Final Covers for Mine Tailings

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Functions of Covers

- Physical containment of waste
- Control percolation into waste
- Control gas movement
  - Ingress (O_2)
  - Egress (Rn, CH_4, CO_2)
- Control vector intrusion
- Persist for design life of containment facility

Categories of Engineered Covers

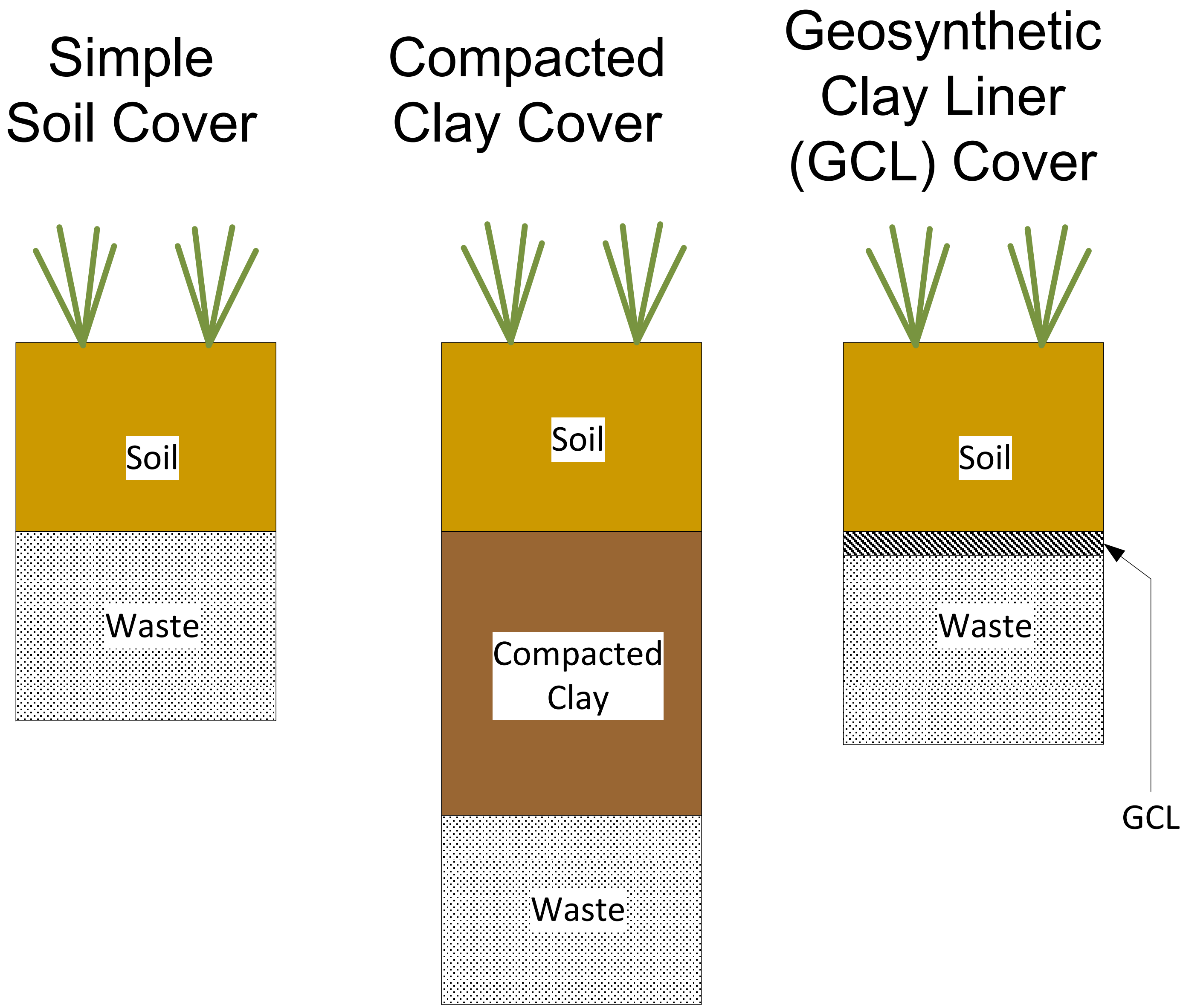
Conventional covers – cover designs where a barrier layer (clay, geomembrane, etc.) having low saturated hydraulic conductivity is the primary impediment to leakage and gas flow.

clay covers, composite covers, GCL covers

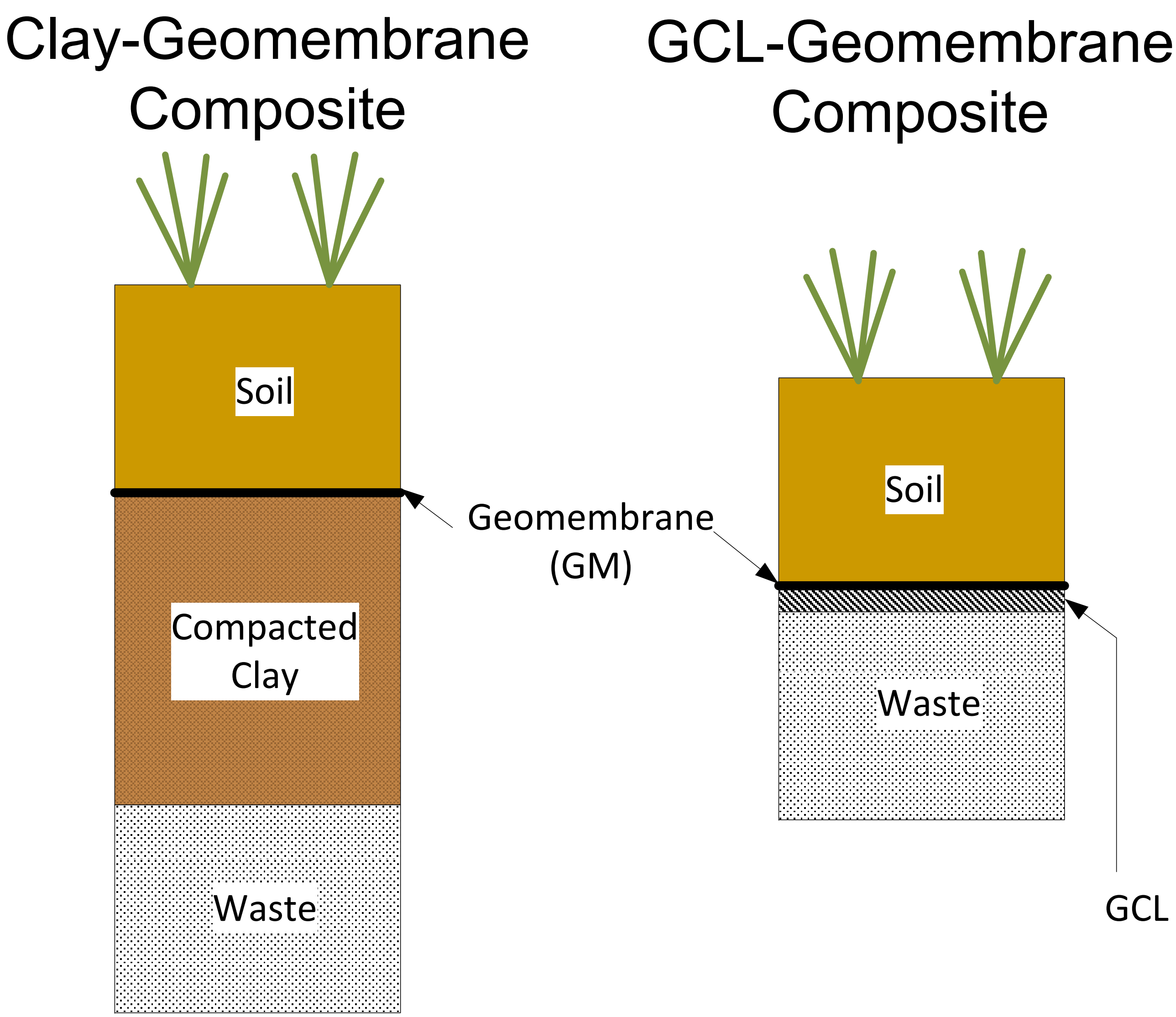
Water balance covers – cover designs where leakage is controlled by balancing the water storage capacity of unsaturated finer-textured soils and the ability of plants and the atmosphere to extract water stored in the soil. Also known as *water balance* covers, *evapotranspiration* (ET) covers, *store-and-release* covers.

monolithic covers, capillary barrier covers

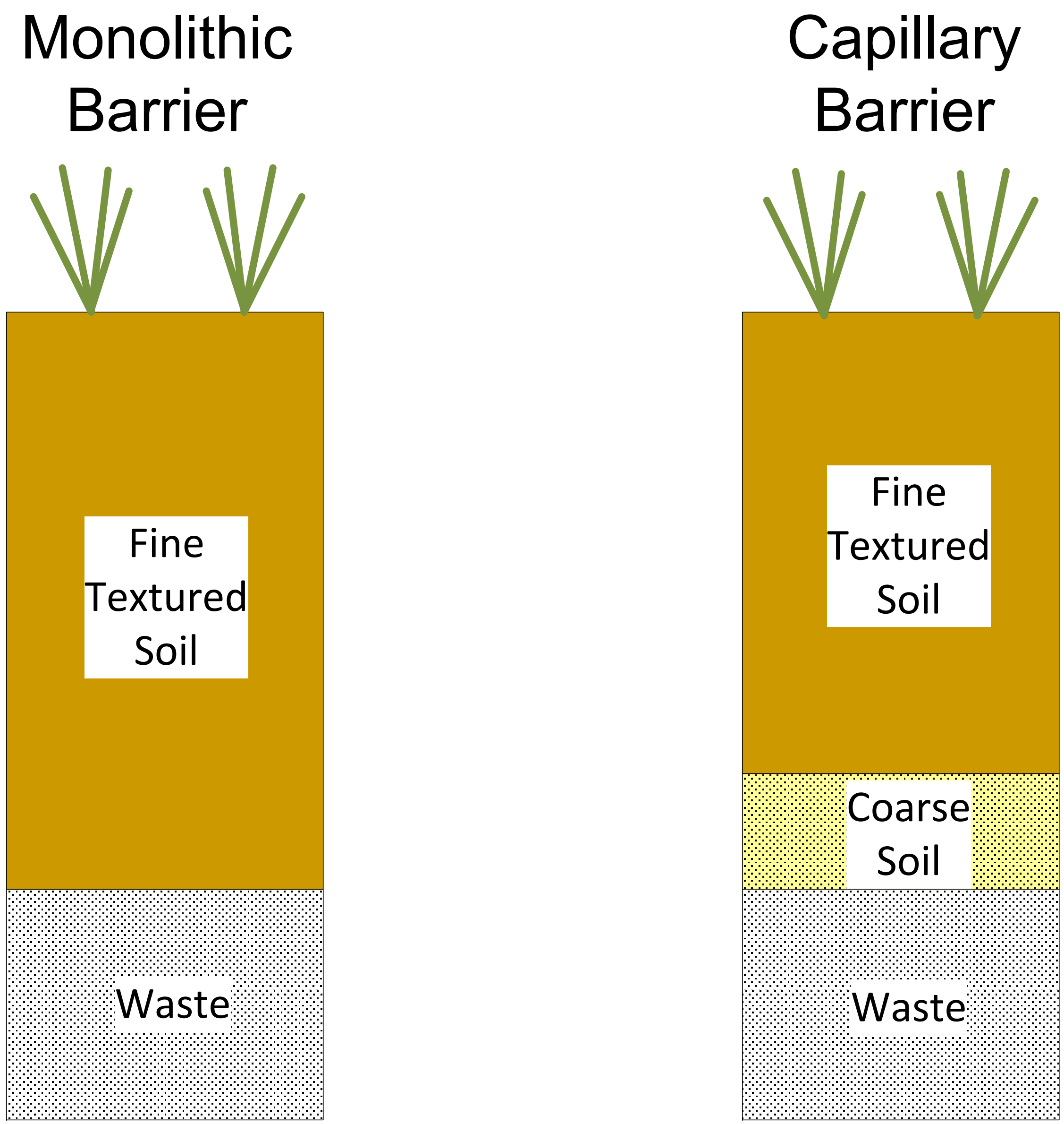
Conventional Resistive Covers with a Soil Barrier



