Integrated Closure Planning for Waste Rock and Tailings in an Arid Climate

Björn Weeks, PhD, P.Eng, Golder Associates
Gabriel Lopez Vasquez, Glencore Argentina
Arnaldo Santander, Golder Associates

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Overview - Site Characteristics

- Located in Northwestern Argentina
- Open pit copper-gold mine 2,600 masl
- Production:
  - Copper: 180,000 ton/year
  - Gold: 600,000 troy ounces/year
- Nearing the end of its productive life

Climate Setting

- Arid/Perarid Climate
- Annual Precipitation of 160 mm/year, ranging from 80 to 350 mm
- Precipitation concentrated in period December – March
- Typically short, high-intensity rain events
- Pan evaporations in the order of 1,400 mm/year

- Estimated precipitations for 24 hour events:
  - 50 year: 52 mm
  - 200 year: 63 mm
  - 1000 year: 75 mm

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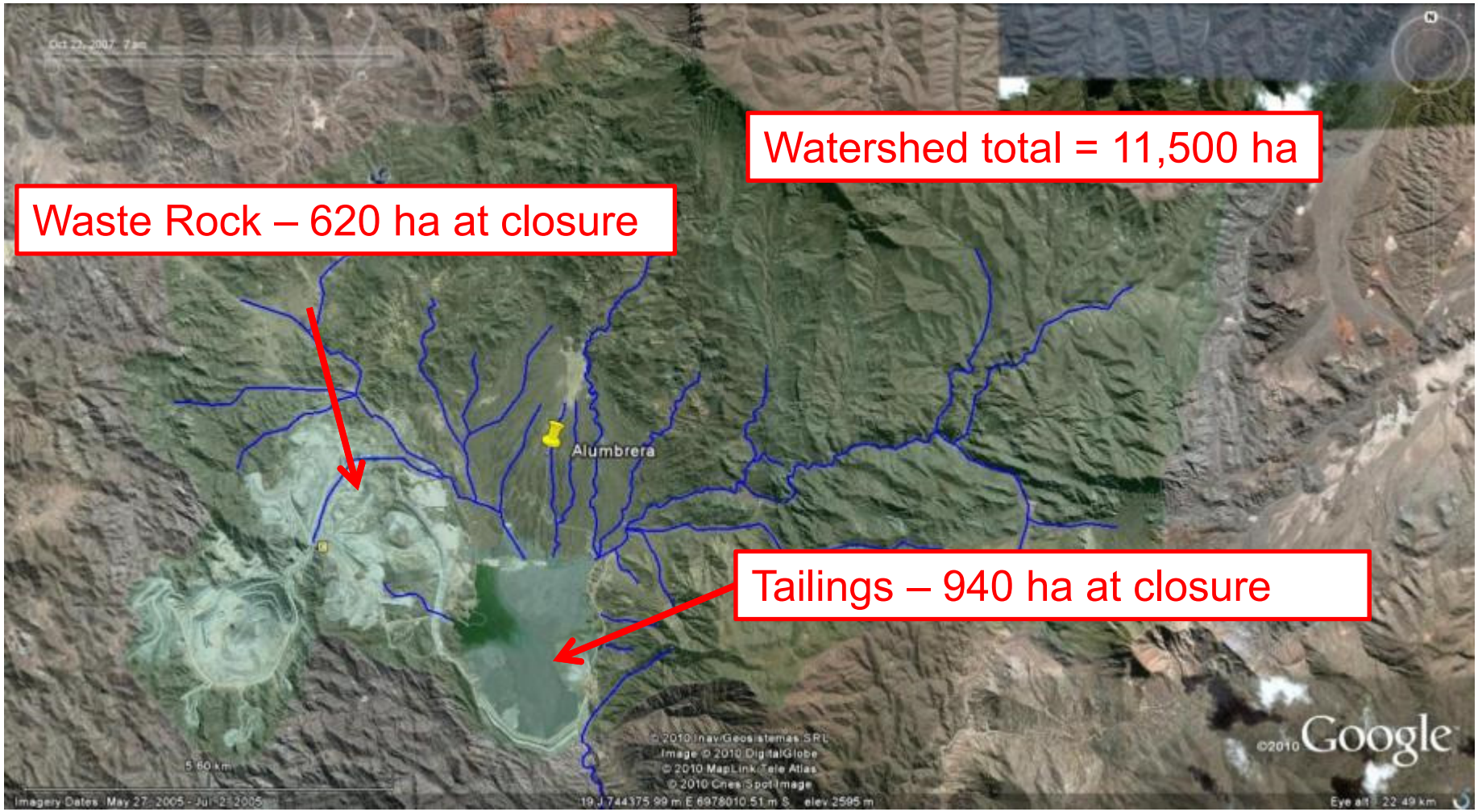
Watershed and Contact Area



Downgradient of Site

Closure Planning Elements for the Site

- Avoid impacts downstream in Vis Vis (Chemical Stability)
  - Geochemical Characterization
    - Waste rock, tailings
    - Alternative cover materials
  - Understand transport systems
    - Water balances
    - Groundwater (calibrated models)
    - Surface water flow
  - Evaluate downstream water quality under different closure scenarios
    - Alternative surface water diversion schemes
    - Cover studies
      - Alternative cover configurations
      - Field tests for tailings and waste rock

Other Closure Planning Studies

- Physical Stability
  - Dam and Dump Stability
  - Landform erosion
    - Alluvial fan upstream of TSF
    - Waste Rock Facilities – long term slopes
  - Tailings consolidation

- Aesthetics
  - Pilot scale revegetation studies (direct revegetation on waste rock)
  - Seed bank development for successful species

Geochemical Characterization

Geochemical Characterization

- Waste Rock
  - Some waste rock is potentially acid generating.
  - Visual evidence of oxidation (steam venting, limited areas)
  - Other waste rock types identified as potential cover material
- Tailings
  - Potentially acid generating (in long term)
  - Contact water currently not acid
- Alluvial materials upstream of TSF
  - Inert (potential cover material)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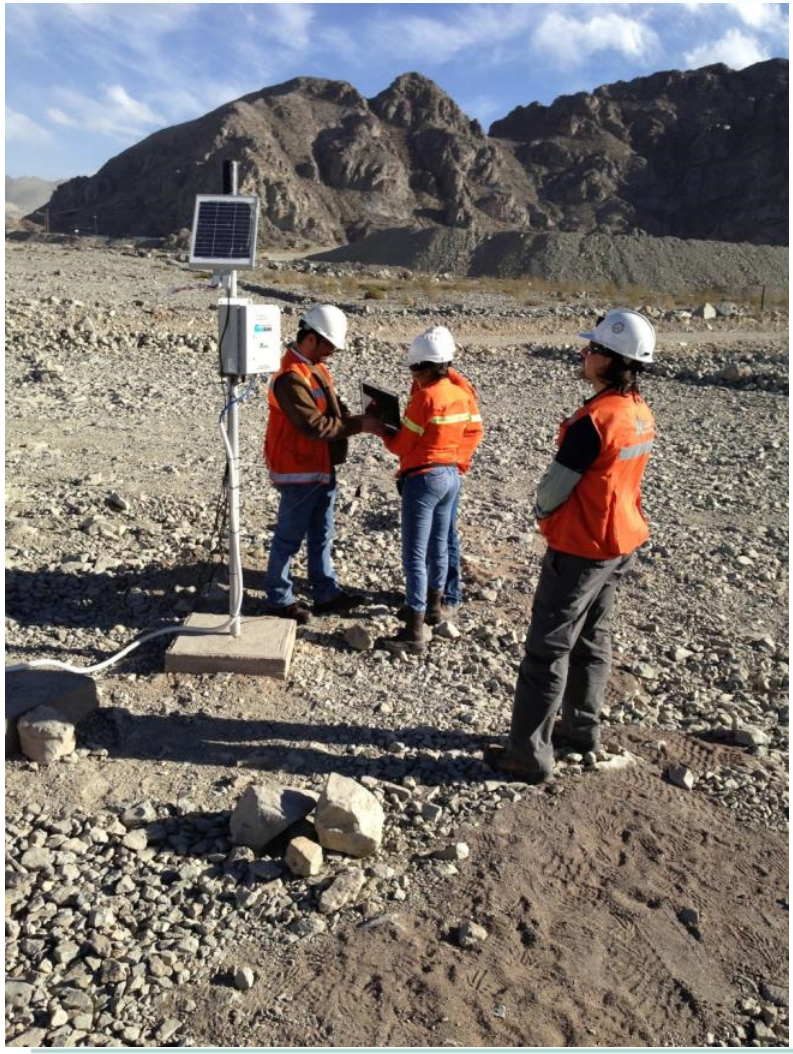
Elements of Characterization Program

