Passive Mine Water Treatment, Fanie Nel discharge, Mpumalanga, South Africa

From Ground Water to Mine Water

Environmental Hydrogeology in Mining

Mine Water Treatment

Kassel, 8. September 2022

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Elke Mugova M. Sc.

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From Mine Water to Ground Water

Environmental Hydrogeology in Mining

Mine Water Treatment

Prof. Dr. Christian Wolkersdorfer (云村)

South African Research Chair for Acid Mine Drainage Treatment

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Contents – Whole Course

- Introduction, Historical Background
- Mining Methods, Technical Terms
- Water and Water Inrushes
- Dewatering methods; Recharge
- Mine Flooding
- Mine Water Geochemistry
- Prediction of Mine Flooding
- Mine Water Treatment

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Contents

- Introduction
- Terminology & Procedures
- Active Mine Water Treatment
- Passive Mine Water treatment
- Calculation example
- Let's look into the Future

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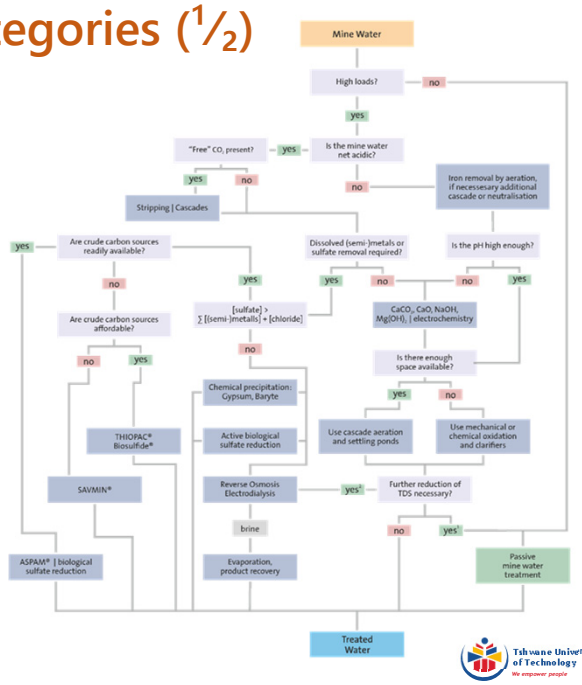
Treatment Technology Categories (½)

- **Neutralisation**
  - Lime based
  - Sodium-based
  - Ammonia
  - Biological sulfate reduction
  - Constructed wetlands
- **Metals Removal**
  - Precipitation
    - Hydroxides
    - Carbonates
    - Sulfates
  - Constructed wetlands



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Treatment Technology Categories (2/2)

- **Desalination**
  - Biological sulfate Removal
  - Ettringite Process
  - Membrane Processes
  - Ion Exchange
  - Constructed wetlands
- **Special Treatment Options**
  - Cyanide removal
  - Radioactive compounds
  - Arsenic removal
  - Electrocoagulation
- **In-situ treatment**

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Mine Water Treatment: Overview

- **Active treatment methods**
  - Neutralization
  - Ion Exchange
  - Reverse Osmosis
  - Distillation
- **Passive treatment methods**
  - Constructed wetlands
  - Limestone Drains
  - Reactive Barriers
  - Vertical Flow Reactors

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General issues

- Two main requirements
  - The **water quality standards** must be maintained at all times
  - **Cost-effective operation** on a long-term basis

- Basically, every mine water can be treated to drinking water standards unless costs are of no consideration
  - Highly mineralised and aggressive water could be treated by the use of reverse-osmosis, nano-filtration or distillation: all these methods consume a large amount of energy and, therefore, are extremely expensive

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General issues (Jeff Taylor, Earth Systems)

- All operational water quality issues have effective technological fixes or management strategies
- Many of the technological fixes are costly
- Good planning can solve some water quality issues.
- Post closure water quality issues are the **BIG** issue for mining companies

from Jeff Taylor, presentation at IMWA 2012: "Treatment & Discharge of Mine Waters – Challenges and Opportunities"

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General issues (Jeff Taylor, Earth Systems)

- The key post closure water quality issue for most mines is AMD/ARD
- AMD can continue for decades to millennia post closure
- AMD can be largely minimized with good planning, and with emerging management strategies can even be substantially prevented
- Need to avoid the need to treat water in perpetuity

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from Jeff Taylor, presentation at IMWA 2012: "Treatment & Discharge of Mine Waters – Challenges and Opportunities"

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General issues

- In principle, **passive treatment systems** are low-cost- and labour systems, but:
  - Highly mineralised mine water can not be treated reliably down to a given standard
  - Some metals cannot be removed by passive systems (e.g. high Zn amounts in neutral mine waters)
  - To treat highly mineralised mine water (many metals, low pH, high water make) by using passive methods, a huge – and expensive – area is necessary

image: Skylark Aerial for JN Bentley and the Coal Authority

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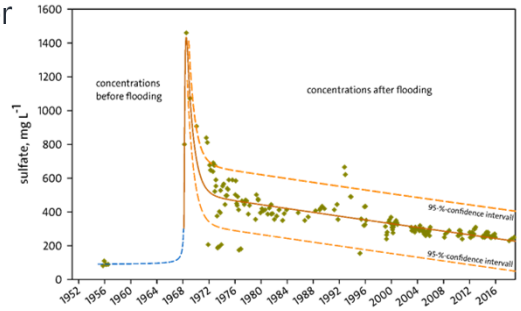
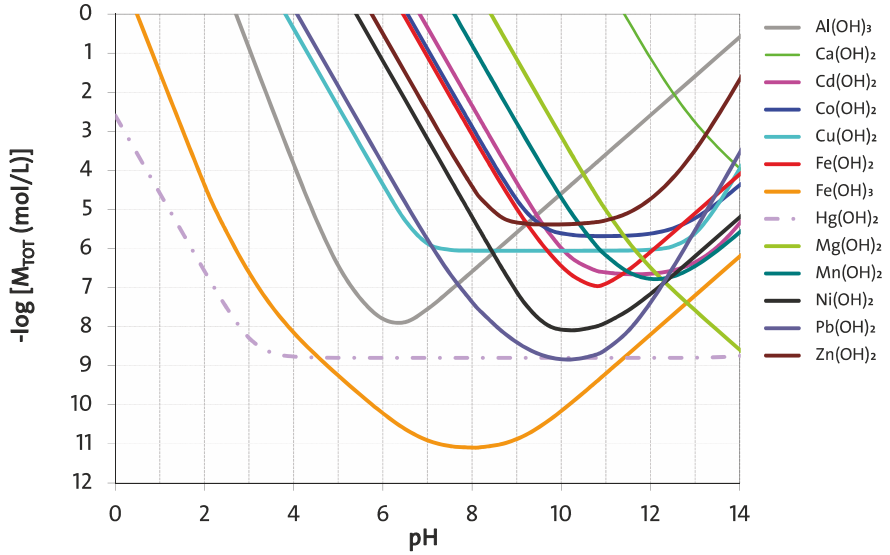
General issues

- To choose the **appropriate treatment technology**, the following points must be considered
  - Existing or available processes
  - Cost-benefit analyses of alternative methods
    - Keep in mind: passive methods can be expensive in the first place, but maintenance is usually of lower cost whereas in active systems it is often vise-versa
  - Possible changes of mine water quality: "longevity of mine water pollution"



pH-dependence of Me-oxide solubility



from Wolkersdorfer 2014, after Cravotta pers. Comm.

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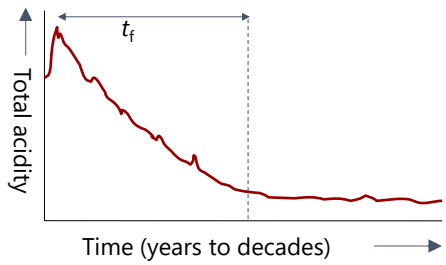
First Flush

- The time of mine water pollution depends on
  - Acidity removal or reduction rate ("first flush"): buffering
  - Rate at which acid containing minerals weather (pyrite, siderite, secondary minerals)



$$t_f = f(\mathrm{aci}, r_w, V, K, R_{GW}) = (3.95 \pm 1.2)\ t_r$$

t_f = duration of first flush
t_r = duration of mine water rebound

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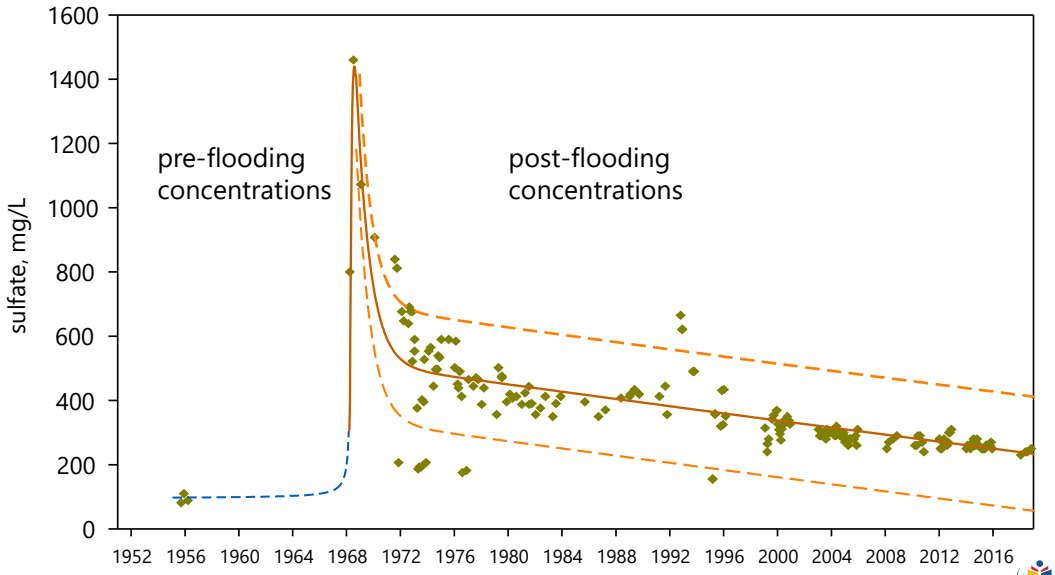
First Flush



Reiche Zeche Freiberg Germany (Wolkersdorfer 2022)

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First Flush

- The rate of acidity reduction is related to the drop of the "first flush" and is mainly controlled by hydraulic factors:
  - Volume of the inter-connected workings
  - Hydraulic connections and hydraulic conductivities of the mine workings
  - Ground water recharge
- The total depletion of the "first flush" can take up to 40 years and even longer
- The flooded mine can be considered a set of interconnected chemical reactors

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How to plan the plant

- In many cases of polluted mine water discharges, the following approach proves to be useful
  - Treat the mine water actively until all the acidity has been depleted

    as a rule: during the time of the first flush, sometimes up to 40 years
  - Thereafter, for the long term treatment of the mine water, install passive treatment systems (buffering of juvenile acidity)

