Sistema de Cobertura de Pilhas e Barragens para Minimizar a Contaminação de Água

Closure Cover Systems for Tailings and Mine Waste To Minimize Acid Rock Drainage

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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
- Long-term surface water and erosion control

Cover System Design

- Control of net infiltration (keep water out!)
- Revegetation
- Control of surface water runoff
- Long-term erosion control


Tailings, AZ, USA


Heap Leach, NV, USA


Waste Rock, Peru


Tailings, Papua New Guinea

Controlling Factors

- Climate
- Mine waste characteristics (waste rock, heap leach, tailings)
- Cover material properties
  - Net infiltration rates (percolation below the evapotranspirative zone)
  - Erosion rates
  - Revegetation potential
- Design for site conditions

CLIMATE EFFECTS ON COVER SYSTEM PERFORMANCE

Evapotranspiration (ET) Cover System: Seasonal storage and release of soil water

Dry Season

Soil is initially dry

Evapotranspiration (ET) Cover System: Seasonal storage and release of soil water

Wet Season

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

Evapotranspiration (ET) Cover System: Seasonal storage and release of soil water

Late Wet Season

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

Evapotranspiration (ET) Cover System: Seasonal storage and release of soil water

Early Dry Season

Evaporation increases and vegetation transpires stored soil water

Evapotranspiration (ET) Cover System: Seasonal storage and release of soil water

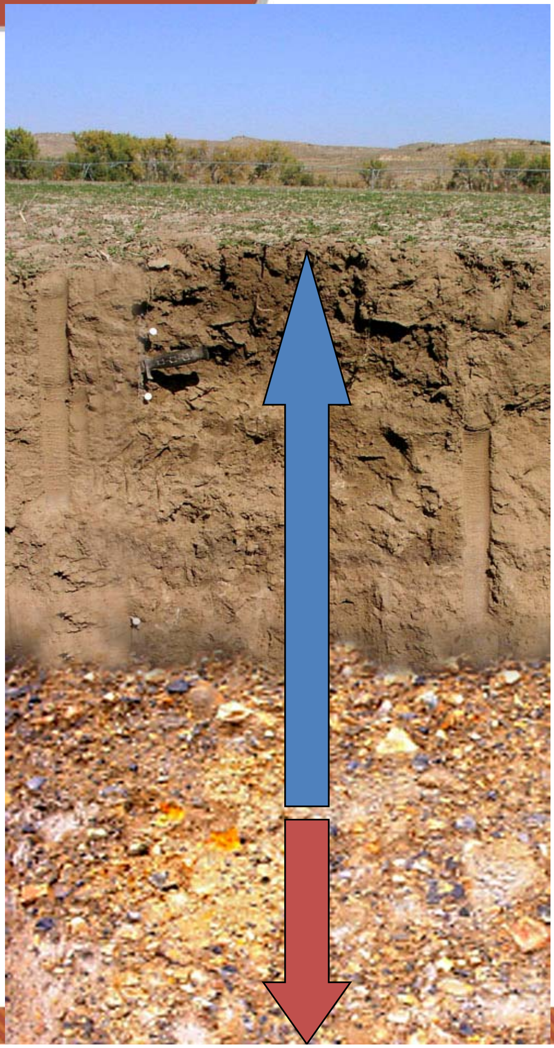
Late Summer or Dry Season

Continued transpiration by vegetation removes stored soil water from root zone

ET 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



ET Cover System Considerations

Gravelly soils help reduce erosion (but low AWC)

Vegetation key to controlling drainage

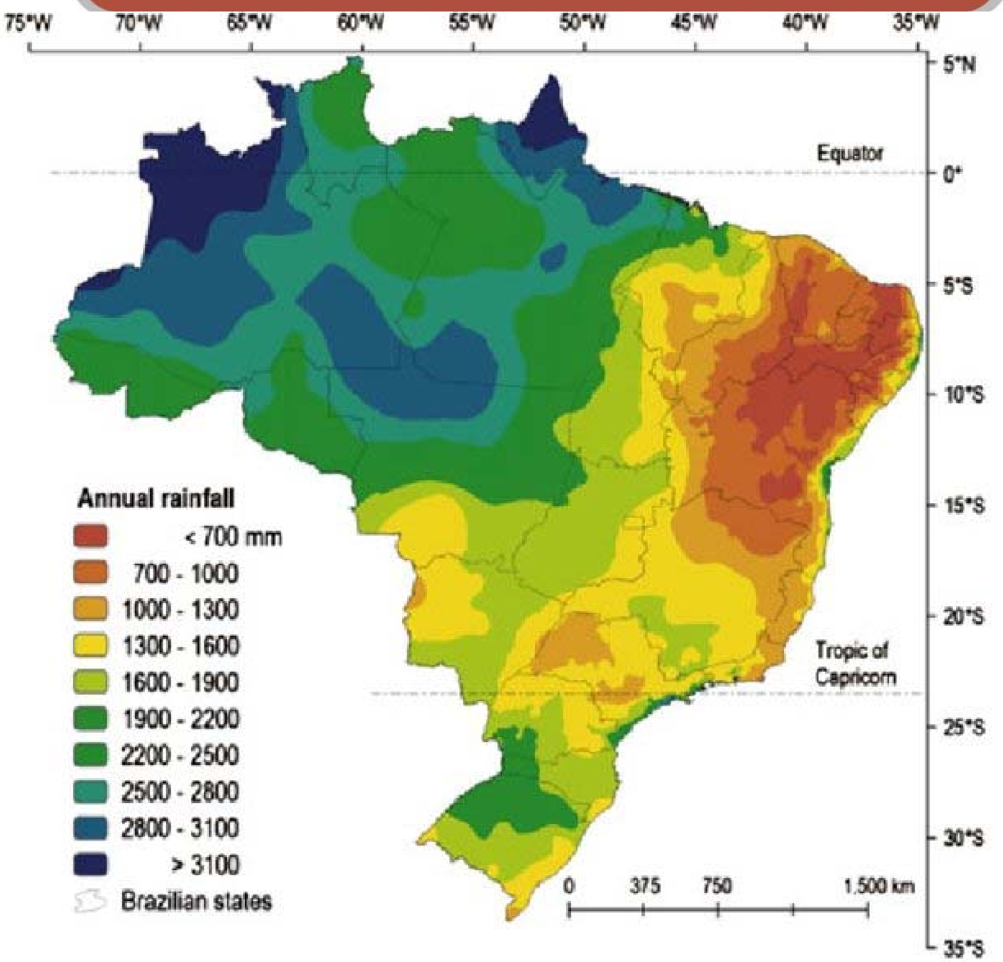
Semi-arid species rooting can go deep (several meters)

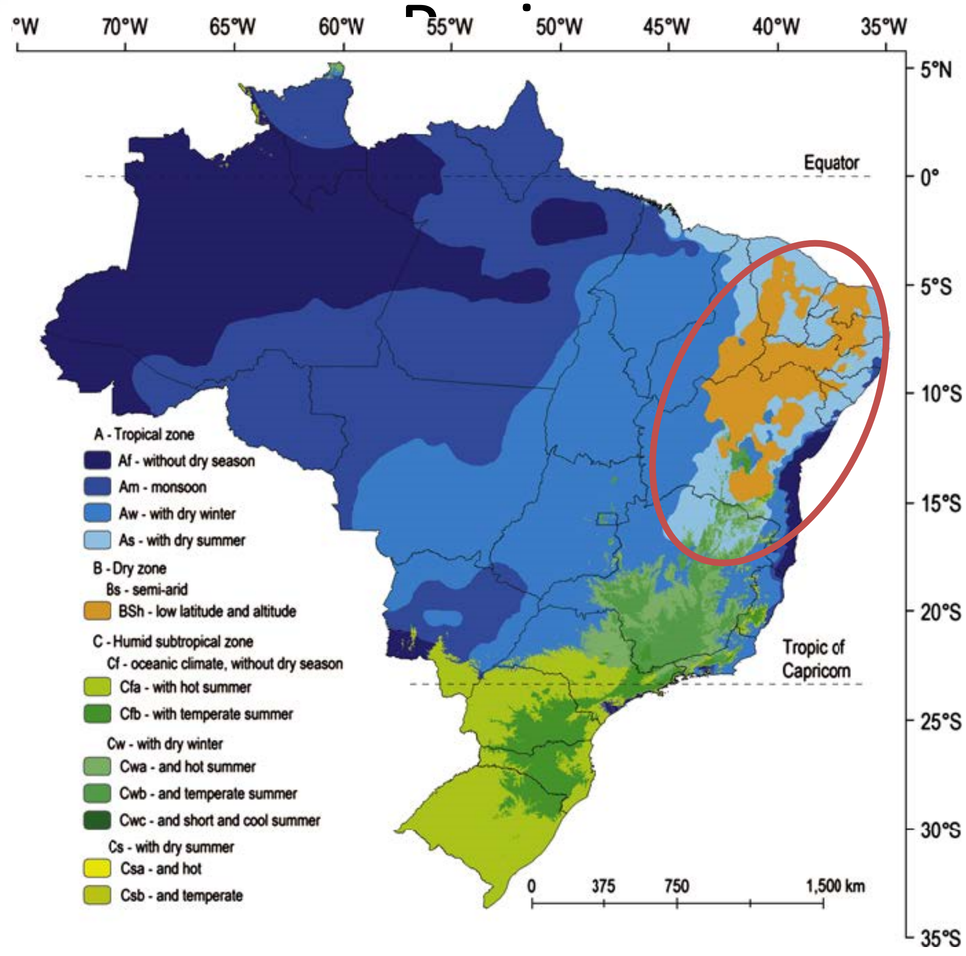
Cover Systems - Measured Net Infiltration Rates