Conventional Resistive Covers with a Composite Barrier



Water Balance Covers



Cover Type	Percolation Rate	Gas Flux	Cost ($/ac)
Simple Soil	Highest	Highest	25,000
Clay	Modest	Modest	75,000
GCL	Modest	Modest	75,000
Composite	Very low	Very Low	125,000
ET Monolithic	Very low - low	Modest	50,000
Capillary Barrier	Very low - low	Modest	50,000

Design Philosophy

Conventional Designs

- regulatory engineering, not site specific
- methods & materials requirements
- no quantitative performance criterion

Alternative (Performance-based) Design

- determine performance criterion (e.g., percolation ≤ prescriptive cover)
- select layering to meet a quantitative performance criterion
- analyze to ensure alternative cover meets performance criterion

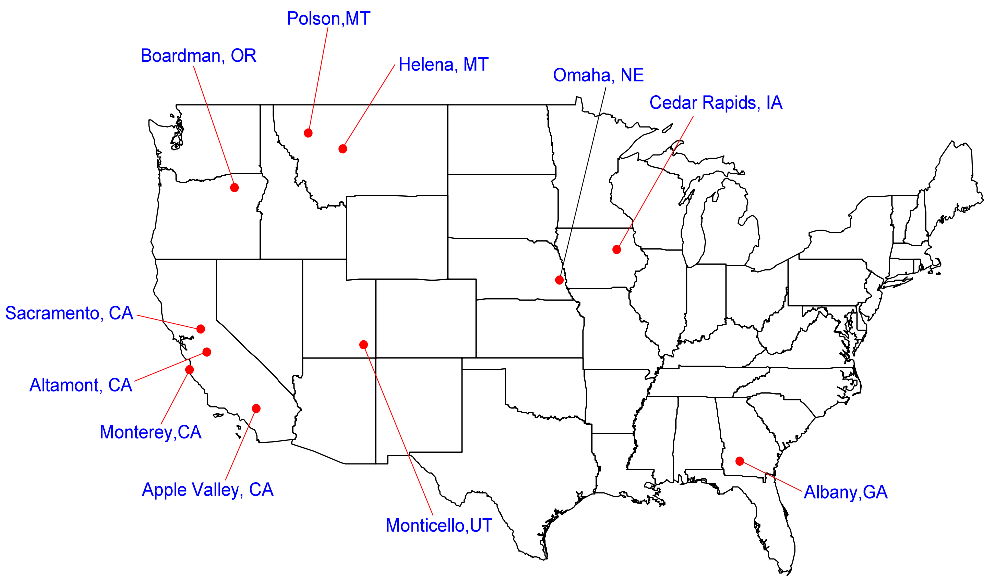
Issues with Prescriptive Regulation

1. With conventional designs typically no performance criteria
2. Alternative designs typically required to show equivalent performance (see 1)
3. Equivalency demonstration is difficult
4. Primary goal (protect HH&E) often neglected
5. Cost (to society) can be higher than necessary
6. An example of the rule of unintended, undesirable consequences
7. Common with indirect regulation

An Alternative Regulatory Philosophy

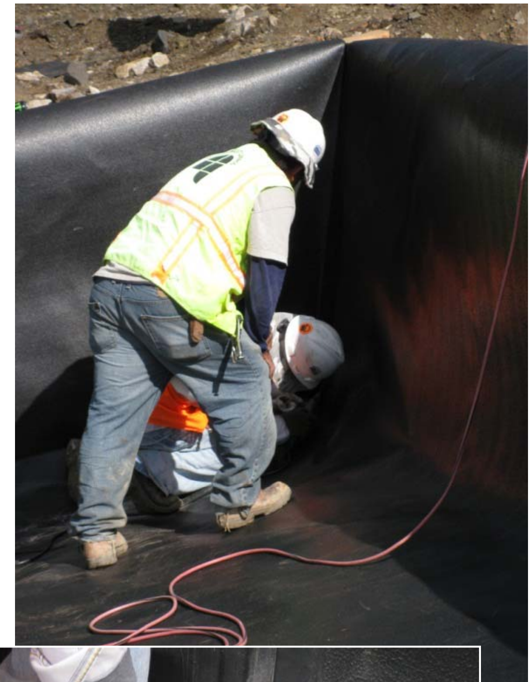
- Focus on primary goal (ex. protection of ground water)
- Prescriptive design *process*
  - Type of waste?
  - Waste packaging?
  - Climate?
  - Depth to groundwater?
  - Attenuation capacity of unsaturated zone?
  - Distance to nearest receptor (ex. pumping well)?
  - Any sensitive environments or species?
  - Each site will have a different list
- Require design engineer to demonstrate compliance with primary goal
- Require appropriate monitoring

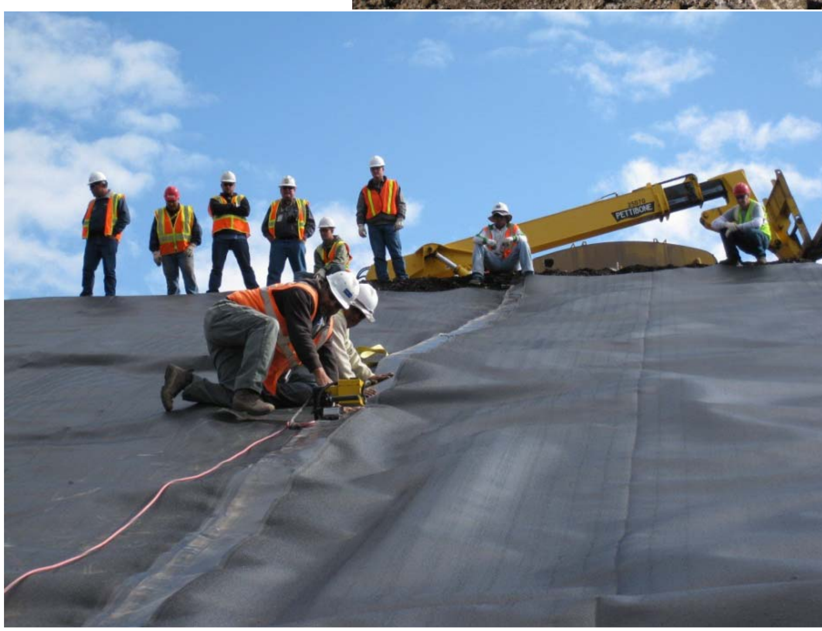
USEPA's Alternative Cover Assessment Program (ACAP)



- Twenty-four test covers at eleven sites in seven states.
- Ten conventional covers (seven composite and three clay)
- Fourteen alternative covers (eight monolithic barriers and six capillary barriers)
- Eight sites with side-by-side comparison of conventional and alternative covers