- Lab testing and field evaluation
- Long-term column tests
- Long-term irrigated field lysimeters
- Drilling program (2013) for the collection of in-situ tailings samples
- Installation of thermistor strings for the measurement of temperature profiles in the waste rock dumps
  - Long-term monitoring
  - Newer strings for additional coverage, replacement of failed thermistors
- Preliminary (prior to 2009) and detailed (post 2012) characterization of upstream alluvial material (cover source characterization)

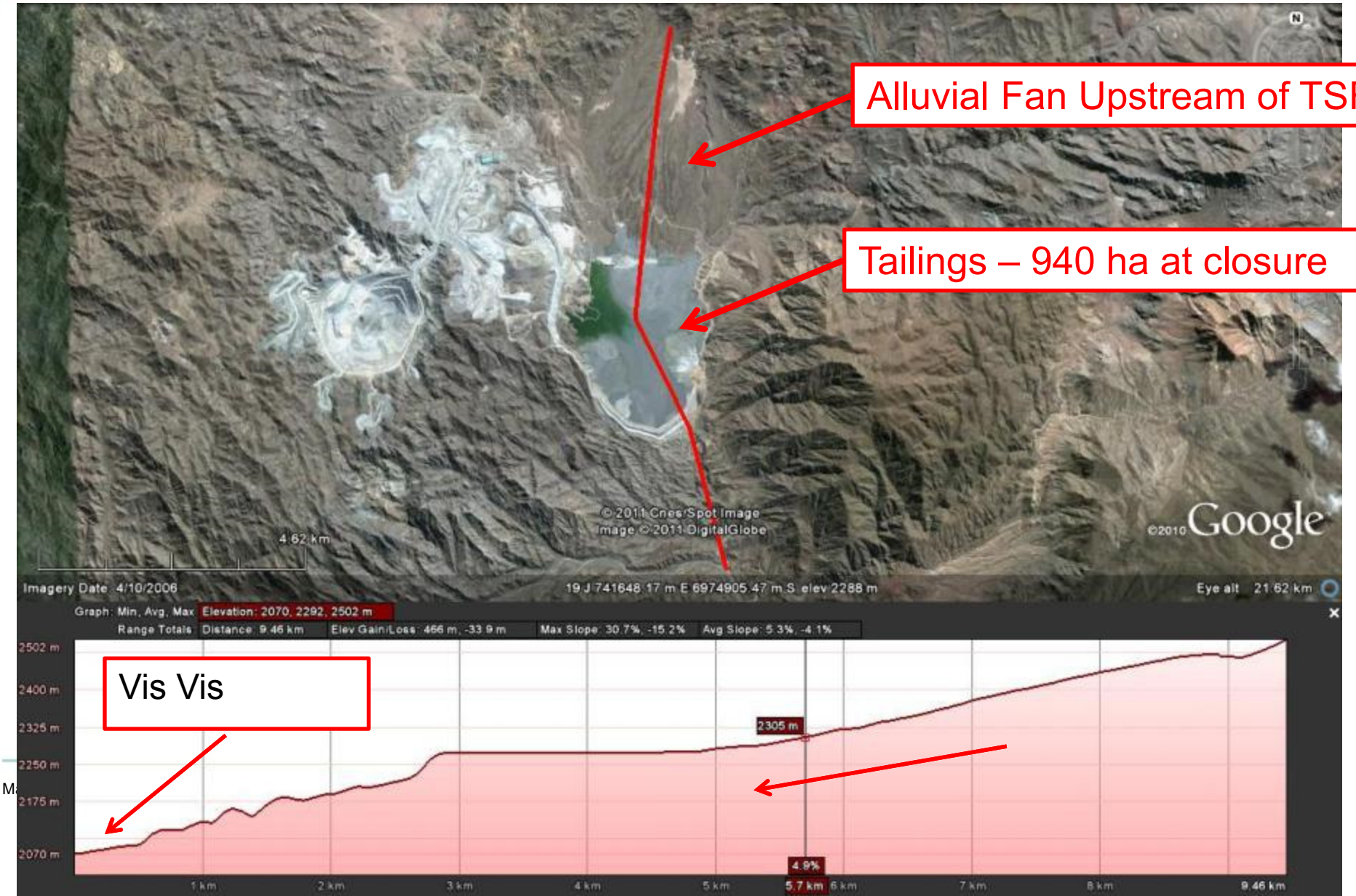

Pileta 1
Colas
Total Sulphur = 2.55 %
Sulphate Sulphur (SO_4) = 2.01 %
Sulphide Sulphur = 0.52 %
ANC (kg H_2SO_4/t) = 10.8
NAG (kg H_2SO_4/t) = 25.4

