Performance of a Composite Cover at Kam Kotia Mine, ON – Hydrology, Gas Transport, and Geochemistry

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Publications

- Zhang, A., Bain, J. G., Schmall, A., Ptacek, C. J., & Blowes, D. W. (2023). Seasonal hydrology and gas transport in a composite cover on sulfide tailings. *Canadian Geotechnical Journal*. https://doi.org/10.1139/cgj-2022-0606
- Zhang, A., Bain, J. G., Schmall, A., Ptacek, C. J., & Blowes, D. W. (2023). Geochemistry and mineralogy of legacy tailings under a composite cover. *Applied Geochemistry.* 159(105819). https://doi.org/10.1016/j.apgeochem.2023.105819

Background

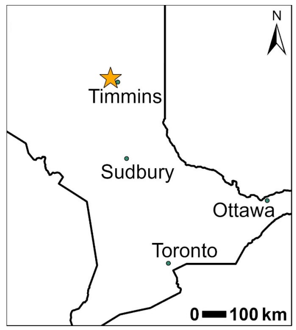
- Multi-layer composite cover
  - A remedial option for mine wastes
  - Barrier to water infiltration and oxygen transport → reduce the production of acid mine drainage (AMD)
- Infiltration
  - Fine-grained material retains moisture above water table
  - Capillary barrier effect (1), (2)
- Gas transport:
  - Fine-grained material: diffusion through partially gas-filled pores
    - Fick's law (3): $\mathrm{F} = -D_e \frac{\partial C}{\partial z}$

Background

- Concerns – geotechnical
  - Breakthrough in capillary barrier (4)
  - Breaches (e.g., punctures, fractures) (5)
- Concerns – geochemical
  - Partially oxidized tailings - stability of secondary phases (esp. Fe(III) oxyhydroxides) (6)
    - Lower redox conditions imposed by the cover
    - Reductive dissolution of Fe(III) oxyhydroxides
  - Potential remobilization of trace elements

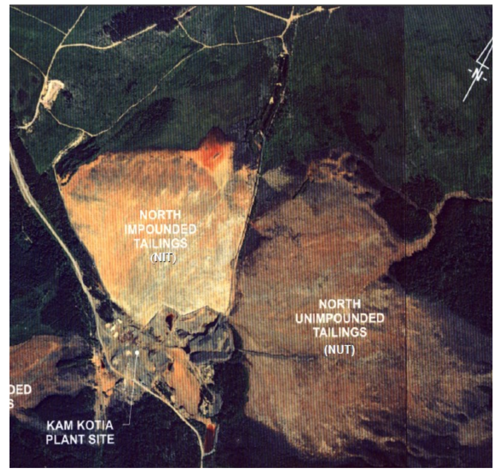
Site Description

- North Impounded Tailings (NIT) of Kam Kotia
- Former Cu, Zn mine near Timmins, Ontario
- Abandoned in 1972
- ~3 million tonnes of tailings deposited within the NIT
- Significant AMD production
- Contamination of groundwater and surface water



★ Kam Kotia Mine Site

Before rehabilitation (1989) (7)



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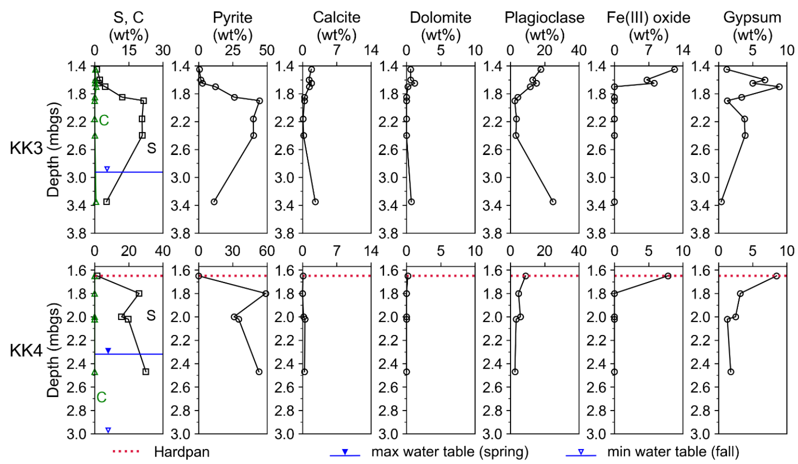
Tailings deposited unconfined 1962-1967: ~ 3 million tonnes
1967 – tailings dams built
Tailings deposited in NIT 1968-1972: 1.2-1.6 million tonnes
Tailings 0-5 m deep

Site Description - Mineralogy

- Unoxidized tailings:
  - Pyrite up to 44 wt% at KK3 & up to 59 wt% at KK4
  - Calcite <3 wt%
- Oxidized zone:
  - Secondary phases (e.g., Fe(III) oxide)



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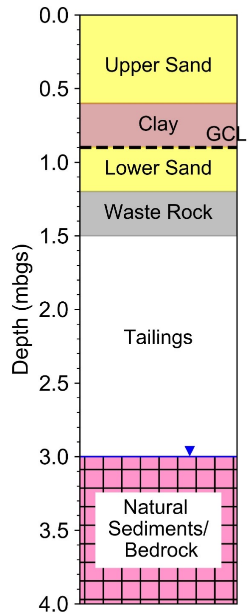
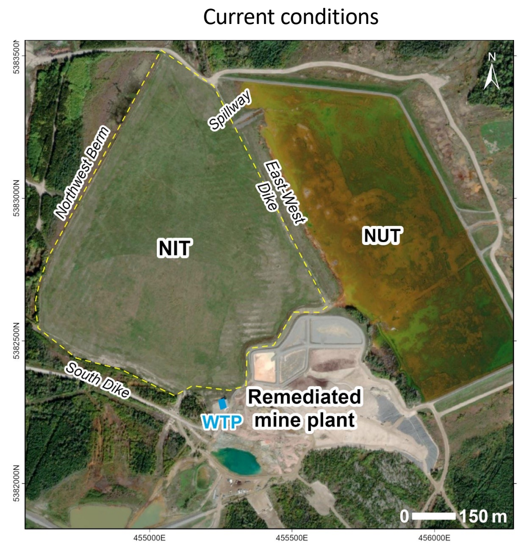
The mineralogy data from the results sections were briefly shown here to illustrate that

