Exposure control-only option
2. Active pumping at S trench	Y	Not in reasonable timeframe (model-supported)
3. Vertical wells in core plume	Y	Not in reasonable timeframe (model-supported)
4. Horizontal wells in core plume	Y	Not in reasonable timeframe
5. Partial or full excavation of upper shale	Y, but impractical	Not in reasonable timeframe in upper sandstone
6. Partial or full excavation of upper shale and sandstone	Y, but impractical	Further hydraulic containment likely required

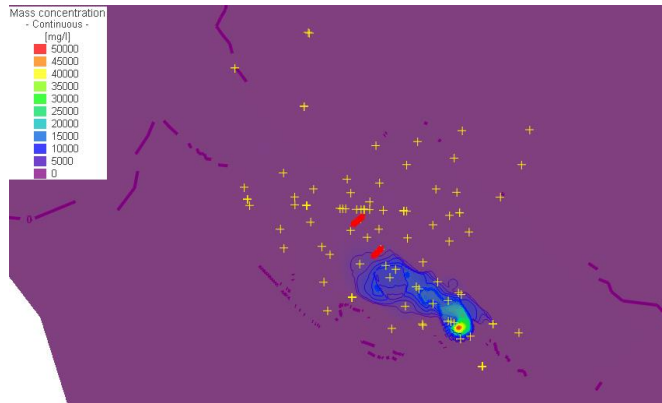
Numerical Groundwater Flow and Transport Modelling – Remediation Option Simulations

- Scenario 1: No future pumping (no further active remediation) at the Site
- Scenario 2: Continue pumping at STPW at historical pumping rates for the next 25 years;
- Scenario 3: Pumping of PW06-13, PW06-14, PW06-15 and PW06-16 to try and more aggressively address the core plume concentrations.

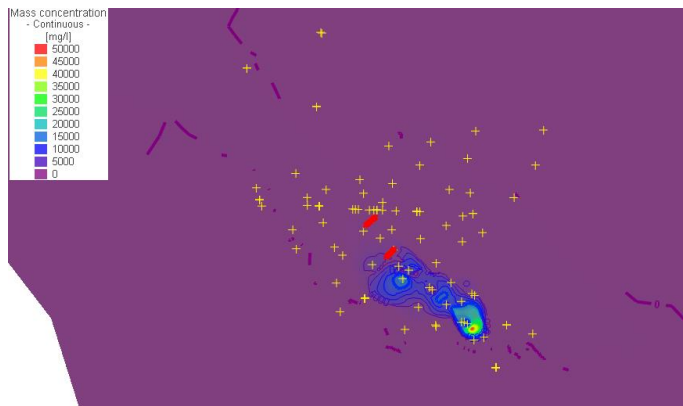
Scenario Results @ 25 Years: Shale



Scenario	Max. Concentration (mg/l)
1	~16,000

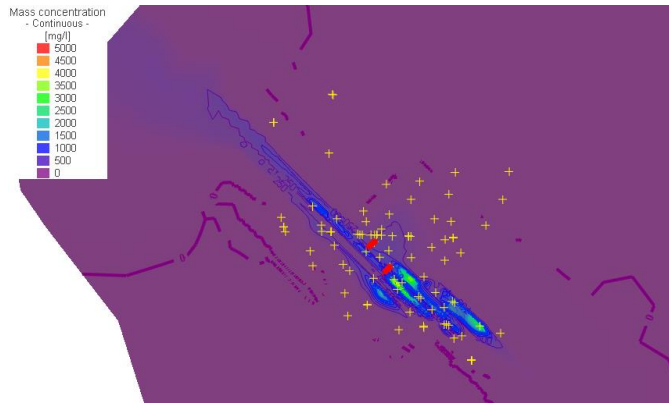


Scenario	Max. Concentration (mg/l)
2	~15,000

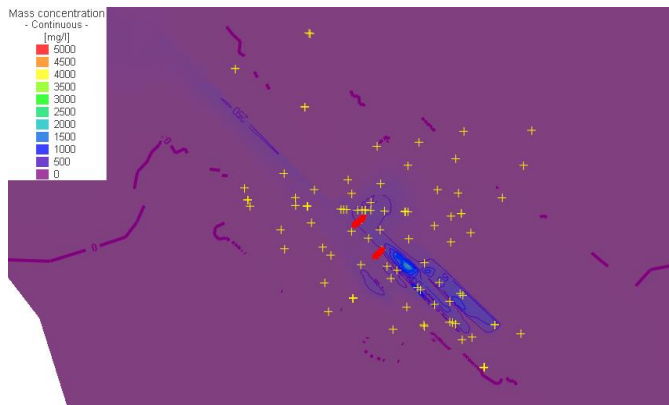


Scenario	Max. Concentration (mg/l)
3	~13,500

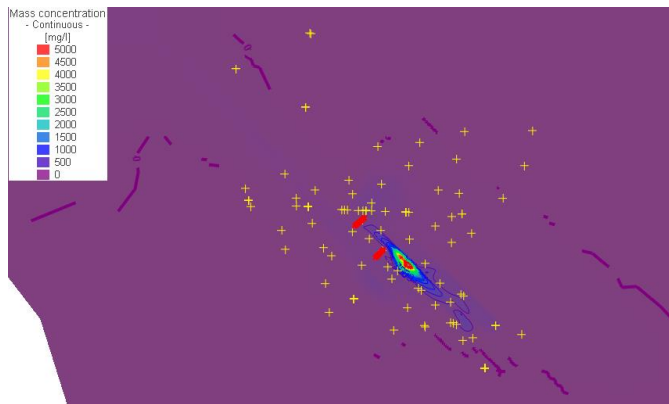
Scenario Results @ 25 Years: Sandstone



Scenario	Max. Concentration (mg/l)
1	~4,000



Scenario	Max. Concentration (mg/l)
2	~2,000



Scenario	Max. Concentration (mg/l)
3	~6,000

Learnings and Implications of Conceptual Model Evolution

- Retained mass in the upper shale unit is now acting as a long-term diffusive source of chloride to the upper sandstone unit
- Ongoing removal from extraction trenches has contributed to plume stability, but has not/will not remediate dissolved phase plume or source areas
- Enhanced groundwater extraction nearer to the core plume area is not expected to result in reduction of chloride concentrations to levels below Alberta Tier 2 guidelines in a reasonable time frame
- Relatively large volumes of freshwater are mixing with relatively small volumes of salinity-impacted water to produce large volumes of marginally-impacted water for disposal

Remediation Action Plan and Path Forward

- Three management strategies for site:
 - Confirmation of near surface soil conditions and remediation (if necessary) of residual impacts to Tier 2 Guidelines
 - Further assessment and removal of LNAPL to the extent reasonably practicable, followed by passive remediation through monitored natural attenuation (MNA) to achieve Tier 2 Guidelines
 - Maintain the stability of or remove the chloride plume through active remediation or long-term source and exposure control.

Remediation Action Plan – Chloride in Shale/Sandstone

- Risk assessment concluded that under current conditions, there are no risks of adverse effects to humans or ecological receptors on the basis that there is no pathway of exposure.
- Multi-criteria decision analysis (MCDA) will be used to identify preferred remedial options (including, but not limited to those already screened), risk management strategies, and reclamation approaches for the site to maintain this risk status.
- Based on current conceptual understanding, the most favourable option would appear to be long-term, optimized source control of the dissolved phase chloride plume to maintain the current plume footprint together with long-term exposure control.