Lecture #1: Surface and Subsurface Hydrology at Hardrock Mine Sites

Prepared for:
Hardrock Mining Geochemistry and
Hydrology Workshop 2

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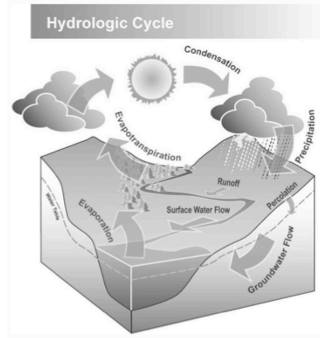
Outline: Surface and Subsurface Hydrology at Hardrock Mine Sites


Tailings at Laguna Huascacocha, Peru.
Photo: A. Maest.

- Hydrologic characterization
  - Near-surface hydrology and characterization
  - Water balance
  - Groundwater hydrogeology and characterization
- Impacts of mine facilities and operations on hydrologic processes and pathways
  - Waste rock, heap leach pads, tailings impoundments, open pits, underground workings
  - Dewatering and water management (process system)
  - Changes in recharge/flow path/discharge

Hydrologic Characterization: Near-surface Processes



Stratus Consulting Inc.

P = RO + ET + I

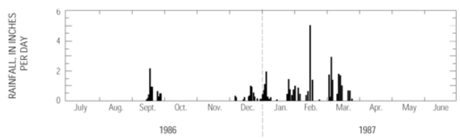
–*Runoff* – estimate from topography, material type, testing of particle size (e.g., SCS runoff curve number)

–*Evapotranspiration* – pan evaporation data, methods for estimating ET from temperature, precipitation, humidity, vegetative cover, etc.

–*Infiltration/recharge* – estimate from laboratory measurements of materials or field infiltrometer tests, other methods for estimating recharge

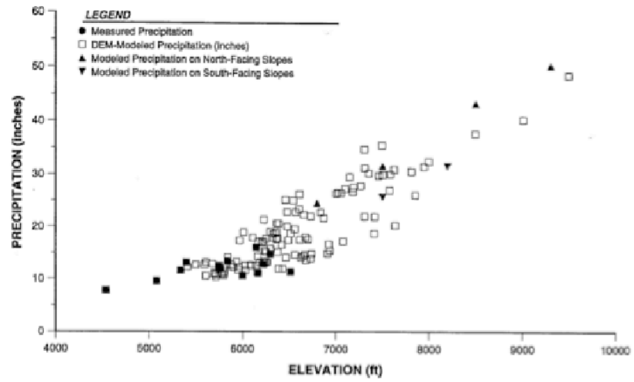
Hydrologic Characterization: Precipitation

- Meteorological data – obtain from regional or mine-maintained stations – precipitation, temperature, wind speed, pan evaporation etc.
- Precipitation data must consider:
  - Amount, frequency, duration, intensity of individual events
  - Long-term variability in precipitation
  - Orographic effects
- Need long-term, continuous meteorological data record – may not be available at remote mine sites, particularly pre-mining



Example of precipitation recorded at Questa Mine, NM

Average Annual Precipitation with Land Surface Elevation – Big Springs Mine, Nevada



Exponent, 1998.

Hydrologic Characterization: Recharge/Infiltration

- Diffuse and focused recharge
- Methods
  - Water-budget (I = P-ET-RO-ΔS)
  - Modeling (unsaturated zone, watershed, groundwater/ surface water)
  - Surface water flow – groundwater/surface water interactions
  - Physical methods
    - Unsaturated zone, e.g., measure change in soil water content
    - Saturated zone, e.g., groundwater levels over time and space
  - Tracers

Adapted from Healy, 2010.

Hydrologic Characterization – Surface Water Flows

Discharge measurements – stream and spring flow rates

- Manual measurements using flow meter, channel cross sections, or bucket and stop watch
- Dedicated gaging stations (mine installed or USGS) – develop rating curve
- Need data sufficient to understand temporal nature of flows, long-term variability

Manual stream gaging, Yanacocha, Peru

Gage for ephemeral stream near Betze Pit, Nevada

Photo credits: Connie Travers.

Hydrologic Characterization – Groundwater/Surface Water Interactions

Photo credit: Connie Travers.