Site Description

- Ontario Ministry of Mines rehabilitation
- Composite cover at NIT
- Construction: late 2004 - Oct 2008



GCL: geosynthetic clay liner



NIT: North Impounded Tailings
NUT: North Unimpounded Tailings
WTP: Water Treatment Plant

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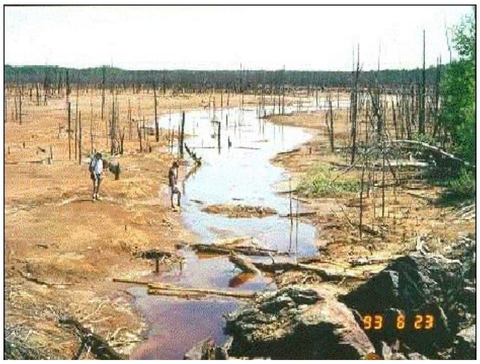
Tailings thickness 0-5 m
Cover performance not previously assessed

Site Description

Before rehabilitation [7]



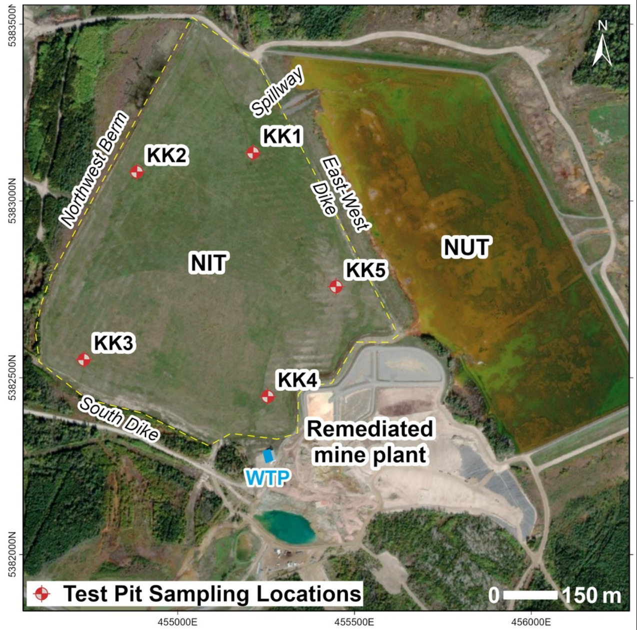
After cover installation

Objective

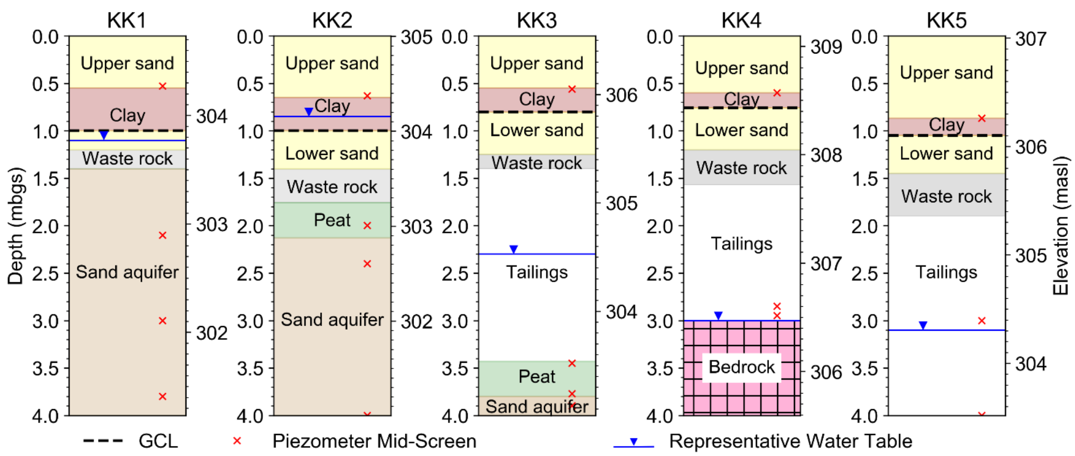
- Evaluate the long-term performance of the composite cover at NIT of Kam Kotia Mine a decade after implementation
  - Characterize the hydrology and gas transport in the composite cover and tailings
  - Characterize the geochemistry and mineralology of the tailings under the cover

Methods

- 5 test pits across NIT (KK1 to KK5) excavated in Oct 2017
- Instrumented with piezometers, suction lysimeters (i.e., soil water solution samplers (SWSS)), soil moisture sensors, gas sampling ports, and tensiometers
- Coring
- Excavated pits subsequently restored layer by layer
  - Openings in the GCL repaired with large patches of GCL sealed with bentonite powder
- Sampling & monitoring May 2018 – Sept 2022



Methods



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Lithology profile encountered at each test pit. Variations in cover thickness
KK4 tailings overlies bedrock
KK1 & KK2 edge of impoundment with minimal tailings thickness – not included in results discussion