Thermistor – Waste Rock Temperature Profile

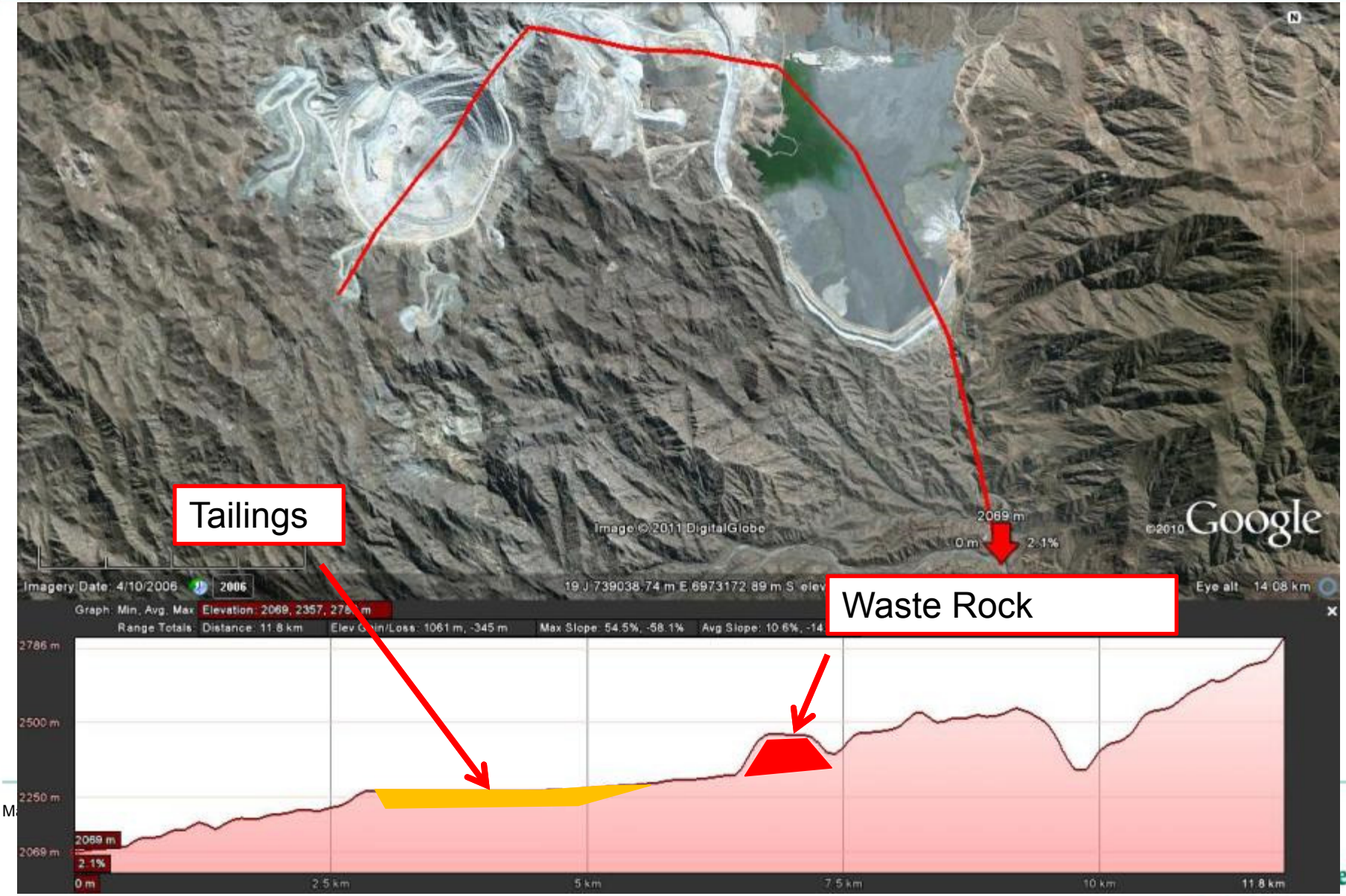


Understanding Flow Systems

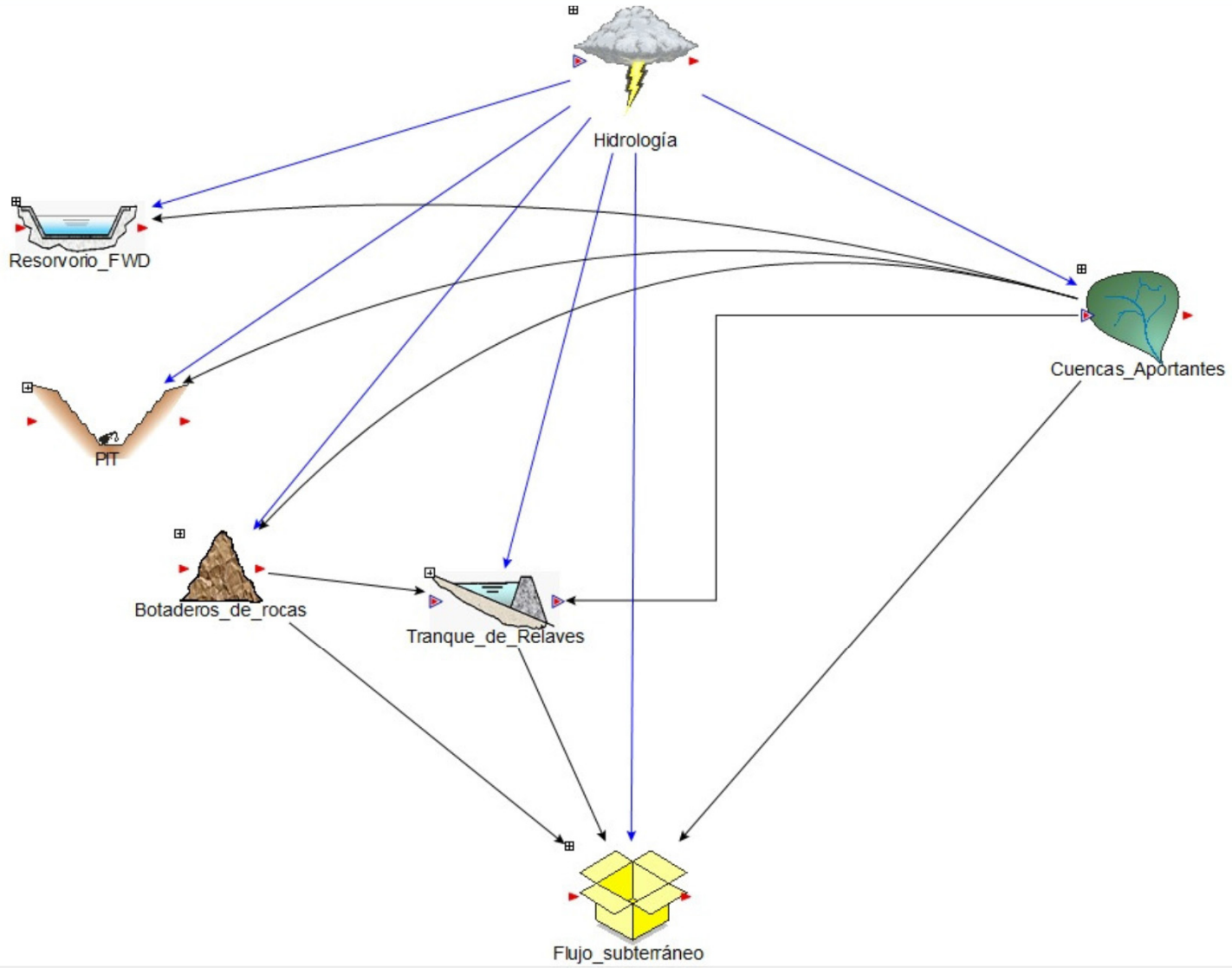
Elevation Cross Section - Tailings



Pit – Waste Rock – Tailings Profile



Site-Wide Water Balance (GoldSim)



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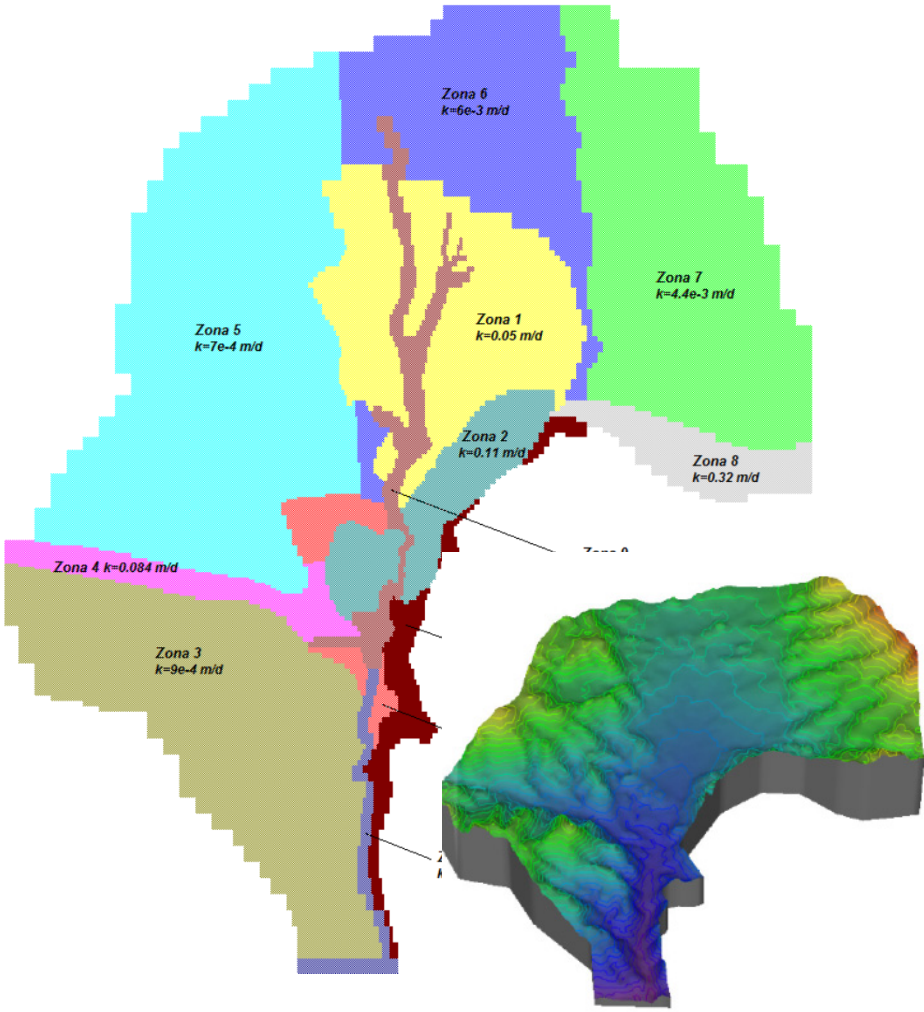
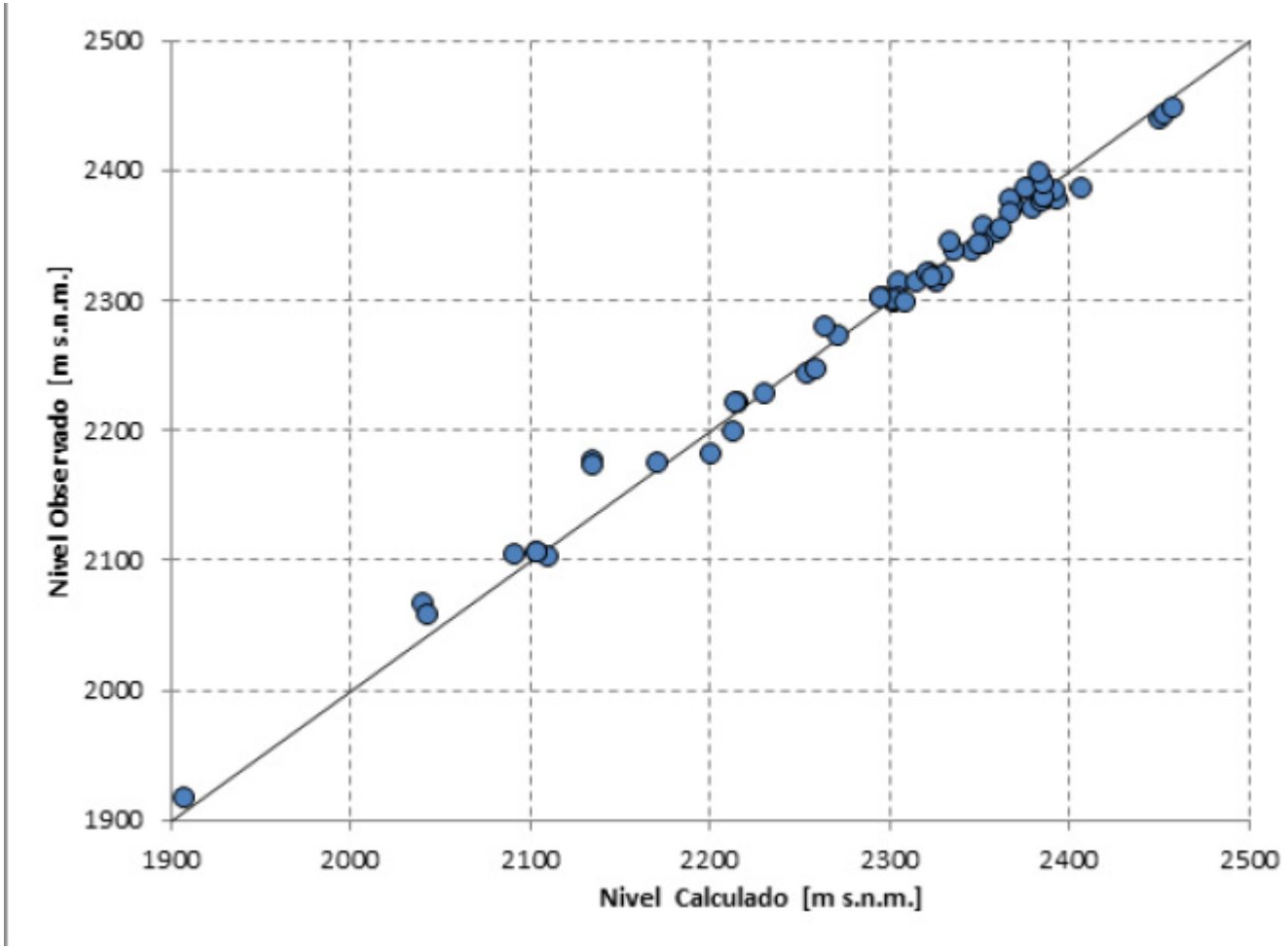
Groundwater flow model

