RIME
UQAT-POLYTECHNIQUE
Research Institute of Mines and Environment

UQAT
UNIVERSITÉ DU QUÉBEC
EN ABITIBI-TÉMISCAMINGUE

POLYTECHNIQUE MONTRÉAL
TECHNOLOGICAL UNIVERSITY

Passive treatment of mine drainage and mining sites rehabilitation using natural and residual materials

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CANADA RESEARCH CHAIR
Treatment and Management of Mine Water

Seminar, Palacky University, Olomouc, May 13, 2025

Outline

- Introduction
  - Personal presentation
  - RIME – UQAT: Who we are, what we do
- Mine water: contaminants and treatment processes
- Cold climate
  - Applied research studies: laboratory vs field
- Conclusion and perspectives

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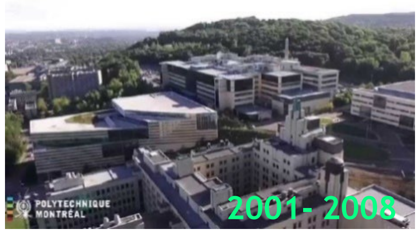
Personal presentation: Training and professional experience



MINISTRY OF ENVIRONMENT
1995 - 2001

Canada Research Chair, CRC Tier 1 (Senior) (2022 - 2029)

Canada Research Chair, CRC Tier 2 (Junior) (2011 - 2021): 2 x 5-year terms

Full Professor (since 2017)

Associate Professor (2011 - 2017)

University of Quebec, QC

Visiting Professor (2019-2020, 6 months)

SUT (Silesian University of Technology), Politechnika Śląska, Poland

Visiting Professor (2025, 3 months)

Universidad de Huelva, Spain

Assistant Professor

Civil and Environmental Engineering Department, KAIST, South Korea

PhD (2004 – 2008)

MSc (2001 – 2003)

Polytechnique Montreal, QC

(Mineral Engineering)

Associate Researcher (2008)

Polytechnique Montreal (Civil, Geological, and Mining Engineering), QC

Scientist (2008)

Natural Resources Canada (NRCan), CANMET, Ottawa, ON

Chemical Engineer

Environmental Protection Agencies, Ministry of Environment, Romania

Chemical Engineer

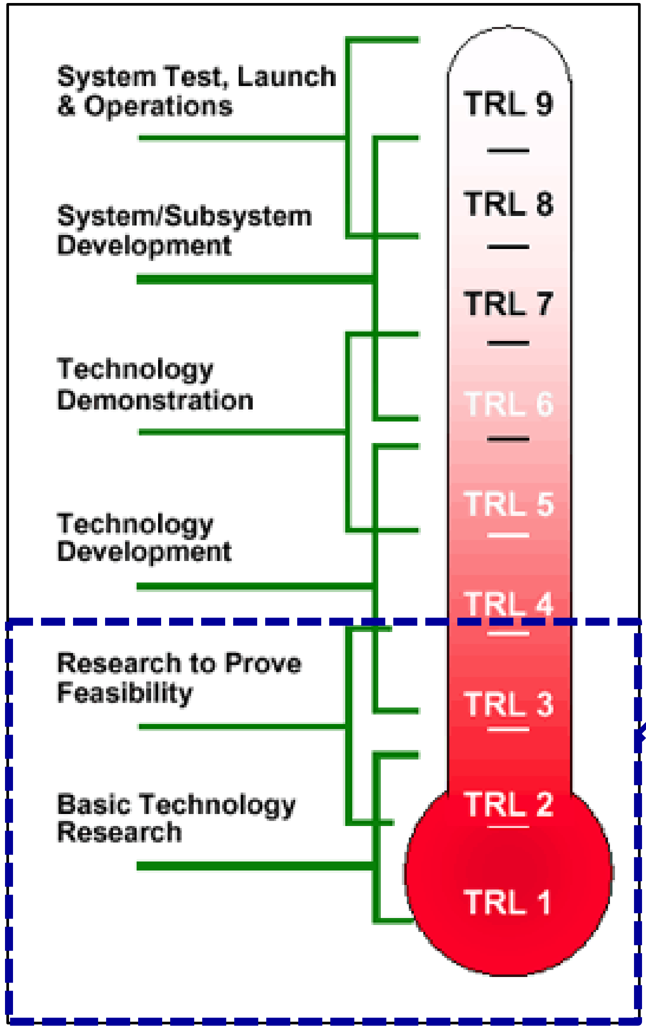
Sulfur Mining Company, Calimani Mountains, Carpathians, Romania

Chemical Engineering Degree

Technical University Iasi (Major: Organic Chemistry), Romania

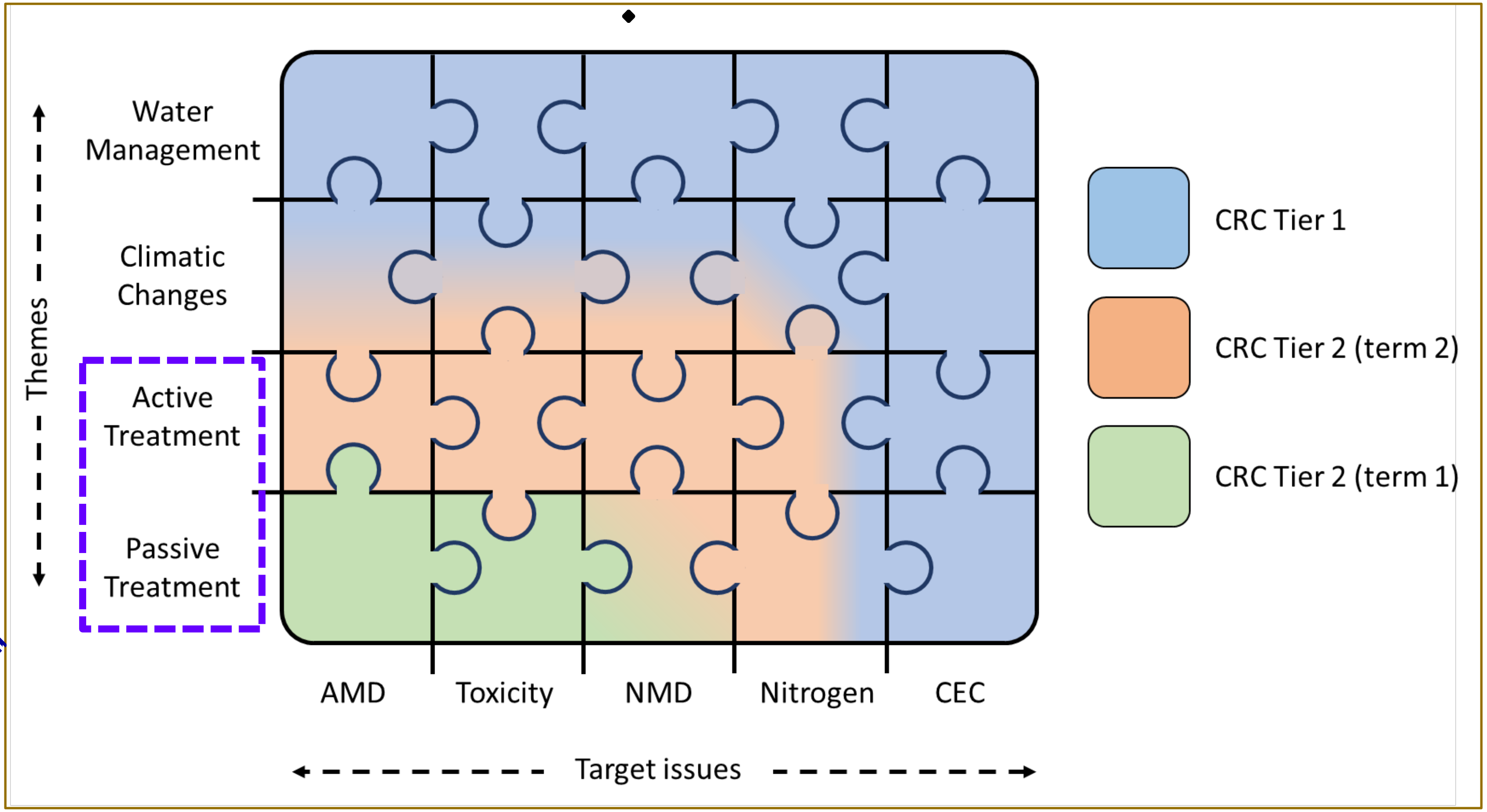
CRC frame: Research focus and knowledge development

Focus of research



[NASA, Internet sources]

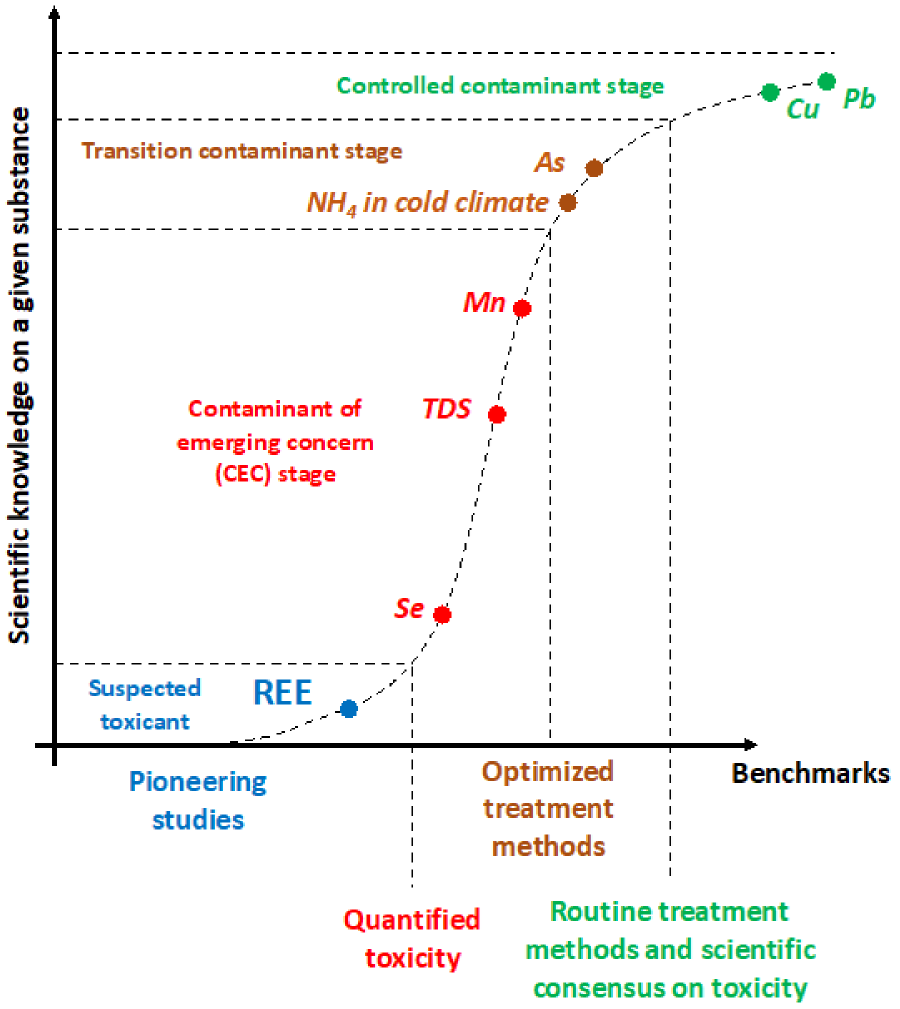
Focus of knowledge to be developed



CEC: Contaminants of Emerging Concern

UQAT

CRC frame: Research focus and knowledge development



CEC definitions based on scientific knowledge of different substances in mine water.
REE: Rare Earth Elements; TDS: Total Dissolved Solids.

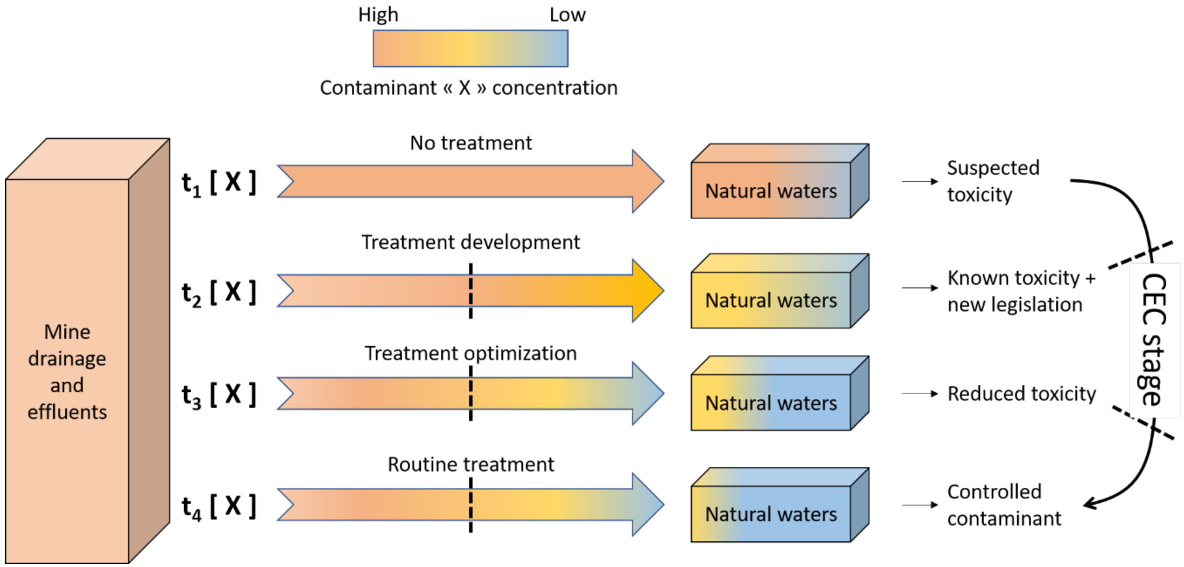
Four groups of contaminants

1) New (rare earth elements: REE, Se, Mn)