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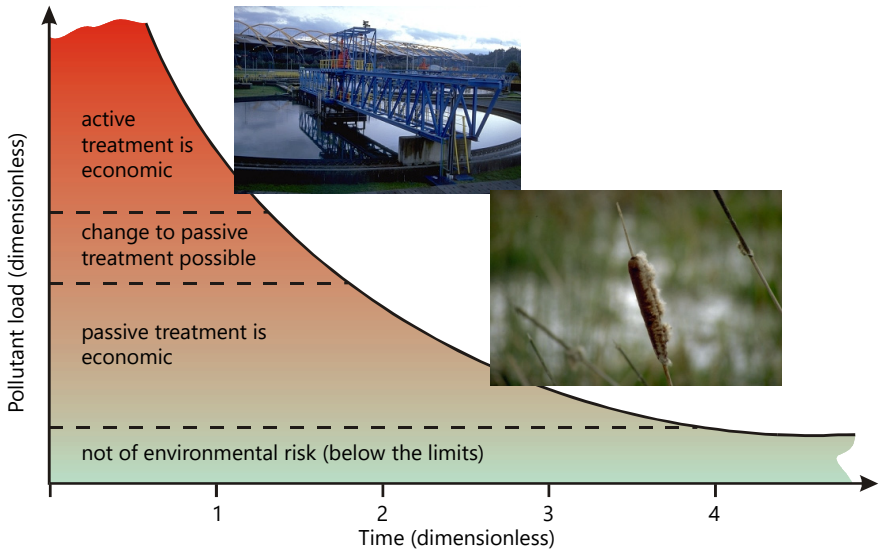
Treatment Strategy



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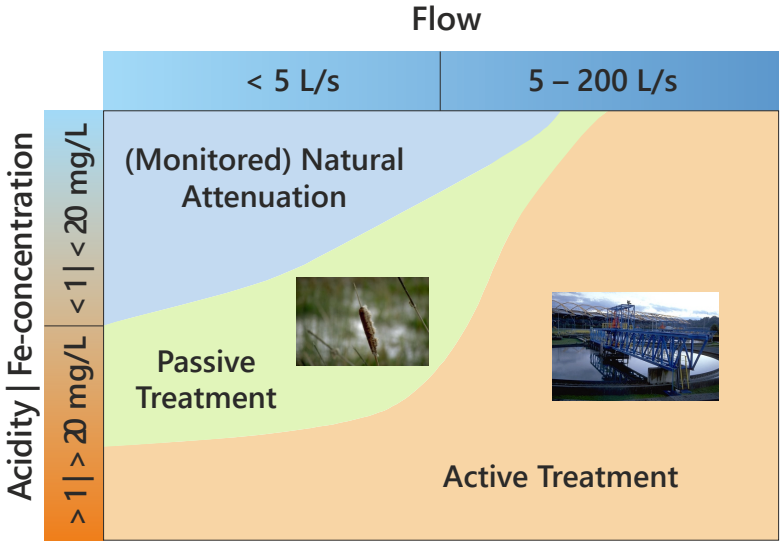
Potential Treatment Strategies



from Geller *et al.* 2013; modified from ERMITE 2004 & Younger 2002

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Treatment Strategy

Environm. Mining Council British Columbia | Ronneburg, Germany | Quaking Houses, England, UK

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Treatment Strategy

- Advantages of this step-wise approach:
  - Design and construction of active and passive systems is done in different stages
  - The required water limits can be fulfilled at all time
  - Passive systems can be constructed before they are necessary and, therefore, have enough time to mature before their first use

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Active treatment systems

- Neutralization
- Ionic exchange
- Reverse osmosis
- Nano-filtration
- Distillation
- Electro-dialyses
- Solvent extraction
- Freeze separation
- Electrocoagulation

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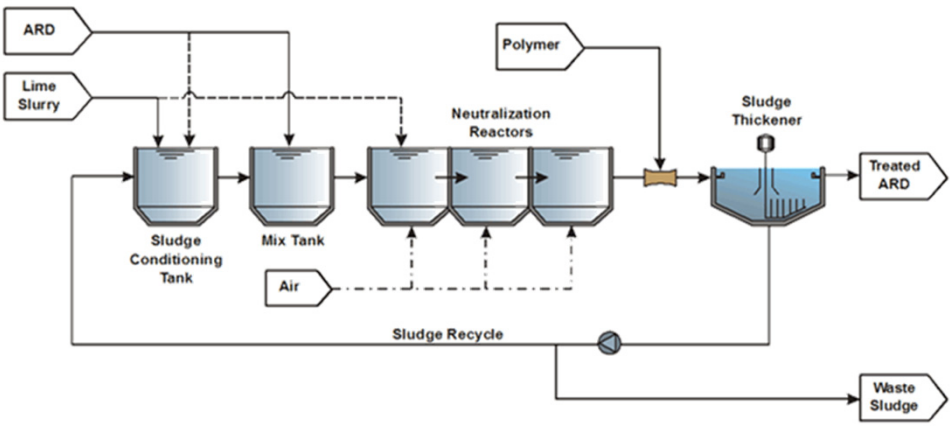
High Density Treatment



adapted from GARD Guide

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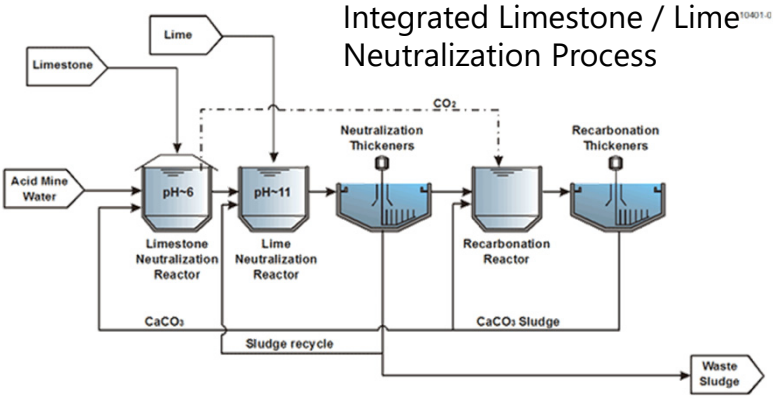
Neutralization Process

Integrated Limestone / Lime Neutralization Process

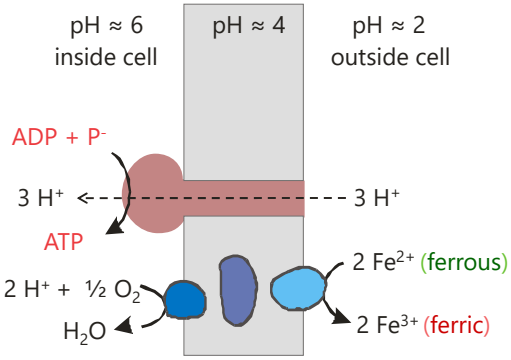


- Pre-neutralization: relatively inexpensive limestone
- Lime neutralization to a pH target (metal dependent)
- Re-carbonation and pH adjustment CO_2 generated in the first process step

adapted from GARD Guide

Neutralization

- **Aeration**
  - Conversion of $Fe^{2+} \rightarrow Fe^{3+}$ (ferrous → ferric)
  - *Acidothiobacillus ferrooxidans, Galionella*



enzymes involved:

cytochrome oxidase
rusticyanin
cytochrome

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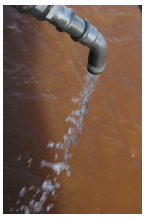
Neutralization

- **Liming**
  - pH raise to increase reaction rate of $Fe(OH)_3$ precipitation (optimum: pH 11)
- **Coagulation and flocculation**
  - Larger and – hopefully more dense – $Fe(OH)_3$-particles to increase the sedimentation rate
- **Settlement (settling ponds)**



Straßberg, Harz, Germany | Schwarze Pumpe, Lausitz, Germany

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Aeration

- Cascades (potential energy)
  - 50 mg L^{-1} Fe^{2+} can be oxidized, if necessary, install a second stage
- Aeration: impeller aerators, bubbles, spray
- Reactions involved:
  - $Fe^{2+} + ¼\ O_2 + H+ \rightarrow Fe^{3+} + ½\ H_2O$
  - $Fe^{3+} + 3\ H_2O \rightarrow Fe(OH)_3 + 3\ H^+$
- Take care: two protons will be released!
- In case there is still too much Fe^{2+} after approximately 10 minutes: hydrogen peroxide (H_2O_2), ozone or hypochloride (OCl^-) might be necessary

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Neutralisation: Alkali materials

Alkali Compound/ Material	Alkali Requirements ton/ton of acidity	Neutralisation Efficiency % of applied alkali used	Relative Cost € / tonnes bulk
Limestone, $CaCO_3$	1.00	30 – 50	8 – 12
Hydrated Lime, $Ca(OH)_2$	0.74	90	50 – 80
Un-hydrated (quick) Lime, CaO	0.56	90	60 – 190
Soda Ash, Na_2CO_3	1.06	60 – 80	150 – 270
Caustic Soda, NaOH	0.80	100	500 – 700
Magna Lime, MgO	0.4	90	project specific
Fly ash	material specific	–	project specific
Kiln dust	material specific	–	project specific
Slag	material specific	–	project specific

adapted from GARD Guide

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Liming

- Acidic mine water will be neutralized
- (Semi-)Metal hydroxides will co-precipitate (e.g. Cd, As)
- Fast but partly incomplete reaction
- Calcium oxide: CaO (very reactive)
- Calcium hydroxide: $Ca(OH)_2$ (extensive mixing)
  - $Ca(OH)_2 + H_2SO_4 \rightarrow CaSO_4.2H_2O$
  - $3\ Ca(OH)_2 + Fe_2(SO_4)_3 + 6\ H_2O \rightarrow 2\ Fe(OH)_3 + 3\ CaSO_4.2H_2O$

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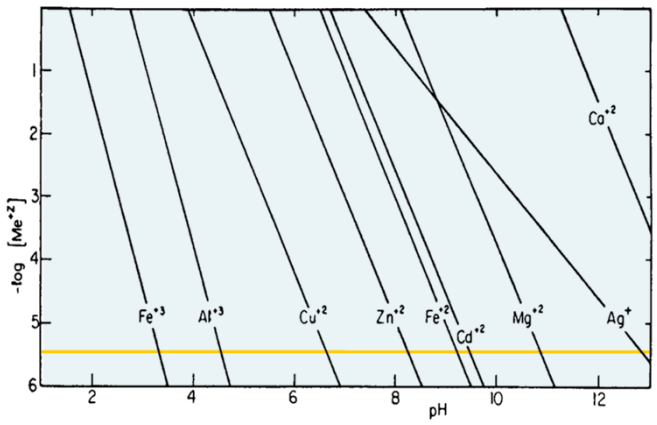
Liming

- Minimum pH-values needed to fully precipitate metals as their oxy-hydrates
  - Fe^{3+} 4.3
  - Al^{3+} 5.2
  - Pb^{2+} 6.3
  - Cu^{2+} 7.2
  - Zn^{2+} 8.4
  - Ni^{2+} 9.3
  - Fe^{2+} 9.5
  - Cd^{2+} 9.7
  - Mn^{2+} 10.6



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Liming

- Necessary amount of $Ca(OH)_2$ to neutralize:
  - mg L^{-1} $Ca(OH)_2$ = total acidity (mg L^{-1} $CaCO_3$) × 0.74
  - mg L^{-1} $Ca(OH)_2$ = total acidity (meq L^{-1}) × 37
- To raise pH sufficiently high (to pH_t) for rapid precipitation:
  - For Fe, a pH of 8 — 8.5 must be achieved
  - mg L^{-1} $Ca(OH)_2$ = $[(1000 \times 10^{-pH_t}) - 10^{-3}] \times 37$
- Total amount $Ca(OH)_2$ needed is sum of both:
  - mg L^{-1} $Ca(OH)_2$ = {total acidity (meq L^{-1}) + $[(1000 \times 10^{-pH_t}) - 10^{-3}]$} × 37