- Characterization methods:
  - Gaining/losing reaches (can change seasonally)
    - Compare stream discharge at different locations
    - Compare stream and adjacent groundwater elevations
  - Loading from groundwater, runoff, tributaries – water quality and discharge
- Consider: amount and reliability of measurements (e.g., are data sufficient to understand baseline/pre-mining conditions and seasonal flow and /or water quality changes?)

Water Balance: Pre-, Syn-, and Post-Mining

Water budget

- “Ins” minus “Outs,, and change in storage – pre-mining, over life of mine, and post-closure
- Site-wide
- Within individual mine facilities

Water Balance Example

Example from the Straight Creek catchment in the Red River Valley, New Mexico (Questa)

- P = 701 gpm
- ET = 540 gpm (77%)
- Q_{GW} = 156 gpm (21.3%)
- Q_{SW} = 5 gpm (0.7%)

$P = ET + Q_S + Q_G$ [water balance or water budget]

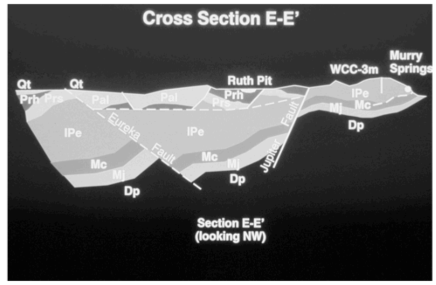
McAda and Naus, 2008.

Hydrologic Characterization – Unsaturated Zone Properties


Photo credit: Connie Travers.

- Hydraulic properties of mine wastes, covers, and native ground
  - Unsaturated flow properties (e.g., porosity, initial water content, permeability as a function of negative pressure)
- Characterization methods
  - Lab tests on mine waste, native materials (e.g., soil water characteristic curve)
  - Measurements in field (infiltrometer)
  - May not adequately characterize presence of macropores? Internal layers?

Hydrologic Characterization – Saturated Zones



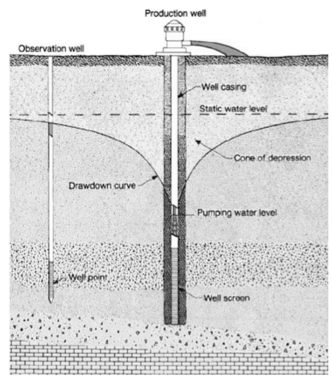
Aquifers and aquitards

- Geologic units present, continuity of aquifers (vertical and lateral extent), presence of faults and fractures
- Characterization methods: geologic surface mapping, drill hole logging, information from regional studies, mine block model, observations of aquifer response during pumping

Image: Cross section Robinson Mining District, Ely, NV. PTI Environmental Services 1993.

Hydrologic Characterization – Saturated Zone Properties

- Hydraulic properties of aquifers and aquitards: hydraulic conductivity, saturated thickness, storage coefficients, unconfined vs. confined units
- Methods for determining hydraulic conductivity (in order of decreasing reliability)
  - Pumping tests (multi-well for storage)
  - “Slug” tests
  - Laboratory permeability
  - Literature values for similar geologic materials



Driscoll, 1986.

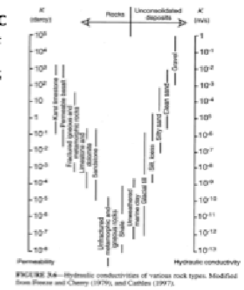
Hydrologic Characterization – K Value Issues

- Hydraulic conductivity ranges over orders of magnitude – need to capture heterogeneity
- Are data available for all significant aquifers/geologic units in mine area (unconfined, confined)?
- Are data grouped in space or time?
- Is flow channelized into higher permeability zones, fractures, conduits?

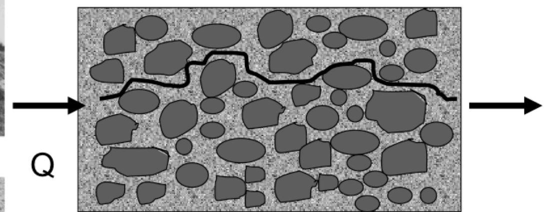
Monitoring well near Robinson District, Ely, Nevada.
Photo credit: Connie Travers.

