Mine Waste Cover Systems and Control of Acid Mine Drainage in South American Tropical Zones

Michael Milczarek and Jason Keller

GeoSystems Analysis, Inc.

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Mine Closure Challenges

- Ingress of oxygen and water into waste
- Control long-term generation of Acid Mine Drainage (AMD)
  - Release into surface water and groundwater
  - Inability to revegetate

Design to Keep Water Out!

- Characterization methods
- Appropriate cover system design
- Modeling
- Monitoring

Tailings, Arizona

Heap Leach, NV

Waste Rock, Peru

Tailings, Papua New Guinea

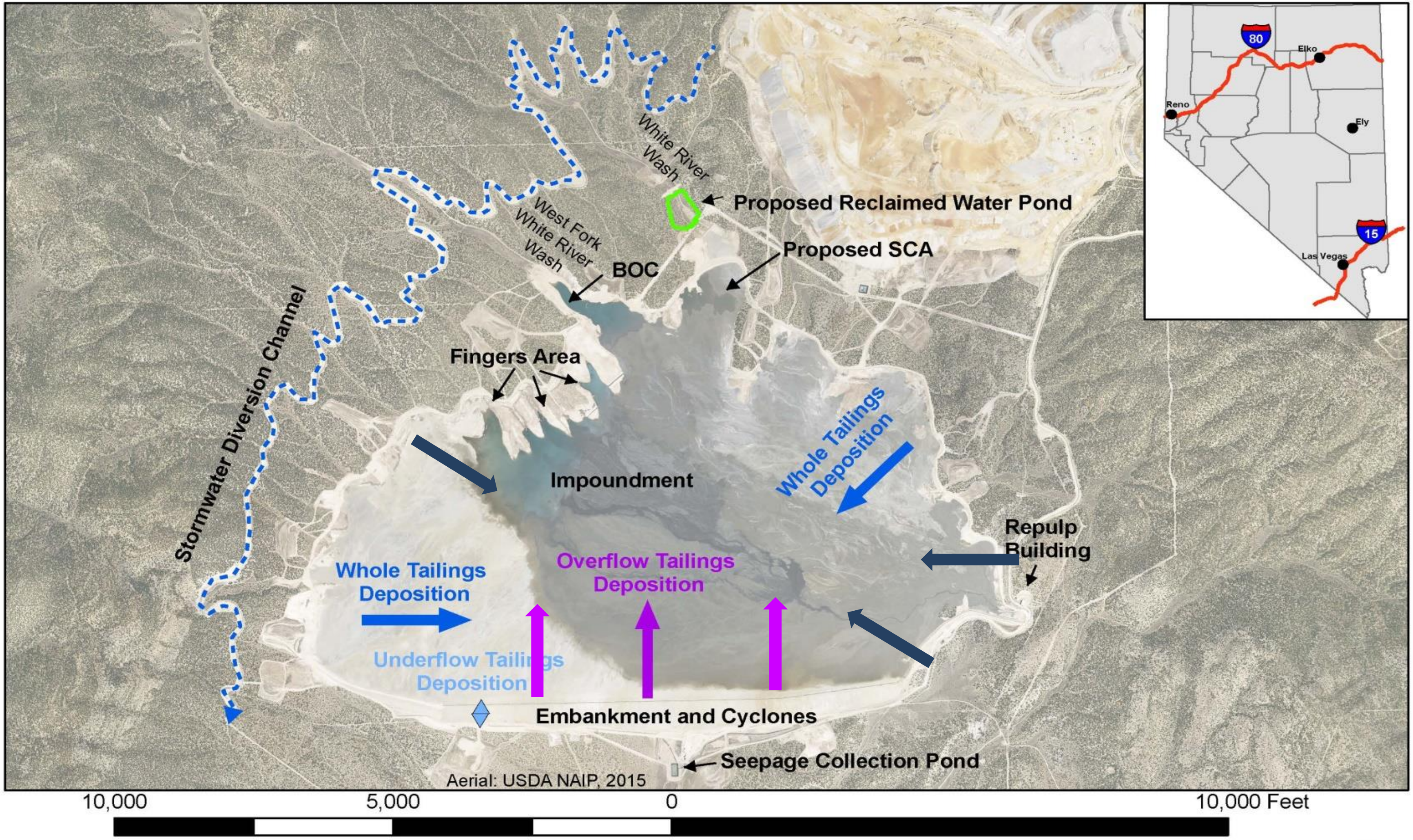
Controlling Factors

- Mine waste characteristics (waste rock, heap leach, tailings)
- Geochemical conditions
- Climate
- Net infiltration rates (percolation below the zero flux plane)

Mine Waste Characteristics

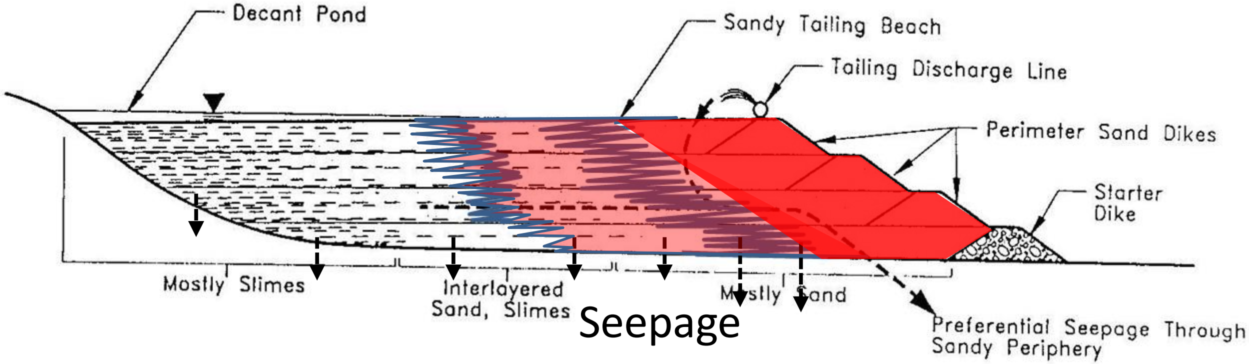
Mine Waste Types

- Tailings Impoundments
  - Fluvial depositional process, highly layered systems
  - Lower permeability layers generally dominate flow
  - Consolidation and deformation over time can be significant
- Waste Rock
  - High percentage of rock/gravel particles can create macropores and preferential flow may dominate unsaturated flow conditions
  - Significant storage capacity in waste rock material
- Heap Leach
  - Similar to waste rock but near-saturated conditions
  - Crushed vs ROM
  - Greater consolidation and variable permeability



80
Elko
Reno
Ely
15
Las Vegas
White River Wash
Proposed Reclaimed Water Pond
West Fork White River Wash
BOC
Proposed SCA
Stormwater Diversion Channel
Fingers Area
Impoundment
Whole Tailings Deposition
Repulp Building
Overflow Tailings Deposition
Whole Tailings Deposition
Underflow Tailings Deposition
Embankment and Cyclones
Seepage Collection Pond
Aerial: USDA NAIP, 2015
10,000
5,000
0
10,000 Feet

