History and Technical Basis of 1999 USGS Estimates of Infiltration at Yucca Mountain, Nevada

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Net Infiltration at Yucca Mountain Outline

- History and timeline: development of conceptual and numerical models
- Development of the conceptual model
  - Processes
  - Observations
  - Spatial distribution
- Conceptual model
- Numerical testing of processes
  - Submodels
  - Bucket model approach
- Distributed results: 1996 milestone report
- 1996→1999 refinements
- Results and future climate
- Supporting data

History of Yucca Mountain Infiltration Program

1981 Winograd supports thick unsaturated zone with no infiltration

1983 Roseboom claims 30-60 ft of soil over bedrock is the same thing
No soil at Yucca Mtn so nonwelded tuff would provide capillary barrier

1986 Natural infiltration (neutron holes), artificial infiltration, matrix properties

1987 Regional meteorology program added

1991 Neutron hole drilling resumes (deeper and new topographic positions)

1992 Integration of infiltration processes with 3D site scale model

1992 Geostatistical precipitation maps of Yucca Mountain

1993 Unsaturated zone flux estimates in boreholes

1994 Artificial infiltration → surficial materials, numerical modeling added

1994 Distributed flux map based on rock properties

1995 Distributed flux map based on infiltration model (INFIL V 1.0)

1996 Infiltration milestone report documenting INFIL V 1.0

1999 Analysis and Modeling Report documenting INFIL V 2.0

Net Infiltration at Yucca Mountain

- Water balance processes and strategy
- Precipitation – ET – drainage ± Δstorage = 0
- The sporadic nature of precipitation in the arid southwest allows us to use this approach

Conventional Wisdom about Infiltration in Arid Environments in Late 80's

- Channels in desert environment thought to be the most important process for infiltration
- Neutron holes concentrated in channels
- Deep boreholes in channels

Developing a Conceptual Model of Net Infiltration at Yucca Mountain

- Observations
  - Water content profiles (soil and bedrock)
  - Climatic trends
  - Subsurface flow and water potential gradients at bedrock interface
  - Differences between geomorphic and topographic locations
  - Soil depth
  - Spatial distribution of surficial bedrock properties

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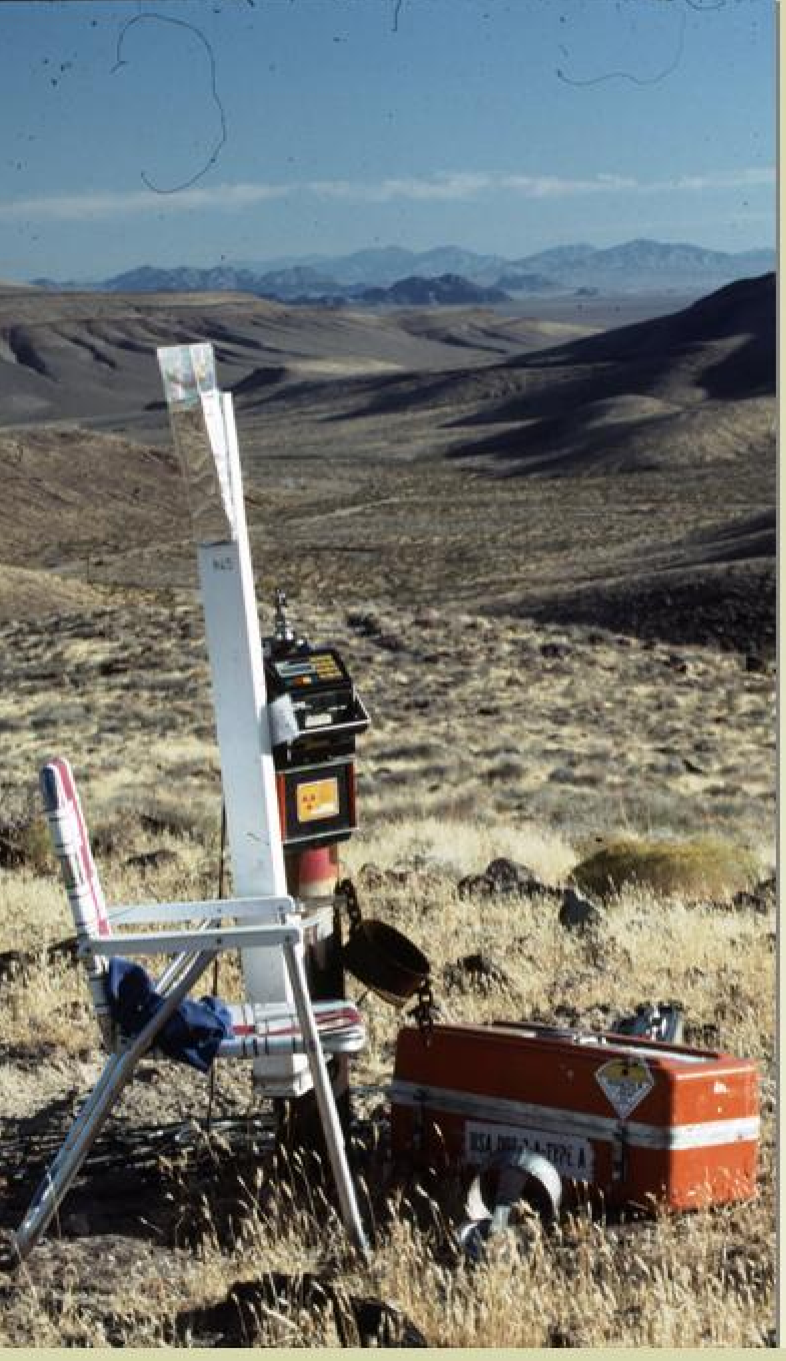
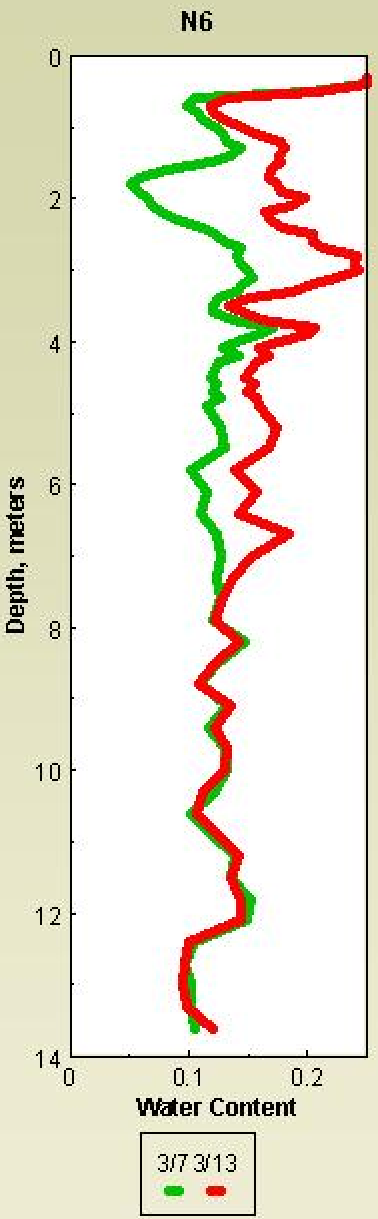


Neutron Logging

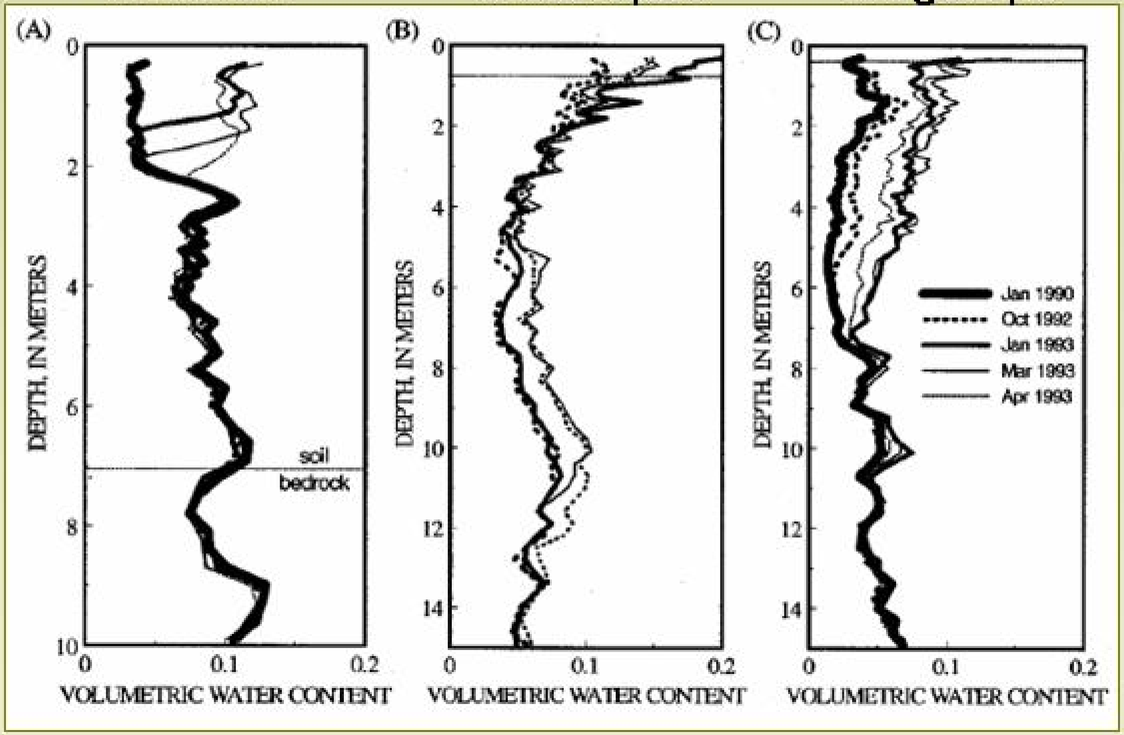
Moisture monitoring in 99 neutron-access boreholes monthly for over 10 years became one of the most useful tools for evaluating the spatial processes contributing to net infiltration and percolation



Neutron Logging

Influence of soil depth and bedrock on infiltration

Channels | Sideslopes | Ridgetops



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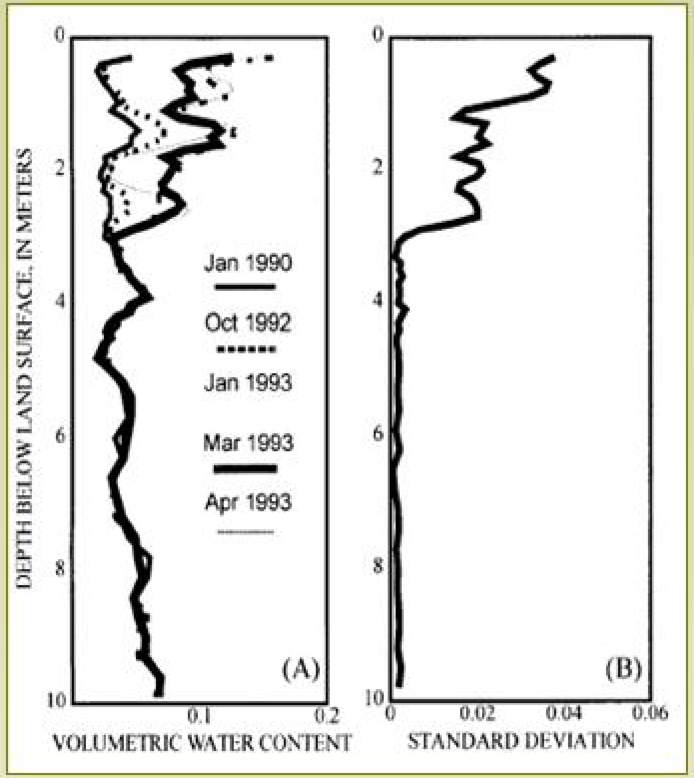
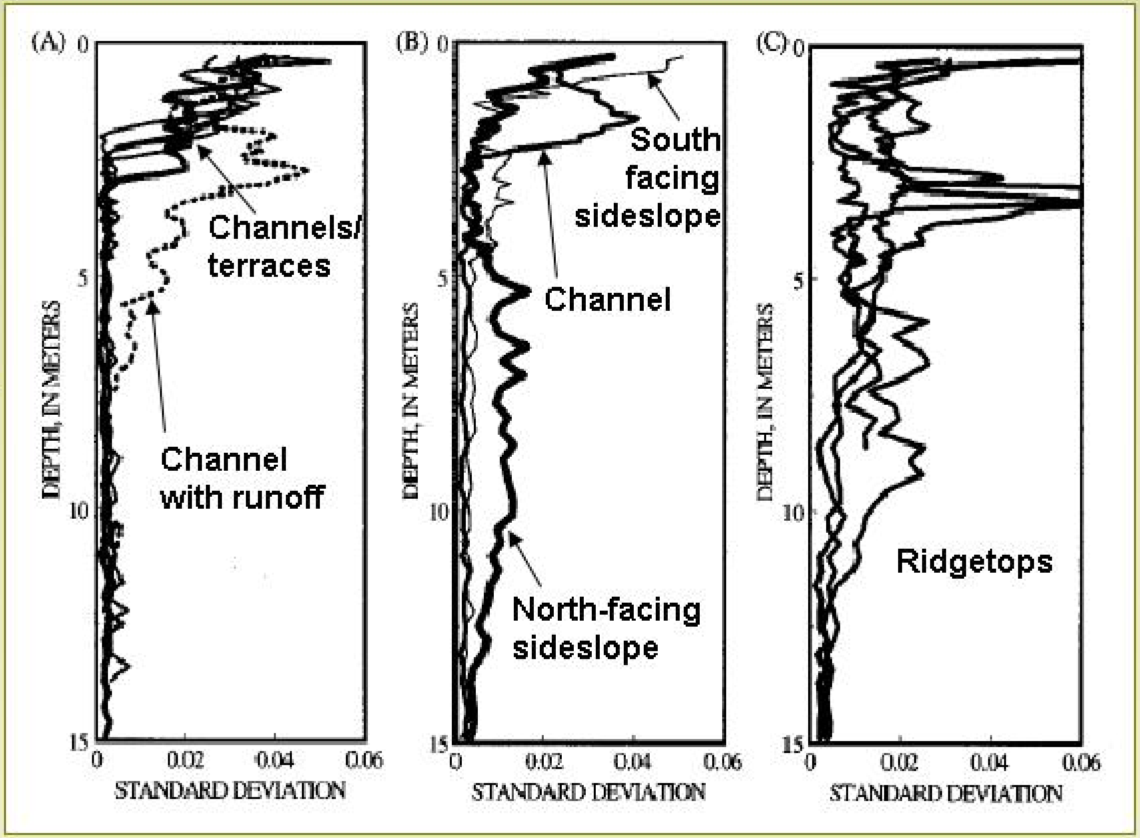
Neutron Logging

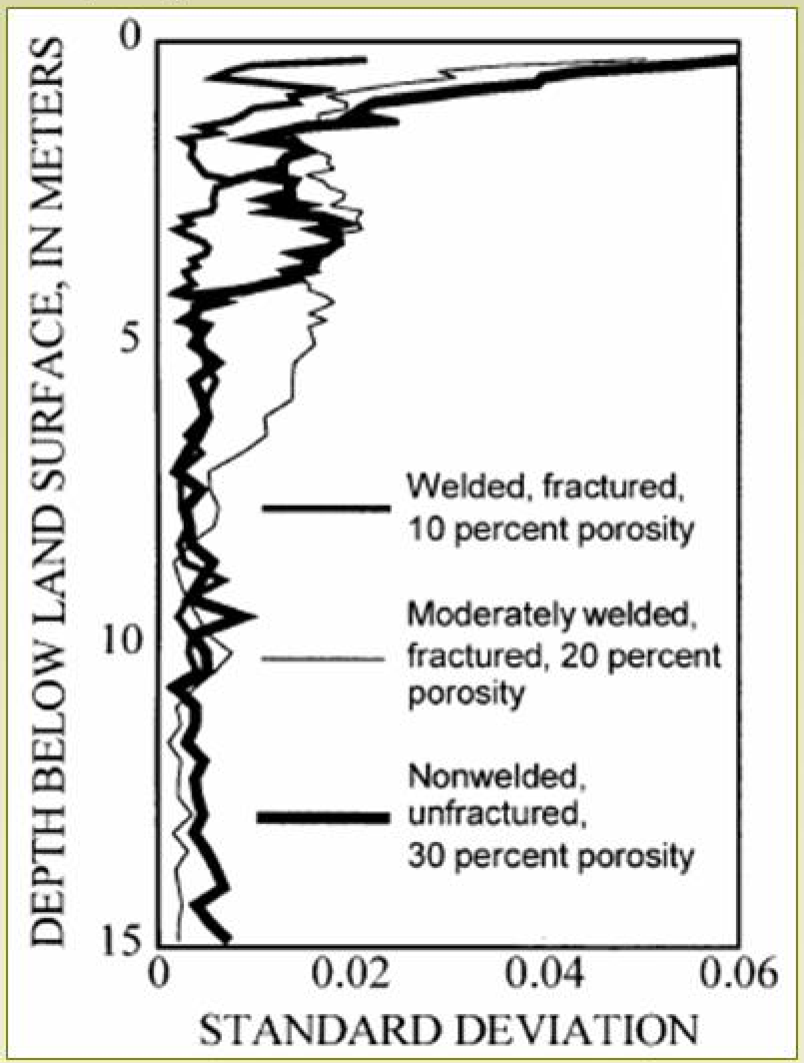
Influence of geomorphic position on depth of penetration





