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Flow Dynamics of Saturated Rock Fill Facilities, Elk Valley BC

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srk consulting

Acknowledgements

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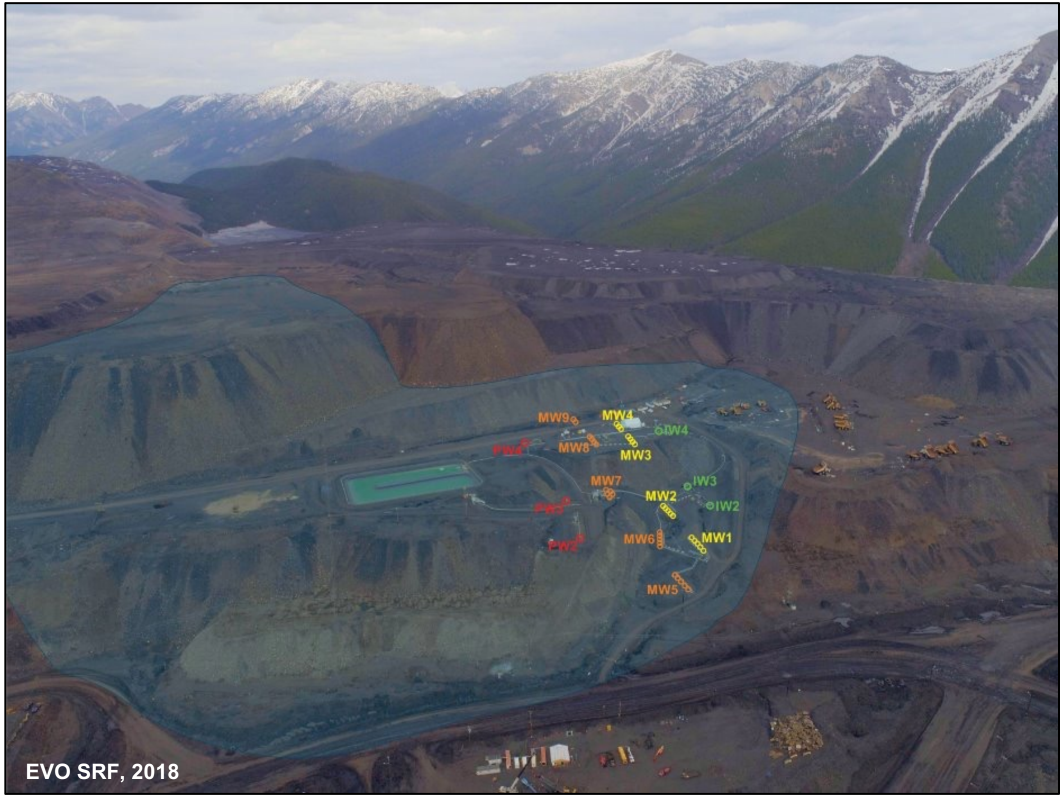
- Work on SRFs has spanned over 15 years, has involved a highly collaborative team across disciplines, consultancies, academic partners, and Elk Valley Resources staff (formerly Teck Coal)

- Contributors include:
  - **EVR/Teck Coal (including R&D, operations, regional water quality modelling, permitting, environmental compliance, engineering, etc.)**
  - **SRK (geochemistry, hydrogeology, engineering, permitting support)**
  - **Enviromin (microbiology)**
  - **USASK (geochemistry and hydrogeology)**
  - **MSU (microbiology)**
  - **Geosyntec (carbon characterization)**
  - **OKC (field support)**
  - **WSP/Golder (regional water quality modeling)**
  - **Wood and Tetra Tech (wellfield engineering)**
  - **Nupqu (sampling)**
  - And many more operators, site & field staff, analytical lab staff, coop students, etc.

SRF expert advisory panel, subject matter experts, and technical team on a site tour at EVO SRF in 2018. From left to right: Steve Day, Marcie Schabert, Silvia Mancini, Shannon Shaw, Lisa Kirk, Len deVlamin, Seth D'Imperio, Rob Klein, Jim Hendry, Brent Peyton, Andrzej Prezpiora, Dan Mackie, Juris Harlamovs, Daryl Hockley, Lee Barbour

Outline

1. Introduction to SRFs
2. Overview of Flow Behavior
3. Numerical Modelling
4. Residence Times
5. Entrainment
6. Conclusions