2) Difficult / complex to treat (salinity, thiosalts)

3) Common (As, Cu, Sb), but with very low thresholds in sensitive environments (e.g., cold conditions)

4) Nitrogen compounds (NH_3-N, nitrites, nitrates), regulated but also controlled via aquatic toxicity, for mines in operation and new mines



(Neculita *et al.*, 2018, 2020; Ryskie *et al.*, 2021)

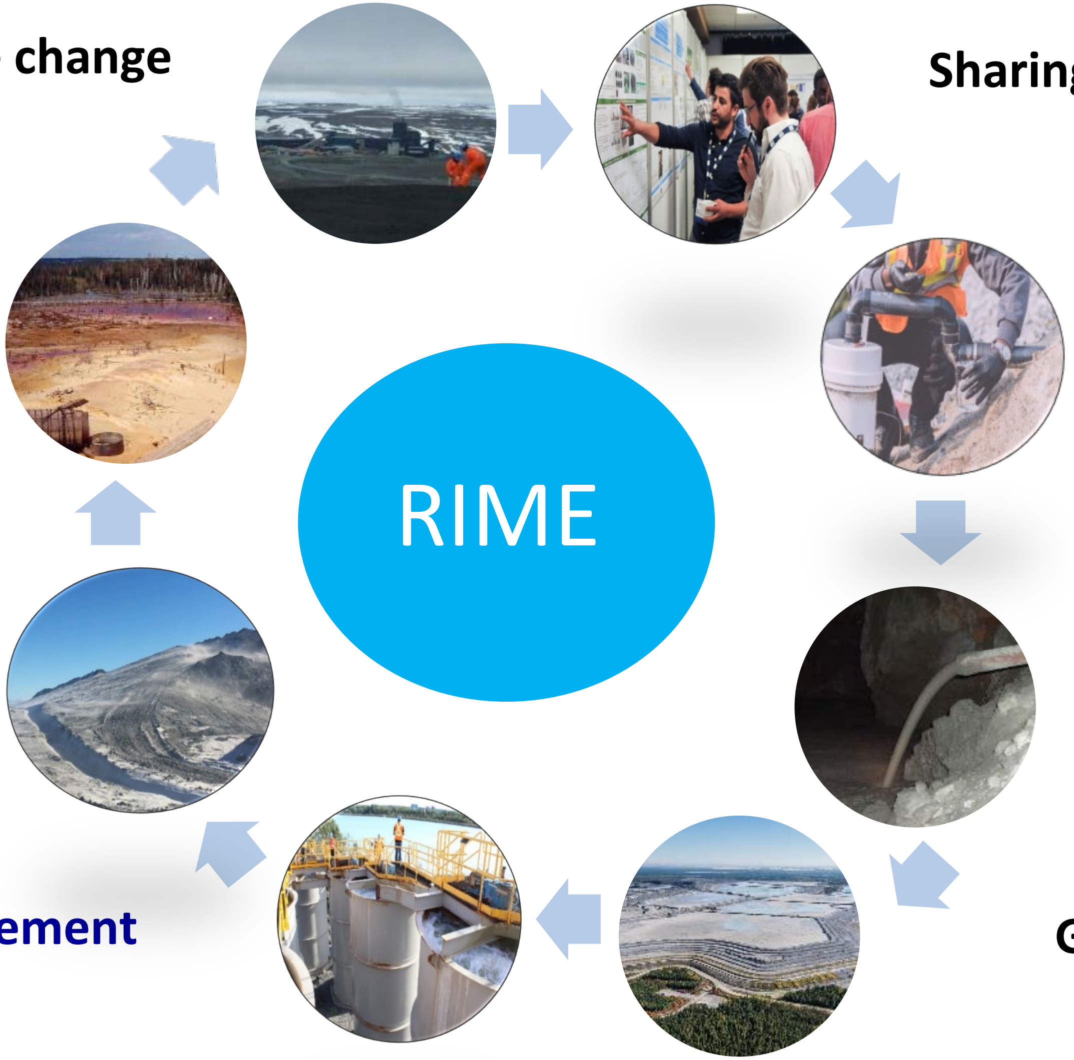
UQAT

RIME UQAT-Polytechnique Montreal: Research topics

Arctic conditions and climate change

Sharing knowledge with communities

Site reclamation and revitalisation



Geology, geoenvironmental characterisation

Prediction of mining effluents quality

Contaminants transport in the environment

Integrated management of mine waste

Valorisation of mine waste

Water treatment and management

Geotechnical stability of tailings impoundments

Created in 2012, as a joint research program on the life-mine cycle

https://www.uqat.ca/uqat/departements/irme/

UQAT

RIME: Industrial partners, access to active mine sites









(https://www.uqat.ca/)

ResMinA: Government partner, access to closed/abandoned/rehabilitated mine sites

- **Rehabilitation of abandoned mine sites**

  - **2023-2028** : Investment of MRNF (Ministry of Natural Resources and Forestry) of 1.2 M$ at RIME-UQAT

  - Research work on **12 abandoned but rehabilitated mine sites** (8 in AT) and **13 non-rehabilitated** (8 in AT) with Directorate of mine site rehabilitation

- → Development of **research projects** (ongoing & upcoming)

Cross-cutting themes

- Integration of social aspects
- Integration of climate changes

Confirmed themes

- Monitoring optimisation post-rehabilitation
- **Passive water treatment systems**
- Severely oxidized tailings
- Vegetation integration

Emergent themes

- **Biodiversity**
- Circular economy and valorization
- Combined strategies of tailings valorization

(https://www.uqat.ca/)

AT: Abitibi-Temiscamingue

UQAT

RIME: Research team & infrastructure, UQAT

Team

- **18** professors
- **14** technicians & professionals
- **5** administrative staff
- > **180** graduate students: advised to completion,
  > 20 nationalities
- > **300** internships

Laboratories & research facilities (technological platform)

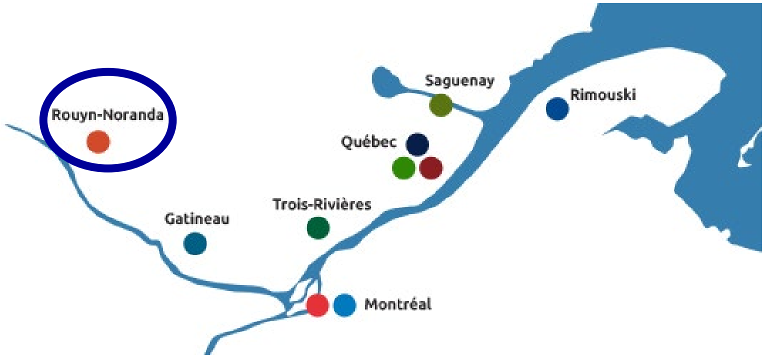
- URSTM (Research & Service Unit in Mineral Technology)
- Infrastructure: Microscopy · Geophysics
  · Analytical Chemistry · Geotechnical and hydrogeology
  · Backfills · XRD · Climate conditions simulations chamber
  · Floating cells · Mobile laboratory

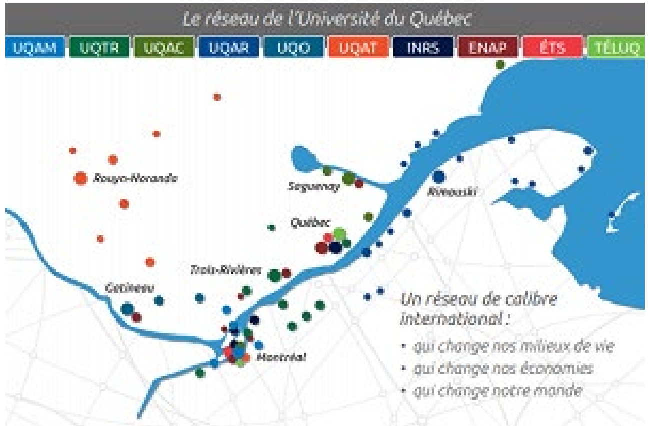
(https://www.uqat.ca/)

UQAT

UQAT: University of Quebec in Abitibi-Témiscamingue

- University of Quebec: 10-University Network

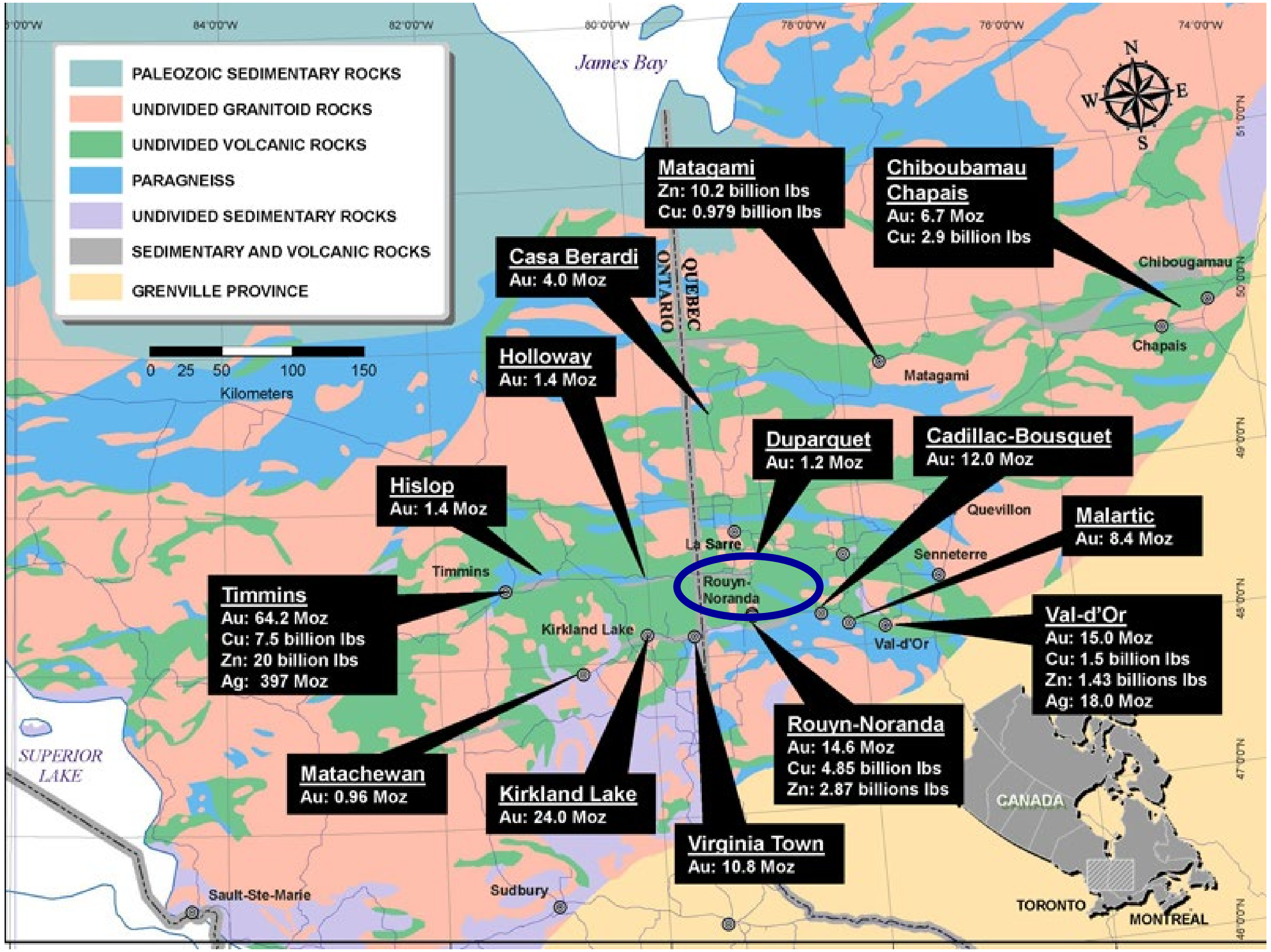


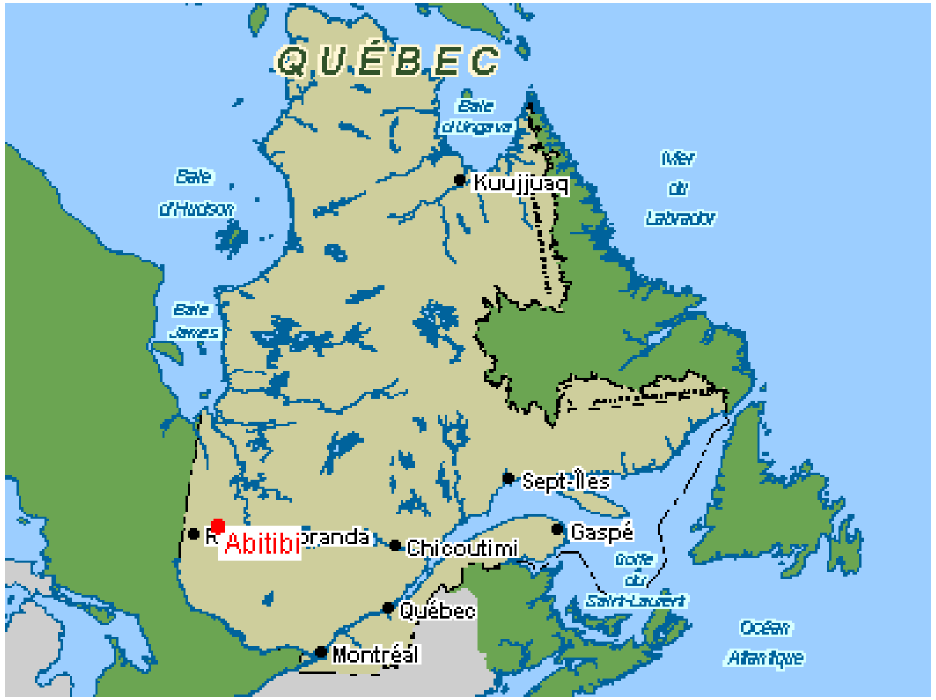


- 10 departments, 3 campuses
  - 2 research institutes: RIME (mines) and IRF (forestry)
- 385 professors and lecturers
- 283 staff
- 6,300 students
- 150 programs
- 12 Research Chairs (2 CRC, Tier 1)
- $10.5M research/year