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Flocculation/Coagulation

- Inorganic material
  - aluminium sulfate, iron sulfate, iron chloride, sodium aluminate
- Mineral flocculants
  - bentonite, metal hydroxides, activated silica
- Natural flocculants
  - Polysaccharides, starch derivates, food thickeners
- Synthetic flocculants
  - Anionic, cationic, polyampholites (e.g. synthofloc®, superfloc®, sachtofloc)

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Settlement and Sludge Management

- Enough storage space must be available
  - Sludge contains: Fe-Hydroxide, Me-hydroxides, unused lime, gypsum, calcium carbonate
- Sludge: 10 % of mine water make
- LDS (Low Density Sludge)
  - 1 — 2 weight % solids
- HDS (High Density Sludge)
  - Sludge circuit
  - Sludge density is 6-fold higher than in LDS
- Deposition

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Plate Filter Press

Žirovski Vrh/Slovenia (Kovinarska Industrija/Ajdovščina)

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Sludge Disposal

- High amounts of metals (e.g. Pb, Zn, Cd) could cause the sludge to be classified as hazardous waste
- HDS or Fe-rich sludge might be used as pigments or in brick industry
- Experience has shown ("$\pi \cdot$ 👍^{2}"-rule):
  - Retention time in lagoons must be greater than ± 24 hours
- No settlement lagoons are necessary if [Fe] < 2 mg L^{-1} and sand filters are installed

image: Jeff Skouson

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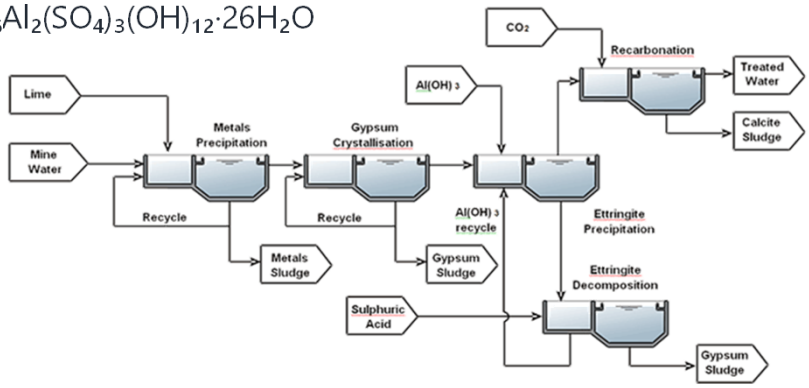
Sulfate Removal

- Barium sulfate process (pilot scale)
- Ettringite precipitation process (pilot scale):
  - SAVMIN™
  - $Ca_6Al_2(SO_4)_3(OH)_{12}{\cdot}26H_2O$



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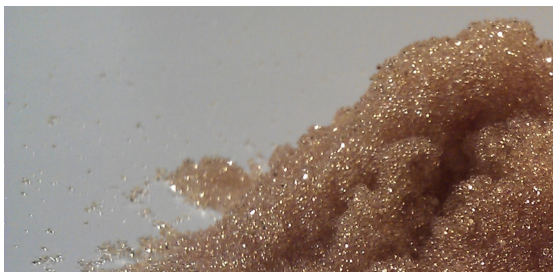
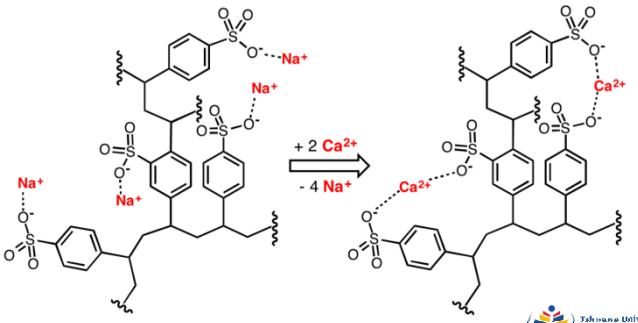
Ion exchange

- Cationic or anionic resins
- Residues mainly gypsum
- regeneration
  - Sulfuric acid (cationic)
  - Sodium hydroxide (anionic)
- Desal-process
- Sul-Bisul-process





Wikimedia commons

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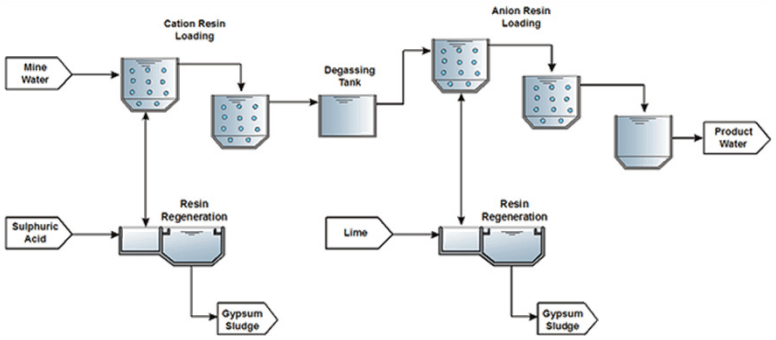
Ion exchange

- Conceptual GYPCIX®-Ion Exchange Treatment Process
- high sulfate type mine drainage



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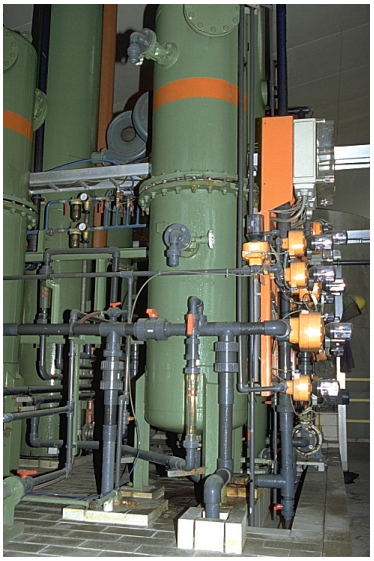
Brixlegg, Tyrol, Ion Exchange Reactor



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Burgfey, Eifel: Pilot Plant

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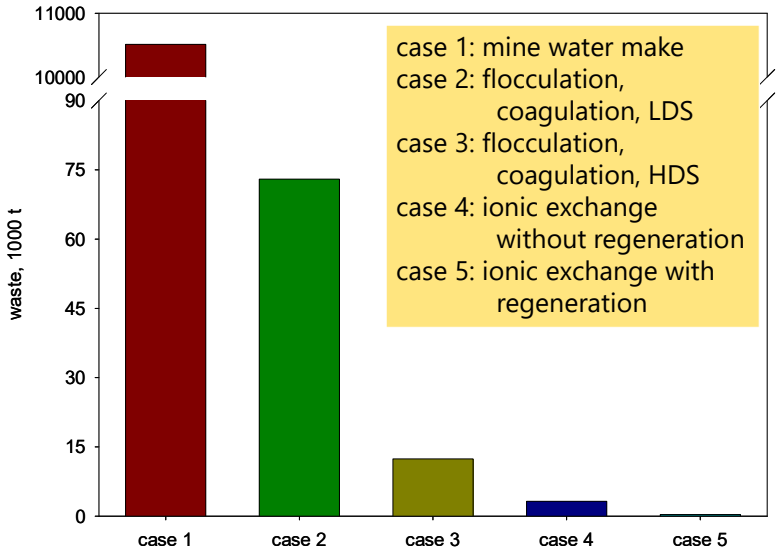
Burgfey, Eifel: Ion Exchange Effectiveness



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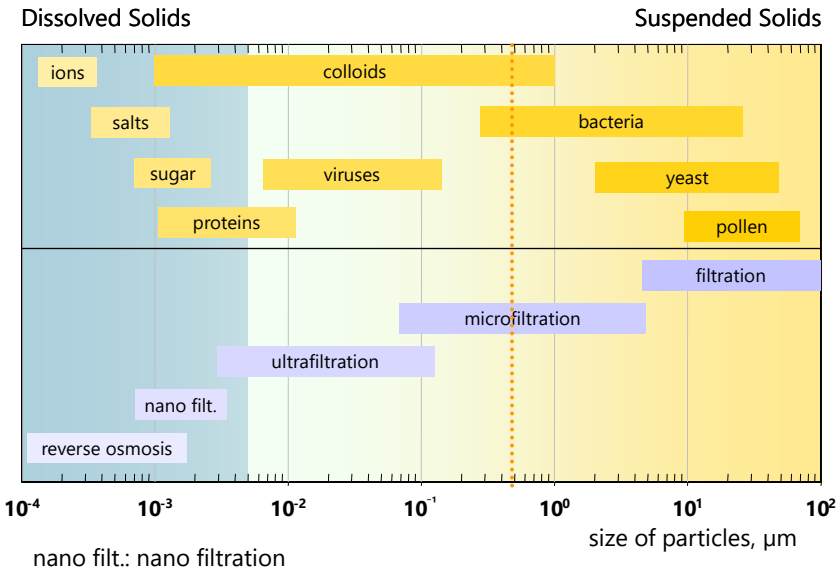
Filtration Methods



nano filt.: nano filtration

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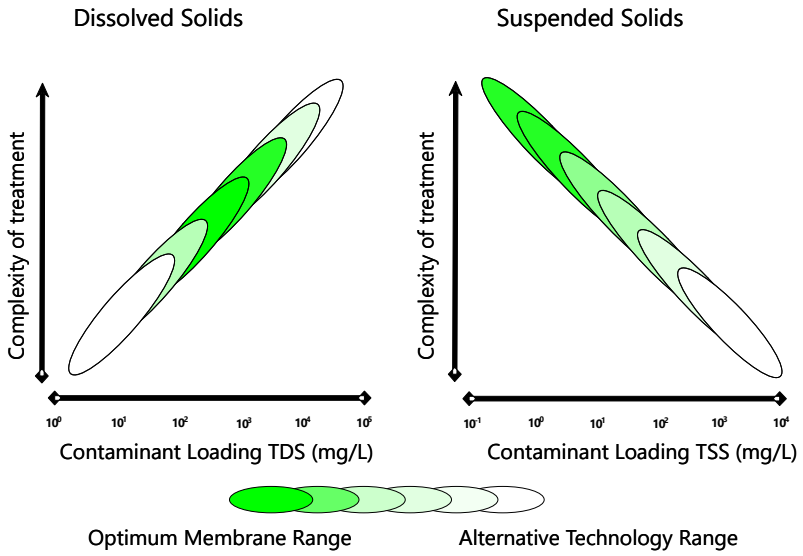
Membrane Technologies