Neutron Logging

Influence of bedrock properties on infiltration



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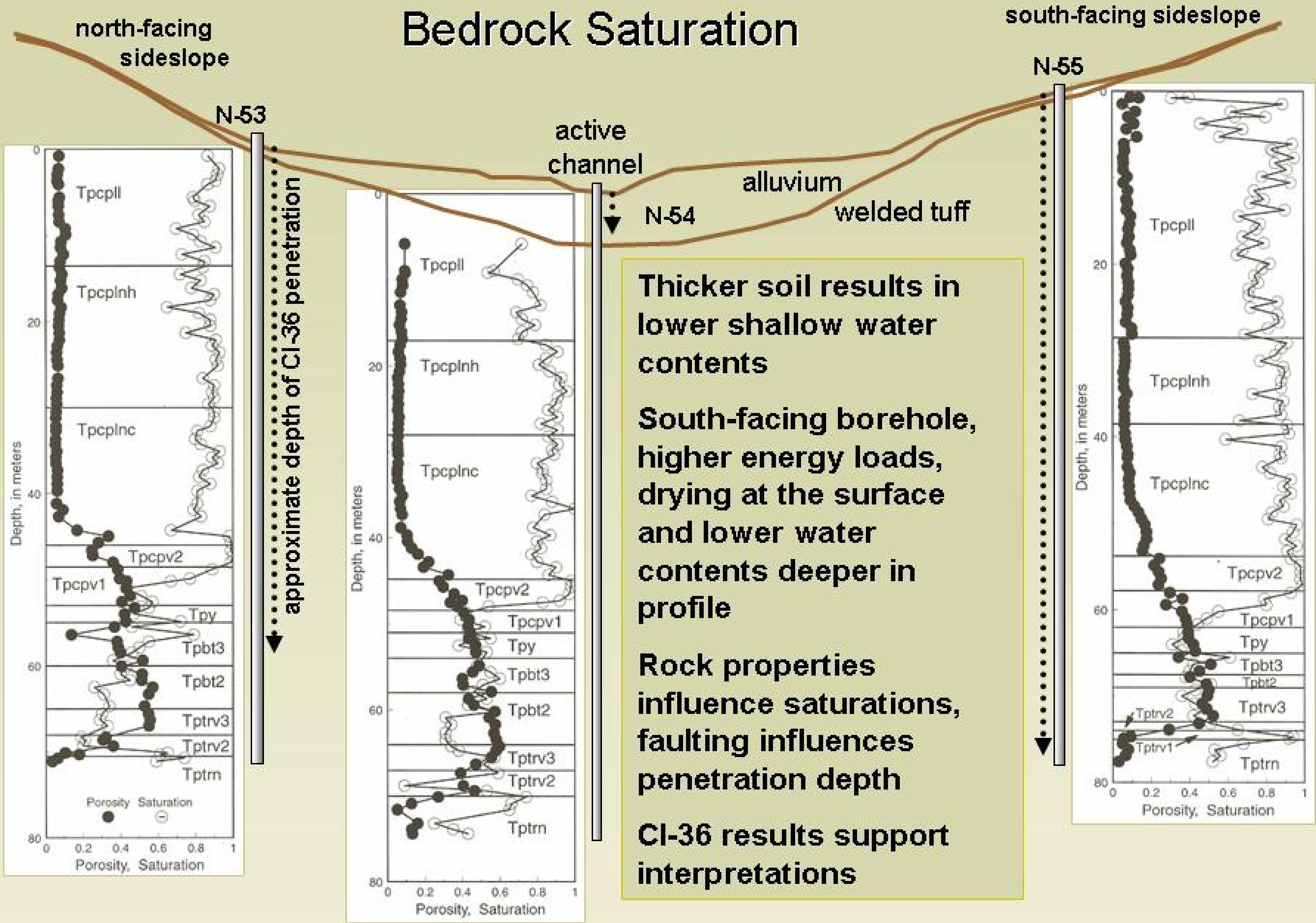
Infiltration Influences Bedrock Saturation

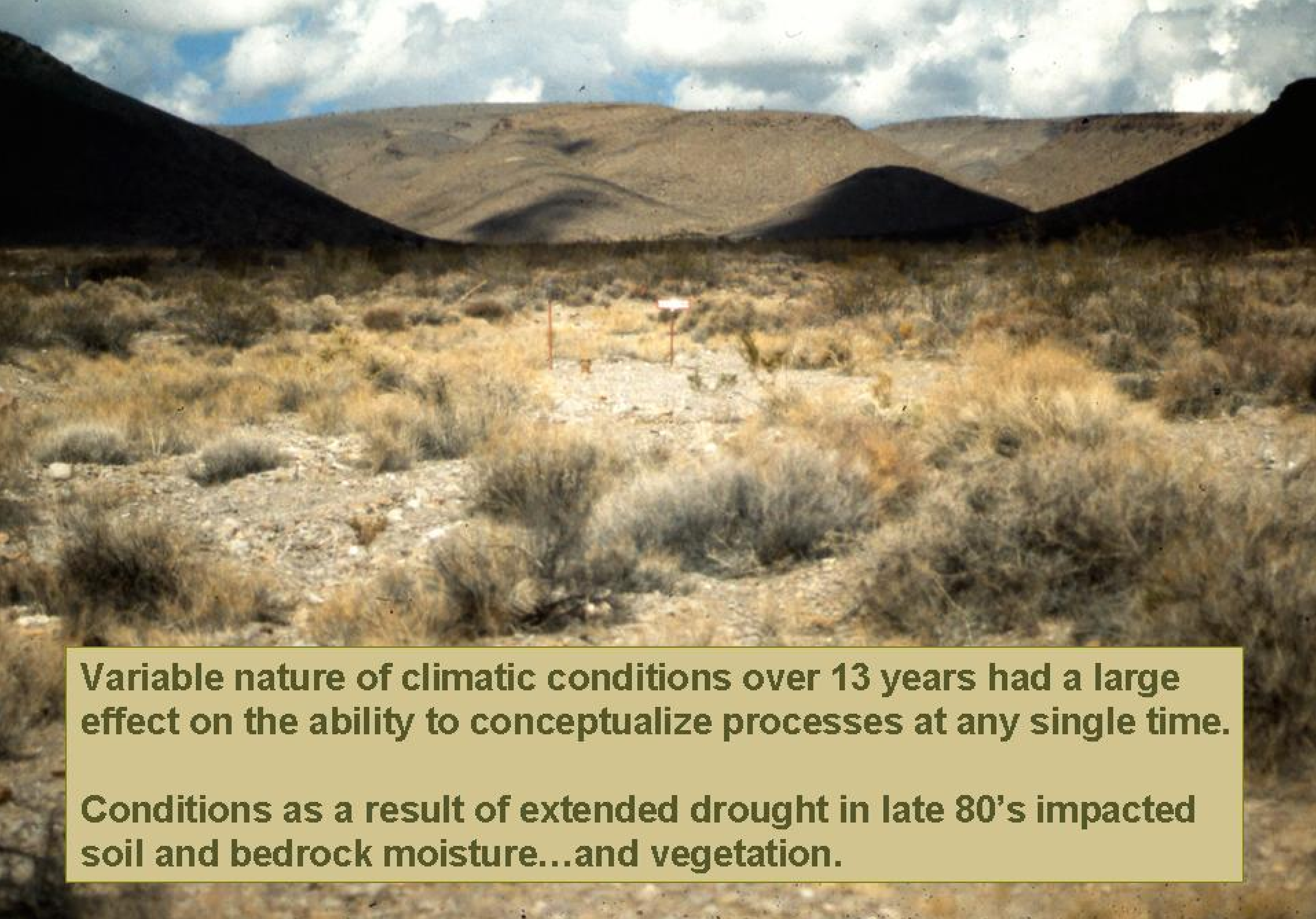


Thicker soil results in lower shallow water contents

South-facing borehole, higher energy loads, drying at the surface and lower water contents deeper in profile

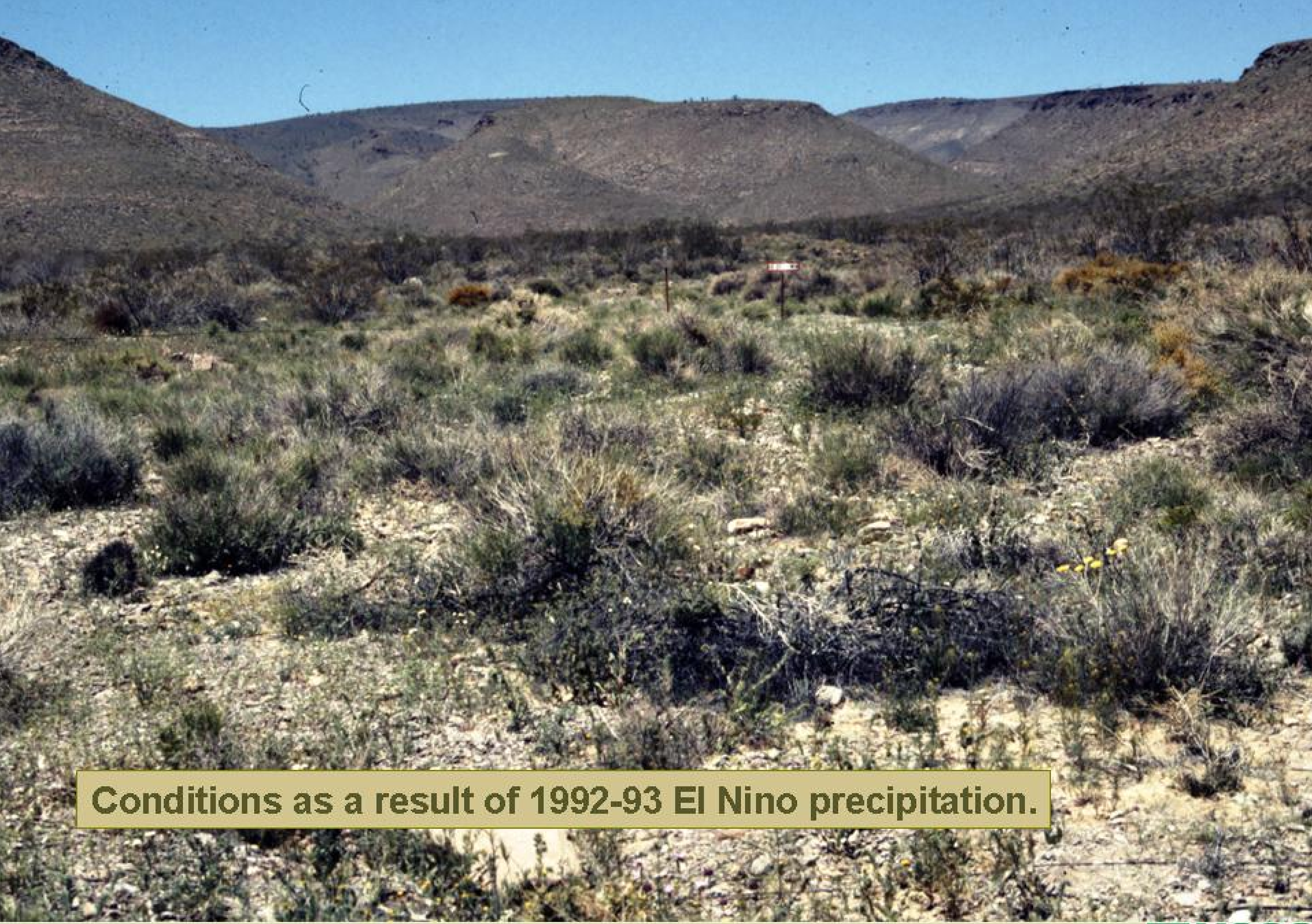
Rock properties influence saturations, faulting influences penetration depth

Cl-36 results support interpretations



Variable nature of climatic conditions over 13 years had a large effect on the ability to conceptualize processes at any single time.

Conditions as a result of extended drought in late 80’s impacted soil and bedrock moisture…and vegetation.



Conditions as a result of 1992-93 El Nino precipitation.

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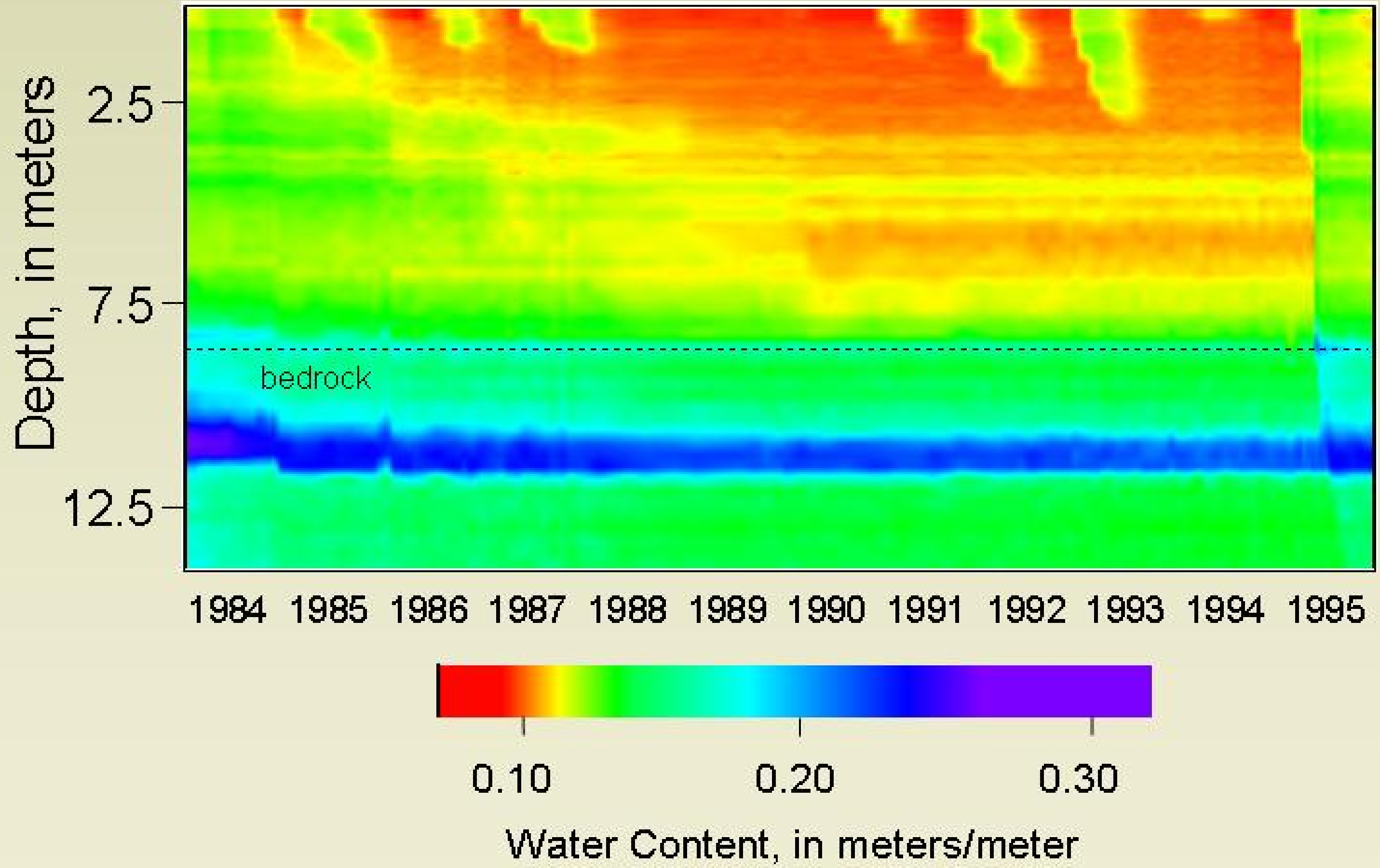
Infiltration at Borehole UZN #1