(https://www.uqat.ca/)

UQAT: Located in an historical mining region (Gold Valley)





(Images: Internet sources)

UQAT

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  - Laboratory vs field applied research studies
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Mine water: contaminants and treatment processes

Contaminants	**Mine drainage** (runoff water)		**N-based compounds** (mine effluents)	
	AMD (acid mine drainage)	NMD (neutral mine drainage)	CN^-, SCN^-	Ammonia (NH_3-N)
Sources	Metal sulfides + O_2 + water		Au, Ag extraction + blasting agents (ANFO)	
Characteristics	**pH < 3; high [] metals (Fe >1g/L), sulfates**	**Metal [] > criteria**	Ore dependent, **but [] > criteria**	
Why prevent or treat?	Regulation, environmental and social impacts			
Challenges	**Several contaminants**	**High contaminant mobility**	**Complexity (toxicity, costs, flowrates)**	
Treatment issues	Sludge management (quantity, stability)	Limited knowledge	Low kinetics of N oxidation	
Research work (RIME)	**Use of natural and residual materials (raw vs modified) for prevention-mitigation of mine water contamination, & mine sites rehabilitation**			

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Natural and residual materials for mine water treatment and sites rehabilitation

Case study	AMD/NMD prevention	Passive treatment
I: East-Sullivan mine site	**Residual organics** cover	Constructed wetlands + water pumping through the organic cover
II: Manitou mine site	**Desulfurized non-acid generating tailings** cover	(To be designed and constructed)
III: Wood-Cadillac mine site	**Inert sand-based** cover	Wood-based biofilter
IV: Lorraine mine site	**CCBE** (cover with capillary barrier effect) – multi-layer	Anoxic dolomite drains + tri-unit biochemical train

V: New materials	Modification / Improvement	Use
Charred dolomite	Enhanced specific surface and porosity, increased pH and alkalinity generation	Synthetic NMD treatment
Modified wood ash		Real NMD treatment
Activated biochar	Porosity arrangement	Real AMD treatment
N-rich residuals	N/A	Non-acid generating tailings revegetation

- **Ongoing research**
- **Concluding remarks**

Location of East-Sullivan and Manitou mine sites

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East-Sullivan mine site: operation, abandonment, rehabilitation

Active (1946-1966), then abandoned until 1980, when government took over the responsibility; reclamation started in 1984

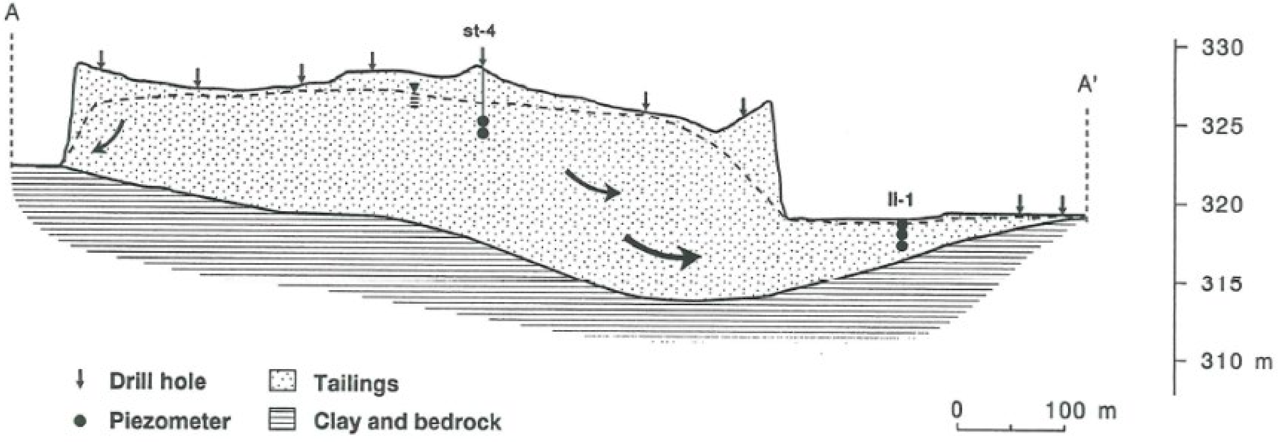


Figure 2. Cross-section A-A' through the East-Sullivan tailings impoundment. Arrows indicate locations of drill holes to the bedrock or clay basement. Dots represent piezometer locations for water sampling.

- **Low pore-water quality in 1992**
  - pH ≈ 2
  - Fe (Fe^{2+}): up to 17 g/L
  - SO_4^{2-}: up to 37 g/L
  - Cu, Pb, Zn : 0.1-1 g/L

→ **High strength AMD**

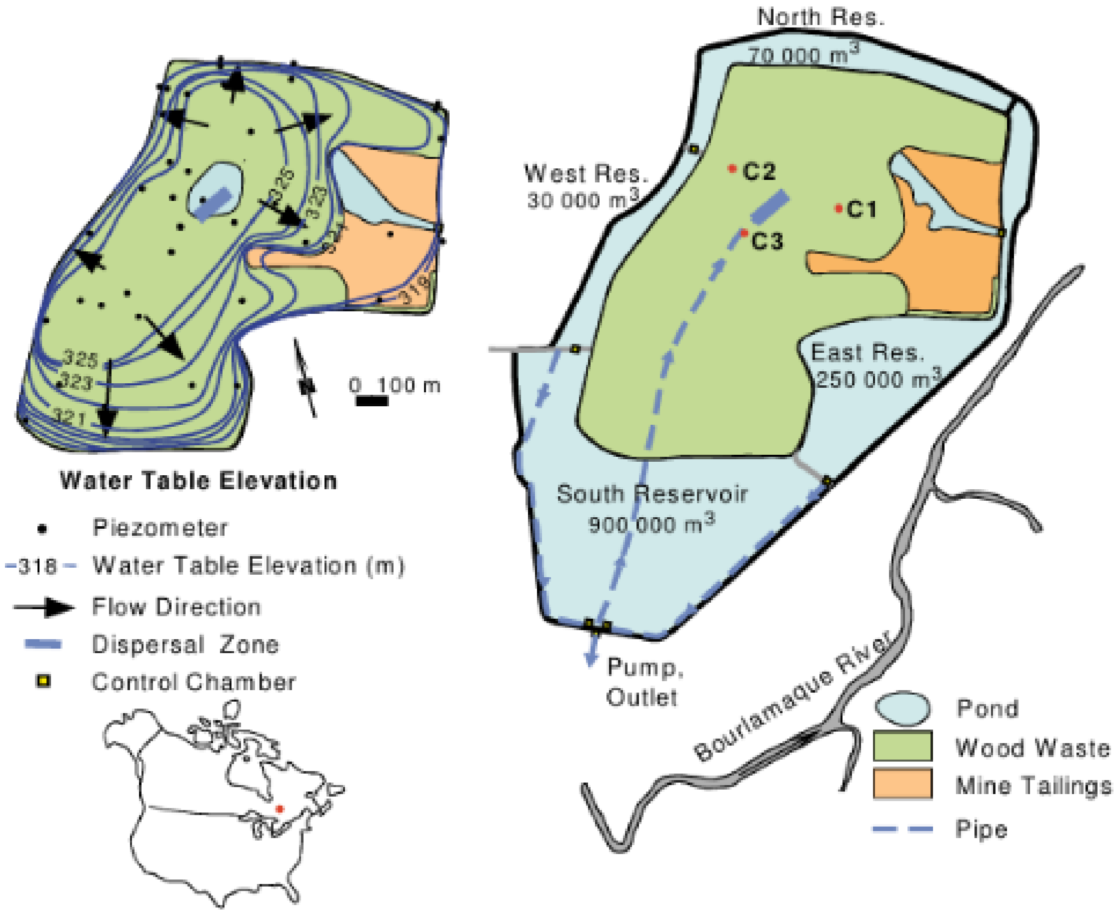
Long-term treatment OR prevention and temporary polishing?

(http://sebastienlavoie.com/maitrise/photos.html; http://www.mrn.gouv.qc.ca/mines/restauration/restauration-sites-east-sullivan.jsp; https://www.oiseauxduquebec.org)

East-Sullivan organic cover: mine site rehabilitation

- **1984: Organic waste (residual wood and biosolids) cover instalment for AMD prevention and [temporary] treatment**
- **1990:** Seepage collection system
- **1992-1996:** Confining dike (6 km) + water polishing in constructed wetlands
- **1998-2005:** Collected AMD in constructed wetlands pumping through the organic cover
- **2019-2020:** Wood cover completion

  ⇒ **Some effluents were still acidic**



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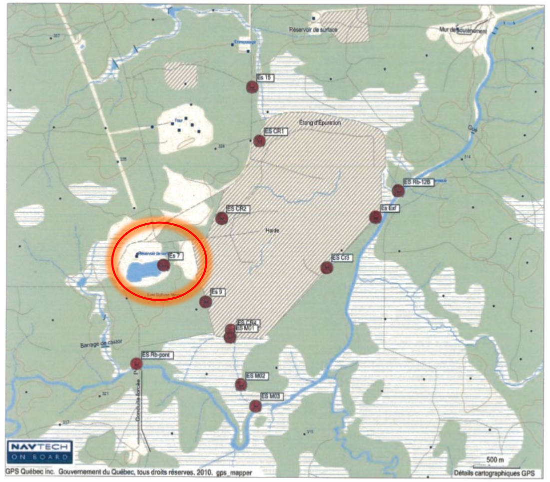
East-Sullivan organic cover: mine site monitoring

- **Network of sampling points**
  - over 15-year data
- **Parameters analyzed**
  - pH, Fe, Cu, Zn (+ Al, Mn, Pb, SO_4^{2-})
- **Compliance, <u>except for the last covered tailings</u>**



- Covered tailings and constructed wetlands: **blooming vegetation** and **birds' refugee** (> 190 species listed)

(Rakotonimaro et al., 2015; Malki & Roy, 2024; https://www.google.ca/flickr.com)

East-Sullivan organic cover: mine site rehabilitation

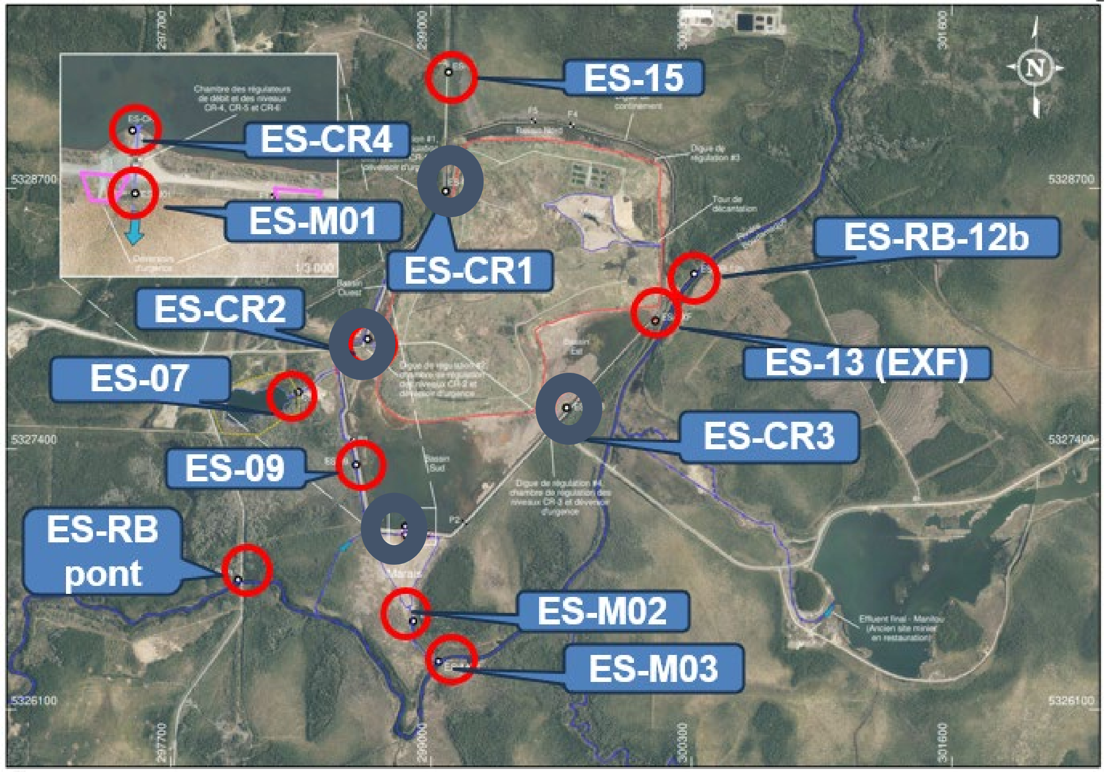
Monitoring over 25 years (2000-2024)

Parameters measured

- pH
- Alkalinity
- Metals: Fe, Al, Mn, Cu, Zn, Pb
- SO_4^{2-}
- Electrical conductivity (CE)
- Total suspended solids (MES)

Available data on a 13-point network

Sampling points	Number of measures
ES-CR1	106
ES-CR2	108
ES-CR3	298
ES-CR4	**633**
ES-M01	148
ES-M02	158
ES-M03	148
ES-RB-12b	54
ES-RB bridge	60
ES-15	**28**
ES-13 (EXF)	46
ES-07	68
ES-09	54



Sampling points on East-Sullivan rehabilitated TSF (tailings storage facility; modified from MRNF map)