Pall Corporation

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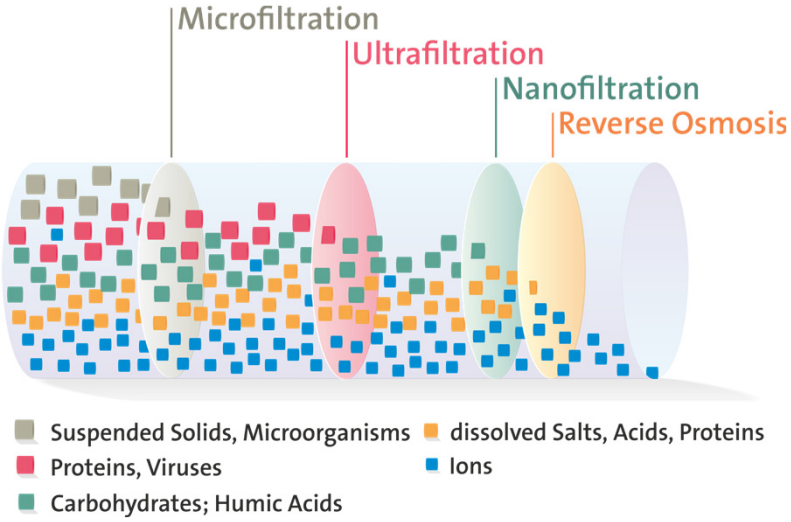
Membrane Processes



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Reverse Osmosis

- Hydrostatic pressure difference: 10 – 100 bar
- Characteristic retardation: 98 – 99.9 % (50 – 300 dalton)
- Besides distillation the most common, and very often less cost-intensive, method to fully or partly desalinate fluids
- Usually: sea water desalination for drinking water supplies
- In the past years the method became important in the purification of heavily polluted drainage waters of waste dumps
- Material used: e.g. polyamides, poly sulfons

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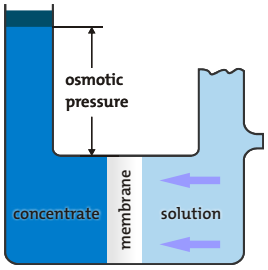
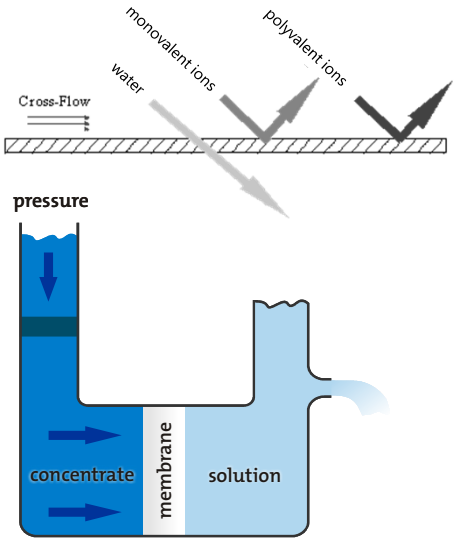
Osmosis/Reverse Osmosis





Osmosis/Reverse Osmosis: Example

- St. Aidans open cast coal site; Leeds/England
- Mine flooded after overflow of River Aire in 1996
- World's largest low-pressure reverse osmosis plant at its time
- Capacity: 20,000 m^3 d^{-1} (Israel: 274,000 m^3 d^{-1})
- Water available for public water supply

Wilson & Brown 1997; ACWA Services Limited

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Reverse Osmosis

Emalahleni/South Africa

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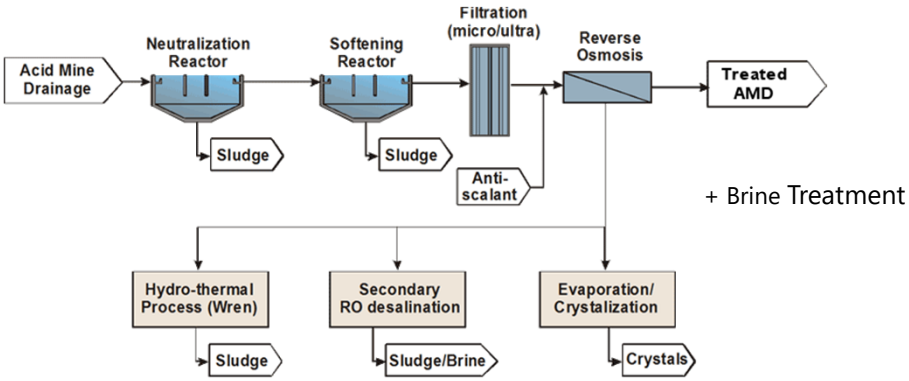
Reverse Osmosis

Conceptual High Recovery Membrane Desalination Process



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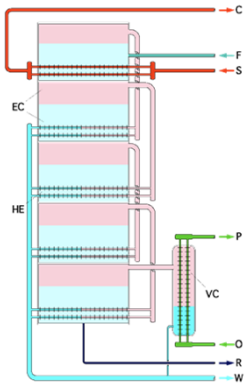
The rising importance of desalination and raw sea water

- Currently Reverse Osmosis because
  - Reduced membrane costs
  - Reduced energy consumption
- Viable source of water supply for mining
- Reliable operation
- Experienced and skilled operators needed
- Holistic approach case to case based
  - e.g. Ultrafiltration more expensive in investments, but less for operation costs in Reverse Osmosis plant
- Yet: final brine treatment might be necessary

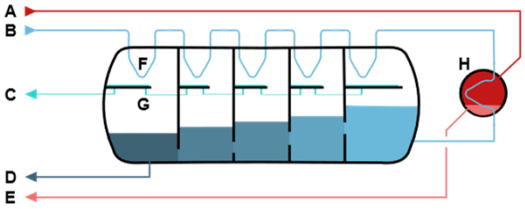
The rising importance of desalination and raw sea water

- Other technologies
  - Multi-Stage Flashing distillation
  - Multi-Effect Distillation



F feed water in
S heating steam in
C heating steam out
W Fresh water (condensate) out
R brine out
O coolant in
P coolant out
VC last-stage cooler
HE heat exchanger

A Steam in
B Seawater in
C Potable water out
D Brine out (waste)
E Condensate out
F Heat exchange
G Condensation collection
H Brine heater

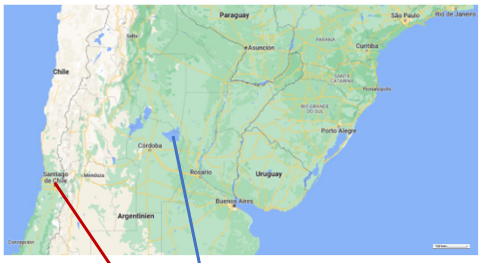


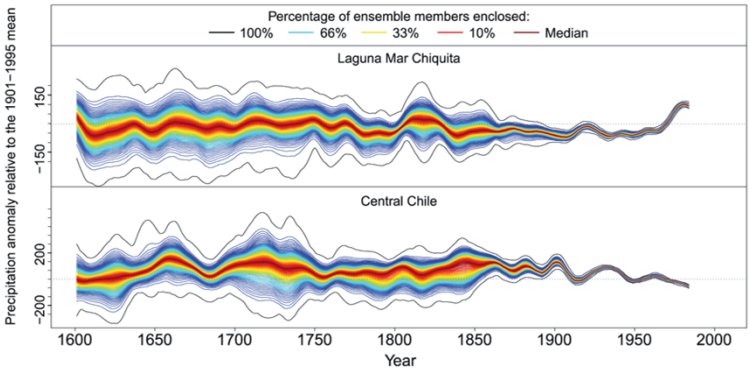
Jebel Ali G Station, Dubai (Weir Westgarth Ltd) | Wikimedia commons

8

The rising importance of desalination and raw sea water

- Currently becoming important
  - Namibia (UraMin project: Trekkopje)
  - Chile; Southern Peru
- Less precipitation





Laguna Mar Chiquita
Central Chile

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Mine Water Treatment 51

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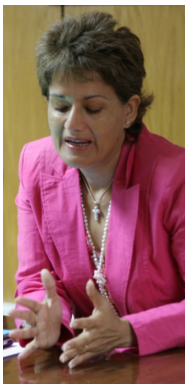
8

The rising importance of desalination and raw sea water

- Concurrent water use of two industries
  - Mining
  - Agriculture



Chilean Grapes | Intendenta Atacama Region Viviana Ireland | El Salvador Mine

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Mine Water Treatment 52

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8

Desalination: Pre-treatment

- The membranes need protection
- Potential fouling Problems
  - Nutrients
  - Bacteria
  - Algae
  - Plankton
  - macro-organisms
- Dissolved air flotation
- Dual Media Filters
- Ultrafiltration

image: Greenchain Group

Mine Water Treatment 53

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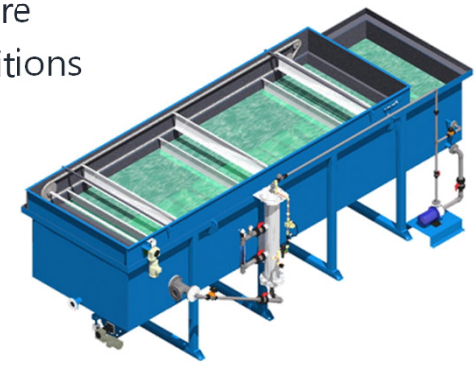
8

Pre-treatment: Dissolved air flotation

- Removes suspended matter
  - Oil
  - Solids
- Dissolve air in water by using pressure
- Release air under atmospheric conditions
  - Flotation tank
  - Basin
- Bubbles form around suspended matter and flow to surface
- Bubbles removed with e.g. a skimmer



Mine Water Treatment 54

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8

Pre-treatment: Dual Media Filters

- Filter units consisting of two or more media
- Advantage
  - Faster flow of raw water
- Commonly used
  - Anthrazite | sand
- Less often backwash needed – consequently lower operation costs

image: Shubham Inc

Mine Water Treatment 55

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8

Pre-treatment: Ultrafiltration

- Removes all suspended solids
- Reduces microbiological activity
- Eliminates plugging of the reverse osmosis membranes

Mine Water Treatment 56

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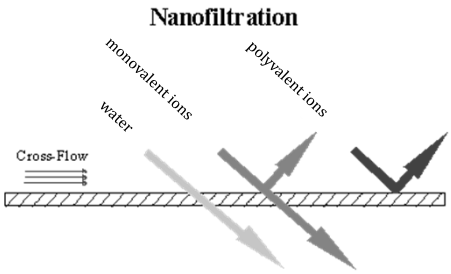
8

Nanofiltration

- Pressure driven filtration method with membranes
- Hydrostatic pressure difference: 5 – 80 bar
- Molecular separation limits: 300 – 2000 Dalton
- Membranes for nano filtration often are charged electrically to give the ability of separation differently charged molecules
- Materials used: polyamides, polysulfone, polydimethyle siloxan



Mine Water Treatment

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8

Distillation

- Heating up of mine water to the boiling point
- High energy consumption, because large amounts of mine water have to be treated
- High concentrated residues
- Residues have to be disposed of in a safe matter
- Commonly used for sea water desalination

Glen Breton Destillery, Cape Breton Island, Nova Scotia, Canada

Mine Water Treatment

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8

Electro Dialyses

- By the use of an electric field and ionic sensitive membranes, differently charged ions can be removed from the solution
- Installation of cationic and anionic membranes
- Bi-polar membranes can be used
- Good separation achievable
- High energy consumption
- Main use: kidney deficiency

Mine Water Treatment 59

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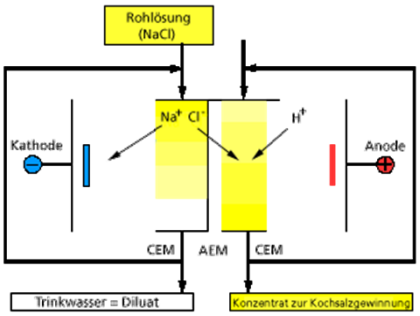
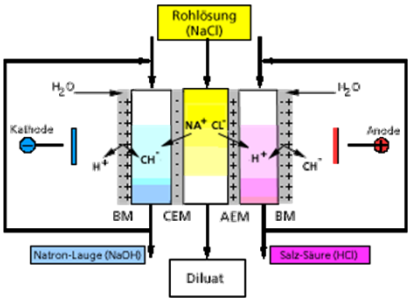
8