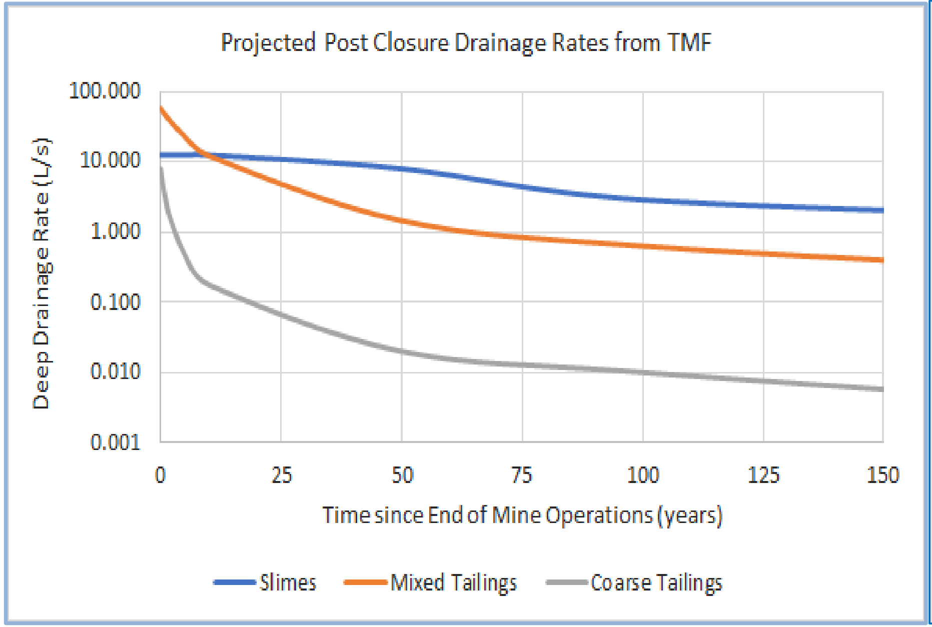
Tailings Construction/Segregation



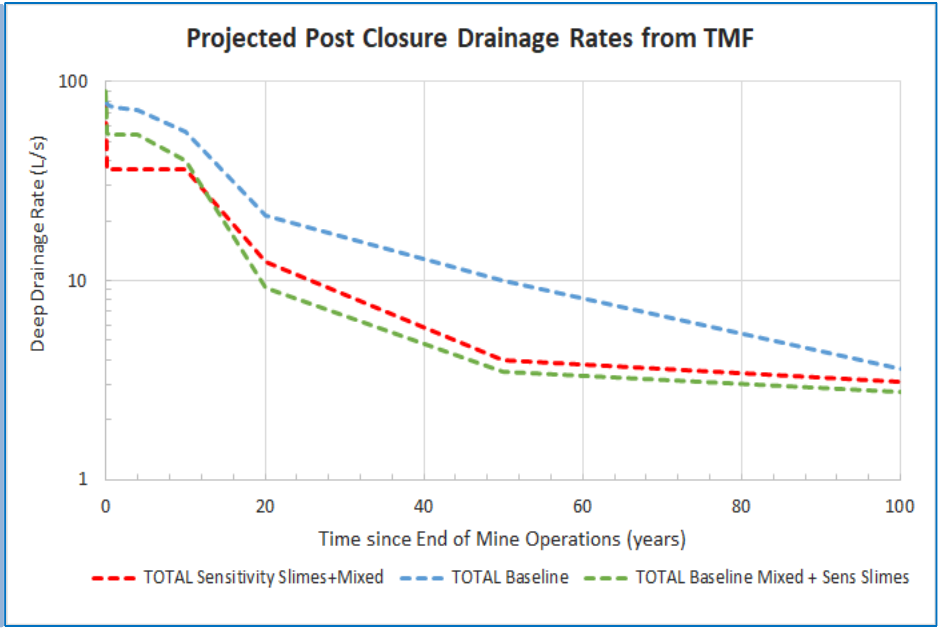
Potential for Oxygen Ingress at Closure

Post-Closure Tailings Draindown Rates

TMF Draindown by Tailings Type

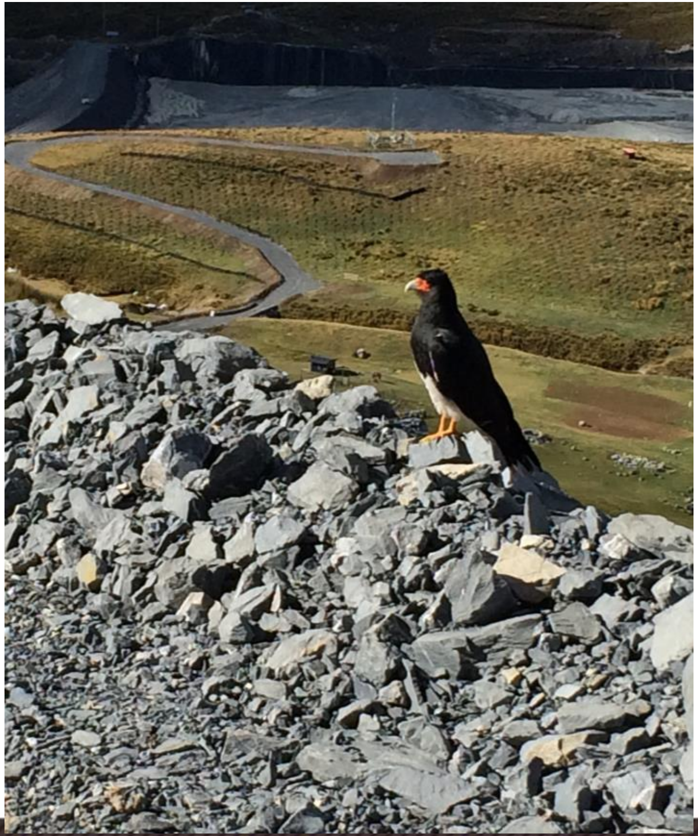


Total Draindown Sensitivity Results

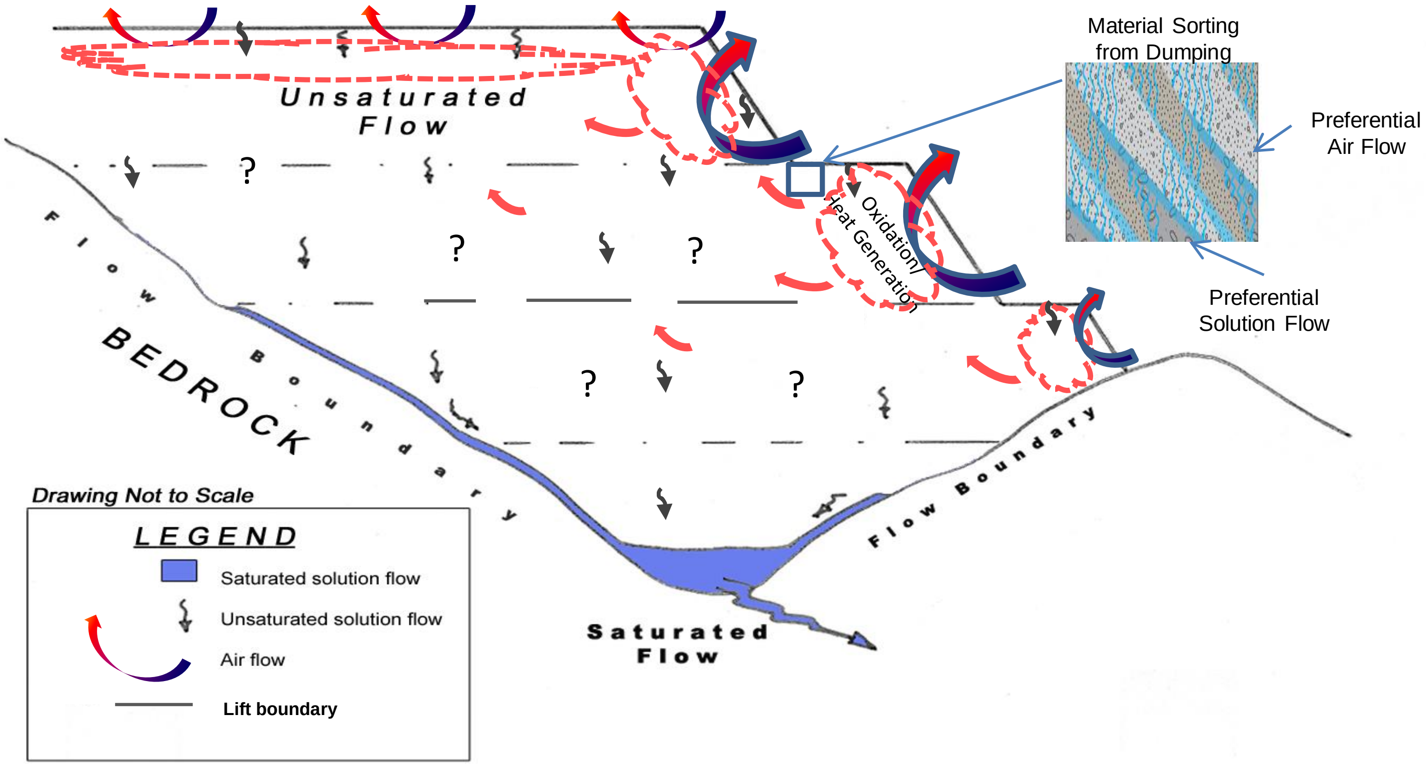


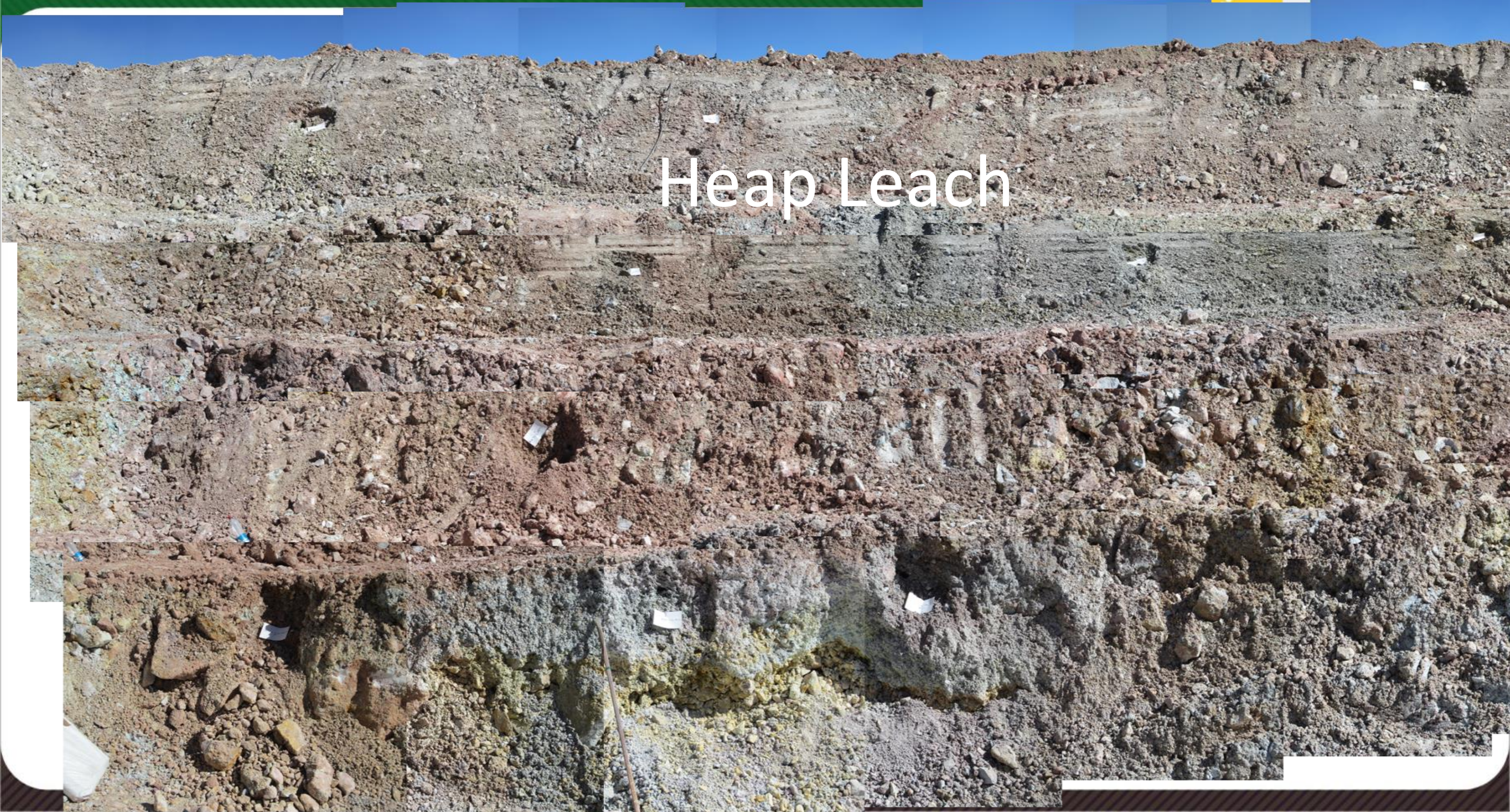
Waste Rock

- Large range of physical and hydraulic properties
  - Geology dependent
  - Orders of magnitude differences in Ksat

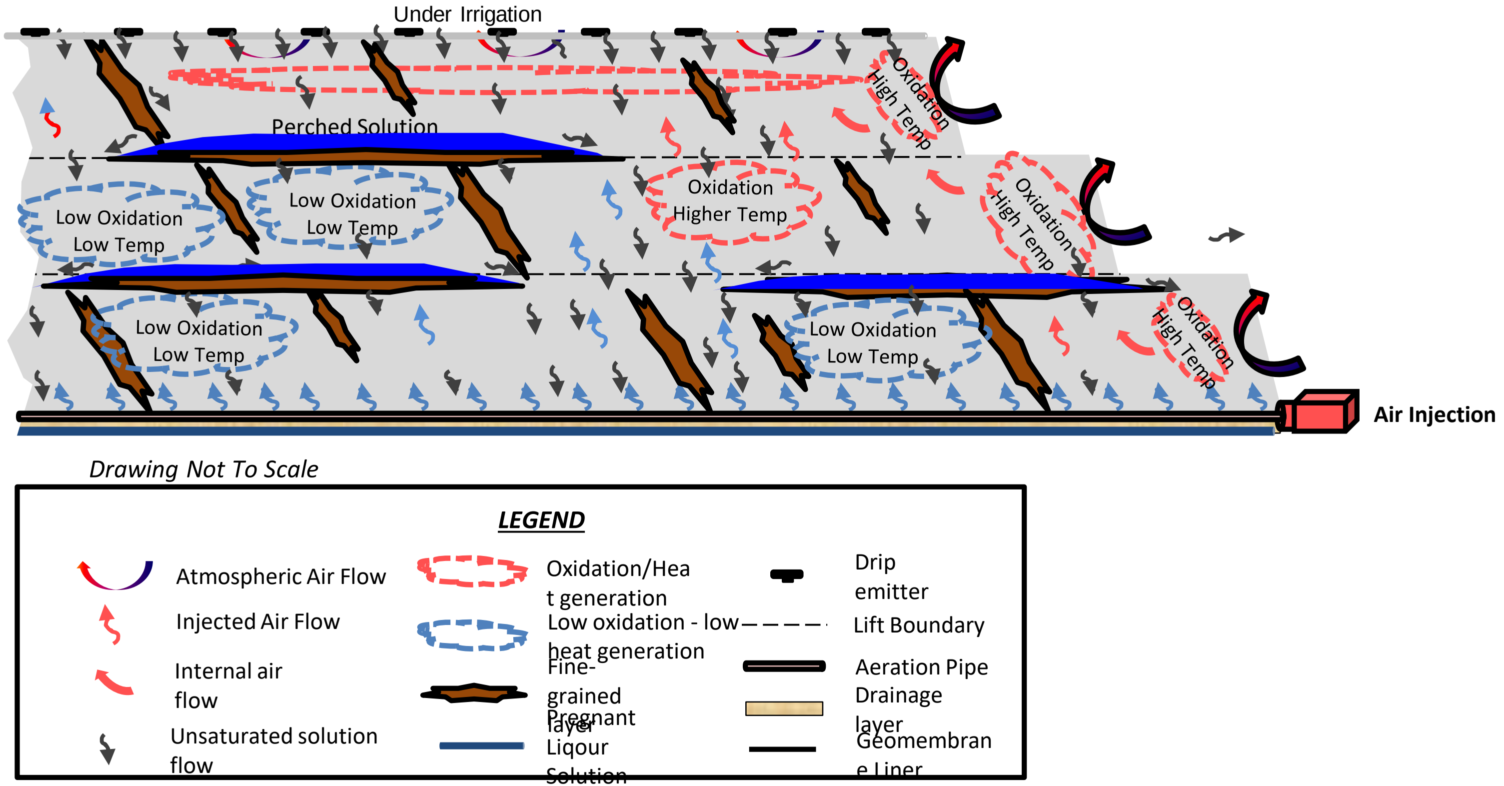


Waste Rock Solution and Air Flow




Heap Leach

Heap Leach Solution and Air Flow (Sulfide Ore)



Waste Geochemical Characteristics

- Sulfide vs non-sulfide mineral deposits
- Acid generation potential vs neutralization potential (AGP/ANP)
- Potentially Acid Generating (PAG) minerals can result in:
  - High acid generation potential (and acidity)
  - High plant available metals (i.e. arsenic)
  - Precipitation of secondary minerals
  - Biologically mediated (pH <5)
  - Reactions primarily in < 5 mm fraction

WASTE ACIDITY

ACID GENERATING POTENTIAL	HIGH pH	CIRCUMNEUTRAL	LOW pH
HIGH AGP	**Moderate Risk** Potentially High Salinity/Phytotoxicity	**Moderate to High Risk** Potentially High Salinity/Phytotoxicity	**High Risk** Typically High Salinity/Phytotoxicity
MODERATE AGP	**Moderate Risk** Potentially High Salinity/Phytotoxicity	**Moderate Risk** Potentially High Salinity/Phytotoxicity	**High Risk** Typically High Salinity/Phytotoxicity
LOW AGP	**Low Risk/Benign** Moderate Salinity	**Low Risk/Benign** Moderate Salinity	**Moderate Risk** Potentially High Salinity/Phytotoxicity

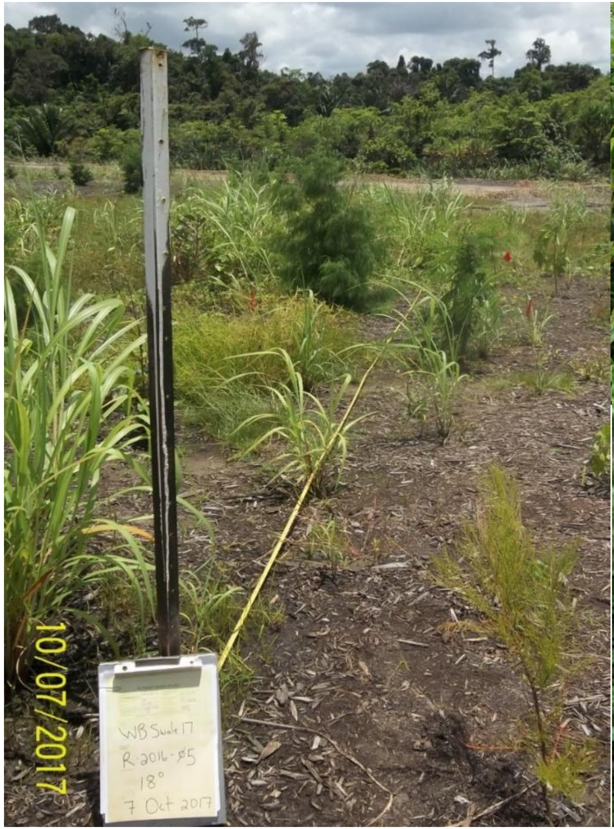
Cover Depth/Design


Direct Reclamation of
Mine Waste
16

Direct Revegetation (non-PAG, circumneutral)

- Typically low plant fertility
- Lack of organic matter and microbiota
- Can be saline even if neutralized
- May need to add amendments
- Use of pioneer species

Direct Revegetation in Wet Climates



Ok Tedi Sand Tailings Stockpile Rehabilitation

- Challenges:
  - Not like natural system
    - Higher pH
    - Higher salinity
    - Much greater depth to groundwater
    - Much coarser
  - Use only native species

Revegetation Plans and Trials

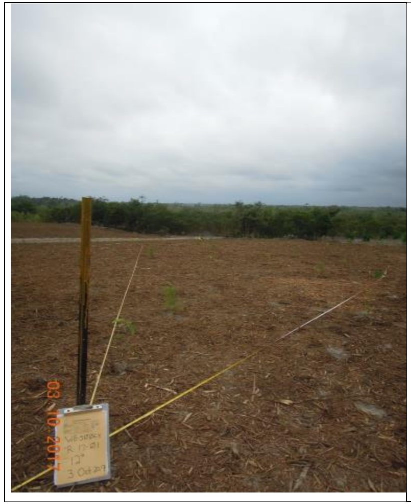
<u>2014-2016</u>

- Greenhouse & Field Trials
- Refine plant species selection
- Effects of compost amendments on plant growth
- Refine seeding and planting methods

<u>2017 - present</u>

- Long-term monitoring program
  - **Ecosystem Function Analysis**
- Train OTML staff
- Data analysis & reporting
- Create GIS geo-database