Relative hydraulic conductivities of major rock types

From Plumlee (1999)

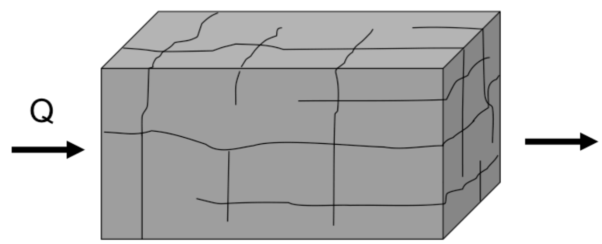


Groundwater Flow Paths in Porous Medium (intergranular flow)



Example: Sandstone

Groundwater Flow Paths in Fractured Rock
(most hardrock mine sites)

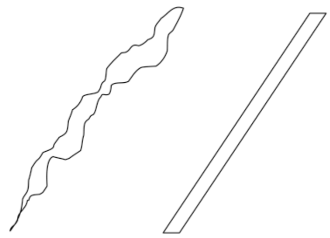


Examples: slate, granite, gneiss

Fractured Rock

Flow is dependent on fracture

- Connectivity
- Spacing
- Aperture (opening)
- Density



Real world fracture vs. ideal fracture

Such data are typically limited or absent at sites

"Equivalent porous medium" often assumed to simplify system

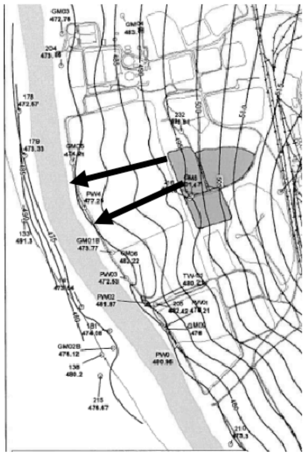
System may be highly anisotropic

Flow directions and contaminant transport hard to characterize, understand, and predict

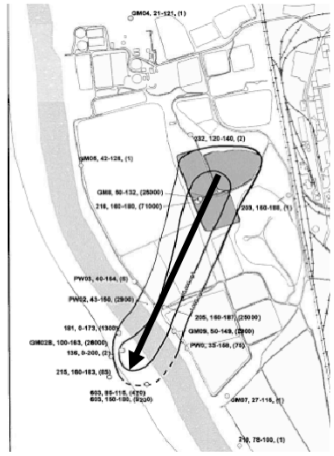
Characterization of Flow Paths in Fractured Rock

- Big challenge – crucial yet difficult to characterize
- Surface/borehole mapping pre-mining; more information as mining progresses
- Fractures aperture, connectivity cannot be measured directly – need hydraulic or tracer tests
- Individual fractures can be tested using packers in boreholes
- Downhole testing (flow meters, geophysical logging, video)
- Tracers, isotopes (Lecture 2)

Fractures Can Create Unexpected Flow Paths and Rapid Travel Times: Avtex Superfund Site



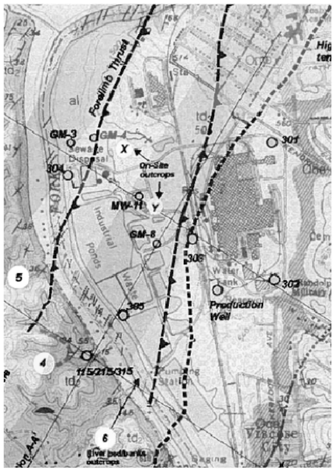
1. Groundwater gradient inferred from water level measurements



2. Direction of contaminant plume migration

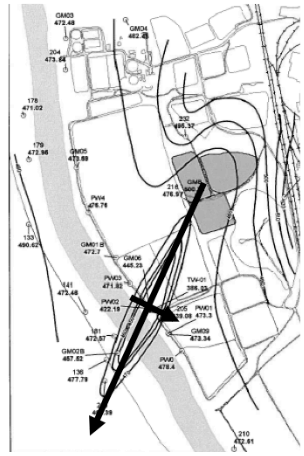
Exponent, 2001.

Fractures Can Create Unexpected Flow Paths – Example from Avtex Superfund Site



Golder Associates, 2001.

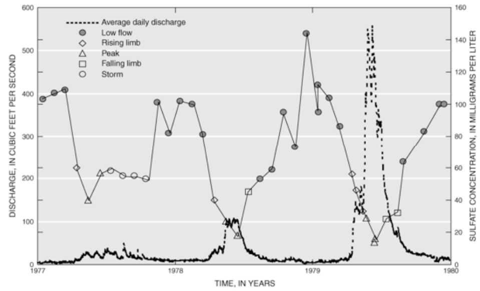
1. Shale bedrock folds and structure



Exponent, 2001.