ACAP Drainage Lysimeters



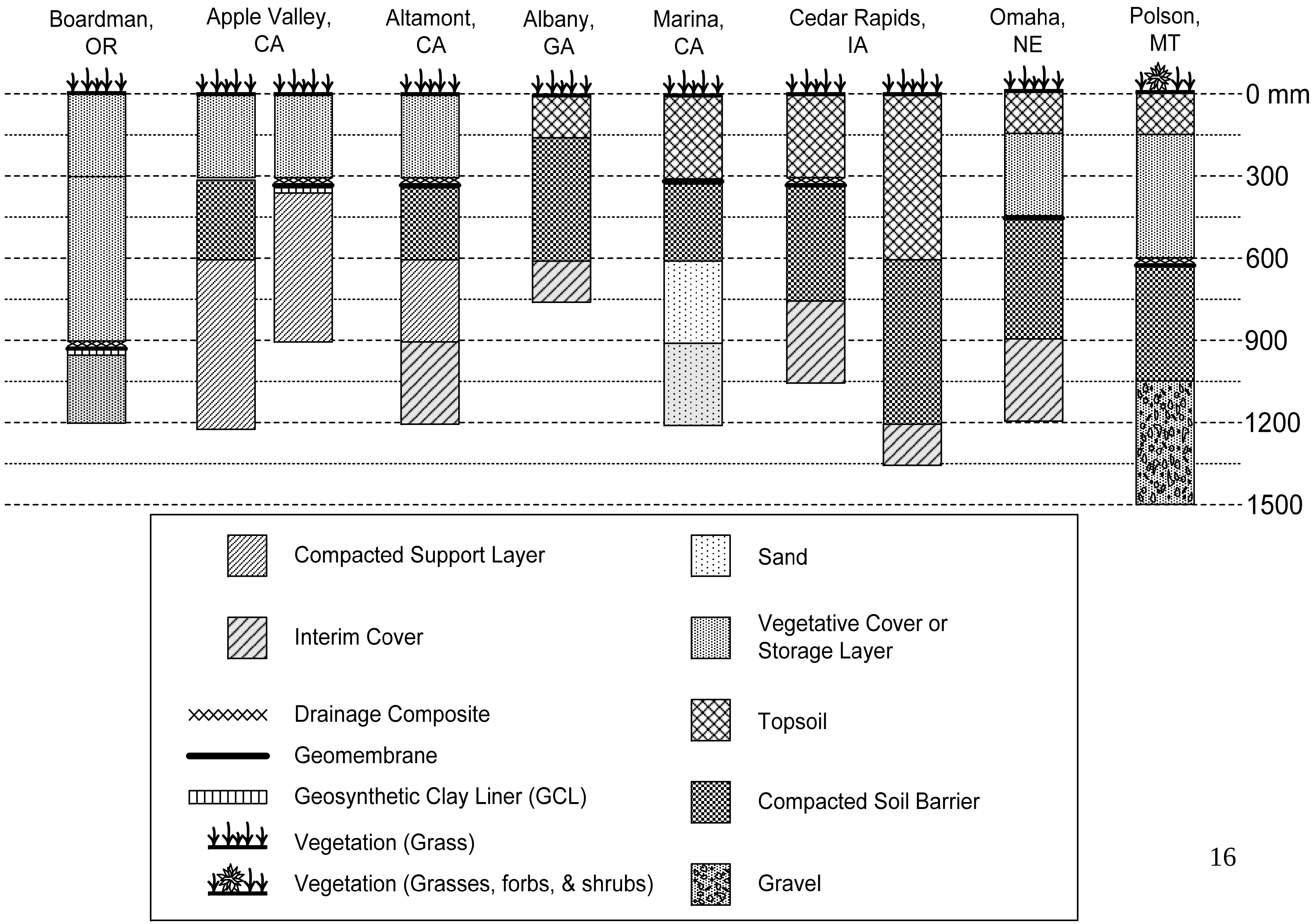


Full-scale construction methods

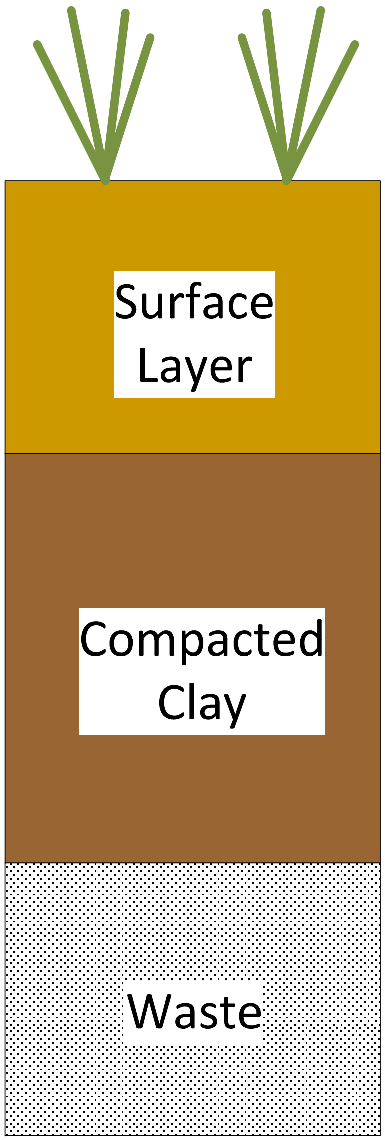
Hundreds of samples and instruments

Lysimeters are the only method for direct measurement of drainage

Conventional Covers Evaluated by ACAP



Compacted Clay Covers



150-1000 mm thick
(6 – 40 inches)

450-900 mm thick
(18 – 36 inches)

Objectives:

(1) Construct a soil barrier (compacted clay) with low saturated hydraulic conductivity.

(2) Protect the clay barrier from damage that may increase hydraulic conductivity

Types of Damage

- Frost

- Desiccation

- Differential settlement (normally a problem with municipal solid waste, but not mining wastes, coal ash, etc.)

- Erosion

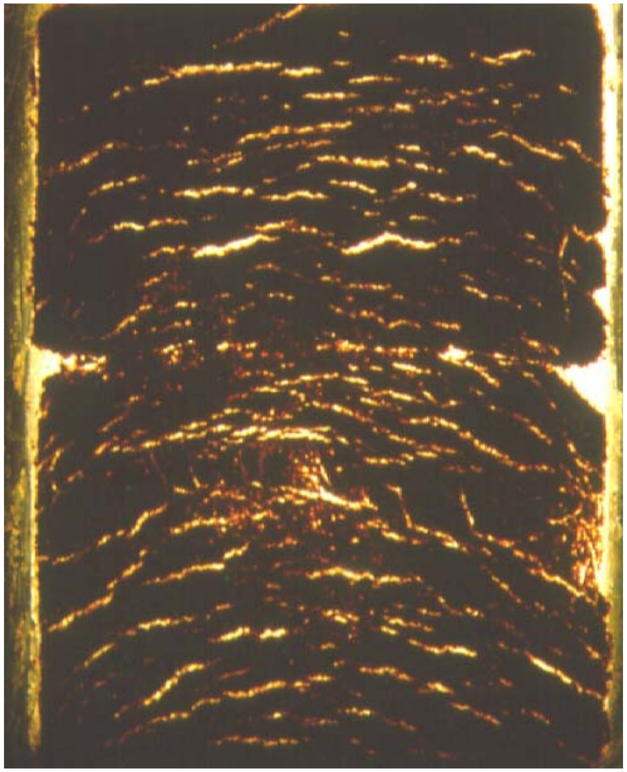
Sensitivity to Frost Damage

Freezing of compacted clay barriers causes:

- formation of ice lenses: cracking

- formation of desiccation cracks as water moves to freezing front

- cracking that causes increases in hydraulic conductivity



Protect clay barrier with insulation (synthetic or burial).

Sensitivity of Compacted Clay to Desiccation Damage

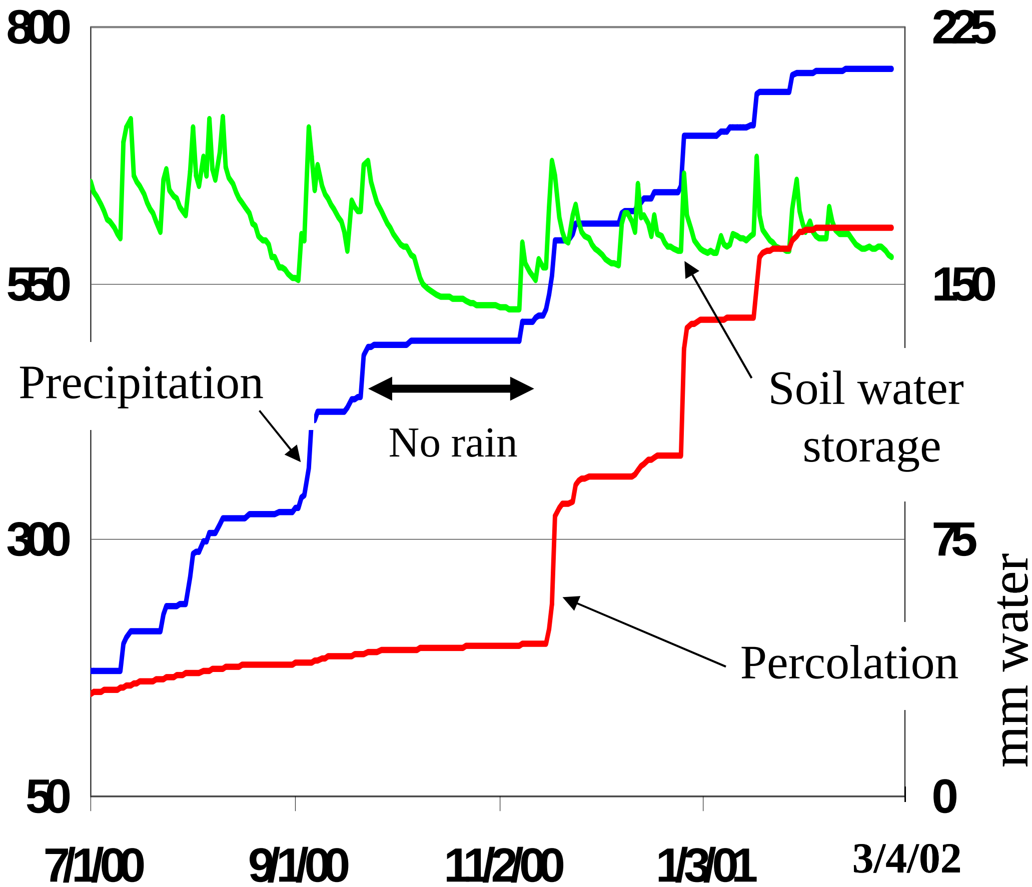
Drying of compacted clay barriers causes desiccation cracks to form, increasing the hydraulic conductivity.

Large-scale cracks may form, as in this clay barrier in southern Georgia four years after construction.

Dye tracer test in soil barrier cover showing preferential flow path

Conventional Clay Cover Performance

- Soil dried for first time during 6-week drought
- Change in response of percolation to precipitation events
  - Quantity
  - “Stair step” response
- No evidence that defects in clay barrier healed when soil water increased