- Semi-arid southwestern USA (200 mm to 500 mm annual precipitation (AP))
  - Uncovered waste rock: 15% to 40% of AP
  - ET Cover over waste rock: 1% to 5% of AP
  - ET Cover over tailings < 1% to 3% of AP
- High elevation Rocky Mountains USA (250 cm to 600 cm snow)
  - Uncovered waste rock: > 50% of AP
  - Covered waste rock and tailings: Depends on cover system, up to 40% of AP
- High elevation Andes (i.e. Perú < 3500 m, 1000 to 1500 mm AP)
  - Uncovered waste rock/heap leach: > 50% AP
  - Covered waste rock: Depends on cover system: up to 40% of AP
- Brazil (600 mm to > 3100 mm AP)**???**

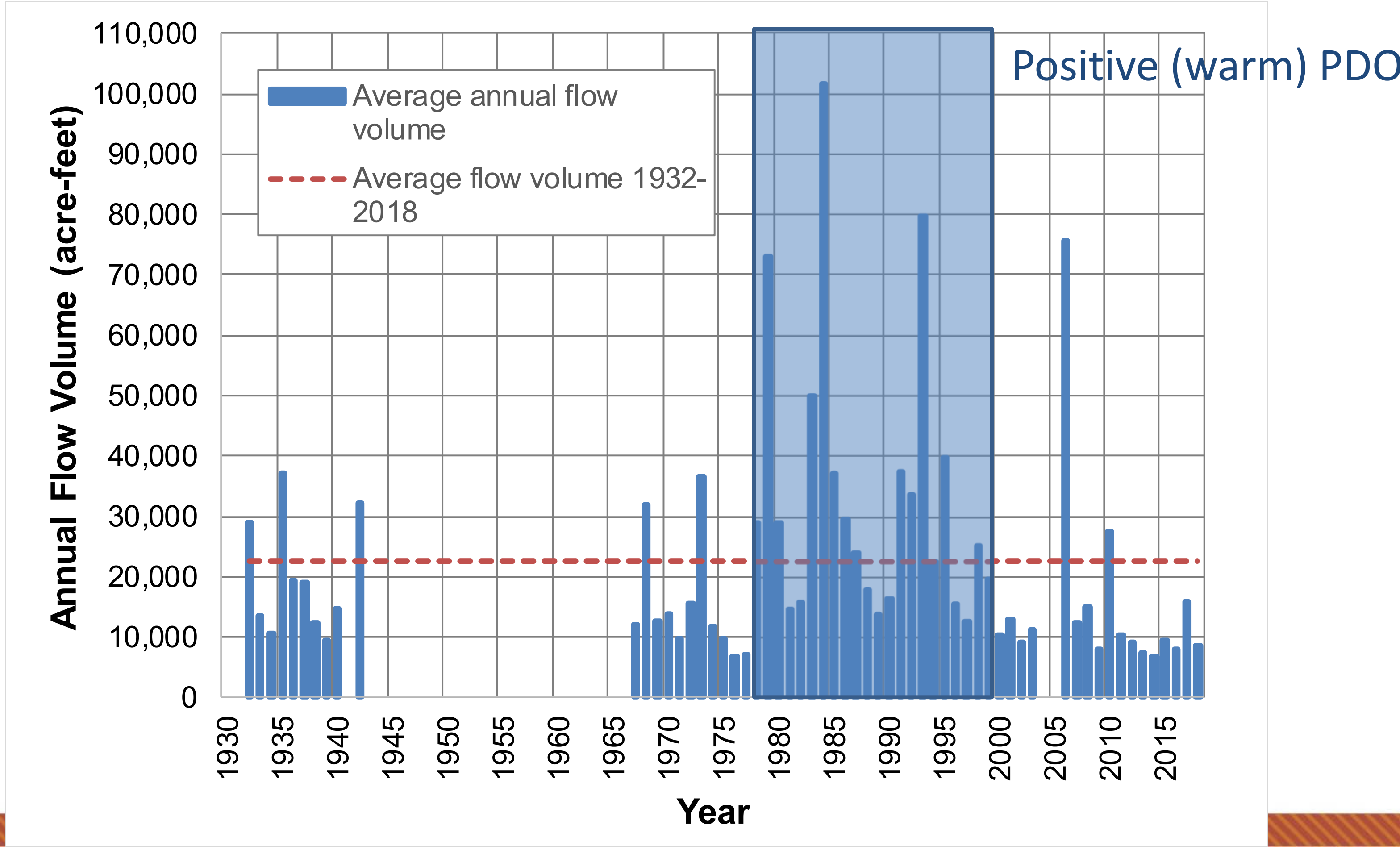
1º CONGRESSO LATINO-AMERICANO DE DRENAGEM ÁCIDA DE MINA
1ST LATIN AMERICAN ACID MINE DRAINAGE CONGRESS
1ER CONGRESO LATINOAMERICANO DE DRENAJE ÁCIDO DE MINA