Active channel, 8-meter deep soil



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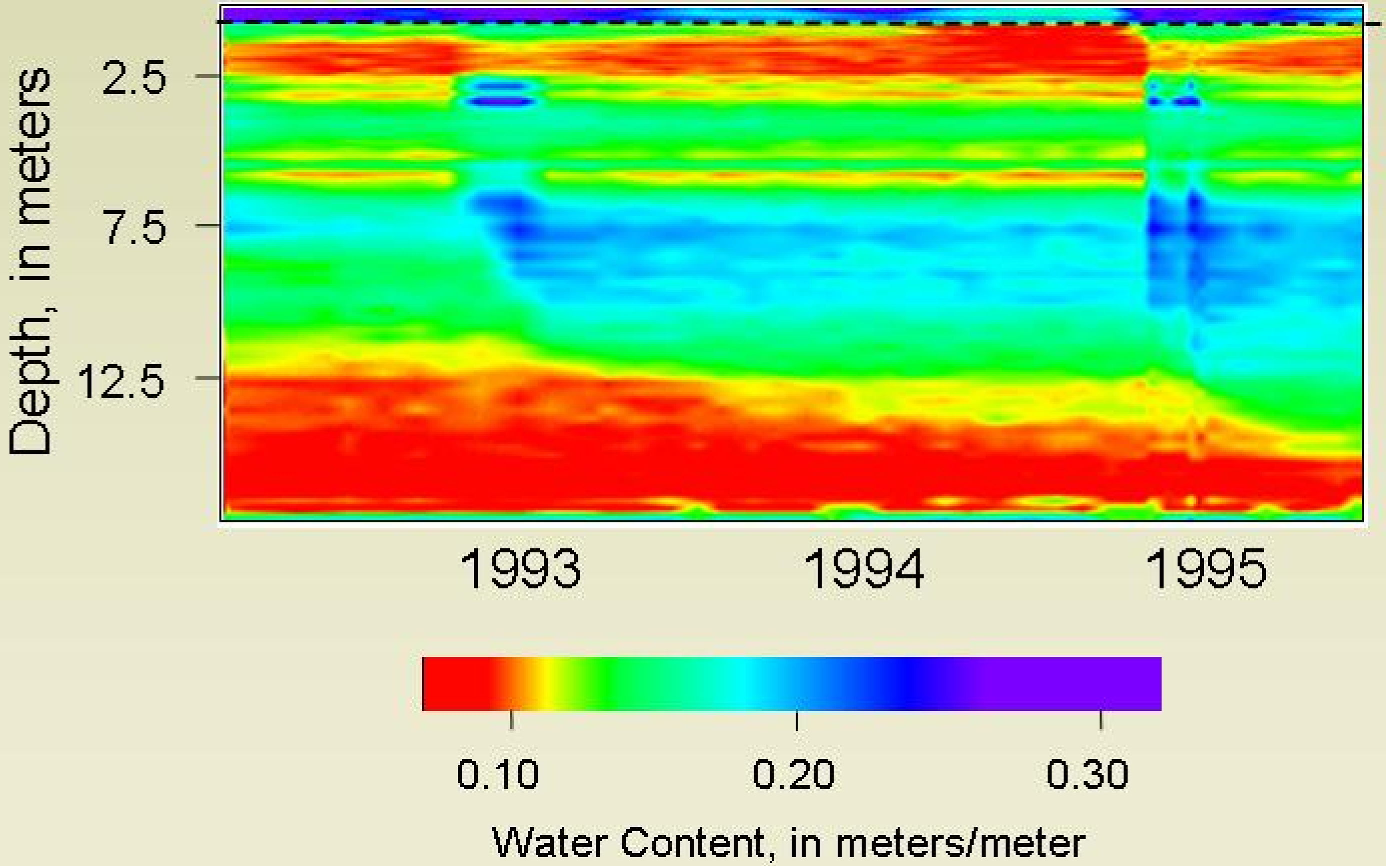
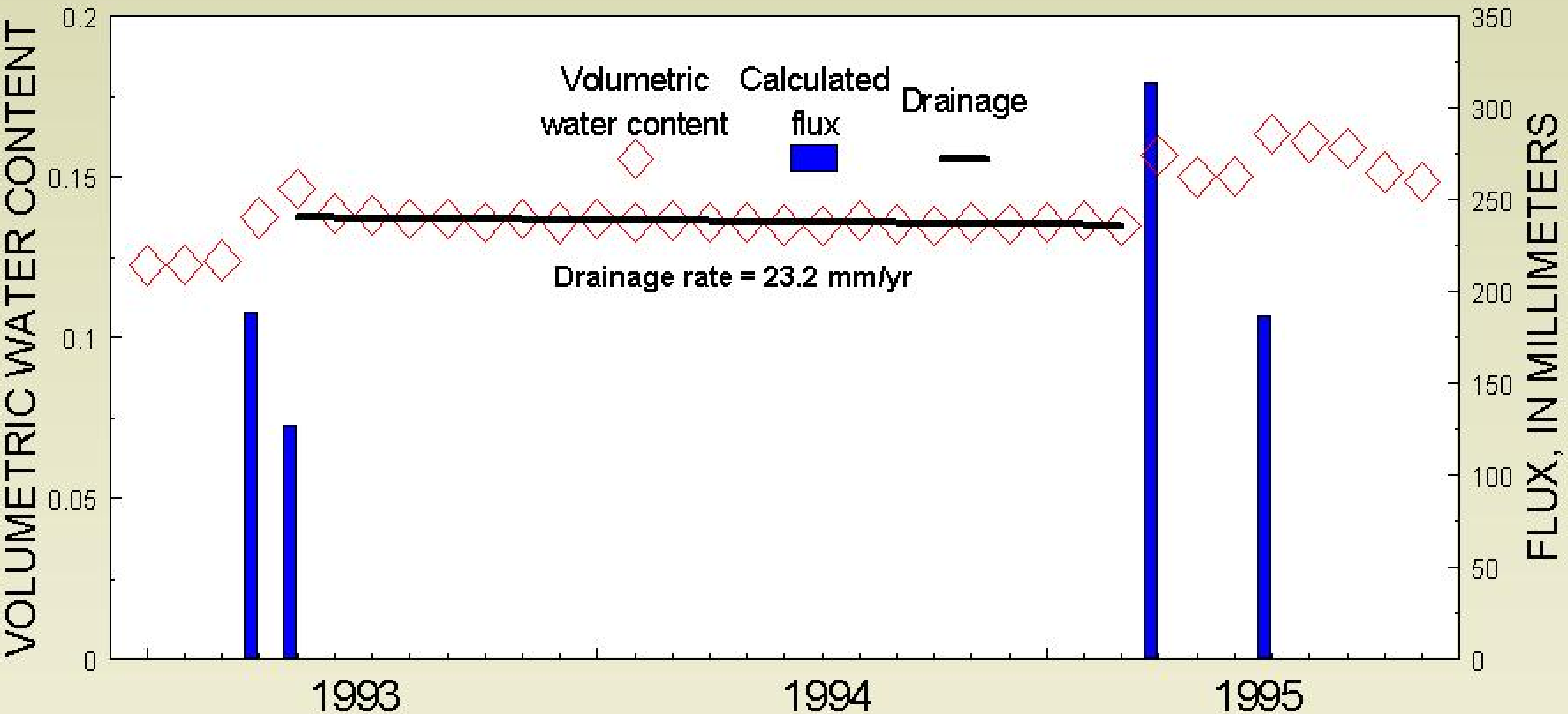
Infiltration at Borehole UZN-15

(75 cm soil over 2 m lower porosity fractured bedrock, underlain by 10 m high porosity fractured bedrock)

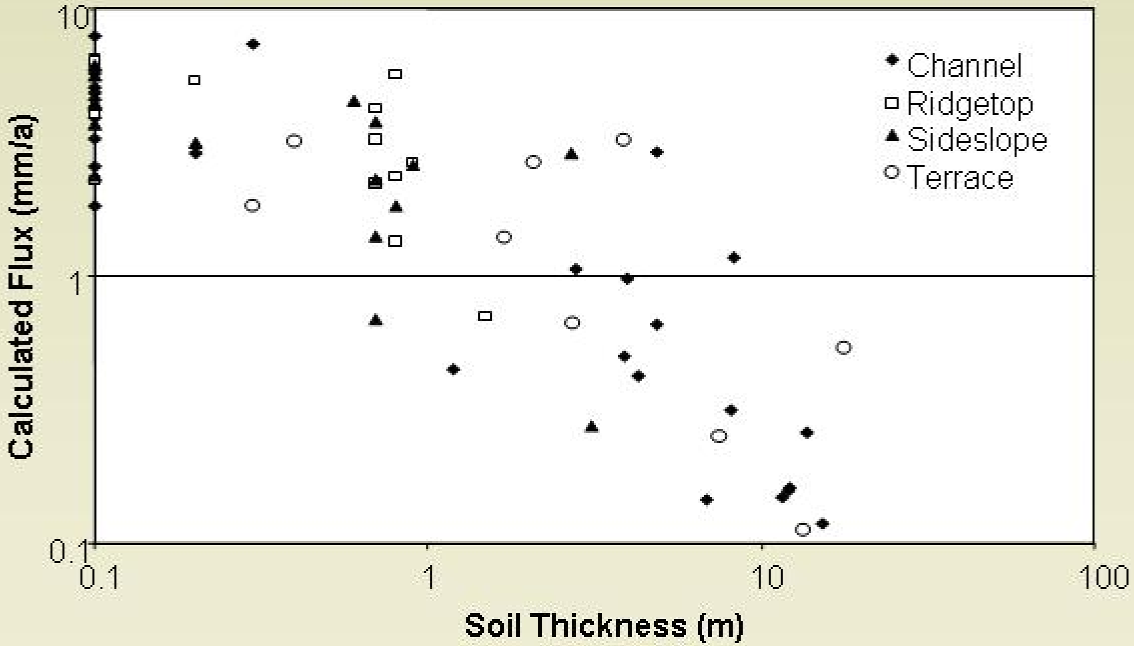


Calculation of Flux from Neutron Borehole Data



Flux calculated for 80 neutron boreholes compared to soil thickness

Alluvium thickness (meters)	Flux in boreholes (mm/yr) Mean	Standard deviation	Number of samples
0.0-0.5	44	17	29
0.5-1.0	28	14	14
1.0-3.0	12	10	8
3.0-6.0	6	9	13
6.0-18.0	1	2	28
All depths	19	29	89



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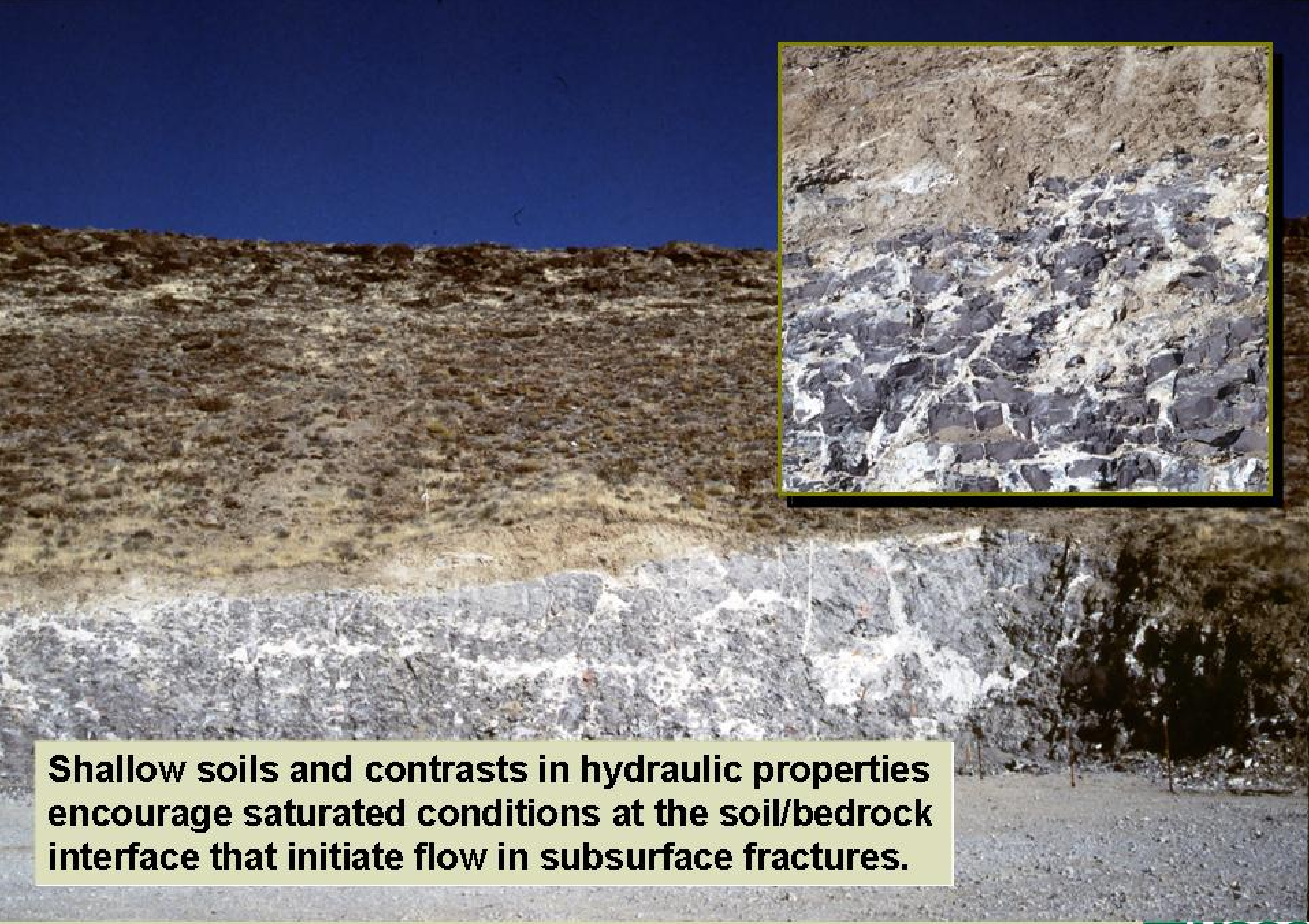

Shallow soils and contrasts in hydraulic properties encourage saturated conditions at the soil/bedrock interface that initiate flow in subsurface fractures.