Methods

- Groundwater monitoring
- Pore-gas monitoring
  - Field measurements – portable O_2/CO_2 analyzer
  - Gas chromatography
- Continuously measured soil moisture, matric suction 2018-2019 & 2022
- Physical parameters (particle-size distribution, porosity, and hydraulic conductivity)
- Numerical modelling of variably saturated flow - Hydrus 1-D [8]
- Effective diffusion coefficient (D_e) & diffusive O_2 flux calculations [1], [3], [9], [10]
- Aqueous geochemistry
  - pH, Eh, EC, alkalinity, major & trace cations, major anions
  - Stable water isotopes (^2H and ^{18}O)
  - Mineral saturation indices (SI) - PHREEQC
- Tailings mineralogy
  - X-Ray Diffraction (XRD)
  - Carbon-Sulfur analysis
- Non-sequential selective chemical extractions

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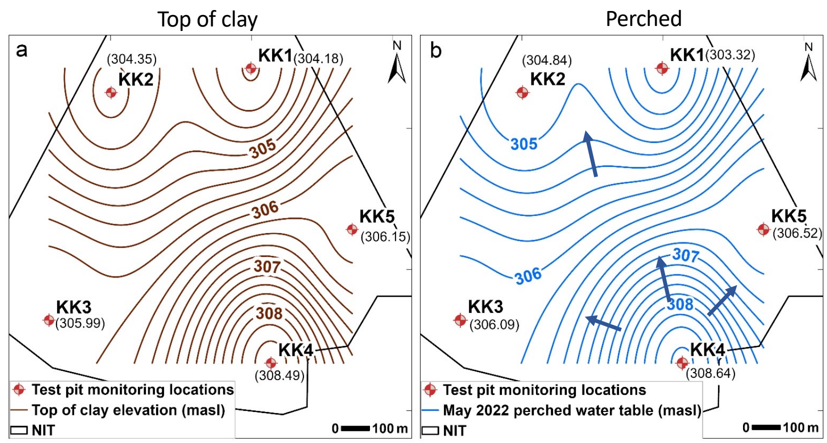
6 rounds of .. And pore water sampling
Tailings core samples taken in 2017
Optical Microscopy
Scanning electron microscopy / energy dispersive X-ray (SEM/EDX)
Synchrotron-based micro X-ray Absorption Near-Edge Spectroscopy (µXANES)

Methods

Groundwater Flow – Perched (Spring)

- Spring: perched condition in upper sand
  - Followed top of cover clay contours
- Snowmelt infiltration
  - Lateral drainage
  - Further infiltration



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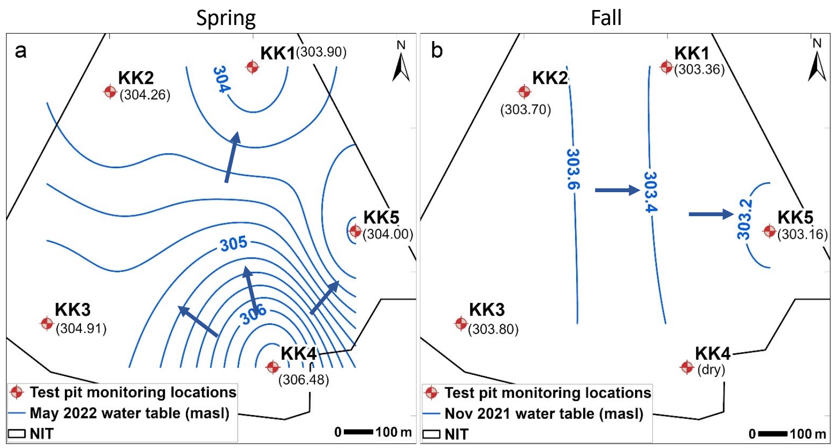
Groundwater monitoring revealed a consistent seasonal pattern in the groundwater flow at NIT

Groundwater Flow – Tailings and Sand Aquifer

- Spring:
  - Groundwater flow: S to N/NE
- Summer, fall, winter:
  - Perched condition not observed
  - Groundwater flow: W to E



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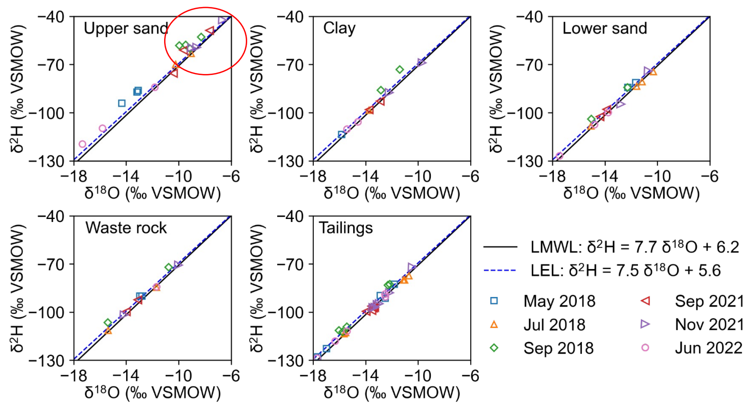
Groundwater dispersed away from the south end of NIT (KK4)

Stable Water Isotopes

- Upper sand: more enriched in heavier water isotopes during the summer and fall
- Other layers: relatively depleted in heavier water isotopes during all sampling times
- Snow is more depleted in the heavier isotopes → snowmelt is a significant source of water in the lower layers