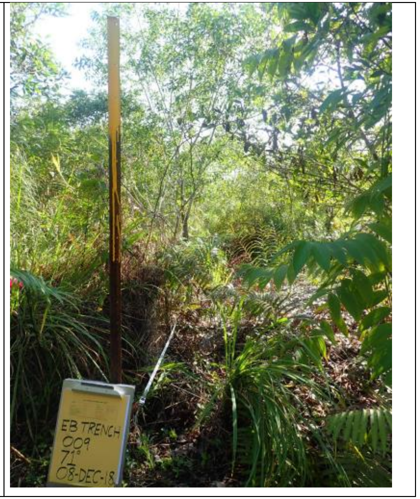
Oct 2017

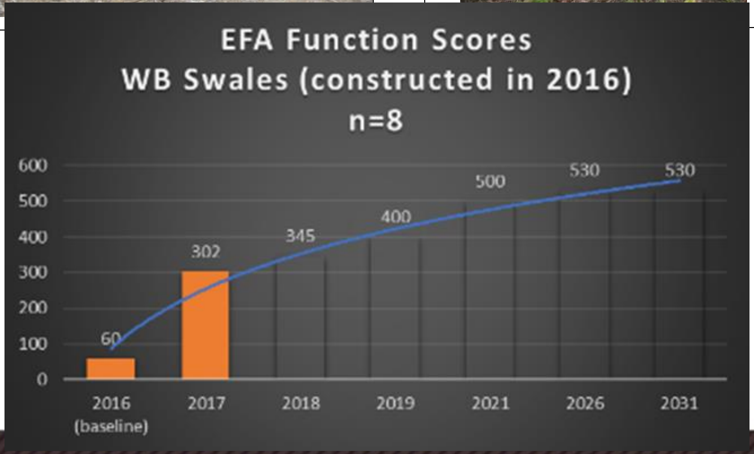


Dec 2018

Oct 2017

Dec 2018



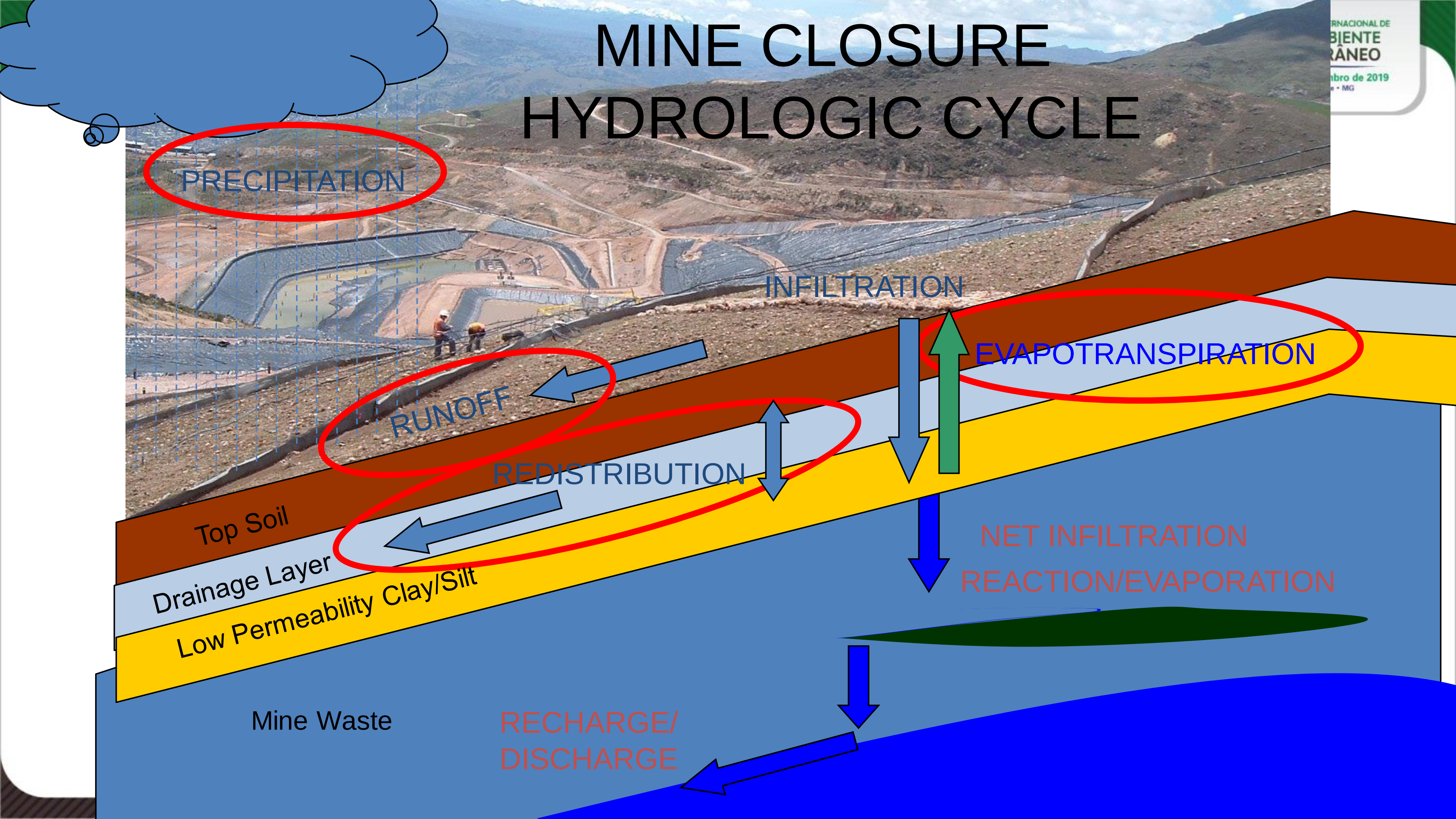


Climate and Design of Cover Systems

Design of Cover Systems

- Identify potential borrow materials
- Characterize waste and cover material
  - Physical and hydraulic properties
  - Geochemical characteristics
  - Ability to support vegetation
- Develop estimates of net infiltration rates
  - Estimates of natural groundwater recharge rates
  - Use of analytical and numerical models
  - Initial tailings drainage (up to decades) much greater than ET cover net percolation

MINE CLOSURE HYDROLOGIC CYCLE



Evapotranspiration (ET) Cover System

ET Cover – Seasonal storage and release of soil water

Fall or Dry Season

Soil is initially dry

Evapotranspiration (ET) Cover System

ET Cover – Seasonal storage and release of soil water

Winter or Wet Season

Rain and/or snowmelt gradually infiltrates, increasing soil water to field capacity

Evapotranspiration (ET) Cover System

ET Cover – Seasonal storage and release of soil water

Spring or late Wet Season

Wetting front moves deeper. Net infiltration is most likely in this season

Evapotranspiration (ET) Cover System

ET Cover – Seasonal storage and release of soil water

Late Spring or Early Dry Season

As temperature warms, evaporation increases and vegetation transpires stored soil water

Evapotranspiration (ET) Cover System

ET Cover – Seasonal storage and release of soil water

Late Summer or Dry Season

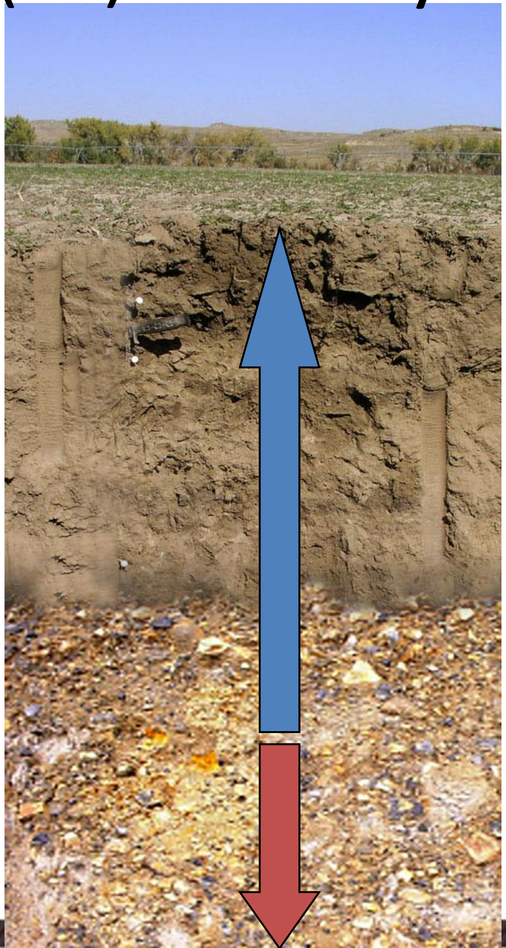
Continued transpiration by vegetation removes stored soil water from root zone

Evapotranspiration (ET) Cover System

Cover System Design Factors

Available Water Holding Capacity (loams ideal)

Soils may provide from less than 3 cm to more than 8 cm per meter AWC



Considerations

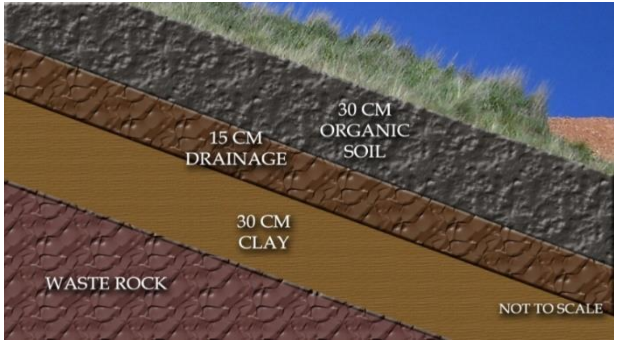
Gravelly soils help reduce erosion (but low AWC)

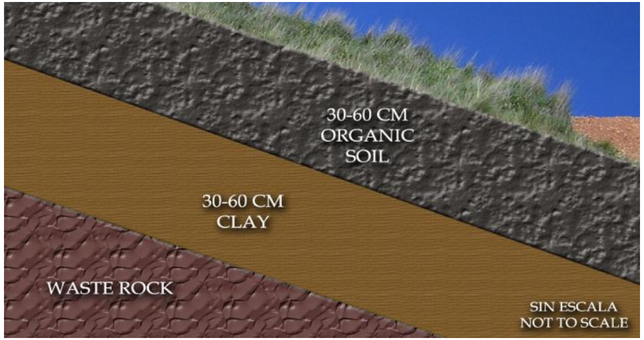
Vegetation key to controlling drainage

Semi-arid species rooting can go deep (several meters)

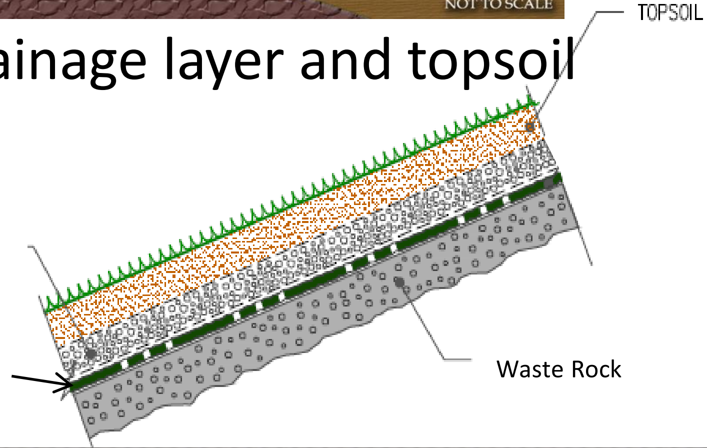
Barrier Cover System Types

- Multi-layer barrier/ET Cover Systems





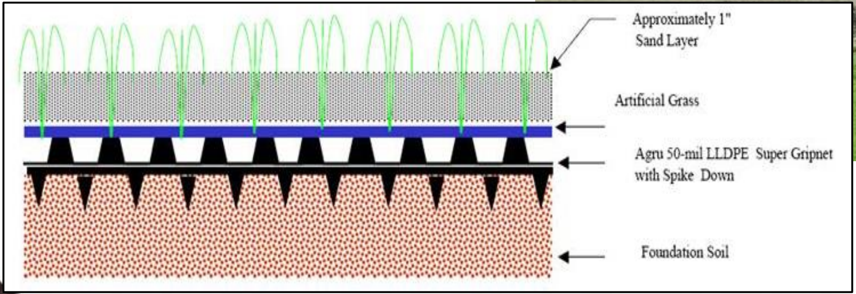
- Geosynthetic liner with drainage layer and topsoil (different types)



Barrier Cover Systems

Agru-turf/

ClosureTurf

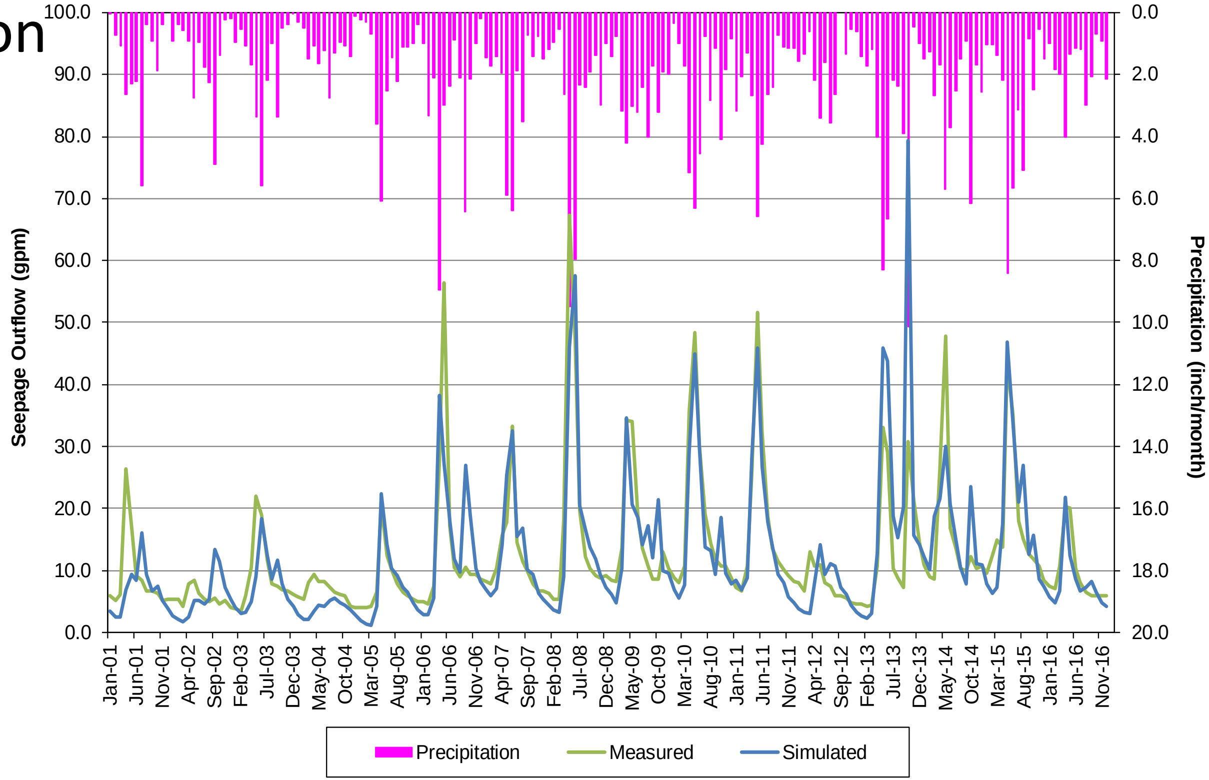


Measured Net Infiltration Rates

- Semi-arid southwestern USA
  - Uncovered waste rock: 15% to 25% of annual precipitation (AP)
  - ET Cover over waste rock: 1% to 5% of AP
  - ET Cover over tailings < 1% to 3% of AP
- Rocky Mountains USA
  - Uncovered waste rock: > 50% of AP
  - Covered waste rock and tailings: Depends on cover system, up to 40% of AP
- High elevation Andes (< 3500 m)
  - Uncovered waste rock: > 50% AP
  - Covered waste rock: Depends on cover system: up to 40% of AP