Introduction:
Overview of SRFs

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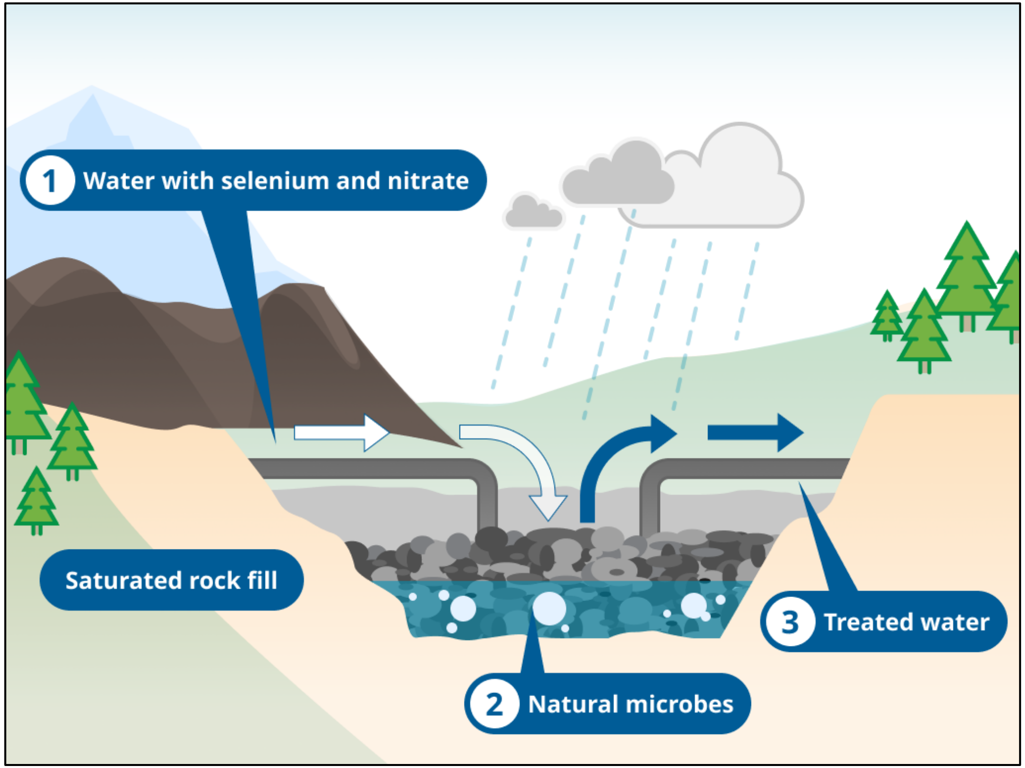
- Saturated Rock Fills (SRFs) are a new water treatment technique developed by EVR that utilizes existing backfilled pits for efficient nitrate and selenium attenuation
- How do they work?
  1. Mine-influenced water, along with a carbon source (methanol) and nutrients, is injected into saturated backfilled pits
  2. The water then flows through waste rock, where microbes reduce the nitrate and selenium
  3. The treated water is then extracted at the opposite side of the pit and discharged to the environment
- The technology has been used to treat up to flow rates of 30,000 m^3/d



Source: elkvalleywaterquality.gov.bc.ca

Introduction:
Research and Development Process

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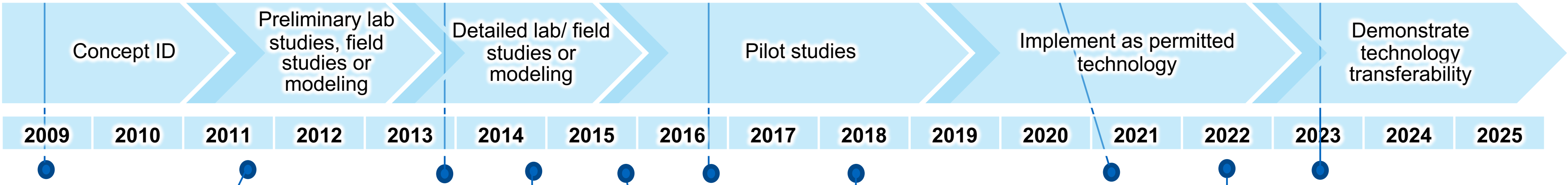
Concept Identification
Correlation of SO_4 and Se in Elk Valley Waters

Detailed Studies
Column and push-pull studies demonstrated biological Se and NO_3 removal rates in flowing systems

Pilot Field Test (EVO)
Successful application of the technology at a flow rate of 500 m^3/d in the F2 pit.

Phase 2 Expansion (EVO)
EVO SRF in F2 pit expanded to have a hydraulic capacity of up to 20,000 m^3/d.

Phase 2 (FRON)
FRON SRF expanded to have a hydraulic capacity of up to 20,000 m^3/d and treat additional external influent sources (e.g., Clode, Liverpool and Post Ponds).



Preliminary Studies
Sampled a number of backfilled pits, conducted batch tests and identified naturally occurring bacteria capable of Se and NO_3 removal

Inventory of Backfilled Pits
F2 pit at EVO selected as key candidate for future studies due to pit specific conditions and nearby water sources.

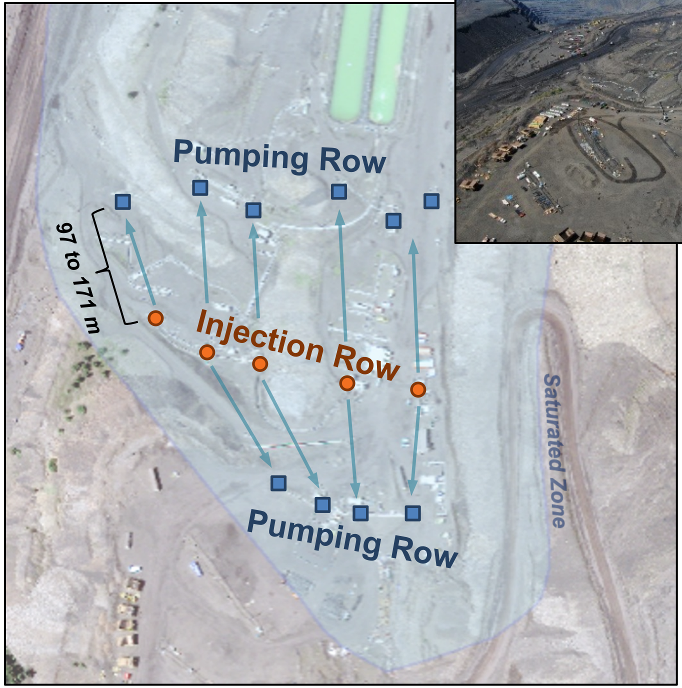
Pilot Studies
Detailed geochemistry, hydrogeology, and microbiological studies conducted to confirm applicability of F2 pit.