- Existing model re-structured
- Incorporating detailed topography
- Recharge flow input to groundwater model defined in GoldSim
- Groundwater model calibrated considering:
  - Well data from 66 points
  - Data back to 1997
  - Surface seeps



Calibration Results RMS < 5%



Closure Scenarios

Evaluating Closure Scenarios

- Evaluation Approach:
  - GoldSim used to simulate the water balance
  - Modflow used to simulate the groundwater flow
  - PHREEQC used to evaluate the impact of the measures on downstream water quality

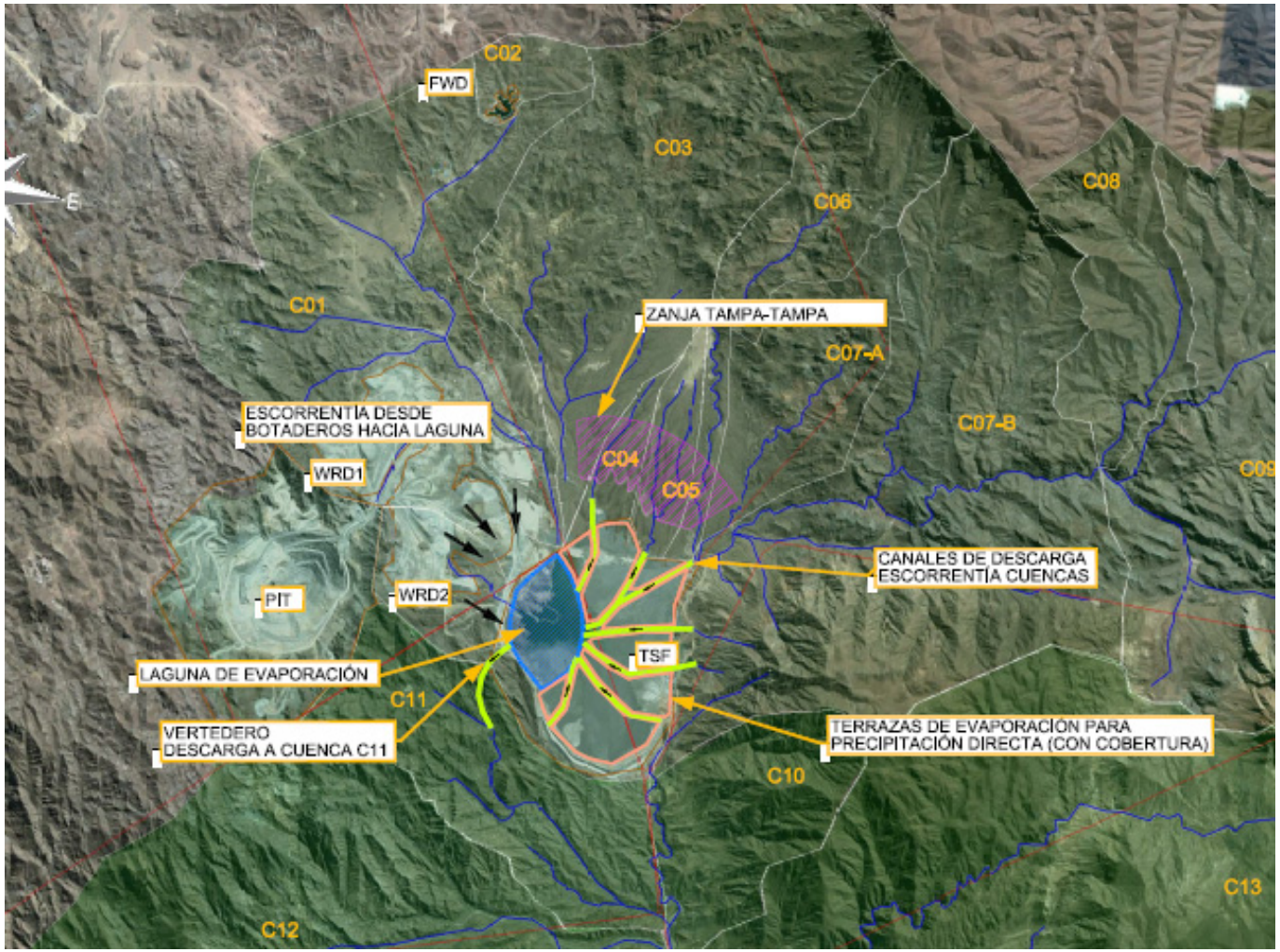
- Scenarios modelled:
  - Historic (calibration of models)
  - No Closure
  - Closure configuration in EIA
  - Alternative Closure scenarios

Example Closure Scenarios

EIA

Case presented in original EIA

- Evaporation pond on TSF
- Spillway
- Surface channels to bring upstream flow to pond.