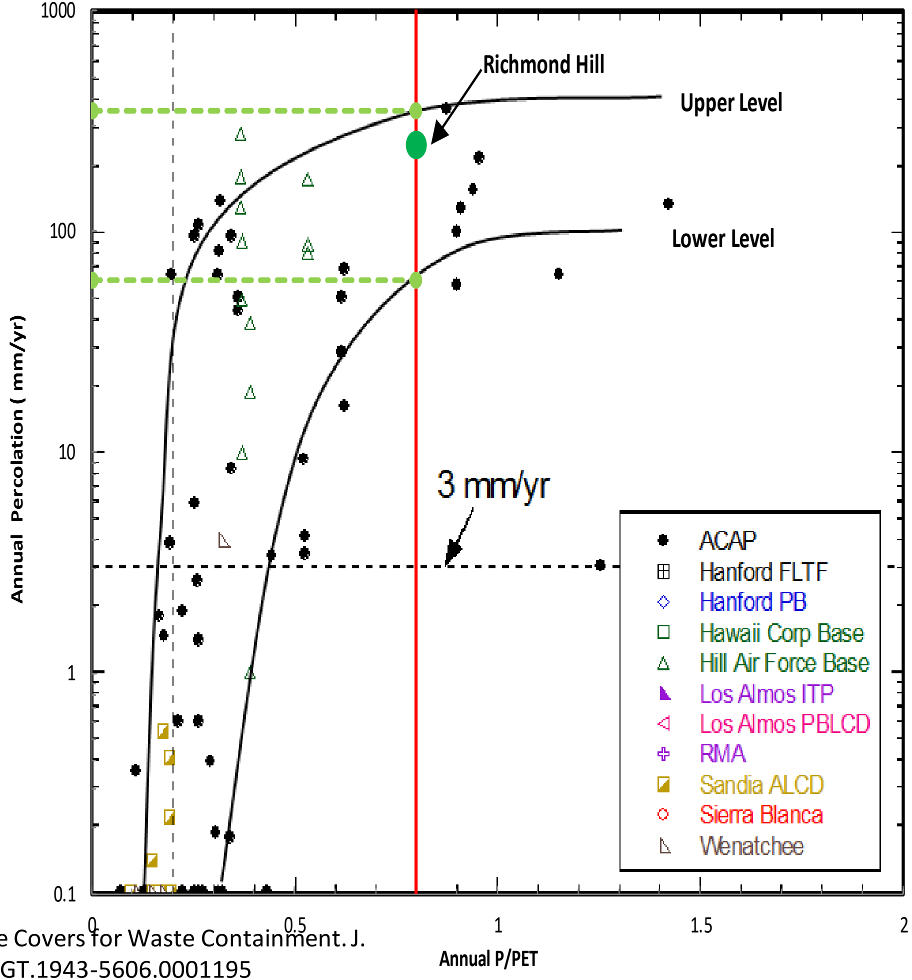
Cover Systems are Dynamic

- Richmond Hill, South Dakota
- Average Net Infiltration (as % of AP)
  - 1998–2000 = 22%
  - 2001–2005 = 32%
  - 2006–2016 = 34%



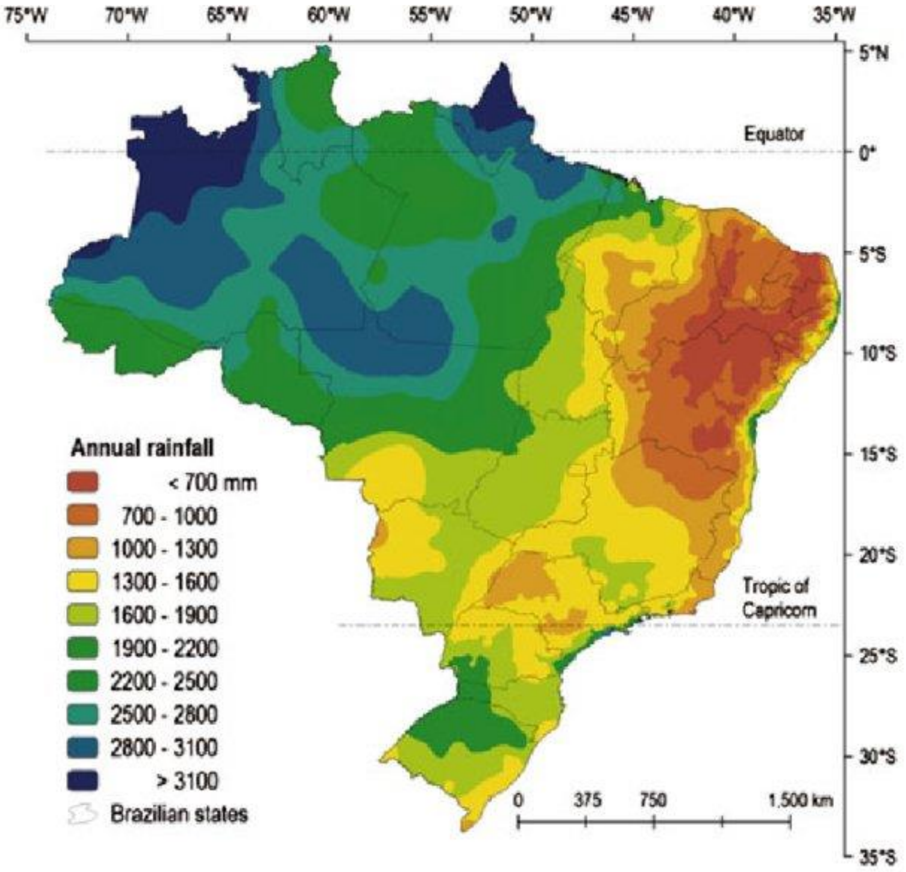
Net Infiltration in ET Covers: P/PET

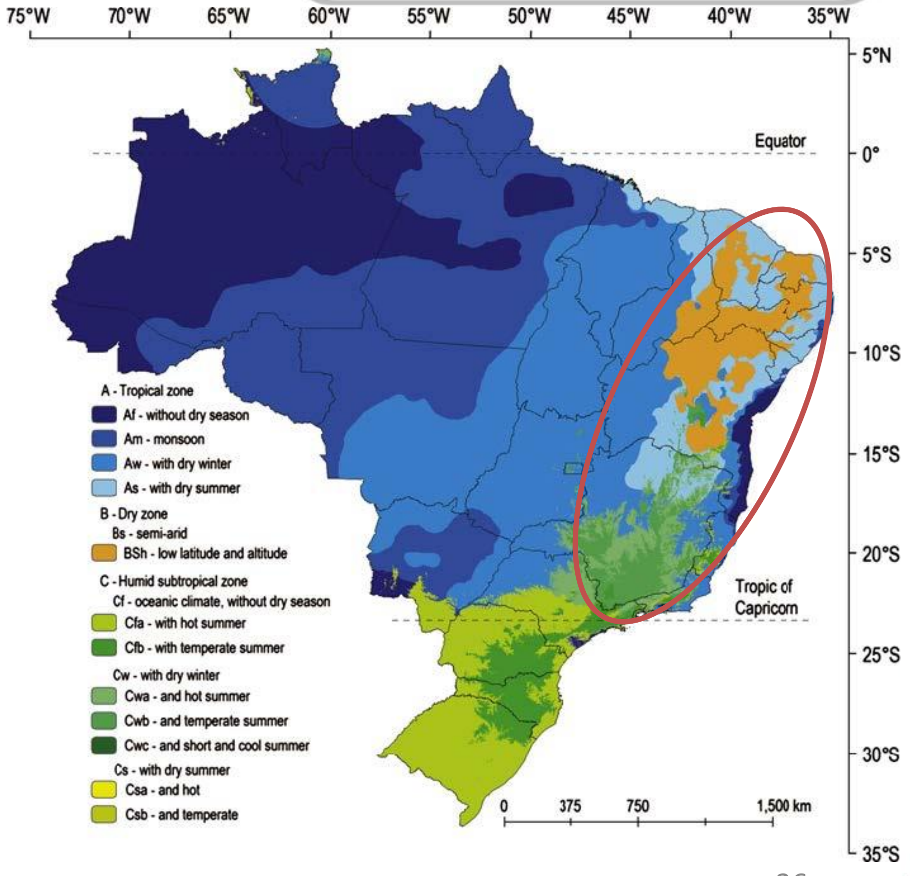
- Monolayer ET Cover Systems
  - P/PET < 0.4, Low percolation rate - 3 mm/yr
  - P/PET > 0.8, High percolation rates
- North American climates, need more data from South America



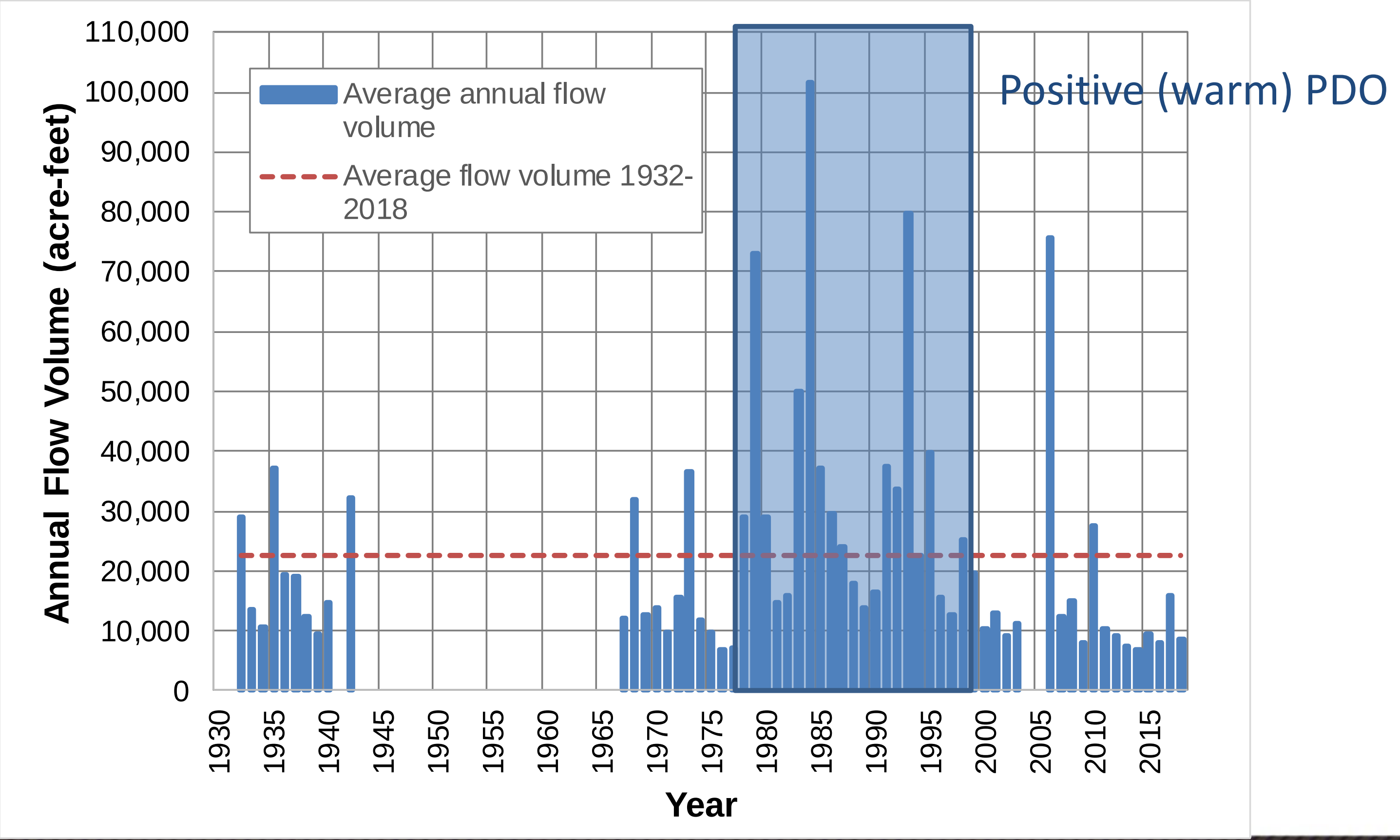
Apiwantragoon P, Benson CH, Albright WH. 2015. Field Hydrology of Water Balance Covers for Waste Containment. J. Geotech. and Geoenvironmental Eng. 141 (2): 04014101-1-20. DOI: 10.1061/(ASCE)GT.1943-5606.0001195

PRECIPITATION AND CLIMATIC REGIMES





Climatic Cycles (PDO/AMO and ENSO)



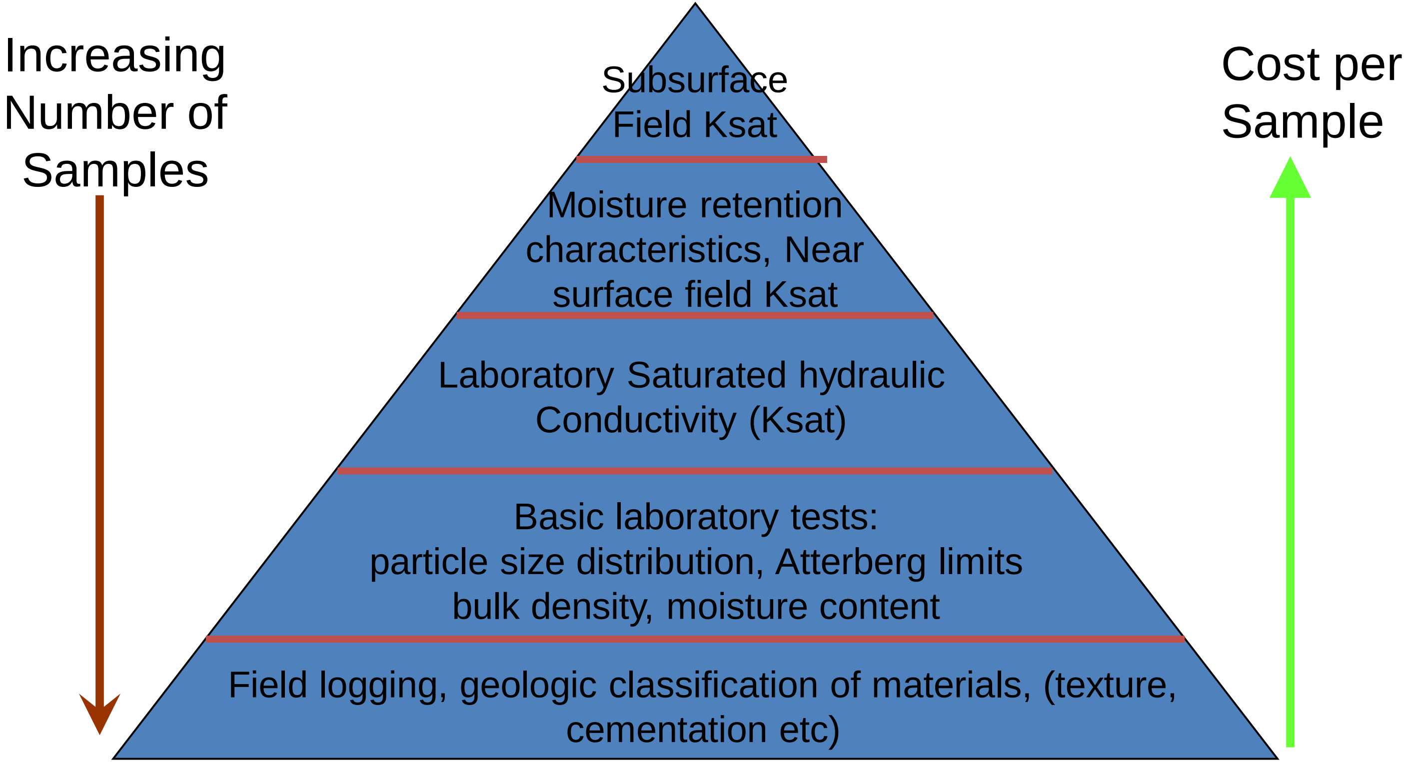
VI CONGRESSO INTERNACIONAL DE MEIO AMBIENTE SUBTERRÂNEO
18 e 19 de novembro de 2019
Belo Horizonte • MG