Electro Dialyses

- mono polar, bi-polar membranes





Mine Water Treatment 60

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8

Mine Water Treatment

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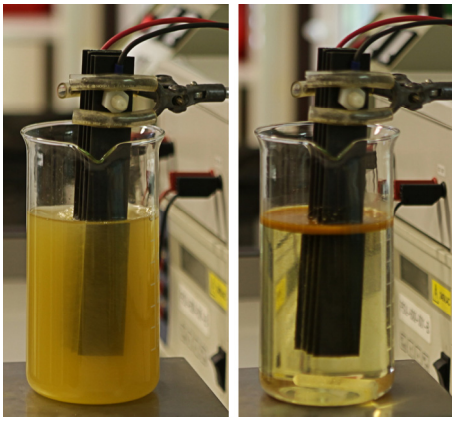
Electrocoagulation



- First use in 1889 in London, UK
- 1946 first large-scale plant for drinking water treatment
- At this time high energy demand, large investment costs
- Research mainly in US and USSR in the past 6 decades
- First mine water tests in 1972
- Electrochemical reactions on cathode and anode modify physicochemical parameters or release metal ions for(co-)precipitation

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Mine Water Treatment

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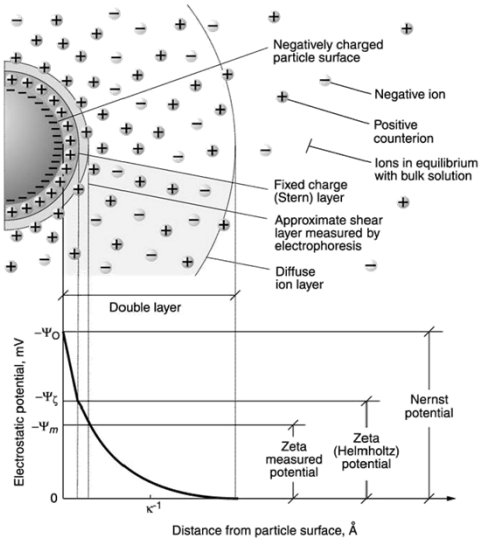
Electrocoagulation – Concept



from Vepsäläinen 2012

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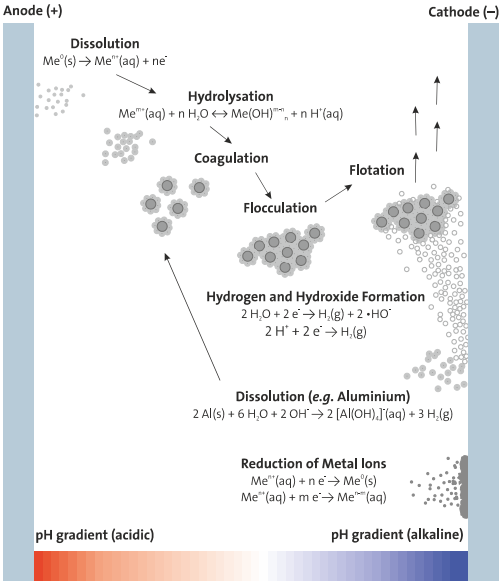
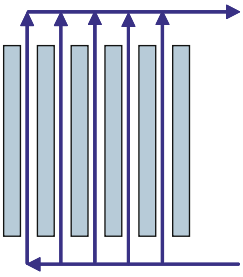
Electrocoagulation – Reactions Occurring

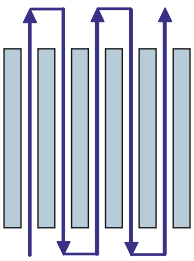


after Vepsäläinen 2012

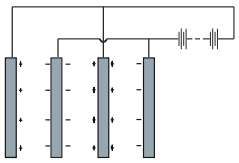
Electrocoagulation – Electrode Configuration



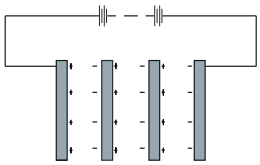
Parallel connection



Series connection



Monopolar connection



Bipolar connection

from Comninellis and Chen 2010

8

Solvent Extraction

- Used since the 1950ies to enrich radionuclides
- Based on relative solubility of a substance in two immiscible liquids (e.g. aqueous and organic)
- Extraction material: derivates and modifications of lactic acid, oxalic acid, gels and ether
- Only suitable for small amounts
- Mainly used for analytical purposes
- used for Cu-enriched leachates, removal of Au from cyanide solutions and REE extraction
- Little interest for mine water yet

Mine Water Treatment 65

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8

Passive Treatment Methods

- "A water treatment system that utilises naturally available energy sources such as topographical gradient, microbial metabolic energy, photosynthesis and chemical energy and requires regular but infrequent maintenance to operate successfully over its design life."

Pulles, Coetser, Heath & Muhlbauer 2004

Mine Water Treatment 66

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8

Passive Treatment Methods

- Reactive barrier/wall (“funnel-and-gate”)
- Anoxic limestone drains
- Aerobic constructed wetlands
- Anaerobic constructed wetlands
- SAPS or RAPS
  - Successive Alkalinity Producing Systems
  - Reducing and Alkalinity Producing System
  - VFL Vertical Flow Reactors
- Settlement lagoons

Mine Water Treatment 67

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8

Reactive Barriers

- Ground water has to flow through a permeable reactive barrier
- Barrier has to bind into impermeable strata
- The whole pollutant plume must flow through barrier
- Not too close at source of contamination (wide reaction front)
- Short cuts must be avoided
- costs: € 100 – € 700/m^2

Mine Water Treatment 68

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8

Reactive Barriers

- Organic reactants
  - wood
  - Coal, lignite
  - peat
- Inorganic reactants
  - Iron (Fe^0)
  - phosphate
  - Amorphic iron oxides
- Micro-organisms

Mine Water Treatment 69

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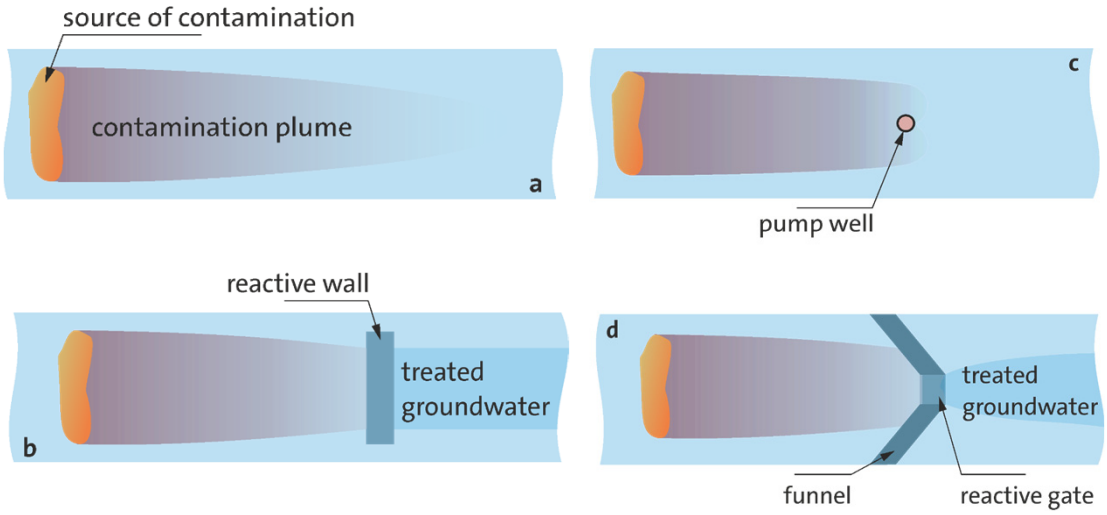
8

Reactive Barriers



after Starr & Cherry 1994

Mine Water Treatment 70

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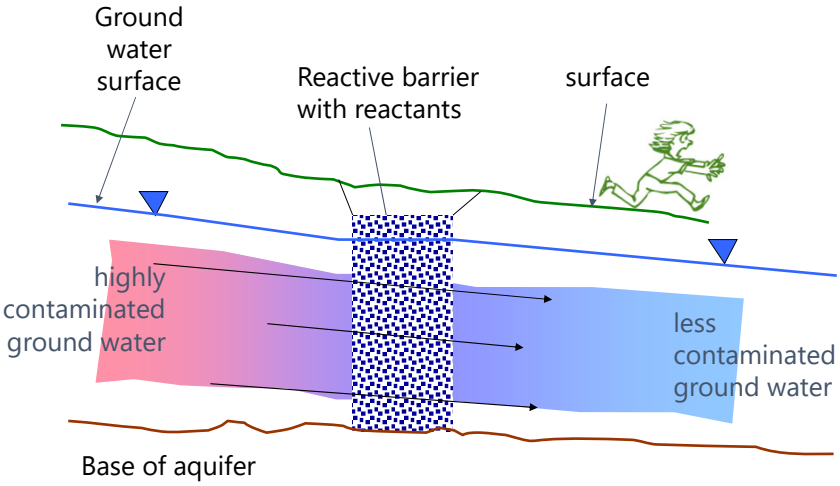
8

Reactive Barrier



after Younger 2000

Mine Water Treatment 71

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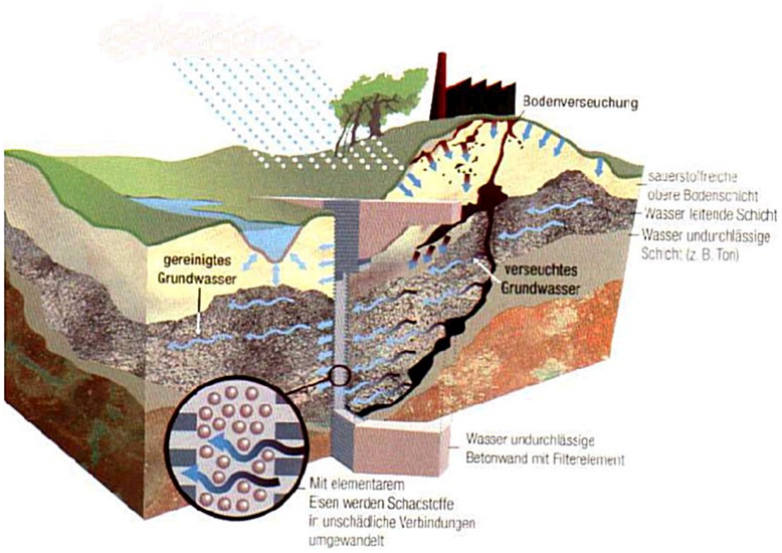
8