Precipitation and Climatic



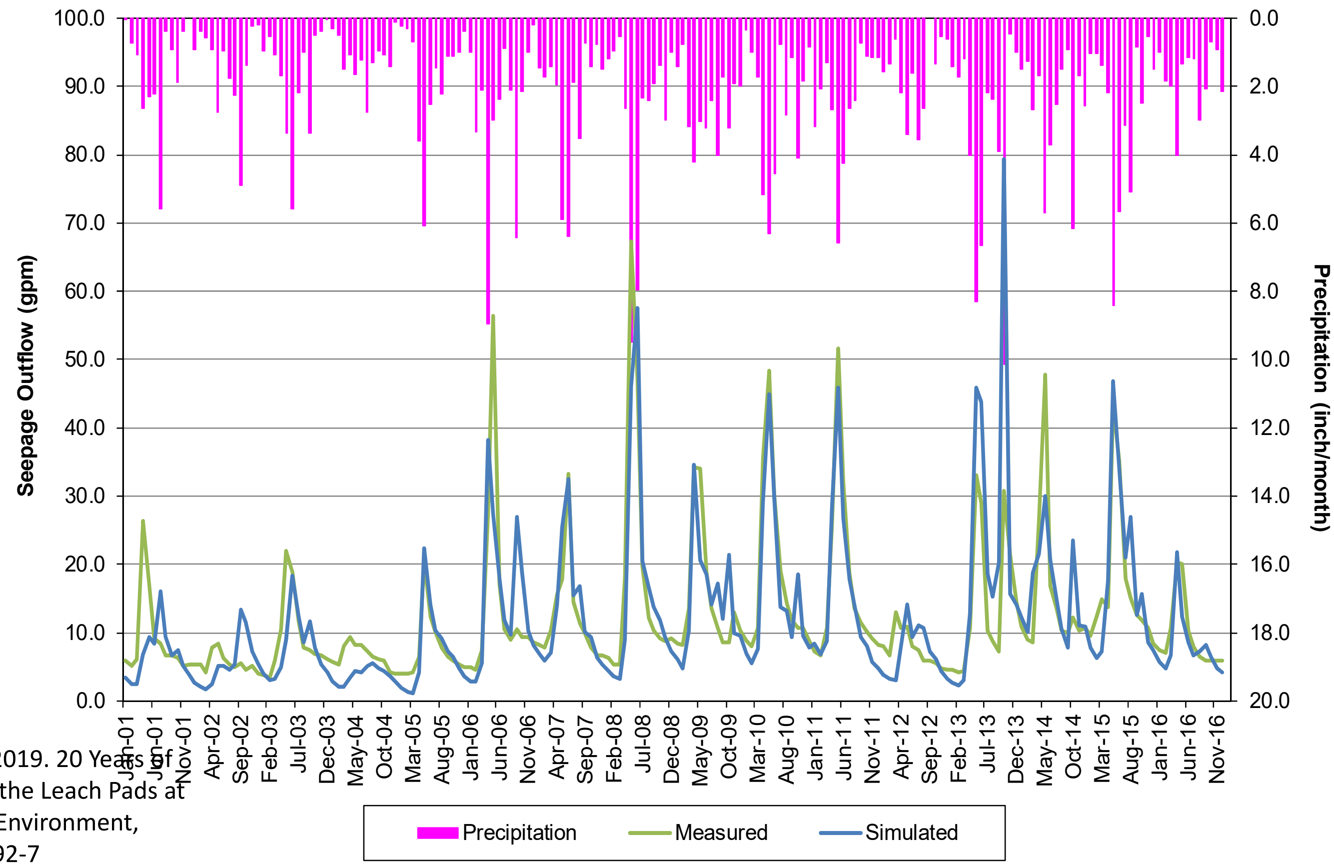


Climatic Cycles (PDO/AMO and ENSO)



ET Cover Systems are Dynamic

- Richmond Hill, South Dakota
  - Low permeability barrier layer with ET cover
- Average Net Infiltration (% of AP)
  - 1998–2000 = 22%
  - 2001–2005 = 32%
  - 2006–2016 = 34%



Zhan G., D. Lattin, J. Keller, M. Milczarek, 2019. 20 Years of Evapotranspiration Cover Performance of the Leach Pads at Richmond Hill Mine. Mine Water and the Environment, https://doi.org/10.1007/s10230-019-00592-7

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
  - 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

Waste Geochemical Characteristics

- Sulfide vs non-sulfide mineral deposits
- Potentially Acid Generating (PAG) minerals:
  - High acid generation potential (and acidity)
  - High plant available metals (i.e. aluminum)
  - Precipitation of secondary minerals
  - Biologically mediated acid generation (pH < 5)
  - Reactions primarily in < 5 mm fraction
- Acid generation potential (AGP) vs Acid neutralization potential (ANP)
  - In general to maintain circumneutral conditions
    - NNP > 20 tons $CaCO_3$/1000 tons
    - ANP/AGP > 1.2

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

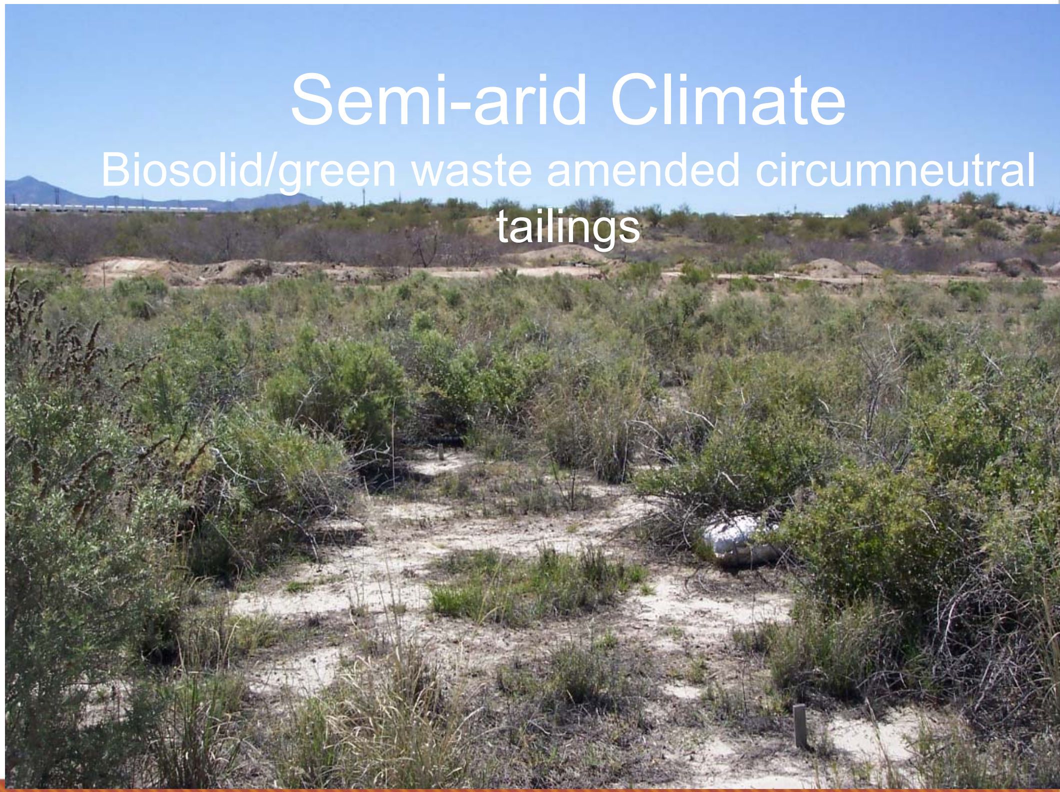
Direct Revegetation (non-PAG waste)

<u>Considerations</u>

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

<u>*IN REALITY – SUCCESSFUL WITH:*</u>

- Non-PAG waste
- High levels of organic amendments
- Relatively humid climates



Ok Tedi Sand Tailings Stockpile Rehabilitation

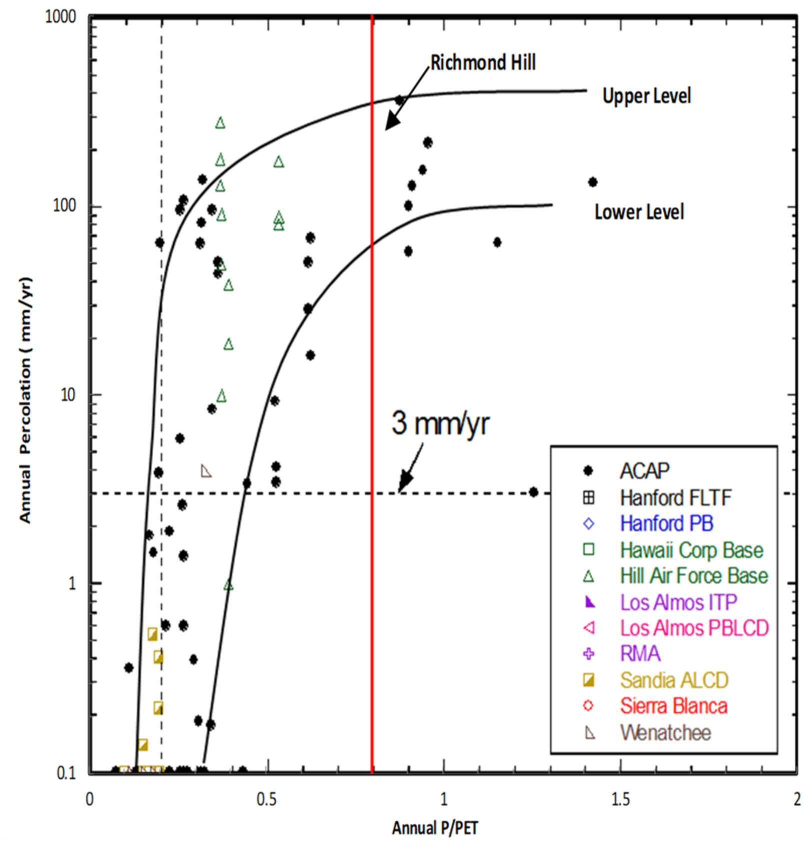
- Challenges:
  - Not like natural system
    - Higher pH
    - Higher salinity
    - Much greater depth to groundwater
    - Coarser soil texture
  - Use only native species
  - Optimization of revegetation methods
    - Short vs long-term vegetation success function of planting/seeding density, species
  - Monitoring of success