Material Characterization

Physical and Hydraulic Properties

- Geologic logging and sample collection
- Physical properties
  - Particle size distribution, Atterberg limits (USCS classification)
  - Bulk density
- Hydraulic properties
  - Saturated hydraulic conductivity (Ksat)
  - Moisture retention characteristics (MRC)
  - Unsaturated hydraulic conductivity (function)
- Geochemical properties for revegetation
  - ABA and extractable elements for mine waste
  - ABA and soil fertility for borrow material

The Pyramid Approach

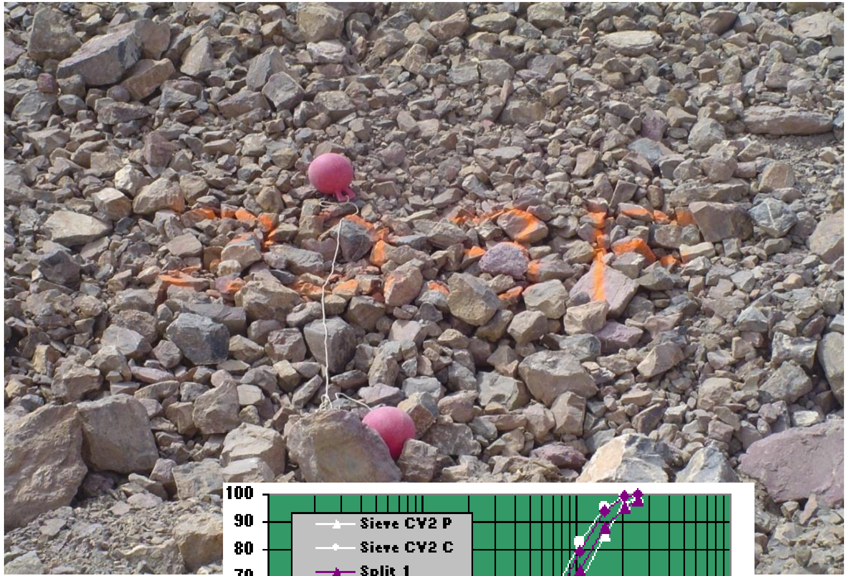


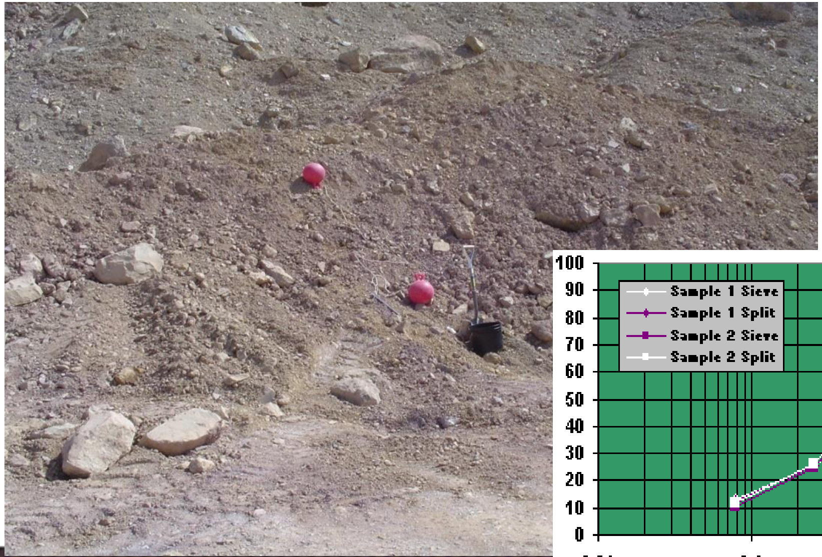
Representative Sample Collection

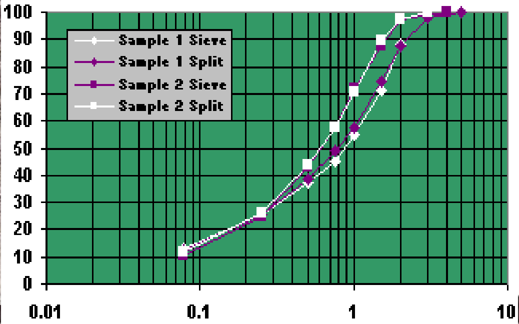
- Back-hoe test pits or augering
- Geologic logging of profile (ASTM 2488)
- Collection of samples for lab testing:
  - Particle size distribution for calibration of geologic logs
  - Samples for moisture content, bulk density, hydraulic properties
- Dig as many as possible!