Barrier for Ground Water Treatment



after Engelhardt 2000

Mine Water Treatment 72

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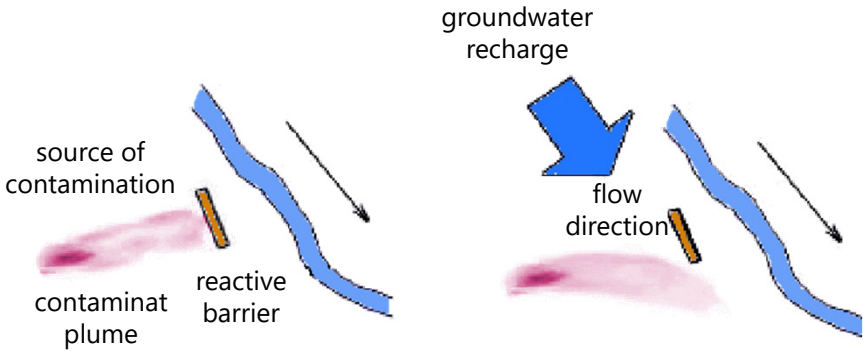
Reactive Barrier: Construction Pitfalls

- Hydrogeological situation not considered → failure of reactive barrier



after Kansy 2000

Uranium Mine Fry Canyon, Utah

Filling of reactive barrier with reactive material

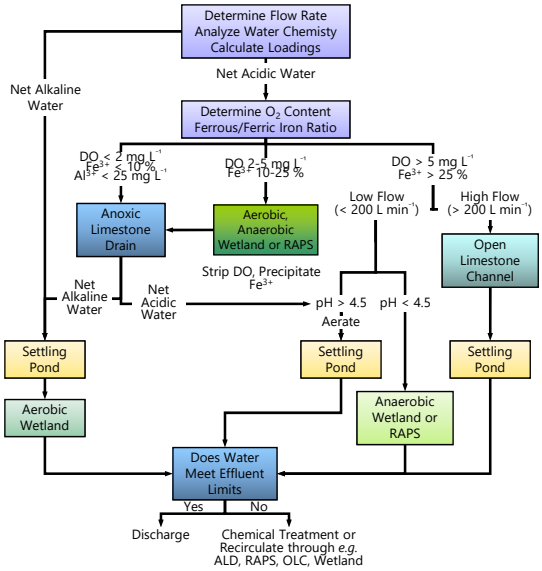
Completed reactive barrier before soil covering

from USGS ("Fry Canyon Reactive Barrier Installation")

8

Passive Treatment Flow Chart

- Flow chart for selecting a passive treatment system based on influent water quality
- Additional treatment may be required for Mn if present at elevated concentration



compiled and modified after Hedin *et al.* 1994; Skousen *et al.* 1998; Skousen *et al.* 2000

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Mine Water Treatment 75

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8

Anoxic Limestone Drain (ALD)

- Closed channels filled with limestone
- Anoxic mine water:
  - Increase of alkalinity
  - Increase of pH-value
- Only for net acidic mine waters
- [Fe^{3+}] must not be too high: < 10 %
- [Al^{3+}] at a maximum of 25 mg L^{-1}
- Dissolved oxygen < 2 mg L^{-1}

GARD Guide

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Mine Water Treatment 76

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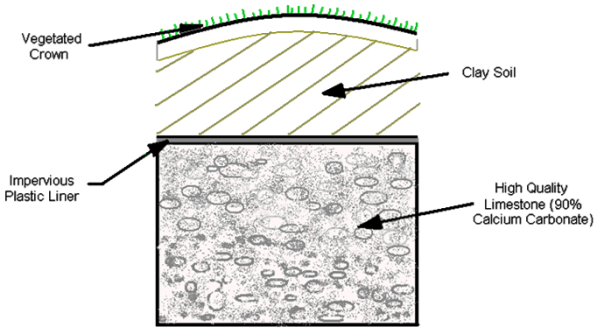
8

Cross Section and Construction



Cross section of anoxic carbonate drain

Tributary of Swatara Creek, PA

Mine Water Treatment

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8

Anoxic Limestone Drain (ALD)

- Failed ALD, because
  - Al-concentration relatively high (8 – 20 mgL^{-1} filtered)
  - O_2-concentration: never determined
  - Fe^{2+}/Fe^{3+}-ratio: never determined

Lehesten/Germany

Mine Water Treatment

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8

Calculation of Carbonate needed (1/2)

- (1) $M_y = Q \cdot [Aci] \cdot 5.2596 \cdot 10^{-4}$
  - $[\{t/a\} = \{L\ min^{-1}\} \cdot \{mg\ L^{-1}\ CaCO_3\} \cdot \{t \cdot min \cdot mg^{-1} \cdot a^{-1}\}]$
- (2) $M_s = t \cdot M_y$
  - $[\{t\} = \{a\} \cdot \{t/a\}]$
- (3) $M_k = M_s \cdot p_k^{-1} \cdot 100\ \%$
  - $[\{t\} = \{t\} \cdot \{1\}]$
- (4) $M_{kt} = M_k \cdot l_k^{-1} \cdot 100\ \%$
  - $[\{t\} = \{t\} \cdot \{1\}]$

M_y: annual quantity of acid
M_s: mass of acid over lifetime of drain
M_k: mass of carbonates to neutralize acid
M_{kt}: mass of carbonates to effect neutralisation

Q: water flow; [Aci]: acidity; t: lifetime of carbonate drain;
p_k: $CaCO_3$-purity of limestone; l_k: dissolution rate of limestone

Mine Water Treatment 79

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Calculation of Carbonate needed (2/2)

- "$\pi \cdot$ 👍^{2}"-rule
- Residence time: 14 hours
- Pore volume limestone: 50 %
- lifetime: 15 years

- Necessary carbonate volume:
  $^1/_{50}$% · volume mine water · 14 hours

Mine Water Treatment 80

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8

Aerobic Wetlands

- pH of mine water circum neutral (> 6.5)
- Water net alkaline
- Shallow water systems (15—50 cm)
- Wetland plants (*Typha, Phragmites, Juncus*) to reduce water velocity
- Fe-removal rates: 10 – 20 g · m^{-2} · d^{-1}

La Houve, France

Mine Water Treatment 81

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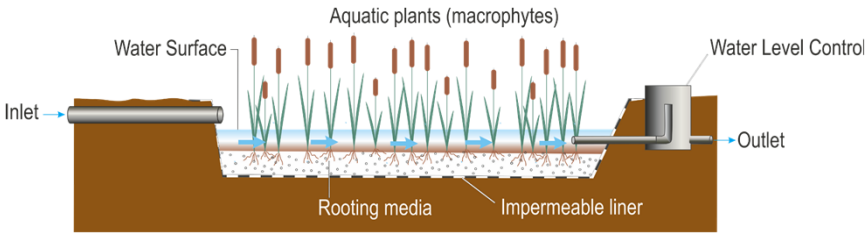
8

Cross Section and Plants



Typha

Phragmites

Juncus

GTK 2014

Mine Water Treatment 82

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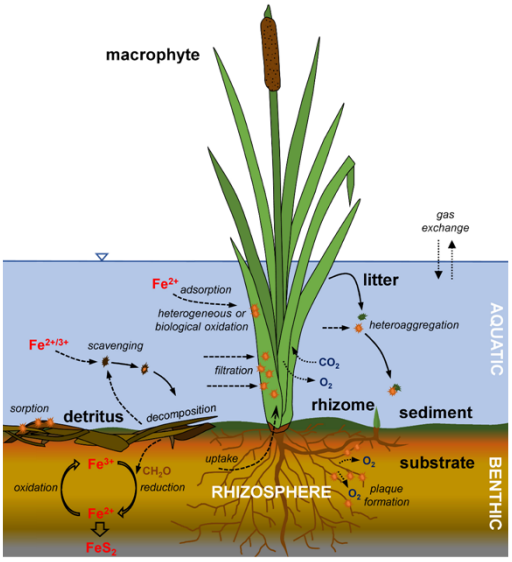
Role of macrophytes in Fe Removal



Opitz et al. 2021

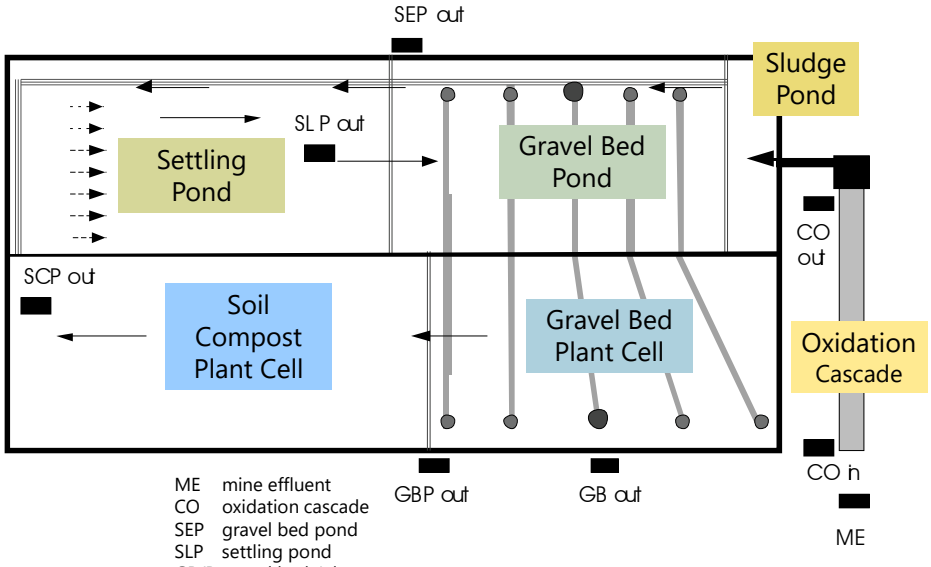
Example: Pöhla/Ore Mountains

Pöhla/Ore Mountains 2000-08-04

8

Mine Water Treatment

Example: Pöhla/Ore Mountains



ME mine effluent
CO oxidation cascade
SEP gravel bed pond
SLP settling pond
GB/P gravel bed /plant
SCP soil compost plant

after Kalin *et al.* 2002

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8

Mine Water Treatment

Example: Straßberg/Harz

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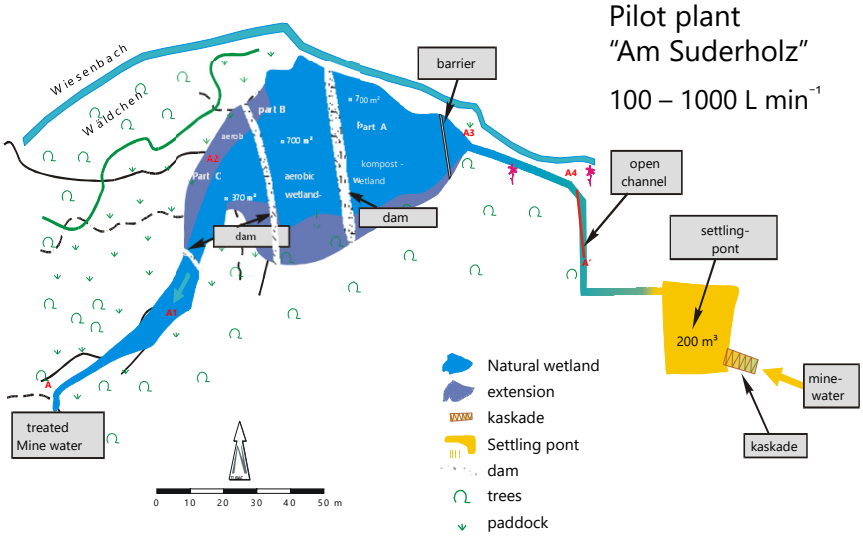
Example: Straßberg/Harz