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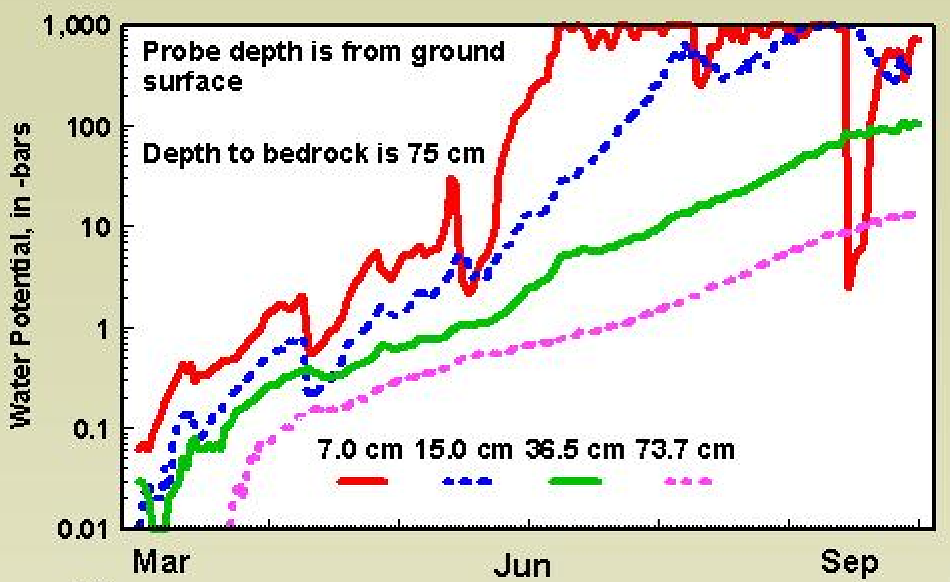
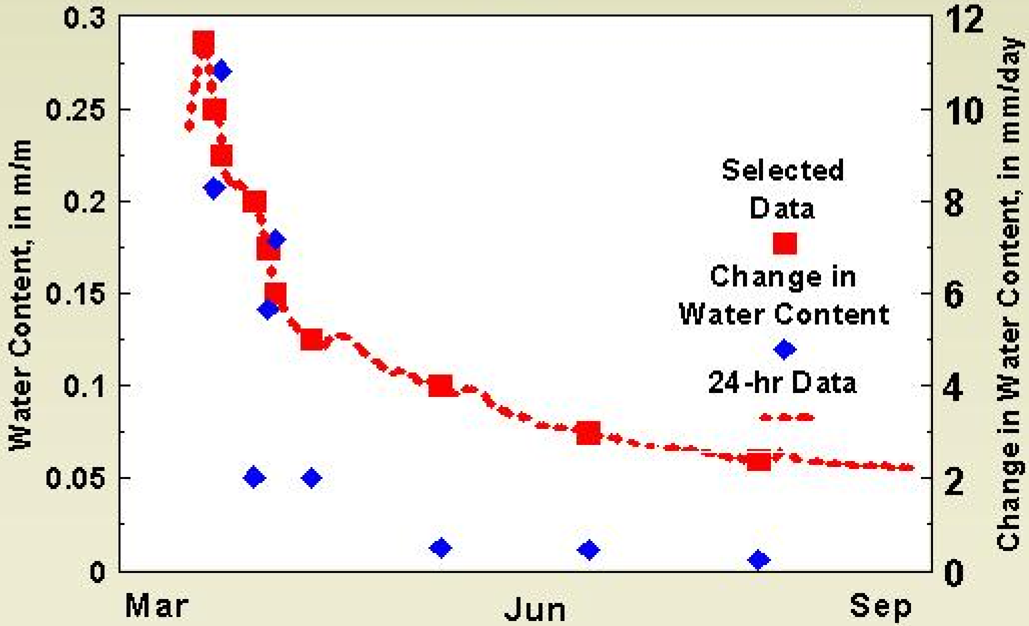
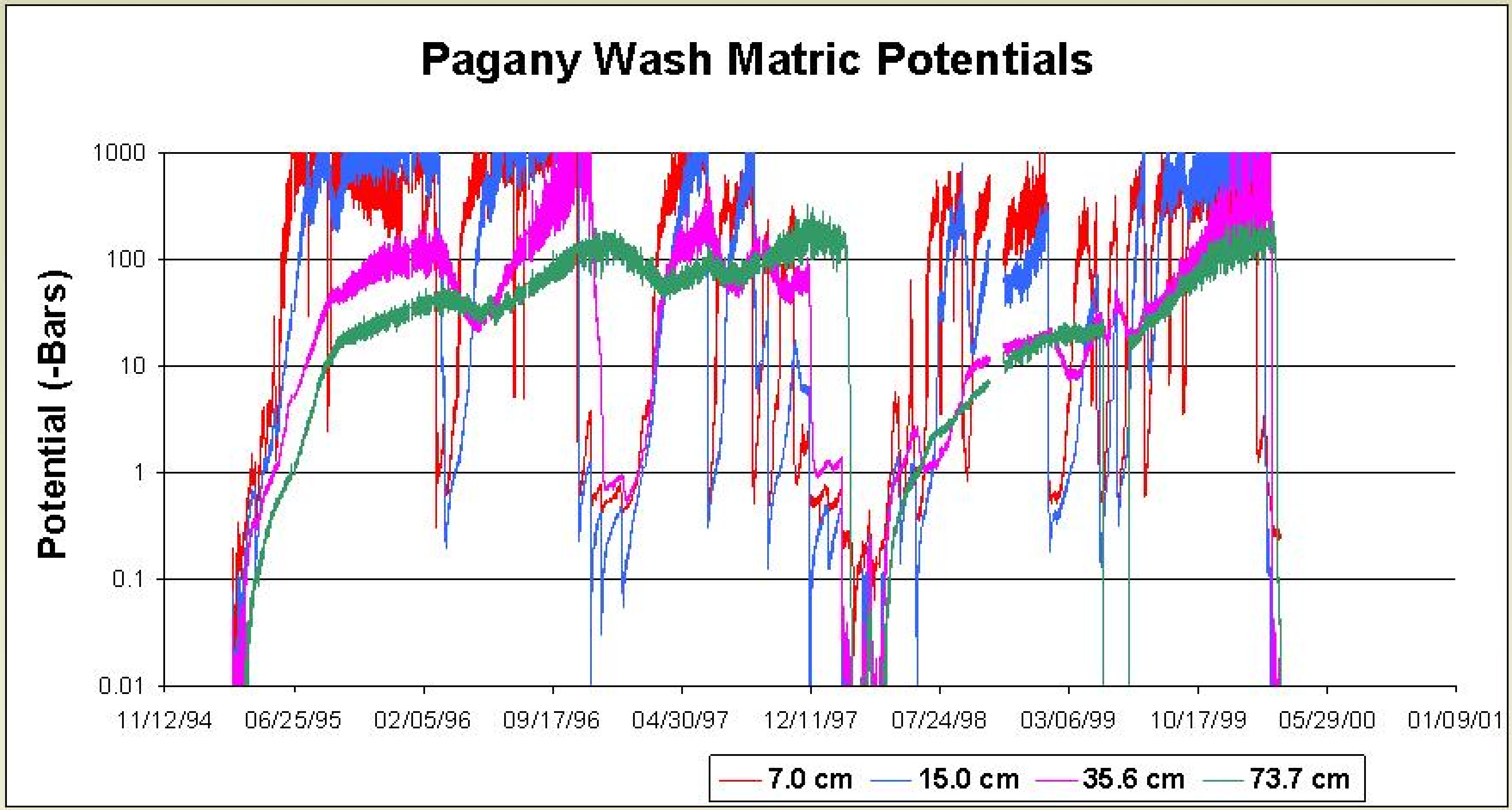
Calculating flux from Heat Dissipation Probe data





Soil Water Potential
Heat Dissipation Probes at N-15



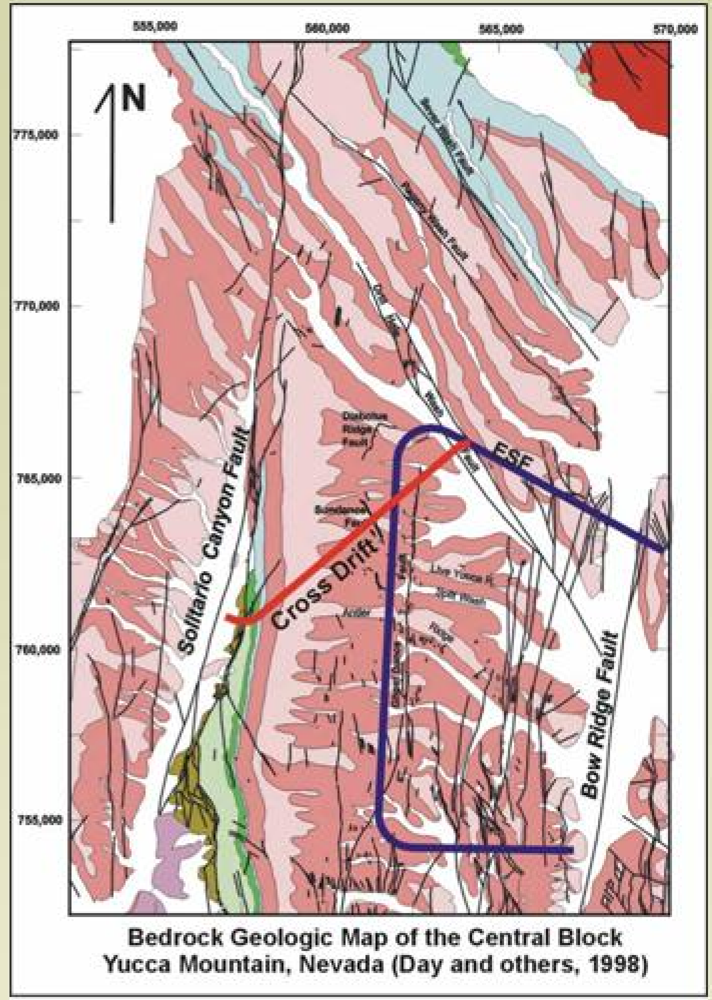
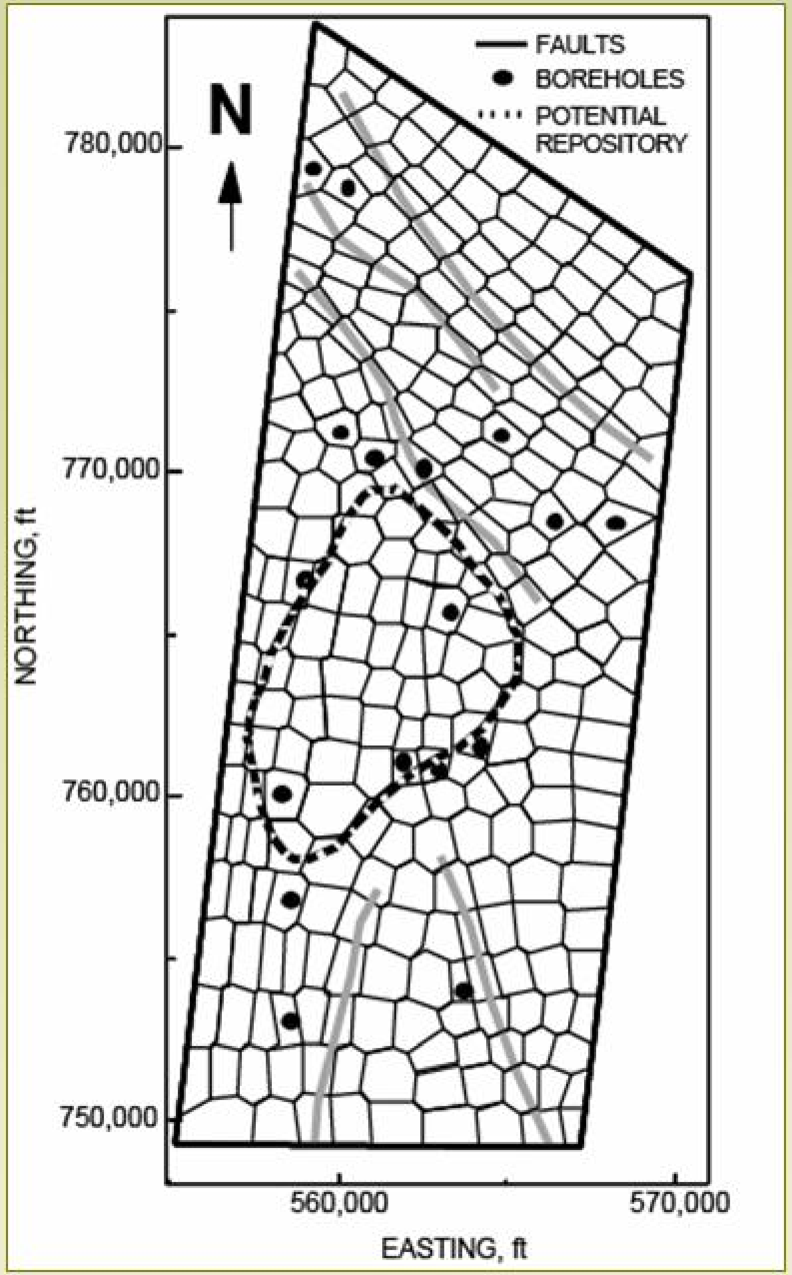
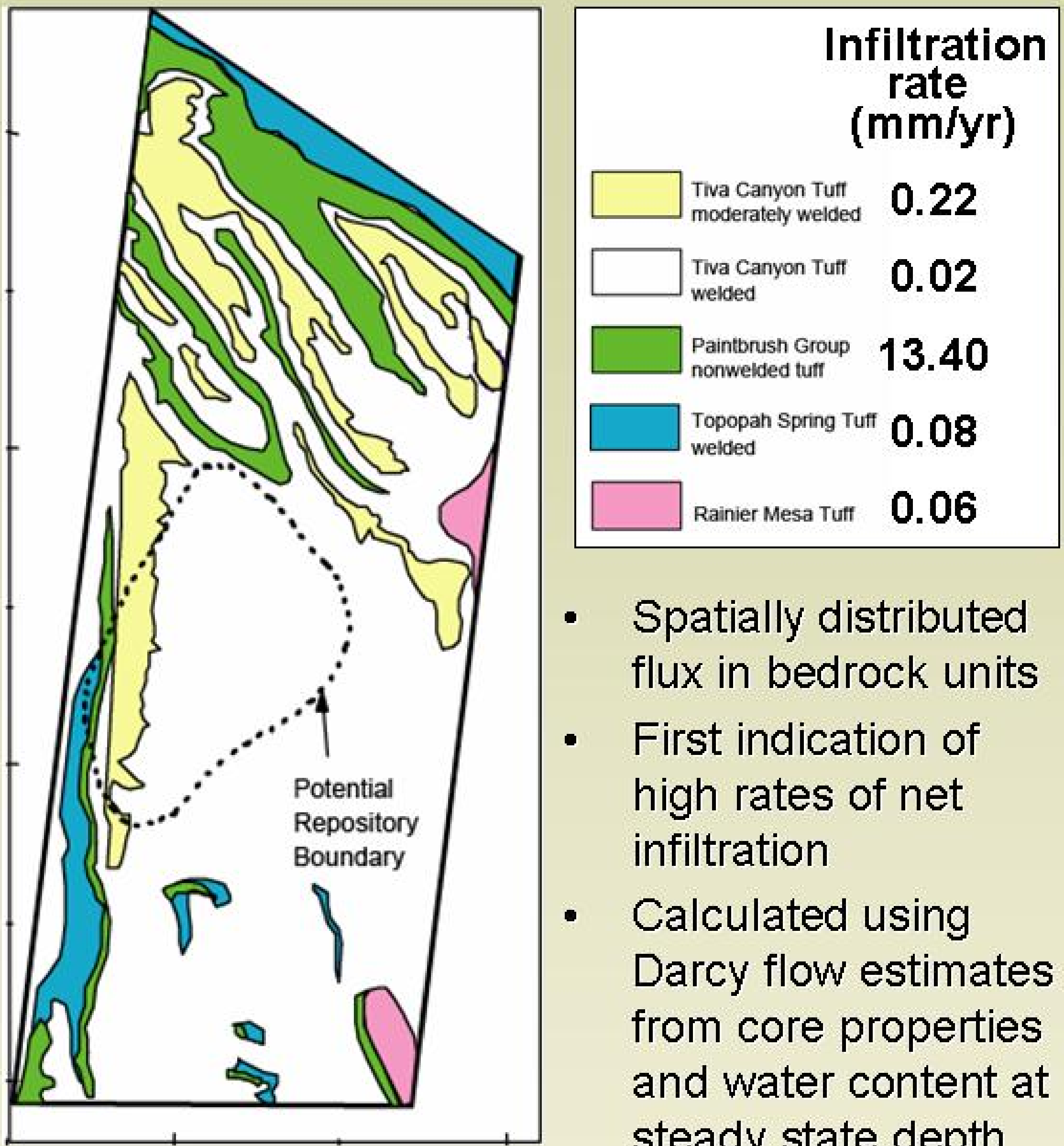


Figure 2. Simplified geologic map of the Yucca Mountain region with plan view of the ESF and the Cross Drift.