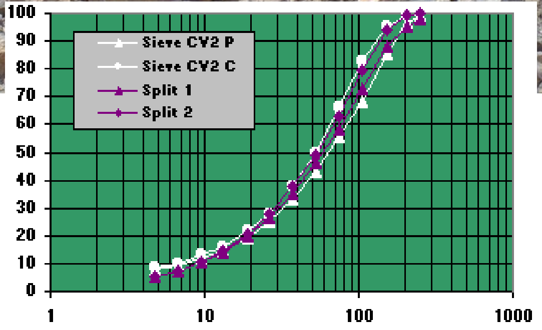
Particle Size Distribution

- Image Processing (Split-net)
  - Good for > 1/2-inch
- Lab testing < 3 inch

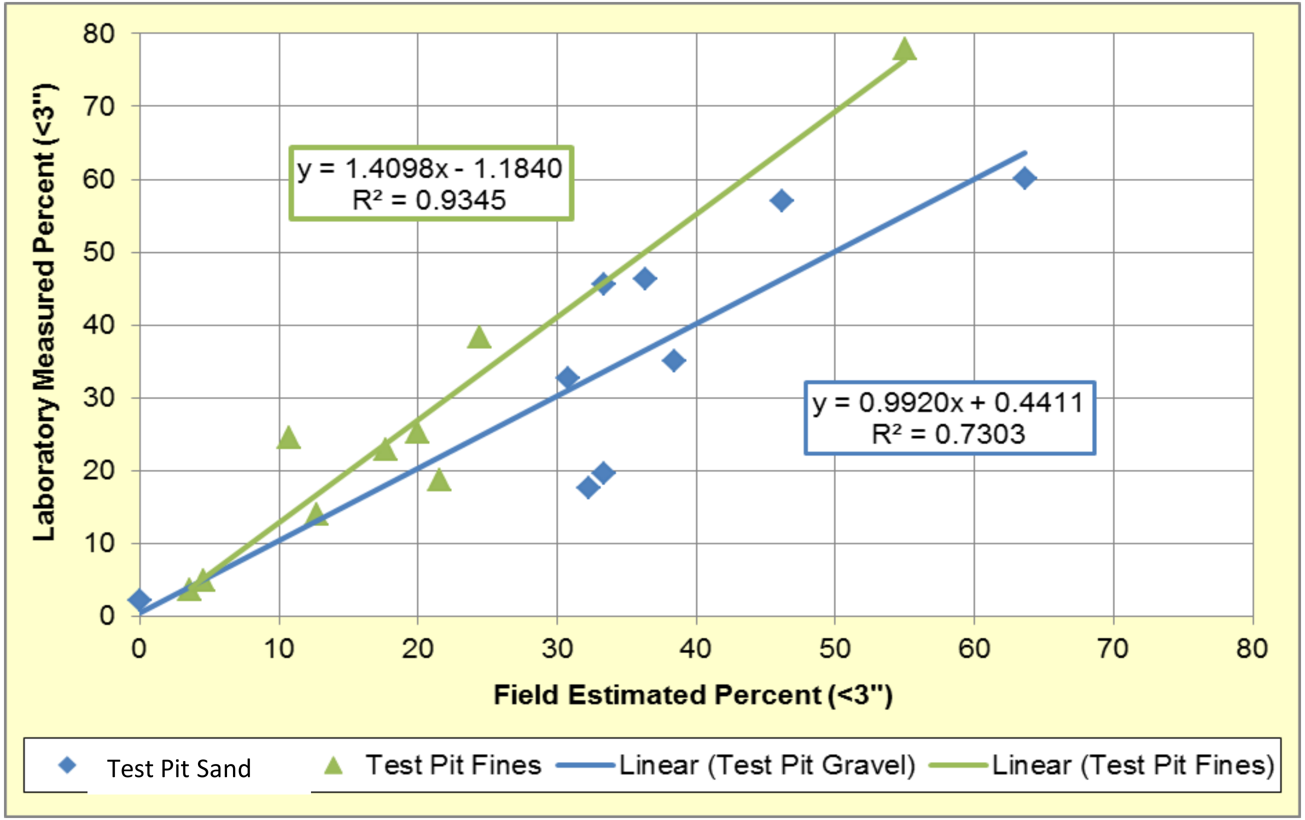




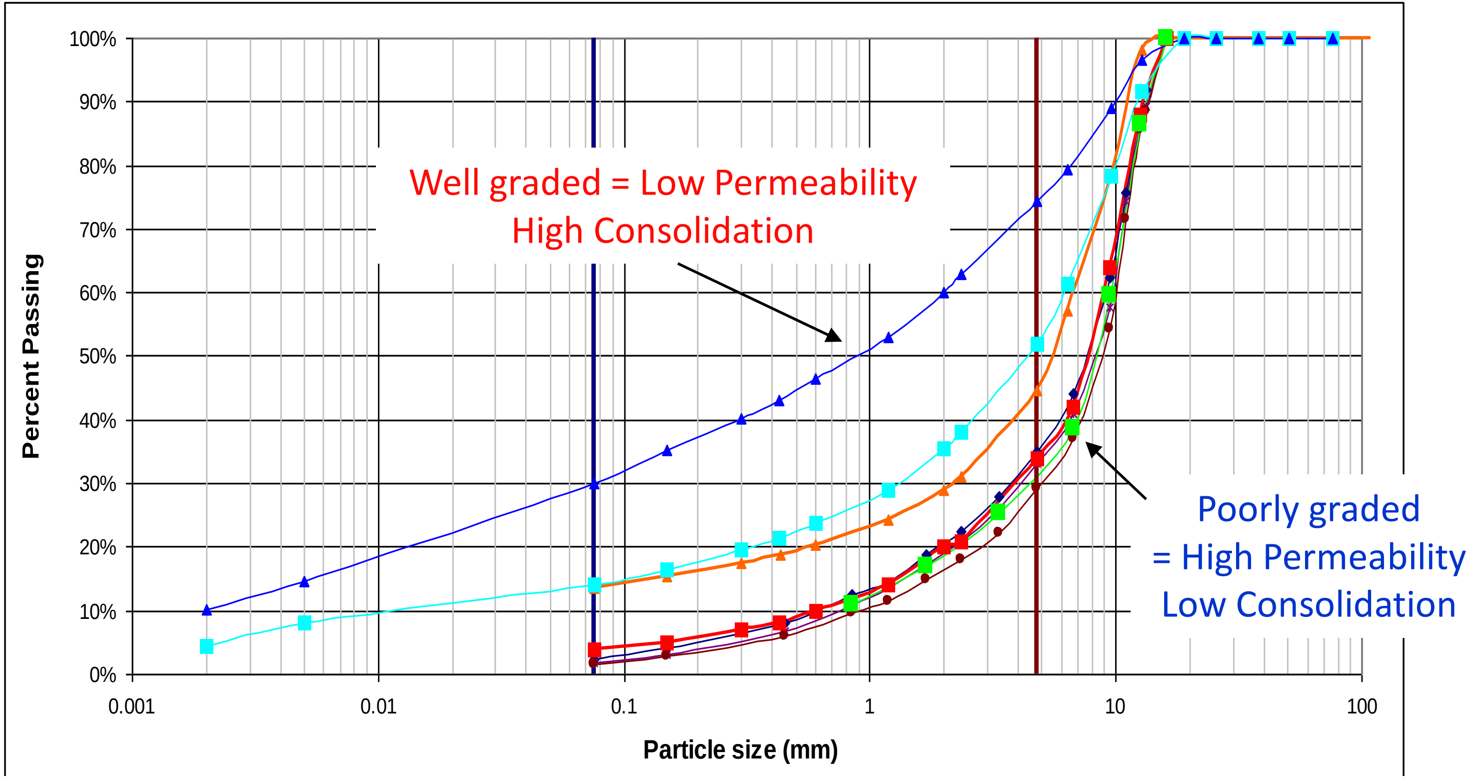


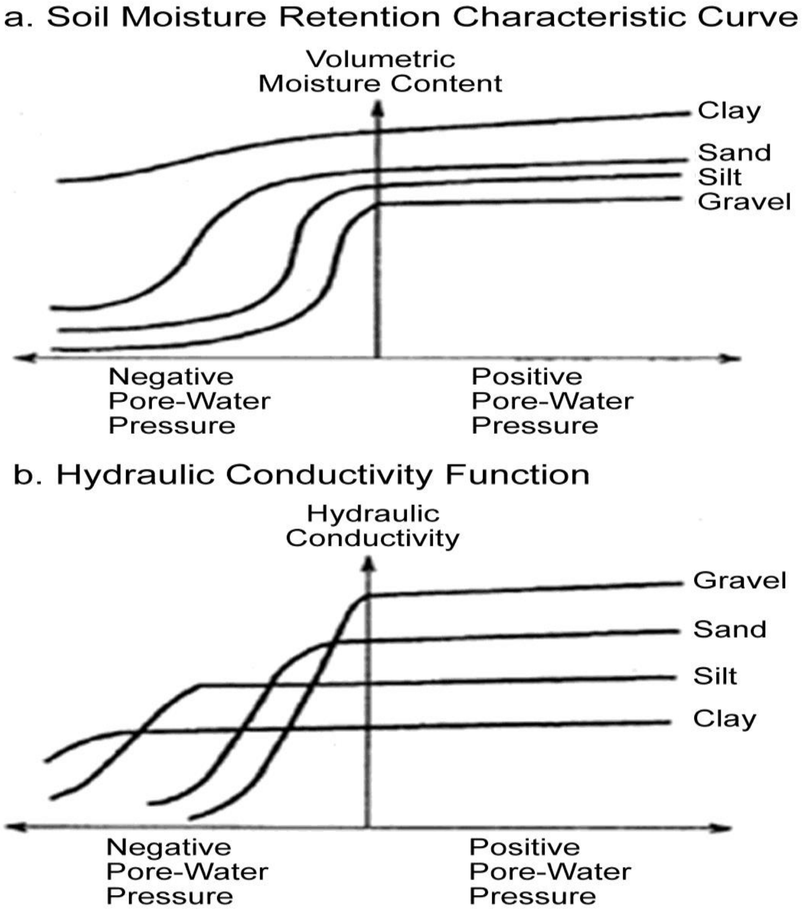


Calibration of Lab and Field PSD



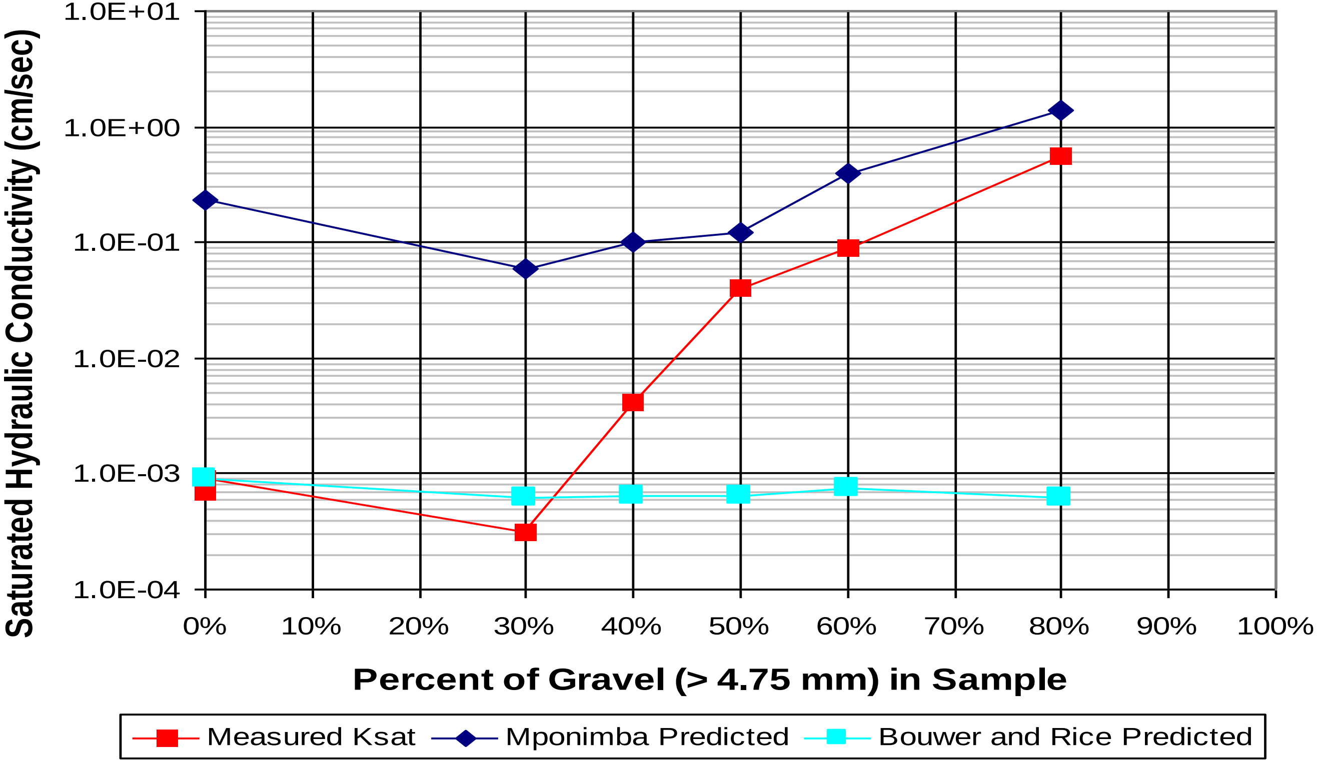
Poorly Graded vs Well Graded



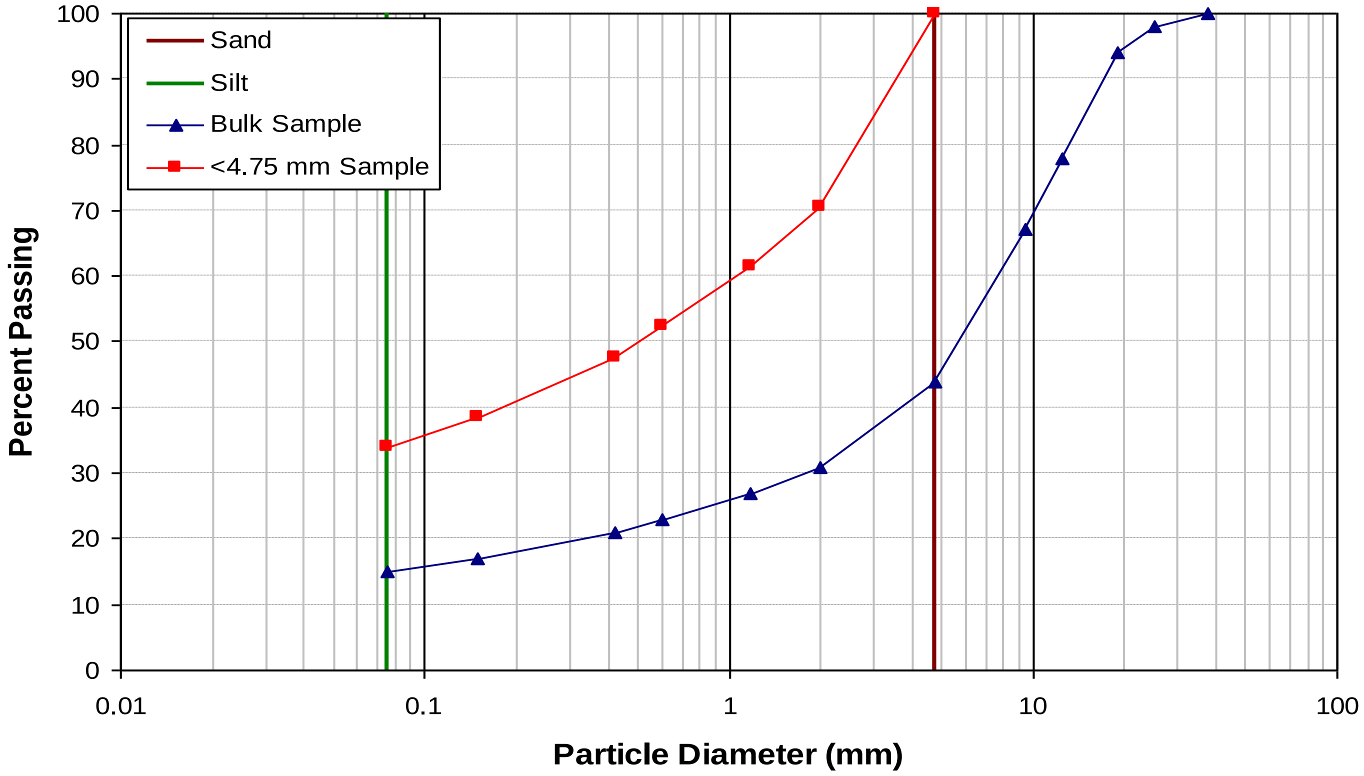


Moisture Retention/ Pressure Potential Relations

Gravel Effects on Saturated Hydraulic Conductivity (from Milczarek et al., 2006)

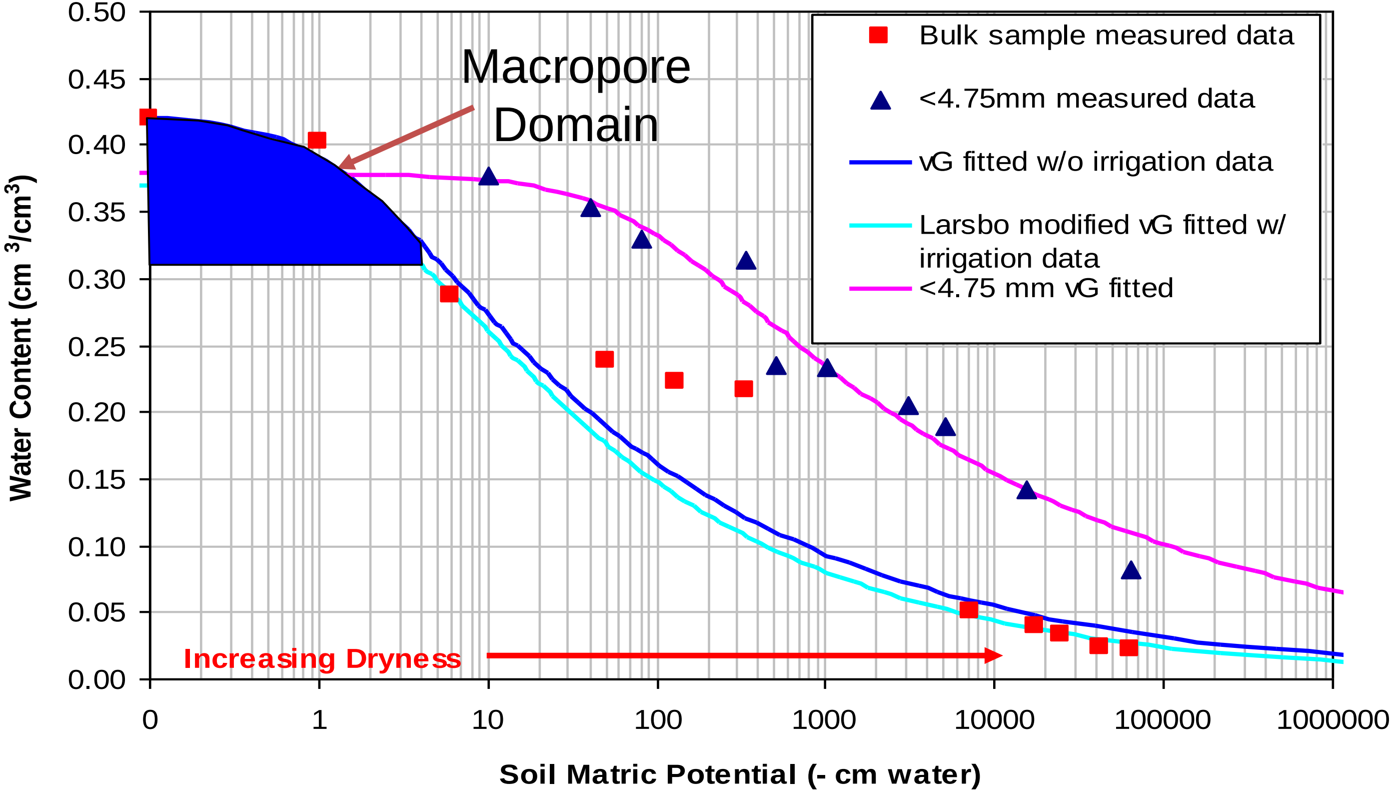


Gravel Effects on Moisture Retention Characteristics (from Keller et al., 2010)

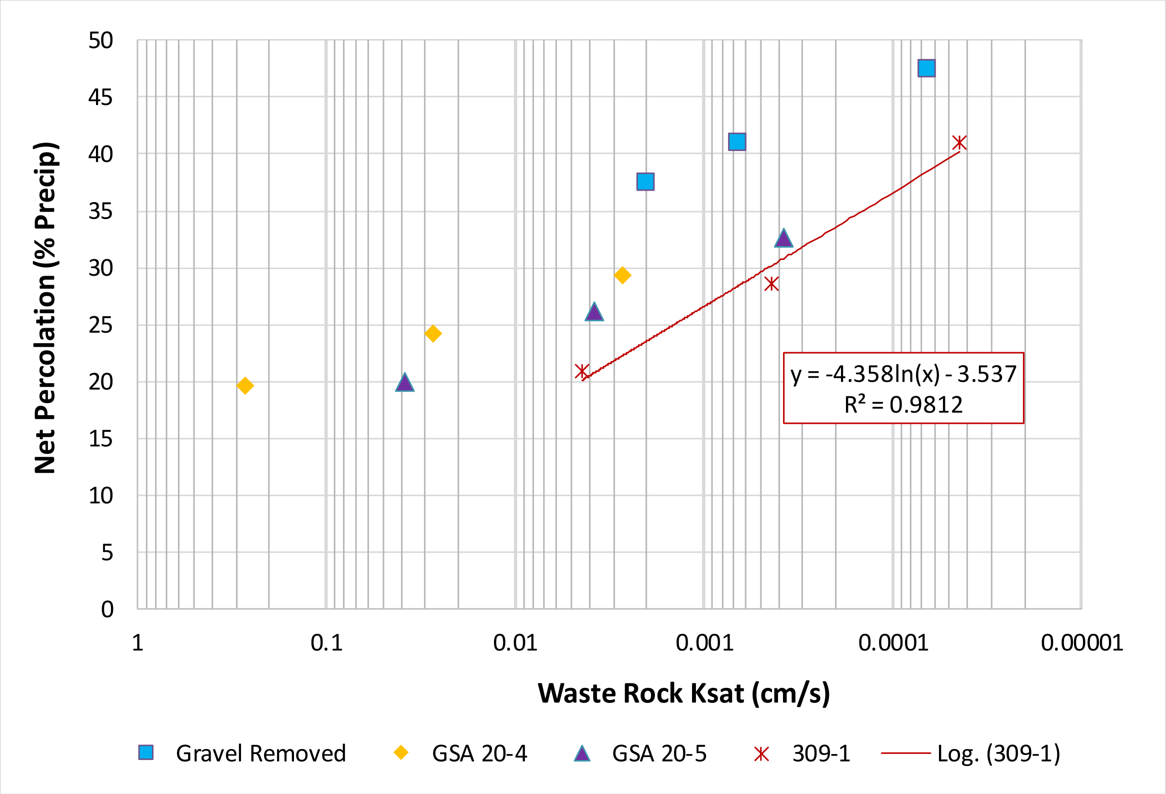


Gravel Effects on MRC

(from Keller et al., 2010)