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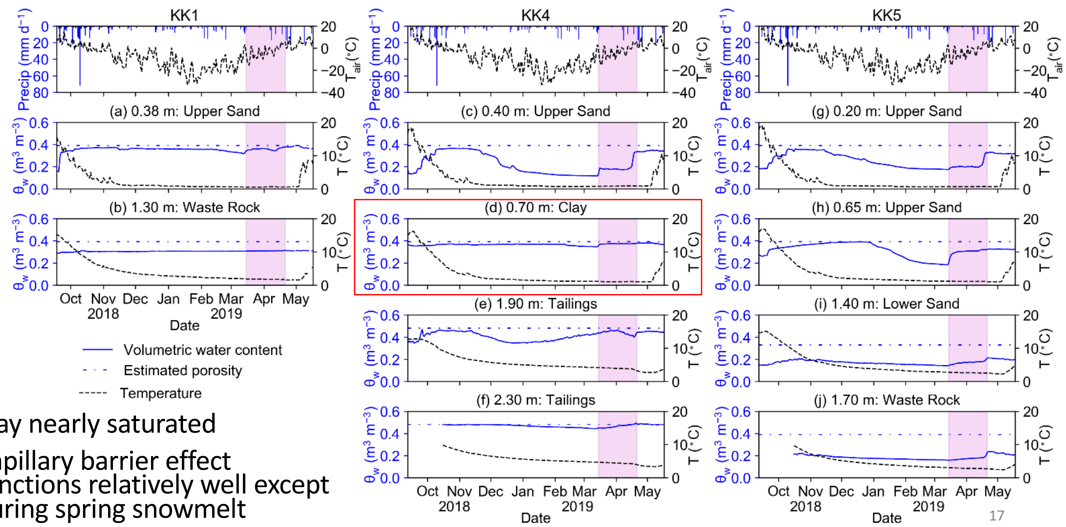
Upper sand: pore water more enriched in heavier water isotopes during the summer and fall
Other layers: relatively depleted in heavier water isotopes during all sampling times
Snow is more depleted in the heavier isotopes, snowmelt is a significant source of water in the lower layers

Vadose Zone Hydrology – θ_w 2018-2019

Volumetric water content (θ_w): converted from dielectric permittivity

Pink area: snowmelt period



- Clay nearly saturated
- Capillary barrier effect functions relatively well except during spring snowmelt

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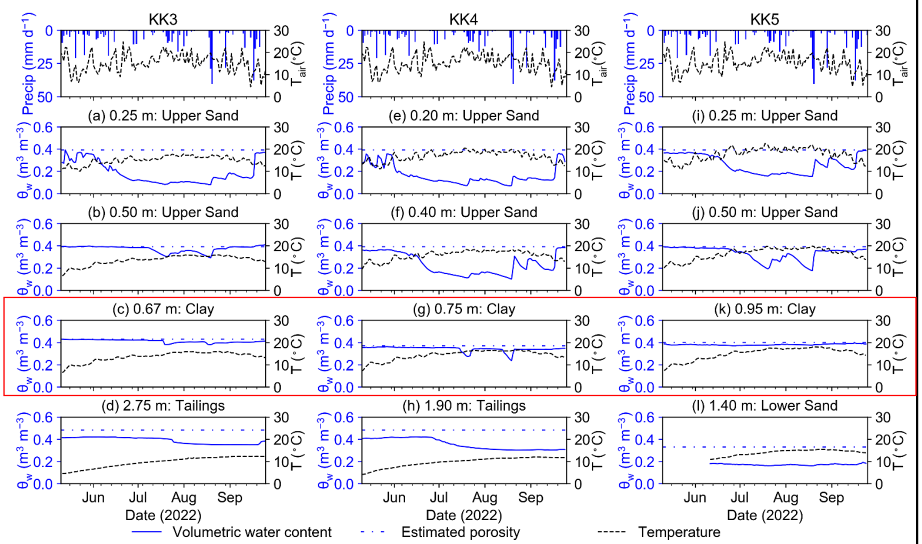
This figure shows continuously measured soil T and volumetric water content converted from dielectric permittivity during 3 seasons from 2018 to 2019
Volumetric water content at clay layer remains relatively stable
Upper lower sand , waste rock fluctuates
Pink: snowmelt period, increase in water content at the end of snowmelt period – and the pressure response can be observed at deeper cover layers and tailings

KK1 waste rock: tension-saturated zone corresponding to a shallow water table

During winter, measured soil T is slightly above 0 and apparent volumetric water content decreased in upper sand and clay (converted from measured dielectric permittivity), which are attributed to partial pore water freezing and zero curtain effect

Vadose Zone Hydrology – θ_w 2022

- Temporary desiccation in clay at KK3 and KK4, not observed at KK5
  - Thickness of upper sand



Summer 2022, temporary desiccation in clay at KK3 and KK4, not observed at KK5
- possible contributing factor to this difference: higher thickness of upper sand ~ 0.9 m at KK5 compared to ~ 0.6 m KK3 and KK4
- decreasing volumetric water content in tailings: due to decrease in water table position

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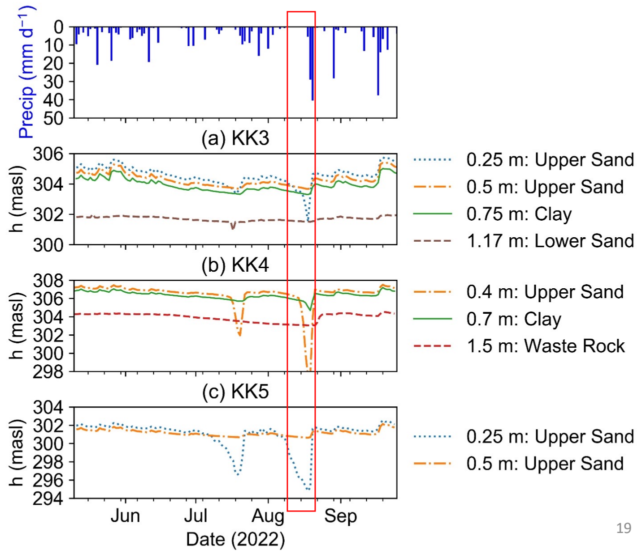
Vadose Zone Hydrology – Tensiometers 2022