Pilot plant
"Am Suderholz"

100 – 1000 L min^{-1}

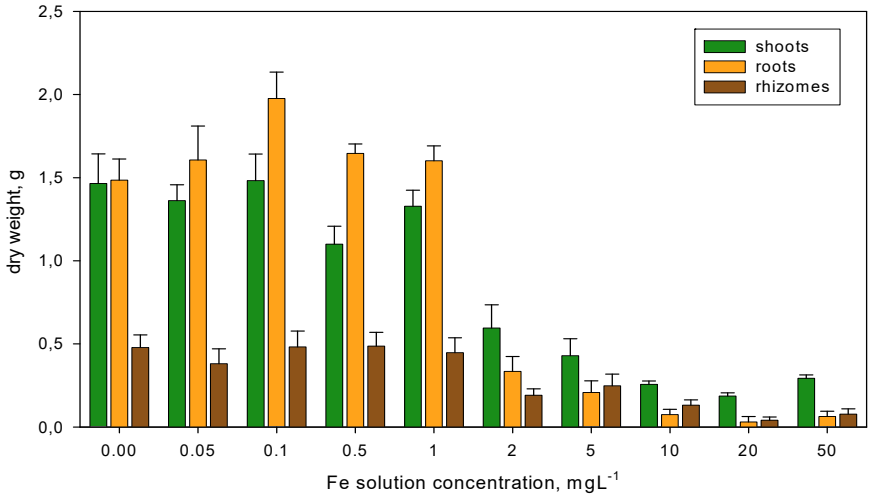
Aerobic Wetlands: Plants' Iron Removal (¼)

- Case study: *Phragmites australis*
- Seeds taken from uncontaminated site
- Seedlings of uniform size selected (5 for each treatment)
- 27 days growth, then $FeSO_4.7H_2O$ added and another 64 days growth
- Plants harvested, divided into roots, rhizomes and shoots and dried at 40 °C for 2 days

8

Aerobic Wetlands: Plants' Iron Removal (2/4)

Phragmites australis: healthy growth



Mine Water Treatment

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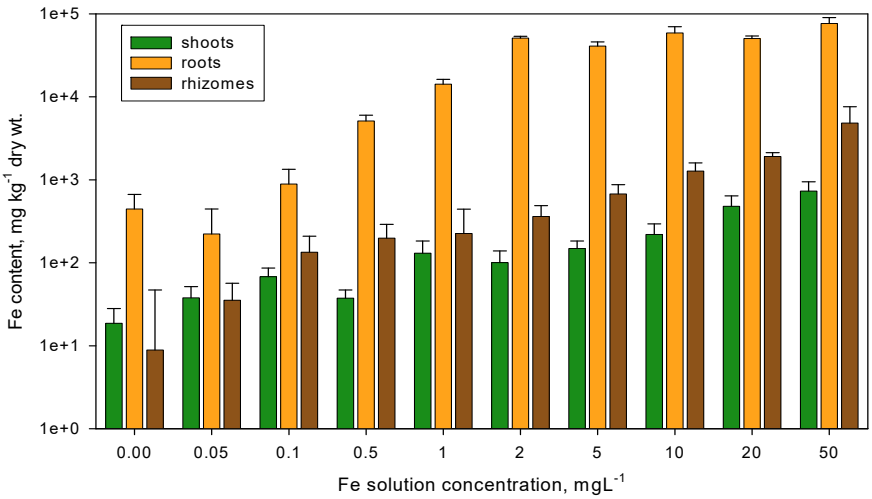
Aerobic Wetlands: Plants' Iron Removal (3/4)

Phragmites australis: Fe uptake



Mine Water Treatment

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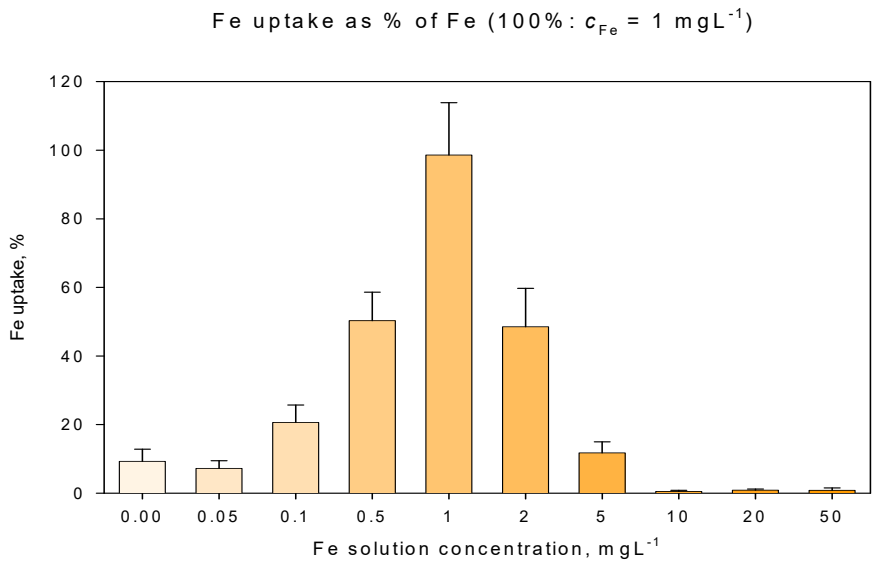
Mine Water Treatment

Aerobic Wetlands: Plants' Iron Removal (4/4)



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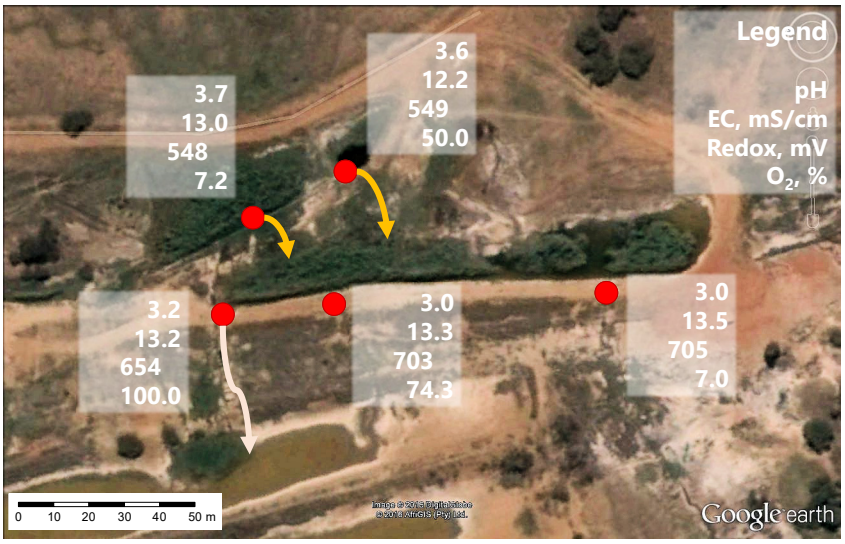
Mine Water Treatment

Aerobic Wetlands: Pitfall



eMalahleni (Witbank), South Africa

92

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8

Anaerobic Wetlands: Compost Wetland (1/2)

- Acid pH (< 5.6)
- Water net acidic or rich in SO_4^{2-}
- Shallow water systems (0 –10 cm) with compost bed (30 – 60 cm)
- Mushroom compost, horse manure, cow manure, bark mulch, straw mixtures
- Mine water flows through or over substrate

Mine Water Treatment

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Anaerobic Wetlands: Compost Wetland (2/2)

- Bacterial sulfate reduction consumes protons and produces bi-carbonate alkalinity (buffering and raise of pH-value)
- Sulfide ions react with ferrous iron (Fe^{2+}) to produce FeS/FeS_2
- Wetland plants (*Typha, Phragmites, Juncus*) to reduce water velocity
- Iron removal: 3 – 7 $g \cdot m^{-2} \cdot d^{-1}$

Mine Water Treatment

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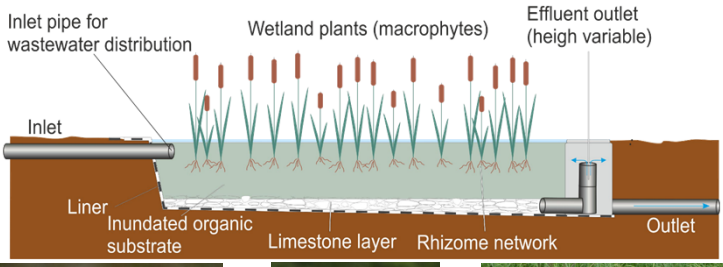
8

Anaerobic Wetlands



Typha

Phragmites

Juncus

GTK 2014

Mine Water Treatment 95

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8

Calculation of Area Needed

- $M_f = Q \cdot c \cdot 1.44$ (load = quantity · concentration · factor)
  - $[\{g \cdot d^{-1}\} = \{L \cdot min^{-1}\} \cdot \{mg \cdot L^{-1}\} \cdot \{g \cdot mg^{-1} \cdot min \cdot d^{-1}\}]$
  - Net alkaline mine water: $c = [Fe_{tot}]$
  - Net acidic mine water: $c = [Aci]$
- $A = M_f$ / RR (area = load / removal rate)
  - $[\{m^2\} = \{g \cdot d^{-1}\} \cdot \{g^{-1} \cdot d \cdot m^2\}]$

- Determination of RR (removal rate):
  - RIC: reasonable improvement criterion
  - CC: compliance criterion

standards	Net alkaline	Net acidic
CC (compliance)	10 g d^{1} m^{-2}	3.5 g d^{1} m^{-2}
RIC (reasonable)	20 g d^{1} m^{-2}	7 g d^{1} m^{-2}

Mine Water Treatment 96

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Calculation of Area Needed: Gernrode/Harz

Flow rate	16.2	$L\ s^{-1}$
Calcium	1122	$mg\ L^{-1}$
Magnesium	100	$mg\ L^{-1}$
Sodium	333	$mg\ L^{-1}$
Potassium	16	$mg\ L^{-1}$
Iron	10.7	$mg\ L^{-1}$
Manganese	4.3	$mg\ L^{-1}$
Zinc	144	$\mu g\ L^{-1}$
Copper	28	$\mu g\ L^{-1}$
Alkalinity	8.1	$mg\ L^{-1}$
Acidity	75.9	$mg\ L^{-1}$
Sulfate	72	$mg\ L^{-1}$
Chloride	1759	$mg\ L^{-1}$
pH	5.6	-
Temperature	11.2	°C
Redox	197	mV
el. Conductivity	4,856	$\mu S\ cm^{-1}$

Q = , $L\ min^{-1}$

$[Fe_{tot}]$ = , $mg\ L^{-1}$

[Aci] = , $mg\ L^{-1}$

$M_{f\text{-}Aci}$ = , $g\ d^{-1}$

$M_{f\text{-}Fe}$ = , $g\ d^{-1}$

$A_{RIC\text{-}Aci}$ = , m^2

$A_{CC\text{-}Aci}$ = , m^2

$A_{RIC\text{-}Fe}$ = , m^2

$A_{CC\text{-}Fe}$ = , m^2

Mine Water Treatment

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Calculation of Area Needed: Gernrode/Harz

