U.S. Department of Energy
Office of Civilian Radioactive Waste Management

www.ocrwm.doe.gov

Overview of Infiltration Activities

Presented to:
NRC/DOE Technical Exchange on Infiltration at Yucca Mountain

Presented by:
Eric Smistad
U.S. Department of Energy

April 2, 2008
Las Vegas, Nevada

Background

- In March 2005, U.S. Department of Energy (DOE) learned of emails written by a small number of U.S. Geological Survey (USGS) employees suggesting that some technical products related to the infiltration model and analysis reports prepared by those USGS employees may not have been fully compliant with the Project quality assurance requirements
- DOE conducted a technical evaluation of USGS infiltration rate estimates and found that the estimates are consistent with independent studies of infiltration and recharge in southwestern U.S. and Nevada and therefore support the 2001 Site Recommendation (OCRWM 2006. *Evaluation of Technical Impact on the Yucca Mountain Project Technical Bases Resulting from Issues Raised by Emails of Former Project Participants*, DOE/RW-0583)
- DOE in 2005 directed Bechtel-SAIC Company and Sandia National Laboratories to develop a new infiltration model in support of the Total System Performance Assessment for License Application

New Infiltration Model for the License Application

- The new infiltration modeling effort included the development of the MASSIF model and an evaluation/ qualification of all direct inputs
- The new infiltration model follows U.S. Nuclear Regulatory Commission guidance in the Yucca Mountain Review Plan (NUREG-1804, REV 02) to ensure that
  - "The effects of … time-varying boundary conditions … are considered, such that net infiltration is not underestimated" (Section 2.2.1.3.5.3: Acceptance Criterion 2(3))
  - "Models use parameter values … that are technically defensible, reasonably account for uncertainties and variabilities, and do not result in an under-representation of the risk estimate" (Section 2.2.1.3.5.3: Acceptance Criterion 3(1))
  - "… the treatment of conceptual model uncertainty does not result in an under-representation of the risk estimate" (Section 2.2.1.3.5.3: Acceptance Criterion 4(3))

New Infiltration Model for the License Application (Continued)

- The results of the new infiltration model are documented in Simulation of Net Infiltration for Present-Day and Potential Future Climates (MDL-NBS-HS-000023 REV 01 and REV 01 AD01) and nine technical reports for supporting input parameters
- The new infiltration rates obtained from the model are incorporated into an update to the site-scale unsaturated zone flow model for use in the TSPA-LA, as documented in UZ Flow Models and Submodels MDL-NBS-HS-000006 REV 03, REV 03 AD 01, and REV 03 ACN 01)

List of Key Infiltration-Related Technical Products Since Site Recommendation

- SNL 2007. *Simulation of Net Infiltration for Present-Day and Potential Future Climates*, MDL-NBS-HS-000023 REV 01 (SNL 2008. REV 01 AD 01)
- SNL 2007. *UZ Flow Models and Submodels*, MDL-NBS-HS-000006 REV 03 (SNL 2007. REV 03 AD 01; SNL 2008. REV 03 ACN 01)
- SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*, MDL-WIS-PA-000005 REV 00 and REV 00 AD 01

List of Nine Technical Products Supporting the New Infiltration Model

- BSC 2005. *Data Qualification Report: Data Qualification Report for Digital Surficial Deposits Mapping File for Use on the Yucca Mountain Project*, TDR-NBS-GS-000029 REV 00
- BSC 2006. *Data Qualification Report Ground Cover and Geographic Coordinate Data from Ecological Study Plots at Yucca Mountain, Nevada*, TDR-NBS-HS-000030 REV 00
- BSC 2006. *Technical Evaluation and Review of Results, Technical Procedures, and Methods Related to the Collection of Moisture Monitoring Data Using Neutron Probes in Shallow Boreholes*, TDR-NBS-HS-000019 REV 00
- BSC 2006. *Data Qualification Report for the Qualification of Air Temperature Data from Meteorological Data Acquisition Station 24 for 1989 through 2004*, TDR-MGR-MD-000050 REV 00
- BSC 2006. *Data Qualification Report for the Qualification of Yucca Mountain Precipitation Data for 1988 - 1992*, TDR-MGR-MD-000051 REV 00
- BSC 2006. *Data Analysis for Infiltration Modeling: Bedrock Saturated Hydraulic Conductivity Calculation*, ANL-NBS-HS-000054 REV 00 and REV 00 ACN 01
- BSC 2006. *Data Analysis for Infiltration Modeling: Technical Evaluation of Previous Soil Depth Estimation Methods and Development of Alternate Parameter Values*, ANL-NBS-HS-000077 REV 01
- BSC 2006. *Data Analysis for Infiltration Modeling: Development of Soil Units and Associated Hydraulic Parameter Values*, ANL-NBS-HS-000055 REV 00 (SNL 2006. REV 00 ACN 01; SNL 2007. REV 00 ACN 02)
- BSC 2006. *Data Analysis for Infiltration Modeling: Extracted Weather Station Data Used to Represent Present-Day and Potential Future Climate Conditions in the Vicinity of Yucca Mountain*, ANL-MGR-MD-000015 REV 00 (SNL 2007. REV 00 ACN 01)

Independent Evaluations of the New Infiltration Model

- March 14, 2007: NWTRB, Panel on Postclosure Performance Meeting on Infiltration
- June 4-18, 2007: DOE OCRWM Office of Quality Assurance Audit OQA-SNL-07-06 of the Infiltration Model Report
- September 28, 2007: Daniel B. Stephens & Associates, Inc., *Summary of Findings of Daniel B. Stephens Upon Review of the Report Simulation of Net Infiltration for Present-Day and Potential Future Climates Prepared by Sandia National Laboratories, May 2007*
- December 2007: NWTRB, *Technical Evaluation of U.S. Department of Energy Yucca Mountain Infiltration Estimates*
- December 21, 2007: NRC, *U.S. Nuclear Regulatory Commission Observation Audit Report OAR-07-03, Observation Audit of the U.S. Department of Energy, Office of Civilian Radioactive Waste Management, Office of Quality Assurance Audit OQA-SNL-07-06, of the Infiltration Model Report*

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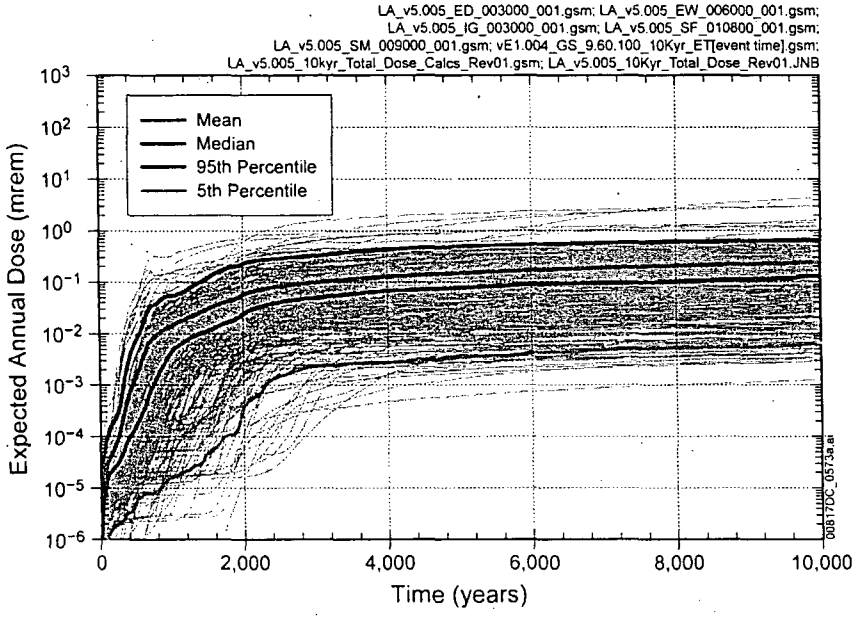
Use of Infiltration Model Results in the Total System Performance Assessment

Presented to:
NRC/DOE Technical Exchange on Infiltration at Yucca Mountain

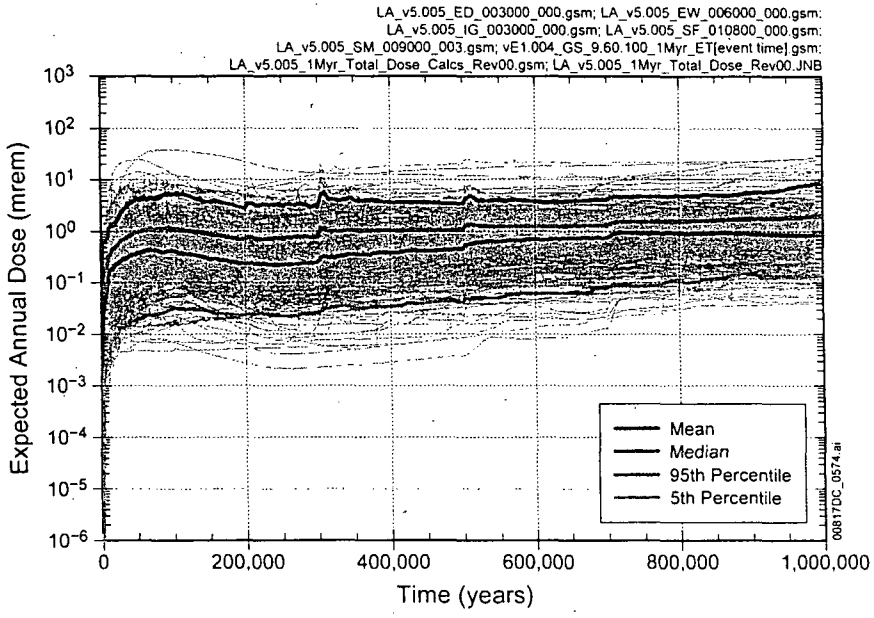
Presented by
Peter Swift
Sandia National Laboratories

April 2, 2008
Las Vegas, Nevada

Total System Performance Assessment Results
Total Mean and Median Annual Dose



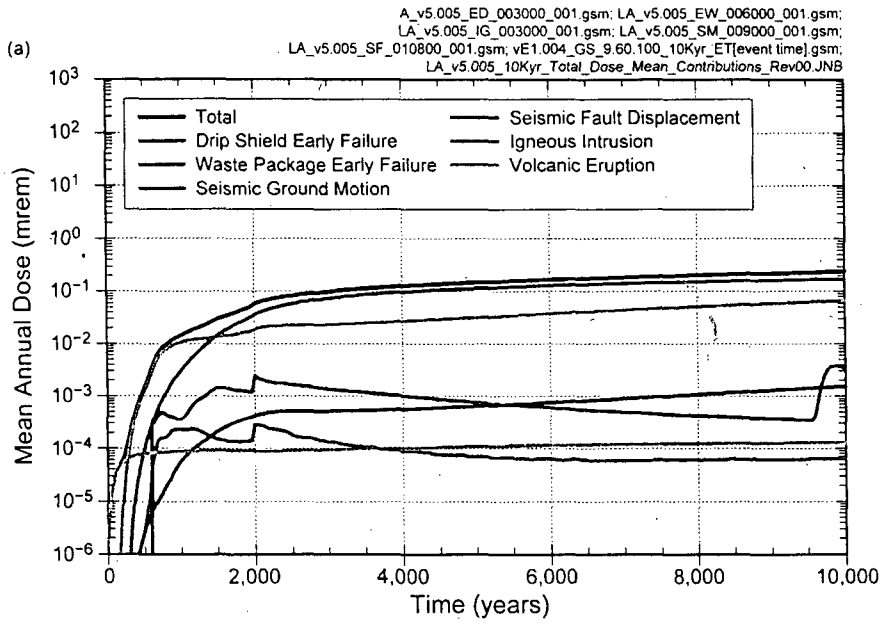
10,000 years



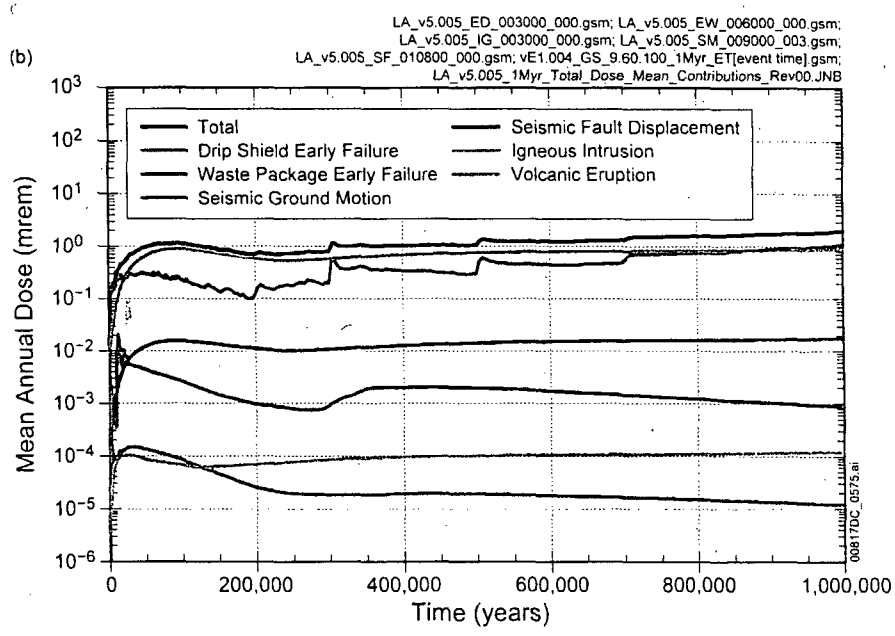
1,000,000 years

MDL-WIS-PA-000005 REV 00 AD 01, Figure 8.1-1[a] and Figure 8.1-2[a]

TSPA Results: Modeling Cases Contributing to Total Mean Annual Dose



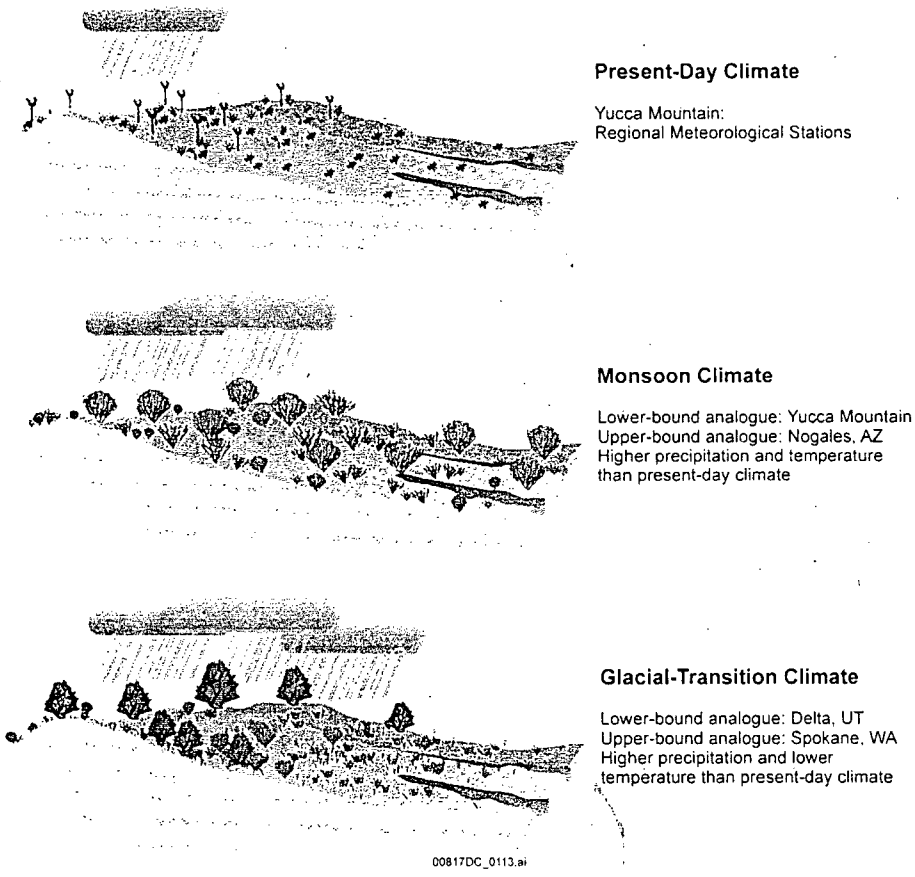
10,000 years



1,000,000 years

MDL-WIS-PA-000005 REV 00 AD 01, Figure 8.1-3[a].