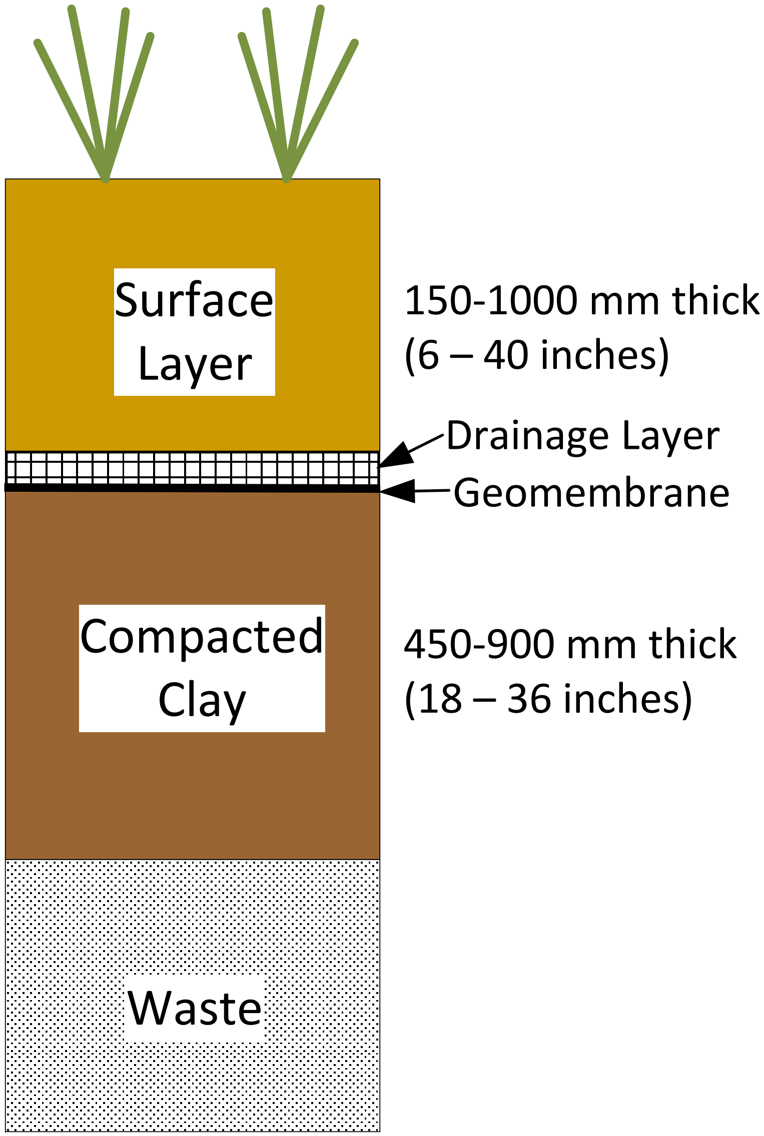


Data from ACAP field site in Albany GA

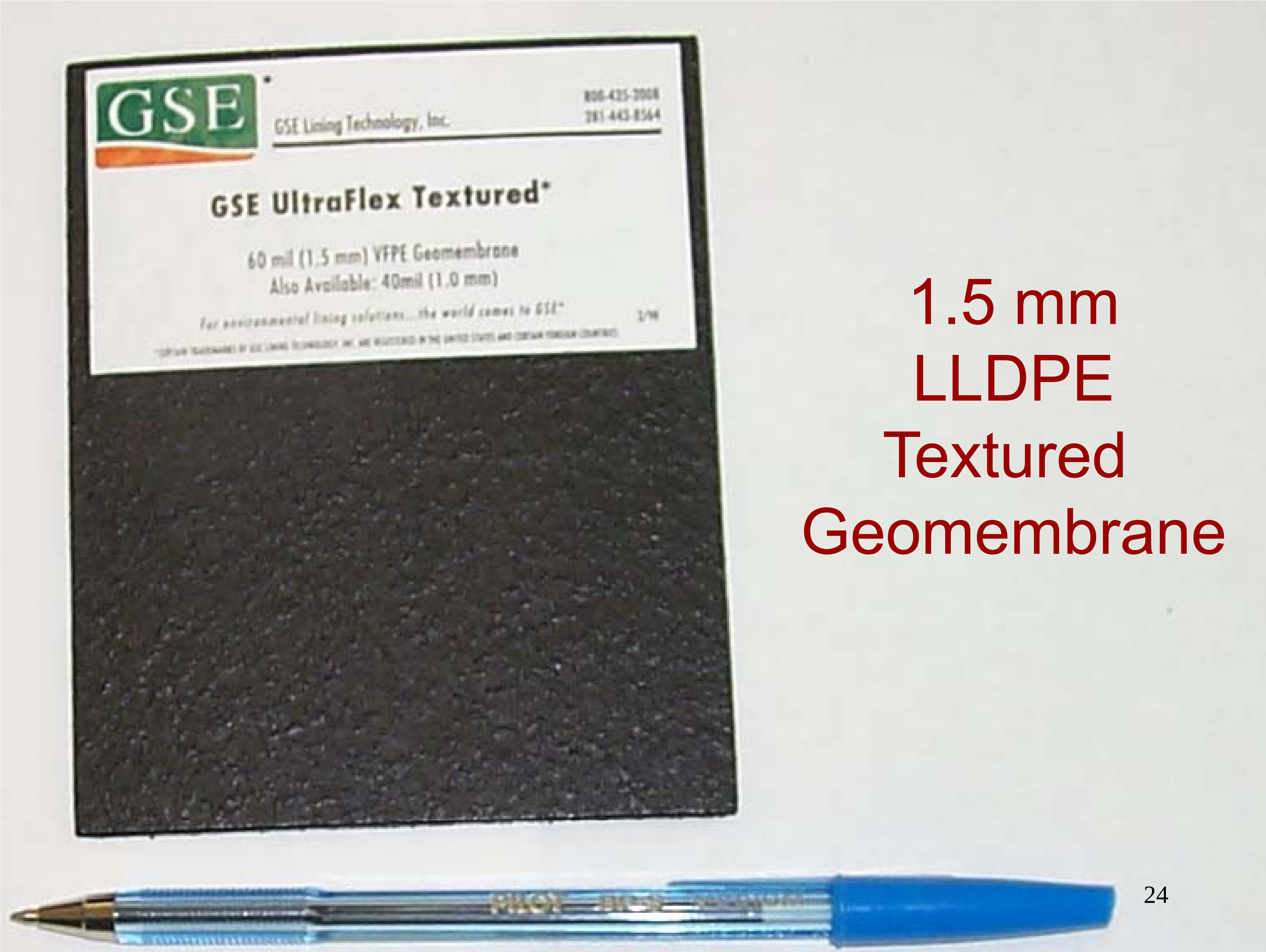
Field Hydraulic Conductivity Measurements on Clay Barrier 4 Years After Construction

Test	Hydraulic Conductivity (cm/s)	$K_{final}/K_{as\text{-}built}$
As-Built	4.0×10^{-8}	1.0
SDRI	2.0×10^{-4}	5000
TSB - 1	5.2×10^{-5}	1300
TSB - 2	3.2×10^{-5}	800
TSB - 3	3.1×10^{-3}	77,500

Typical Composite Cover



- Geomembrane added directly on top of clay barrier or GCL
- Drainage layer frequently added on top of geomembrane to enhance stability by limiting pore water pressures.



1.5 mm
LLDPE
Textured
Geomembrane

Geocomposite Drain

For covers, chemical compatibility normally is not a concern when selecting geomembrane polymer. Key issues are:

- constructibility
- durability
- cost
- availability with texturing

All of the cited geomembranes can be welded in the field using wedge or extrusion techniques to obtain welds with higher strength than parent material.

LLDPE and HDPE geomembranes are most commonly used for covers

Drainage Layers

Functions:

Reduce Head on Barrier Layer

-Reduce Pore Pressure Build Up

Materials:

- Coarse-Grained Soil (clean sand, crushed rock)
- Geocomposite Drain

Design Approach:

-Select drain that provides acceptable head

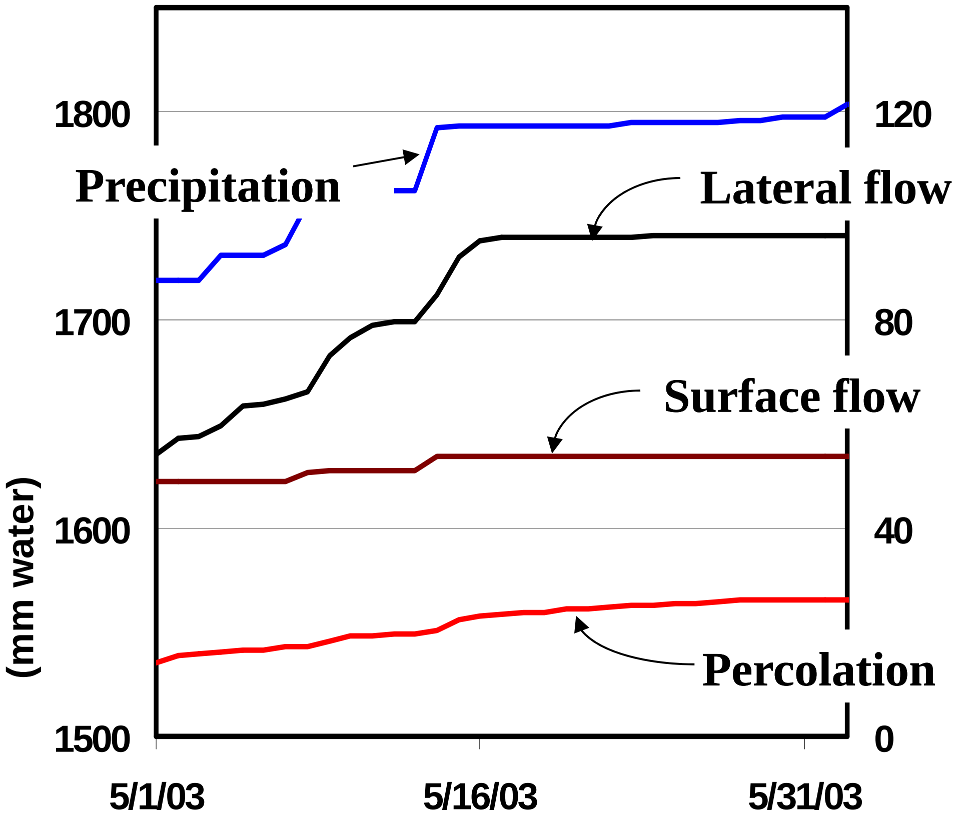
-Adequate hydraulic conductivity

-HELP, conservative (over-predicts lateral drainage)

-Giroud & Houlihan's Method

Conventional Composite Cover Performance

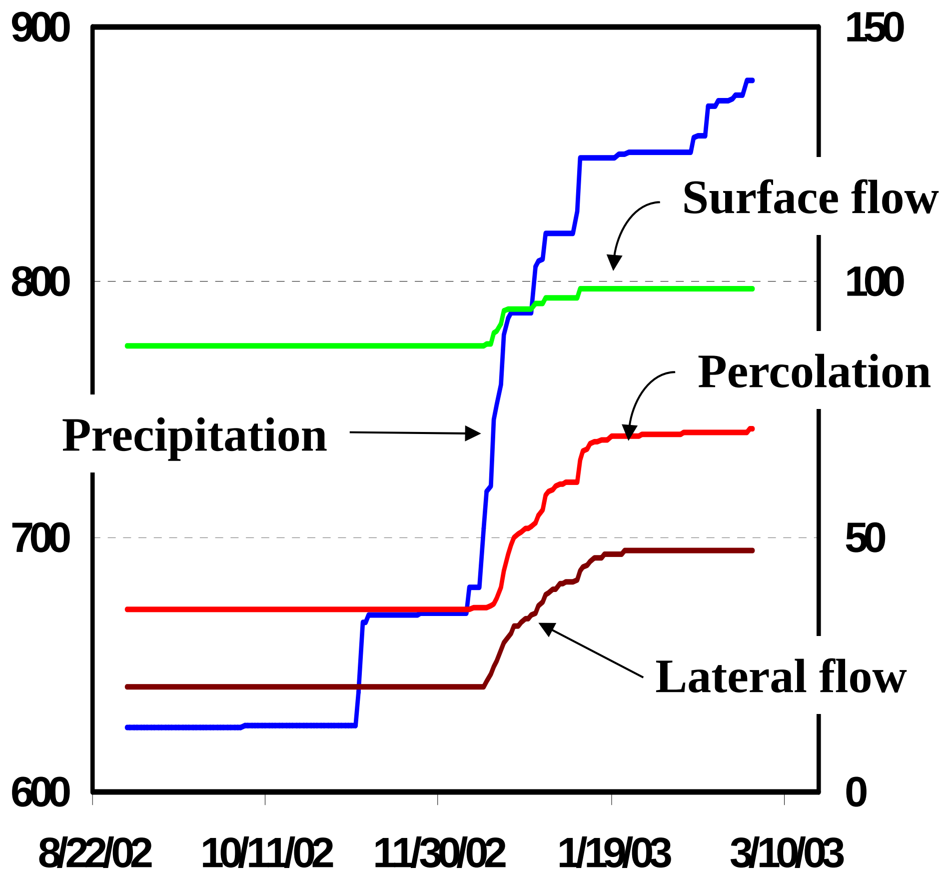
- Percolation correlated with
  - Heavy precipitation events
  - Surface flow
  - Lateral flow on geomembrane



Data from ACAP field site in Cedar Rapids IA

Damage to Geomembrane Affects Performance

- No cushion between the geomembrane and the soil, punctures likely in geomembrane
- Relatively high rate of percolation
- Illustrates importance of careful geomembrane installation