- Dry period in August: Ψ (matric suction) increased (h decreased) in the upper sand layer until recovered following precipitation events
  - Ψ also increased in the clay layer at KK4



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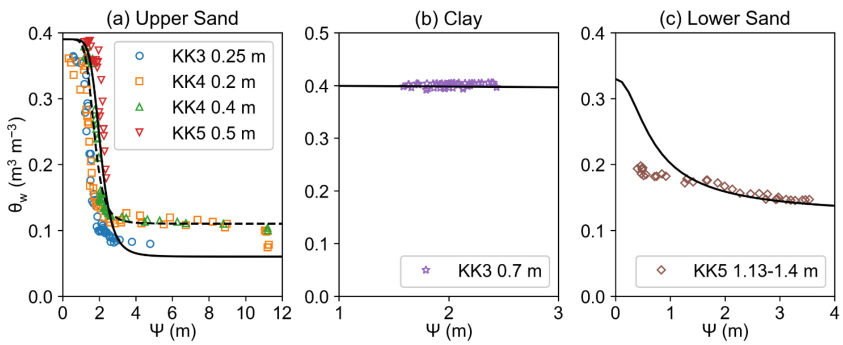
This figure shows the matric suction data measured by tensiometers converted to hydraulic head. The time periods are consistent with the volumetric water content time series in the previous slide

Fitted Soil-Water Retention Curves

- van Genuchten (1980) [11]
- Good agreement between the *in situ* data and the fitted curves
- Used in subsequent modelling of variably saturated flow



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(a) α = 0.5 m^{-1}, n=7, θ_r = 0.06, and θ_s = 0.39 (R^2 = 0.63);
(b) clay: α = 0.04 m^{-1}, n=1.3, θ_r = 0.15, and θ_s = 0.4 (R^2 = 0.54);
(c) lower sand: α = 2 m^{-1}, n=2.2, θ_r = 0.12, and θ_s = 0.33 (R^2 = 0.84).

Variably Saturated Flow and Heat Transport Simulations - Input

- Hydrus 1-D Processes: water flow, heat transport, and snow hydrology
- Simulation period: *in situ* instrumentation records
- 0.01 m spatial discretization
- Top boundary: atmospheric
  - Water balance at the surface: P = ET + I
  - ET: FAO-56 modified Penman-Monteith model [12]
    - Modification: ET=0 during winter conditions
- Bottom boundary: constant head (measured average water table)
- Heat transport boundaries: measured soil temperatures
- Freeze-thaw process assessed in a separate simulation
  - Limited depths of freezing

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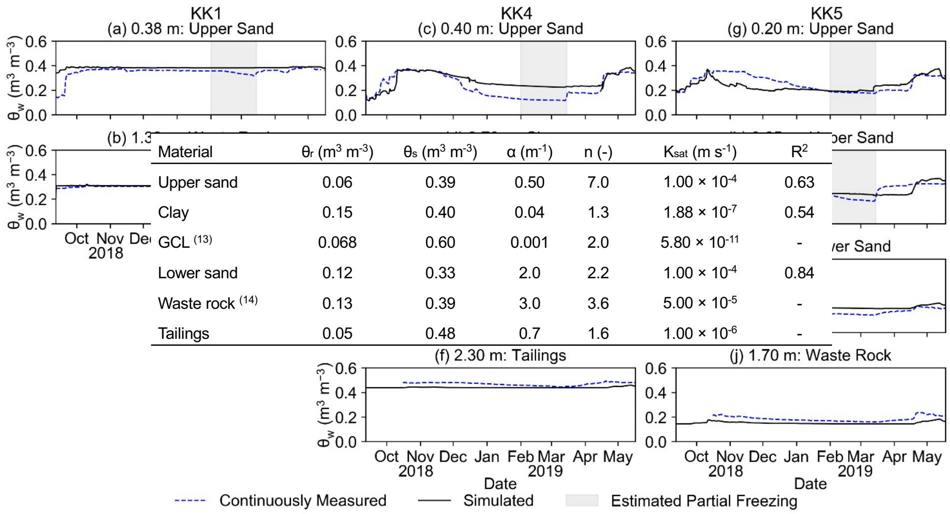
This program uses the finite element method to solve Richard's equation for saturated-unsaturated water flow and convection-dispersion equation for heat transfer

Simulations including freeze-thaw suggests limited depths of freezing (maximum 0.13 m), so omission of freeze-thaw did not significantly impact the heat transport simulations

Variably Saturated Flow and Heat Transport Simulations



Material	θ_r (m^3 m^{-3})	θ_s (m^3 m^{-3})	α (m^{-1})	n (-)	K_{sat} (m s^{-1})	R^2
Upper sand	0.06	0.39	0.50	7.0	1.00×10^{-4}	0.63
Clay	0.15	0.40	0.04	1.3	1.88×10^{-7}	0.54
GCL [13]	0.068	0.60	0.001	2.0	5.80×10^{-11}	-
Lower sand	0.12	0.33	2.0	2.2	1.00×10^{-4}	0.84
Waste rock [14]	0.13	0.39	3.0	3.6	5.00×10^{-5}	-
Tailings	0.05	0.48	0.7	1.6	1.00×10^{-6}	-