Future Climate Analysis for TSPA-LA



MDL-WIS-PA-000005 REV 00 Figure 6.3.1-3

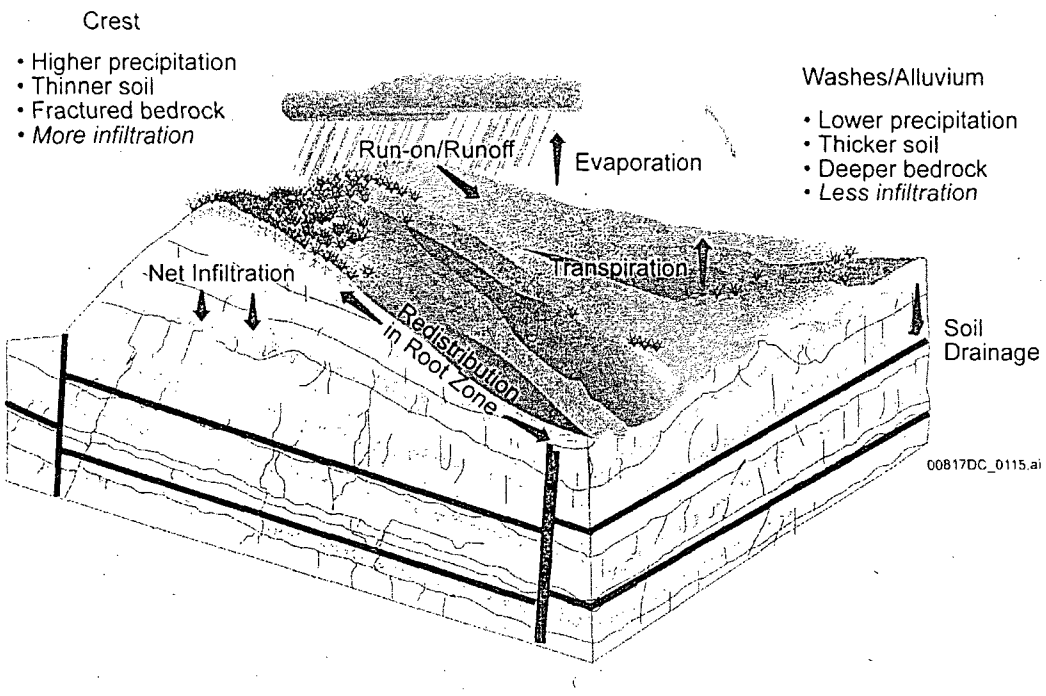
Analysis outputs used in downstream models

Infiltration model: precipitation and temperature

TSPA: climate state durations

- 0-600 years: present day climate
- 600-2000 years: monsoon climate
- 2000-10,000 years: glacial transition climate
- After 10,000 years: proposed regulatory specification of constant climate characterized by uncertain percolation flux

Infiltration Model



MDL-WIS-PA-000005 REV 00 Figure 6.3.1-5

Model Inputs

Described in MDL-NBS-HS-000023 REV 01 AD 01 and later presentation

Model outputs

Uncertainty characterized by 40 infiltration maps for each climate state

10th, 30th, 50th, and 90th percentile maps provided to Unsaturated Zone (UZ) flow model for each climate state (12 maps)

Weighting for TSPA established consistent with data from UZ (MDL-NBS-HS-000006 REV 03 and later presentation)

Uncertainty propagated into TSPA

Sampled pointer variable used to select infiltration map

Weighting Infiltration Maps in TSPA

- Infiltration maps were generated independent of field data from deep unsaturated zone
- Chloride content and temperature at depth provide information about past infiltration and percolation flux
- Generalized Likelihood Uncertainty Estimation (GLUE) method used to establish infiltration map weights consistent with data from depth
  - See MDL-NBS-HS-000006 REV 003 Section 6.8 and later presentation

Infiltration Case	Present-Day Climate (mm/yr)	Monsoon Climate (mm/yr)	Glacial-Transition Climate (mm/yr)	Post-10k Years (mm/yr) [a]	Probability-Weighting Factors (All Climate States)
10th Percentile	3.03	6.74	11.03	16.89	0.6191
30th Percentile	7.96	12.89	20.45	28.99	0.1568
50th Percentile	12.28	15.37	25.99	34.67	0.1645
90th Percentile	26.78	73.26	46.68	48.84	0.0596

Sources: SNL 2007 [DIRS 184614], Tables 6.1-2, 6.1-3, and LB0701PAWFINFM.001_R0 [DIRS 179283].

[a] Note that for the Post 10,000 Years data the Infiltration cases differ and represent scaled versions of the present-day 90th percentile, the 50th percentile Glacial Transition, the 90th percentile glacial transition, and the 90th percentile monsoon maps, respectively.

Net Infiltration Rates Averaged over the Unsaturated Zone Model Domain and Probability-Weighting Factors for the Infiltration Scenarios

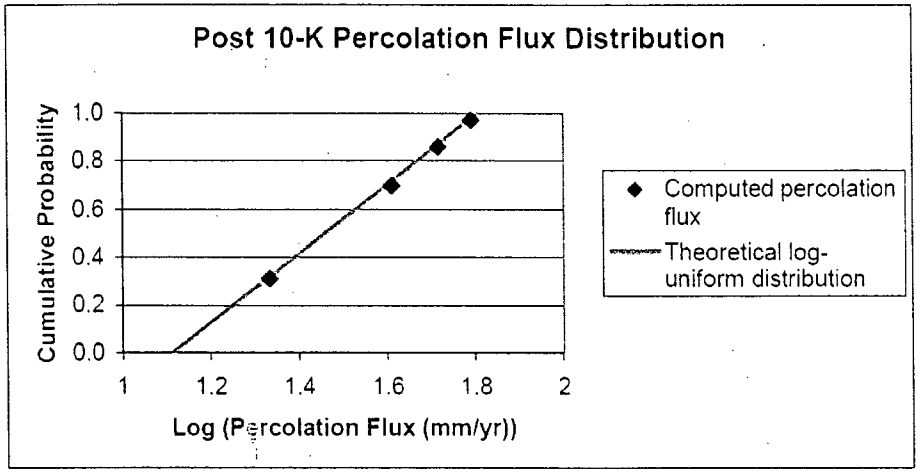
Source: MDL-WIS-PA-00005 REV 00 Table 6.3.1-2.

Uncertainty in Climate after 10,000 Years

- Proposed 10 CFR Part 63.342(c)(2):
  - "The constant value to be used to represent climate change is to be based on a log-uniform probability distribution for deep percolation rates from 13 to 64 mm/yr" (70 FR 53320)
  - I.e., constant, but uncertain, deep percolation flux with a specified spatial average over the repository footprint
    - Log-uniform, 13-64 mm/yr
- Project approach (MDL-NBS-HS-000006 REV 03, Section 6.1.4)
  - Spatially averaged flux at repository horizon ± 3% of spatially averaged infiltration
  - Repository footprint average infiltration for 12 maps (10th, 30th, 50th, and 90th percentiles for 3 climate states) provides basis for fitting specified log-uniform distribution

Uncertainty in Climate after 10,000 Years

- **Project approach to post-10 kyr uncertainty in climate**
  - Calculate repository-footprint average infiltration for 12 infiltration maps
  - Identify "target values" on proposed NRC distribution that correspond to midpoints of weighting factors used for pre-10 kyr infiltration
  - Scale maps with closest average infiltration values to match targets
  - Calculate corresponding UZ flow fields for each of four post-10 kyr maps
  - Use in TSPA with same weighting factors used in pre-10 kyr analyses



Percentile	Average Infil of Selected Map Over UZ Model Domain		Target Average Infil within Repository Footprint	
	Average (mm/yr)	Scenario	Rate (mm/yr)	Mid-point Cumulative Probability
10	16.89	present-day 90th percentile	21.29	0.3096
30	28.99	glacial transition 50th percentile	39.52	0.6975
50	34.67	glacial transition 90th percentile	51.05	0.8582
90	48.84	monsoon 90th percentiles	61.03	0.9702

Source: MDL-NBS-HS-000006 REV 03, Table 6.1-3 and Figure 6.1-6

TSPA Sensitivity Analysis Results 10,000-year Total Mean Annual Dose

(a)

	3,000 Years			5,000 Years			10,000 Years		
Step[a]	Variable[b]	R^{2c}	SRRC[d]	Variable	R^2	SRRC	Variable	R^2	SRRC
1	SCCTHRP	0.55	−0.72	SCCTHRP	0.66	−0.79	SCCTHRP	0.69	−0.83
2	IGRATE	0.62	0.28	IGRATE	0.71	0.24	IGRATE	0.73	0.22
3	SZGWSPDM	0.67	0.21	SZGWSPDM	0.74	0.15	SZGWSPDM	0.76	0.16
4	INFIL	0.71	0.19	MICTC99	0.76	0.14	MICTC99	0.77	0.14
5	MICTC99	0.73	0.15	MICC14	0.78	0.12	WFDEGEXF	0.78	0.10
6	SZFISPVO	0.75	0.14	INFIL	0.79	0.11	MICC14	0.79	0.11
7	MICC14	0.76	0.12	DSNFMASS	0.80	0.11	UZGAM	0.80	−0.09
8	DSNFMASS	0.77	0.10	SZFISPVO	0.81	0.09	INFIL	0.81	0.09
9	UZFAG8	0.78	−0.10	UZFAG8	0.82	−0.10	CSWFA0AC	0.81	−0.07
10	UZGAM	0.79	−0.09	UZGAM	0.82	−0.10	UZKDSRDT	0.82	0.07
11	SZDIFCVO	0.79	−0.08	WFDEGEXF	0.83	0.10			
12	WFDEGEXF	0.80	0.08	WDCRCDEN	0.83	0.08			
13	KDUSMEC	0.80	0.08	WDZOLID	0.84	−0.07			
14	MICPA231	0.81	−0.08	WDGCUA22	0.84	0.07			
15				BCKRA226	0.85	−0.06			

a: Steps in stepwise rank regression analysis
b: Variables listed in order of selection in stepwise regression
c: Cumulative R^2 value with entry of each variable into regression model
d: Standardized rank regression coefficients (SRRCs) in final regression model

MDL-WIS-PA-000005 REV 00 AD 01, Figure K8.1-2[a](a). Stepwise Rank Regression Analyses for Total Mean Expected Annual Dose for 10,000 Years after Closure

TSPA Regression Analyses:

- Uncertain parameters contributing significantly to epistemic uncertainty in mean annual dose

For total dose at 10,000 years, significant uncertain parameters are

- Stress corrosion crack threshold
- Probability of igneous intrusion
- Saturated zone groundwater specific discharge
- Infiltration map uncertainty appears as a minor contributor at early time only, when transport time uncertainty is significant

TSPA Sensitivity Analysis Results
1,000,000-year Total Mean Annual Dose

(a)

	EXPDOSE: 50,000 Years			EXPDOSE: 200,000 Years			EXPDOSE: 500,000 Years		
Step[a]	Variable[b]	R^2[c]	SRRC[d]	Variable	R^2	SRRC	Variable	R^2	SRRC
1	SCCTHRP	0.27	-0.48	IGRATE	0.38	0.61	IGRATE	0.29	0.54
2	IGRATE	0.43	0.41	SZGWSPDM	0.48	0.28	WDGCA22	0.46	-0.38
3	SZGWSPDM	0.55	0.33	EP1LOWPU	0.53	0.23	SZGWSPDM	0.53	0.24
4	EP1LOWPU	0.60	0.20	SCCTHRP	0.57	-0.21	EP1LOWNU	0.56	0.19
5	MICNP237	0.62	0.11	SZFISPVO	0.60	0.15	MICNP237	0.59	0.16
6	INFIL	0.63	0.13	INFIL	0.62	0.16	EP1LOWPU	0.61	0.17
7	EP1NPO2	0.65	0.13	EP1NPO2	0.64	0.14	SZCONCOL	0.64	0.15
8	MICTC99	0.66	0.11	GOESITED	0.66	-0.14	SZFISPVO	0.66	0.15
9	ALPHAL	0.67	0.10	MICSE79	0.68	0.09	INFIL	0.67	0.11
10				MICNP237	0.69	0.14	GOESITED	0.68	-0.10
11				EP1LOWNU	0.70	0.11	SZKDCSVO	0.69	-0.10
12				SZCONCOL	0.71	0.11	HFOSITED	0.69	-0.09
13				PHCSS	0.72	-0.11	SZDIFCVO	0.70	-0.09
14				HFOSA	0.73	-0.09			
15				SZDIFCVO	0.73	-0.09			
16				SEEPCOND	0.74	-0.09			

MDL-WIS-PA-000005 REV 00 AD 01, Figure K8.2-2[a](a). Stepwise Rank Regression Analyses for Total Mean Expected Annual Dose for 1,000,000 Years after Closure

TSPA Regression Analyses:

- Uncertain parameters contributing significantly to epistemic uncertainty in mean annual dose

For total dose at 500,000 years, significant uncertain parameters are

- Probability of igneous intrusion
- Alloy 22 general corrosion temperature dependency
- Saturated zone groundwater specific discharge
- Infiltration map uncertainty is not significant

Conclusions

- Infiltration incorporated in TSPA through UZ flow model
- Uncertainty in infiltration incorporated in TSPA through sampling on infiltration maps
  - Pre-10,000 years, weighting calibrated to UZ chloride and temperature data using Generalized Likelihood Uncertainty Estimation
  - Post-10,000 years, uncertainty treatment is prescribed by proposed rule
- Uncertainty associated with infiltration is a minor contributor to uncertainty in total dose

References

- Bechtel SAIC 2004. *Future Climate Analysis*, ANL-NBS-GS-000008 Rev 01
- SNL 2007. *Simulation of Net Infiltration for Present-Day and Potential Future Climates*, MDL-NBS-HS-000023 Rev 01 (SNL 2008. Rev 03 AD 01)
- SNL 2007. *UZ Flow Models and Submodels*, MDL-NBS-HS-000006 Rev 03 (SNL 2007. Rev 03 AD 01; SNL 2008. Rev 03 AD 02 ACN 01).
- SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application*, MDL-WIS-PA-000005 Rev 00 and Rev 00 AD01

Uncertain Epistemic Parameters Appearing in Slides 11 and 12 (from MDL-WIS-PA-000005 REV 00 Table K3-1)