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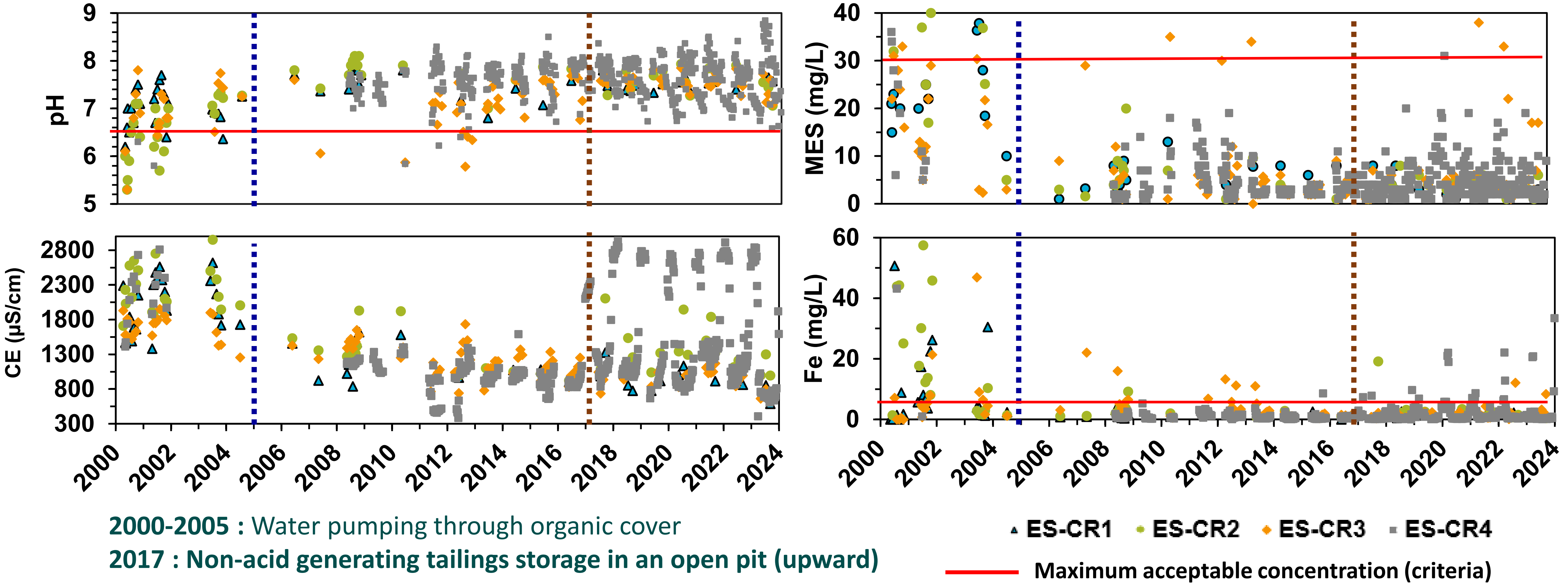
East-Sullivan organic cover: mine site rehabilitation

Monitoring over 25 years (2020-2024): efficient AMD prevention & mitigation



2000-2005 : Water pumping through organic cover

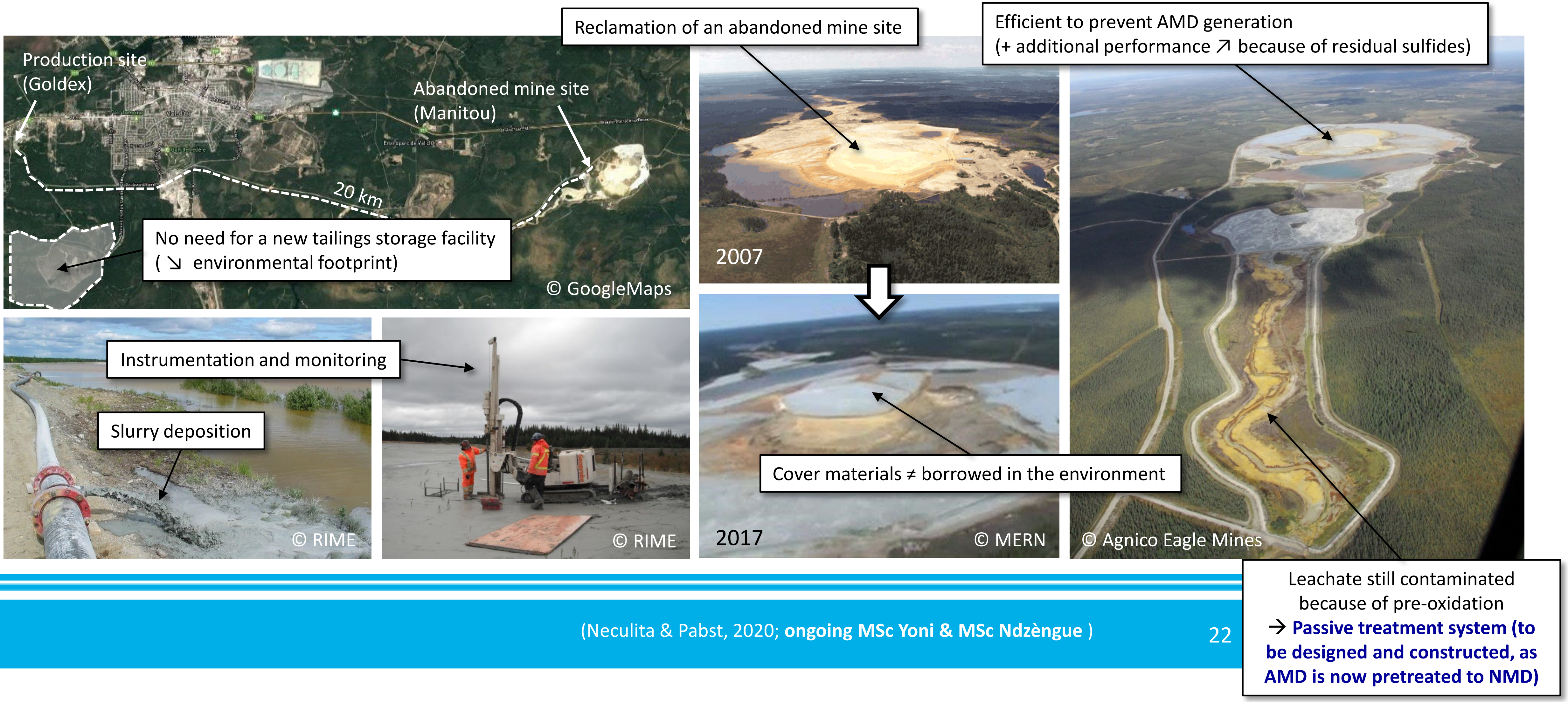
2017 : Non-acid generating tailings storage in an open pit (upward)

(ongoing MSc Malki, 2025; Roy et al., 2025)

Desulfurized tailings cover: Manitou mine

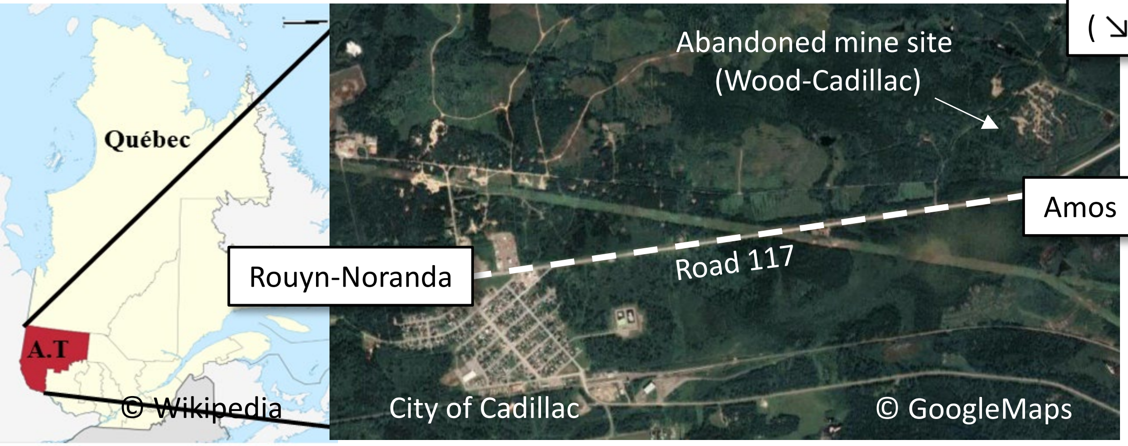
Active (1942-1979), then abandoned until 1980, when government took over the responsibility; reclamation started in 2009

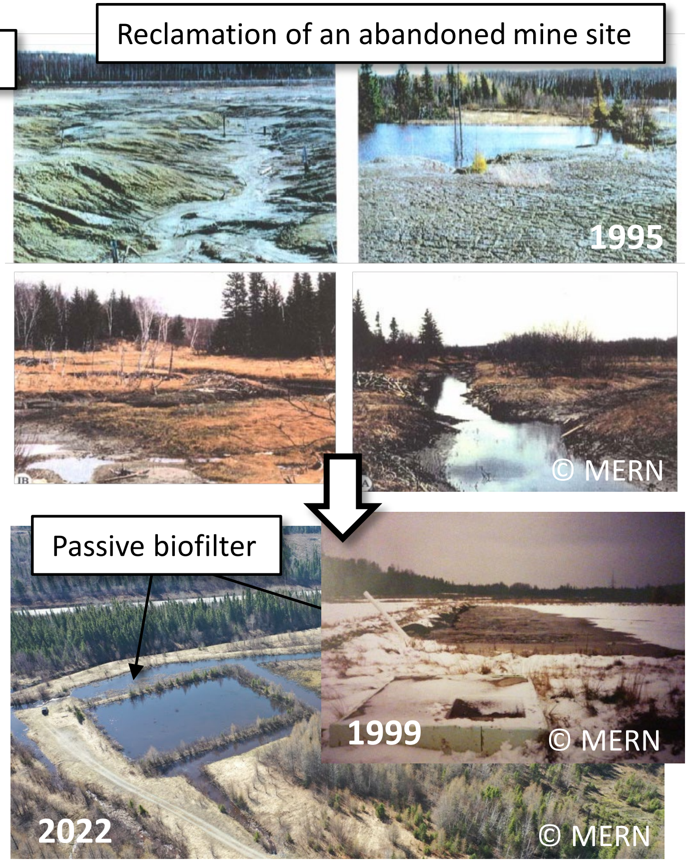
- Prevention and pretreatment of AMD (pH: 2-3; 10-12 g/L Fe; 0.6-1 g/L Zn; 0.1-1 g/L Cu; 30-40 g/L SO_4^{2-})

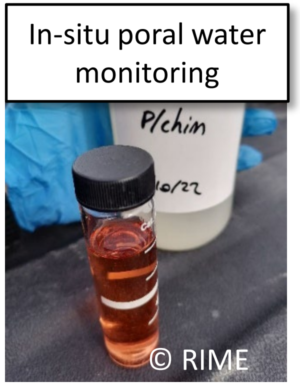


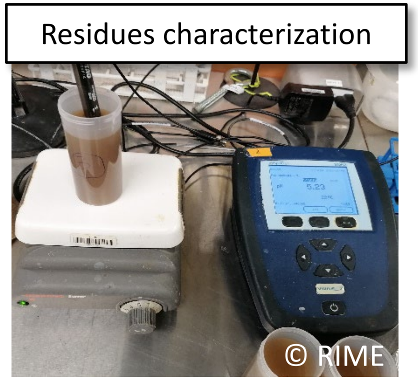
Sand cover + wood-based biofilter: Wood-Cadillac mine site

- Efficient passive treatment of As-NMD: removal of As & metals; decrease of SO_4^{2-} [] to < 200 mg/L









(Germain & Cyr, 2003; **ongoing PhD Mehdaoui & PhD Thevenot**; Mehdaoui et al., 2024, 2025a,b; Thevenot et al., 2024, 2025a,b)

III Sand cover + wood-based biofilter: Wood-Cadillac mine site

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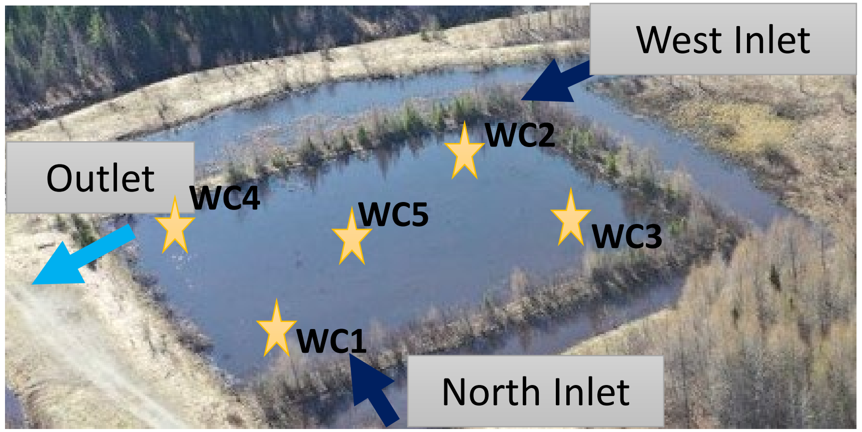
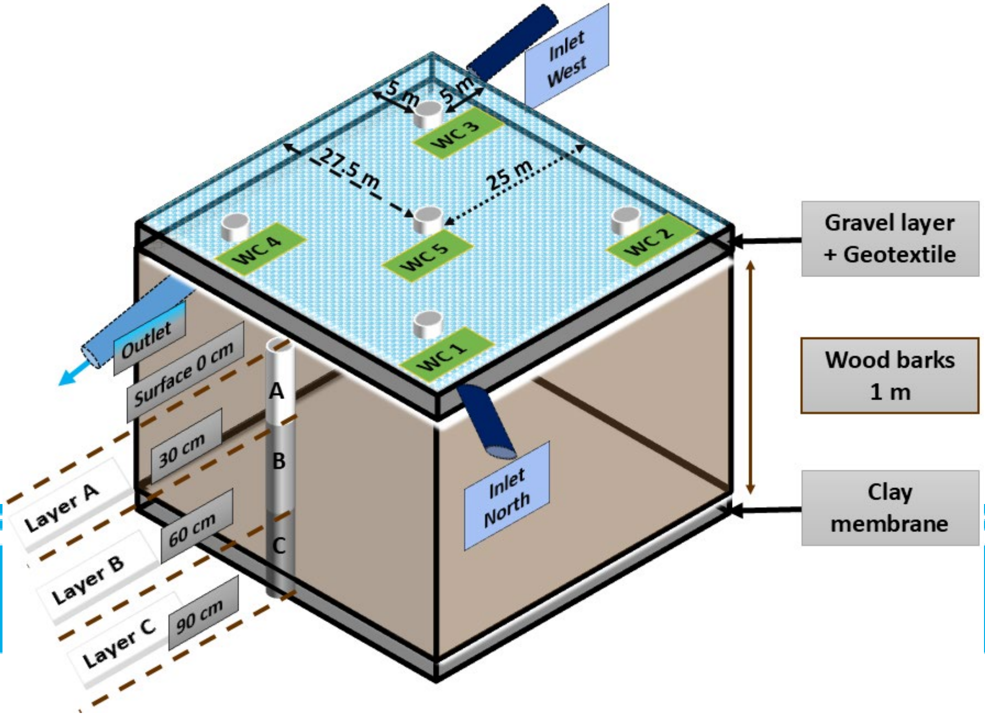