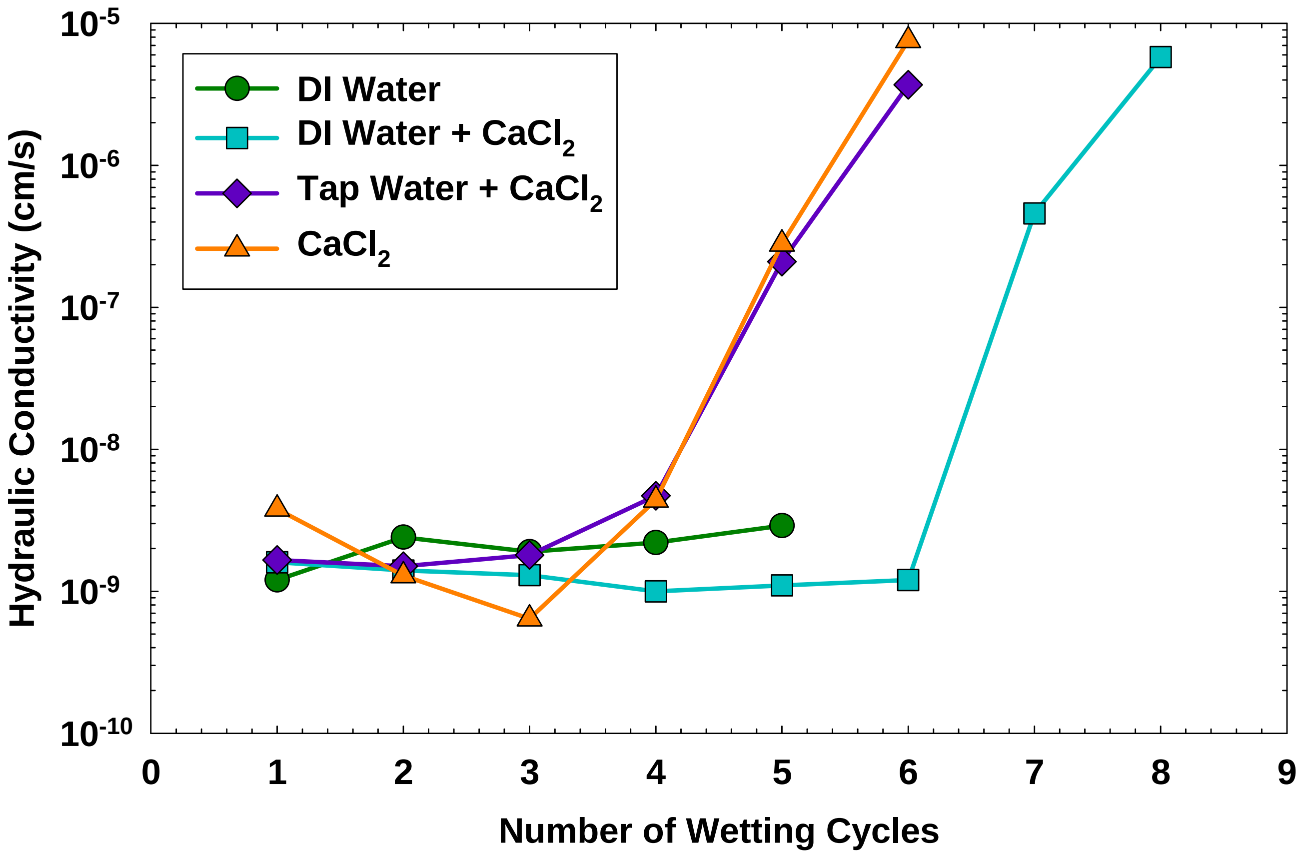


Data from ACAP field site in Marina CA

Summary: Conventional Designs

- Composite designs
  - Restrict percolation to low (<~5 mm/yr) levels at all locations
  - Percolation typically coincides with flow on membrane
  - Require careful construction practice and QA
- Clay barrier designs
  - Performance quickly (<2 yrs) degrades
  - Percolation probably due to preferential flow through macro-features related to desiccation, freeze/thaw, roots
  - Damage likely to persist
  - Probably not suitable for near-surface applications that require low-permeability barrier

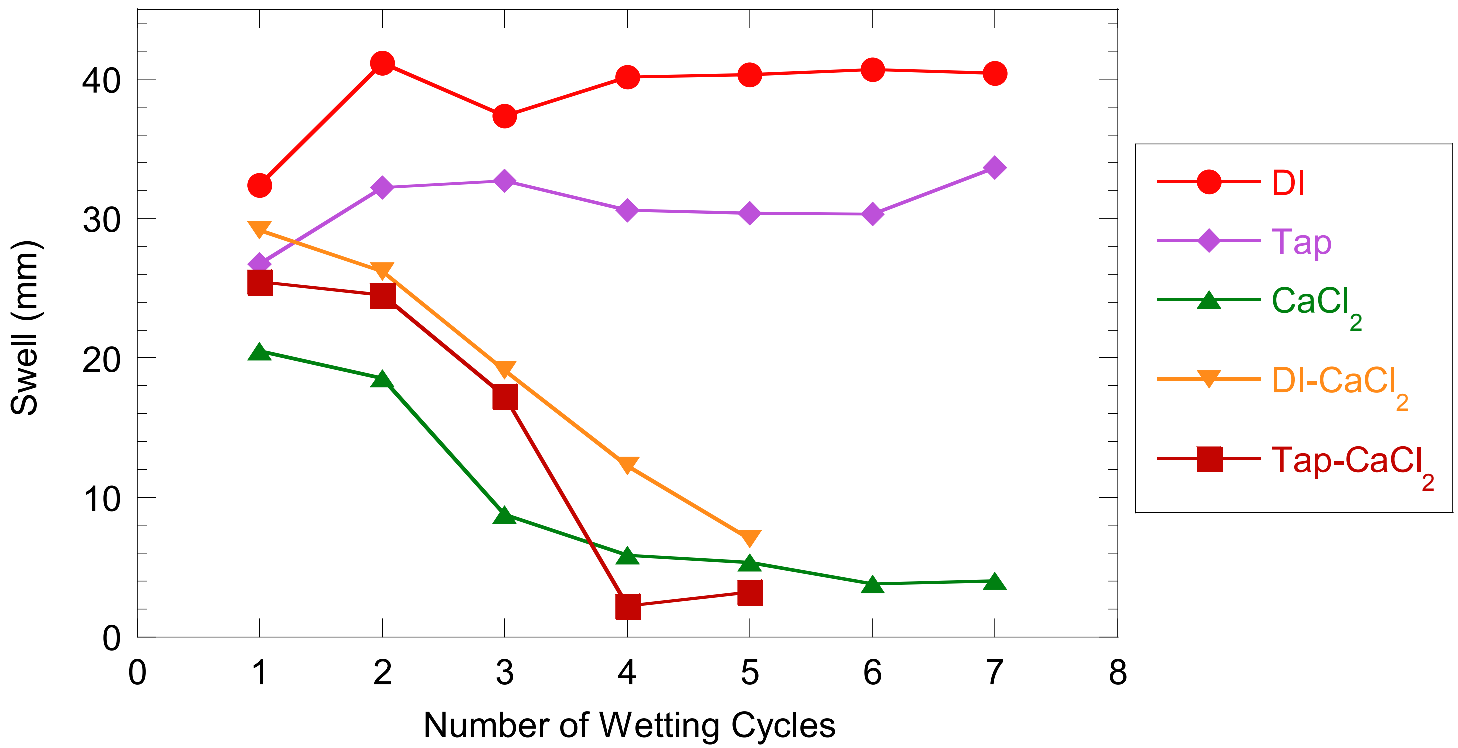
UW Desiccation Study:
Effect on Hydraulic Conductivity of GCLs



Divalent for monovalent cation exchange results in inability to close desiccation cracks, resulting in large increase in K.

*Lin, L. and Benson, C. (2000), Effect of Wet-Dry Cycling on Swelling and Hydraulic Conductivity of Geosynthetic Clay Liners, *J. of Geotech. and Geoenvironmental Eng.*, 126(1), 40-49.

UW Desiccation Study: Effect on Swelling of GCLs*



Divalent for monovalent exchange results in loss of swelling capability … and potentially healing capability

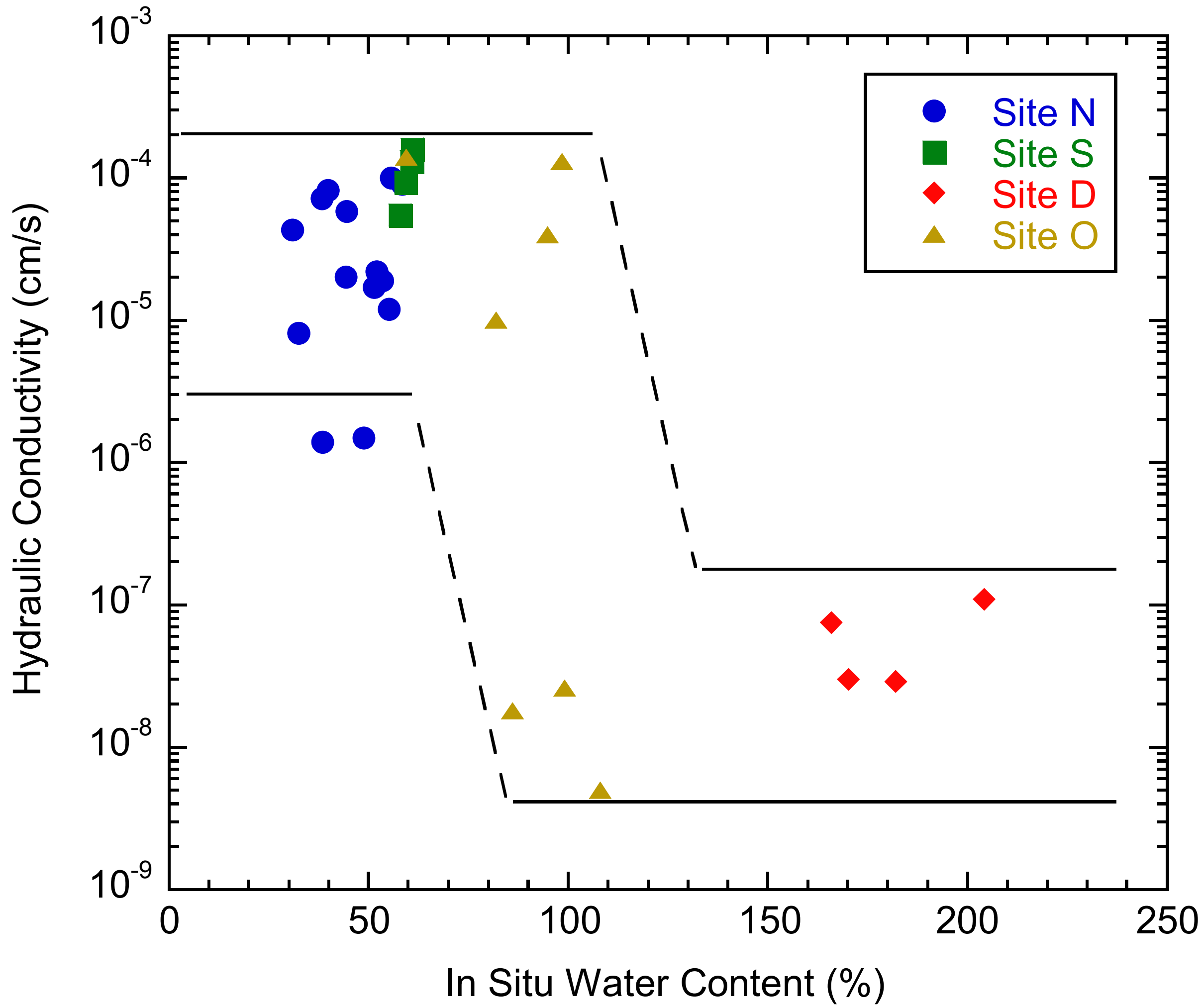
*Lin, L. and Benson, C. (2000), Effect of Wet-Dry Cycling on Swelling and Hydraulic Conductivity of Geosynthetic Clay Liners, *J. of Geotech. and Geoenvironmental Eng.*, 126(1), 40-49.