COVER SYSTEM DESIGN

Net Infiltration through ET Covers: P/PET

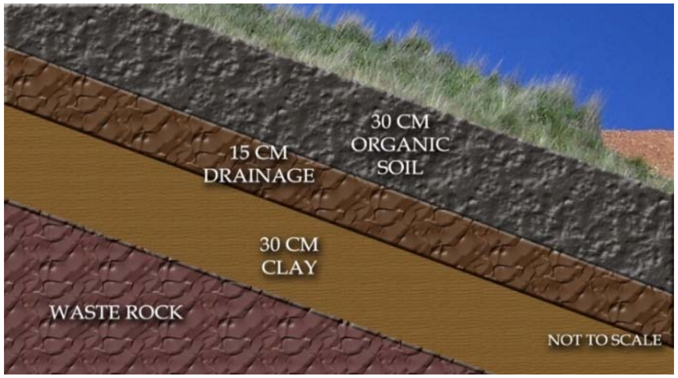
- Where Precipitation (P)/Potential Evapotranspiration (PET) < 0.4
  - Design for ET cover system
- Where P/PET > 0.4 < 0.8
  - Consider barrier layers on flat areas, ET on side-slopes for PAG material
  - Possible direct revegetation for non-PAG material
- Where P/PET > 0.8
  - Design for barrier layer design for PAG material
  - Direct revegetation for non-PAG material
- In general, thickness/complexity of cover system:

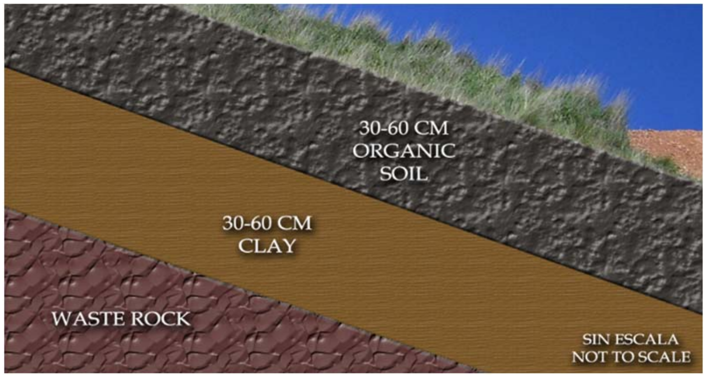
Tailings → Waste Rock/Heap Leach



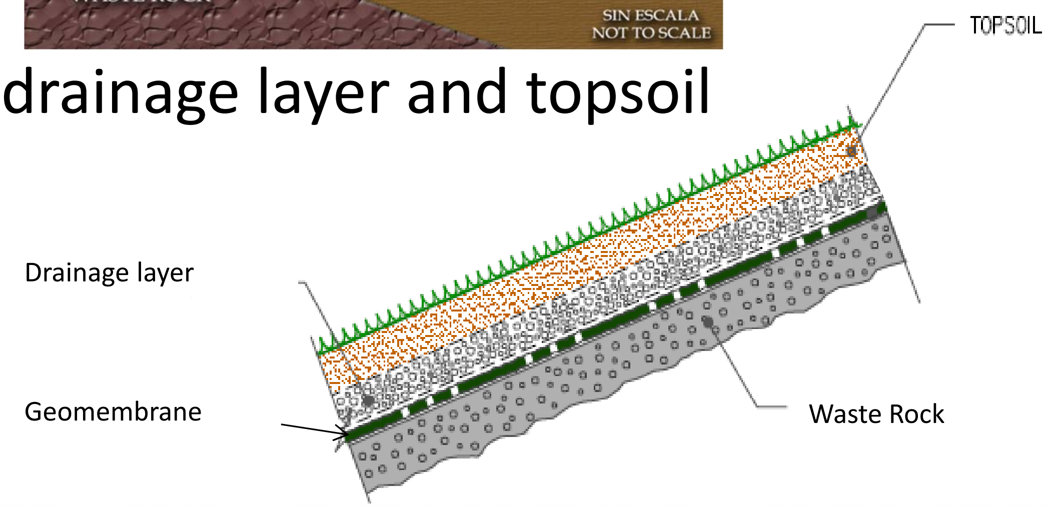
Barrier Cover System Types

- Multi-layer barrier/ET Cover Systems



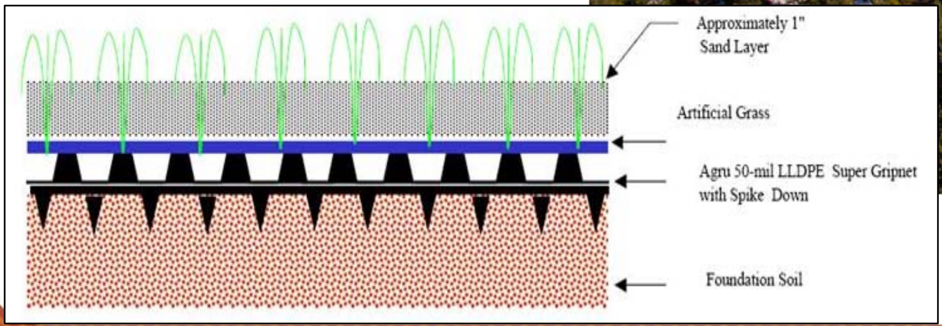


- Geosynthetic liner with drainage layer and topsoil (different types)



Barrier Cover System Types

ClosureTurf/
HydroTurf



Cover System Design Process

- Identify and characterize waste and potential borrow materials
  - Physical and hydraulic properties
  - Geochemical characteristics
  - Ability to support vegetation
- Develop alternative cover systems for evaluation
- Develop estimates of Cover System performance (net infiltration and erosion control)
- Select optimum designs and conduct Trade-off Analysis
  - CAPEX/OPEX between cover system design and long-term maintenance and water treatment costs

Waste and Cover Material Evaluation

- Review mine dumping records, available soil and surface geology maps
  - Relate soil texture to permeability
    - Available/literature field values, Pedo-transfer functions (i.e Kozeny-Carmen, Soil Vision)
- Material investigations (test pitting and drilling)
  - Geologic logging and sample collection
  - Physical (particle size distribution, geotechnical)
  - Hydraulic (saturated hydraulic conductivity (Ksat), Moisture retention characteristics (MRC)
  - Geochemical (ABA, soil fertility)
  - Rooting and vegetation cover surveys in native soils
- Modeling to evaluate cover system efficiency and erosion
  - Unsaturated/saturated flow over predicted long-term climate record (i.e. 100 years)
- Selection of optimum cover material