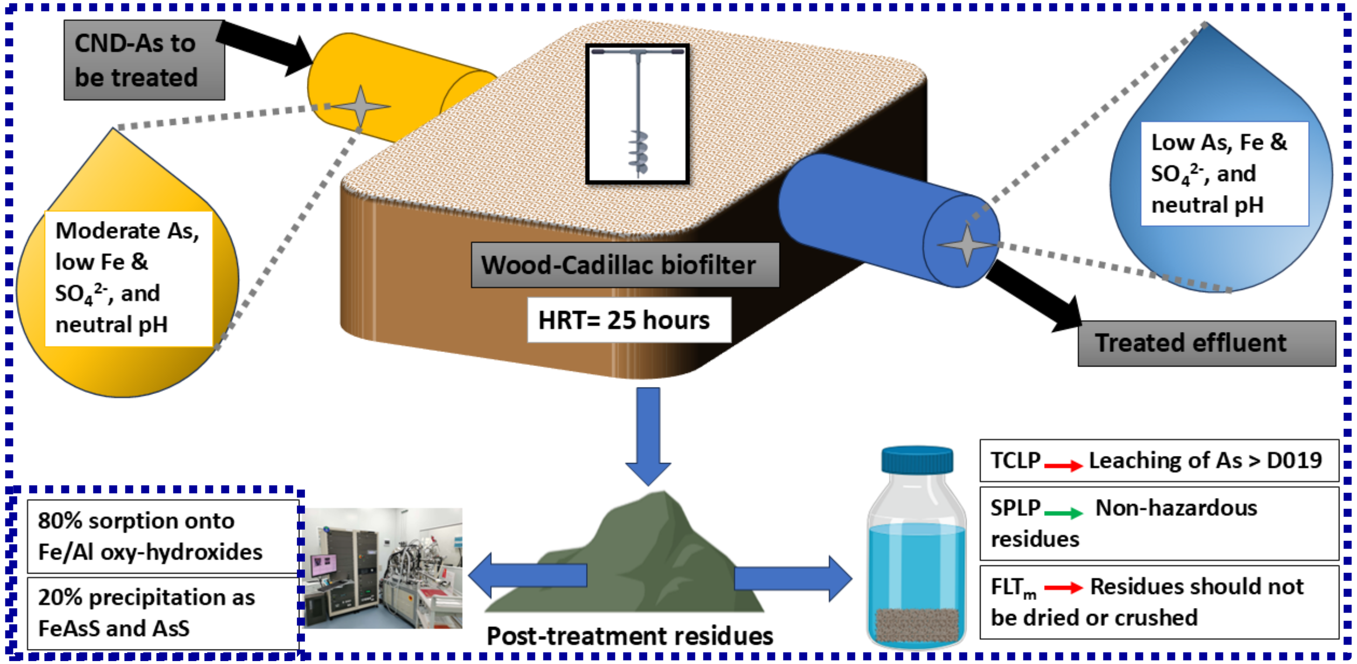
5 sampling points

30 samples

3 depths



Main findings on contaminated residues field post-treatment: no As leaching



(Mehdaoui et al., 2024, 2025a,b; Thevenot et al., 2024, 2025a,b)

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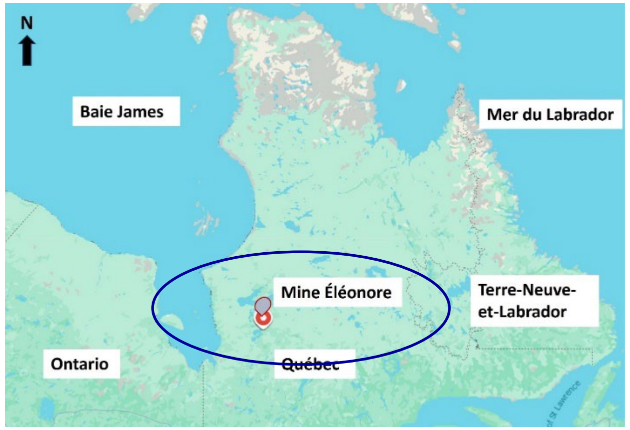
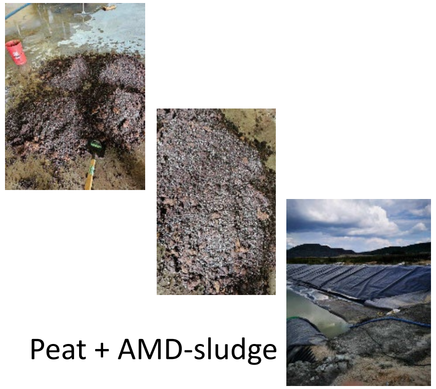
Lab vs field pilot biofilters: Eleonore mine site

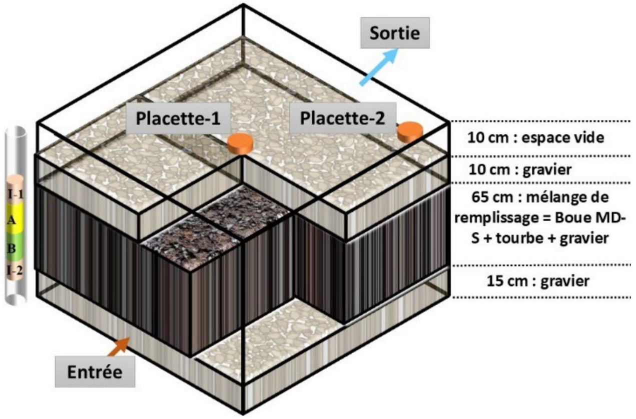
- Efficient passive treatment of As-NMD: removal of As & metals; decrease of SO_4^{2-} [] to < 200 mg/L



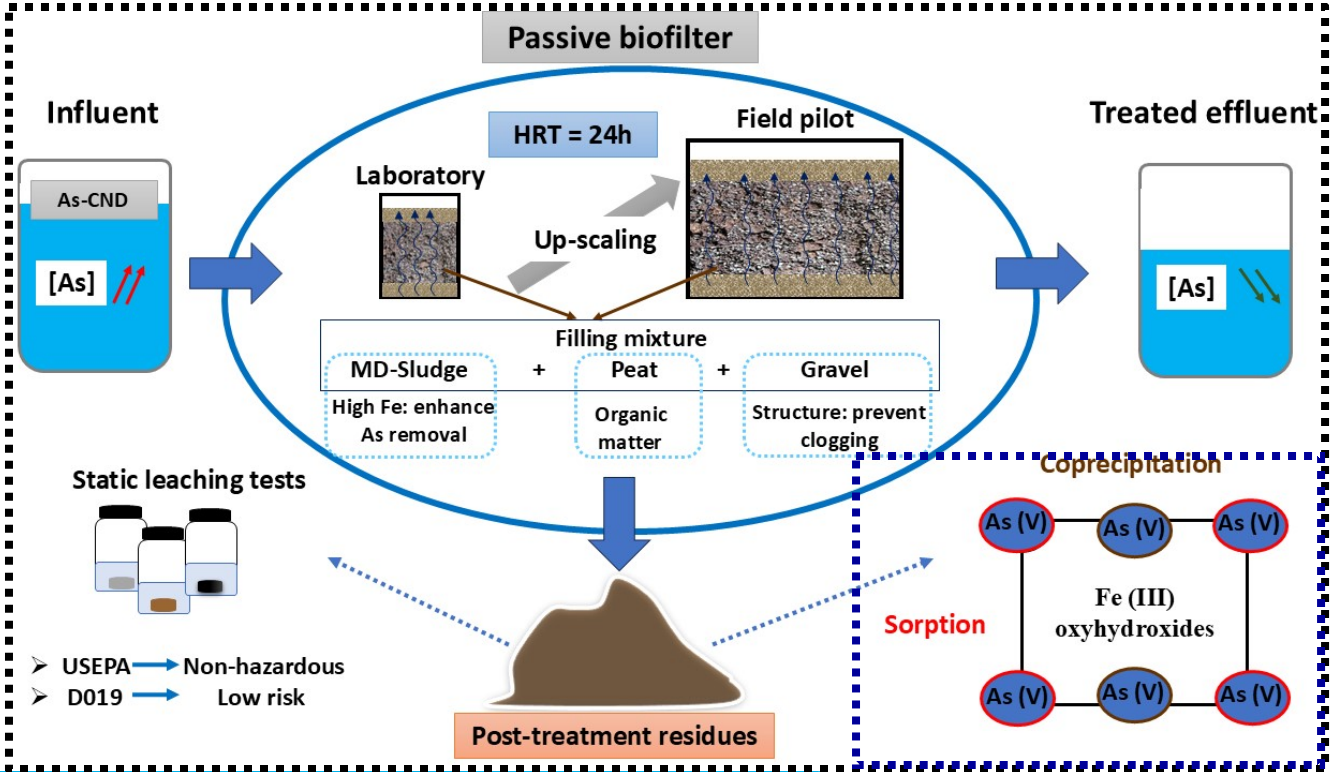
Mine site & passive pilot biofilters



Peat + AMD-sludge

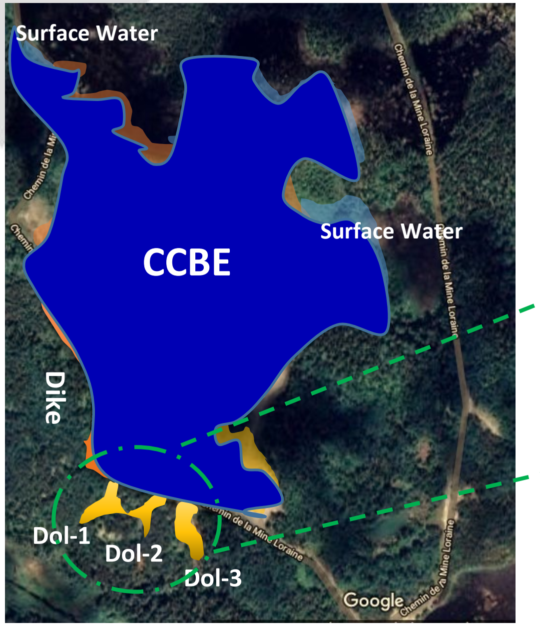


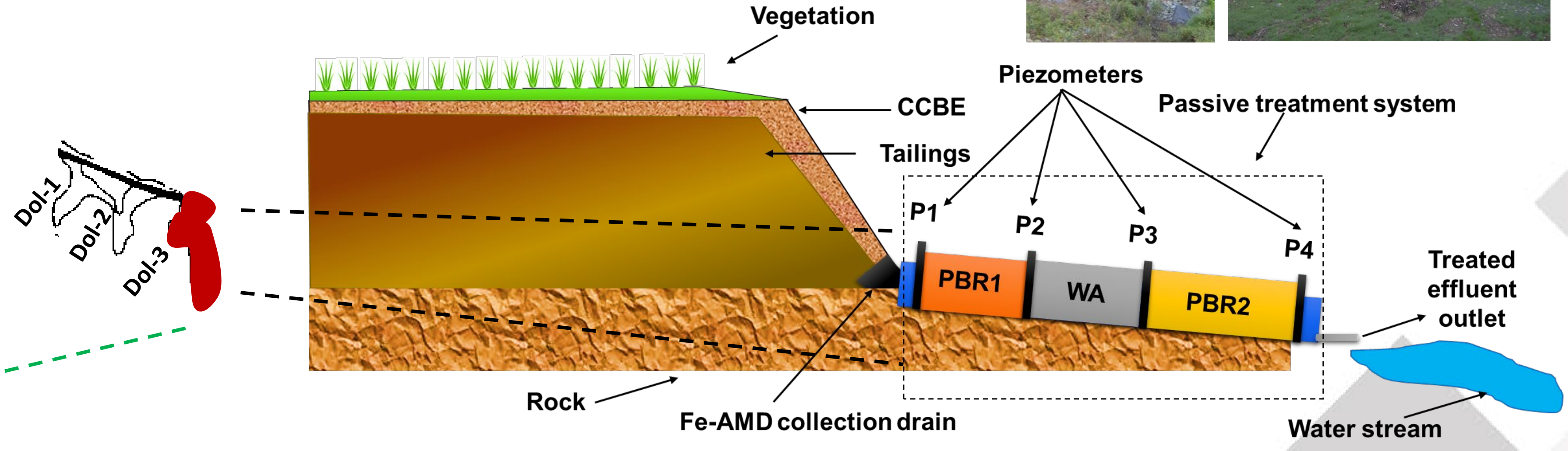
Main findings on contaminated residues lab vs field pilot post-treatment: no As leaching