2. Anisotropy caused by fractures apparent in pumping test drawdown

Sources of Uncertainty in Hydrologic Characterization



Red River, Questa Mine, NM.
Maest et al., 2005.

- Large natural (e.g., seasonal) variability in hydrologic and geochemical conditions
- Inability to sample "all" material of interest – must infer from limited number of samples
- Measured parameters at points, or in lab, may not represent larger field-scale processes
- Hydrogeologic complexity, particularly fractures
- Extrapolation to future (e.g., changing climatic conditions)

Influence of Mine Facilities on Hydrologic Processes and Contaminant Pathways

- Potential effects of mine facilities, operations, and mine water management on water quantity and quality
- Effective mitigation measures
- Design of mine facilities such as tailings dams, diversions, culverts, stormwater detention ponds

Round Mountain Mine, Nevada.
Photo credit: David Schumacher.

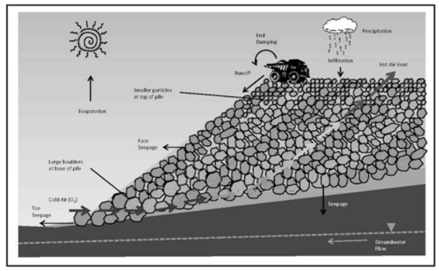
Influence of Mine Facilities on Hydrologic Processes and Contaminant Pathways

- Changes in near-surface processes (change in evapotranspiration, runoff, recharge rates)
  - Interruption/change in recharge (waste rock, heap leach, tailings impoundments, pits)
  - Infiltration of wetting front through waste rock, discharge/loading to groundwater
  - Tailings impoundments – discharge/loading to groundwater
  - Creation of pregnant and barren ponds and pit lakes increases evaporative losses

Influence of Mine Facilities on Hydrological Processes and Contaminant Pathways (cont.)

- Changes in groundwater and surface water flow
  - Dewatering of pits and underground mines – influence on spring and stream flows
  - Flooding of underground workings – conduits for flow and transport
  - Discharge of treated mine water – influence on surface water quantity and quality
  - Creation of pit lakes and impoundments alters groundwater flow patterns and pathways

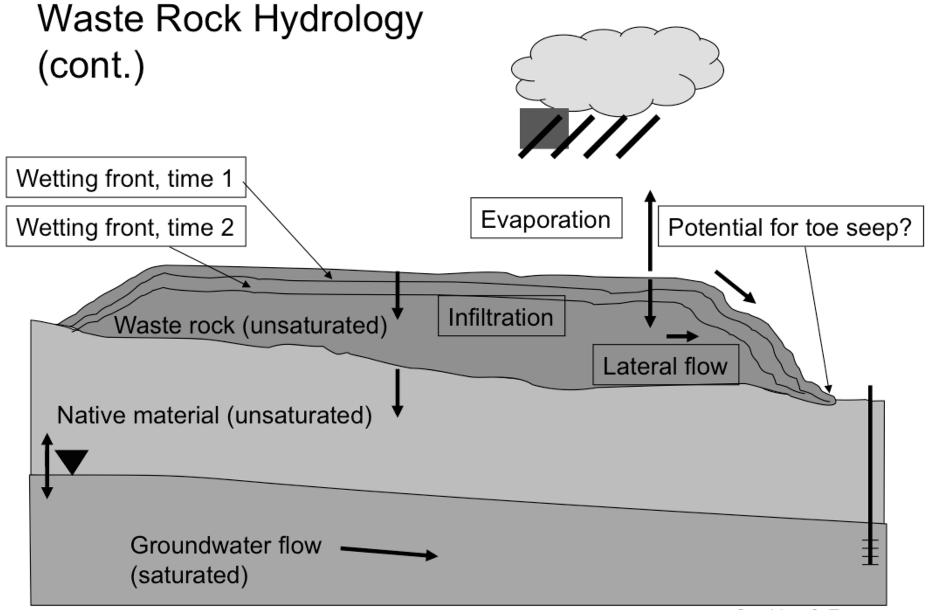
Waste Rock Hydrology



http://www.gardguide.com/index.php/Image: ARDNMDandSDinaWasteRockPile.jpg.