ALPHAL. van Genuchten capillary strength parameter in lithophysal rock units (Pa). *Distribution:* Triangular. *Range:* -105 to 105. *Mean/Median/Mode:* 0. *TSPA-LA Name:* Alpha_Uncert_Lith_a. *Location in TSPA-LA:* Sections 6.3.3.1.2 and 6.3.3.1.3; Tables 6.3.3-1, 6.3.3-3 and 6.3.5-4
BCKRA226. Natural background levels of combined ^{226}Ra and ^{228}Ra in groundwater (pCi/L). *Distribution:* Truncated normal. *Range:* 0 to 0.71. *Mean/Median/Mode:* 0.5. *TSPA-LA Name:* Background_Ra226_Ra228_a. *Location in TSPA-LA:* Sections 6.3.10.2, 6.3.11.2, and Table 6.3.10-6.
CSWFA0AC. Correlated regression coefficient a0 in the abstracted rate model under acidic conditions (dimensionless). *Distribution:* Normal. *Mean/Median/Mode:* 0. *Standard Deviation:* 1. *TSPA-LA Name:* CSNF_WF_Uncert_a0_Acid_a. *Location in TSPA-LA:* Section 6.3.7.4.1.2; Equation 6.3.7-6.
DSNFMASS. Scale factor used to characterize uncertainty in radionuclide content of DSNF (dimensionless). *Distribution:* Triangular. *Range:* 0.45 to 2.9. *Most Likely:* 0.62. *TSPA-LA Name:* DSNF_Mass_Uncert_a. *Location in TSPA-LA:* Sections 6.3.7.1.2 and 6.3.7.1.3; Table 6.3.7-7.
EP1LOWPU. Logarithm of the scale factor used to characterize uncertainty in plutonium solubility at an ionic strength below 1 molal (dimensionless). *Distribution:* Truncated normal. *Range:* -1.4 to 1.4. *Mean/Median/Mode:* 0. *Standard Deviation:* 0.7. *TSPA-LA Name:* Pu_Eps_1_low_a. *Location in TSPA-LA:* Sections 6.3.7.5.1, 6.3.7.5.2 and 6.3.7.5.3; Table 6.3.7-44; Equation 6.3.7-13a.
EP1LOWNU. Logarithm of the scale factor used to characterize uncertainty in uranium solubility under nominal or seismic conditions at an ionic strength below 1 molal (dimensionless). *Distribution:* Truncated normal. *Range:* -1 to 1. *Mean/Median/Mode:* 0. *Standard Deviation:* 0.5. *TSPA-LA Name:* U_Eps_1_low_Nominal_a. *Location in TSPA-LA:* Section 6.3.7.5.1, 6.3.7.5.2 and 6.3.7.5.3; Table 6.3.7-54; Equation 6.3.7-13a.
EP1NPO2. Logarithm of the scale factor used to characterize uncertainty in NpO_2 solubility at an ionic strength below 1 molal (dimensionless). *Distribution:* Truncated normal. *Range:* -1.2 to 1.2. *Mean:* 0. *Standard Deviation:* 0.6. *TSPA-LA Name:* NpO2_Eps_1_low_a. *Location in TSPA-LA:* Sections 6.3.7.5.1, 6.3.7.5.2 and 6.3.7.5.3; Table 6.3.7-43; Equation 6.3.7-13a.
GOESITED. Density of sorption sites on goethite (1/nm^2). *Distribution:* Discrete. *Range:* 1.02 to 8.59. *TSPA-LA Name:* Goethite_Site_Density_a. *Location in TSPA-LA:* Table 6.3.8-3.
HFOSA. Hydrous ferric oxide (HFO) surface area (m^2/g). *Distribution:* Truncated log normal. *Range:* 68 to 600. *Mean:* 275.6. *Standard Deviation:* 113.4. *TSPA-LA Name:* HFO_SA_a. *Location in TSPA-LA:* Table 6.3.8-4; S_{CP} in Equation 6.3.8-19.
HFOSA. Hydrous ferric oxide (HFO) surface area (m^2/g). *Distribution:* Truncated log normal. *Range:* 68 to 600. *Mean:* 275.6. *Standard Deviation:* 113.4. *TSPA-LA Name:* HFO_SA_a. *Location in TSPA-LA:* Table 6.3.8-4; S_{CP} in Equation 6.3.8-19.
HFOSITED. Sorption site density for hydrous ferric oxide (HFO) (1/nm^2). *Distribution:* Discrete. *Range:* 0.56 to 5.65. *TSPA-LA Name:* HFO_Site_Density_a. *Location in TSPA-LA:* Table 6.3.8-3.
IGRATE. Frequency of intersection of the repository footprint by a volcanic event (yr^{-1}). *Distribution:* Piecewise uniform. *Range:* 0 to 7.76E-07. *TSPA-LA Name:* Igneous_Event_Prob_a. *Location in TSPA-LA:* Table 6.5-2.
INFIL. Pointer variable for determining infiltration conditions: 10th, 30th, 50th or 90th percentile infiltration scenario (dimensionless). *Distribution:* Discrete. *Range:* 1 to 4. *TSPA-LA Name:* Infiltration_Scenario_a. *Location in TSPA-LA:* Section 6.3.1.2; Tables 6.3.1-2 and 6.3.5-4.
KDUSMEC. Distribution coefficient for reversible sorption of uranium to waste form (smectite) colloids (mL/g). *Distribution:* Log uniform. *Range:* 5.00E+02 to 5.00E+04. *TSPA-LA Name:* Kd_U_Rev_Smectite_a. *Location in TSPA-LA:* Sections 6.3.7.6.2 and 6.3.7.6.3; Equation 6.3.7-20; Tables 6.3.7-62 and 6.3.7-66.
MICC14. Groundwater Biosphere Dose Conversion Factor (BDCF) for ^{14}C in modern interglacial climate ((Sv/year)/(Bq/m^3)). *Distribution:* Discrete. *Range:* 7.18E-10 to 2.56E-08. *Mean:* 1.93E-09. *Standard Deviation:* 1.85E-09. *TSPA-LA Name:* GW_BDCF_MIC_C14. *Location in TSPA-LA:* Sections 6.3.11.2 and 6.3.11.3; Table 6.3.11-3.
MICNP237. Groundwater Biosphere Dose Conversion Factor (BDCF) for ^{237}Np in modern interglacial climate ((Sv/year)/(Bq/m^3)). *Distribution:* Discrete. *Range:* 1.06E-07 to 8.05E-07. *Mean:* 2.74E-07. *Standard Deviation:* 9.70E-08. *TSPA-LA Name:* GW_BDCF_MIC_Np237. *Location in TSPA-LA:* Sections 6.3.11.2 and 6.3.11.3; Table 6.3.11-3.
MICPA231. Groundwater Biosphere Dose Conversion Factor (BDCF) for ^{231}Pa in modern interglacial climate ((Sv/year)/(Bq/m^3)). *Distribution:* Discrete. *Range:* 6.58E-07 to 8.56E-06. *Mean:* 2.44E-06. *Standard Deviation:* 1.02E-06. *TSPA-LA Name:* GW_BDCF_MIC_Pa231. *Location in TSPA-LA:* Sections 6.3.11.2 and 6.3.11.3; Table 6.3.11-3.

Uncertain Epistemic Parameters Appearing in Slides 11 and 12 (from MDL-WIS-PA-000005 REV 00 Table K3-1) (continued)

MICSE79. Groundwater Biosphere Dose Conversion Factor (BDCF) for ^{79}Se in modern interglacial climate. ((Sv/year)/(Bq/m^3)). *Distribution:* Discrete. *Range:* 3.62E-09 to 1.51E-06. *Mean:* 2.42E-08. *Standard Deviation:* 7.48E-08. *TSPA-LA Name:* GW_BDCF_MIC_Se79. *Location in TSPA-LA:* Sections 6.3.11.2 and 6.3.11.3; Table-6.3.11-3.
MICTC99. Groundwater Biosphere Dose Conversion Factor (BDCF) for ^{99}Tc in modern interglacial climate ((Sv/year)/(Bq/m^3)). *Distribution:* Discrete. *Range:* 5.28E-10 to 2.85E-08. *Mean:* 1.12E-09. *Standard Deviation:* 1.26E-09. *TSPA-LA Name:* GW_BDCF_MIC_Tc99. *Location in TSPA-LA:* Sections 6.3.11.2 and 6.3.11.3; Table-6.3.11-3.
PHCSS. Pointer variable used to determine pH in CSNF Cell1 under liquid influx conditions (dimensionless). *Distribution:* Uniform. *Range:* 0 to 1. *TSPA-LA Name:* Inpkg_pH_CSNF_S_Rand_a. *Location in TSPA-LA:* Section 6.3.7.2.2 Part IV.
SEEPCON. Pointer variable to determine the seepage/condensation regime for the first failed waste package in a percolation subregion (dimensionless). *Distribution:* Uniform. *Range:* 0 to 1. *TSPA-LA Name:* Seepage_Condensation_Prob_a*.
SCCTHRP. Residual stress threshold for SCC nucleation of Alloy 22 (as a percentage of yield strength in MPa) (dimensionless). *Distribution:* Uniform. *Range:* 90 to 105. *TSPA-LA Name:* Stress_Thresh_A22_a. *Location in TSPA-LA:* Section 6.6.1.3.7; Table 6.6-2.
SZCONCOL. Logarithm of ambient concentration of colloids in groundwater (g/mL). *Distribution:* Piecewise uniform. *Range:* -9 to -3.6. *TSPA-LA Name:* Conc_Col. *Location in TSPA-LA:* Table 6.3.10-2.
SZDIFCVO. Logarithm of effective diffusion coefficient in fractured volcanic units (m^2/s). *Distribution:* Piecewise uniform. *Range:* -11.3 to -9.3. *TSPA-LA Name:* DCVO. *Location in TSPA-LA:* Sections 6.3.10.2 and 6.3.10.5; Table 6.3.10-2.
SZFISPVO. Flowing interval spacing in fractured volcanic units (m). *Distribution:* Piecewise uniform. *Range:* 1.86 to 80. *TSPA-LA Name:* FISVO. *Location in TSPA-LA:* Section 6.3.10.5; Table 6.3.10-2.
SZGWSPDM. Logarithm of the scale factor used to characterize uncertainty in groundwater specific discharge (dimensionless). *Distribution:* Piecewise uniform. *Range:* -0.951 to 0.951. *TSPA-LA Name:* GWSPD. *Location in TSPA-LA:* Section 6.3.10.2; Table 6.3.10-2.
SZKDCSVO. Cesium sorption coefficient in volcanic units (mL/g). *Distribution:* Piecewise uniform. *Range:* 100 to 6783. *TSPA-LA Name:* Kd_Cs_Vo. *Location in TSPA-LA:* Section 6.3.10.2; Table 6.3.10-2.
UZFAG8. Fracture aperture for group 8 rock units (tswf[4,5], tswf[6,7], tswf8, pcf38) (m). *Calculated by:* Por_group8_a/ff_group8_a. *TSPA-LA Name:* fa_group8_a. *Location in TSPA-LA:* Section 6.3.9.2; Equation 6.3.9-2; Fracture porosity values and frequency values are shown in Tables 6.3.9-6 and 6.3.9-7.
UZGAM. Active fracture model (AFM) Gamma parameter (dimensionless). *Distribution:* Uniform. *Range:* 0.2 to 0.6. *TSPA-LA Name:* Gamma_AFM_a. *Location in TSPA-LA:* Sections 6.3.9.2, 6.3.9.3 and 6.3.9.4.1; Table 6.3.9-5.
UZKDSRDT. Sorption coefficient for strontium in devitrified tuff units of UZ (mL/g). *Distribution:* Uniform. *Range:* 10 to 70. *TSPA-LA Name:* KdSr_Devit_a. *Location in TSPA-LA:* Sections 6.3.9.2 and 6.3.9.3; Equation 6.3.9-3; Table 6.3.9-2.
WDCRCDEN. Ratio of SCC area to unit of seismic damaged area for a waste package (dimensionless). *Distribution:* Uniform. *Range:* 0.00327 to 0.0131. *TSPA-LA Name:* WP_Crack_Area_Density_a. *Location in TSPA-LA:* Table 6.6-2.
WDGCA22. Temperature dependent slope term of Alloy 22 general corrosion rate (K). *Distribution:* Truncated normal. *Range:* 666 to 7731. *Mean:* 4905. *Standard Deviation:* 1413. *TSPA-LA Name:* C1_GenCorr_A22_a. *Location in TSPA-LA:* Sections 6.3.5.1.2 and 6.3.5.1.3; Tables 6.3.5-3 and 6.3.5-4; Equation 6.3.5-4.
WDGCUA22. Variable for selecting distribution for general corrosion rate (low, medium, or high) (dimensionless). *Distribution:* Discrete. *Range:* 1 to 3. *TSPA-LA Name:* GC_ULevel_A22_a. *Location in TSPA-LA:* Table 6.3.5-4.
WDZOLID. Deviation from median yield strength range for outer lid (dimensionless). *Distribution:* Truncated normal. *Range:* -3 to 3. *Mean/Median/Mode:* 0. *Standard Deviation:* 1. *TSPA-LA Name:* z_OL_a. *Location in TSPA-LA:* Sections 6.3.5.1.2 and 6.3.5.1.3; Table 6.3.5-3.
WFDEGEXF. The surface area exposure factor for the amount of HLW glass contacted by water (dimensionless). *Distribution:* Triangular. *Range:* 4 to 17. *Mode:* 4. *TSPA-LA Name:* Exposure_Factor_a. *Location in TSPA-LA:* Sections 6.3.7.4.3.2 and 6.3.7.4.3.3; Equation 6.3.7-9; Table 6.3.7-32.

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Office of Civilian Radioactive Waste Management

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The MASSIF Net Infiltration Model

Presented to:
NRC/DOE Technical Exchange on Infiltration at Yucca Mountain

Presented by:
Joshua S Stein, Ph. D.
Principal Member of Technical Staff,
Sandia National Laboratories (SNL)

April 2, 2008
Las Vegas, Nevada

Primary Contributors

- Joshua Stein (SNL) – Principal investigator and team lead
- Dan Levitt (Los Alamos National Laboratory) – Conceptual model and validation
- Al Reed (SNL) – MASSIF model developer, runoff comparisons
- Richard Allen (University of Idaho) – Evapotranspiration (ET) model consultant
- David Groeneveld (HydroBio) – Satellite analyses of Yucca Mountain (YM) vegetation
- John Stormont (University of New Mexico) – Conceptual model and data review
- Kaylie Rasmuson (Bechtel SAIC Company (BSC)) – YM vegetation characterization

Primary Contributors (Continued)

- Robert Walsh (Apogen Technologies) – Precipitation and uncertainty analysis
- Cedric Sallaberry (SNL) – Precipitation and sensitivity analysis
- Elena Kalinina (GRAM) – HYDRUS-1D and lysimeter comparison
- Daniel B. Stephens (Daniel B. Stephens & Associates) – Independent model reviewer

Background

- July 2005—SNL was tasked to
  - Develop a new net infiltration model and revise and replace the original analysis/model reports (AMR) related to net infiltration
    - *Simulation of Net Infiltration for Present-Day and Potential Future Climates,* MDL-NBS-HS-000023 REV 00 (BSC 2004. REV 00)
    - *Analysis of Infiltration Uncertainty,* ANL-NBS-HS-000027 REV 01 (BSC 2003. REV 01)
- BSC produced nine data qualification reports to support the new model (documents listed in earlier presentation)
  - Bedrock distribution and properties, soil type and properties, soil depth, site vegetation measurements, site weather data, and Neutron logging data
- A new model (MASSIF) has been developed and documented in MDL-NBS-HS-000023 REV 01 (SNL 2008. REV 01 AD 01). *(Specific references to this document are listed in the following slides in green italicized text.)*

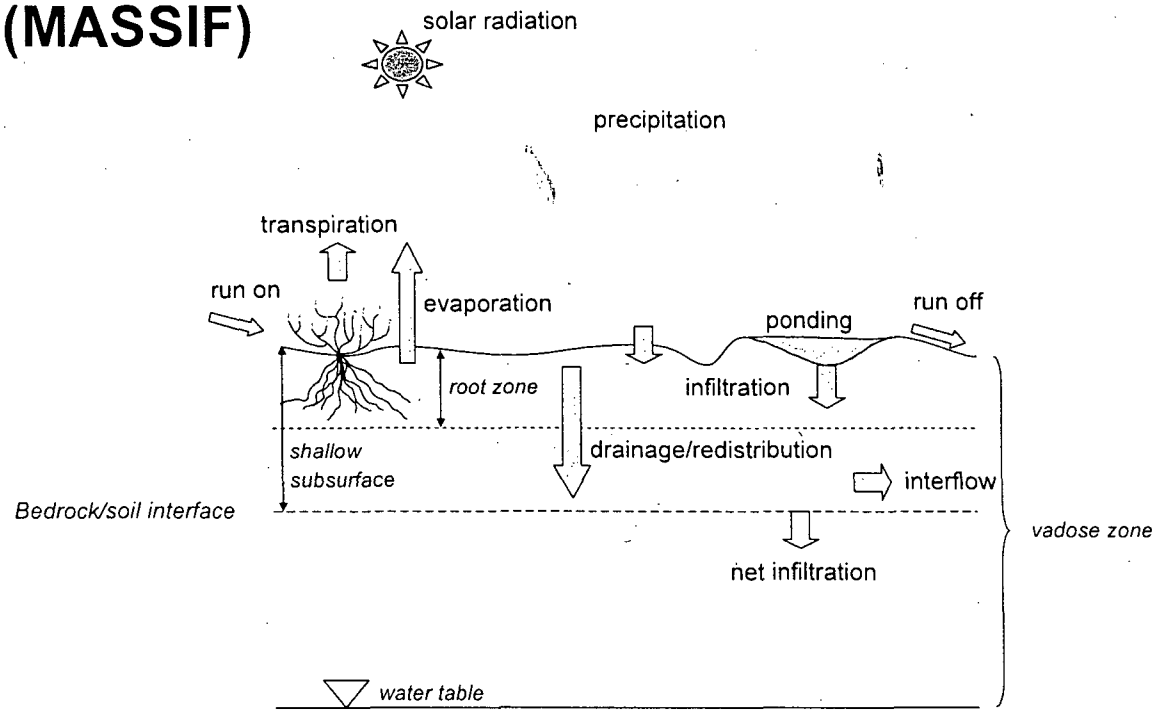
Goals for New Modeling Approach

- Use a conceptual model consistent with available data and appropriate for size of domain
- Include rigorous estimate of uncertainty in net infiltration
- NRC *Yucca Mountain Review Plan* (NUREG-1804, Rev 2) specifies that the DOE model should not underestimate net infiltration or risk estimate (Section 2.2.1.3.5.3)
  - Boundary conditions (Criterion 2.3)
  - Parameter values (Criterion 3.1)
  - Conceptual model Criterion 4.3)
- MASSIF is implemented using Mathcad software in order to create a calculation environment with the following features:
  - Calculation algorithm and routines are extensively documented where they are defined
  - Inputs and results are presented and archived in context with the calculations
  - The calculation is transparent such that a technical person skilled in Mathcad can follow and reproduce the work without recourse to the originator