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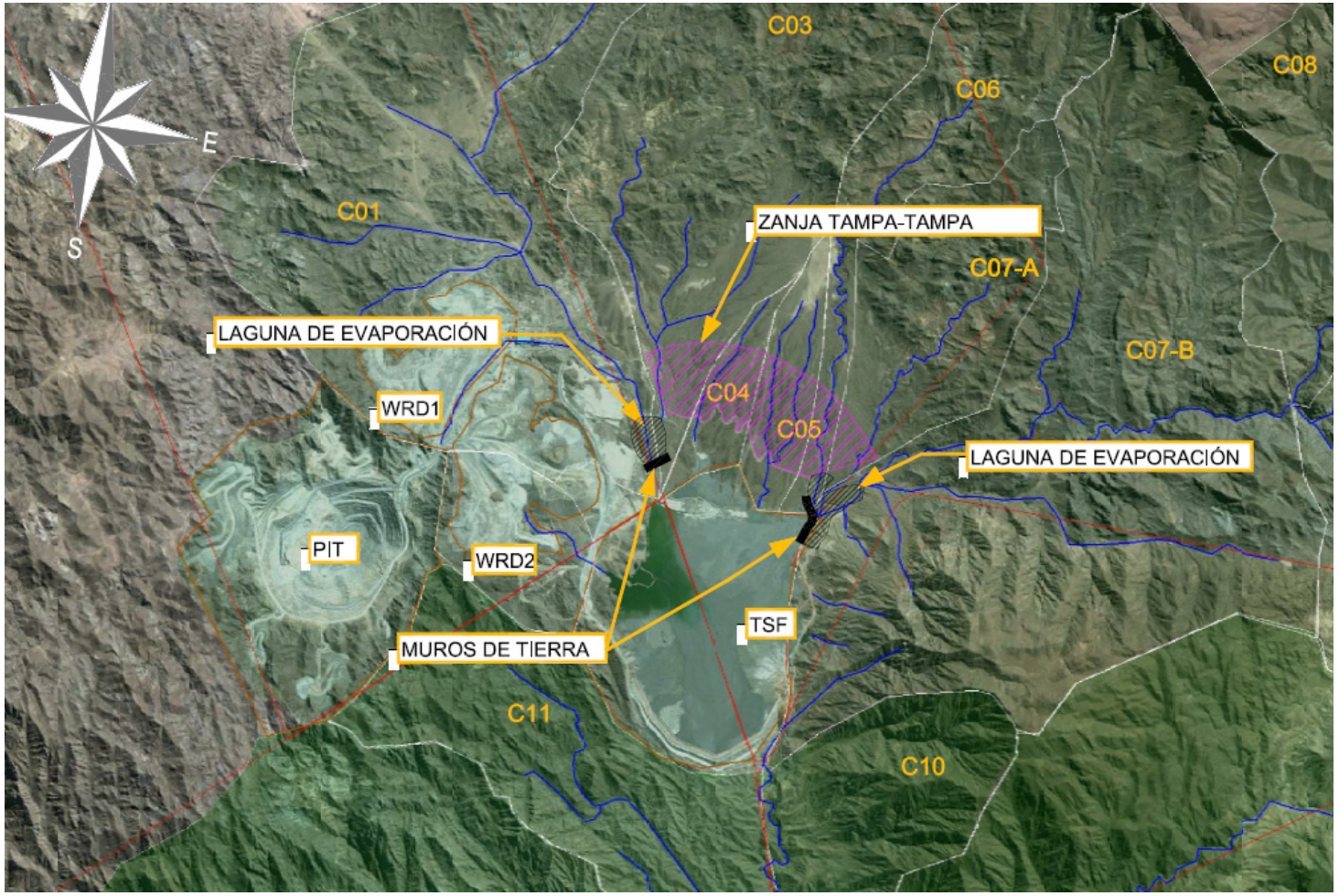
Example Closure Scenarios

Structures to retain and evaporate water upstream of TSF



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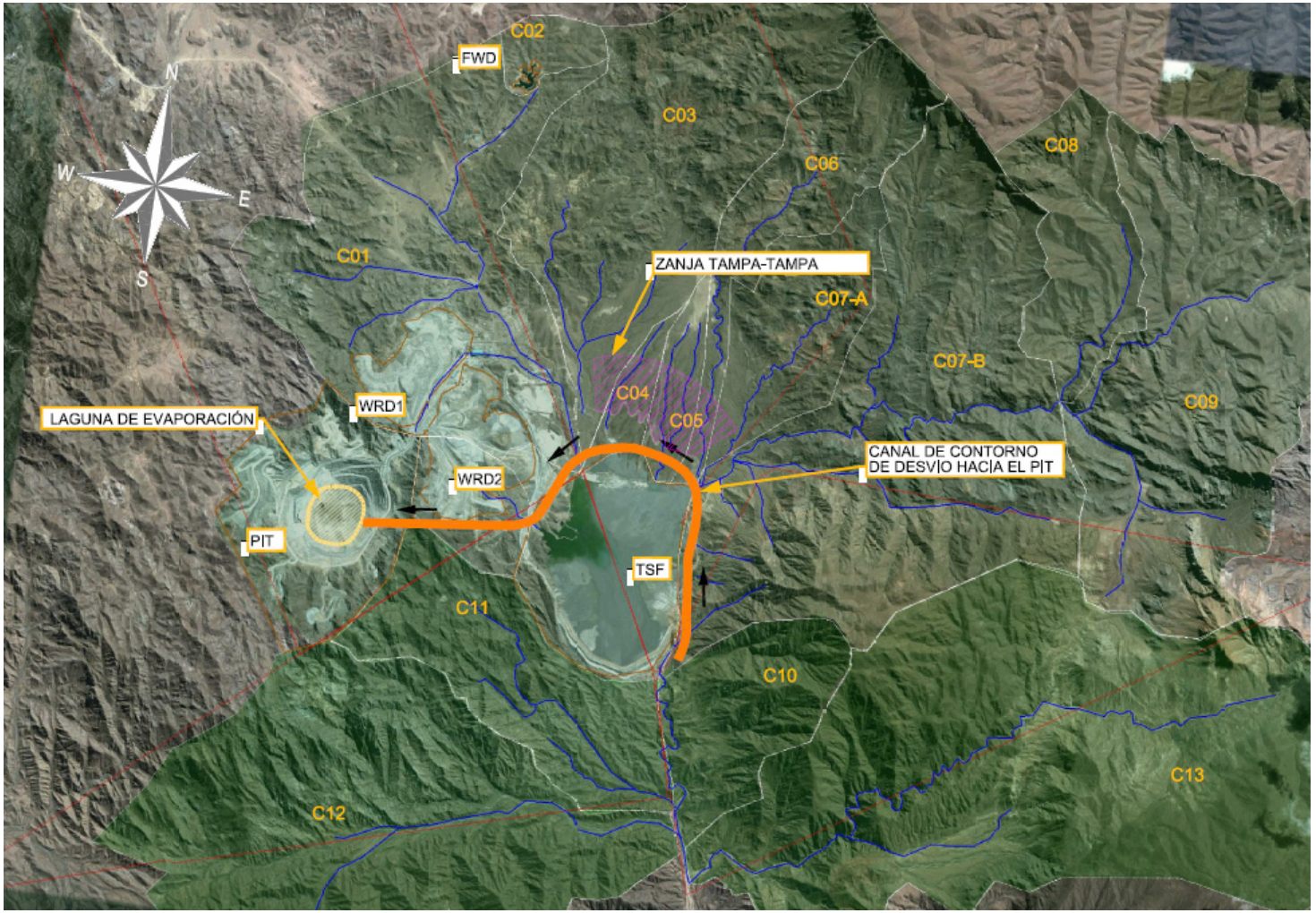
Example Closure Scenarios

Diversion of surface water to pit for evaporation.



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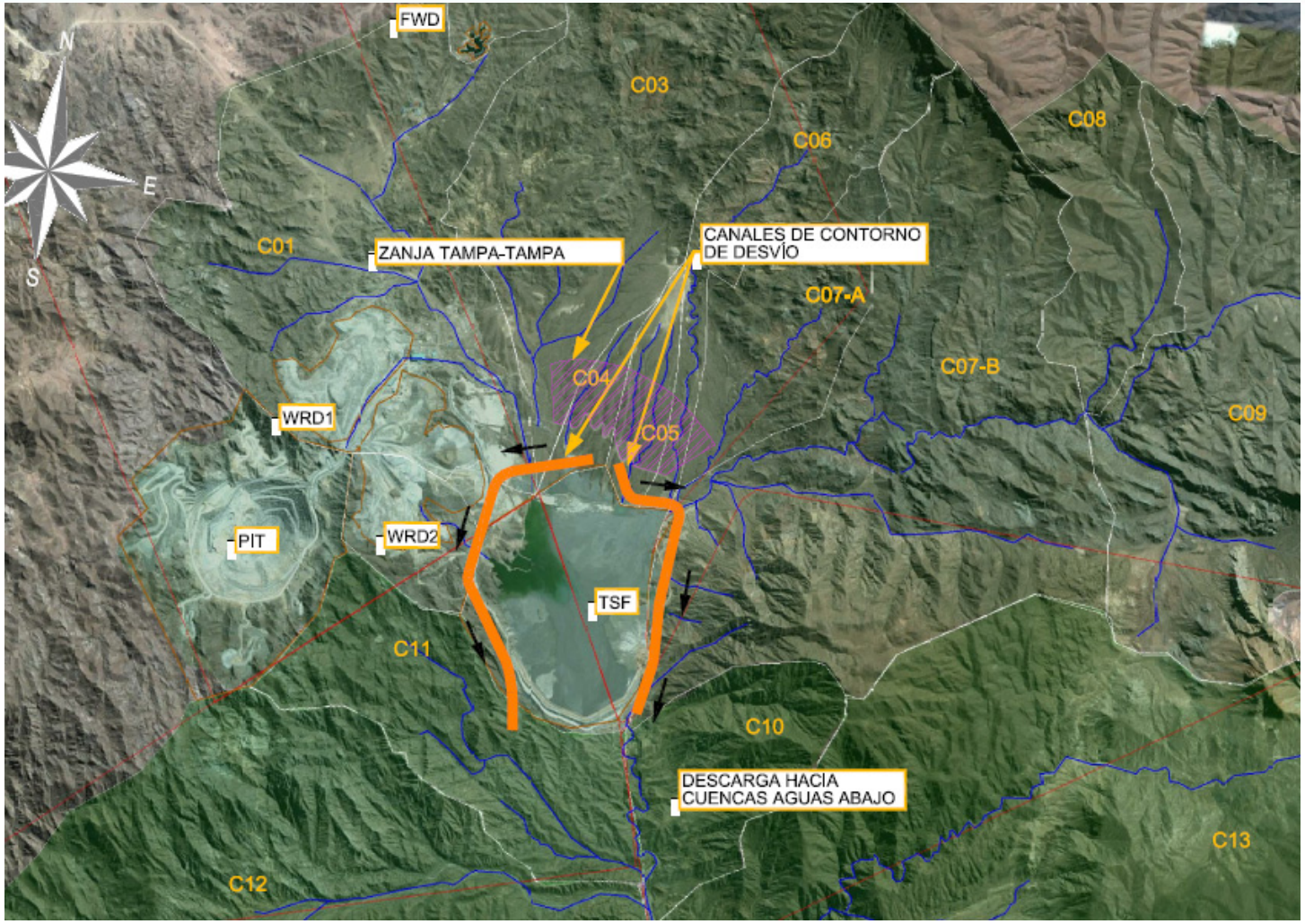
Example Closure Scenarios