Surficial geology, measured rock properties, and subsurface moisture conditions, provided spatial information for distributing flux estimates

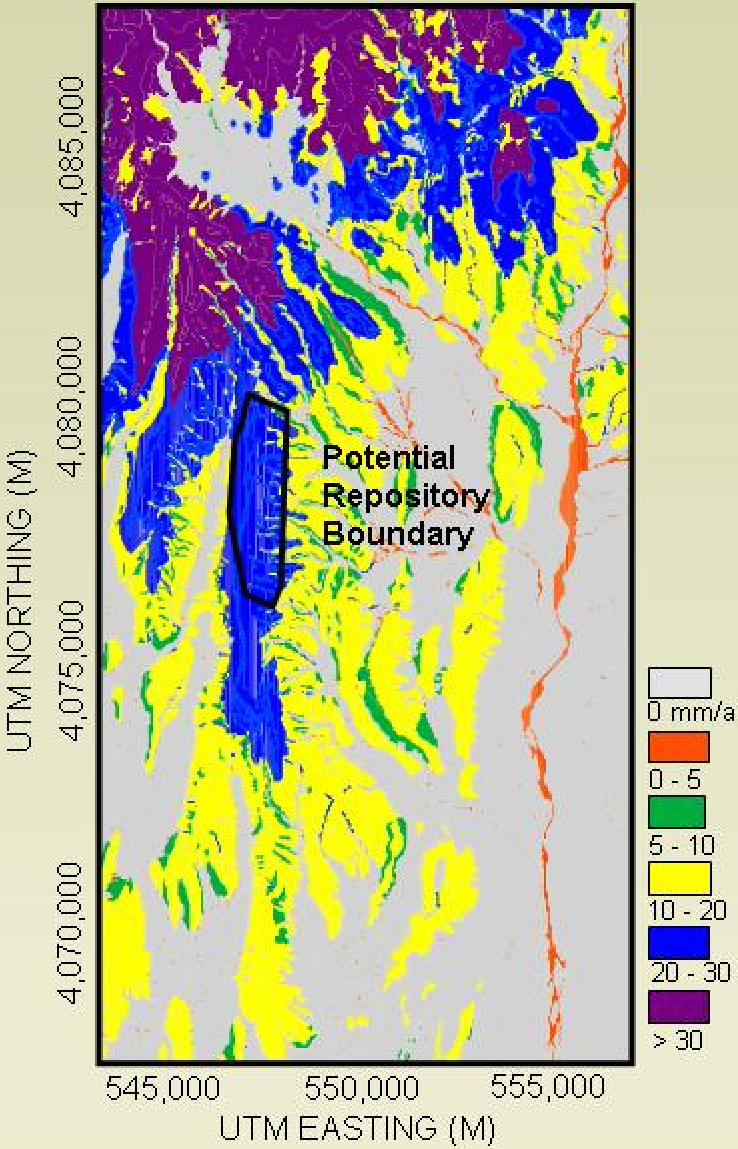


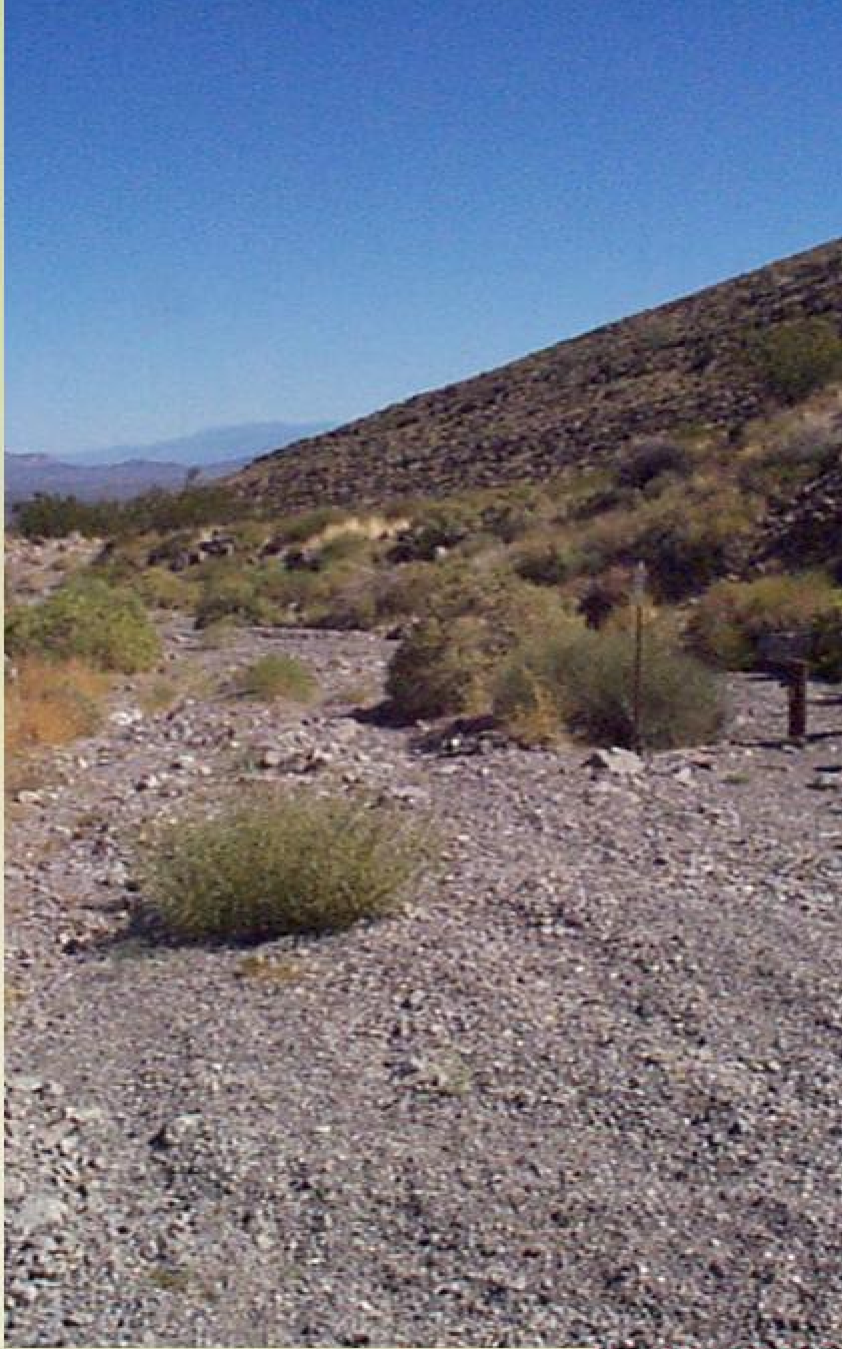
- Original 3-D site scale model grid with early version of potential repository boundary
- Highlights fault controlled channels
- Integration with 3-D site scale model development began in 1991, encouraging spatially distributed estimates of upper boundary conditions



- Spatially distributed flux in bedrock units
- First indication of high rates of net infiltration
- Calculated using Darcy flow estimates from core properties and water content at steady state depth (Flint and Flint, 1994)

Spatially distributed net infiltration 1995 using neutron hole data and statistical methods

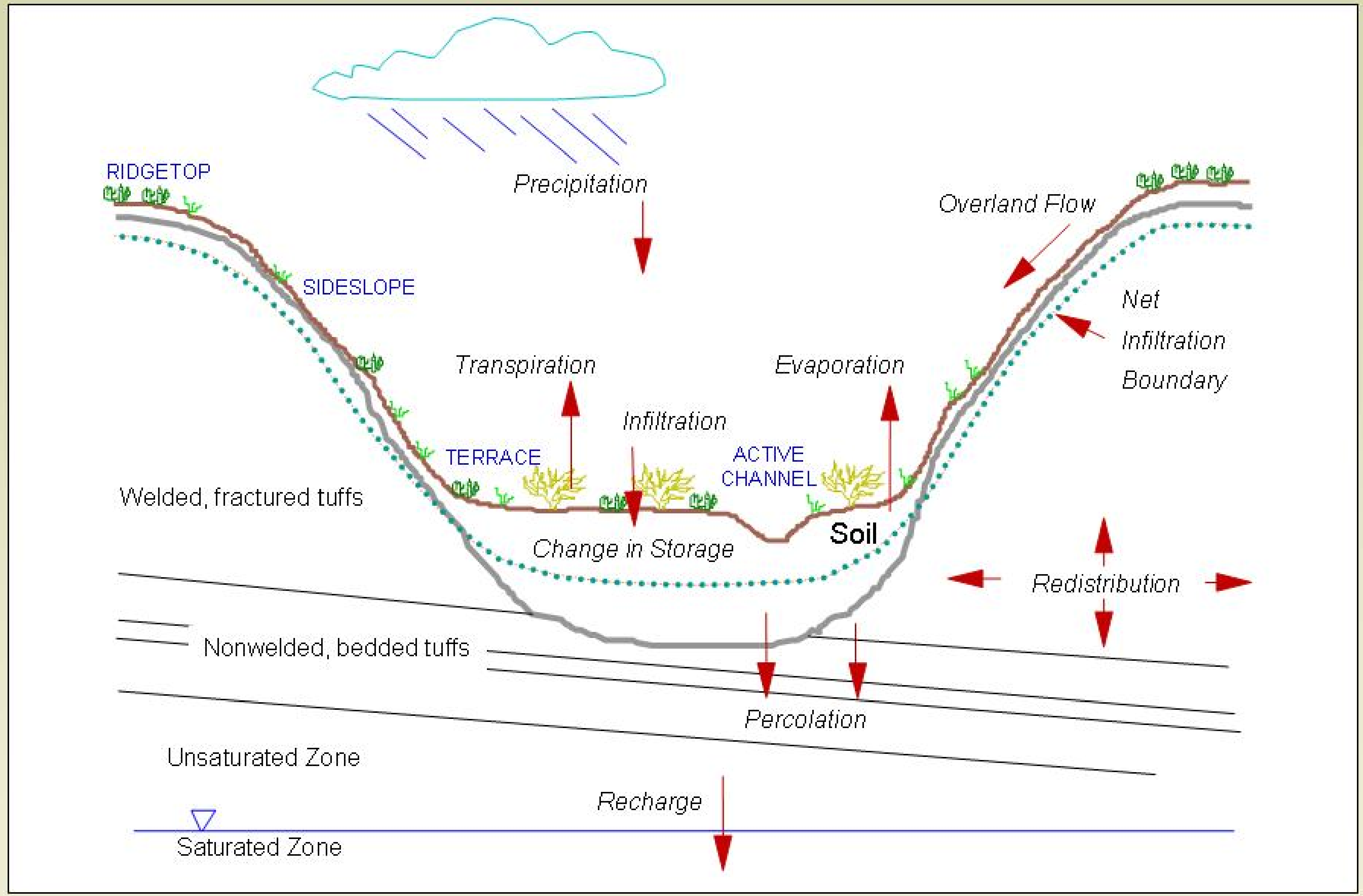




Net Infiltration at Yucca Mountain

- Factors controlling infiltration
  - Precipitation
  - Soil thickness
    - Soil porosity
    - Drainage characteristics
  - Bedrock permeability
  - Evapotranspiration

Conceptual Schematic of Water-Balance Processes and Subsurface Flow



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Additional observations to refine the conceptual model of infiltration

- **Observations leading to spatial distribution of parameters and processes**
  - Spatial variability of storms
  - Snow melt
  - North vs south facing slopes
  - Deterministic rock properties
- **Observations leading to model process refinement**
  - Rooting depths exposed after flooding
  - Plant water potential in fractured rock

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Net Infiltration at Yucca Mountain

Conceptual understanding

- Arid conditions→ net infiltration is an infrequent occurrence
- Particularly wet winters allow for near saturated conditions at the soil-bedrock interface→ fracture flow and deep penetration of infiltrated water below the zone of evapotranspiration
- Deep soils have sufficient soil water storage capacity to retain most precipitation in the root zone for evapotranspiration
- Runoff accumulates and infiltrates enough water to overcome the storage capacity of the root zone in deeper soils allowing for deep penetration of infiltrated water below the zone of evapotranspiration

Numerical Modeling of Infiltration

- Apply the physics of the water-balance processes to arid climates
- Define the physical setting
  - Slope
  - Aspect
  - Elevation
  - Soil properties
  - Rock properties
  - Vegetation

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Numerical Modeling of Infiltration

Converting the conceptual model to a numerical/mathematical model

- Solutions to the water-balance equation require sub modeling:
  - Precipitation
  - Infiltration
  - Evapotranspiration
  - Percolation
  - Runoff/Runon

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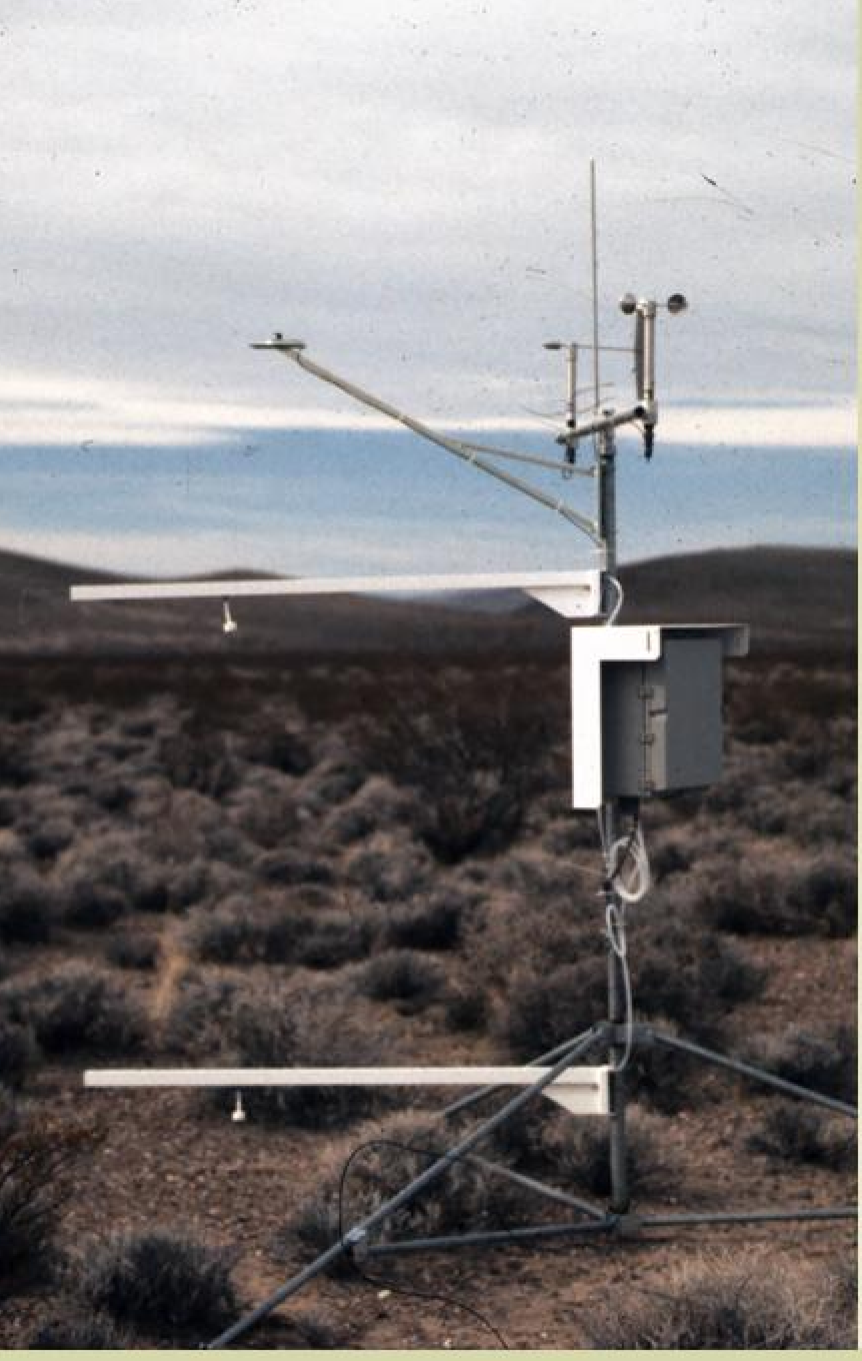
Co-located raingages at all 99 neutron holes

Precipitation model
(Temporal and Spatial Distribution)

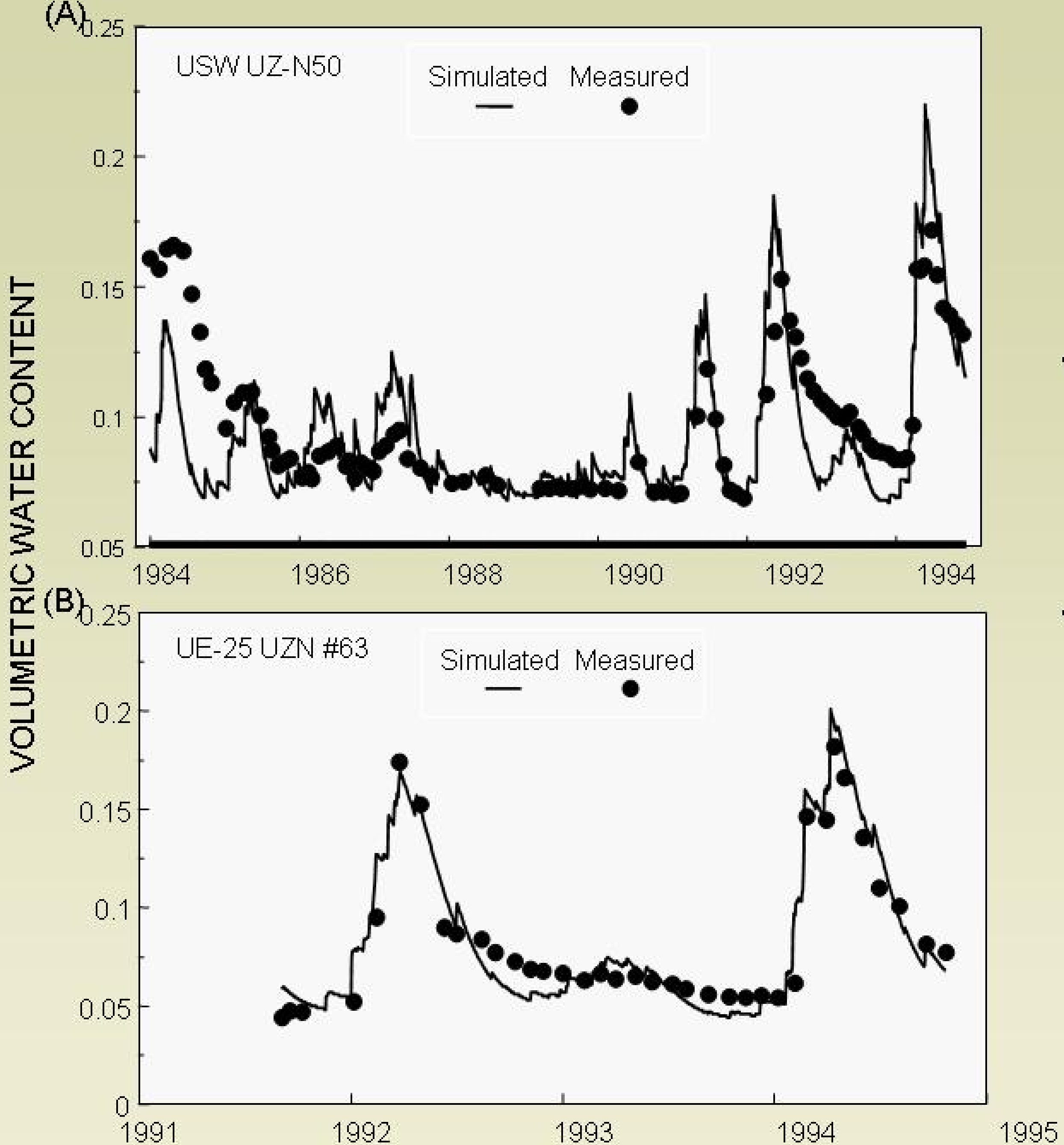
- Use surrogate rainfall (limited records)
  - 4JA (Low elevation NTS station, lower bound modern climate)
  - Area 12 (High elevation NTS station, upper bound modern climate)
- Or, use a stochastic simulator (longer term)
  - 3rd order two-state Markov chain
    - To determine the occurrence of daily precipitation
    - Monthly transition probabilities
  - Modified, exponential cumulative-probability-distribution function
    - To determine the magnitude of daily precipitation
    - Four seasonal probability distributions
  - Conditioned on local rainfall data
- Scaled to local elevation using the regional relation between precipitation and elevation