MASSIF Conceptual Model

Water Balance Equation

- **Mass Accounting System for Soil Infiltration and Flow (MASSIF)**



R_{off} = Runoff
R_{on} = Runon
SM = Snowmelt
SF = Snowfall
SUB = Sublimation
$\Delta\theta$ = Change in storage
ET = Evapotranspiration
NI = Net Infiltration

Grid based on data from Shuttle Radar Topography Mission (30 × 30-m grid)

Figure 6.2.1-1

$$R_{off} = P + R_{on} + SM - SF - SUB + \Delta\theta - ET - NI$$

MASSIF Conceptual Model
Precipitation and Snow Processes

- Daily precipitation is stochastically simulated *Section 6.5.1[a] and Appendix F[a]*
- Ten representative years, including low probability, high precipitation years are selected for each realization
- Precipitation is lapse-corrected for elevation *Section F2.1[a]*
- Snowfall occurs when average daily temperature is below 0°C *Section 6.4.1.2*
- Water from snow enters the soil as snowmelt (function of average daily temperature) *Section 6.4.1.4*
- Sublimation losses are represented *Section 6.4.1.4*

$$R_{off} = P + R_{on} + SM - SF - SUB + \Delta\theta - ET - NI$$

MASSIF Conceptual Model
Subsurface Water Movement and Storage

- Soil water movement and storage is controlled by a layered field capacity model designed to be compatible with the Food and Agriculture Organization (FAO)-56 evapotranspiration model *Section 6.4.2 and 6.4.4*
  - Layer 1 = Surface evaporation layer (0.1 to 0.2 m); includes top portion of root zone and is divided into two portions
    - Fraction of grid cell under plant canopy (changes with time)
    - Fraction of grid cell outside plant canopy (changes with time)
  - Layer 2 = Remaining portion of root zone
  - Layer 3 = Soil below root zone (only present if soil is deep)
  - Bottom boundary is top of bedrock (roots do not remove water from bedrock)

$$R_{off} = P + R_{on} + SM - SF - SUB + \Delta\theta - ET - NI$$

MASSIF Conceptual Model
Subsurface Water Movement and Storage

(Continued)

- Water flows from upper to lower layers when field capacity is exceeded in the upper layer; flow is limited by soil conductivity
- Net infiltration occurs once soil layer contacting bedrock exceeds field capacity
- Daily net infiltration limited by bedrock conductivity

MASSIF Conceptual Model
Runoff and Runon

- Domain is divided into 11 separate watersheds using ARC GIS Terrain Processing toolbox
- Each watershed drains to a single cell at the boundary of the infiltration model domain
- Unsaturated zone (UZ) modeling domain is fully covered by the watersheds
- Each cell drains to the neighboring cell with the lowest elevation ("U8" algorithm) (*sinks are filled*)

Watershed Delineation

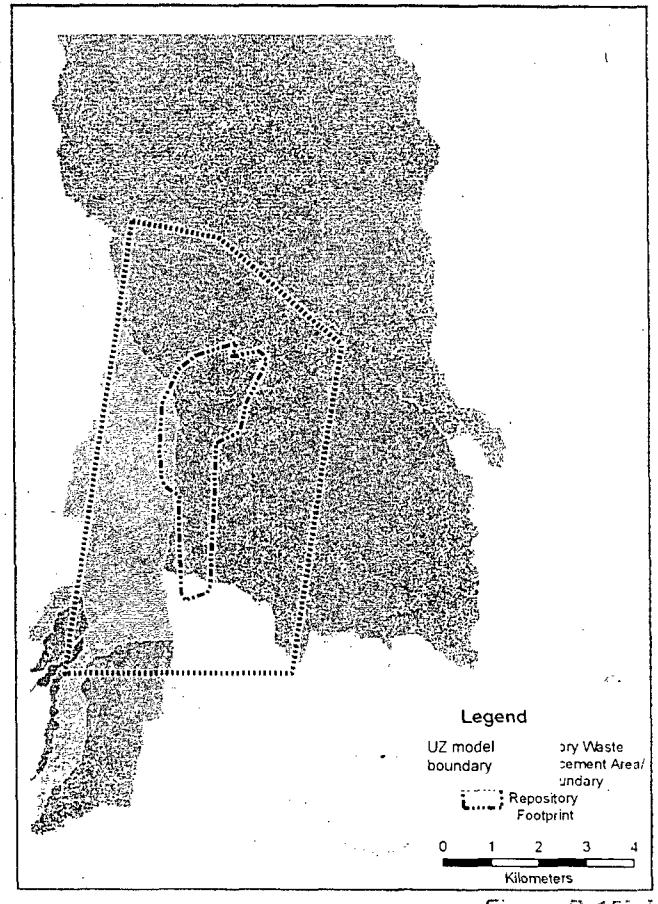


Figure B-15[a]

$$R_{off} = P + R_{on} + SM - SF - SUB + \Delta\theta - ET - NI$$

MASSIF Conceptual Model
ET Model

- **FAO-56—An internationally accepted set of guidelines to calculate ET** *Section 6.4.4 and Appendix C[a]*
- **Empirical, mass-balance approach based on reference ET (ET_0)**
- **$ET = (K_s \times K_{cb} + K_e)\, ET_0$**

  K_s = Water stress coefficient [0 to 1] *f(soil props, vegetation)*

  K_{cb} = Basal crop coefficient [0 to 1.35] *f(vegetation)*

  K_e = Soil evaporation coefficient [0 to 1] *f(soil props, vegetation)*

$$R_{off} = P + R_{on} + SM - SF - SUB + \Delta\theta - ET - NI$$

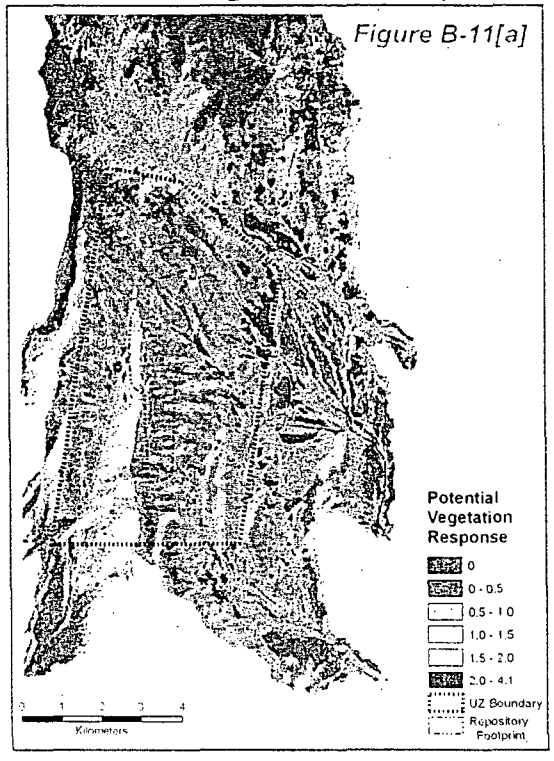
MASSIF Conceptual Model Reference ET

- **Penman-Monteith equation used to estimate reference ET** *Section 6.4.5 and Appendix C[a]*
  - **Solar radiation**
    - **Estimated on a horizontal surface from Hargreaves equation (based on daily temperature range)**
    - **Land-surface slope-azimuth correction applied**
    - **Approach validated by comparison to direct measurements**
  - **Minimum and maximum temperature modeled separately on wet and dry days** *Appendix F[a]*
  - **Wind speed derived from present-day site measurements and varies with day of year** *Appendix F[a]*

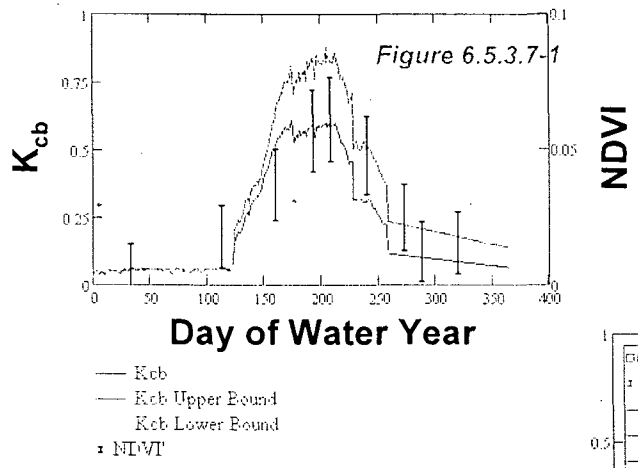
MASSIF Conceptual Model
Estimating K_{cb}

- Normalized difference vegetation index (NDVI) is predicted as a function of location, day of year, and total annual precipitation
- K_{cb} calculated from NDVI observed during wet and moderate years at YMP

Potential Vegetation Response

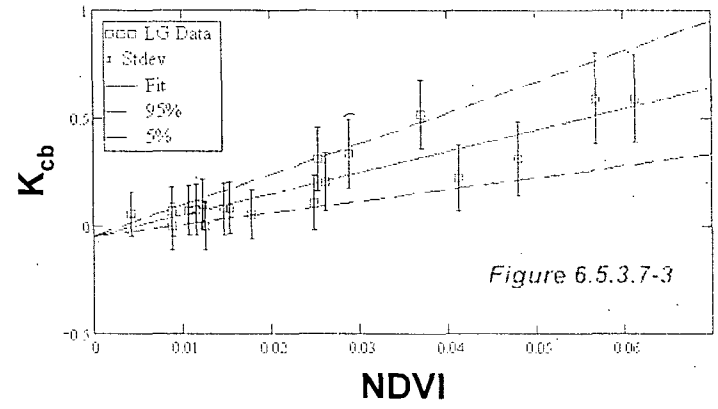


Wet Year K_{cb} and NDVI



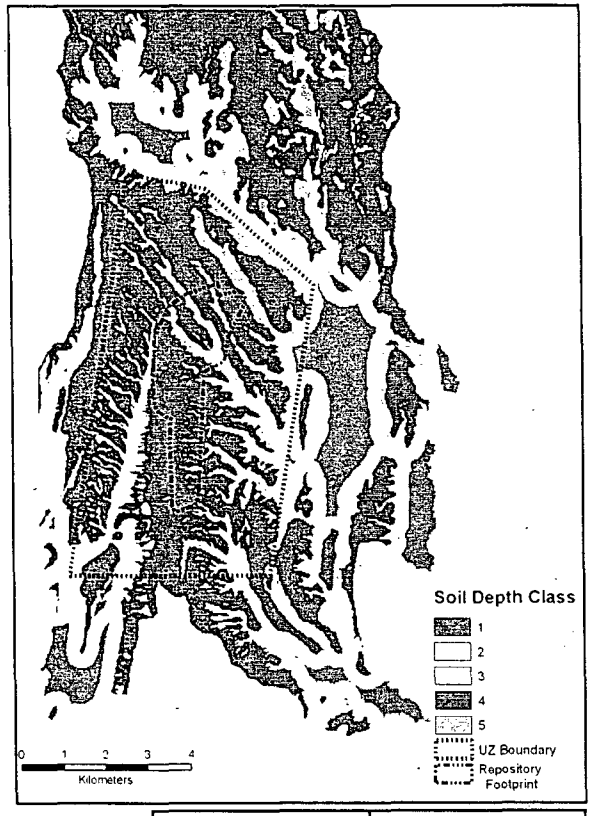
$$NDVI = \frac{NIR - \mathrm{Re}\,d}{NIR + \mathrm{Re}\,d}$$

NVDI vs. K_{cb}
Error bars show uncertainty

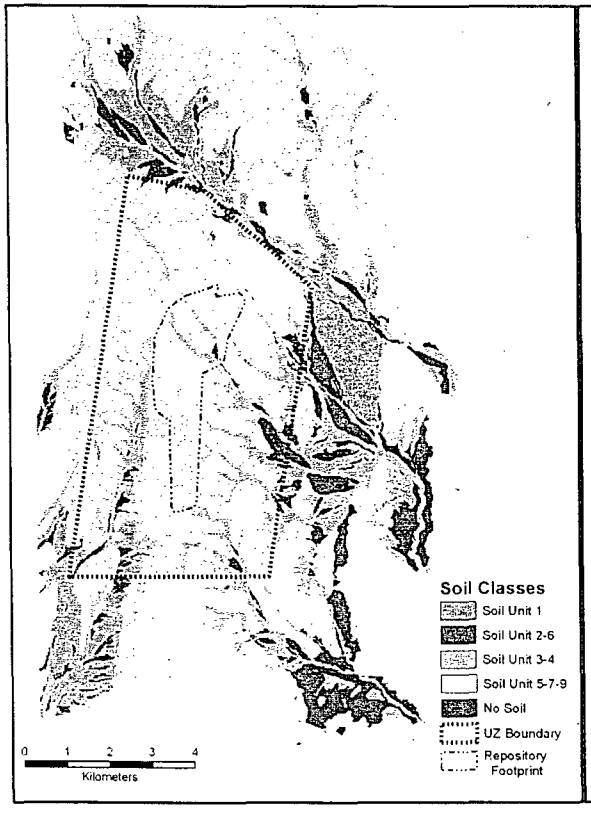


Soil and Bedrock Maps

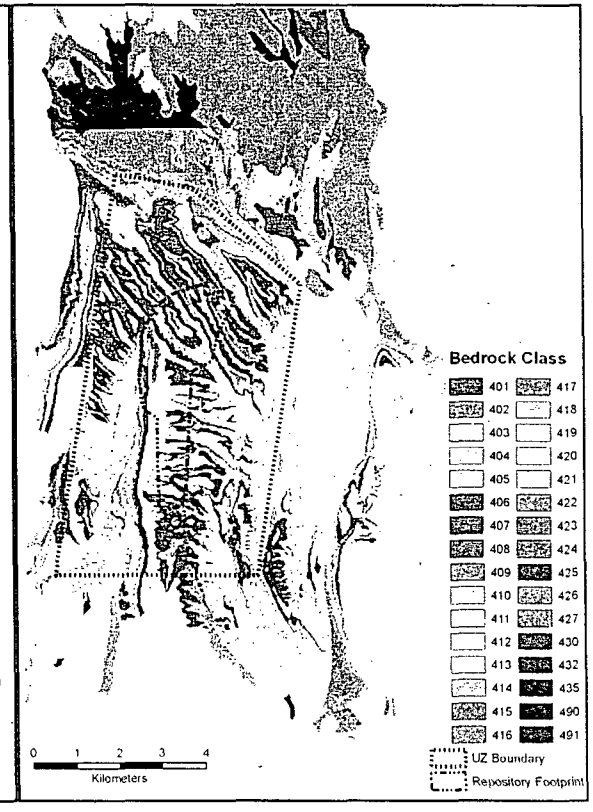
Soil Depth Class



Soil Classes



Bedrock Type



Soil Depth	Value (m)
Depth Zone 1	95
Depth Zone 2	16
Depth Zone 3	3
Depth Zone 4	0.1 – 0.5
Depth Zone 5	0

Table 6.5.2.4-3[a], Figures 6.5.2.4-1[a], 6.5.2.2-2[a], and 6.5.2.5-1[a]

Soil Properties

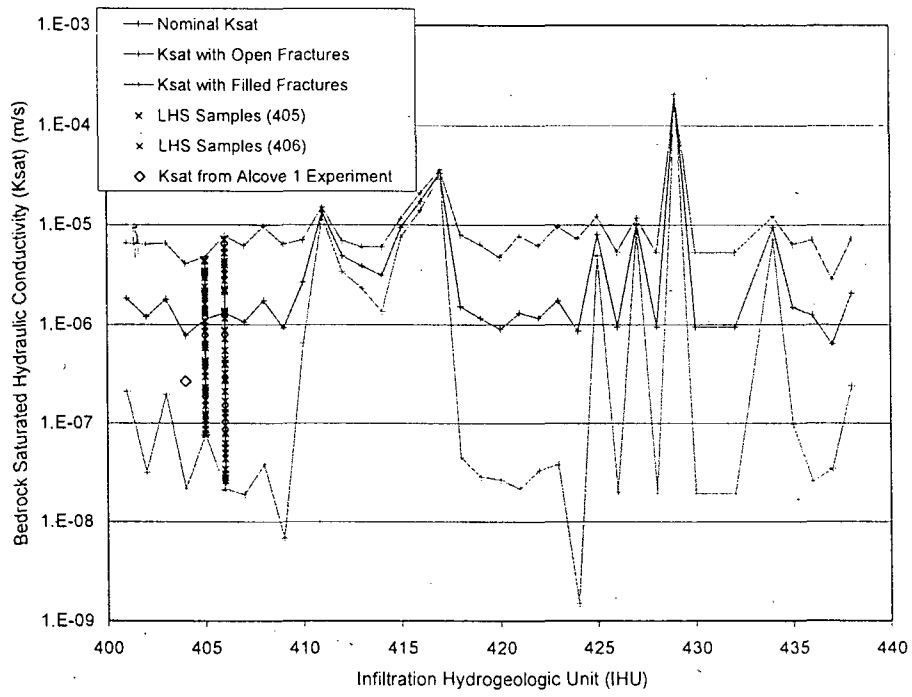
- The MASSIF infiltration model uses soil properties estimated using a pedotransfer approach *Section 6.5.2.3*
  - Soil texture data from each of the Yucca Mountain soil classes
  - Soil hydraulic properties from a Hanford, WA soil property database
    - Hydraulic conductivity
    - Field Capacity (defined between −0.33 and −0.1-bar suction pressure)
    - Wilting point (defined at −60 bar)
    - Saturated moisture content
  - Nonparametric approach (based on textural characteristics) matched soils from Yucca Mountain to similar soils from Hanford
- Uncertainty in soil properties is evaluated

Bedrock Conductivity

- Conductivity estimated from weighted arithmetic mean of matrix, filled, and open fracture components
  - Upper bound—200 micron open fracture component
  - Lower bound—100% fractures filled with caliche

Section 6.5.2.6

- Available field observations (visual surveys of fracture filling and infiltration tests) support an open fracture component to near surface bedrock conductivity



Source: SNL 2008 [DIRS 182145], Section 6.5.2.6, Table 6.5.2.6-1. Alcove 1 Ksat from BSC 2006 [DIRS 176355], Section 6.4.5.3. Latin Hypercube sampling data points from MASSIF output DTN: SN0701T0502206.037 [DIRS 184289] (\Welcome to Massif\Massif\Present Day Uncertainty\LHS_PD_R1.OUT and LHS_PD_R2.OUT).