Water diversion channels east and west of pond



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Use of Models

- Models were all preliminary and investigative in nature
- The models are effectively “stacked” with water balance information used in the geochemical model *(not coupled)*
- Simulations in GoldSim used to provide inputs for a variety of conditions (wet and dry years over a 100 year cycle)
- Used to test the relative importance of elements in the system
- Examples:
  - How could alternative diversion schemes affect water quality from a mass balance point of view?
  - How much does infiltration through covers impact water quality downstream? (setting design goals – what is good performance? What do the covers need to achieve?)

Preliminary Results - Tailings

- Complete perimeter diversions provided best water quality downstream under most conditions
- Results were far more sensitive to variations in the quality of the tailings contact water than to the different flow diversion scenarios
- Future development of acidic conditions in all (or part) of the tailings would define downstream water quality
  - Motivation for more detailed tailings characterization
  - Upstream/downstream water characterization
  - Sampling of porewater in tailings

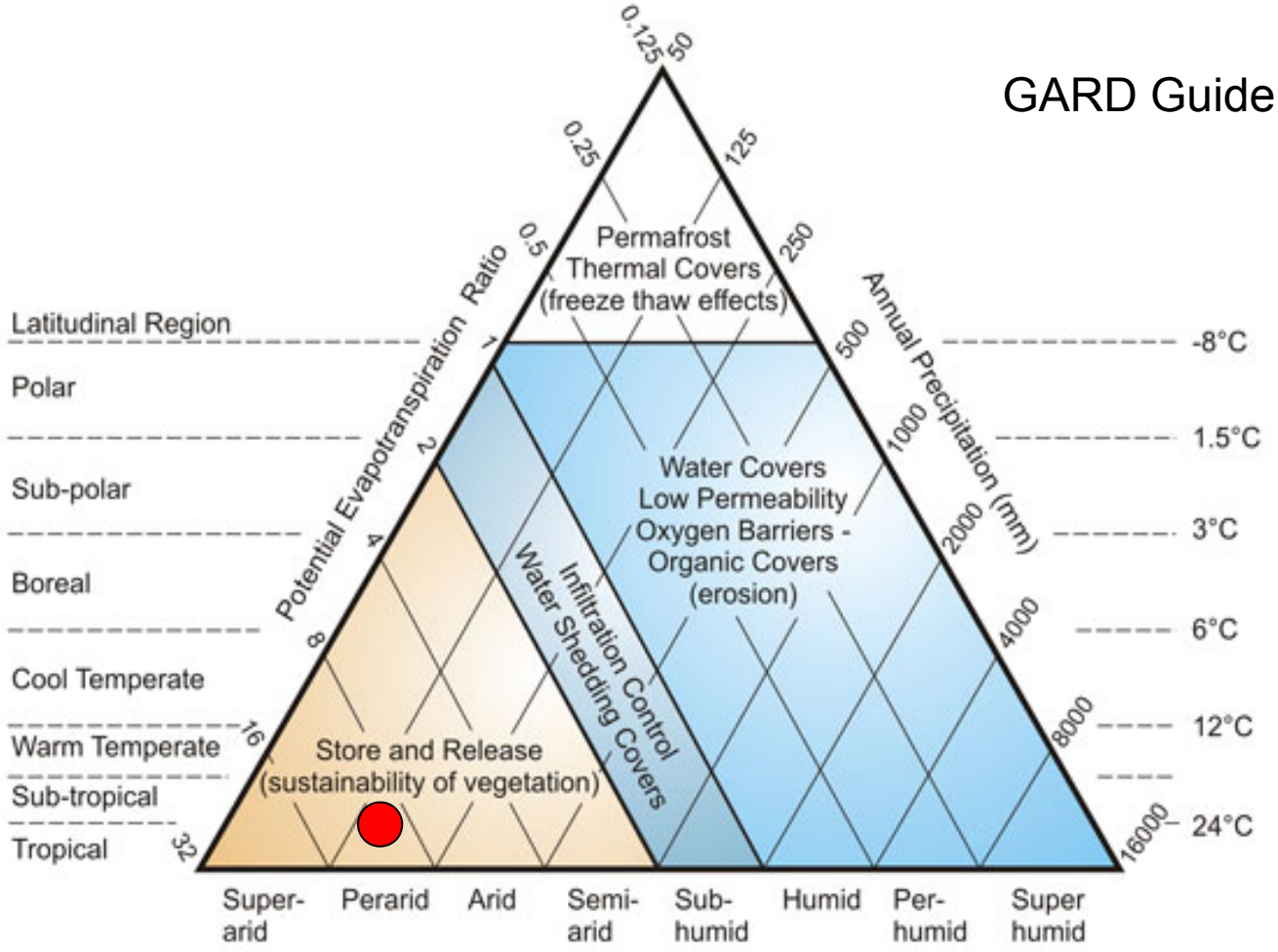
Preliminary Results – Waste Rock

- Waste Rock Contact water more important in low flow conditions
- Improving the quality of the tailings cover proportionally increases the importance of contact water from the waste rock dumps
- For both Tailings and Waste Rock:
  - Accurate infiltration predictions key to evaluate impacts
  - Highlights the importance of field tested infiltration measurement

