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

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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
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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 - $7.4 \times 10^{-6}$ m/s
- Sandstone - $5.6 \times 10^{-5}$ 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
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 Chn (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 rigourously 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

- 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.

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

\[ n = \text{porosity} \]

- Diffusion from fracture to matrix
- Back diffusion
Analytical Modelling

\[ J_I(t) = -2nD_e \frac{\partial C(x,t)}{\partial x} \bigg|_{x=0} = 2nC_0 \sqrt{\frac{RD_e}{\pi}} \]  
Eq (3)

\[ M_1(t) = \int_0^t J_D(0,\tau) d\tau = 4nC_0 \sqrt{\frac{RD_e}{\pi}} \]  
Eq (4)

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

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

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

Recovery of 30\% of initial mass

Intrusion time [years]
- 40
- 30
- 20
- 10

Total mass remaining [Kg]

Time [years]
DFN Numerical Modelling

Nagare, Park, et al. [Groundwater]
Numerical Groundwater Flow and Transport Modelling Results
## Screening Level Assessment of Remediation Options

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

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Max. Concentration (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>~16,000</td>
</tr>
<tr>
<td>2</td>
<td>~15,000</td>
</tr>
<tr>
<td>3</td>
<td>~13,500</td>
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</table>
Scenario Results @ 25 Years: Sandstone

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Max. Concentration (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>~4,000</td>
</tr>
<tr>
<td>2</td>
<td>~2,000</td>
</tr>
<tr>
<td>3</td>
<td>~6,000</td>
</tr>
</tbody>
</table>
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.