Gravel Effects on Unsaturated Flow Modeling




Modeling

Some Numerical Tools

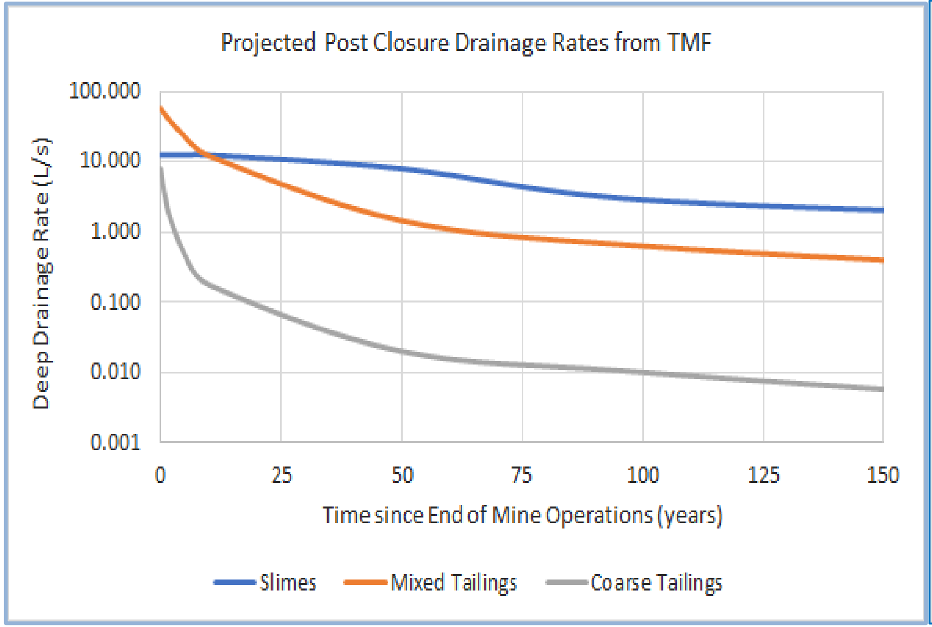
- **Unsaturated/saturated**
  - MODFLOW USG (3D, USGS and others)
  - MODFLOW SURFACT (3D, USGS and others)
  - FEFLOW (3D, Diersch, 2002)
  - HYDRUS-1D/2D/3D (Simunek et al., various 1998-2016)
  - VADOSE/W, SEEP/W (1D/2D/3D, GEO-SLOPE International)
  - SV FLUX (Soil Vision)
  - TOUGH2 (3D, Pruess et al., 1999)
  - STOMP (3D, White and Oostrom 2000)
  - MACRO 5.1/5.2 (1D, Larsbo et al., 2005, 2012)
- **Selection of model depends on complexity of problem**
  - Keep It Simple Stupid (KISS)
  - Each model has its own set of weaknesses
  - Advisable to start in 1D or 2D

Modeling Needs

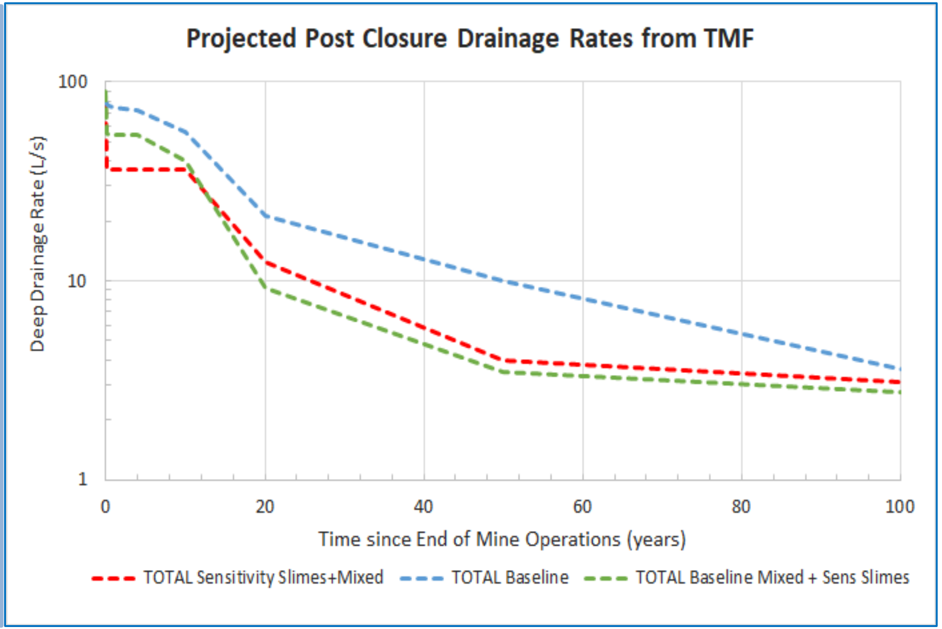
- Hydraulic properties (Ksat and VG parameters)
  - All cover system layers including the waste
- Proper domain and boundary conditions
  - At least 10 m deep for arid/semi-arid climates, free drainage
  - Long-term climate record for P and PET
    - Simulate from site record - CLIMGEN (Stöckle and Nelson, 1999)
    - https://power.larc.nasa.gov/data-access-viewer/
  - Evapotranspiration (EEFlux, https://eeflux-level1.appspot.com/)
  - Rooting depth and Leaf Area Index (i.e. MODIS)
  - Estimated runoff (pre-process depending on code)
- Initial conditions - establish initial steady-state

Post-Closure Tailings Draindown Rates

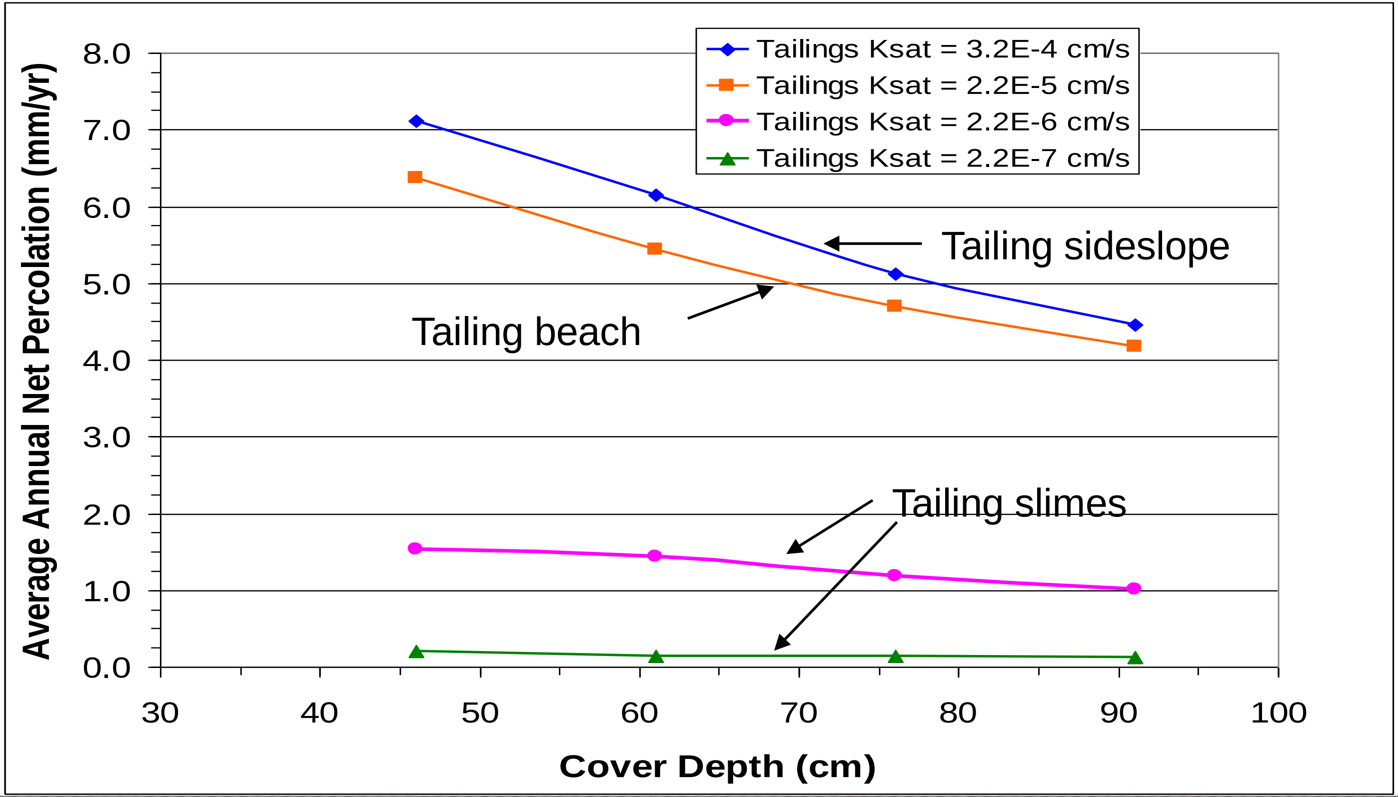
TMF Draindown by Tailings Type



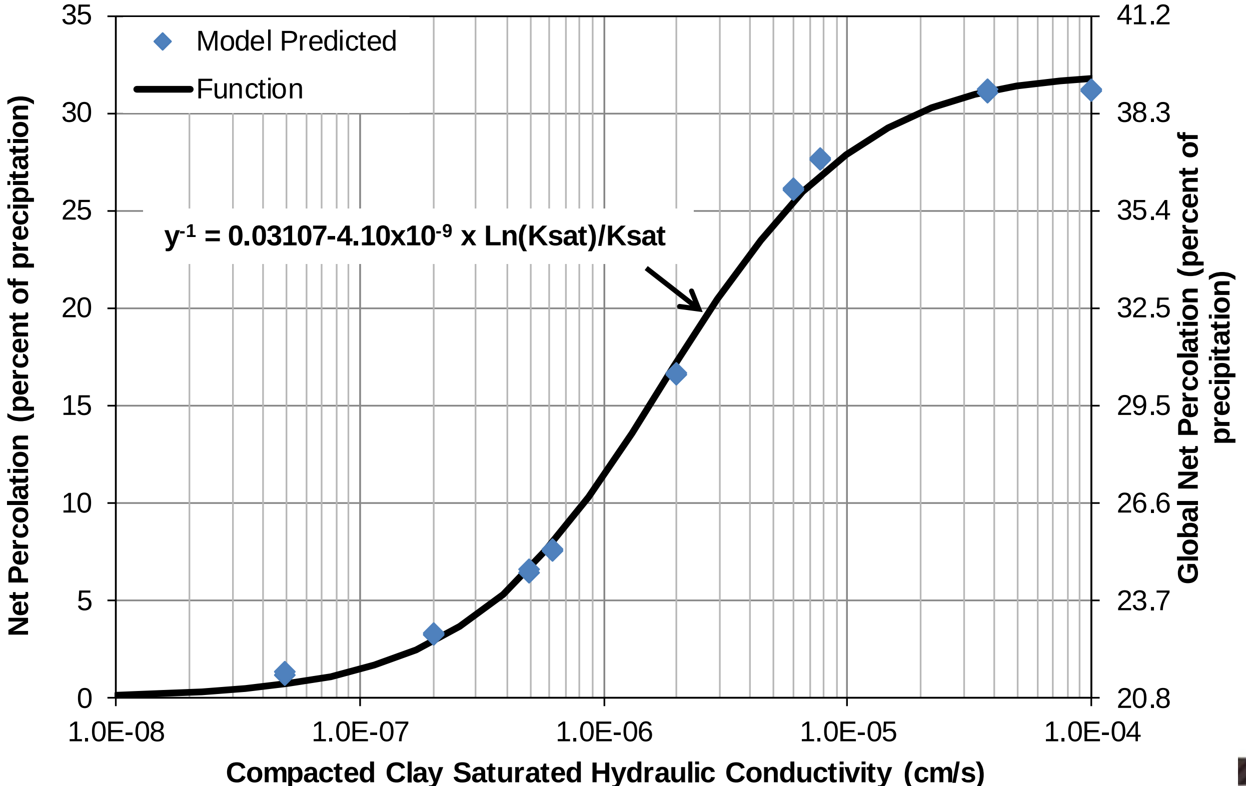
Total Draindown Sensitivity Results



Predicted Effect of Increasing Cover Thickness



Predicted Effect of Low Permeability Barrier with Drainage Layer



Long-term Stability and Erosion Control

Erosion Control

- Besides water treatment, major post-closure cost
- Climatic specific
  - Semi-arid climates with potential for high intensity precipitation (i.e. > 5 cm/hr) need high percent of rock on side-slopes
  - Temperate climates need a mix of rock and vegetation
  - High precipitation climates can rely on vegetation



Natural Side-Slopes (Sonoran Desert)

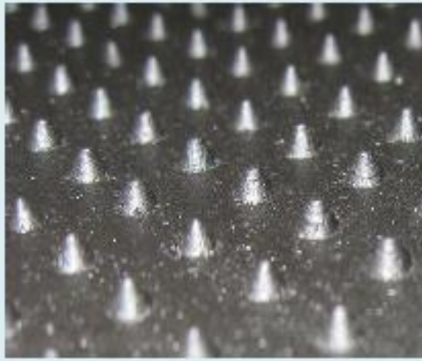
Natural Side-Slopes (Sonoran Desert)

Erosion Test – 10 cm in 2 hours

10 Years after reclamation

Side-Slope Challenges

- Placement of geosynthetics on slopes > 2.5(H):1(V)
- Placement of materials on slopes > 2.0(H):1(V)