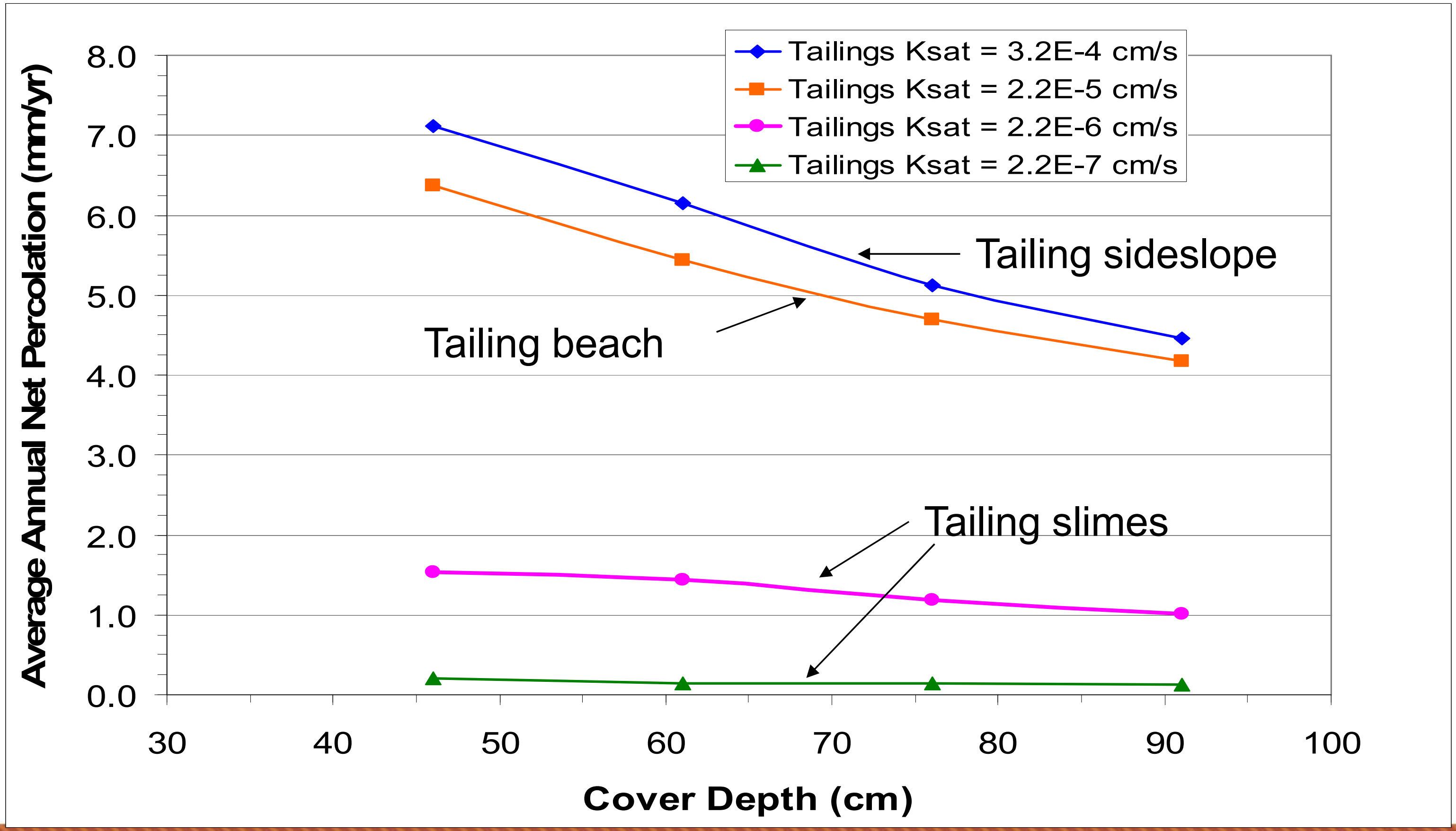
Modeling Considerations

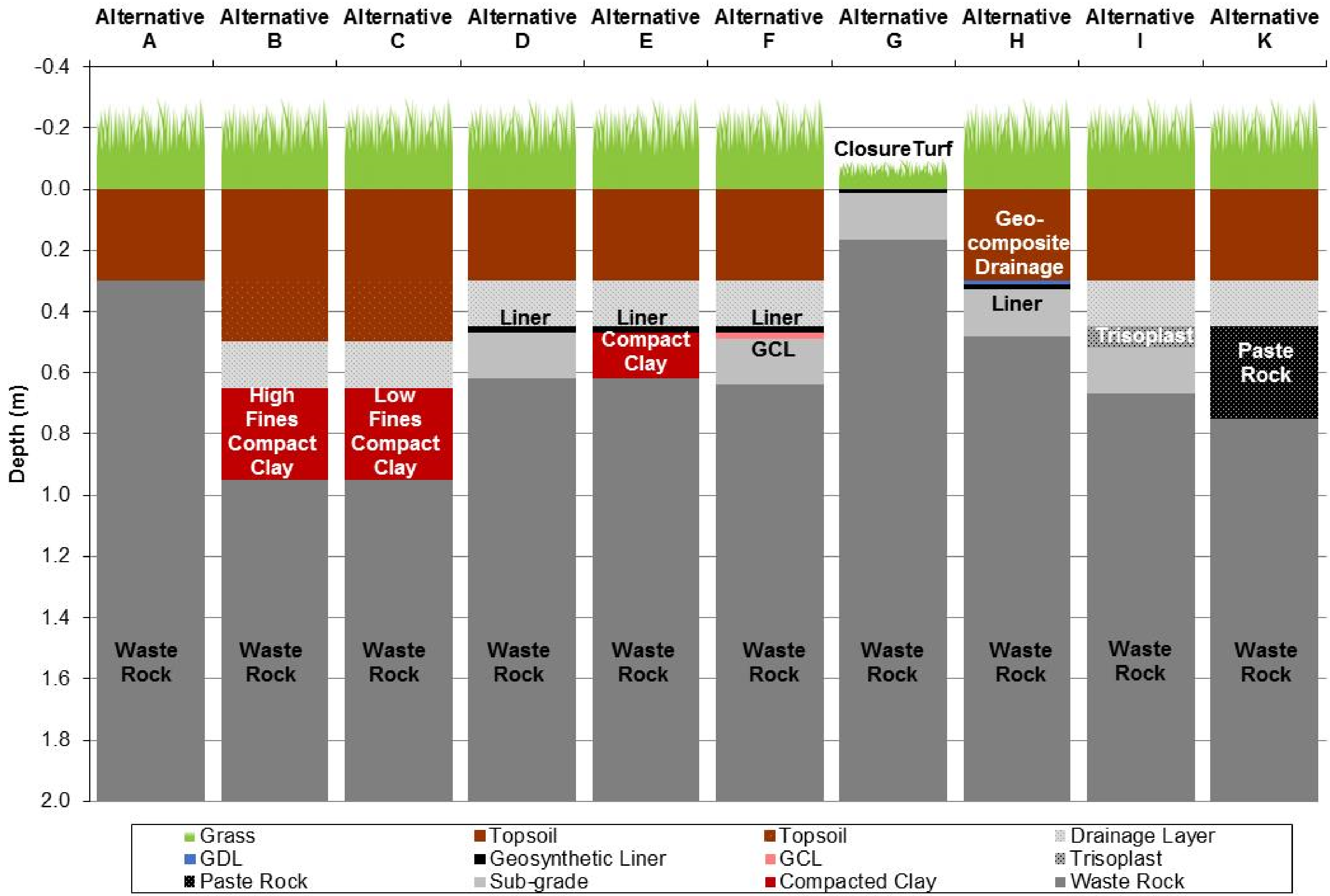
- Tailings Impoundments
  - Fluvial depositional process, highly layered systems
  - Lower permeability layers generally dominate flow
  - Consolidation and deformation over time is not well modeled
- Waste Rock
  - High percentage of gravel particles can create macropores
  - Preferential flow in macropores may dominate
  - Most unsaturated flow models poorly simulate preferential flow
- Heap Leach
  - Similar to waste rock but near-saturated (preferential flow is worse)
  - Greater consolidation and variable permeability
- Keep It Simple Stupid (KISS)
- Advisable to start in 1D or 2D

Unsaturated/Saturated Models

- 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)
- TOUGH2 (3D, Pruess et al., 1999)
- STOMP (3D, White and Oostrom 2000)
- MACRO 5.1/5.2 (1D, Larsbo et al., 2005, 2012)