Full Scale Trial (EVO)
Wellfield designed to treat up to 10,000 m^3/d, with greater than 90% Se and NO_3 removed.

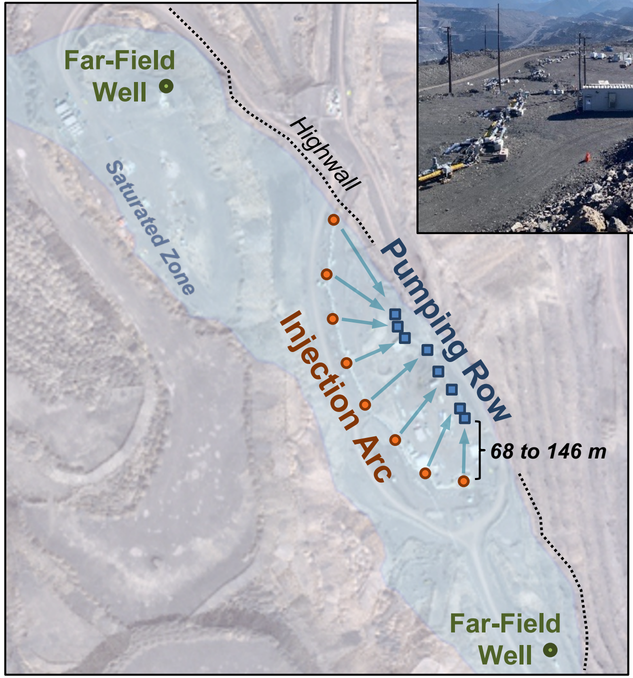
Phase 1 (FRON)
Second SRF facility started at FRON in E4 pit, with initial treatment set to target 2,500 and 4,500 m^3/d of natural recharge entering the pit.

Introduction:
Existing SRF Facilities

Elkview (EVO)

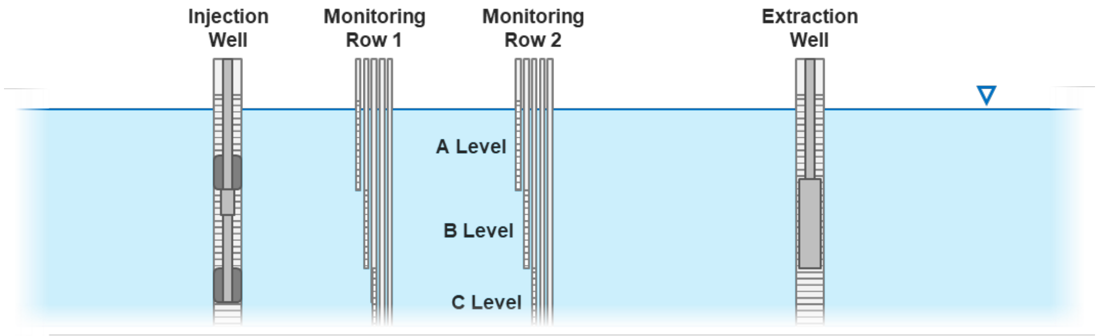


Fording River North (FRO-N)



Observed Flow Behavior:
EVO Wellfield Arrangement

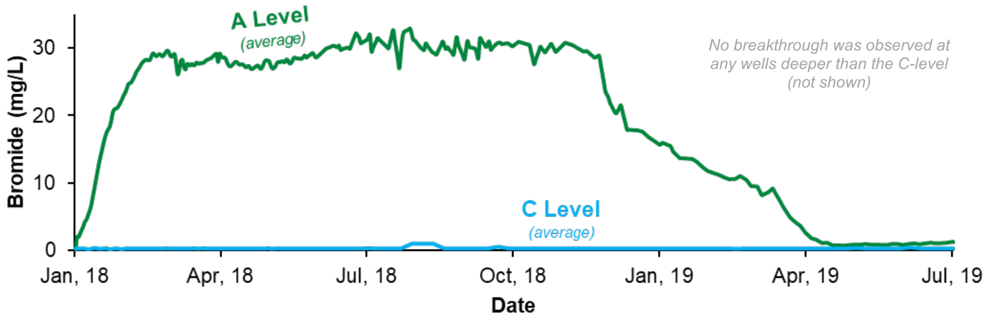
- At the EVO SRF, the wellfield was originally composed of:
  - Three injection wells
  - Two rows of clustered monitoring wells, with five levels per cluster (15 m each)
    - Shallowest: A-Level
    - Deepest: E-Level
  - Three pumping wells
- Distance between injection and extraction wells was 150 m