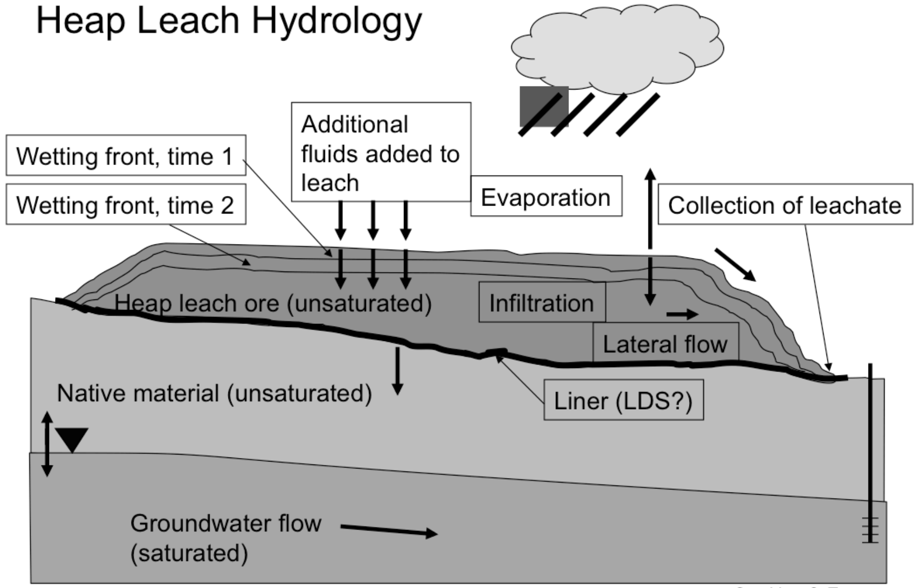
- Low initial moisture content
- Infiltration during/after snow melt, precipitation
- Wetting front migrates from surface of dump downward; in arid environments could take tens to hundreds of years
- Dump may have low permeability layers (lifts) and macropores that influence hydrology
- Waste rock covers typically designed to increase evapotranspiration/decrease infiltration

Waste Rock Hydrology (cont.)



Graphics: C. Travers.

Heap Leach Hydrology



Graphics: C. Travers.

Tailings Impoundment Hydrology

- Tailings slurry contains fines (silt/clay range) with high water content (pores saturated)
- Fluctuating water levels (wetting/drying, draining) can oxidize sulfides, generate ARD/ML and secondary metal salts
- Water cover may be maintained on impoundment
- Unlined tailings impoundment will drain slowly to groundwater
- Covers typically designed to increase evapotranspiration and/or decrease infiltration

Tailings Impoundments

TAILINGS LAYERS

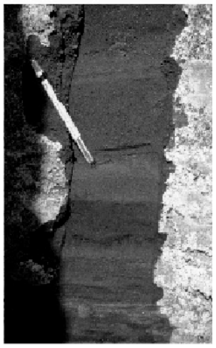
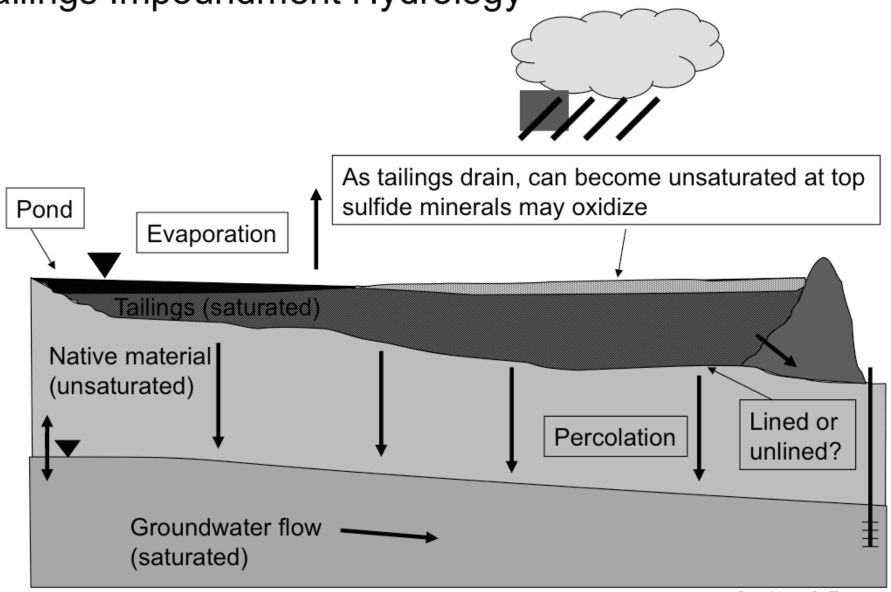


Photo credit: Bullfrog tailings, NM, SARB Consulting, 2009.