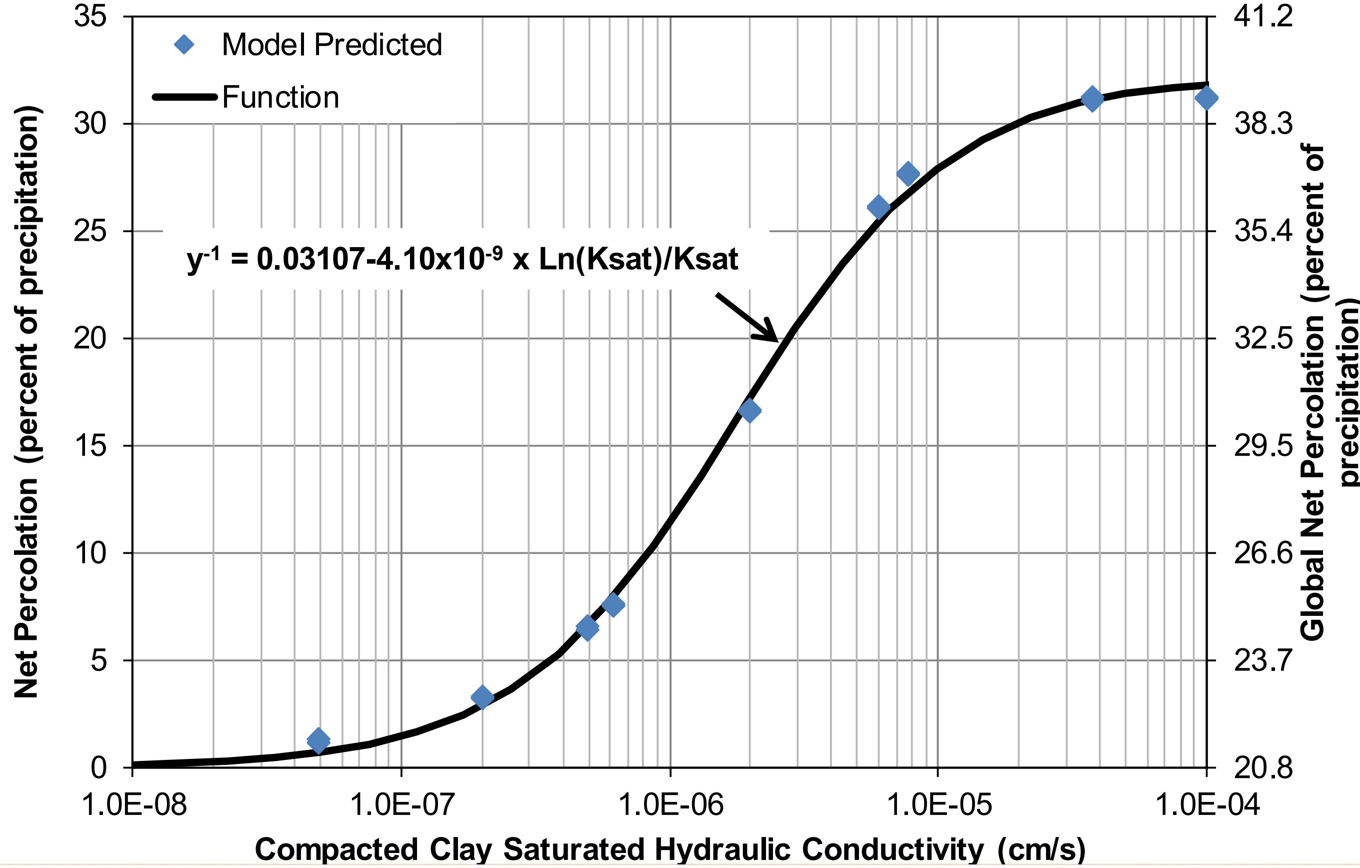
Predicted Effect of Increasing Cover Thickness: Semi-Arid Climate





Alternative A
Alternative B
Alternative C
Alternative D
Alternative E
Alternative F
Alternative G
Alternative H
Alternative I
Alternative K
Depth (m)
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Closure Turf
Geo-composite Drainage
Liner
Liner
Liner
Liner
Compact Clay
GCL
Trisoplast
Paste Rock
High Fines Compact Clay
Low Fines Compact Clay
Waste Rock
Grass
Topsoil
Topsoil
Drainage Layer
GDL
Geosynthetic Liner
GCL
Trisoplast
Paste Rock
Sub-grade
Compacted Clay
Waste Rock

Predicted Effect of Low Permeability Layer with Drainage Layer



EROSION CONTROL

Erosion and Surface Water 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


Channel erosion – AA Pad Goldstrike Mine

Surface Water/Erosion Control

New gully

Intermediate gullies

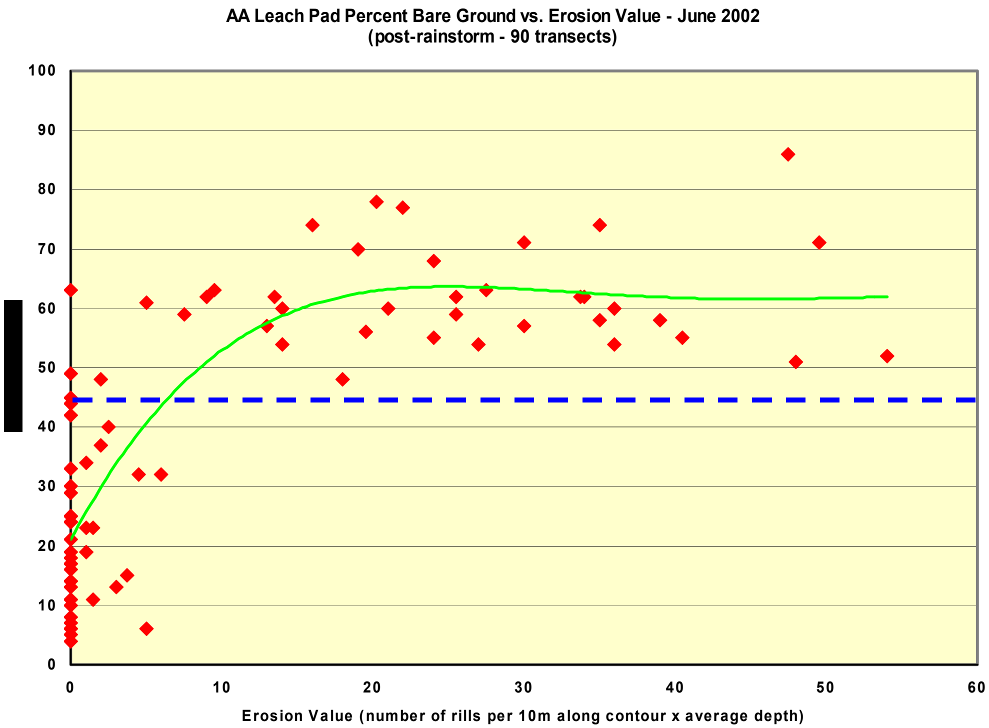
Mature gullies

Maintain Integrity of Cover

- Gully formation is progressive from downslope to upslope
- Once gully formation starts, damage to the cover can occur rapidly, leading to rupture of the cover and exposure of the underlying waste.
- Gully formation dramatically increases soil loss rates.

Gullying can be caused by combination of inadequate cover material/vegetation, slope angle, long slope length, overtopping of surface water conveyances

Erosion Resistance



Slope Gradient

- ➢ As the slope gradient increases, gravitational and inertial (flow) forces increase

Surface Properties

- ➢ As rock size increases, erosion resistance increases
  - Widely graded rock is generally less resistant to erosive stresses than narrowly graded rock
  - Angular to sub-angular rock (high friction angle) generally more stable than rounded rock
- Soil surfaces will self-armor if sufficient rock present

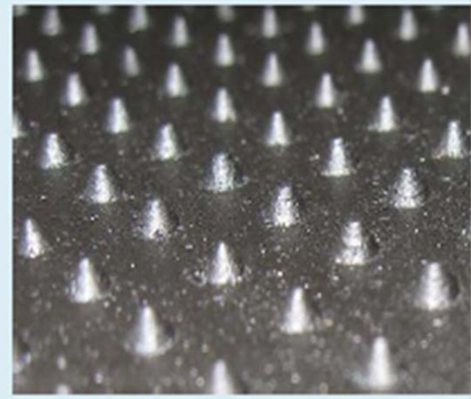
Vegetation

- ➢ As vegetation cover increases, direct raindrop impact decreases
- ➢ Vegetation increases surface roughness and slows flow velocities

Semi-arid sites require some level of rock armoring on side-slopes due to low vegetation cover