UW Study: GCLs Exhumed from In-Service Caps

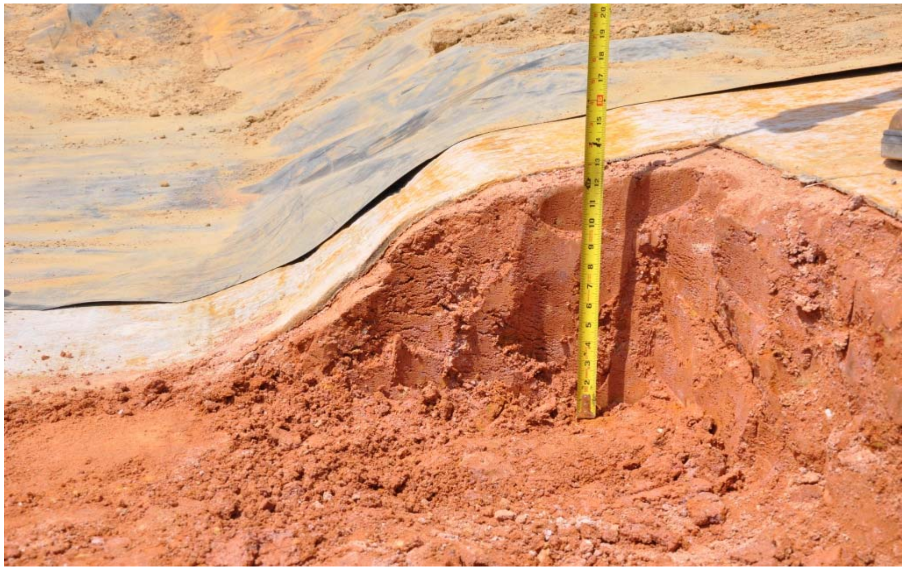
All specimens underwent Ca/Mg for Na exchange

Only those with w > 120% maintained low K

Need to protect GCL from drying and/or cation exchange.



Differential Settlement



- This case study has relatively small distortion
- Differential settlement an issue with waste containers
- Need more research

- Distortion
  - ~300 mm V
  - ~450 mm H
- No damage to GM
- Large increase in K to soil barrier
- GCL
  - Extensive cation exchange
  - Retained very low hydraulic conductivity
  - Humid climate and overlying GM – hydrated quickly, did not experience desiccation
- Cover likely retained function due to intact GM and GCL

ACAP Data for Conventional Covers

Cover Type	Site	Precipitation Average (mm/yr)	Surface Runoff Average (mm)	Lateral Flow Average (mm)	ET Average (mm)	Percolation Average (mm/yr)
Composite	Altamont	379	59.0	4.0	1.5	0.1*
	Apple Valley	169	6.8	0.0	0.0	Trace
	Boardman	177	0.0	0.2	0.0	0.0*
	Marina	433	98.7	47.4	23.1	28.3
	Polson	350.0	17.7	40.5	0.4	Trace
	Cedar Rapids	981	54.1	96.2	12.2	2.8*
	Omaha	731	86.8	43.3	6.0	0.7*
Soil Barrier	Apple Valley	169	3.4	0.0	0.0	7.4 (4.1%)
	Albany	1263	359.4	NA	195.2	195.2 (17.1%)
	Cedar Rapids	981	79.6	29.5	51.6	51.6 (6.0%)

*Composite percolation data are scaled from field measurements to account for x10 increase in geomembrane flaws. Marina data not scaled due to geomembrane damage during construction

[yellow] = semi-arid/sub-humid/arid. [green] = humid.

Summary:
Field Performance of Conventional Covers

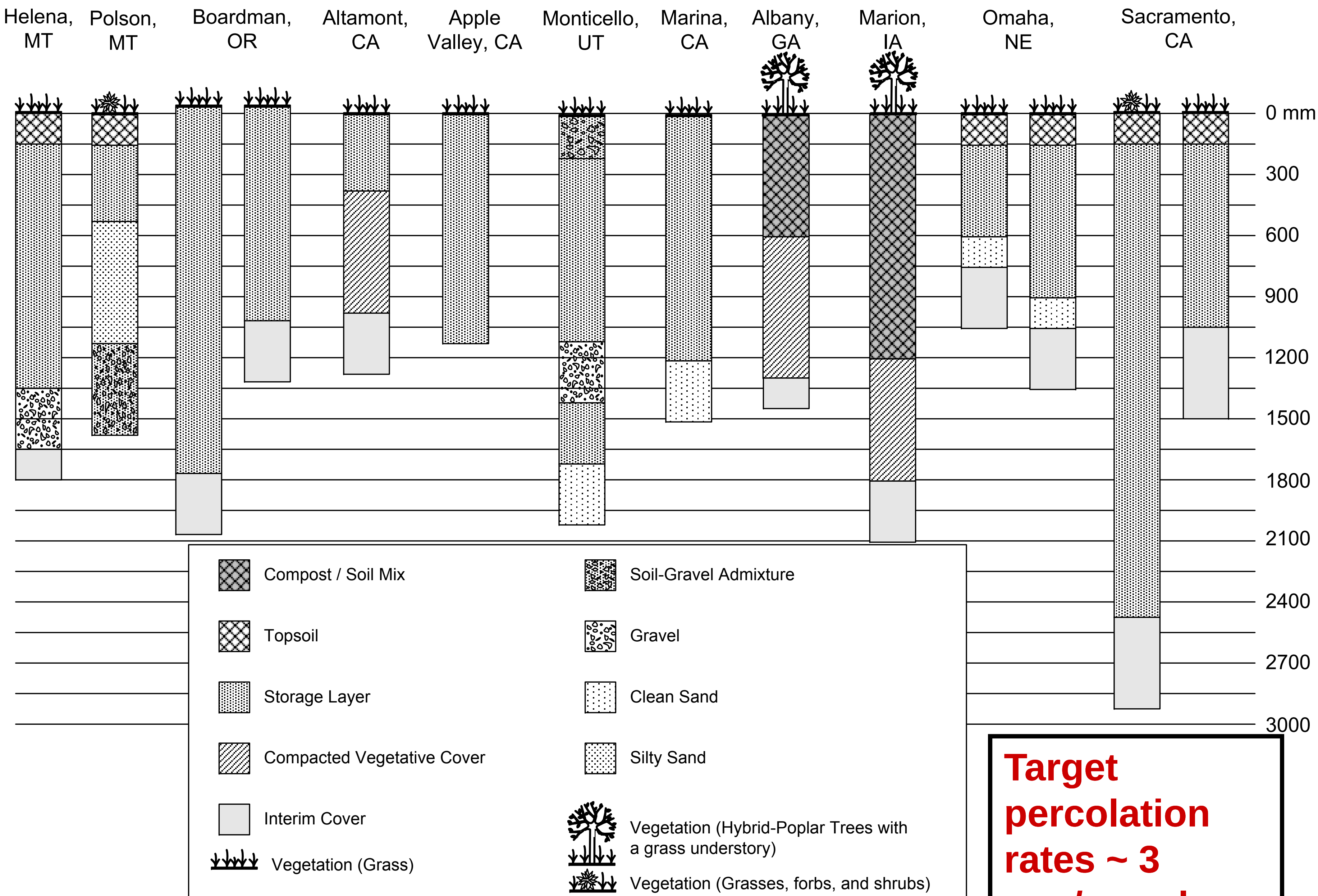
- Percolation rates for composites are very low:
    < 1 mm/yr in semi-arid and arid climates
    < 5 mm/yr in humid climates

- Percolation rates for soil covers much higher than expected:
    - 195 mm/yr at Albany, GA
    - appears dominated by preferential flow

- Surface runoff is a small fraction of the water balance (<10%)

- Lateral drainage is a small fraction of the water balance (< 5%)

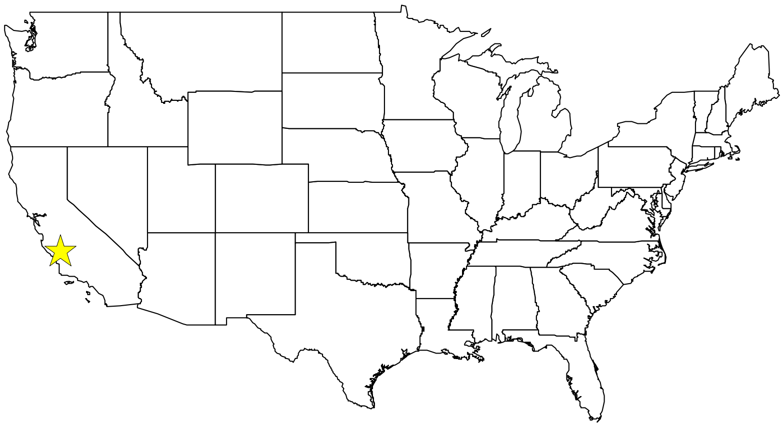
Water Balance Covers Evaluated by ACAP

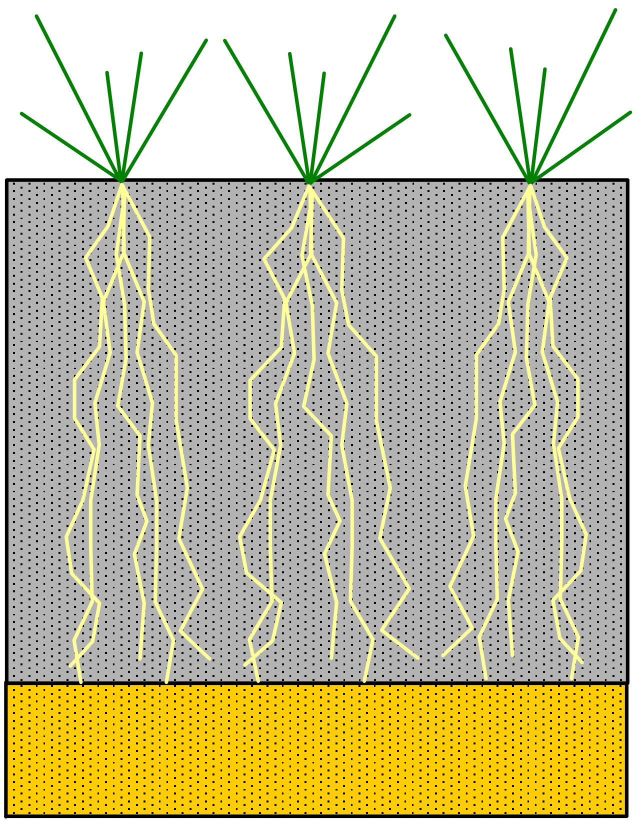


Target percolation rates ~ 3 mm/yr or less.