IV

CCBE + passive treatment: Lorraine mine site





- **1964-1968:** Extraction of **Cu, Au, Ag, and Ni**
  - Acid generating tailings: 15.5 ha (up to 6 m)
  - AMD: pH=3.6, 7 g/L Fe and 15 g/L sulfates
- **In 1998: Mine site reclamation**
  - Multi-layer dry cover with capillary barrier effect (**CCBE**): O_2 prevention
  - AMD treatment: **3 anoxic dolomite drains** (Dol-1 to Dol-3)
- **In 2011: Dol-3 clogged**, replaced by **tri-unit system: PBR1-WA-PBR2**

  (AMD: pH < 4, 3g/L Fe)
  - **PBR1**: 40% organics, 60% inorganics (**pH ↗, sulfate removal**)
  - **WA**: 100 % wood ash (**Fe treatment**)
  - **PBR2**: 77% organics, 23 % inorganics (**polishing**)

(Jouini et al., 2022)

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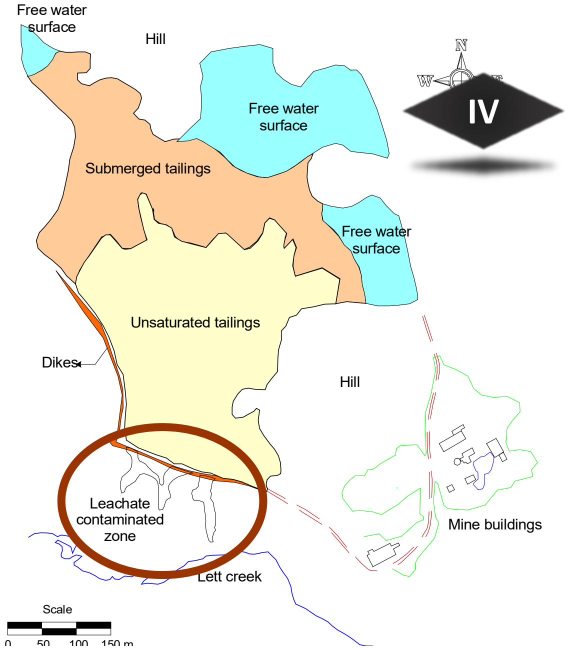
CCBE + passive treatment: Lorraine mine site

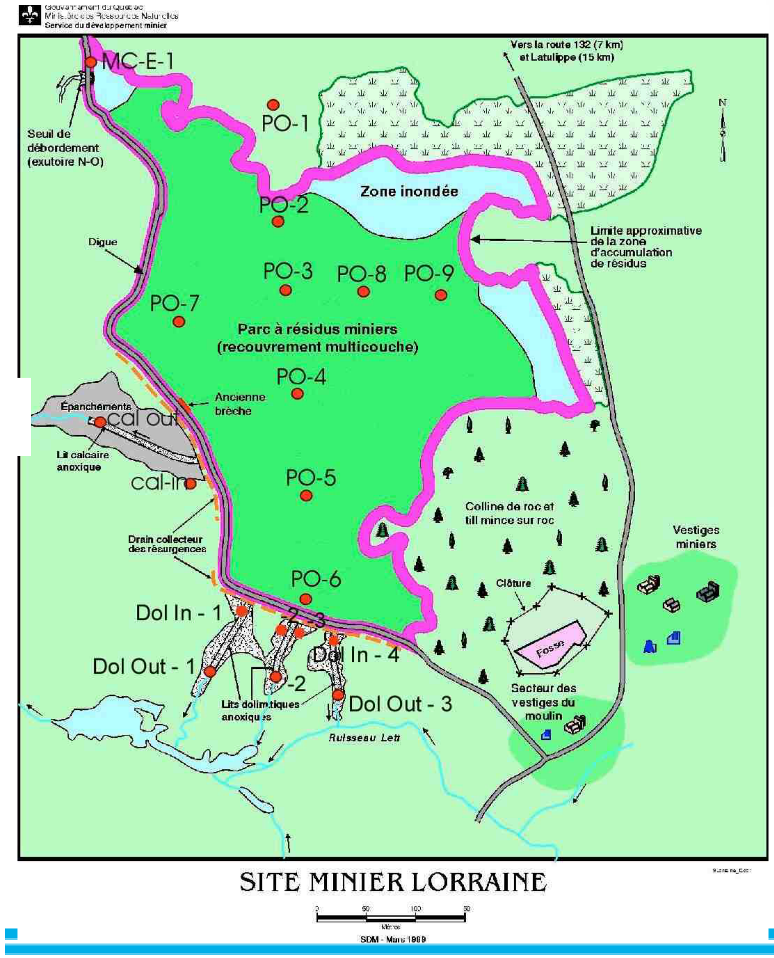


1964-1968 : extraction of Cu, Au, Ag, Ni

acid-generating tailings: 15.5 ha (up to 6 m)

AMD: pH 3.6, 7 g/L Fe, 15 g/L sulfate

2000: CCBE + 3 dolomitic drains



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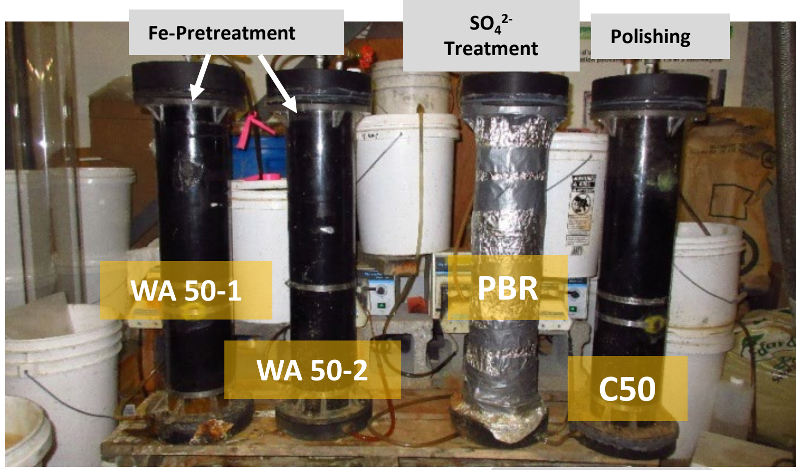
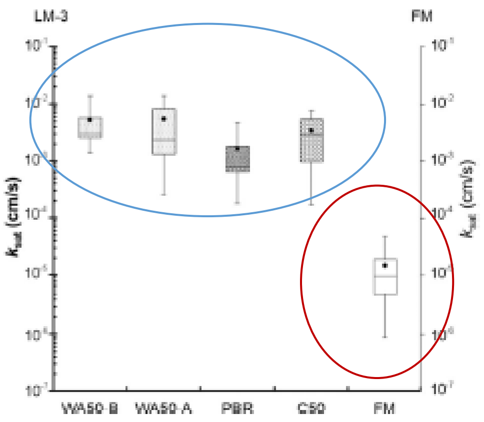
- Tri-unit system **progressive loss of efficiency**: PBR1-WA-PBR2
  - **Porosity clogging** by Fe minerals
  - **Preferential flow** and partial water **bypassing** the system

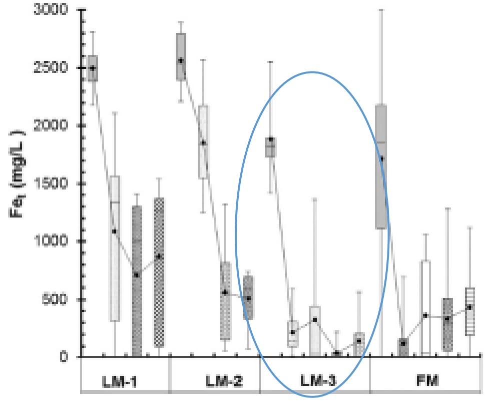
New multi-step system ?

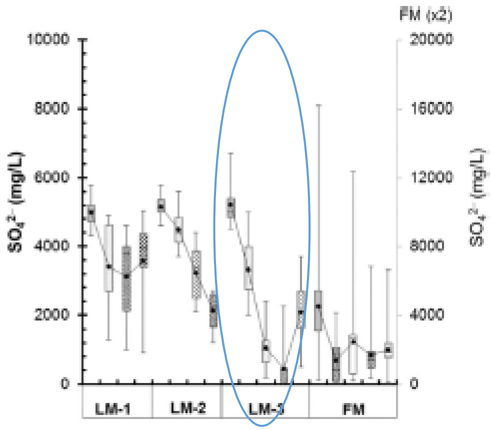
- Multi-step system **calcite-/dolomite-DAS (dispersed alkaline substrate: coarse material + neutralizing agents)** & **passive biochemical reactors**
  - 2 Fe pretreatment units (50% wood chips + 50% wood ash)
  - 1 SO_4^{2-} treatment unit (70% organic + 30% inorganic matter)
  - 1 polishing unit (50% calcite + 50% wood chips)



- **Correction factor** of **0.2–0.8** for **Q and Fe removal** + factor **1/100** for $\mathbf{k_{sat}}$ (measured in laboratory)







What about contaminated residues post-treatment?

(Rötting, 2007; Rakotonimaro et al., 2018)

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Geochemical stability of AMD passive treatment solids

Step I: Sampling and environmental behavior evaluation

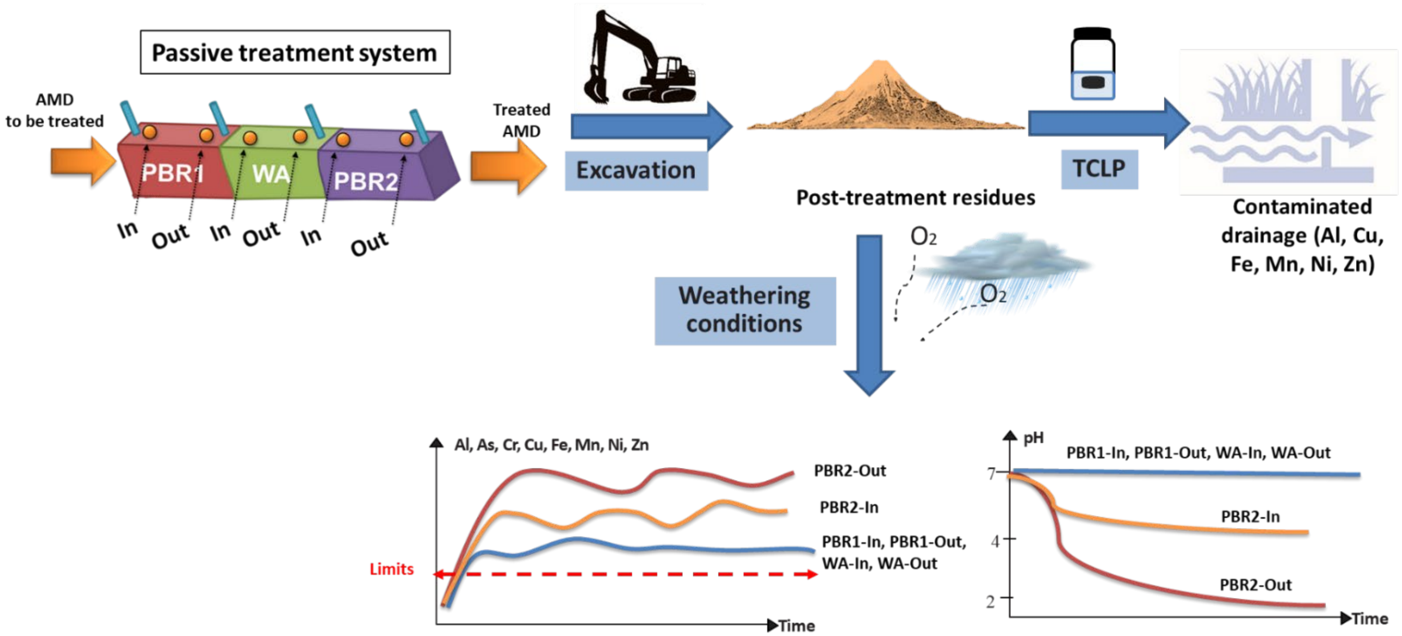

Table 3
Summary of exceeding criteria and classification of residues.

Residues		Static test								Kinetic test		Classification			
		Acid generation potential	Extractable Metals			TCLP									
			>A[a]	>B[a]	>C[a]	>SWQC[b]	T1-AII[c]	TCLP	LDR[d]	Acid?	>SWQC	High risk?	Hazardous?	Leachable?	AMD/NMD?
PBR1	In	No	Ba, Cr	None	None	Al, Fe, Ni, Zn	None	None	None	No	Al, As, Cu, Ni, Zn	No	No	Yes	NMD
	Out	No	None	None	None	Fe, Mn, Ni, Zn	None	None	None	No	Al, Ni, Cu, Zn	No	No	Yes	NMD
WA	In	No	Ba, Cu, Ni, Zn	Ni	None	Al, Mn, Ni, Zn	None	None	None	No	Al, Co, Cr, Cu, Ni, Mn, Zn	No	No	Yes	NMD
	Out	No	Ba, Cu, Zn	None	None	Al, Mn, Ni, Zn	None	None	None	No	Al, Cu, Ni, Mn, Zn	No	No	Yes	NMD
PBR2	In	Yes	Ba, Zn	None	None	Al, Ba, Fe, Mn, Ni, Zn	None	None	None	Yes	Al, Cu, Mn, Ni, Zn	No	No	Yes	AMD
	Out	Yes	Ba	None	None	Fe, Ni, Zn	None	None	None	Yes	Al, Co, Cr, Cu, Fe, Mn, Ni, Pb, Zn	No	No	Yes	AMD

NMD: Neutral Mine Drainage.
AMD: Acid Mine Drainage.
[a] A, B and C criteria according to SPRCSP.
[b] Surface water quality criteria at 91.6 mg/L $CaCO_3$ of water hardness.
[c] Annex II (T1-AII) of the D019 (MDDELCC, 2012).
[d] Landfill disposal restrictions (USEPA, 2019).