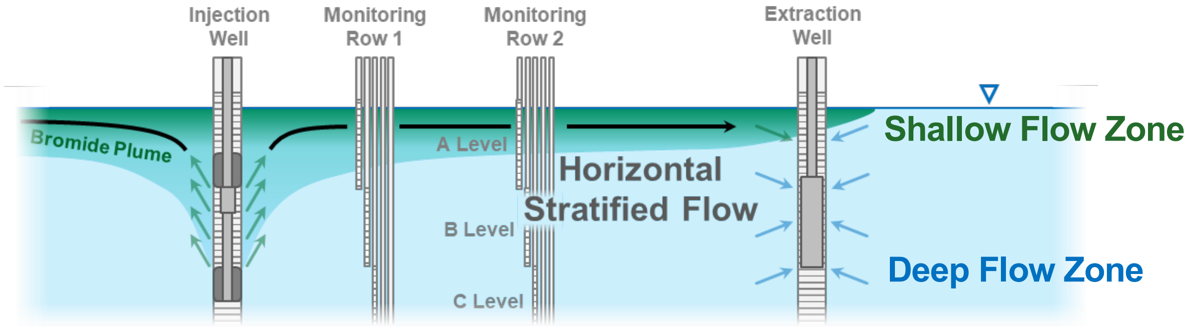


schematic for illustrative purposes

Observed Flow Behavior:
Stratification

- A fundamental feature of the SRFs has been the lateral spreading of influent within specific density horizons
- In the EVO SRF, this was observed by rapid breakthrough of bromide tracers in the A-Level (shallowest) monitoring wells
- The stratification structure is simplified into two primary zones:
    1. Shallow Flow Zone
    2. Deep Flow Zone





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Observed Flow Behavior:
Cause of Stratification

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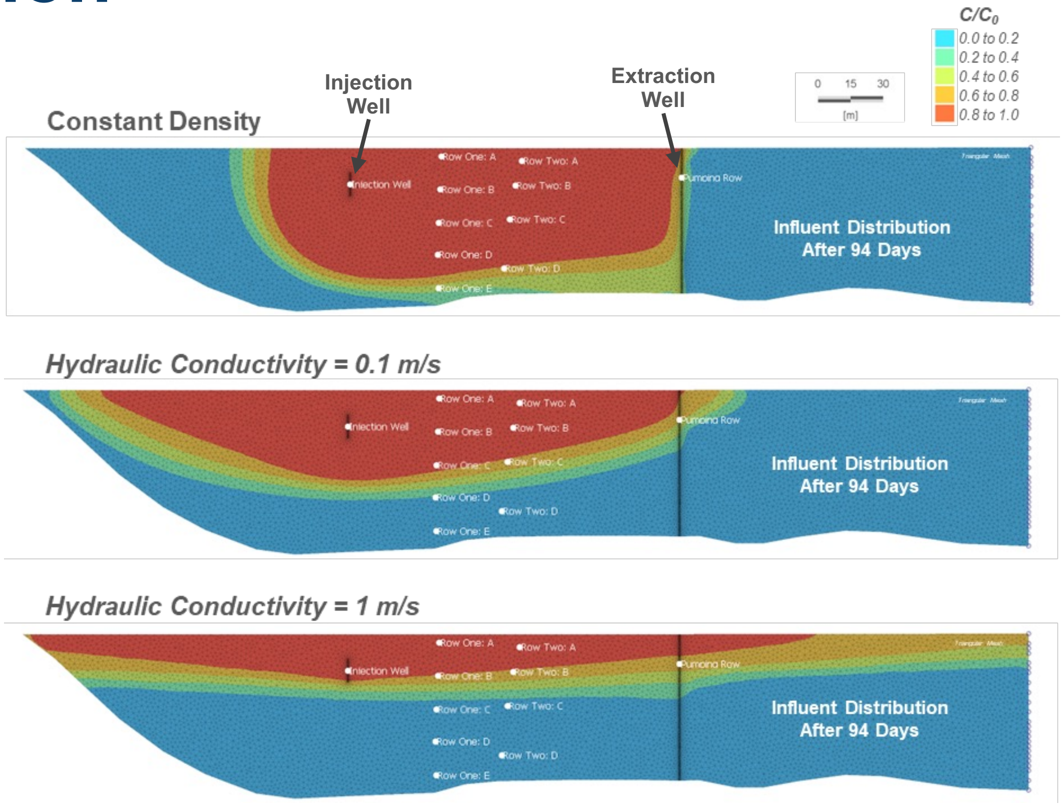
- The stratification is due to the lower density of the influent compared to in-situ waters
  - This is mainly driven by TDS contrasts between the two waters (~1,500 mg/L), with temperature playing a secondary role
- Can be seen in a series of density dependent mechanistic models were set up in FEFLOW
- The results suggested a hydraulic conductivity near 1 m/s is required to reproduce the observed stratification
  - At these high permeabilities the hydraulic gradient decreases, increasing the relative strength of the density force, causing the system to stratify.
- These findings were later supported by more detailed FEFLOW modeling of the EVO and FRON SRFs