Cover Design – Infiltration Measurement

Cover Concept

GARD Guide, Ch. 6

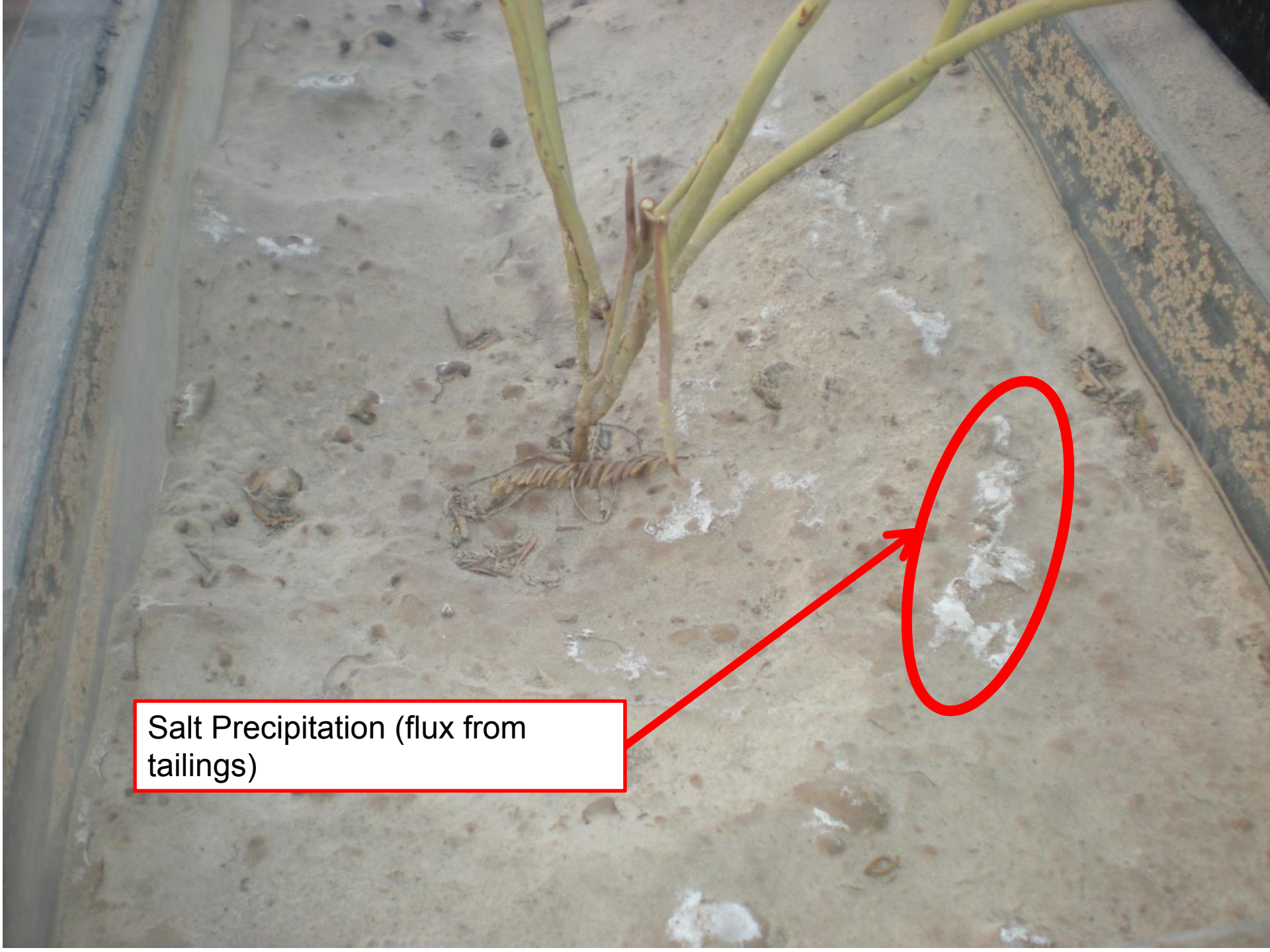


Cover Design

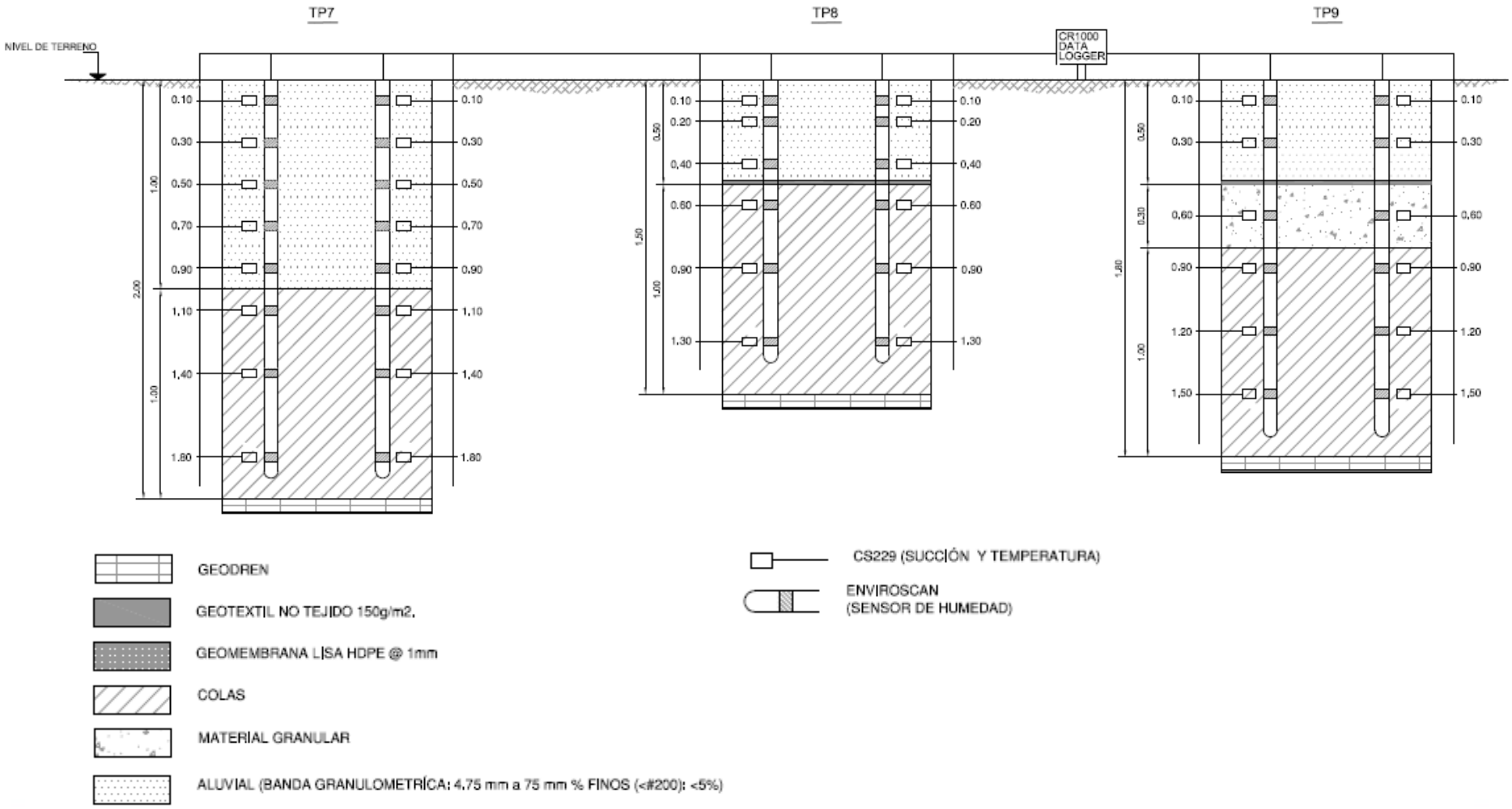
- Ongoing evaluation of covers at site since 2003
- Limitations in locally available material for cover construction
- General approach defined:
  - Encapsulation waste rock by “inert” waste rock
  - Use of alluvial material from upstream of TSF to construct tailings cover.
  - Revegetation where possible
- Instrumented field tests to evaluate alternative cover configurations

Field Box – Alluvial material over tailings

- 0.5 m alluvial over tailings
- Non-acidified tailings
- Equivalent profile to field tests run since 2003


Salt Precipitation (flux from tailings)

Cover Profiles – Tailings Covers



Construction of Lysimeters

Construction (2013)

Tailings Lysimeters

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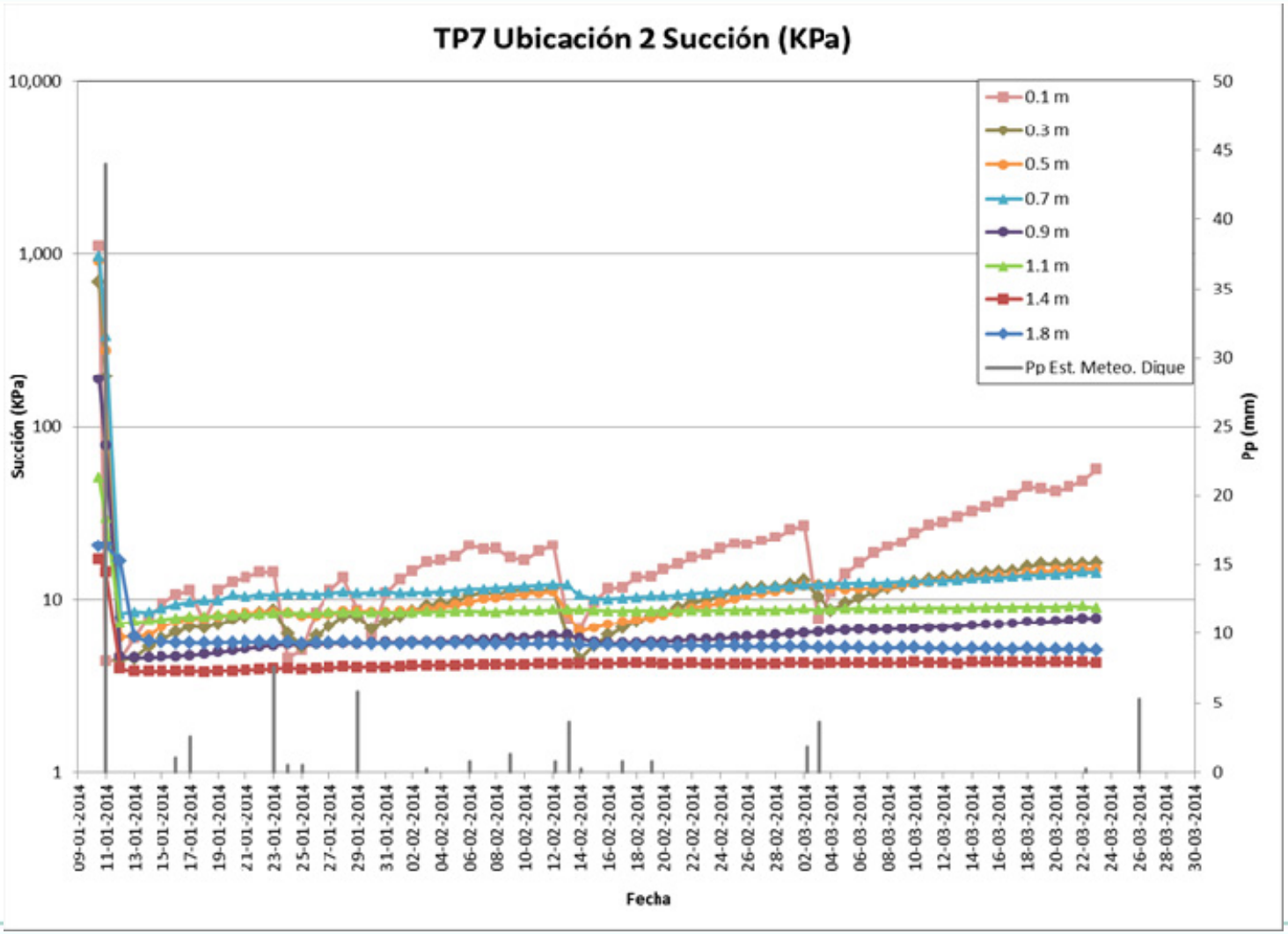
Eg Suction Profiles (1 m Aluvial over Tails)