Q = 972 , $L\ min^{-1}$

$[Fe_{tot}]$ = 7.7 , $mg\ L^{-1}$

[Aci] = 67.7 , $mg\ L^{-1}$

$M_{f\text{-}Aci}$ = 106236 , $g\ d^{-1}$

$M_{f\text{-}Fe}$ = 14977 , $g\ d^{-1}$

$A_{RIC\text{-}Aci}$ = 15177 , m^2

$A_{CC\text{-}Aci}$ = 30353 , m^2

$A_{RIC\text{-}Fe}$ = 749 , m^2

$A_{CC\text{-}Fe}$ = 1498 , m^2

Mine Water Treatment

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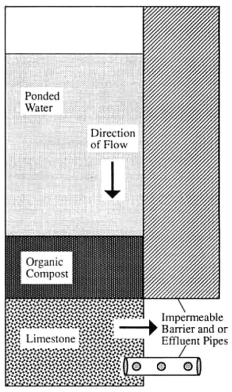
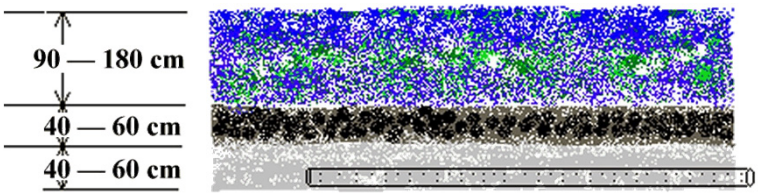
RAPS: Reducing and Alkalinity Producing Systems

- Combination of anoxic limestone drains (ALD) and anaerobic wetlands
- Water flows gravity driven downward through the anoxic wetland: compost and carbonate
- Hydraulic head at least 1.5 m, better 2.5 m
- Lifetime 15 – 20 years

- Initially called SAPS (successive alkalinity producing system) by Kepler & McCleary (1994)



Cross Section and Scheme



- The system never must fall dry (precipitation of Fe-oxihydrates)
- Compost: horse manure, cow manure, mushroom compost, bark mulch
- Both, compost and limestone must be permeable
- Calculation of limestone needed equals anoxic limestone drain (ALD)

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Mine Water Treatment

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Passive Uranium Removal

- Precipitation under reducing conditions
  - at the sulfate reduction zone
  - as Uraninite
- Sorption
  - Plants (e.g. roots)
  - Iron-hydroxide as co-precipitate
  - Biological processes involved
  - Titaniumsilicate (TiSi)
- Plant uptake
  - Low in the case of uranium

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Mine Water Treatment

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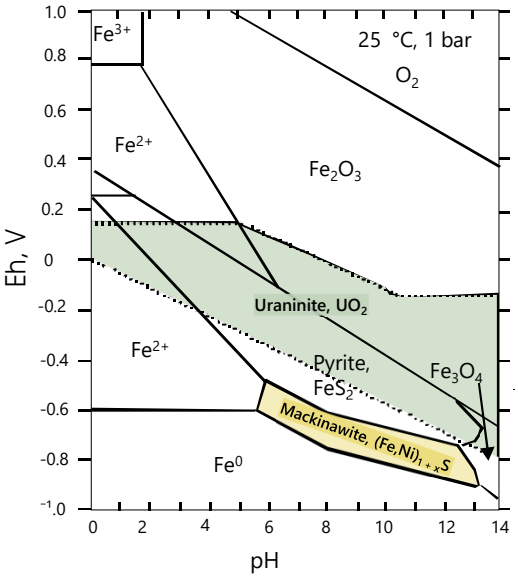
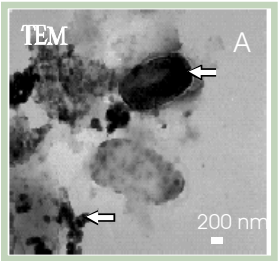
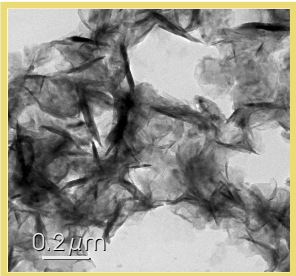
Passive Uranium Removal







Lutze *et al.* 2002

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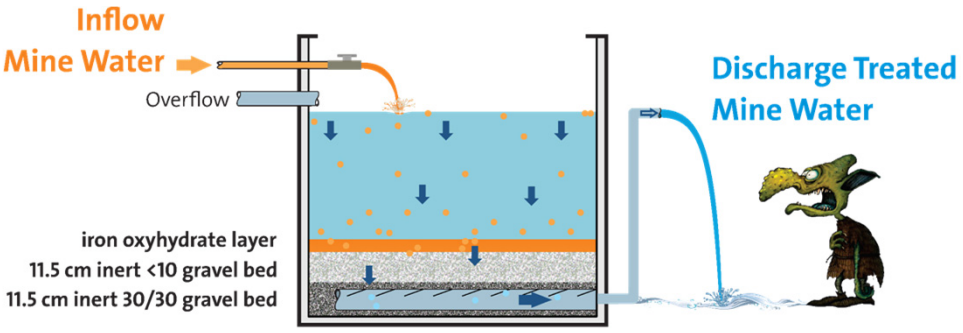
Mine Water Treatment

VFRs – Vertical Flow Reactors

- Simple construction
- Alkaline conditions
- Acid conditions with low iron
- Bacterial processes involved – details not studied yet



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Mine Water Treatment

VFRs – Vertical Flow Reactors

Cwm Rheidol, Wales, UK VFR

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Mine Water Treatment

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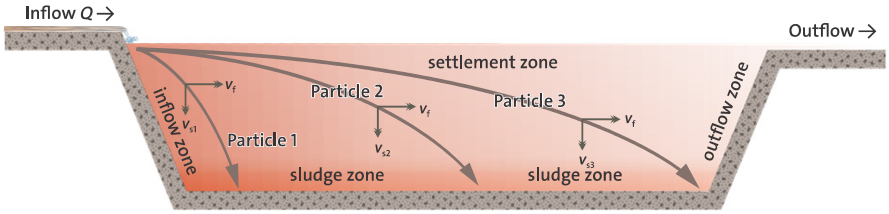
Settling Lagoons

- Simple construction
- Possible, wherever a fast precipitation occurs
- Acidity must not be too high



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Mine Water Treatment

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Settling Lagoons

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Mine Water Treatment

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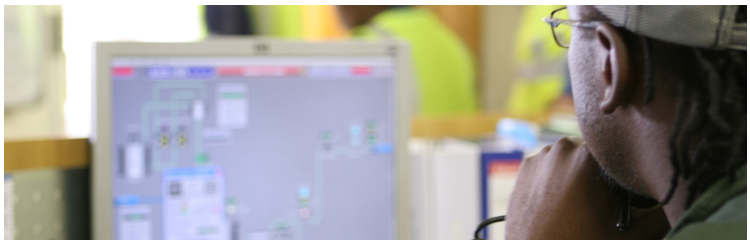
Strategic insights into leading technology

- Education and Training
  - Well educated operators
  - Aware of potential environmental impacts
  - Know how process operates
  - Are allowed to make own decisions



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Mine Water Treatment

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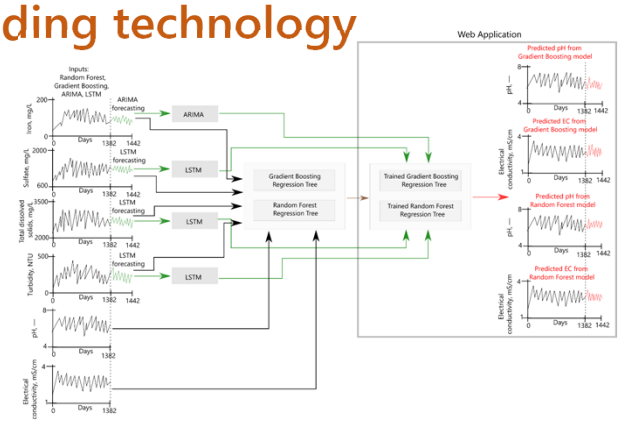
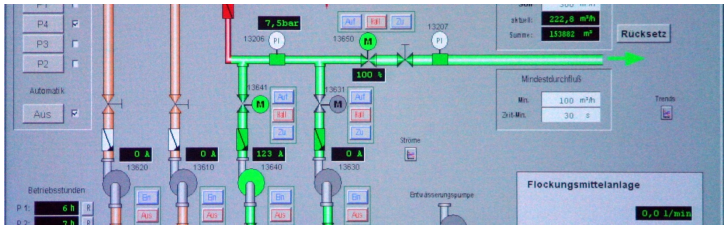
Strategic insights into leading technology

- Mine Water Management
  - Recycle
  - Reuse
  - Aquifer Storage and Recovery
  - Surface Storage
  - Expert Systems
  - Artificial Intelligence





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Mine Water Treatment

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Strategic insights into leading technology

- Membrane Techniques
  - Ultrafiltration
  - Reverse Osmosis
  - Chemical Pre-treatment

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Mine Water Treatment

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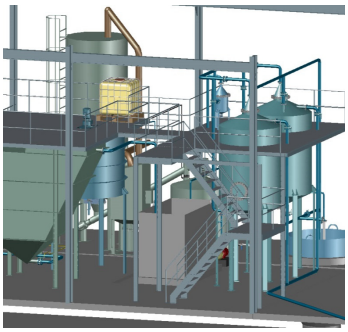
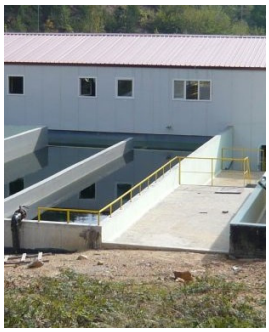
Strategic insights into leading technology

- Ion Exchange (used since 1969 for mine water)
  - GYP-CIX® (Bowell 2000: Berkeley Pit, Montana)
  - BIO-Fix (Bennett et al 1991: lab tests)
  - Zeolites (different authors and applications)





itrcweb.org, Soudan Mine | ionteching.com, Adit 93 Kremitkovtzi, Bulgaria | ionteching.com Assarel-Medet, Bulgaria

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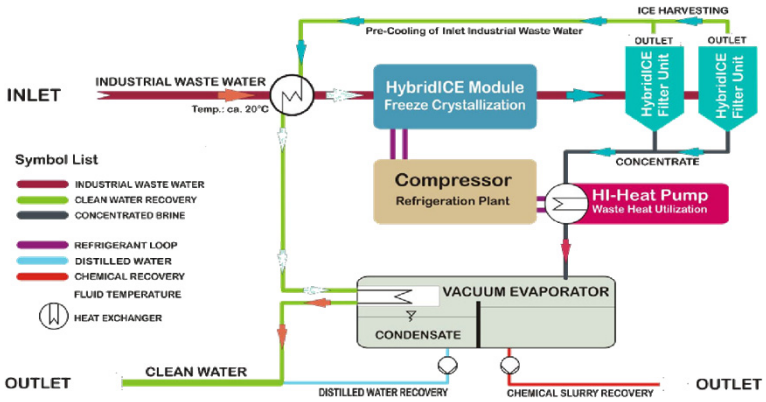
Mine Water Treatment

Strategic insights into leading technology

- Hybrid ICE Freeze Crystallization Technology
  - German – South African development



e.g. Reddy & Lewis 2010

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Mine Water Treatment

Strategic insights into leading technology

- Freeze Crystallization Technology

Tshwane University of Technology (TUT) | New Vaal Colliery, Proxa Inc. & Anglo Coal

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- **www.wolkersdorfer.info/helpful-lines.html**