Observed Flow Behavior:
Expansion/Contraction of Layers

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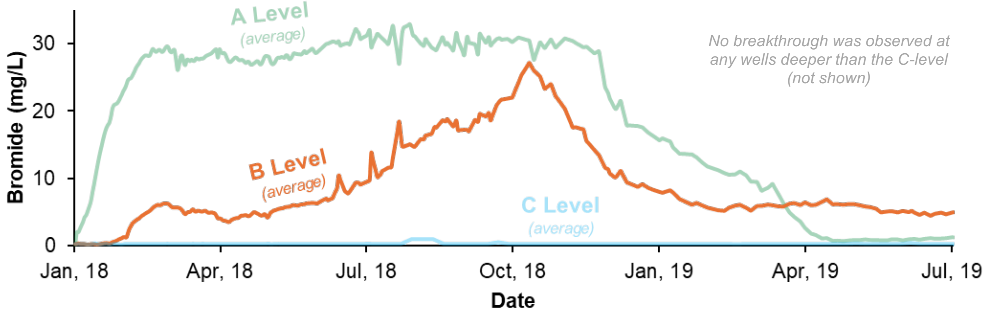
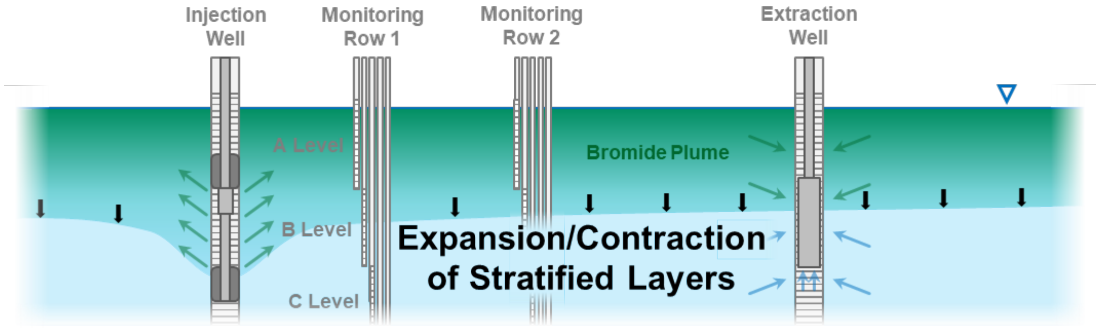
- The stratification is not static but varies over time in response to the current pumping conditions and recharge rates
  - The shallow zone will tend to grow when injection rates exceed extraction, and vise versa
- This is evident in the EVO SRF data with a rapid breakthrough of bromide tracer in the A-Level (shallowest) wells, and slower breakthrough in the B-Level (intermediate) wells
  - Attributed to the rapid stratification in the shallowest portions of the saturated zone, followed by the gradual downward expansion into the B-Level



No breakthrough was observed at any wells deeper than the C-level (not shown)



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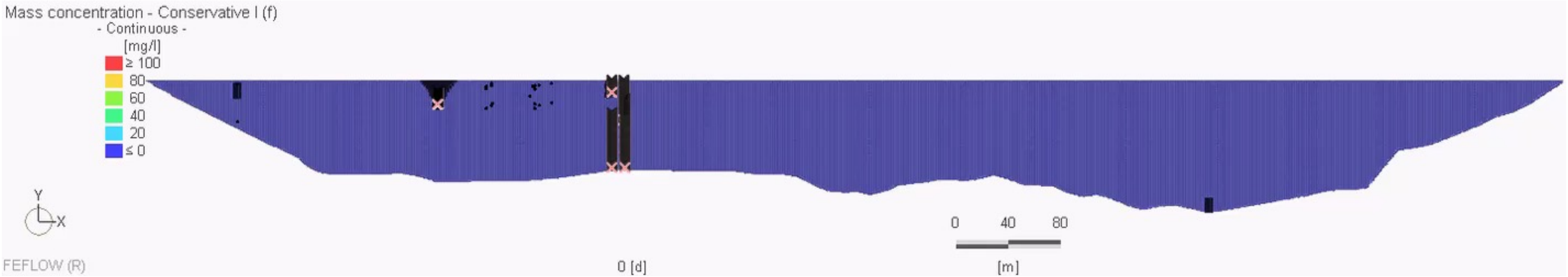
Numerical Modelling:
EVO SRF 2D Model



- Based on the conceptual understanding of flow dynamics, a 2D vertically oriented numerical flow and conservative transport model was developed in FEFLOW for the EVO SRF
- The model incorporated density mechanics based on differences in the TDS between the influent and in-situ fluids
- Calibration was achieved based on the following key inputs:

  Hydraulic Conductivity: 1 m/s

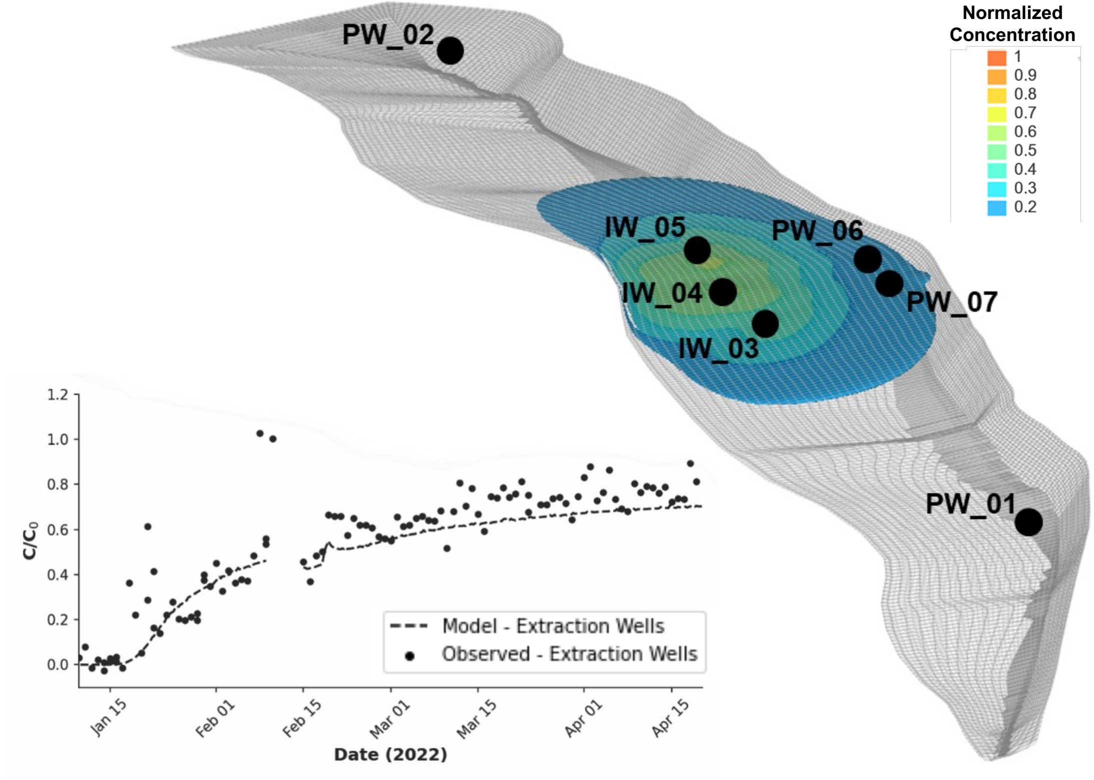
  Effective Porosity: 21%

Numerical Modelling:
FRON SRF 3D Model

- The 2D EVO numerical model was used as a basis for a 3D FRON model
- The model provided a rare opportunity in groundwater for an independent validation of the earlier EVO model
  - i.e., would the conceptual and numerical model be the same at FRON?
- The model results proved to be reasonably reliable using the EVO parameterization, validating the earlier work
- Only a slight update was required during calibration to FRON Phase 1:

  Hydraulic Conductivity: 2 m/s

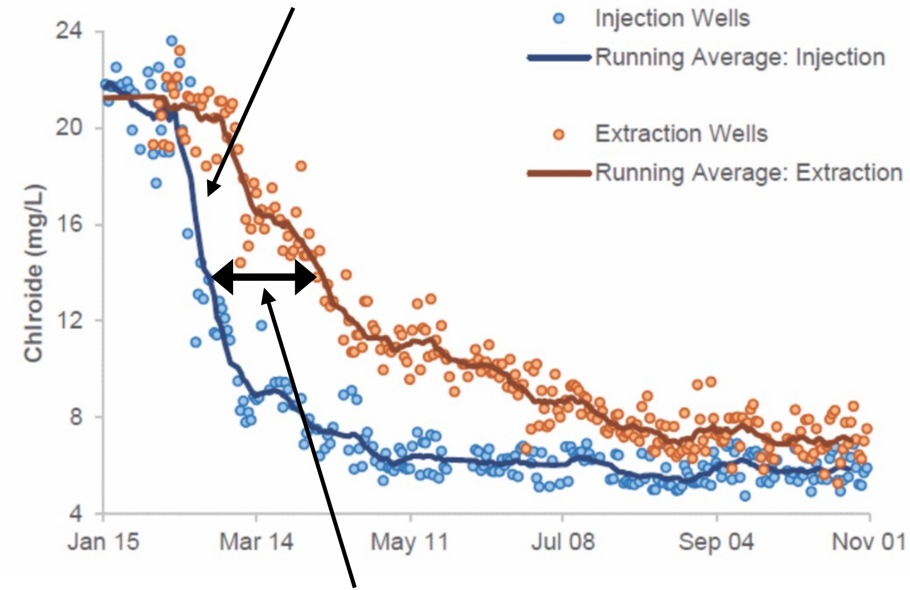
  Effective Porosity: 15%



Residence Times:
Total Wellfield

- Residence times distributions have been assessed using both natural and/or artificial tracers (e.g., chloride and bromide).
- Median residence times to the extraction wells have varied but they typically averaged around one month during early phases of the EVO and FRON SRFs, and later dropped as flow rates increased (e.g., in 2023 the median residence time was estimated to be one to two weeks at FRON).
- Residence times vary in response to the influence conditions
  - Mainly driven by flow rates, but also influenced by influent TDS/temperature, recharge/in-situ conditions, etc.

Natural tracer caused by the switch from Natal to Erickson water at the EVO SRF in 2021



Difference between influent vs. effluent concentrations indicative of residence time through waste rock

Entrained Water: Conservative Tracers

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- Long-term tracer concentrations at extraction wells never converge to the full influent concentration, which is indicative of mixing with another source