Uncertainty Analysis Calculation Set Up

- **Parameter uncertainty distributions defined for all parameters (> 200 parameters)** *(Section 6.5.5 and Appendix I)*
- **Parameter uncertainty screening process**
  - Geospatial parameters covering more than 15% of UZ modeling domain are screened in
  - Nongeospatial parameters with relative standard uncertainty greater than 15% screened in
- **Screened-in parameters (11 to 15) sampled with Latin Hypercube Sampling (LHS)**
  - For each climate, two replicates of 20 realizations were generated
    - Results from two replicates were compared to assess stability of results
    - Results are compiled from two replicates combined (40 realizations)

Net Infiltration Results

MASSIF Net Infiltration Results

	Present Day (PD) (mm/yr)	Monsoon (MO) (mm/yr)	Glacial Transition (GT) (mm/yr)
10th	3.9	6.3	13.2
30th	7.3	14.4	22.8
50th	13.0	22.9	28.6
90th	26.8	52.6	47.0

Tables 6.5.7.1-3[a], 6.5.7.2-3[a], and 6.5.7.3-3[a]

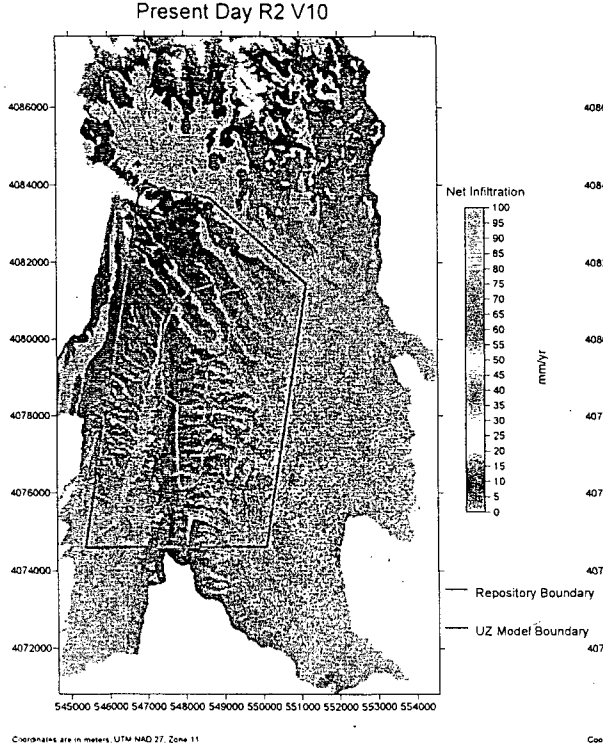
MASSIF Mean Water Flux Fractions

	Present Day (% precip)	Monsoon (% precip)	Glacial Transition (% precip)
%Infil	8	9	10
%ET	88	85	86
%Runoff	2	5	1
%Storage	2	1	2
%Sub	<1	<1	1

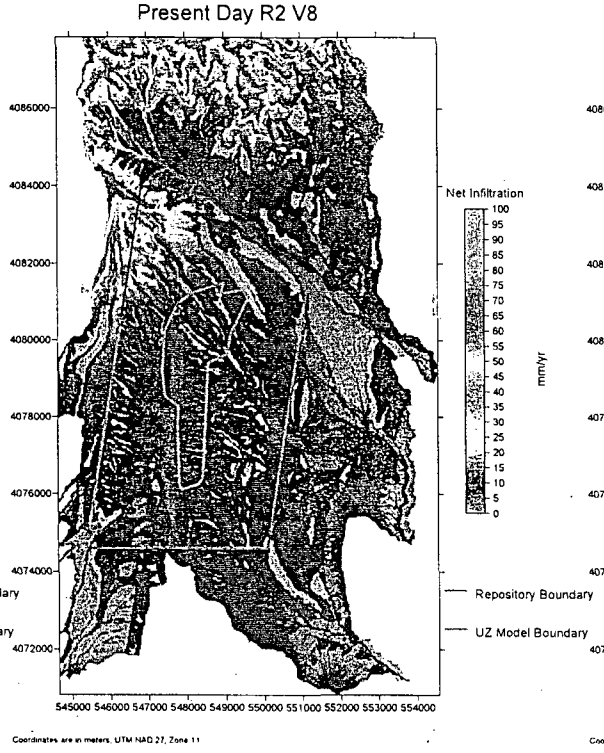
Tables 6.5.7.4-1, 6.5.7.4-2, and 6.5.7.4-3

Net Infiltration Results
Present-Day Climate

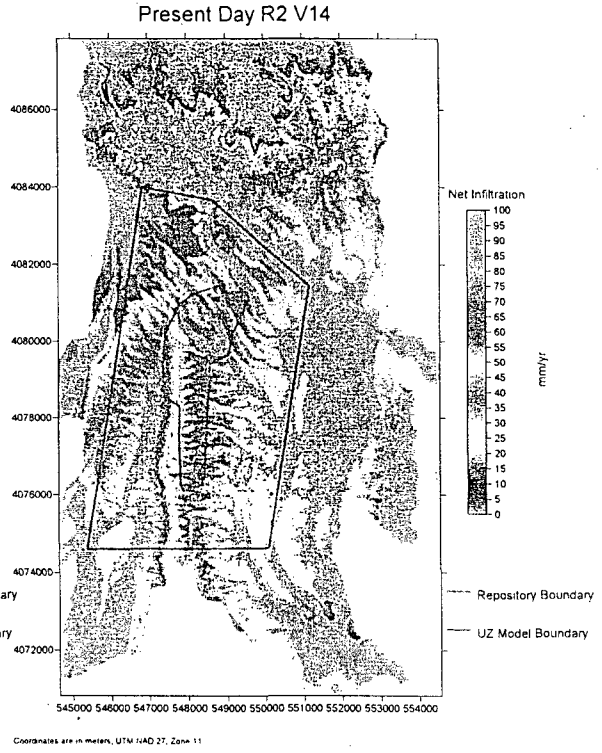
10th Percentile



50th Percentile



90th Percentile

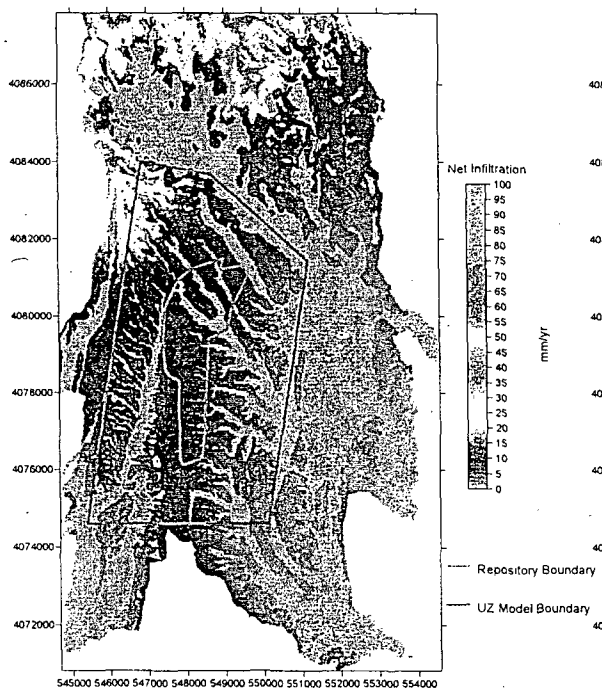


Figures 6.5.7.1-2[a], 6.5.7.1-4[a], and 6.5.7.1-5[a]

Net Infiltration Results
Monsoon Climate

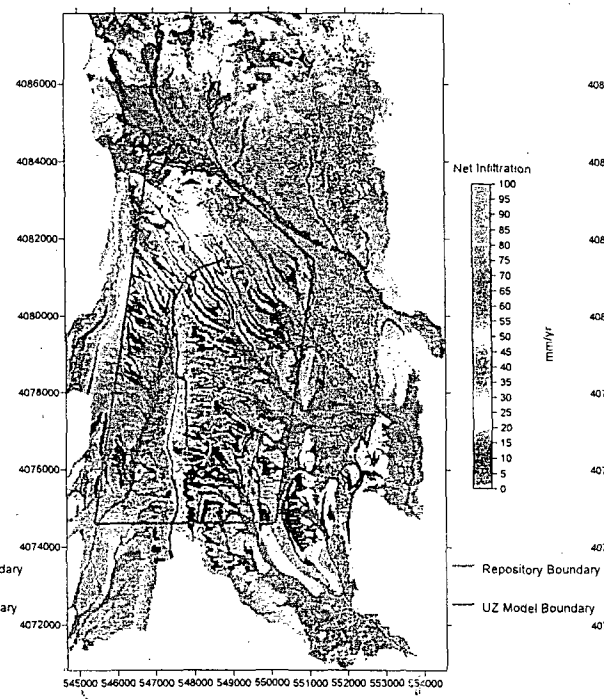
10th Percentile

Monsoon R1 V17



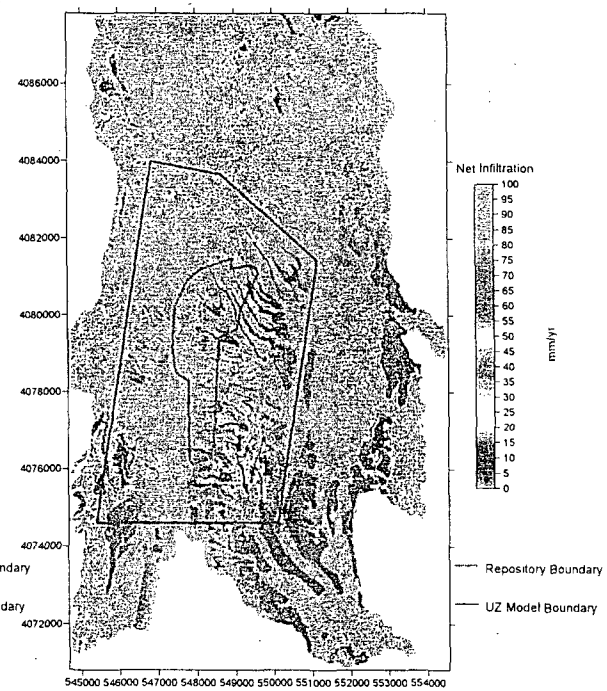
50th Percentile

Monsoon R1 V2



90th Percentile

Monsoon R1 V7

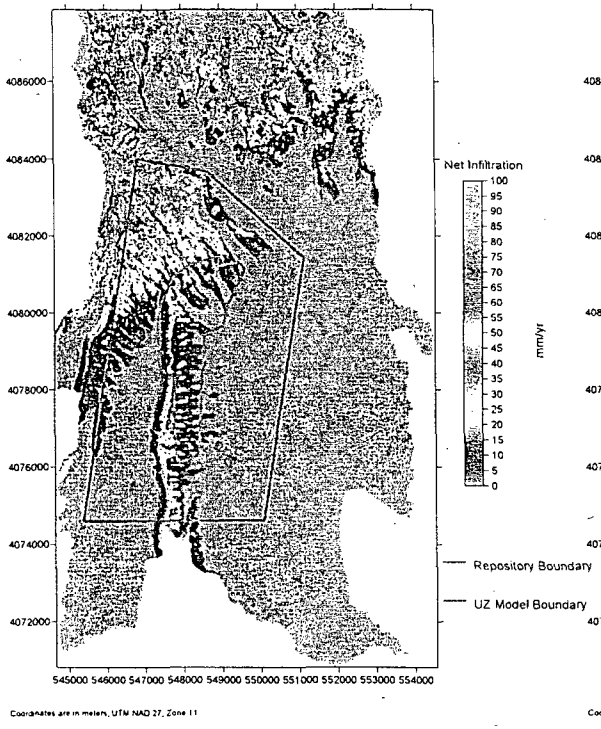


Figures 6.5.7.2-2[a], 6.5.7.2-4[a], and 6.5.7.2-5[a]

Net Infiltration Results
Glacial-Transition Climate

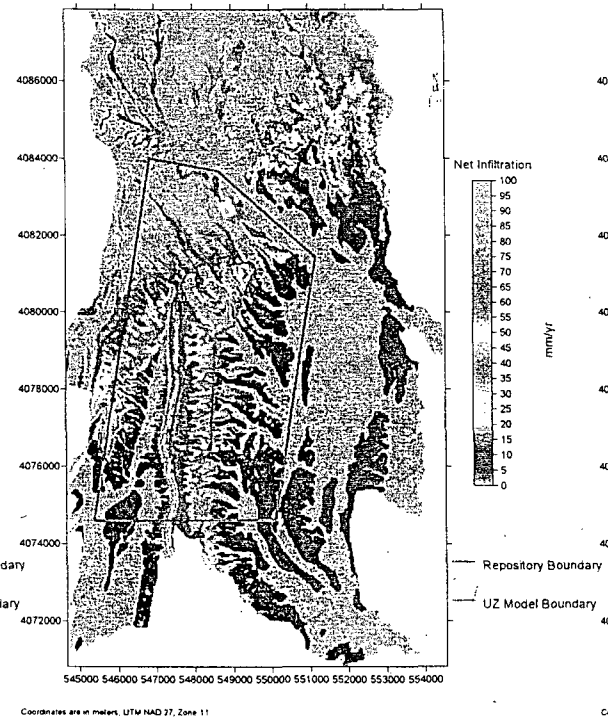
10th Percentile

Glacial Transition R2 V6



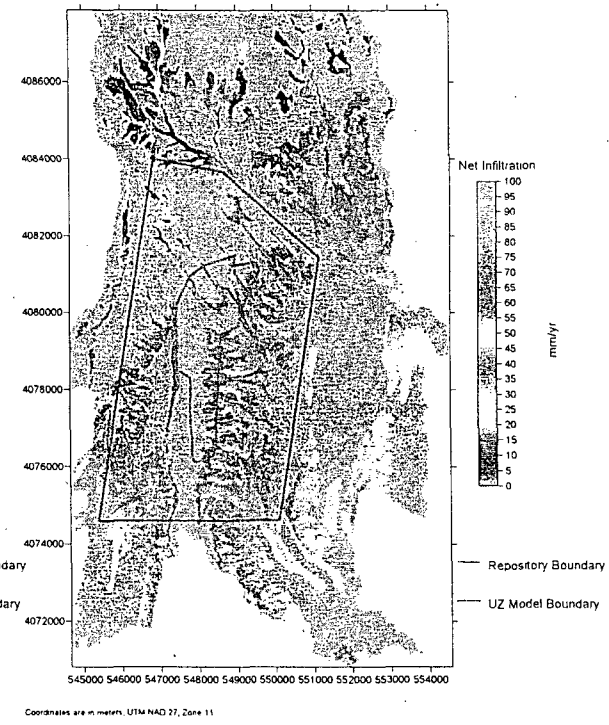
50th Percentile

Glacial Transition R1 V18



90th Percentile

Glacial Transition R2 V1



Figures 6.5.7.3-2[a], 6.5.7.3-4[a], and 6.5.7.3-5[a]