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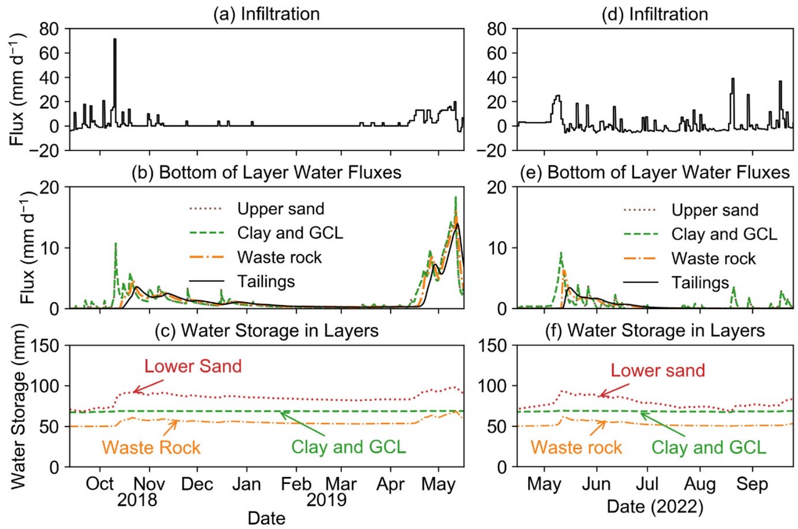
θ_r: residual volumetric water content; θ_s: saturated volumetric water content (=ϕ); α, *n*: van Genuchten (1980) parameters for water retention curves; K_{sat}: saturated hydraulic conductivity; R^2: goodness-of-fit of soil-water retention curve fitting, if applicable.

Note: K_{sat} values for upper sand, clay and lower sand were adopted from Aubertin and Molson (2005). Hydraulic parameters for GCL were adopted from Benson et al. (2007).

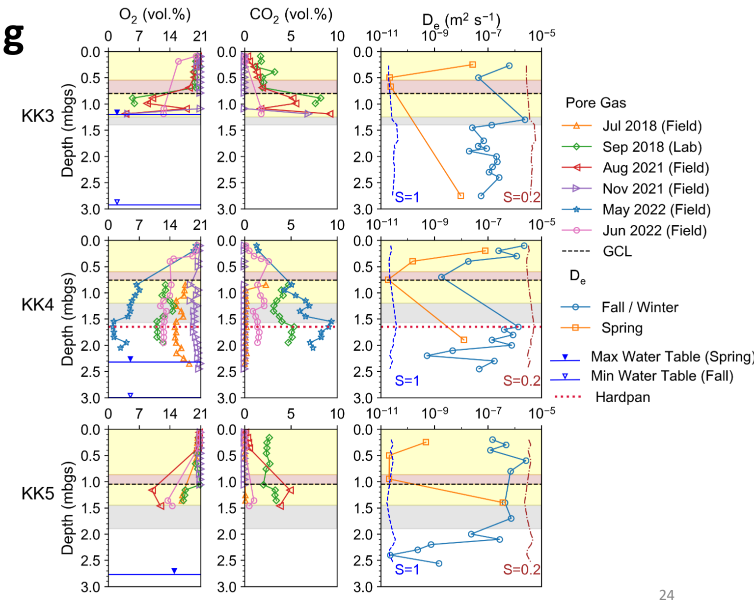
Variably Saturated Flow and Heat Transport Simulations

- High basal water flux (at bottom of tailings) following spring snowmelt
- Limited basal flux rest of the year
- Progressive attenuation of fluxes by cover layers



Pore-Gas Monitoring

- KK3 & KK5: O_2 decreased and CO_2 increased across the GCL
  - Cover impeded O_2 transport
- KK4: seasonal variations
  - Moderate O_2 in summer & fall (10-15 vol.%)
  - November 2021: atmospheric O_2
    - Potential cover imperfections
  - May 2022: depleted O_2
- Effective diffusion coefficient (D_e): higher in the fall/winter



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This figure shows the depth profile of pore gas concentrations with depth ranging from 0 to 3 m. The different background colors represent different cover layers. To recap.

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Calculated Annual O_2 Diffusive Flux

Location	With composite cover		Uncovered tailings	
	$\dot{D}_e$ ($m^2\ s^{-1}$)	O_2 flux ($g\ m^{-2}\ yr^{-1}$)	$\dot{D}_e$ ($m^2\ s^{-1}$)	O_2 flux ($g\ m^{-2}\ yr^{-1}$)
KK4	1.7×10^{-10}	0.5	3.3×10^{-8}	2000
KK5	1.7×10^{-10}	0.5	4.3×10^{-8}	4000

$\dot{D}_e$: equivalent effective diffusion coefficient

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O_2 fluxes into uncovered tailings were four orders of magnitude greater than those under the composite cover

simplifications in these calculations should be noted. The cover was assumed to be without defects. Diffusion was assumed to be the only gas transport process in covered and uncovered tailings

Conclusions – Hydrology and Gas Transport

- Clay layer remained saturated in the spring, fall, and winter
- Temporary desiccation in clay during the summer
- Atmospheric pore-gas O_2 concentrations at KK4 (1 out of 3 monitoring locations) in Nov 2021
  - Potential cover imperfections that enabled O_2 transport into the tailings
- Snowmelt infiltration in the spring
  - Percolation → compromise in the capillary barrier effect & increase in water saturation → limited oxygen transport
- Composite cover at NIT reduced infiltration and O_2 diffusion a decade after installation