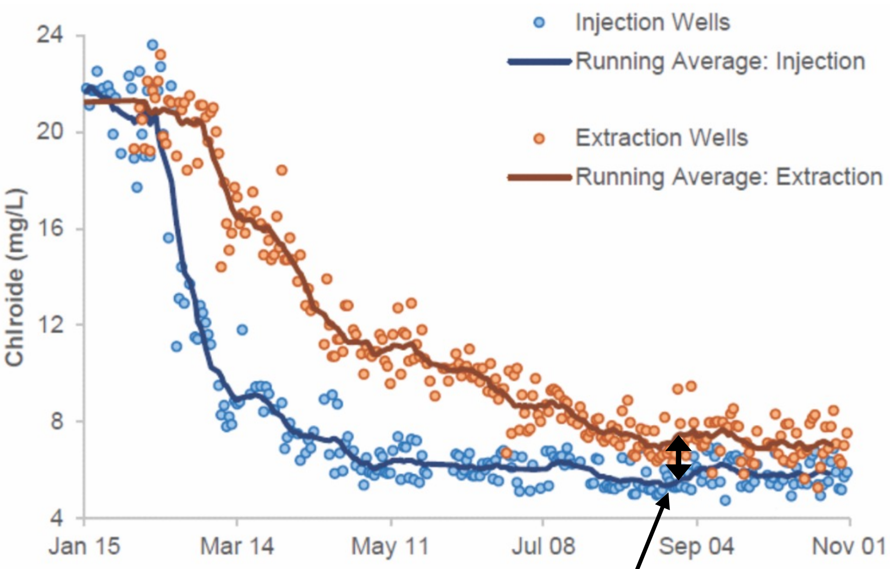
- Effluent is a combination of:

  Treated Influent: consists of all injected water that travels through the SRF and reports to the wellfield extraction wells

  Any remaining uncollected influent would leave the wellfield

  Entrained Water: consists of non-injected water that mixes with the injected water and is collected at the wellfield extraction wells. This mainly consists of either in-situ water that existed in the pits prior to operation of the SRFs or new recharge that enters the facilities, mainly from percolation of precipitation through waste rock

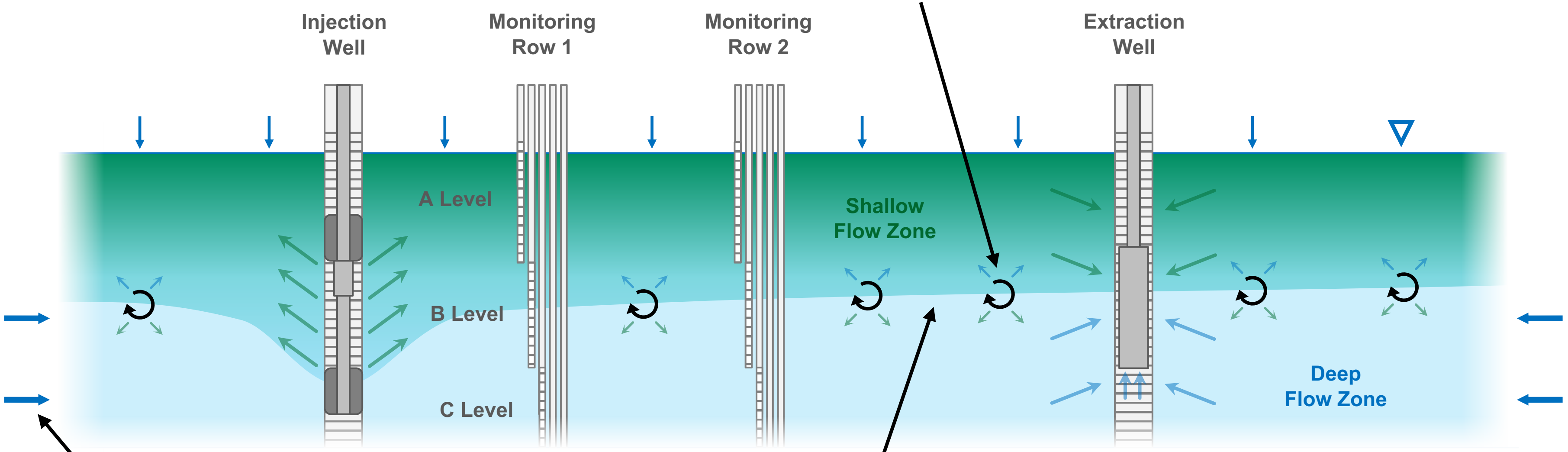
  Entrained waters are assumed to be untreated; however, some treatment may occur if the water that is entrained occurs near the injection wells.



Tracers never converge to 100% influent water, indicative of the mixing with other sources (i.e., deeper in-situ and recharge waters)

Entrained Water: Conceptual Model

Entrainment effects are always in balance
Any entrained water offset by either an expansion of the shallow flow zone and/or the loss of treated water to the deep flow zone



The deep zone can be replenished from recharge

Entrainment is caused by mixing between the shallow and deep zones

Entrained Water: Sources

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- Entrainment processes can vary slightly due to site specific differences.