Betze Pit tailings, Nevada.

Tailings Impoundment Hydrology



Graphics: C. Travers.

Dewatering and Flooding of Open Pits

- Mine/pit dewatering can lower water table/cone of depression and flows in springs, streams
- Post-mining
  - Evaporative sink, evaporative concentration
  - Flow-through, potential for groundwater degradation
- Pit backfill could alter hydrology and contaminant pathways

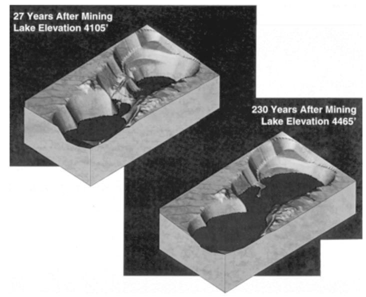
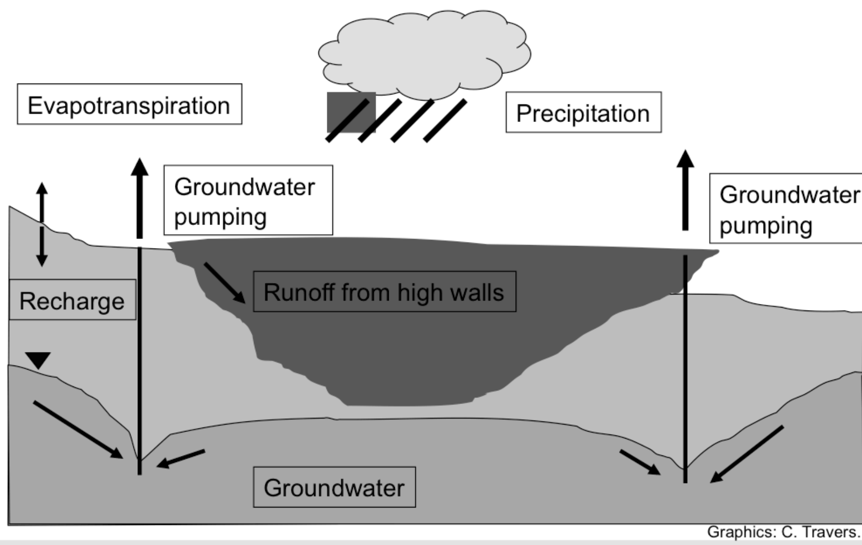


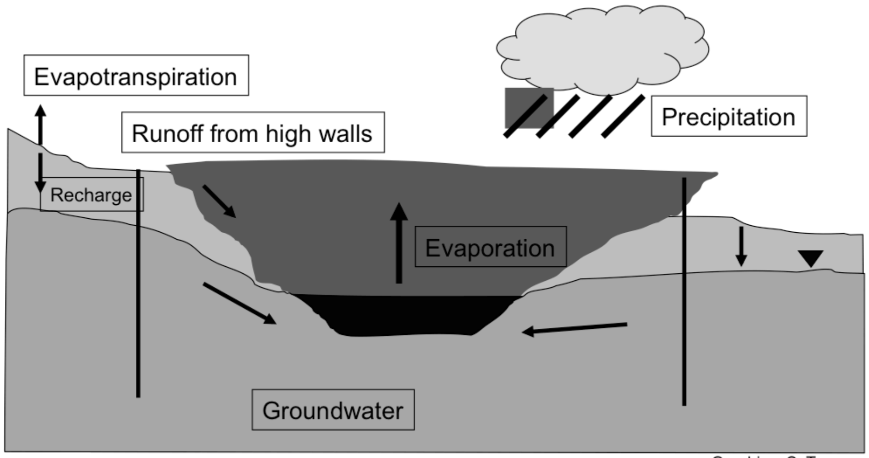
Image from PTI Environmental Services, 1996.