- **Residues post-treatment: source of AMD/NMD**
- **Solidification-stabilization required**

(Jouini et al., 2020a, 2022)

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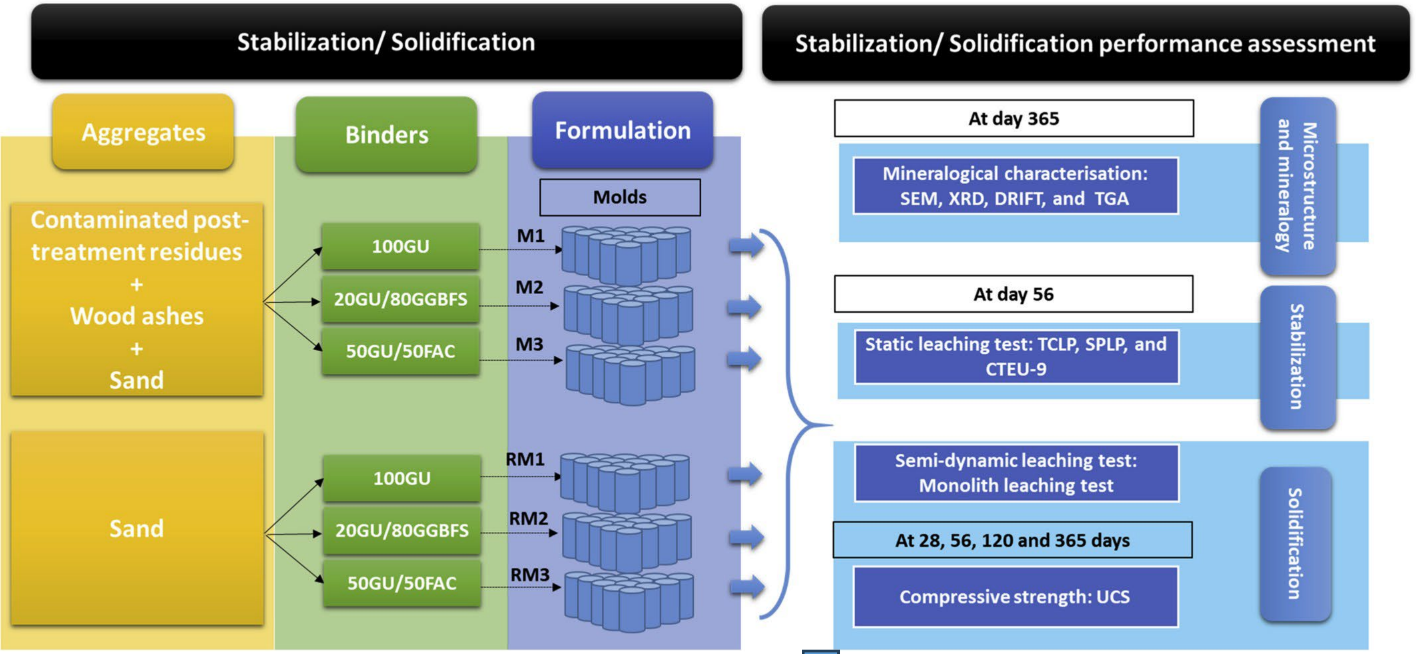
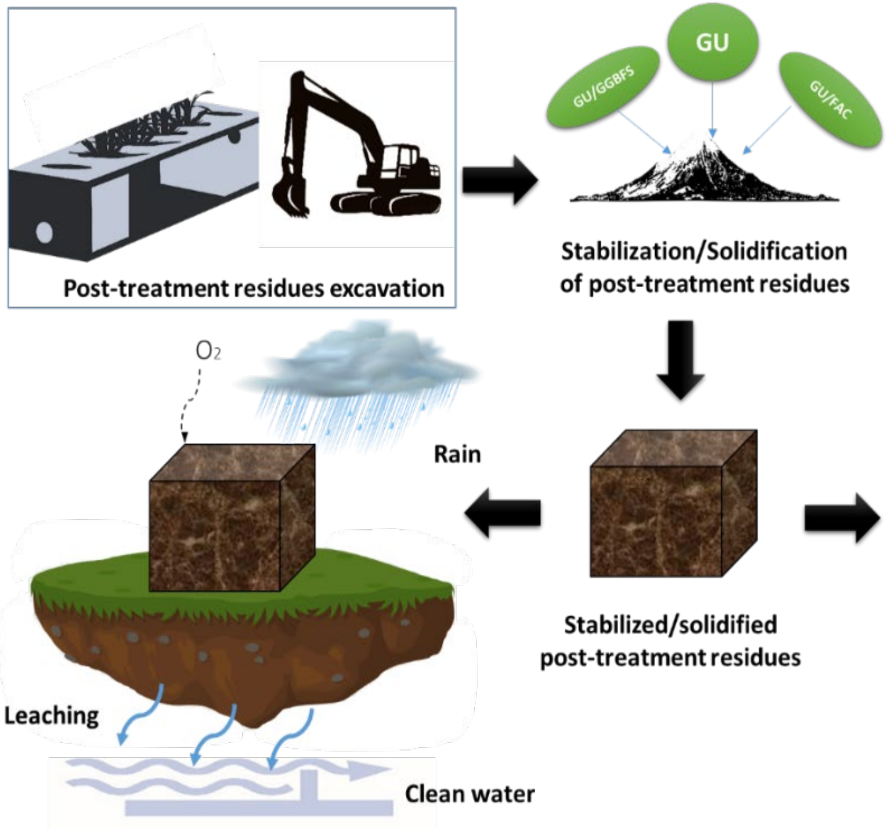
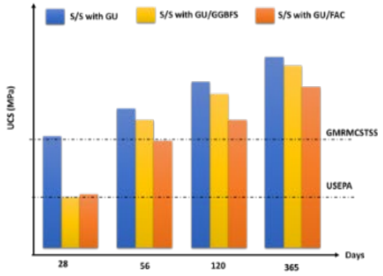
Geochemical stability of AMD passive treatment solids

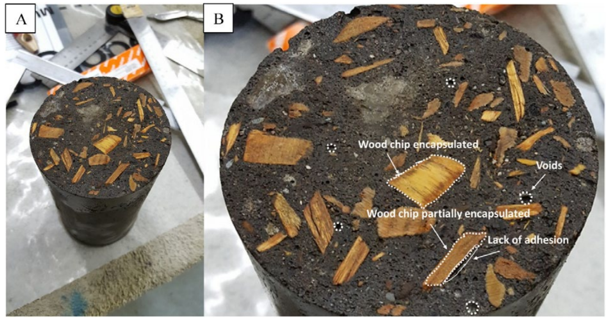
Step II: Solidification - Stabilization







Strength



(Jouini et al., 2020b, 2022)

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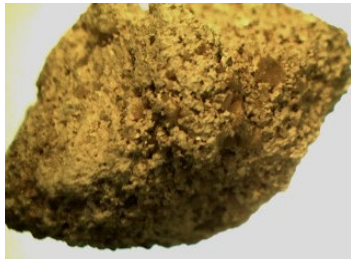
Va

New materials: Sources and modification procedures

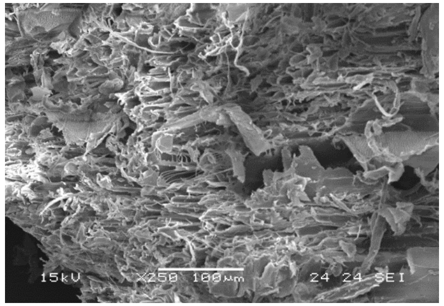


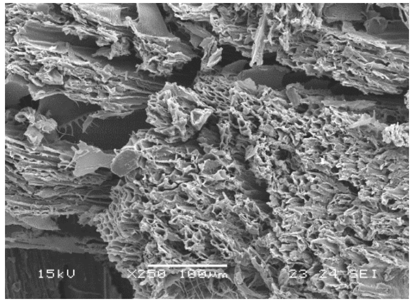
Material	Parameter		Composition (%)		
	pH_{paste}	Porosity	**Dolomite** [$CaMg(CO_3)_2$]	**Calcite** [$CaCO_3$]	**Magnesia** [MgO]
Raw dolomite	7.9	0.44	**87.1**	BDL	BDL
Half-charred dolomite	**11.6**	**0.56**	**7.2**	**53.7**	**19.9**

- **Half-charred dolomite: dolomite** content **decreased, two new minerals** were **created**

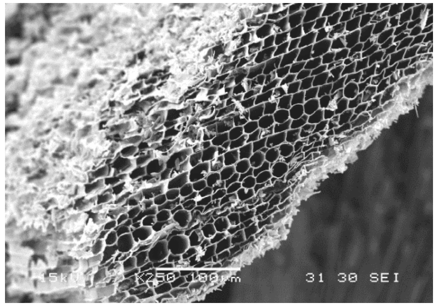
Parameter	Ash B	**Ash B modified**	Ash W	**Ash W modified**
pH_{paste}	13.8	12.6	9.3	12.8
CEC, meq /100g dry	138	322	66	311

- **Wood ash: modification generated high CEC and paste pH new materials**





Step 2: Activation (chemically: KOH, H_3PO_4 or physically: steam, CO_2)



- **Activated biochar: arranged porosity**

Step 1: Torrefaction, slow to flash pyrolysis, or gasification under different operating conditions

(Calugaru et al., 2016-2020; Braghiroli et al., 2018-2021)

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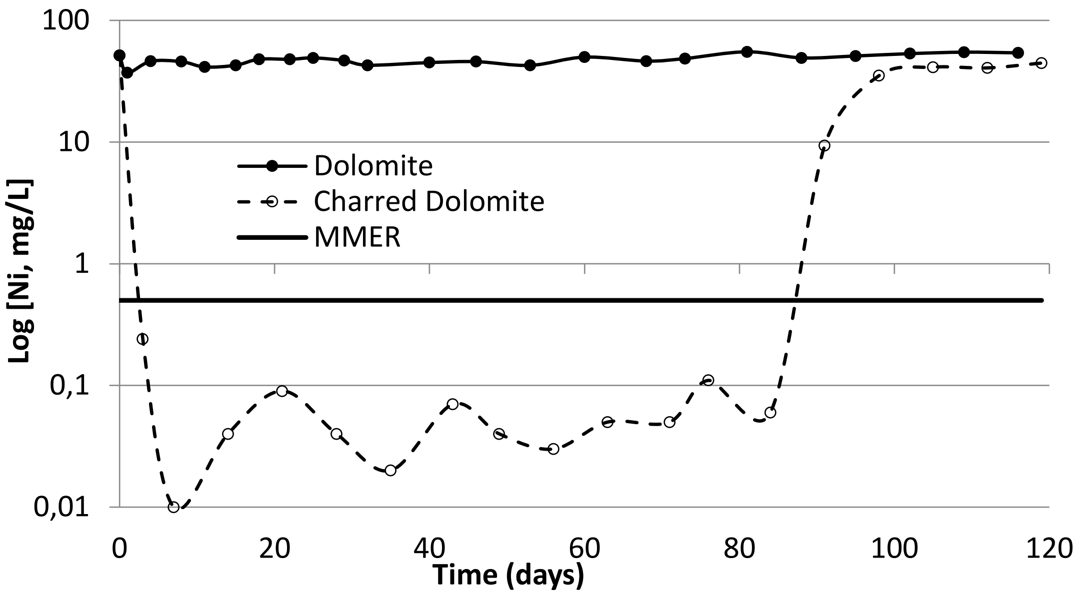
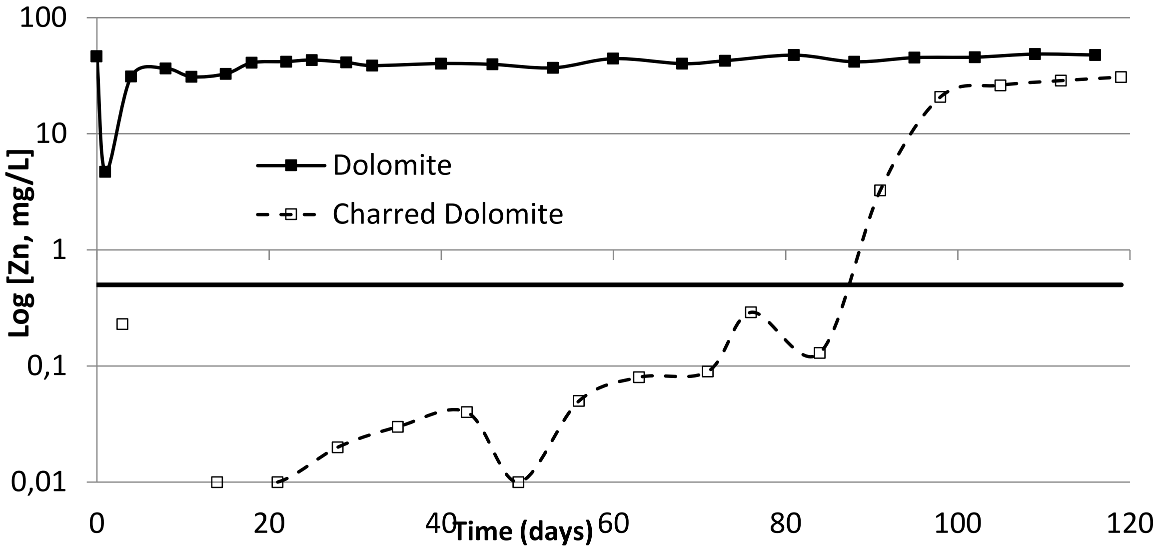
Raw vs modified dolomite: Ni, Zn removal in synthetic NMD

- **Significantly better efficiency of charred dolomite for Ni and Zn removal** (50 mg/L each)





Criteria

- **Preconcentrate of Ni or Zn: relatively easy to recover Ni or Zn**

(Calugaru et al., 2019)