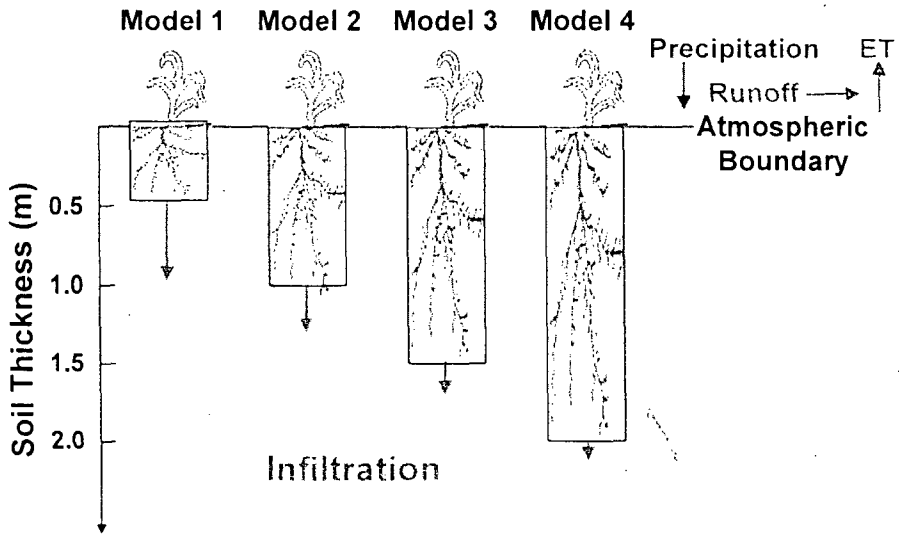
Sensitivity Analysis

- Stepwise regression method applied
  - Analysis 1—40 realizations per climate *Section 6.7, Appendix H*
  - Analysis 2—Alternative analysis done by fixing precipitation inputs for all realizations *Section 6.7, Appendix H*
    - Focus on physical property uncertainties (epistemic) rather than uncertainties related to future weather patterns (aleatory)
  - Analysis 3—Extended analysis (42 uncertain parameters, 200 realizations *Section 7.1.4*
  - Results of Analysis 1—Annual precipitation and shallow soil depth account for 70% of the variance in mean net infiltration
  - Results of Analysis 2—Shallow soil depth and water holding capacity of soil account for 90% of remaining variance in mean net infiltration (with precipitation fixed)
  - Results of Analysis 3—Important parameters did not change

Model Validation Comparisons

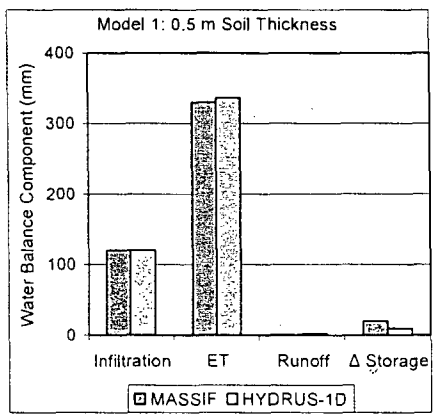
- Confidence building during model development
  - Precipitation submodel validated with comparisons to weather records *Section 7.1.1[a]*
  - ET submodel validated by simulating weighing lysimeter datasets from Nevada Test Site (NTS) and Reynolds Creek, ID *Section 7.1.2[a]*
  - Runoff results validated by simulating YM (1994 to1998) and comparing to stream gages *Section 7.1.3[a]*
  - Extended sensitivity study *Section 7.1.4*
- Post-model-development validation
  - Corroboration of net infiltration results with site and regional data
    - Seepage in South Ramp (2005) *Section 7.2.1.1.1[a]*
    - Pagany Wash infiltration data (1998) *Section 7.2.1.1.2[a]*
    - Published regional recharge estimates *Section 7.2.1.2[a], 7.2.1.3[a], and 7.2.1.4[a]*
  - Alternative model comparison
    - HYDRUS-1D *Section 7.2.2[a]*
    - Expert elicitation (CRWMS M&O, 1997) *Section 7.2.3[a]*

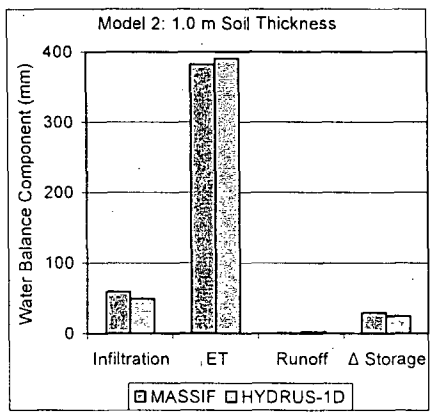
Alternative Model Comparisons

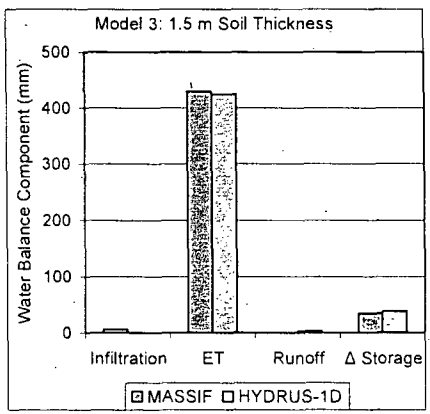


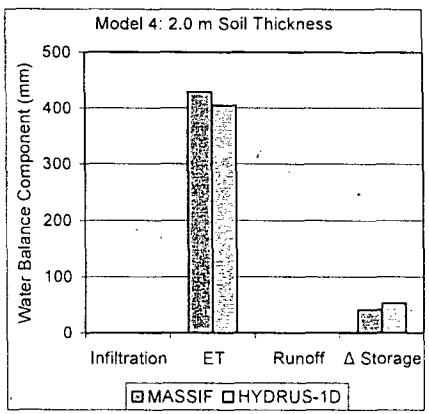
Figures 7.2.2-1[a] and 7.2.2-4[a]

- **MASSIF simulations were compared to HYDRUS-1D (Richards equation model) simulations at four locations**
- **Transient responses to precipitation and events and drying periods were somewhat different between models, however cumulative responses were quite similar**



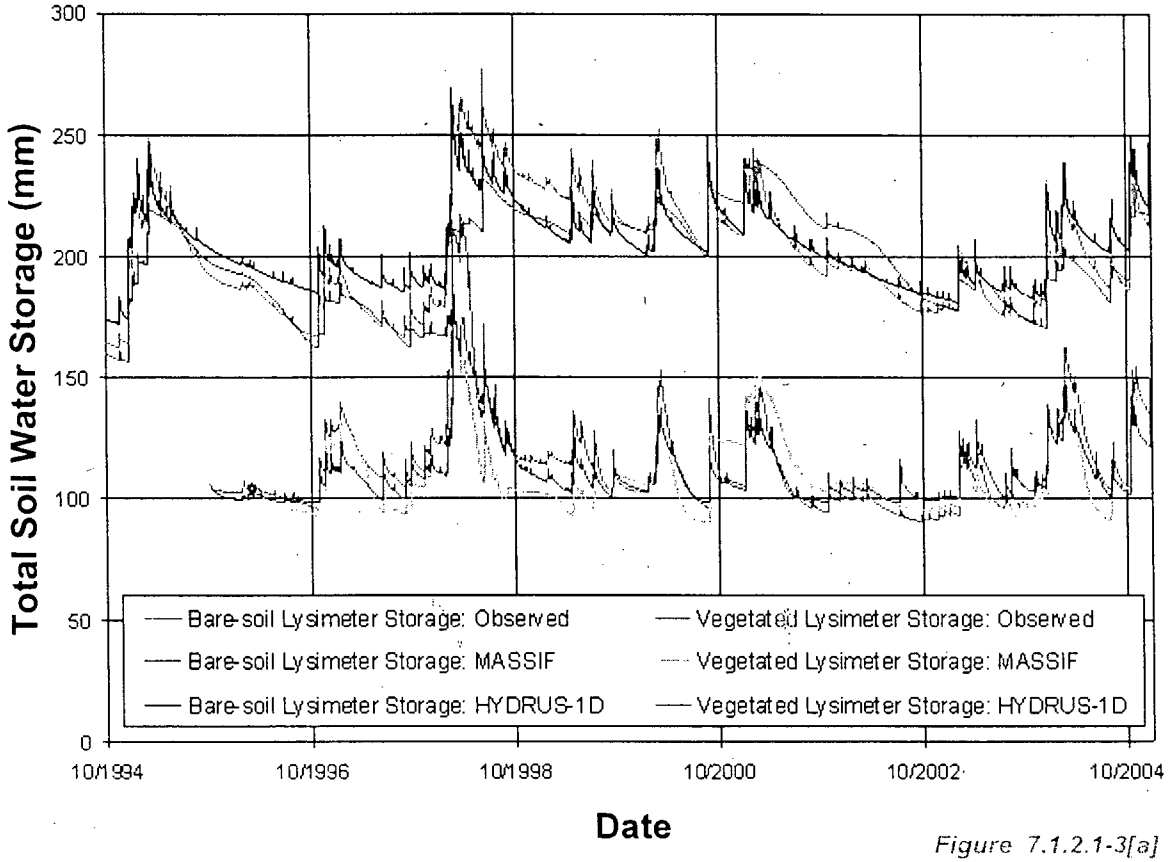






Model Validation Comparisons

MASSIF (and HYDRUS-1D) Used to Simulate Nevada Test Site, Area 5 Weighing Lysimeters



Bare-soil

Vegetated

Figure 7.1.2.1-3[a]

Model Validation Comparisons

- MASSIF runoff predictions compared with observed runoff in Wren Wash, Water Year 1995
- Model reasonably predicts timing and runoff amount when soil conductivity is reduced by a factor of 2 to 3 from the nominal value
- Mean net infiltration over a watershed (and full domain) is insensitive to soil conductivity changes required to match runoff data
- Spatial distribution of net infiltration is sensitive to soil conductivity distribution and value

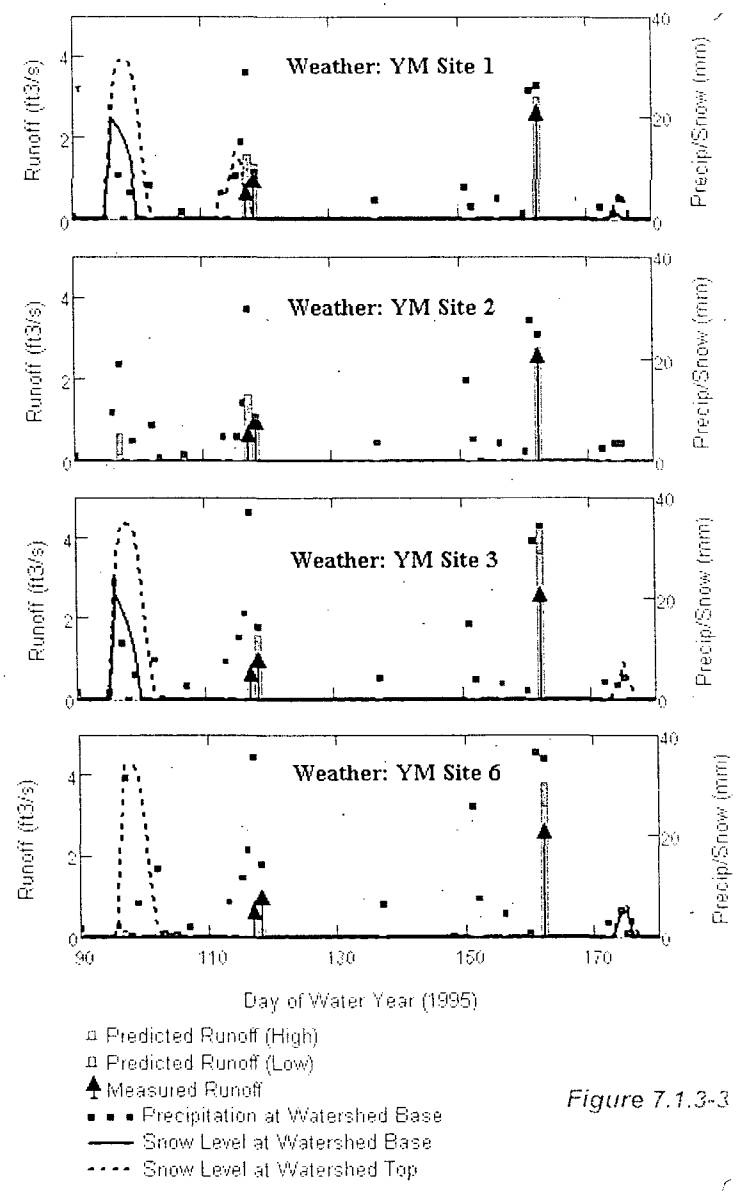
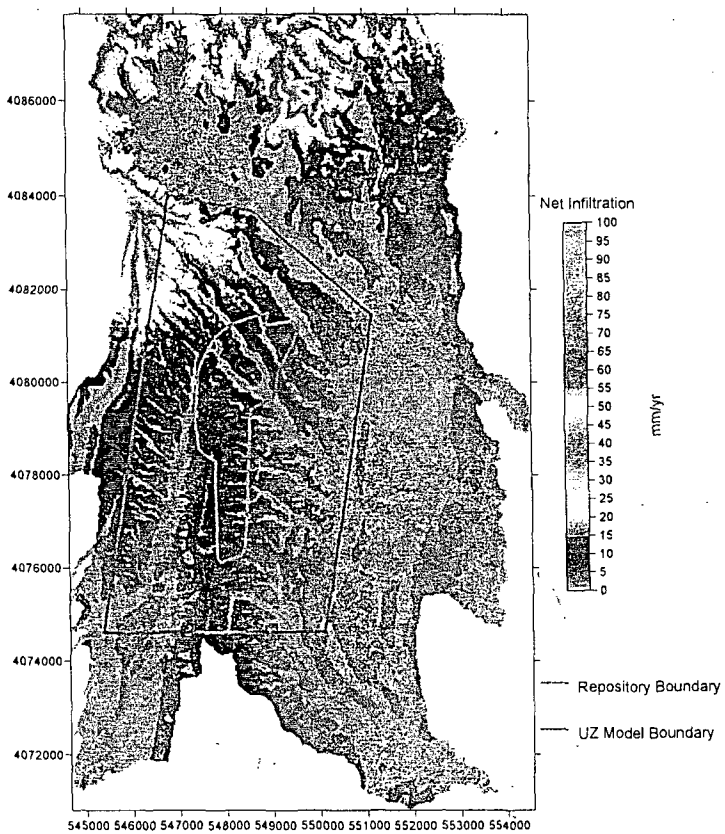


Figure 7.1.3-3

Example Model Comparisons

30th Percentile

Present Day R2 V2



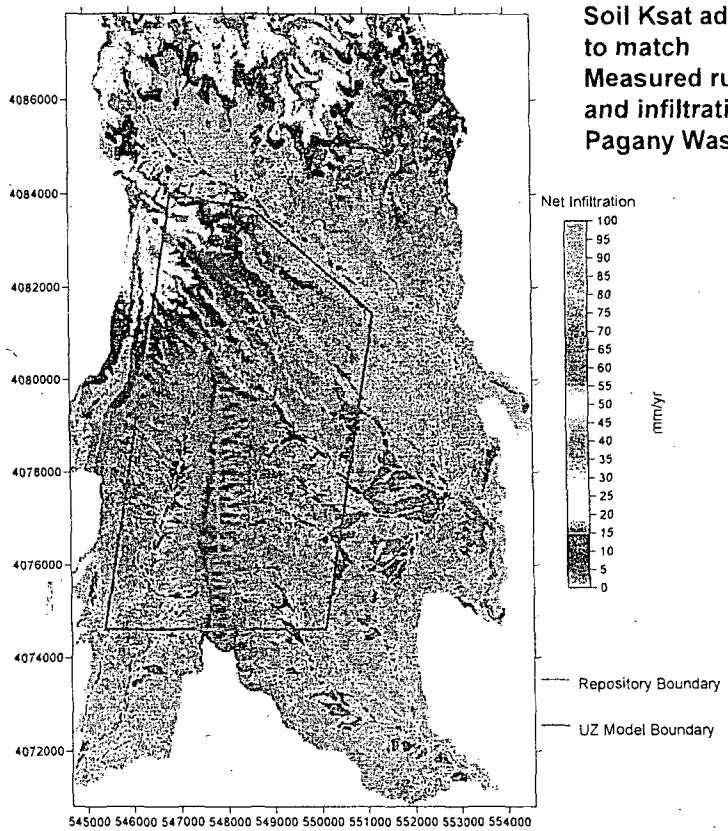
Coordinates are in meters; UTM NAD 27, Zone 11

Mean net infiltration = 7.3 mm/yr

Figure 6.5.7.1-3[a]