Evapotranspiration Model

- Modified Priestley-Taylor Equation
  - $\lambda E = \acute{\alpha} S/(S+\gamma)(R_n - G)$
    - $\acute{\alpha} = a(1-\exp(-b^*\theta_v))$ where a=1.26, and b=10
    - $S/(S+\gamma)=f(T_a)$
- Net Radiation (R_n)
  - $R_n = K_d - K_u + L_d - L_u$
    - $K_u = K_d$*albedo
    - $L_d - L_u = 5.6697E\text{-}8^*(Ea-.98)^*T_a^4$
      - $Ea = .0000092^*T_a$ (Swinbank equation)
- Ground Heat (G)
  - $G = -20 + .386(R_n)$
- Solar radiation model (K_d)
  - SOLRAD (Flint and Childs, 1987)
  - Detailed site geometry and atmospheric properties
    - slope, aspect, elevation, topographic shading (direct and diffuse radiation)
    - ozone, precipitable water, atmospheric turbidity, circumsolar-diffuse radiation, ground albedo

Measured and Modeled Water Content



- Using measured evapotranspiration in numerical modeling
- Simulations of measured subsurface water content helps to confirm numerical representation of conceptual model

Infiltration and Runoff Model

Infiltration

- All precipitation is modeled as infiltration except when storage capacity of the soil is exceeded and runoff is generated (1996 version)
- Precipitation, runon, and snowmelt infiltrate unless they exceed the saturated hydraulic conductivity or porosity, then runoff is generated (1999 version)
  - 2 hour summer storm events
  - 12 hour winter storm events

Runoff

- Counted then removed (1996 version)
- Routed downstream (1999 version)
  - Kinematic overland flow
  - Reinfiltrates downstream or continues to runoff

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Percolation

Soil drains to field capacity (≈-0.01MPa)

- Uniformly distributed through the soil profile (1996)
  - Excess water (water above field capacity) is allowed to infiltrate in the bedrock at the saturated conductivity of the bedrock
  - Water in excess of the bedrock saturated conductivity is held in storage in a “bucket” until the next day
    - If the bucket storage is exceeded then the excess in runoff (bucket storage capacity) is the soil depth times soil porosity-field capacity
- Forward cascade moves down one soil layer at a time (1999)
  - Layer 1 drains to field capacity and the remaining water is added to the residual water in layer 2, then water in excess is moved to layer 3 and so on to bedrock
  - Excess water (water above field capacity) at the bedrock interface percolates into the bedrock at the saturated conductivity of the bedrock
- Reverse cascade moves excess water up one soil layer at a time (1999)
  - Water reaching the surface becomes runoff
- Bedrock root zone up to 2 m thick captured some infiltration (40 mm storage)

Numerical Modeling of Infiltration

- Calibrate the model by matching observations and data
- Run the model for a range of geomorphic or topographic positions, soils, and climates to see how the system responds in areas that we have no data and under climates that have not been observed
- Test the model against data independent of the calibration data

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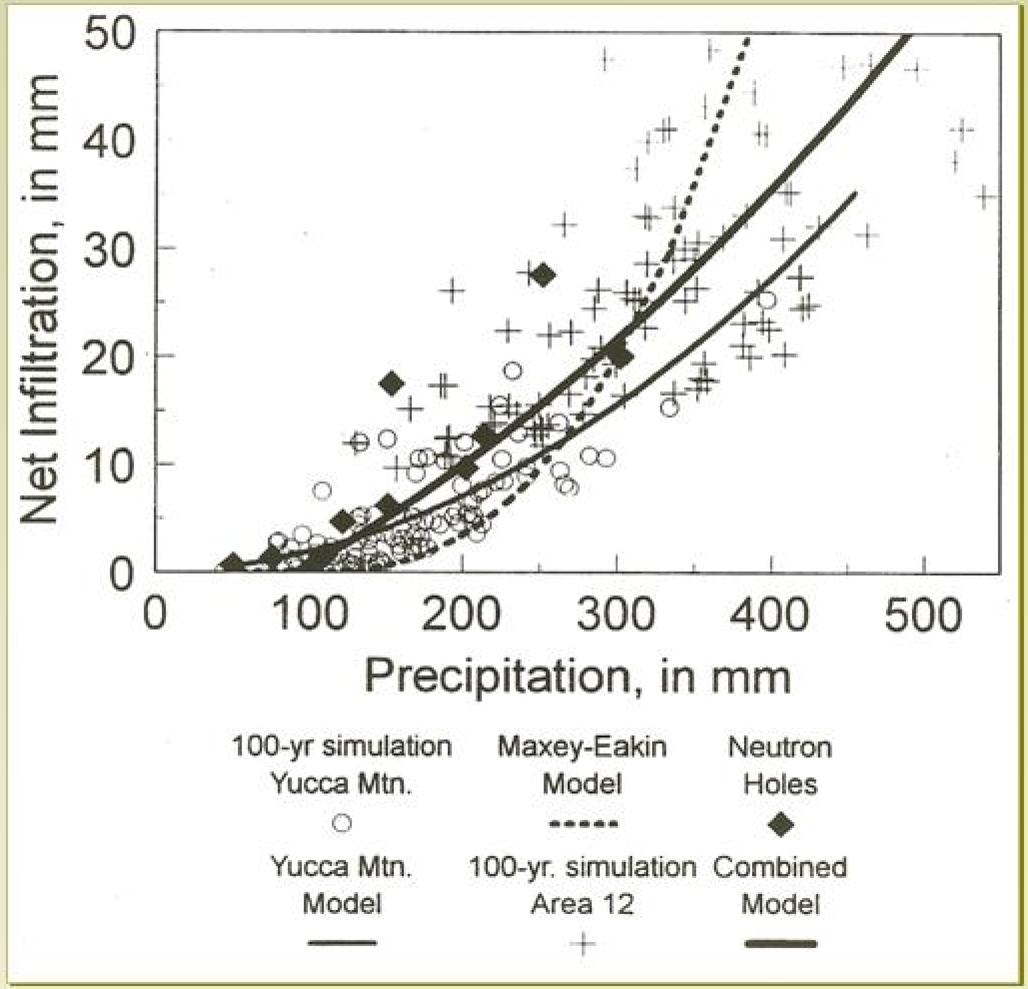
Relation of Infiltration to Precipitation



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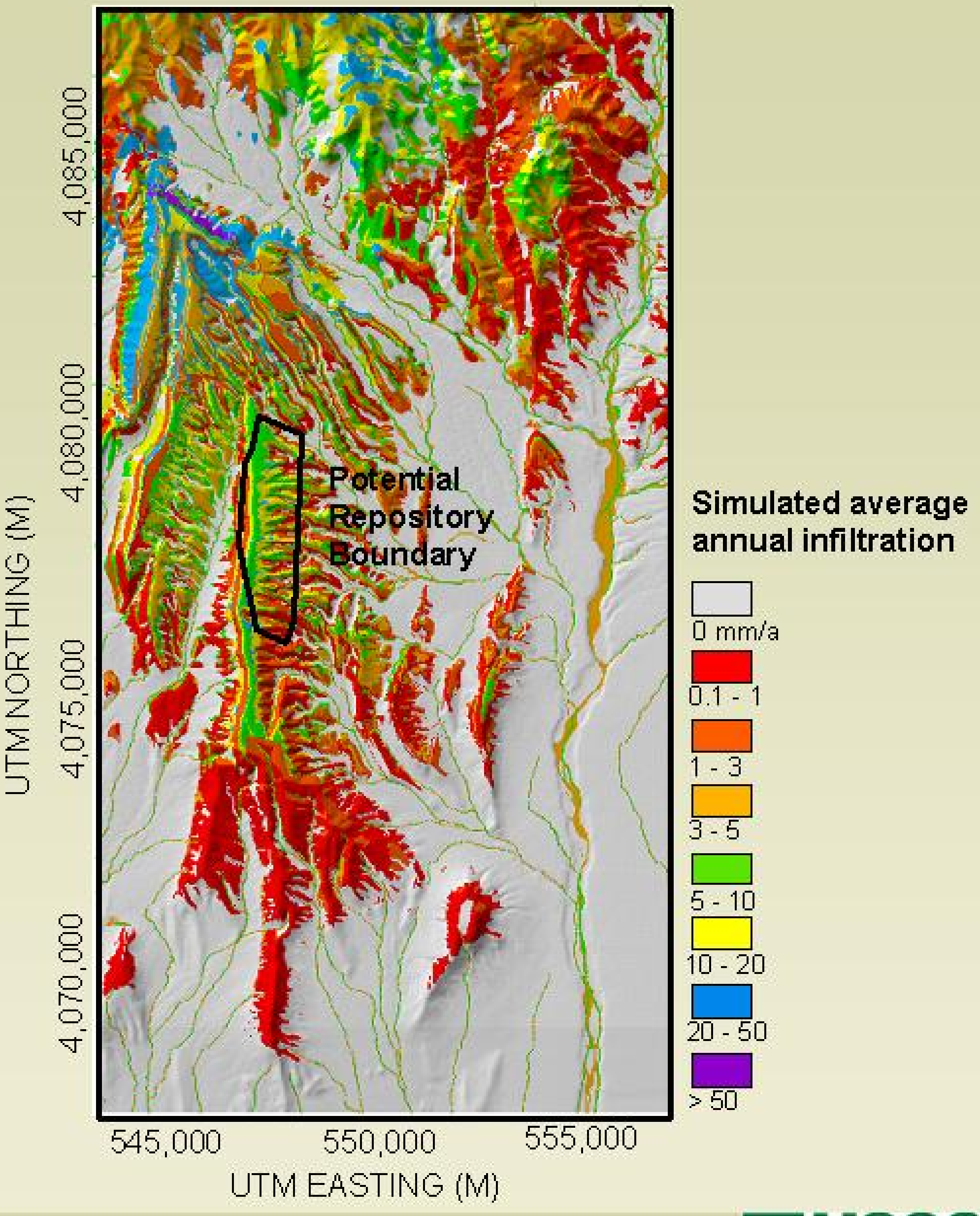
Net Infiltration Model 1996 Results



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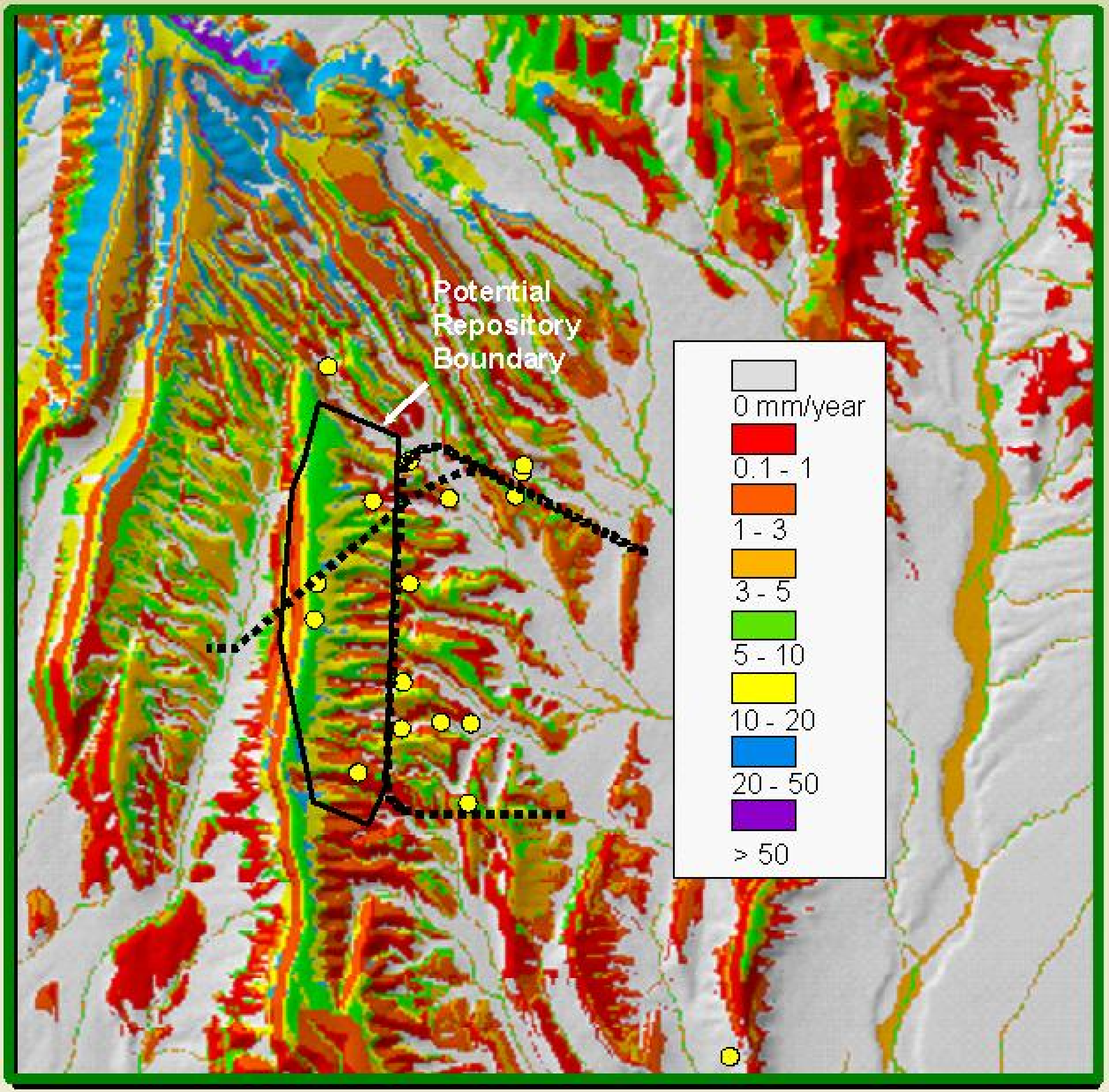
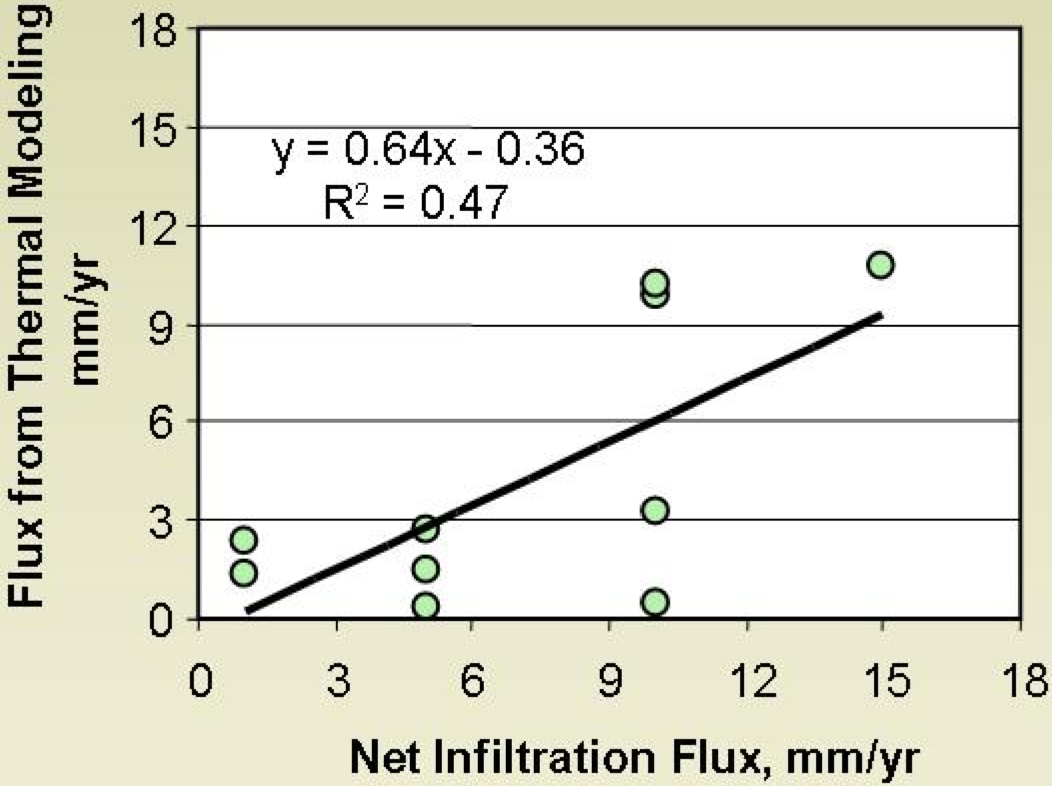