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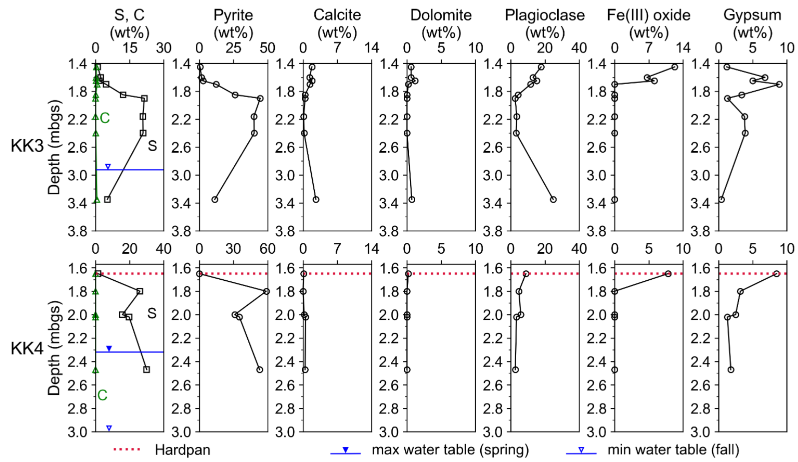
The clay layer stayed nearly saturated in the spring, fall, and winter, but temporary desiccation occurred during the summer. Atmospheric pore-gas oxygen concentrations at one out of three monitoring locations indicate potential cover imperfections that enabled oxygen transport into the tailings. Snowmelt infiltration in the spring resulted in percolation that compromised the capillary barrier effect. The resulting increase in water saturation limited oxygen transport.

Mineralogy – XRD & C/S

- Unoxidized tailings:
  - Pyrite up to 44 wt% at KK3 & up to 59 wt% at KK4
  - Calcite <3 wt%
- Oxidized zone:
  - Depletion of pyrite
  - Enrichment of secondary minerals (e.g., Fe(III) oxide)
  - ~0.25 m thick at KK3
  - ~0.1 m thick at KK4 with thin (< 0.02 m) hardpan



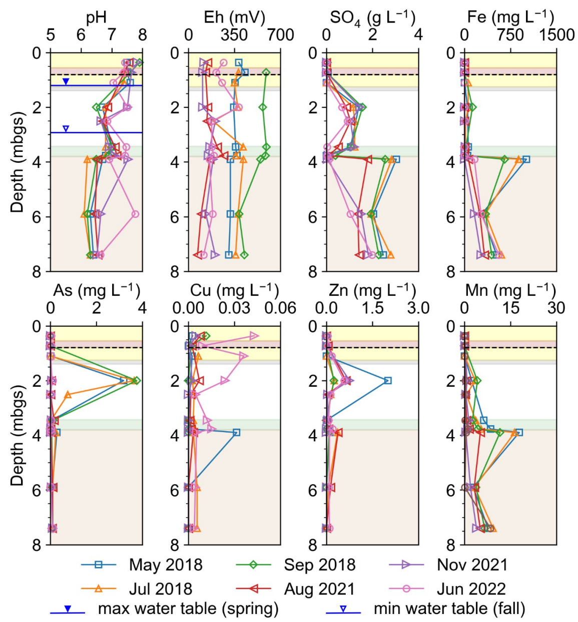
NIT tailings were previously oxidized for decades

secondary minerals: goethite, hematite, maghemite, and gypsum - still remain a decade cover placement

At kk3: Below the oxidized zone, pyrite content gradually increases until it reaches 40 wt%

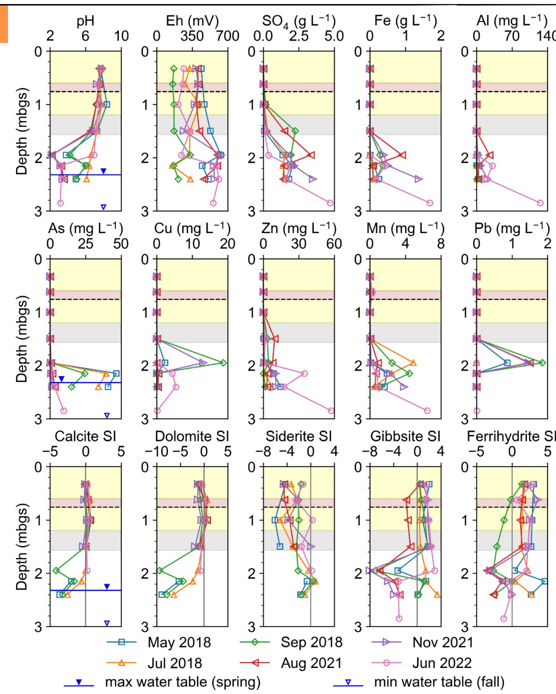
Aqueous Geochemistry - KK3

- Tailings pore water
  - Circumneutral pH
  - Relatively low trace element concentrations



Aqueous Geochemistry - KK4

- Tailings pore water
  - Low pH
  - Elevated Fe, As, Cu, Zn, Pb, and sulfate concentrations
  - Mobilized by sulfide oxidation and/or acidic dissolution of Fe(III) oxyhydroxides
  - Calcite & dolomite depleted
  - Aluminosilicate & Al-hydroxide dissolution



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Pore water approaches saturation wrt siderite