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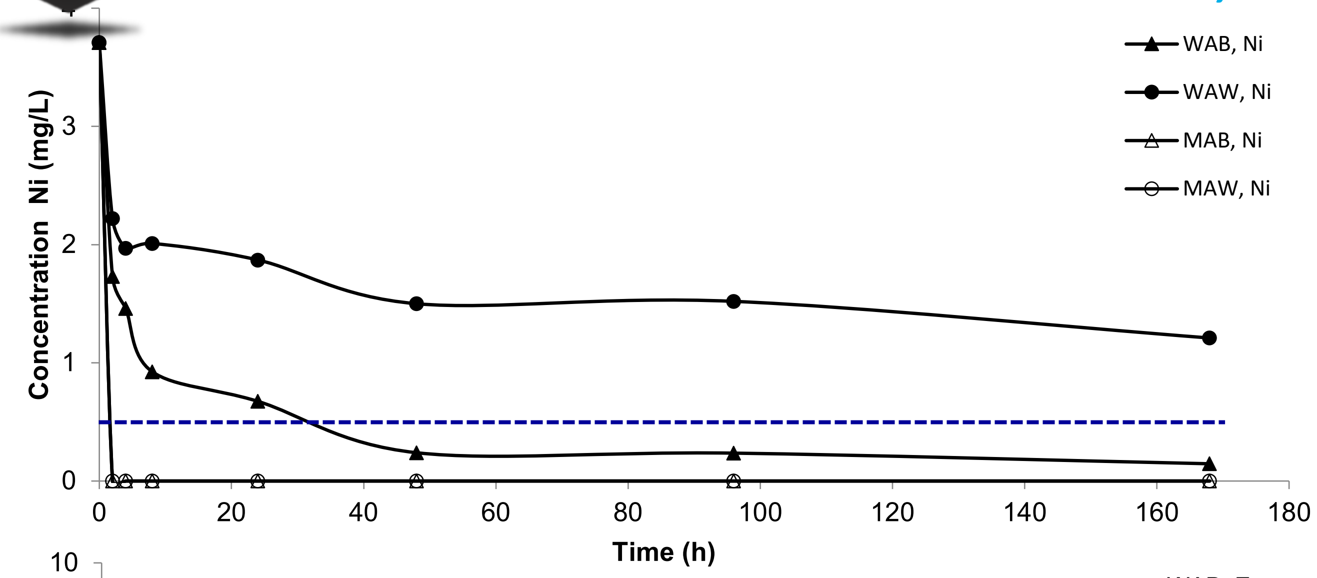
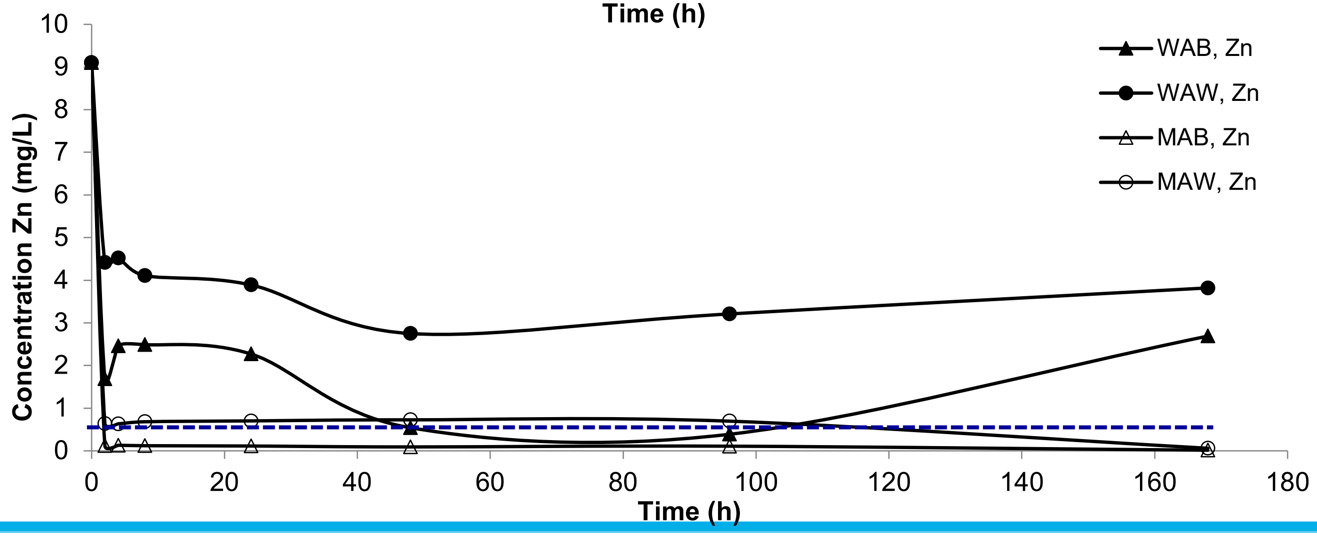
Raw vs modified wood ash: Ni, Zn removal in real NMD



Effluent #1 (pH 7.89, 3.71 mg/L Ni)

- Ni removal (<0.5 mg/L)
  - 2h for both modified ash (MAB & MAW)



Effluent #2 (pH 6.85, 9.1 mg/L Zn)

- Zn removal (<0.5 mg/L)
  - 2h for MAB
  - 7 days for MAW (93% within 2h), but 2h for Mn removal (99% of 4.2 mg/L)

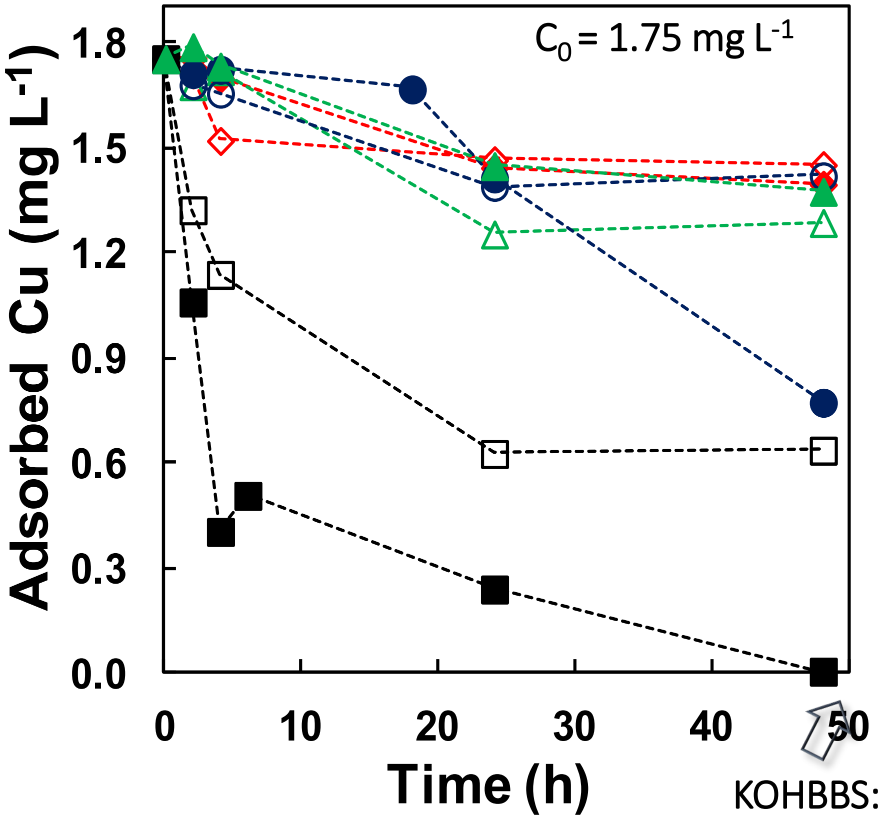
(Calugaru et al., 2017)

Va

Activated biochar: Cu removal in real AMD

- **KOHBBS:** Efficient for Cu removal in **real** effluents

S_{BET} = 1700 m^2/g; 100% de micropores; 22.4% oxygenated groups



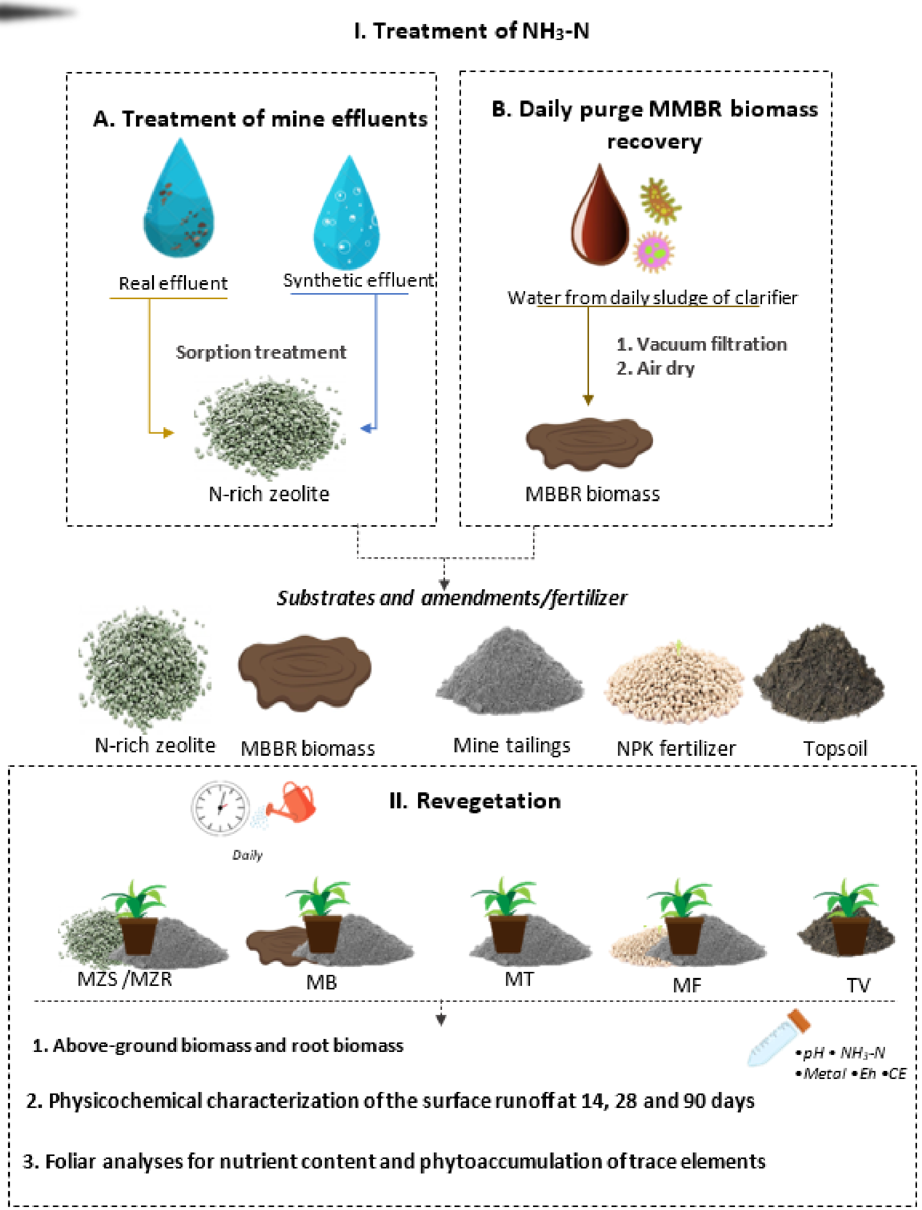
KOHBBS: C_t = 0.0055 mg/L

Parameter	Real AMD (mg/L)	After adsorption (KOHBBS) (mg/L)	Efficiency (%)
Co	9.4	0.5	**95 ↓**
Cu	**1.75**	**0.006**	**~ 100 ↓**
Fe	468	405	**13 ↓**
Mn	10.9	9.7	**11 ↓**
Pb	0.14	0.08	**43 ↓**
Zn	4.9	4.6	**6 ↓**

(Braghiroli et al., 2019)

N-rich residuals use in tailings revegetalization

Vb



Summary of main findings

N-rich zeolite **vs** MBBR biomass

N-rich zeolite

- Plants biomass similar to tailings alone
- Foliar Na concentrations 6-9 times higher vs other treatments

MBBR biomass

- Plants biomass similar to fertilized tailings and topsoil
- High Se concentrations in leaves

Better performance

- Foliar N concentrations and root biomass failed to discriminate between the two tested types of amendment

(**MSc Saint-Aimé, 2023**; Saint-Aimé et al., 2023)

Ongoing & upcoming research

Scientific knowledge for informed new practical applications

- **Organic cover**: is elevated water table required? Is water pumping through the cover necessary? [(1 MSc + 1 PhD): in recruitment]
- **Low-sulfides no-acid generating tailings cover**: evolution and fate of potential contaminants under oxic vs anoxic and abiotic vs biotic conditions* [2 MSc (in completion) + 1 PDF(completed)]
- **Passive NMD treatment in residual organics-based biofilters**: contaminants removal mechanisms and residues stability* [2 PhD (in completion) + 2 PDF (completed)]
- **Raw vs half-charred dolomite**: prevention of AMD generation from pyrrhotite-rich tailings(passivation) and passive polishing [(2 MSc + 1 PhD): ongoing]
- **N-rich residuals from mine water treatment**: potential of surrounding environment contamination (uptake by vegetation, runoff) [(2 PhD + 1 PDF): to be recruited]

*Findings were presented during ***ICARD 2024*** (Mehdaoui et al., 2024; Thevenot et al., 2024), are in publication or were / will be presented during PhD theses defenses (W/S2025) or during ***Tailings and Mine Waste 2025***

Concluding remarks

- **Successful rehabilitation approach** for oxidized tailings on mine sites (precious and base metals) **must combine prevention** (tailings covering) and **passive treatment**
- **Residual materials valorization** (already available on site or in the proximity) limits disposal concerns, environmental footprint, and mine sites rehabilitation costs
- **Materials** (natural and residual): efficient in **mine tailings covers** for AMD prevention or **transformed**, with promising results in contaminated mine water treatment
- Metal recovery, whenever feasible, **could decrease water treatment costs**
- Pilot scale production and testing of modified materials is limited
- Metal recovery, sorbent and treated water reuse, are rarely addressed

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Děkuju!

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Thank you!

Merci!

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