Soil Conductivity Variation

Present Day R2 V2 VAR



Coordinates are in meters; UTM NAD 27, Zone 11

Soil Ksat adjusted to match Measured runoff and infiltration in Pagany Wash

Mean net infiltration = 7.7 mm/yr

Figure 7.1.3.2-2[a]

Example Model Comparisons (Continued)

MASSIF Net Infiltration Estimates Compared with Empirical Models Developed at Other Sites

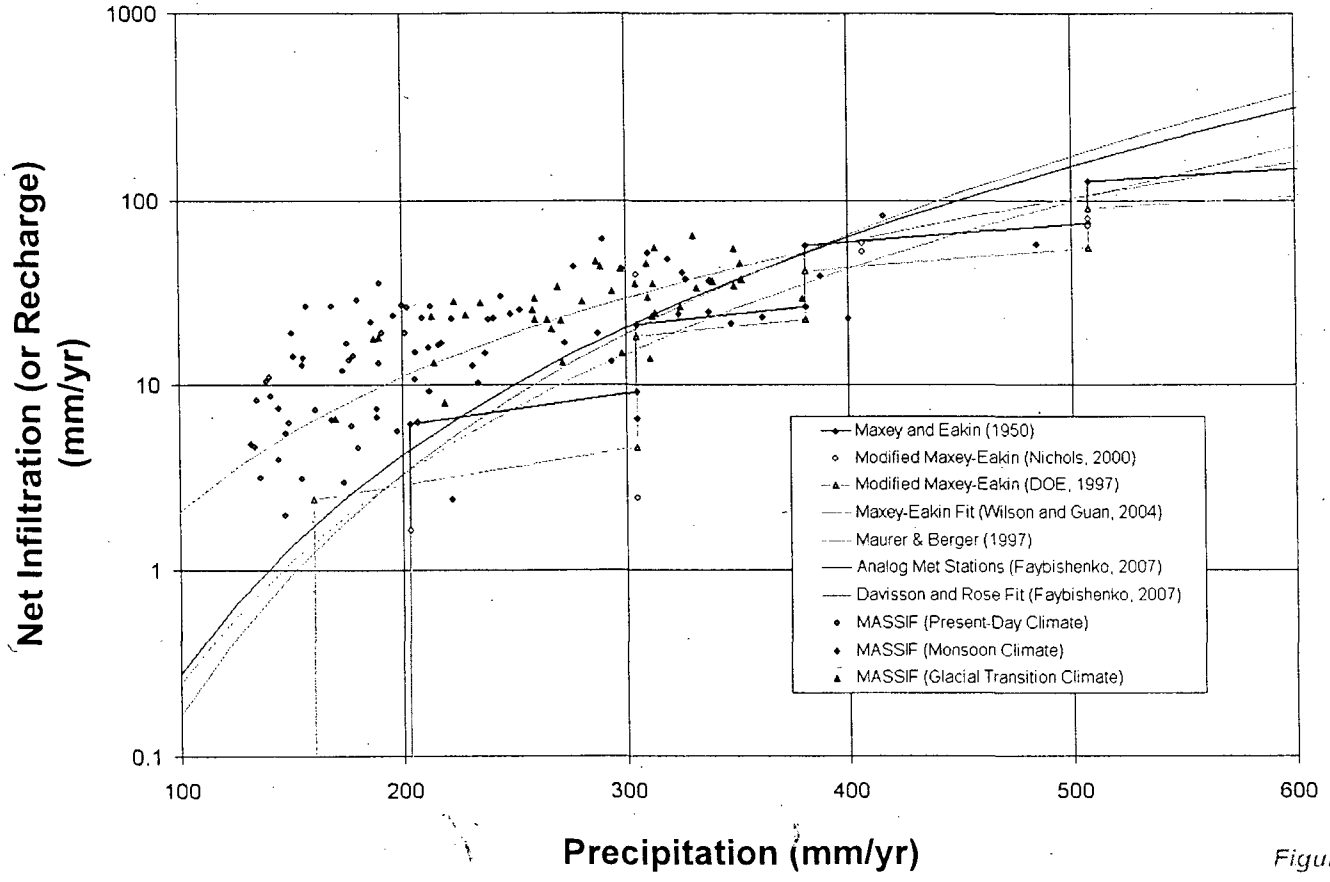


Figure 7.2.1.2-1[a]

Example Model Comparisons (Continued)

MASSIF Net Infiltration Estimates Compared with Estimates for Nevada Hydrographic Areas

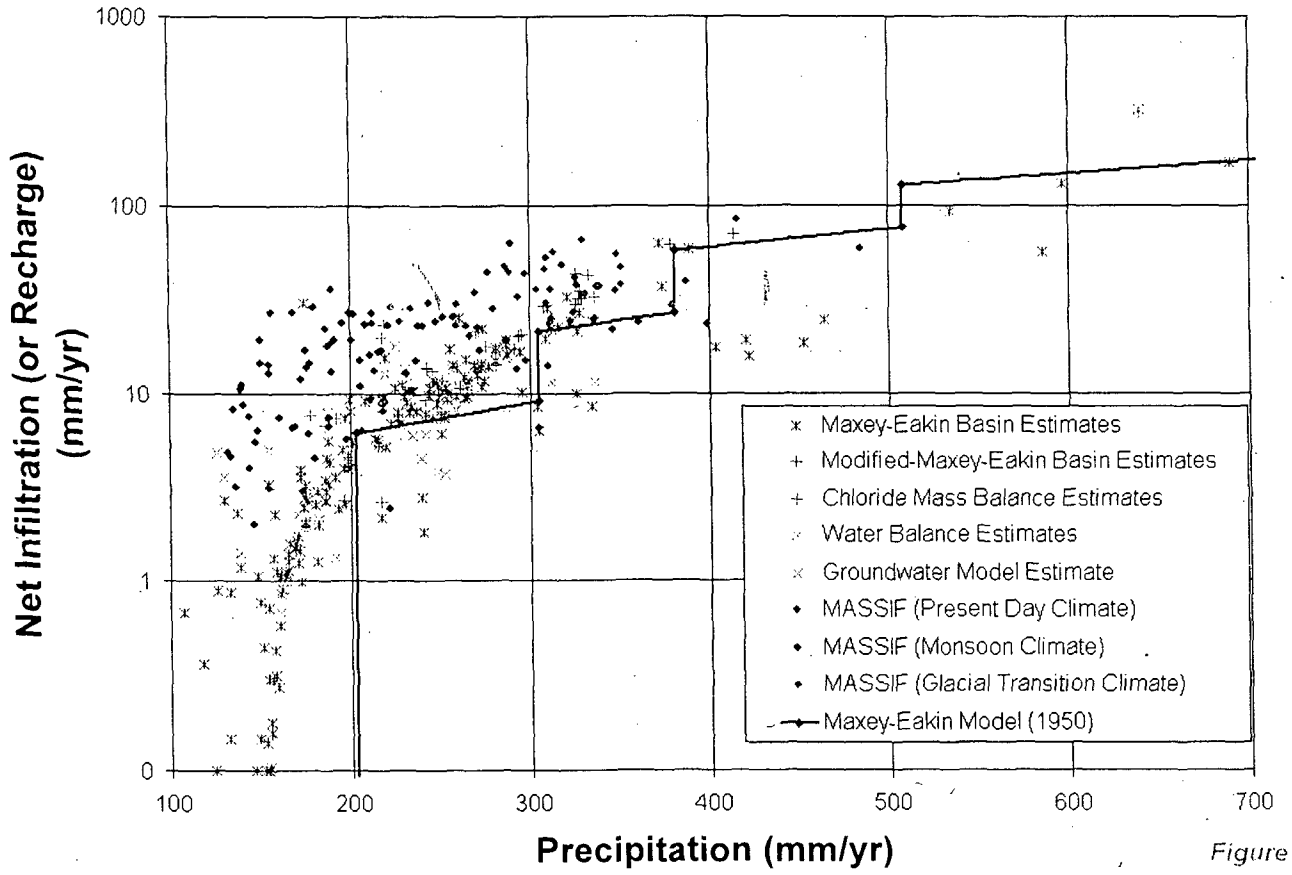


Figure 7.2.1.2-2[a]

Summary and Conclusions

- MASSIF model generates maps representing the range of net infiltration expected at the Yucca Mountain site for the next 10,000 years
- MASSIF predictions are based on a daily water mass balance calculation which includes the effects of low probability wet periods
- Site specific data and appropriate analogs are used to define parameter uncertainties
- Net infiltration estimates validated with comparisons to field data, analog site estimates, and alternative model estimates
- When conceptual processes are uncertain or unquantifiable, conservative assumptions have ensured that mean net infiltration has not been underestimated

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Status of Infiltration-related Key Technical Issue Agreements

Gene Peters, Branch Chief, Performance Assessment
Division of High-Level Waste Repository Safety
U. S. Nuclear Regulatory Commision

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Key Technical Issue Agreements Background

- In 2001, NRC and DOE identified Key Technical Issues (KTI) to facilitate prelicensing interactions.
- NRC and DOE developed 293 Agreements for the 11 KTIs.
- KTI Agreements are considered closed once DOE provides information on the topic to NRC, and NRC staff has no further questions (261 Agreements are currently closed).
- Although Agreements may be closed during prelicensing, NRC will make its final determination on any issue relevant to licensing during review of a potential license application.

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Key Technical Issues Related to Infiltration

Key Technical Issue (KTI)	Abbreviation	Short Description
Radionuclide Transport	RT	Identification of key geochemical processes that may control radionuclide transport at Yucca Mountain
Thermal Effects on Flow	TEF	Understanding the effects of heat generated by the waste on water flow around and in the repository
Total System Performance Assessment and Integration	TSPAI	Development of the capability to conduct and review total system performance assessments
Unsaturated and Saturated Flow under Isothermal Conditions	USFIC	Characterization of ground water flow near the repository under ambient temperature conditions

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KTI Agreements Related to Infiltration

Directly Related

Agreement	Status
TSPAI.3.18	Closed (February 2005)
TSPAI.3.19	Closed (February 2005)
TSPAI.3.20	Closed (February 2002)
TSPAI.3.21	Closed (February 2005)
TSPAI.3.27	Closed (February 2005)
USFIC.3.01	Open (Additional Information Needed)
USFIC.3.02	Closed (February 2005)

Indirectly Related

Agreement	Status
RT.3.01	Response Held (April 2005)
RT.3.04	Response Held (April 2005)
TEF.2.10	Response Held (April 2005)
TEF.2.11	Response Held (April 2005)
TEF.2.12	Response Held (April 2005)
TEF.2.13	Response Held (April 2005)
TSPAI.3.28	Response Held (April 2005)
TSPAI.3.29	Response Held (April 2005)
TSPAI.3.22	Closed (February 2005)
TSPAI.3.26	Closed (February 2005)
TSPAI.4.04	Closed (January 2005)

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NRC Staff Consideration of New Infiltration Studies on KTI Agreements

NRC staff has reviewed the available information from DOE's new infiltration studies and concludes:

- the nine previously closed Agreements are not significantly impacted by new studies and do not need to be re-opened during prelicensing
- the responses for eight Agreements that were held in 2005 are not significantly impacted by new studies, and the agreements will be closed by letter from NRC to DOE
- the Additional Information Need for the one Agreement (USFIC.3.01) remains unchanged, and this agreement remains open

As with all KTI Agreements, NRC will make its final determination on any issue relevant to licensing during review of a potential license application.

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Status of Infiltration-related KTI Agreements: Summary

- Eight "Held" Agreements will be closed, by letter from NRC to DOE.
- Nine closed Agreements will not be re-opened during prelicensing.
- One Agreement remains open, additional information needed.
- Regardless of status of KTI Agreements, NRC will consider all issues relevant to licensing during review of a potential license application.

U.S. Department of Energy
Office of Civilian Radioactive Waste Management

www.ocrwm.doe.gov

Integration of the Infiltration and UZ Flow Models in TSPA

Presented to:
NRC/DOE Technical Exchange on Infiltration at Yucca Mountain

Presented by:
Ming Zhu, Ph.D., P.E.
Sandia National Laboratories

April 2, 2008
Las Vegas, Nevada

Outline

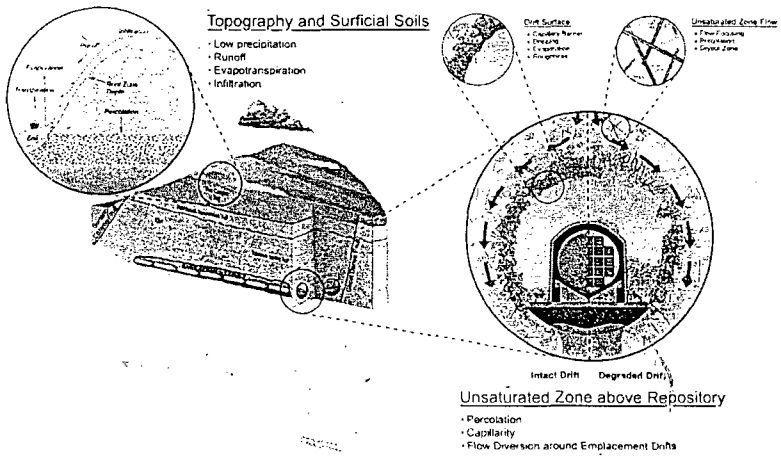
- List of Relevant Analysis and Model Reports
- Use of Infiltration and UZ Flow Models in TSPA
- Overview of UZ Flow Model and Calibration Results
- Need for Integration of the Infiltration Model with the UZ Flow Model
- Why Use Temperature and Chloride Data?
- Methodology for Infiltration-UZ Flow Integration
- Inputs and Uncertainty
- Calculated Weighting Factors
- Corroboration with Results of Expert Elicitation and Calcite Study
- Summary

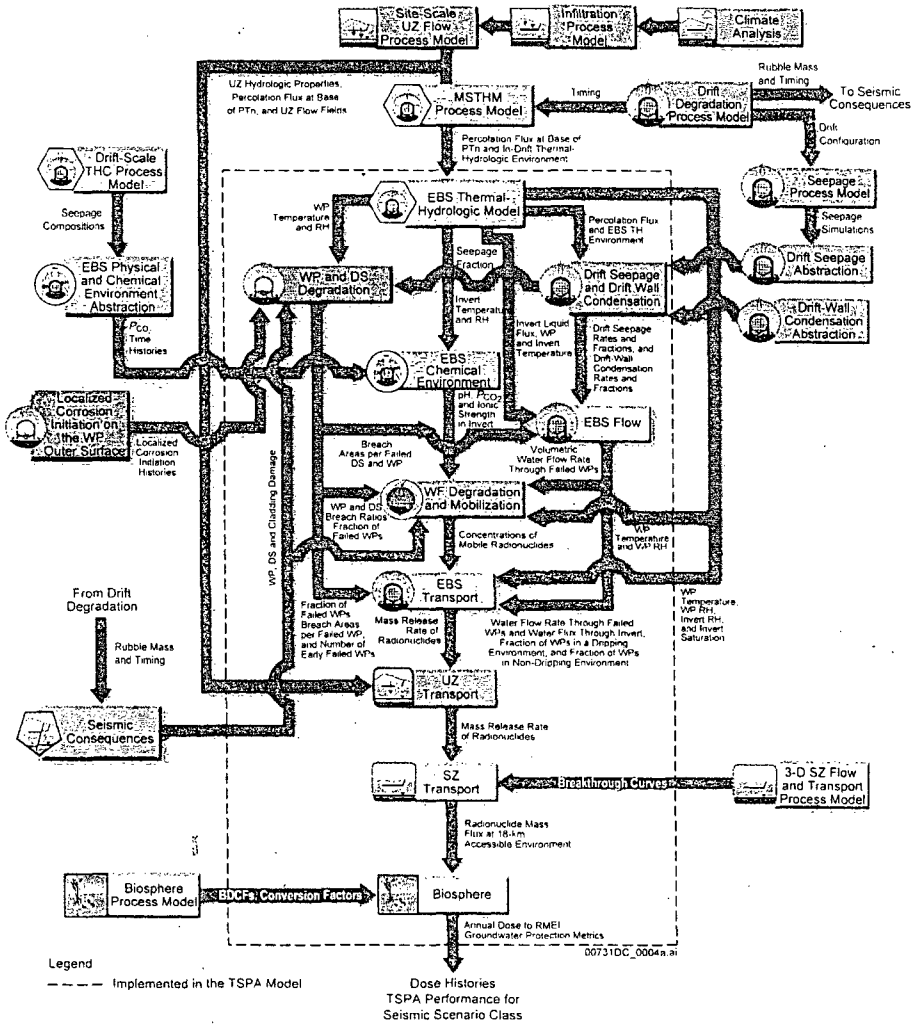
List of Relevant Analysis and Model Reports