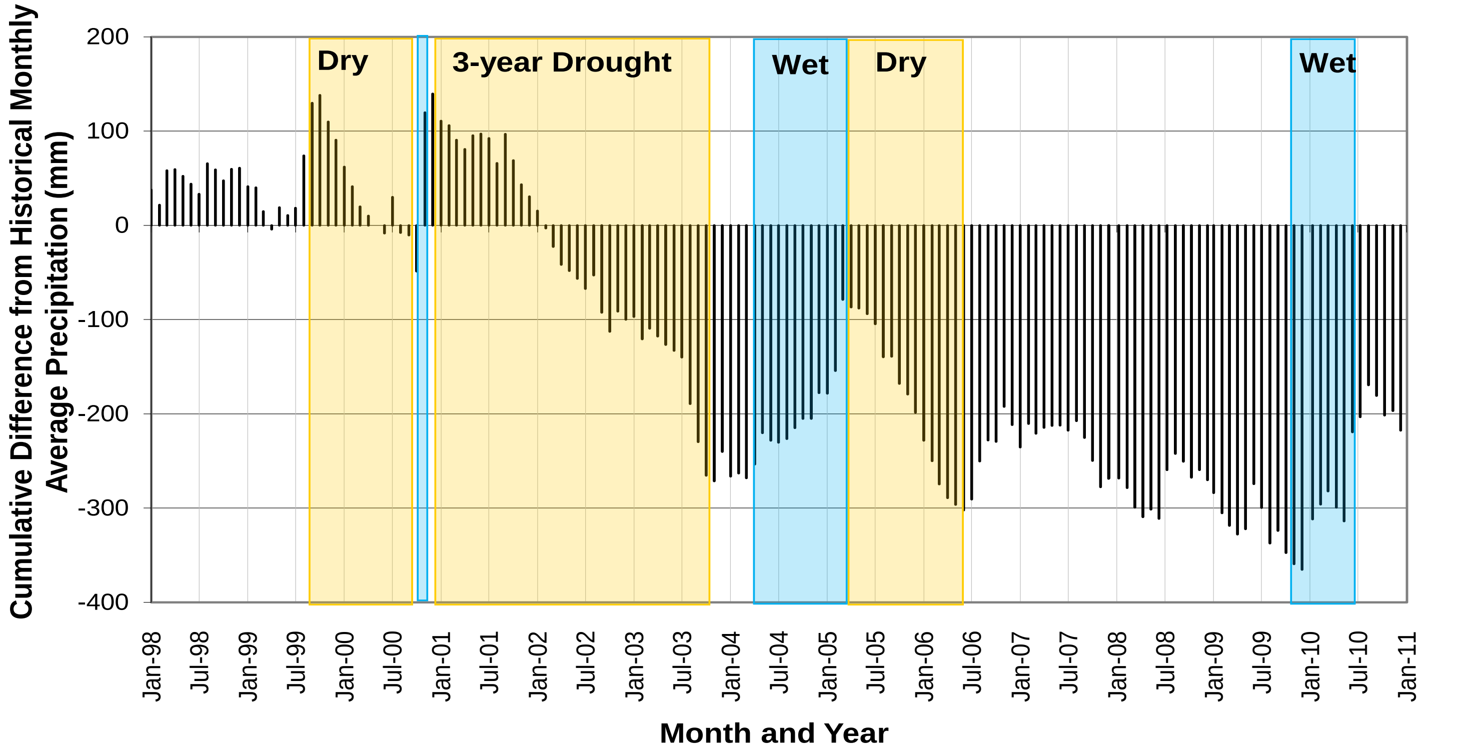


Long-term Tests and Monitoring

Long-term Tests and Monitoring

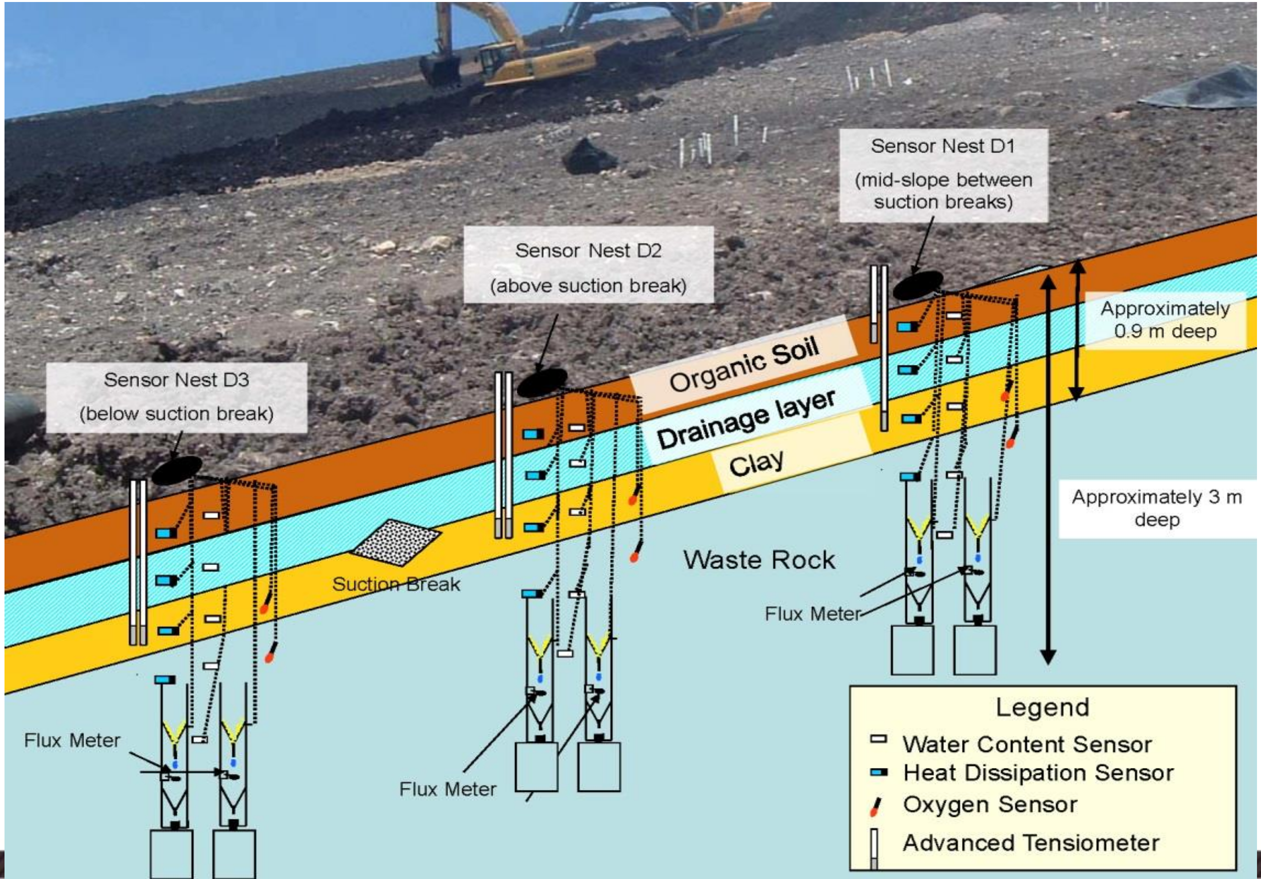
- Reclamation of large-scale disturbance needs large-scale and long-term data
- Recommend 7 to 10 years (minimum)
- Test plots or full-scale reclamation
- Monitoring parameters
  - Climate
  - Vegetation
  - Soil moisture dynamics (at least pressure potential)
  - Erosion/Landscape function
- Deconstruction at end

Cumulative Difference from Historic Precipitation

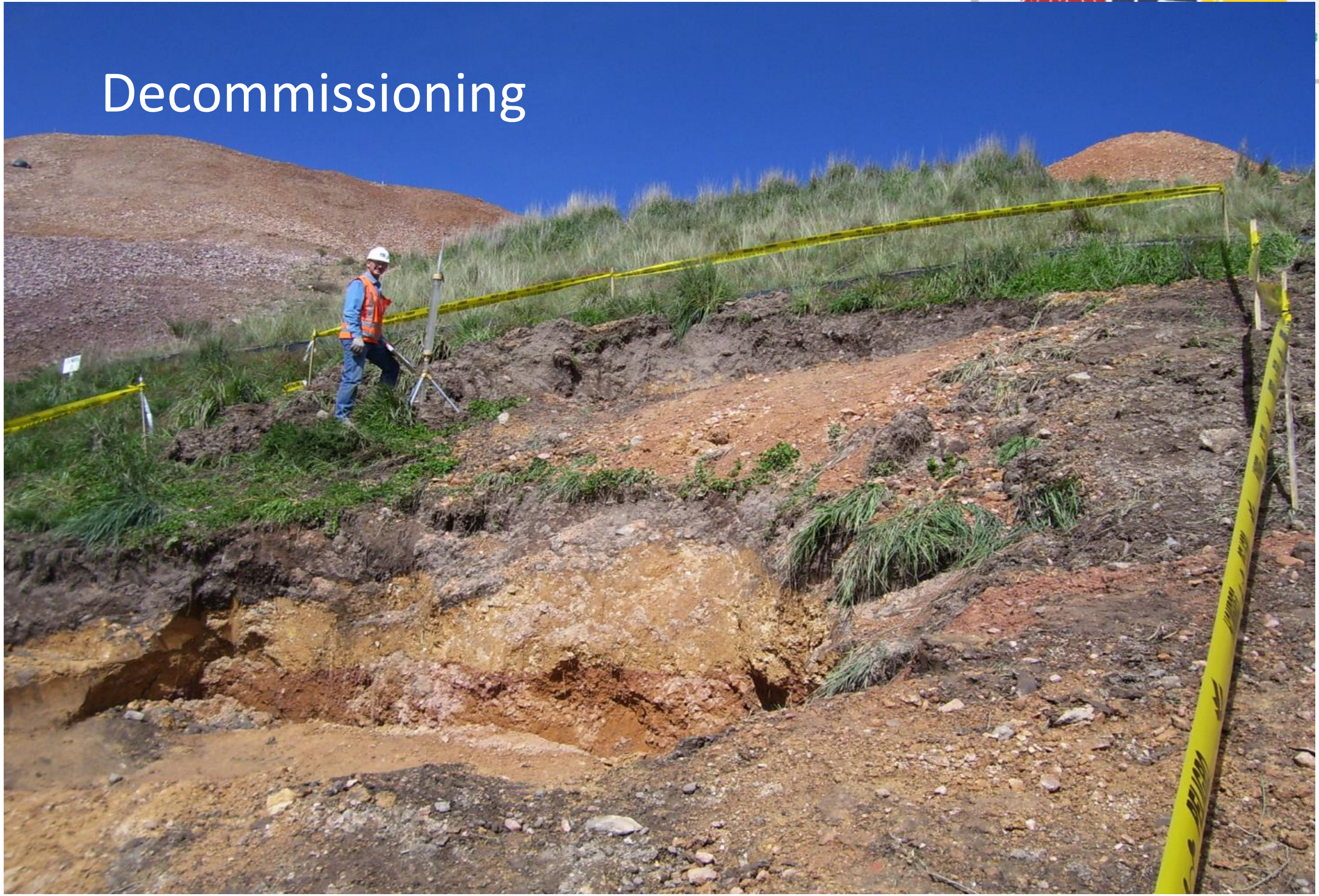


FMI Morenci weather data from Townsite weather station; historic monthly average from Clifton AZ, 1893-2010

Sensor Nest Monitoring



Decommissioning



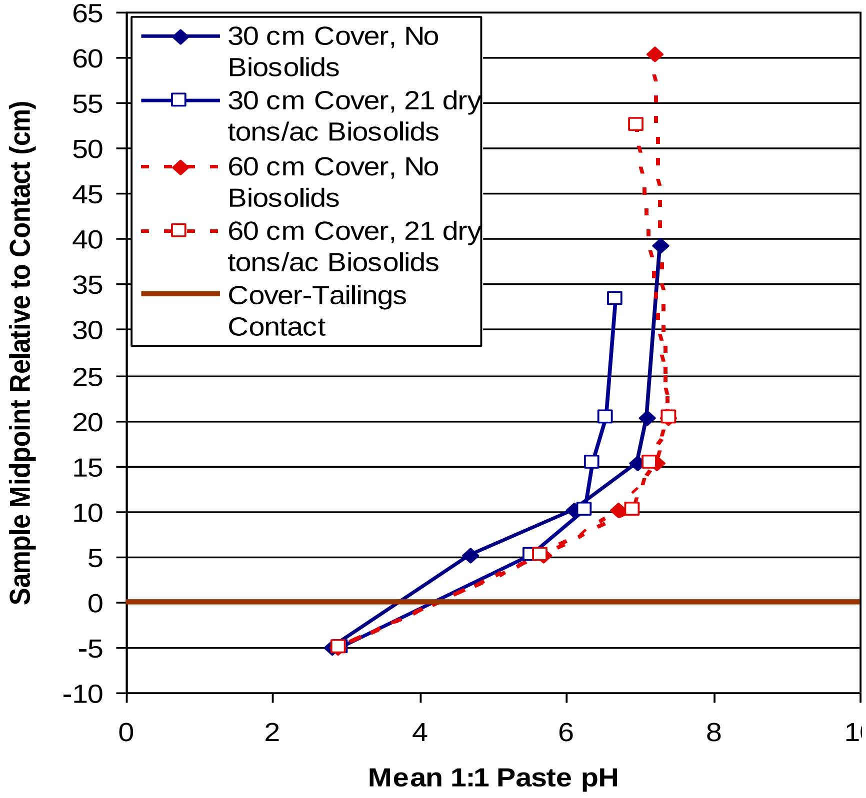
Rooting Assessment

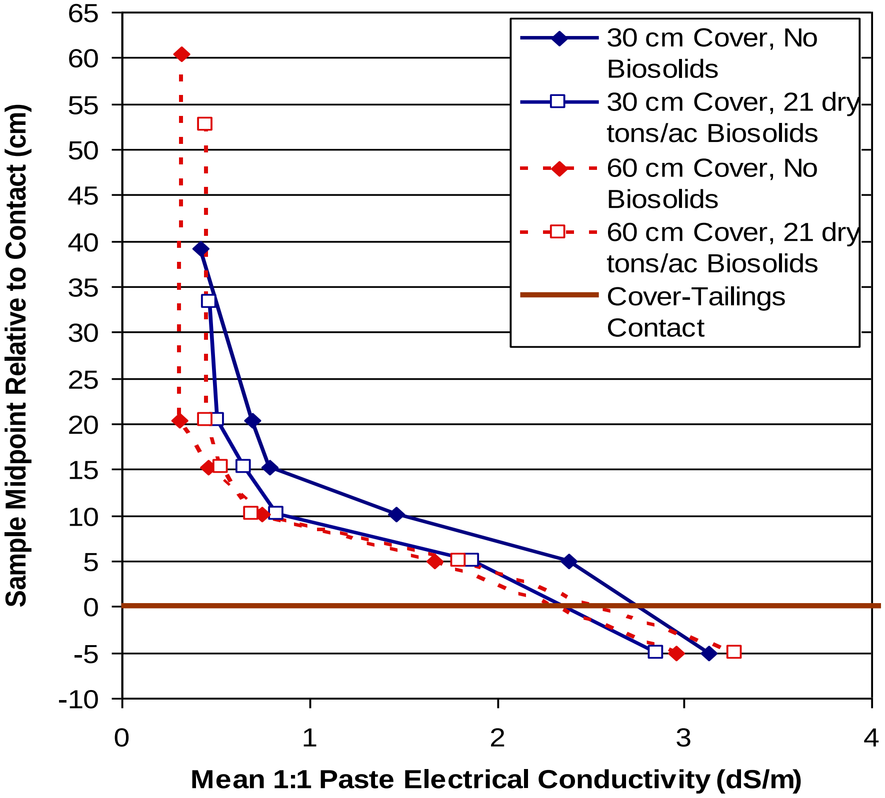

Tailing/Cover Contact


Tailing/Cover Contact

pH and EC Profiles

(from Milczarek et al., 2011)





Closing Thoughts

- Need careful characterization
  - Representative samples
  - Appropriate methods – lab and field
- Use site-specific knowledge
  - Vegetation, natural side-slope conditions, recharge rates
- Use of models
  - All models are bad, some are useful – compare alternatives
- Need to monitor for long-term
- Lots of work needs to be done on better understanding of covers in tropical environments, side-slope reclamation

Muito Obrigado!