Operation: Dewatering of Open Pits



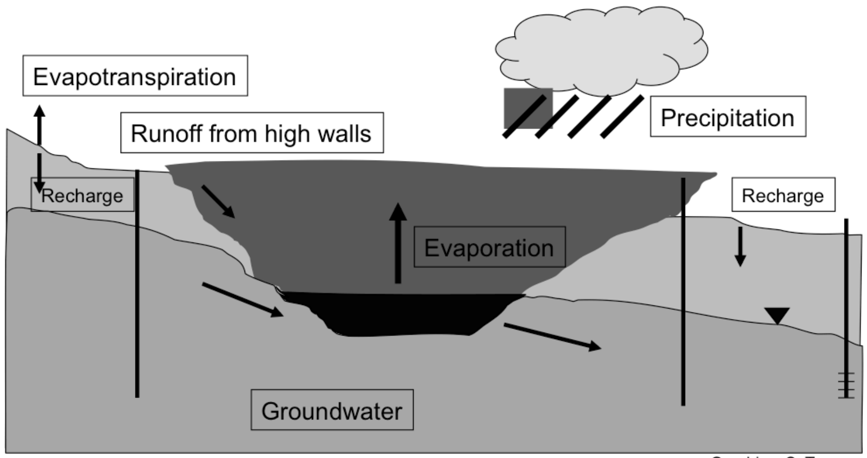
Graphics: C. Travers.

Post-mining: Cessation of Pumping, Pit Lake Formation – Evaporative Sink



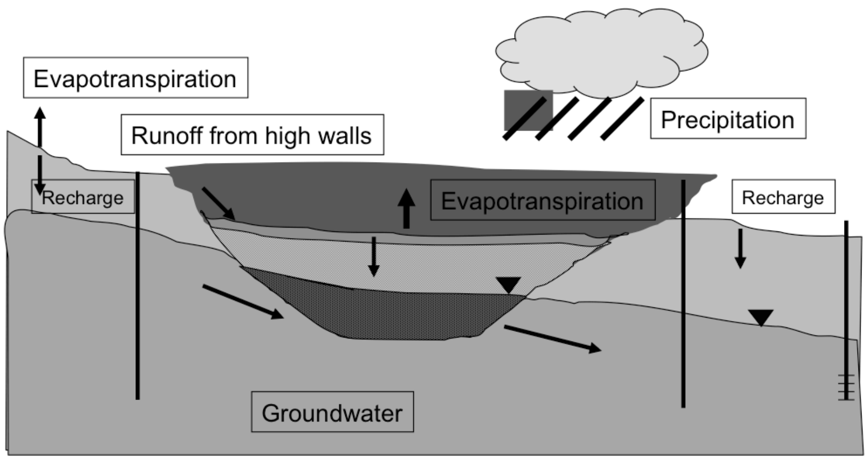
Graphics: C. Travers.

Post-mining: Cessation of Pumping, Pit Lake Formation – Flow-through Pit



Graphics: C. Travers.

Post-mining: Cessation of Pumping, Pit Backfilled with Waste Rock

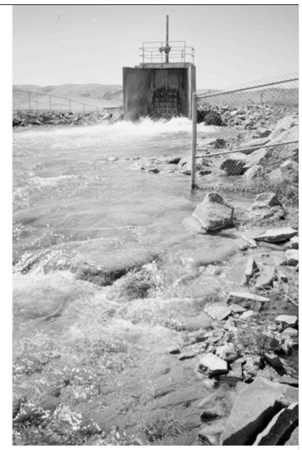


Graphics: C. Travers.

Hydrologic Characterization: Mine Plan over Time

Changes in mine plan often result in changes in hydrologic conditions – may need to re-evaluate as mine plan changes

- Increased hydrologic information as mining proceeds
- Expansion of mine/facilities
- Dewatering/flooding of open pit or underground workings
- Closure of facilities



Discharge from Barrick Goldstrike Mine, Nevada.

Photo credit: Connie Travers.

Summary – Hydrologic Characterization : Processes and Pathways

- Baseline/pre-mining
  - Characterize natural hydrologic system
  - Need good understanding of water balance (capture natural variability), site-wide and within facilities
  - Mine sites: complex flow systems, especially fractured rock
- Mine-altered hydrologic system
  - Changes in recharge/discharge/flow paths – facilities and mine water management
  - Loading of contaminants/changes in water quality
  - Re-evaluate as mining proceeds – additional data; changes in mine plan