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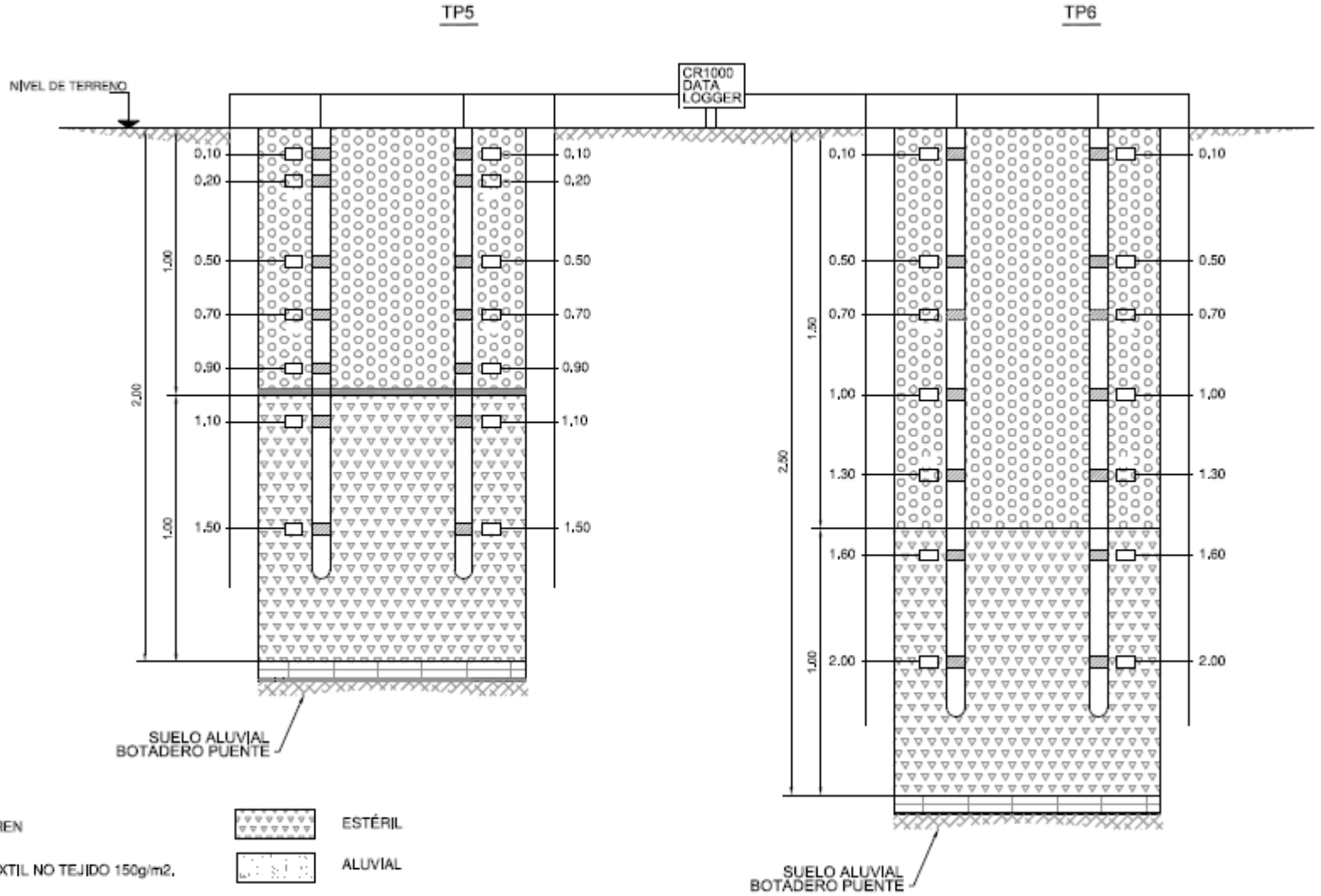
Cover Profiles – Waste Rock



Waste Rock Lysimeters

Cover Observations

- Monitoring of previous cover configurations show good performance in normal and dry years
- Despite generally dry conditions, periodic, high-intensity rainfalls are challenging for store-and-release covers built without a barrier layer
- In particularly wet years, the storage capacity can be overwhelmed, resulting in plug flow through cover.
- Revert to water balance/geochemical modeling to see if these infrequent events are acceptable or not.

Summary

- Site owners have been involved with on-going closure studies since 2003:
  - Geochemical characterizations
  - Groundwater monitoring and modeling
  - Cover design for waste rock and tailings deposits
  - Erosion measurement and modeling
  - Revegetation studies, and seed bank development
  - Pit lake modelling and predictive studies

Summary

- Integration of water balance, hydrogeological, and geochemical models has provided a tool to evaluate alternative closure scenarios
- Closure studies are well advanced, and many of the studies needed to define or justify closure measures have been completed
- Site owners are in the process of completing the studies needed to finalize various aspects of the closure design.

Gracias

Erosion

Storm Events – Immense Erosive Power

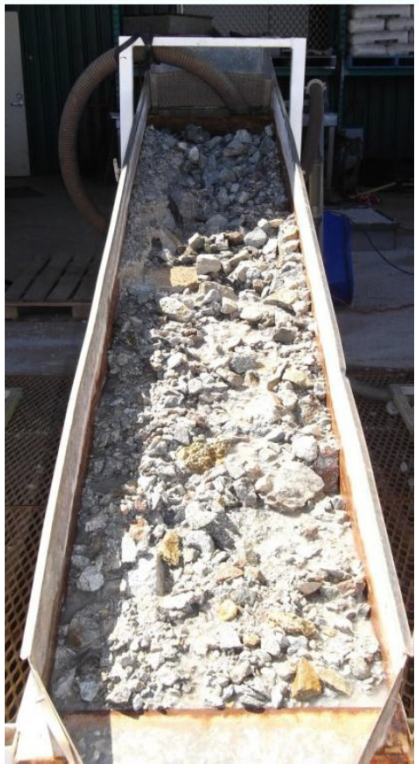
Erosion of Upstream Alluvial Fan

- Alluvial Fan upstream of TSF has significant erosion potential
- Preliminary evaluation of erosion using RUSLE show that sediment from fan must be taken into account for long-term planning
- Alternatives:
  - Periodic maintenance of affected surface water diversions
  - Incorporate sediment accumulation over TSF into design.

Erosion Studies

- Studies conducted to define erosion properties for exposed waste rock (candidate cover materials)
- Eg- “Epidota Clorita” waste rock before synthetic precipitation (30%, 20% and 10% slopes (Flumes 2m long, 0.4 m wide)

After Runoff Event



Erosion Study Results

- Studies included
  - Field observations
  - Flume studies
  - Rainfall simulators
  - Numerical Models
- Results of early studies permitted ruling out need for more sophisticated erosion modeling (eg, SIBERIA)
- Provided sufficient background information to demonstrate erosion resistance of cover rock to authorities

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Revegetation

Typical Natural Vegetation Density

Waste Rock – Edge of Revegetation

Fully developed revegetation of waste rock