ACAP Site Characteristics

Site Location	Elev. (m)	Annual Precip. (mm)	Annual Snowfall (mm)	Annual P/PET	Climate	Monthly Avg. Air Temp.
Apple Valley, CA	898	119	38	0.06	arid	-1, 37
Boardman, OR	95	225	185	0.23	semi-arid	-2, 32
Helena, MT	15	312	1288	0.44	semi-arid	-11, 28
Altamont, CA	227	358	2	0.31	semi-arid	2, 32
Monticello, UT	1204	385	1498	0.34	semi-arid	-9, 29
Sacramento, CA	320	434	0	0.33	semi-arid	3, 34
Underwood, ND	622	442	813	0.47	semi-arid	-19, 28
Marina, CA	31	466	0	0.46	semi-arid	6, 22
Polson, MT	892	380	648	0.58	sub-humid	-7 ,28
Omaha, NB	378	760	711	0.64	sub-humid	-6, 25
Cedar Rapids, IA	290	915	724	1.03	humid	-8, 23
Albany, GA	60	1263	3	1.10	humid	8, 33

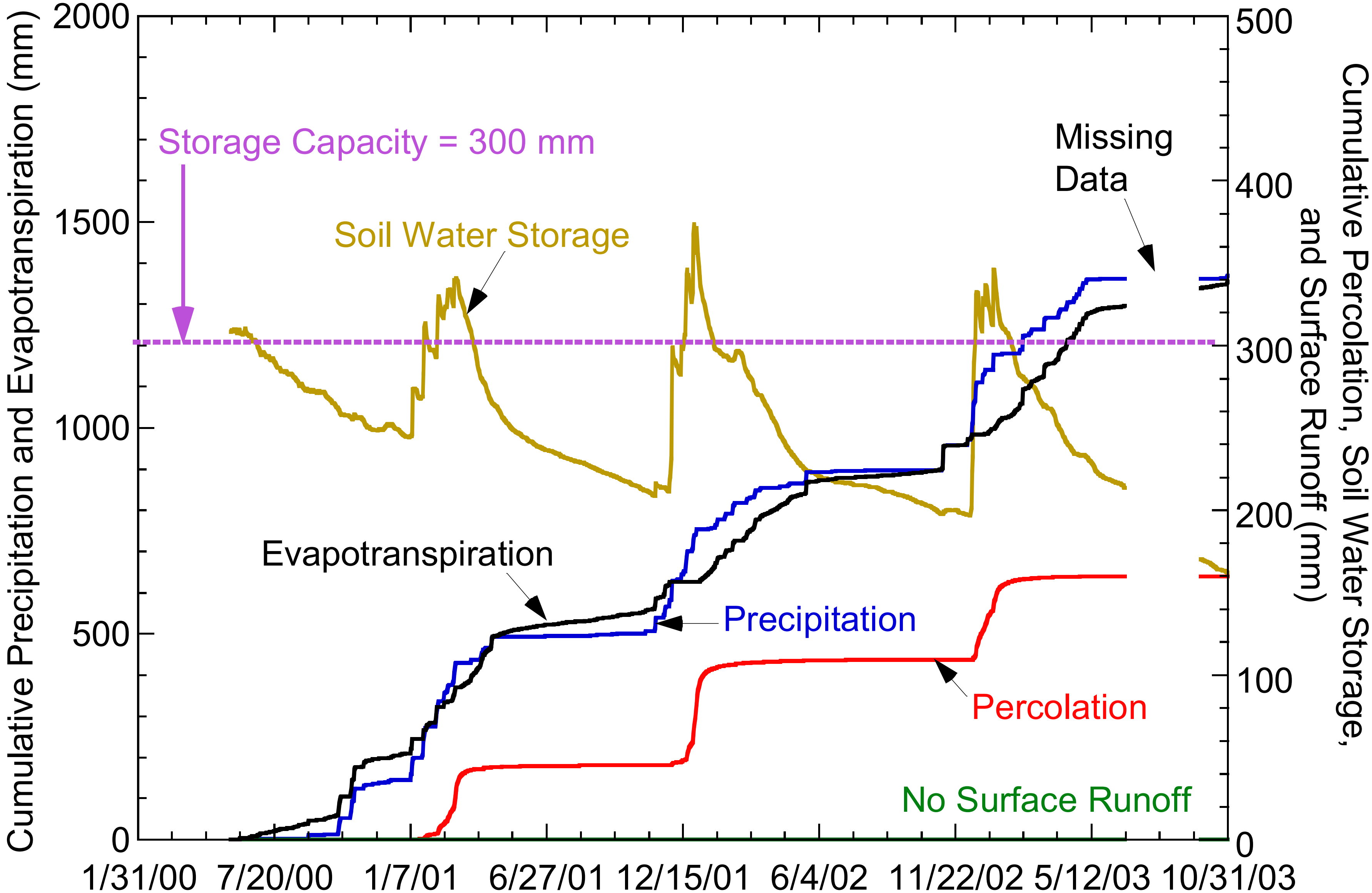




Marina, CA

- **Costal semi-arid climate**
- **Precipitation = 466 mm/yr**
- **P/PET = 0.46**
- **Capillary barrier (theory), but effectively a monolithic barrier**

Water Balance of Capillary Barrier: Marina, CA



Percolation occurs every year when storage capacity is exceeded.