Surface Fluxes: close up of modeled net infiltration

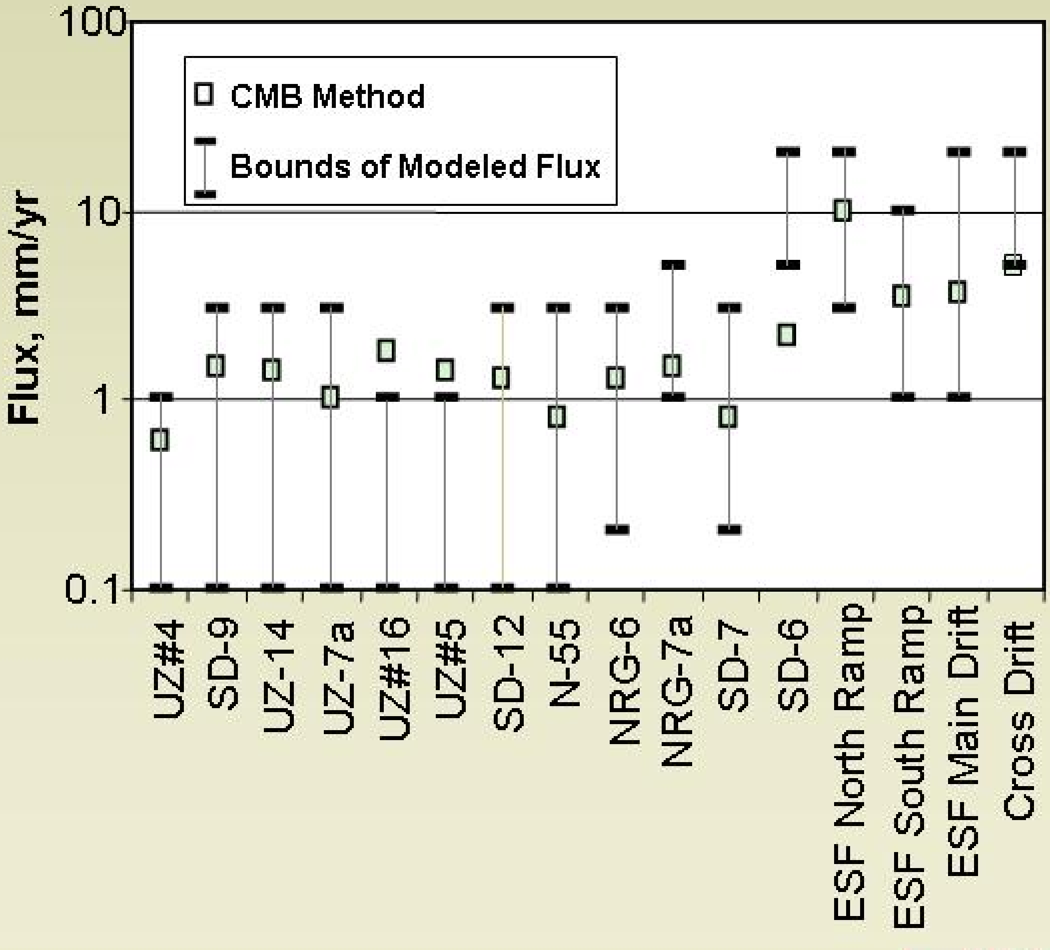
Corroborative Datasets and Observations

- Darcy flux calculations in the PTn
- Tritium
- C-14
- Thermal profiles
- Chloride mass balance
- Other chemistry techniques

Comparison of Flux from Thermal Modeling with Net Infiltration



Comparison of Flux from Chloride Mass Balance with Net Infiltration



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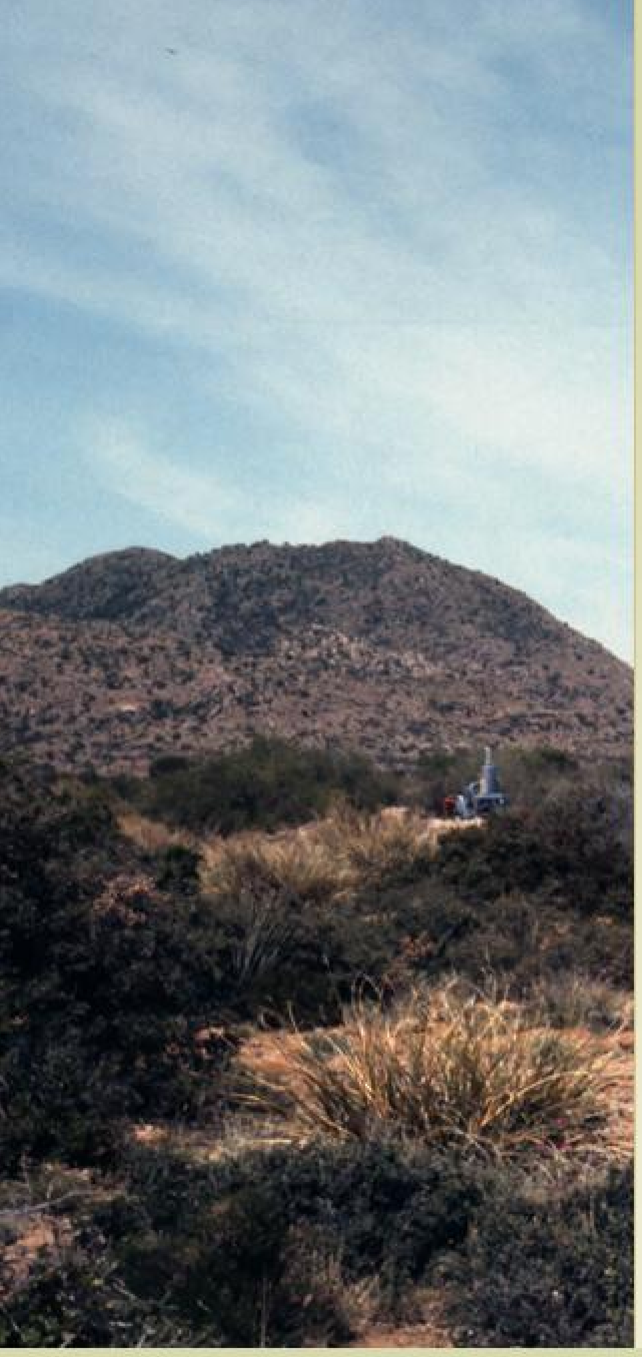
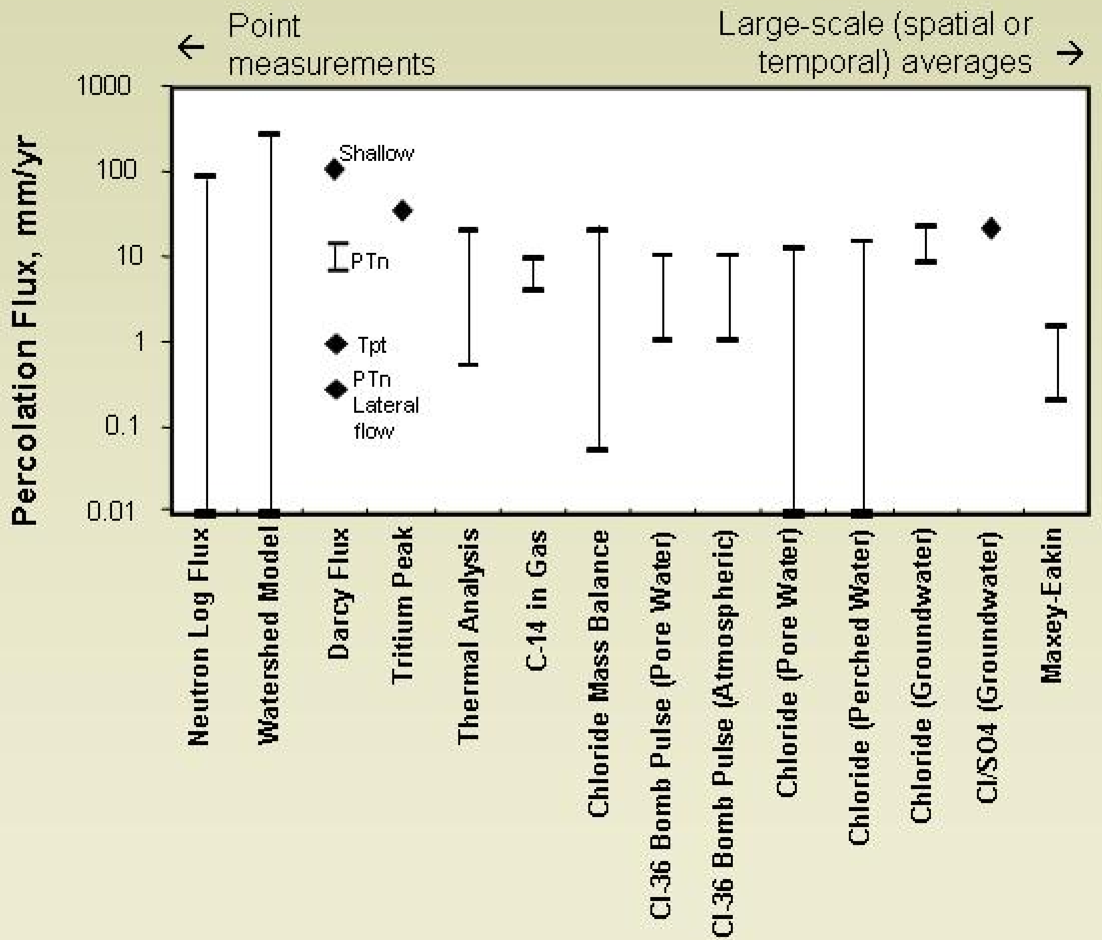
Comparison of percolation fluxes estimated by various methods





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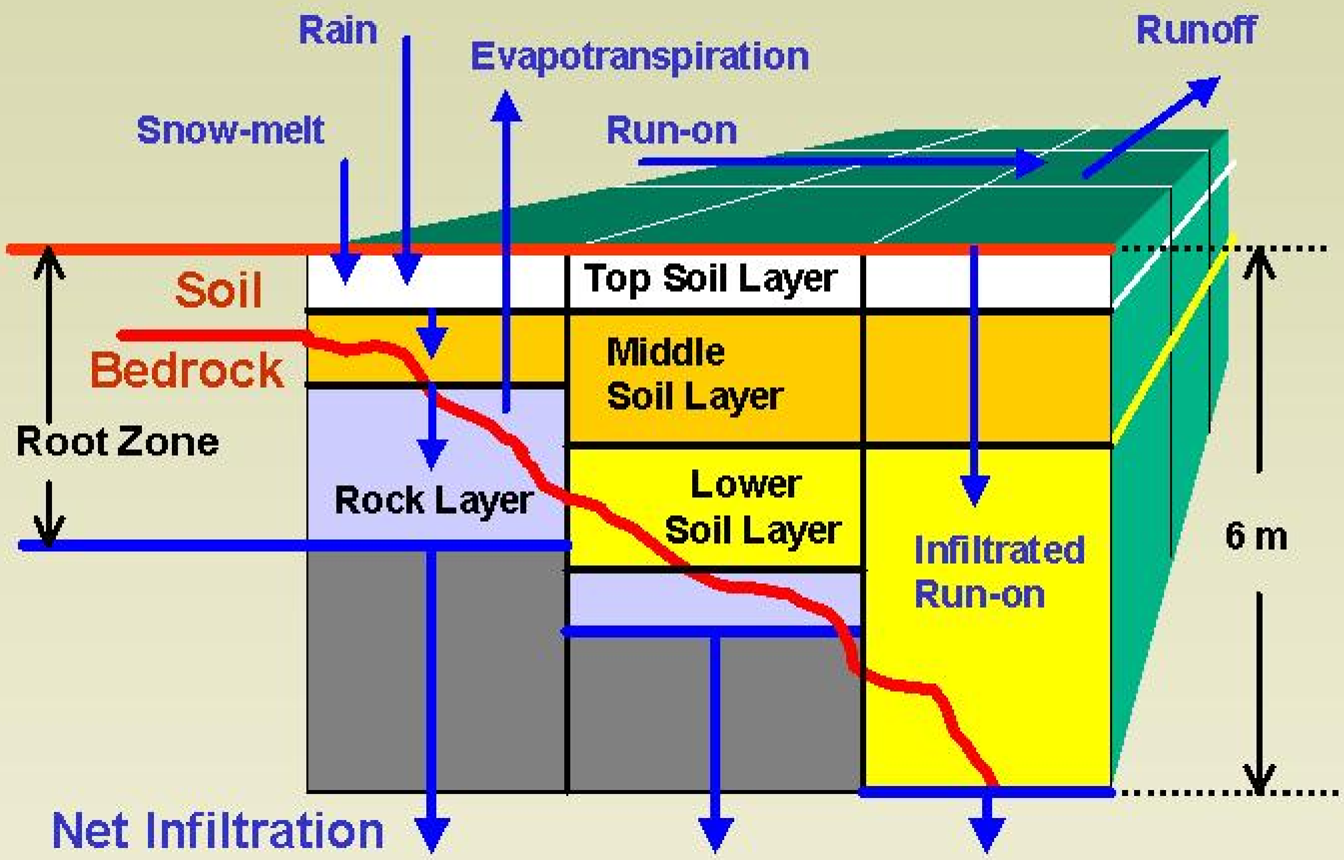
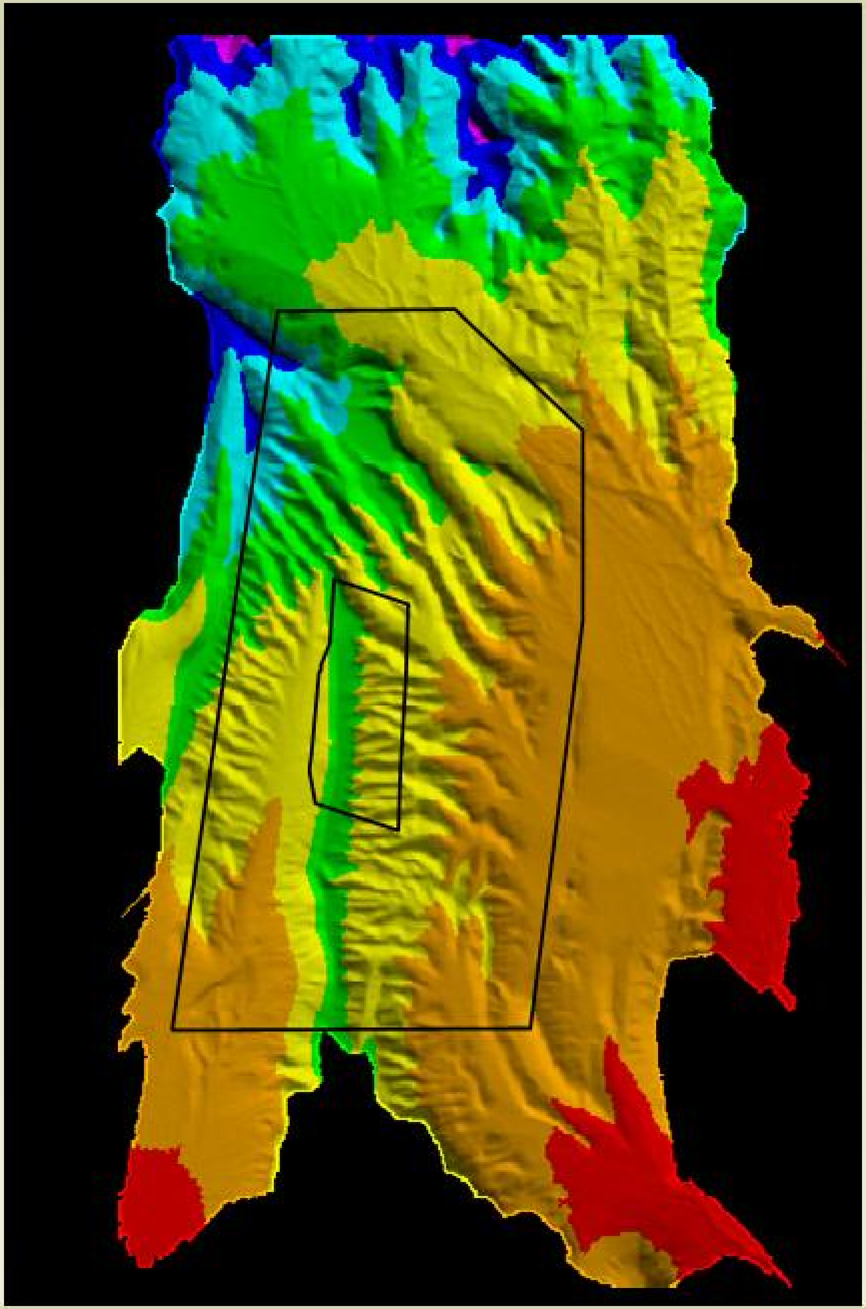
Refinements to the Numerical Model 1996 - 1999