  EVO SRF:

  Low Recharge

  Large Pore Volume

  FRON SRF:

  High Recharge

  Small Pore Volume

- Results in different primary sources of entrainment within the pits:

  EVO SRF: entrainment is mainly sourced from large reserve of in-situ water

  FRON SRF: entrainment originates primarily from on-going recharge entering the pit

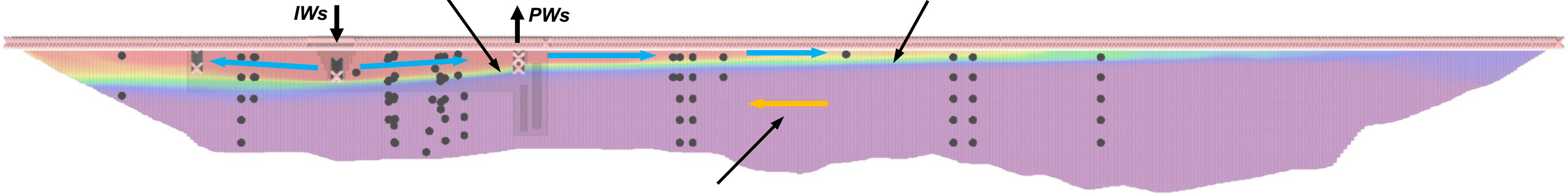
Parameter	EVO SRF	FRON SRF
Net Recharge Rate	370 to 650 m^3/d	2,500 to 3,400 m^3/d
Leakage Rate	low 100s m^3/d	low 100s m^3/d
Catchment Area	800,000 m^2	2,400,000 m^2
Pore Volume	~4,000,000 m^3	~1,000,000 m^3
Pit Volume Replacement Time	~14 years	~0.8 years

Entrained Water:
Stratification and Entrainment

- Entrainment linked to stratification effects, with density gradients acting to flatten any perturbations in the stratification layers, which causes:
  - An outward force pushing a portion of the injected water away from the wellfield and towards the edges of the pit, as the density effect attempts to form a flat shallow flow layer
  - Simultaneously, in-situ and/or recharge water is drawn toward the area beneath the wellfield, to fill the space vacated by the outward-flowing water in the shallow flow zone
- These density effects, coupled with the on-going recharge of new water into the pit, act to constantly pull new water into the area beneath the wellfield, which can then be entrained and extracted at the pumping wells

1. Active injection, and lateral recharge, can cause a slight slope in the stratification layering

2. This slope is an unstable configuration, which density forces will attempt to flatten



3. These density effects cause lighter injected water to be drawn toward the edges of the pit, while denser non-injected water is pulled inward toward the wellfield, as the forces work to flatten the stratification

Entrained Water:
Predicting Entrainment

- Originally done using complex density dependent numerical flow models, which was a slow process.
- In 2023, a load balance model was developed to allow for the direct assessment of entrainment in EVR's RWQM.
- The model used machine learning principles and incorporated five key inputs that were found to control entrainment:
    1. Wellfield flow rate
    2. Influent TDS
    3. Amount of area the wellfield occupies relative to the total footprint of the pit
    4. Total recharge rate into SRF
    5. Leakage rate out of SRF
- The load balance model has been constantly revalidated on an annual basis, showing reasonable fits to observed conservative flow behavior and proving to be a reliable tool to estimate entrainment.

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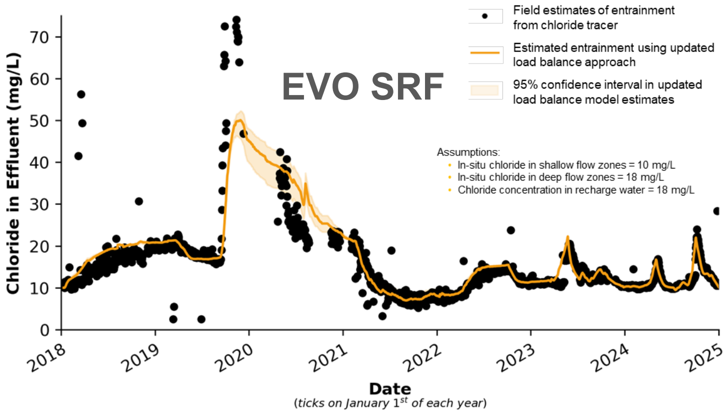

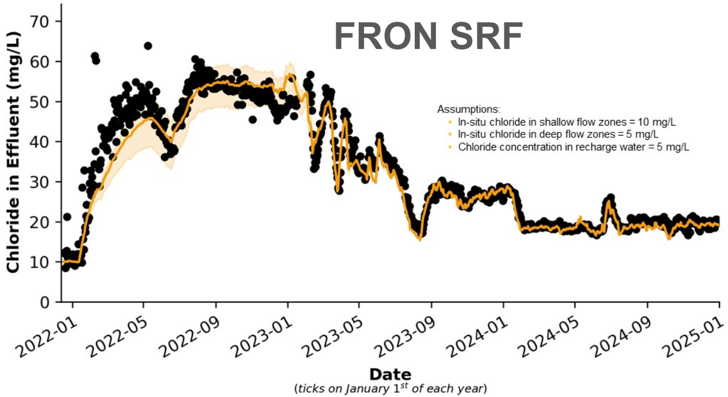

Conclusions

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- The key learning from the EVO and FRON SRFs is that SRF design and operation is influenced by several hydrogeological factors. While not overly complex, these need to be taken into consideration. These include:
  - Water injected into the SRFs will tend to stratify. This is due to:
    - The very high hydraulic conductivity of the backfilled material (1 to 2 m/s).
    - Density differences between the injected and in-situ waters.
  - In the Elk Valley, these stratification effects tend to produce two flow zones:
    1. Shallow Flow Zone
    2. Deep Flow Zone
  - Mixing between these zones will cause non-injected water to be entrained into the wellfield influencing the effluent chemistry.
    - There are two primary sources of entrainment: in-situ and recharge waters.

EVO SRF, 2018

Thank you

For further information, visit:

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