Other 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

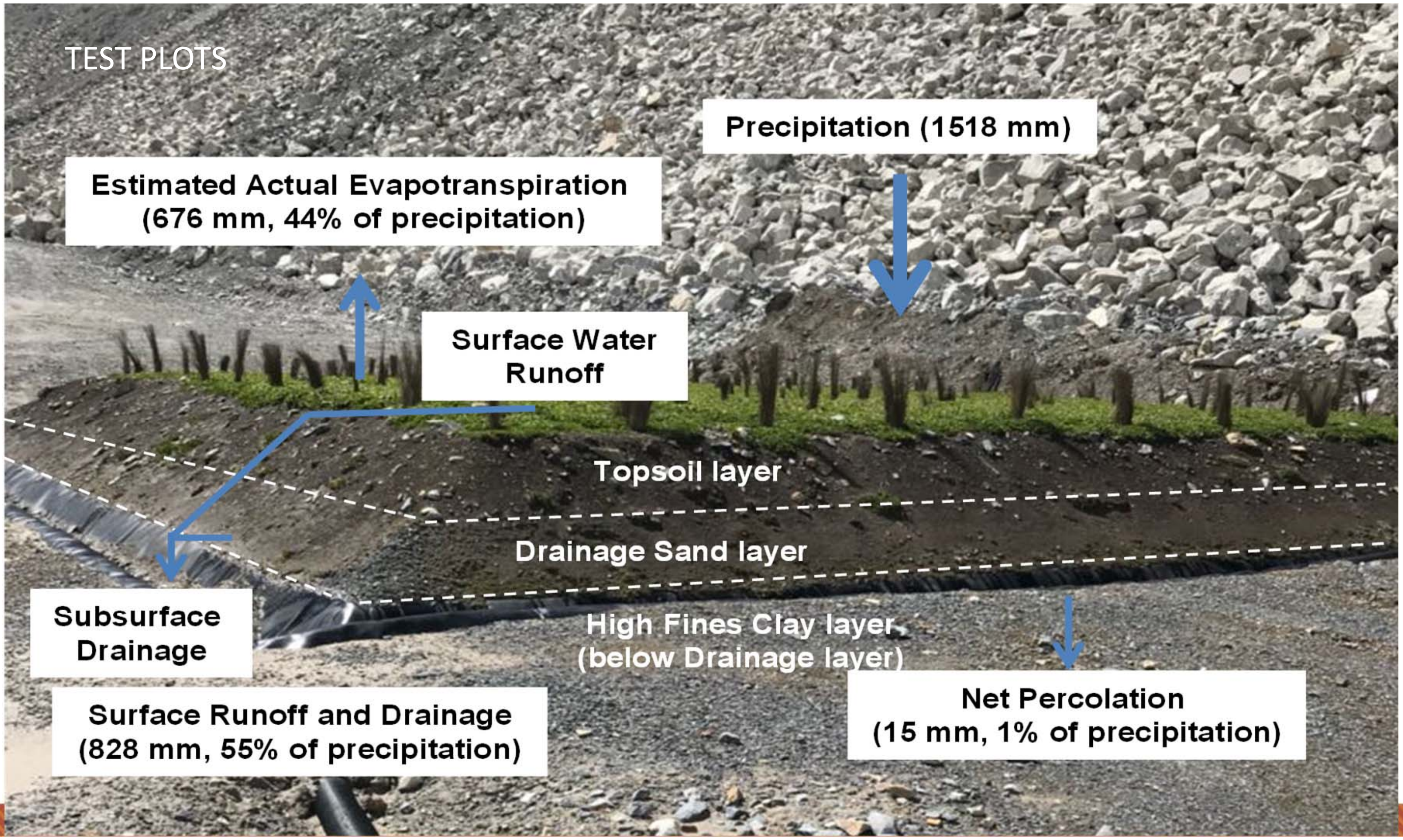
Long-term Tests and Monitoring

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

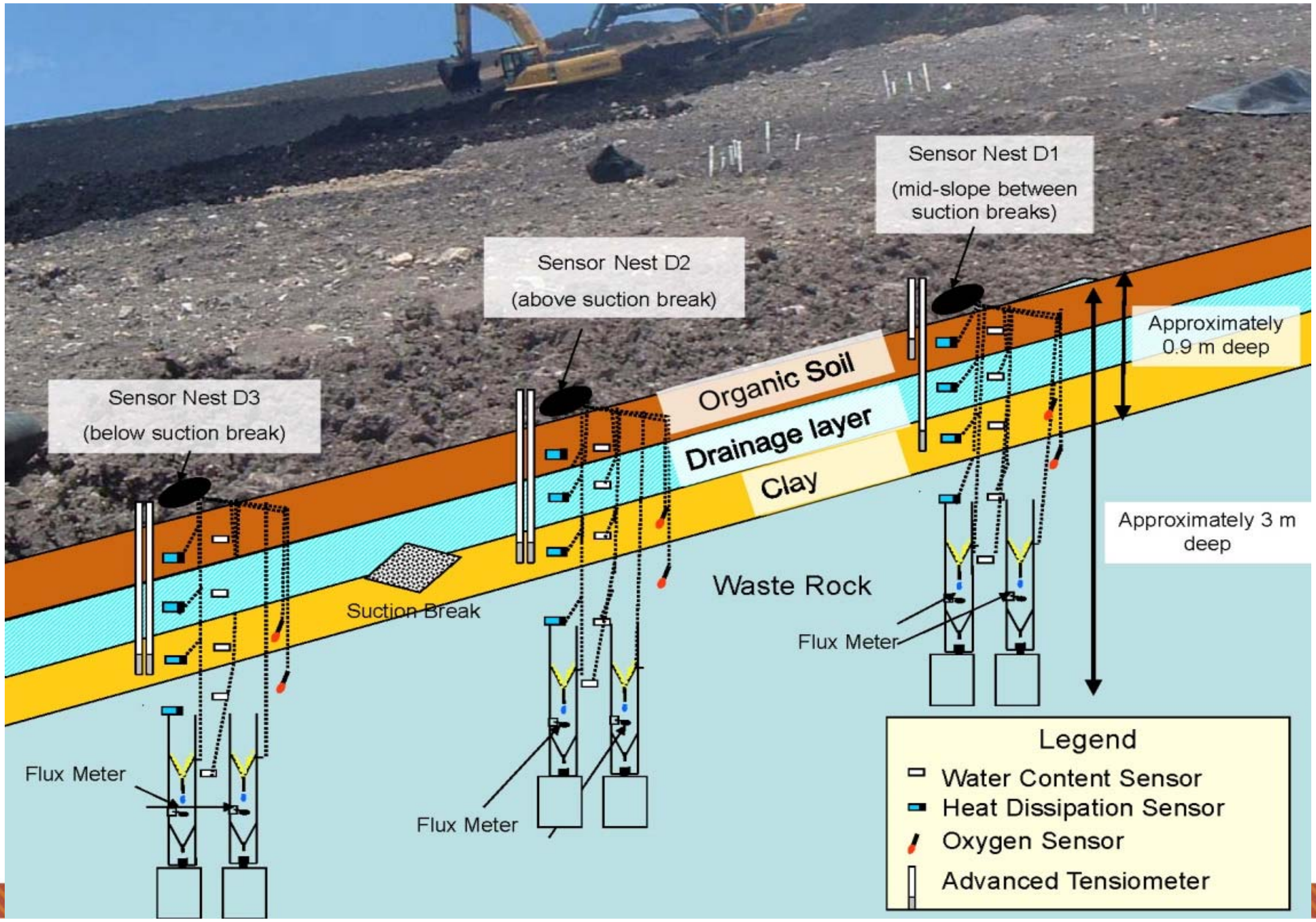
Vegetation and Rooting Assessments

- Predominant native species
  - Pioneer/disturbance species
- Rooting surveys to estimate minimum cover depth