- Surface routing
- Multiple soil layers
- Model calibration using streamflow
- Future climate scenarios

Layered Root Zone Water Balance Model





Modern Day Climate

Estimated Precipitation Rate (mm/yr)

Red	140 - 160
Orange	160 - 180
Yellow	180 - 200
Green	200 - 220
Cyan	220 - 240
Blue	240 - 260
Dark purple	260 - 280
Violet	280 - 300

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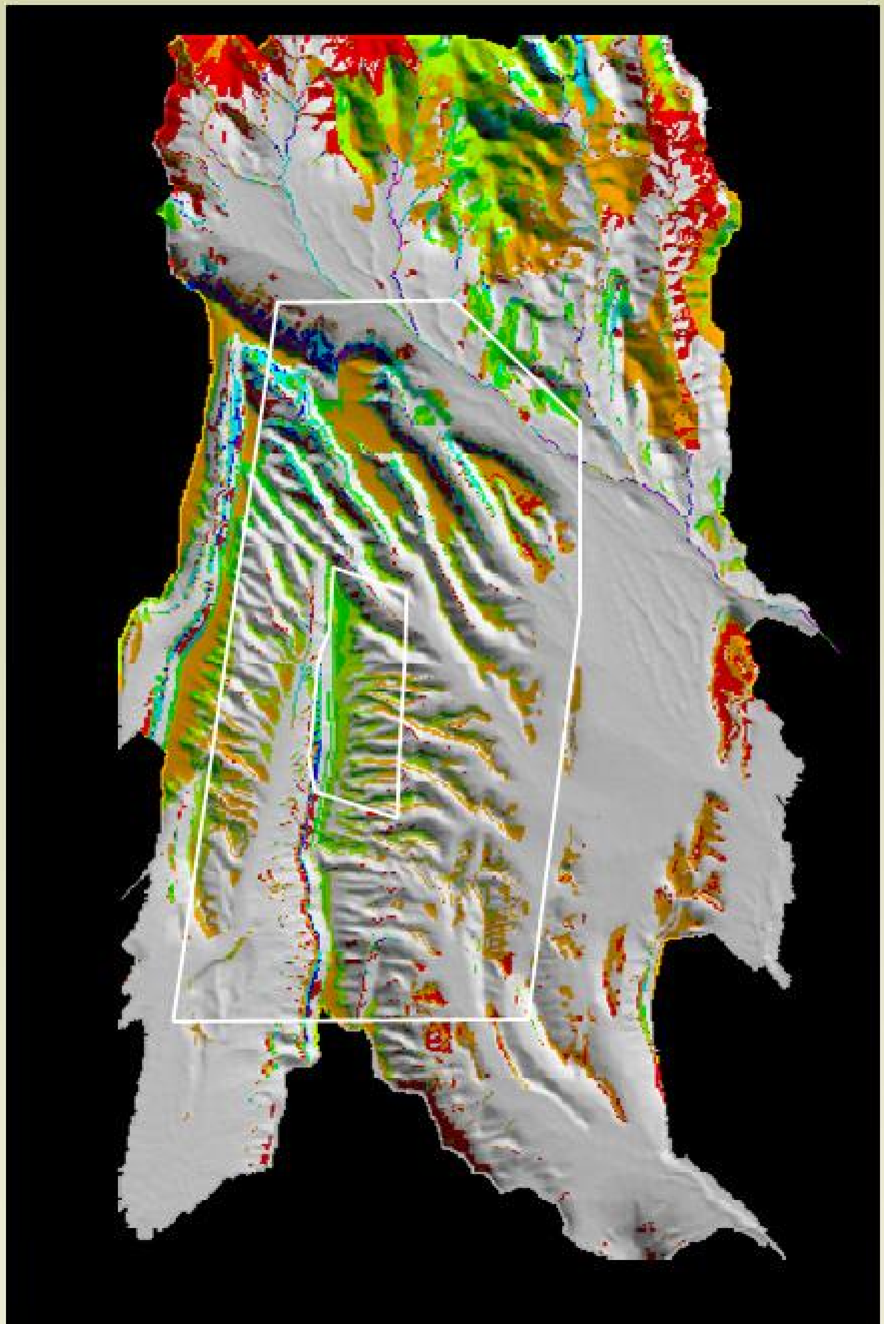


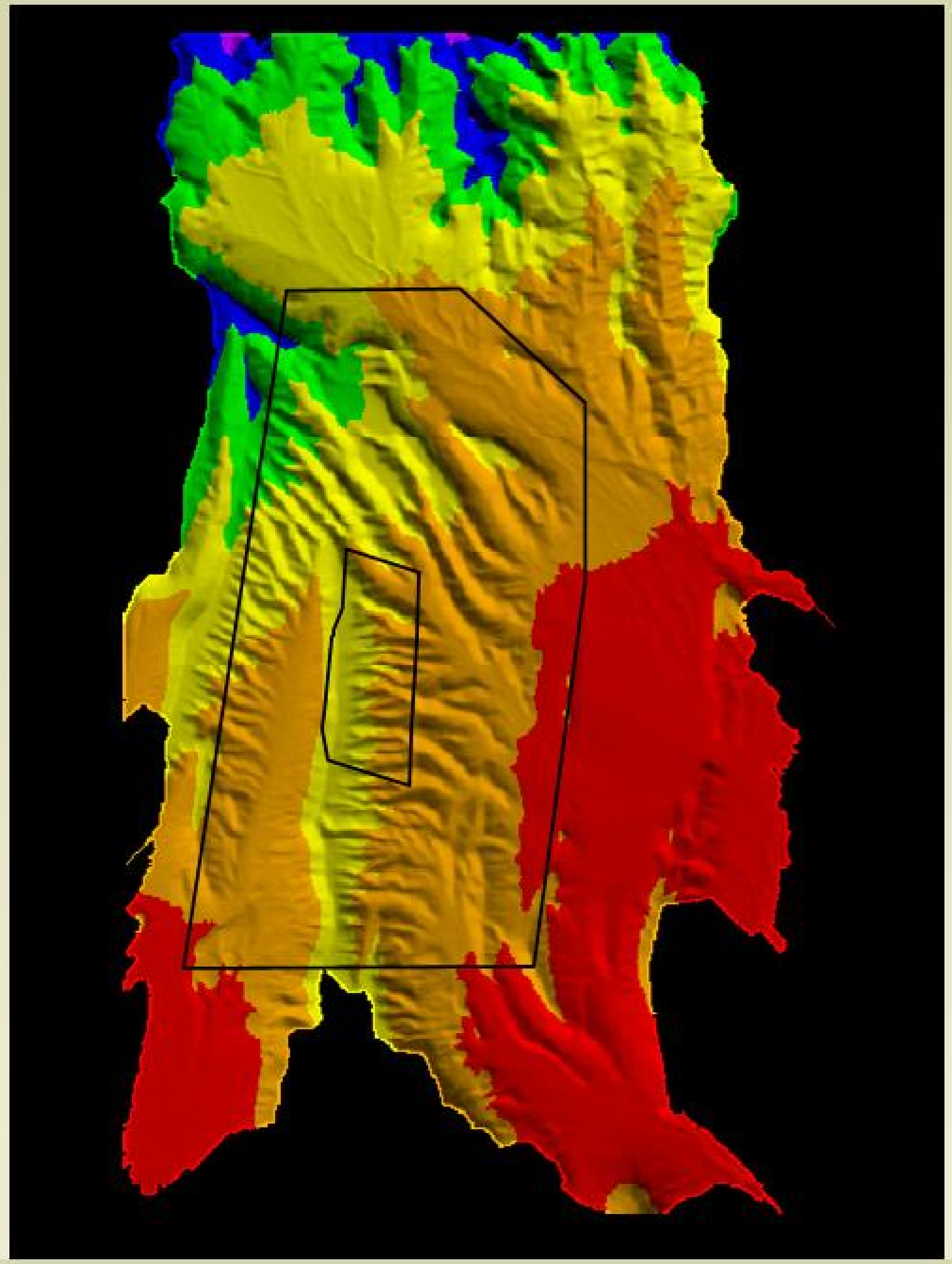
Modern Day Climate

Estimated Net Infiltration Rate (mm/yr)

- 0
- 0.1 - 1
- 1 - 5
- 5 - 10
- 10 - 20
- 20 - 50
- 50 - 100
- 100 - 200
- 200 - 1000

Summary of Results for Modern Climate

- Infiltration model domain (123.7 km^2)
  - Mean precipitation 188.5 mm/yr (1996 results 170 mm/yr)
  - Mean net infiltration 3.6 mm/yr (1996 results 4.5 mm/yr)
- 1999 UZ flow and transport model domain (38.7 km^2)
  - Mean precipitation 190.6 mm/yr
  - Mean net infiltration 4.6 mm/yr
- 1999 design potential repository area (4.7 km^2)
  - Mean precipitation 196.9 mm/yr
  - Mean net infiltration 4.7 mm/yr



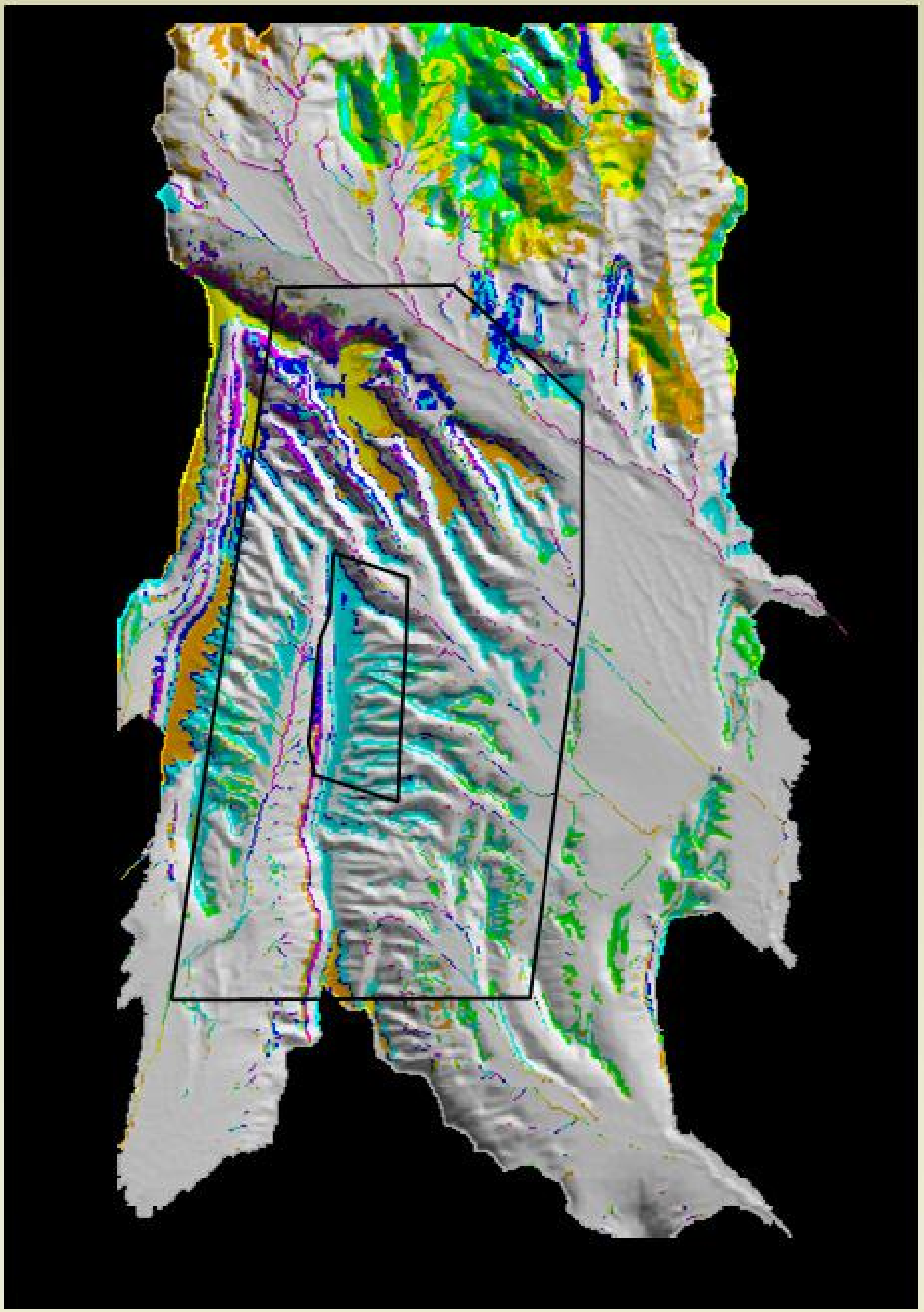
Long Term Future Climate

Estimated Precipitation Rate (mm/yr)

Red	280 - 300
Orange	300 - 320
Yellow	320 - 340
Green	340 - 360
Blue	360 - 380
Purple	380 - 400

Long Term Future Climate

Estimated Net Infiltration Rate (mm/yr)



(gray)	0 - 0.1
(red)	0.1 - 1
(orange)	1 - 5
(yellow)	5 - 10
(green)	10 - 20
(cyan)	20 - 50
(blue)	50 - 100
(purple)	100 - 1000
(magenta)	1000 - 3000

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Summary of Results for Long Term Future Climate

- Infiltration model domain (123.7 km^2)
  - Mean precipitation 316.1 mm/yr
  - Mean net infiltration 13.4 mm/yr
- 1999 UZ flow and transport model domain (38.7 km^2)
  - Mean precipitation 317.8 mm/yr
  - Mean net infiltration 17.8 mm/yr
- 1999 design potential repository area (4.7 km^2)
  - Mean precipitation 323.1 mm/yr
  - Mean net infiltration 19.8 mm/yr

Results of net infiltration studies at Yucca Mountain are described in:

Conceptual and Numerical Model of Infiltration for the Yucca Mountain Area, Nevada
USGS Milestone Report 3GUI623M, September 1996

Simulation of Net Infiltration for Modern and Potential Future Climates
Analysis and Modeling Report ANL-NBS-HS-000032, Draft November 1999, Approved June 2000

Summary

- Field observations and measurements made throughout the wettest and driest periods of climate cycles were necessary to establish a conceptual model of infiltration
- The conceptual model was converted to a numerical model and calibrated to borehole and streamflow data
- The model results are in agreement with thermal analyses, chloride mass balance calculations, and other isotopic approaches
- Single infiltration events may exceed 100-200 mm in a month; 6 major events occurred from 1980-1995
- Primary controls on net infiltration are precipitation, soil water storage and bedrock permeability
- Grid-based deterministic models provide a good method to spatially distribute calculated infiltration for past, present and future climates

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