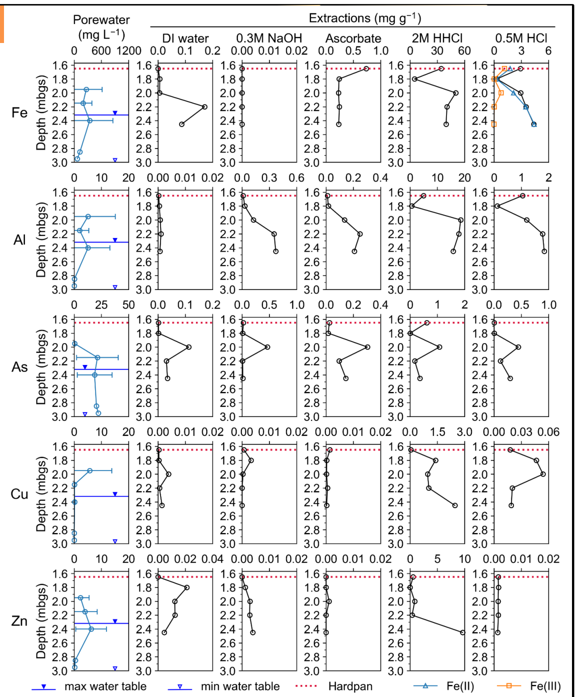
Non-Sequential Selective Chemical Extractions [15]

- Help clarify trace element mobility & secondary phase sequestration under different geochemical conditions in the tailings

Step	Reagent	Representative Geochemical Environment	Targeted Phases
1	DI water purged with Ar [16]	Water-saturated	Water-soluble
2	0.3 M NaOH [17]	Alkaline	Insoluble sulfates
3	Ascorbate: 0.12 M Na-ascorbate, 0.6 M Na-bicarbonate, 0.17 M Na-citrate [18]	Weakly reducing	Amorphous oxyhydroxides
4	2 M HHCl (hydroxylamine hydrochloride) in 25% acetic acid [16]	Strongly reducing	Amorphous & crystalline oxyhydroxides, adsorbed (all reducible oxyhydroxides)
5	0.5 M HCl [19]	Acidic	Poorly crystalline, adsorbed, carbonates (acid-soluble)

Chemical Extractions – KK4

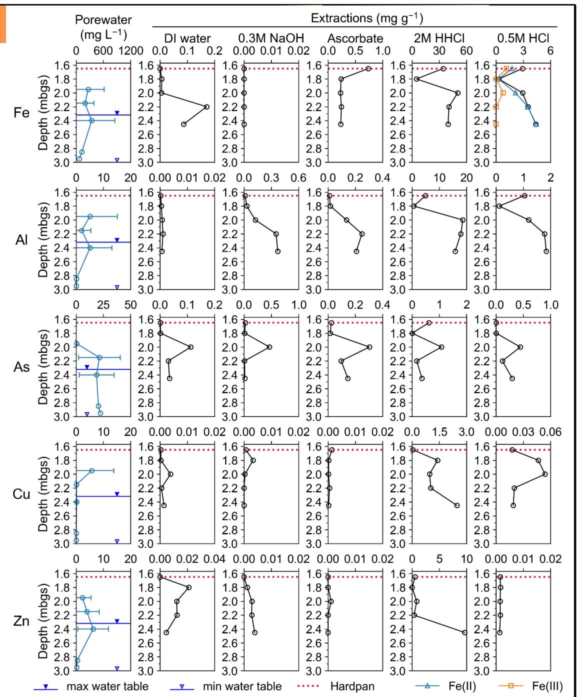
- Extractable Fe highest in total reducible fraction (2M HHCl) – crystalline oxyhydroxide
  - Fe(II) – siderite [$FeCO_3$] in 0.5M HCl increase with depth
- Extractable Al:
  - Gibbsite [$Al(OH)_3$]
  - Amorphous & crystalline Fe(III) oxyhydroxides



@hardpan: Al hydroxysulfates (e.g. basaluminite and alunite)

Chemical Extractions – KK4

- Extractable As: in all fractions
  - Previously sequestered As can be liberated under a variety of conditions
- Extractable Zn: deeper in tailings
  - Crystalline oxyhydroxide
- Extractable Cu: low at hardpan
  - Crystalline oxyhydroxide
  - Covellite [CuS]



Conclusions – Tailings Geochemistry and Mineralogy

- Circumneutral pH and improvement in water quality at KK3 - intact cover location
  - Cover decreased AMD generation and transport
- Near-atmospheric pore-gas O_2 concentrations, low pH, and elevated aqueous concentrations of elements at KK4 - with cover defect
  - Localized sulfide oxidation
- Crystalline Fe(III) oxyhydroxide is the main sink of trace metal(loid)s
- No evidence of strongly reducing conditions or large-scale reductive dissolution of Fe(III) oxyhydroxides

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Circumneutral pH and improvement in water quality at intact cover location suggest that the cover decreased AMD generation and transport. In contrast, near-atmospheric pore-gas oxygen concentrations, low pH, and elevated aqueous concentrations of Fe, sulfate, Zn, Cu, As, and Pb were observed at one location with cover defect, suggesting localized sulfide oxidation.

Implications

- Both geochemical and hydrological characteristics are important
- Composite cover at NIT is beneficial for impeding water infiltration and gas transport
  - Limit sulfide oxidation
  - Limit contaminant release and transport
  - Persistence of some elements (As, Mn and Zn)
- Composite cover did not cause notable remobilization of sequestered trace elements via reductive dissolution of oxidized secondary phases in the underlying tailings
- Special consideration on minimizing and preventing localized areas of cover defects

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When considering the overall impact of cover as remedial approach

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