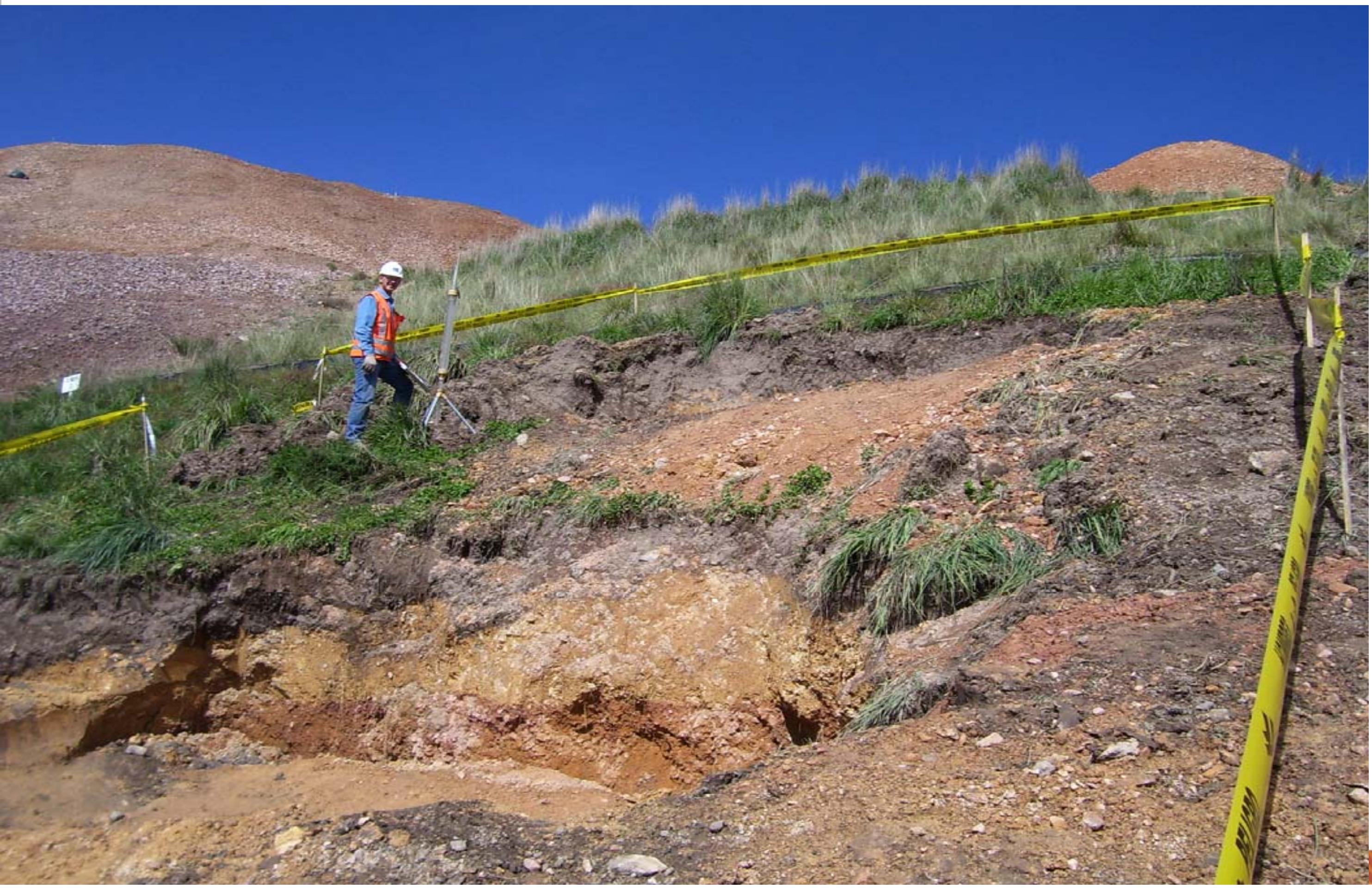
Test Plot Studies



Sensor Nest Monitoring



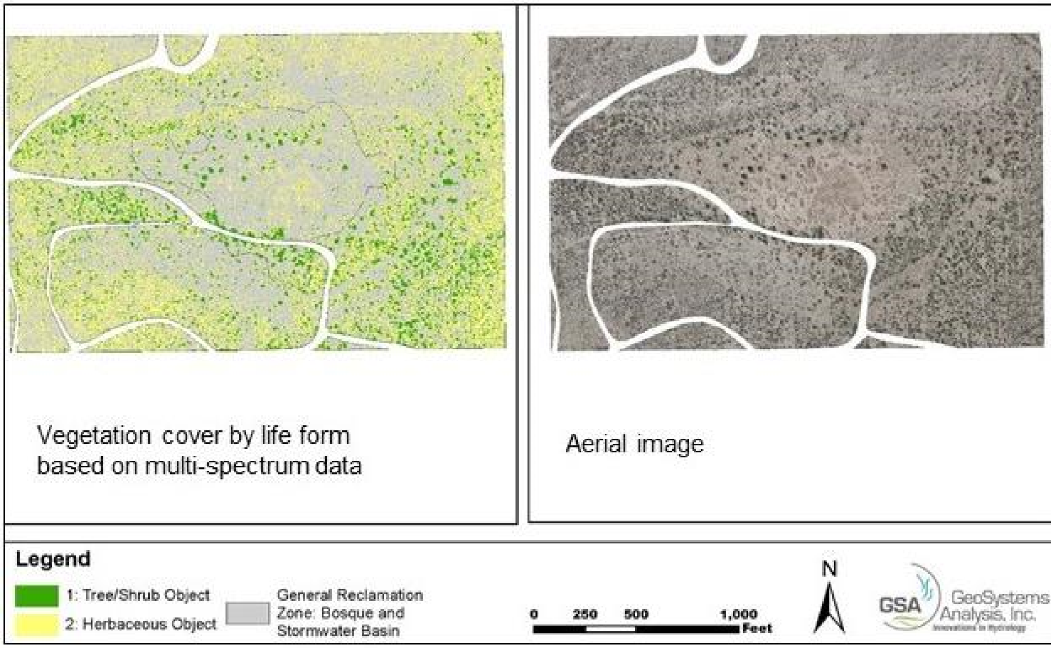
Decommissioning



- Rooting surveys
- Measure in-situ physical and hydraulic properties

Vegetation and Erosion Monitoring

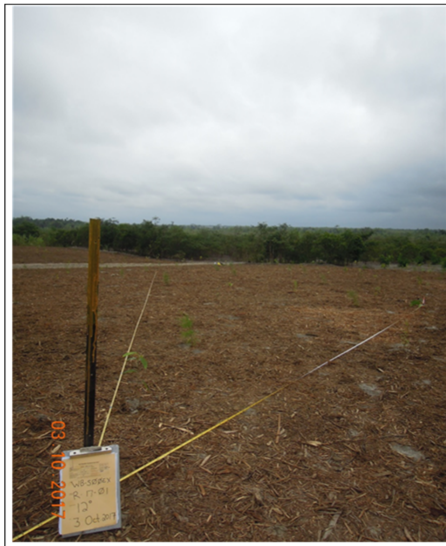
- Erosion transects
  - Number of rills/depth of rills
- 4-band spectral or LIDAR imagery to quantify severity



- Vegetation transects
  - Need statistically valid number
- Use of multi-spectral satellite/drone imagery to expand field-based data
  - NDVI/GNDVI

ECOSYSTEM FUNCTION ANALYSIS (EFA) MONITORING

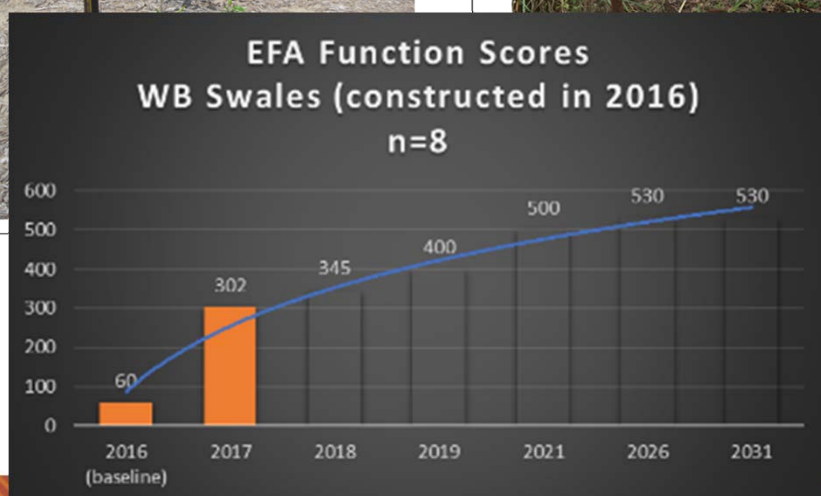
Oct 2017



Dec 2018

Oct 2017

Dec 2018



Closing Thoughts

- Climate and borrow material properties should guide the design
  - Use P/PET ratios to guide initial design evaluations
- Use site-specific knowledge
  - Vegetation, natural side-slope conditions, estimated recharge rates
- Need careful field investigations
  - Representative samples
  - Appropriate methods – lab and field
- Use models to evaluate relative performance of different designs
  - Cover system depths
  - Use of barrier layers
- 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!
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