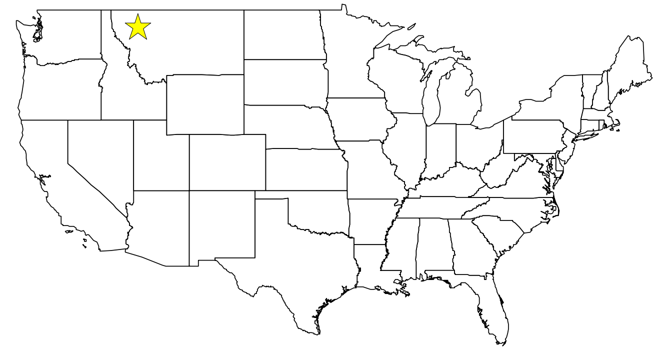
Polson, MT

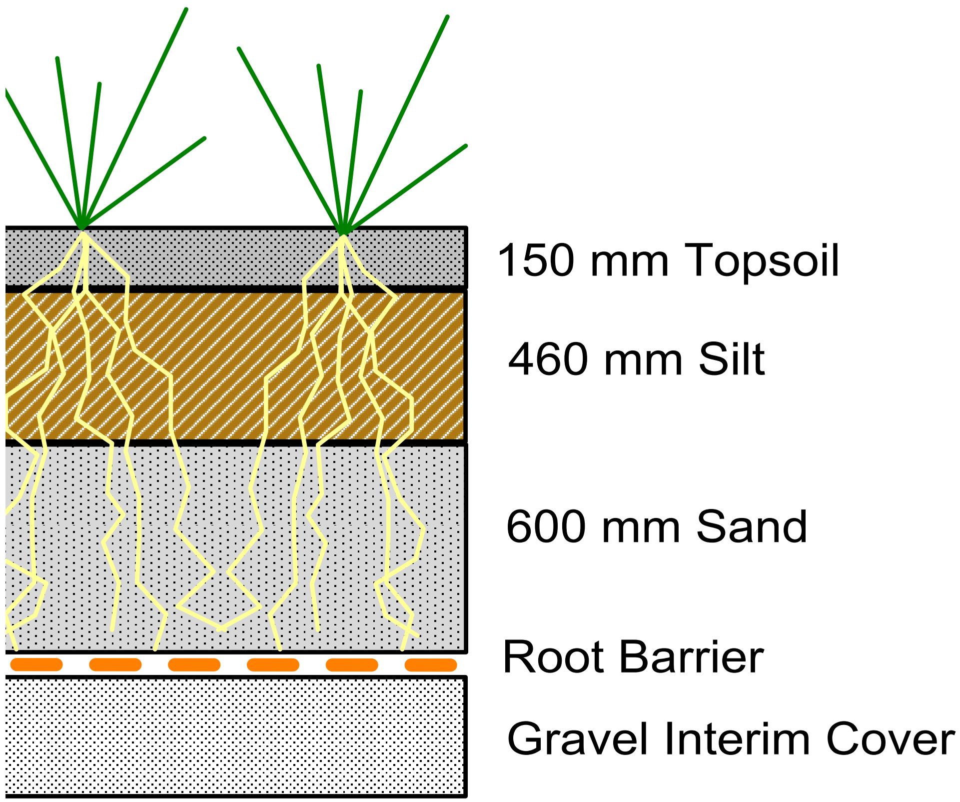
Cool and Seasonal Semi-Humid Climate

Capillary Barrier

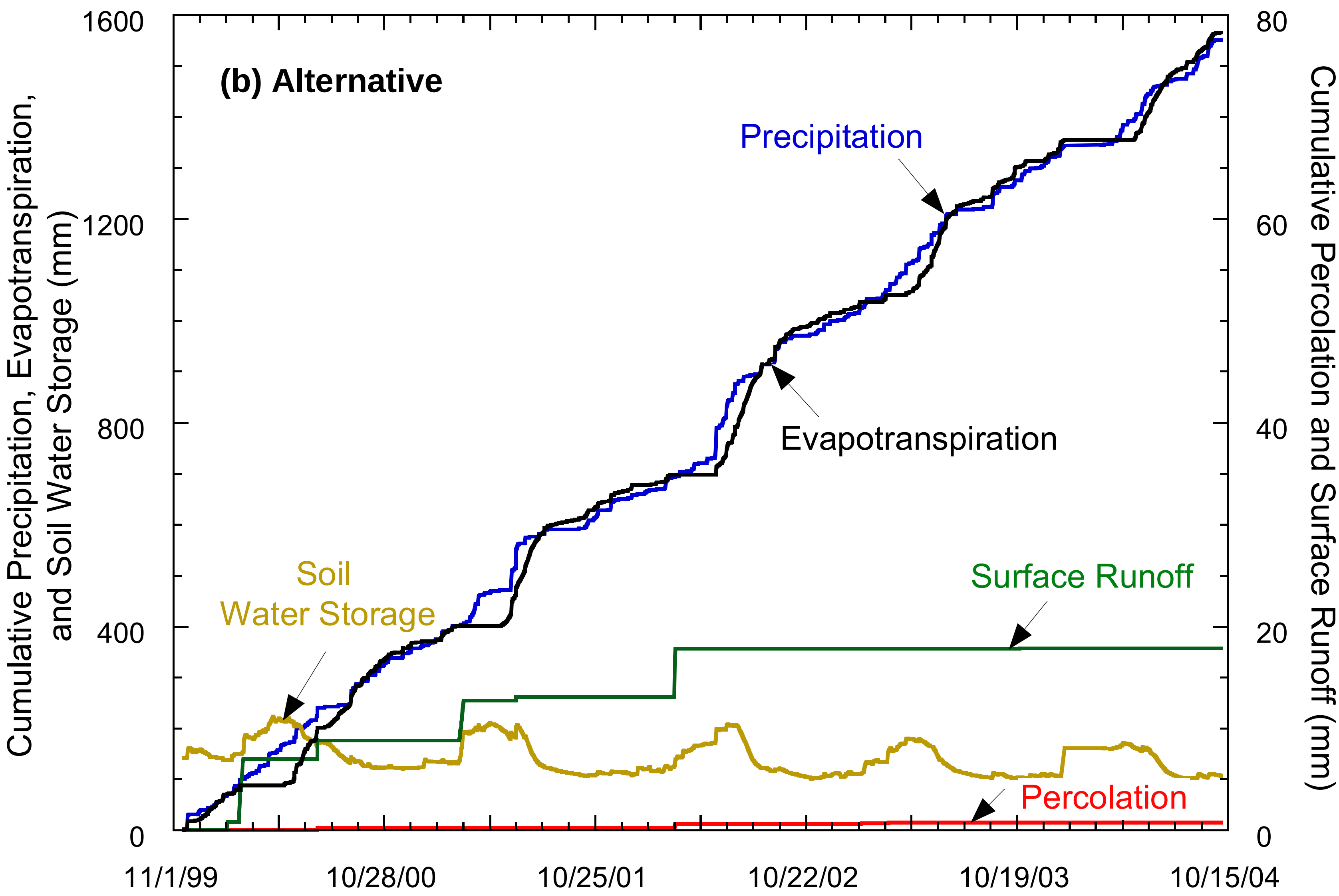
Precipitation ~ 380 mm/yr)

P/PET = 0.58





Capillary Barrier: Polson, MT

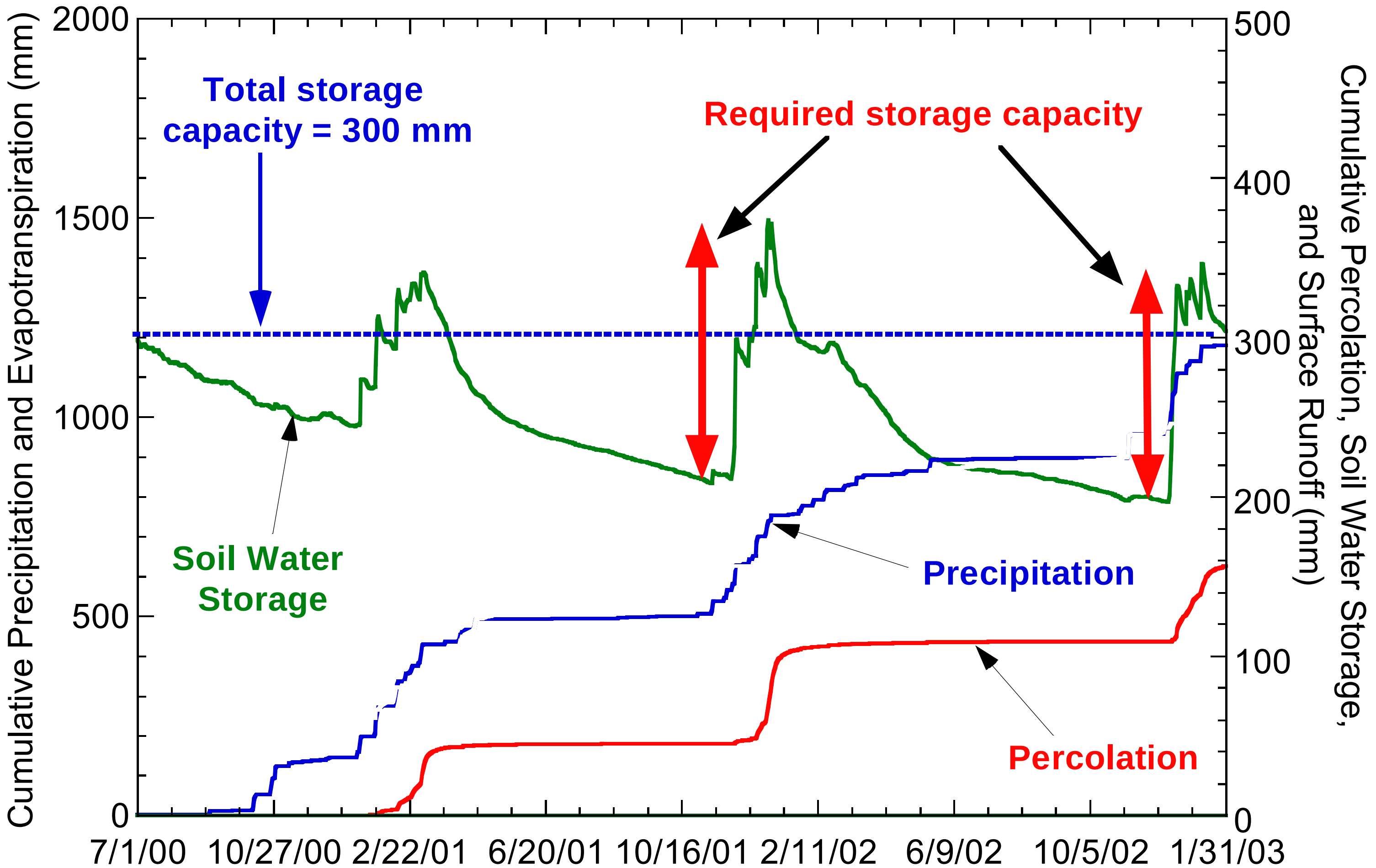


0.8 mm percolation over 5 yr! Less than composite.

ACAP Data for Water Balance Covers

Site	Maximum			Average	
	Precip. (mm)	Perc. (mm)	Year	Precip. (mm)	Perc. (mm)
Albany, GA	1380.2	218.3	4	1202.3	109.2
Altamont, CA	498.6	139.3	4	379.7	44.8
Apple Valley, CA	272.0	1.8	3	167.4	0.5
Boardman, OR (Thin)	210.8	0.0	3	181.4	0.0
Boardman, OR (Thick)		0.0			0.0
Cedar Rapids, IA	898.4	366.1	4	930.0	207.3
Helena, MT	351.5	0.1	5	272.4	0.0
Marina, CA	406.9	82.4	4	462.8	63.3
Monticello, UT	662.9	3.4	5	387.0	0.7
Omaha, NE (Thin)	612.4	101.0	1	732.5	56.1
Omaha, NE (Thick)		57.9			27.0
Polson, MT	308.1	0.4		349.1	0.2
Sacramento, CA (Thin)	361.2	108.4	-	422.0	54.8
Sacramento, CA (Thick)	455.7	8.5	3		2.7
Underwood, ND	585.2	9.4	1	384.1	7.1

Water Balance Covers: How They Function

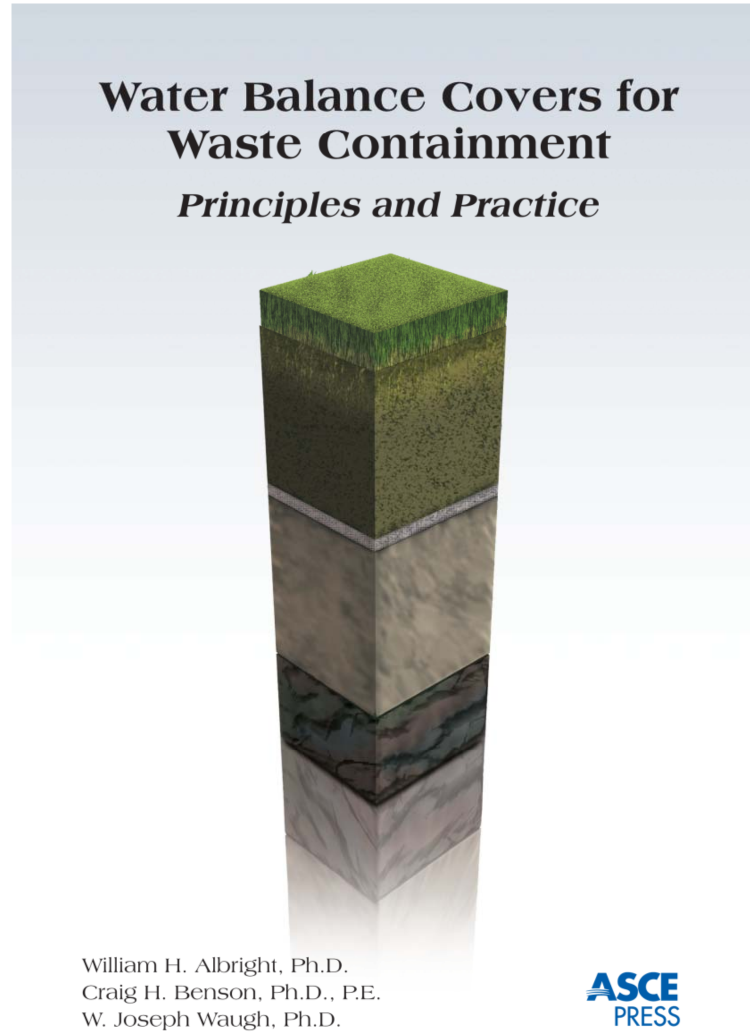


Key to design is available storage capacity (soil properties and cover thickness) must equal or exceed required storage (climate characteristics)

A Two-Step Method for Design of Water Balance Covers

1. Preliminary design: estimate required thickness by matching required and available storage using ACAP approach based on a robust, nation-wide field data set

2. Refine the design with numerical simulations to evaluate:
   - Important design parameters
   - “what if?” assessments



A Regulatory Framework

Regulatory Requirements

- The goal: Protect human health and environment!
- Factors to consider
  - Waste characteristics
  - Hazardous life of waste
  - Waste packaging
  - Depth to ground water
  - Attenuation capacity of geo strata
  - Distance to nearest receptor or sensitive environment
  - Climate
  - Stakeholder views, public acceptance
  - Containment Philosophy
    - Minimize release
    - Controlled release
  - Modify list to be site-specific

Site and Engineer Responsibilities

- Conduct prescribed site and waste analysis
- Define required closure performance
  - Percolation
  - Gas release
  - Erosion
  - Containment life
- Select appropriate closure concept (composite, water balance, ?)
- Result is site-specific, performance-based design
- Monitor and maintain
- Engineer and regulator must develop long-term relationship based on past performance, trust, and a shared dedication to the 'real' goals.

Publications

Albright, W.H., Benson, C.H., and Waugh, W.J., 2010. Water Balance Covers for Waste Containment: Principles and Practice. ASCE Press, Reston VA.

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