- SNL 2007. *Calibrated Unsaturated Zone Properties.* ANL-NBS-HS-000058 REV 00
- SNL 2007. *UZ Flow Models and Submodels.* MDL-NBS-HS-000006 REV 03 (SNL 2007. REV 03 AD 01; SNL 2008. REV 03 AD 01 ACN 01)
- SNL 2007. *Simulation of Net Infiltration for Present-Day and Potential Future Climates.* MDL-NBS-HS-000023 REV 01 (SNL 2008. REV 01 AD 01)
- SNL 2008. *Total System Performance Assessment Model/Analysis for the License Application.* MDL-WIS-PA-000005 REV 00 and REV 00 AD 01

Use of Infiltration and UZ Flow Models in TSPA

- Infiltration and UZ Flow Models are integral parts of TSPA for the assessment of the upper natural barrier
- Integration is needed to ensure consistency in treatment of uncertainty between the models





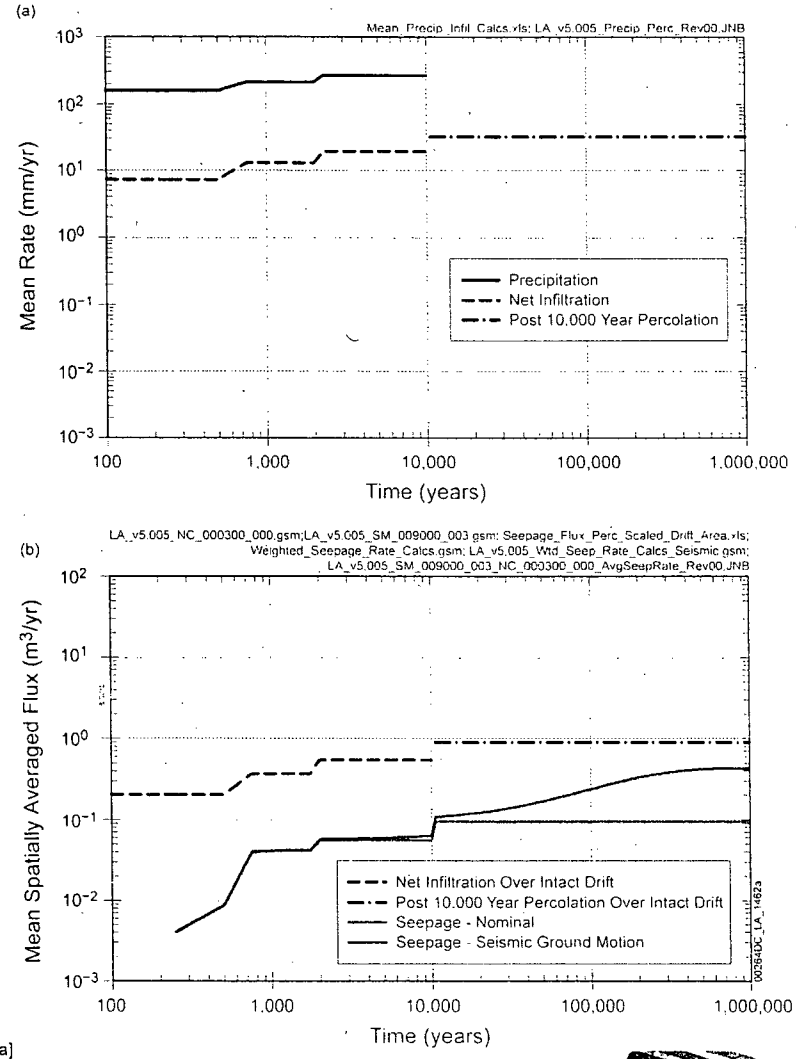
Source: Adapted from MDL-WIS-PA-000005 REV 00 AD 01, Figure 6.1.4-6

Implementation of UZ Flow in TSPA

- Steady-state UZ flow fields are generated for
  - Three pre-10k yr climates states (present-day, monsoon, glacial-transition), and a post-10k yr period
  - Four uncertainty cases:10th, 30th, 50th, and 90th percentile cases
    - From the infiltration model for each climate state during the pre-10k period
    - For the post-10k yr period, average infiltration rates through repository footprint are set equal to average percolation rates through repository footprint stipulated in the proposed NRC rule; infiltration maps selected from the pre-10k yr period are scaled to provide appropriate rates
- UZ flow fields are sampled according to the weights developed for uncertainty cases from the infiltration and UZ flow model information
- Resulting UZ flow fields are used directly by TSPA
  - Percolation flux at PTn/TSw interface used for drift seepage and thermal hydrology boundary conditions and properties
  - Flow fields directly implemented in TSPA using Finite Element Heat and Mass (FEHM) particle tracking method for radionuclide transport

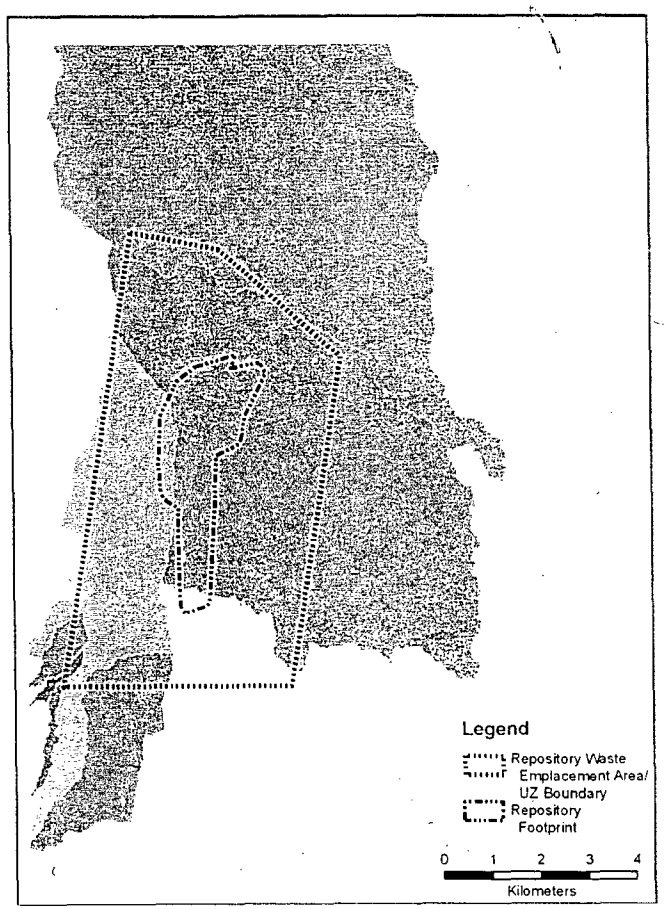
Effects of Infiltration and UZ Flow on Performance of Upper Natural Barrier

- The combination of reduced infiltration into Yucca Mountain, and the vaporization and capillary barrier effects in the TSw unit, results in a seepage flux that will be substantially reduced from the precipitation flux at the surface
- Figure (a) illustrates the effectiveness of surficial soils and topography in preventing or reducing the rate of water flow into the unsaturated zone
- Figure (b) illustrates the effectiveness of vaporization and capillary diversion in limiting water movement into the drifts

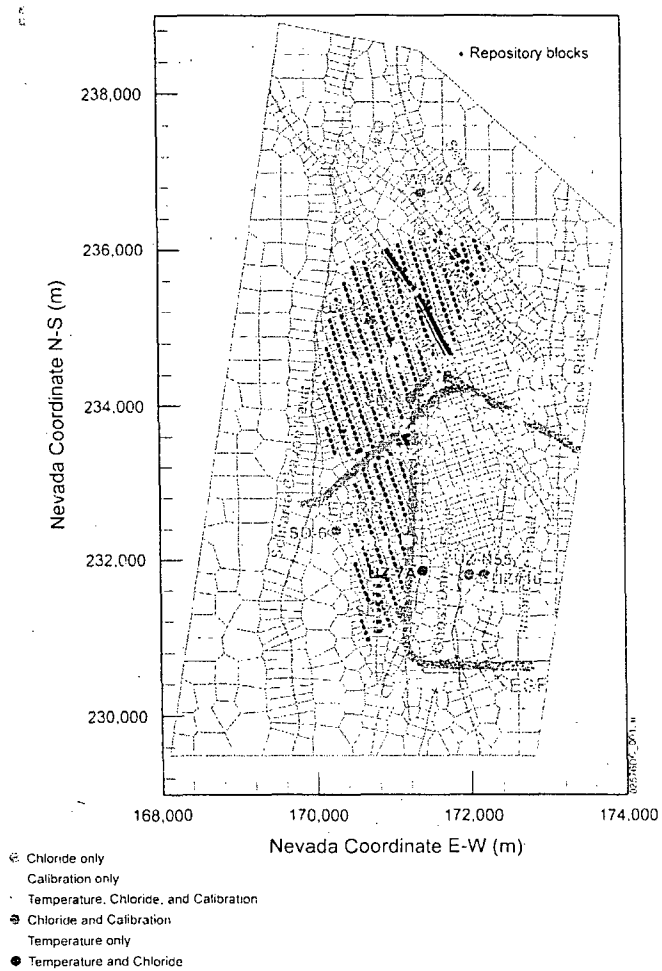


Source: MDL-WIS-PA-000005 REV 00 AD 01, Figure 8.3-3[a]

Domains of Infiltration and UZ Models, Borehole and Tunnel Locations



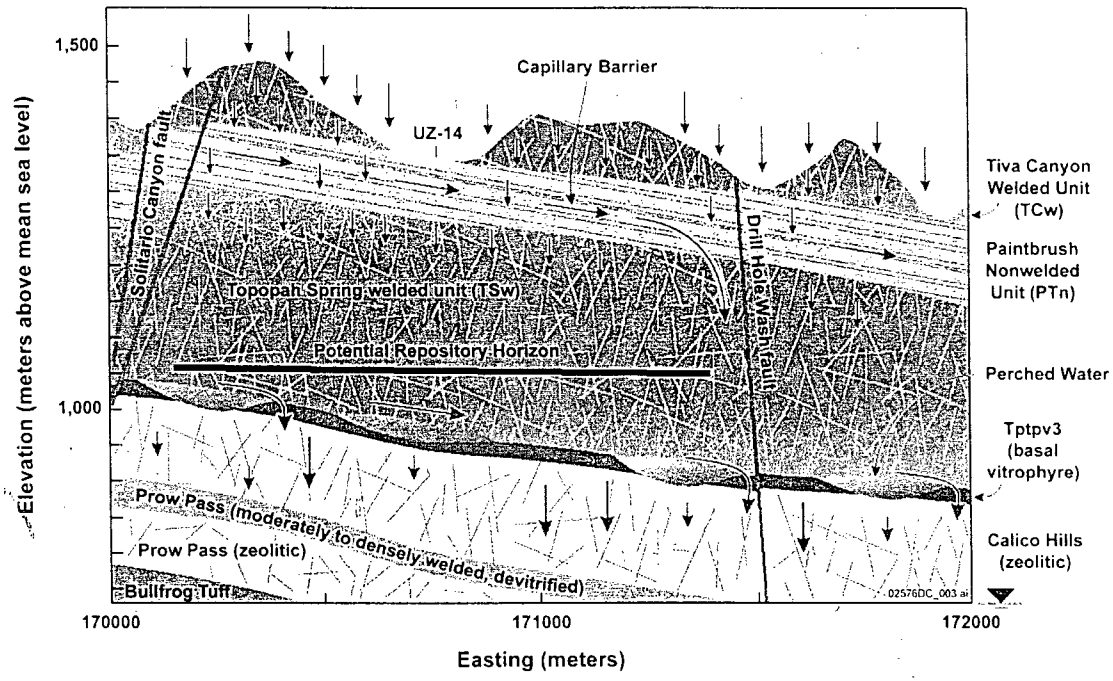
Source: MDL-NBS-HS-000023 REV01 AD01, Figure B-15[a]



Source: Modified from MDL-NBS-HS-000006 REV02 AD01, Figure 6.1-1

UZ Flow Model Overview

- Steady-state flow
- Spatially variable infiltration
- Dual-permeability model
  - Fracture/matrix interactions
  - Medium-scale flow focusing
- Lateral flow
  - Capillary and permeability barriers
- Flow in faults
- Perched water



Source: Modified from MDL-NBS-HS-000006 REV02 AD01, Figure 6.2-1

Repository Footprint Flow Distribution for Present-Day 50th% Infiltration Scenario

	Fracture %	Matrix %	Fault %
TCw/PTn Interface	98.81	0.03	1.16
Repository Horizon	96.68	2.03	1.28
Water Table	47.26	15.70	37.04

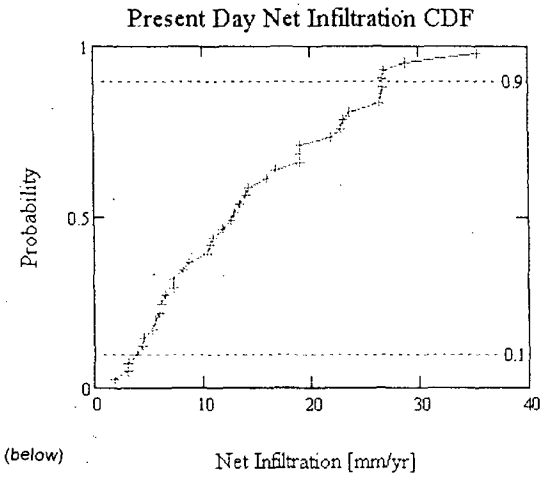
Source: MDL-NBS-HS-000006 REV02 AD01, Tables 6.6-1, 6.6-2, and 6.6-3

Top Boundary from the Infiltration Model

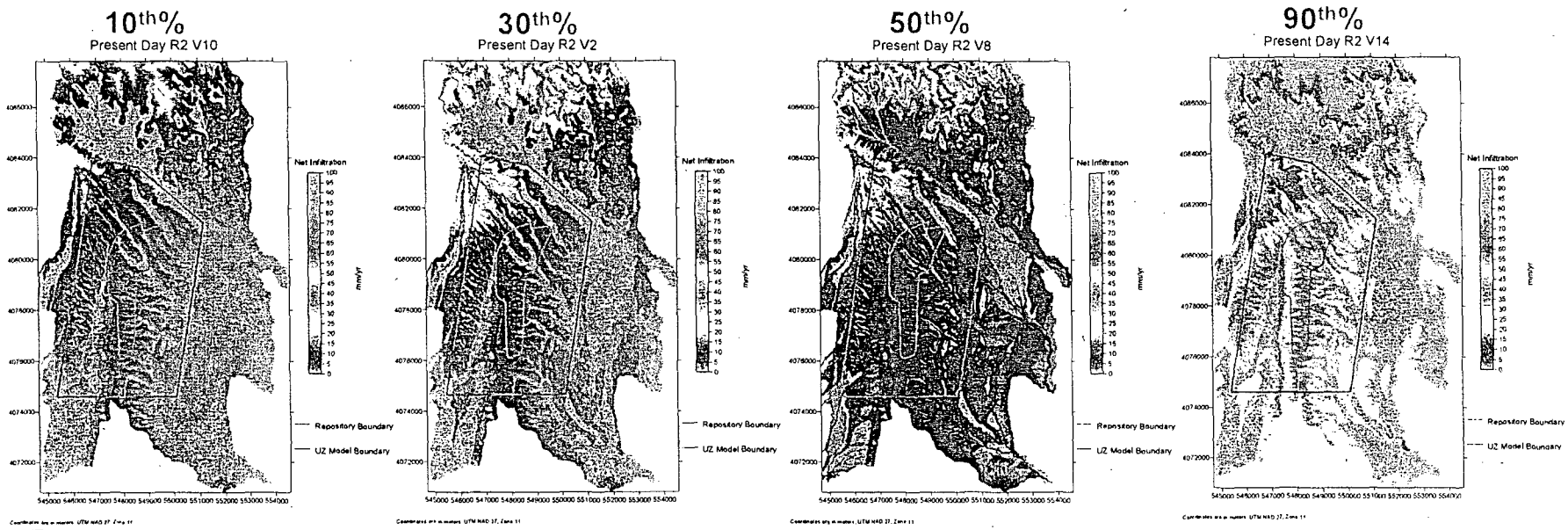
- 2 Latin Hypercube Sampling replicates of 20 realizations each
- Uniform CDF from the 40 realizations (40 "maps")
- 4 infiltration maps (10th, 30th, 50th, and 90th percentile)

Precipitation and Net Infiltration over Infiltration Model Domain for Present-Day (MDL-NBS-HS-000023 REV 01, Section 6.5.7.1)

Case	Precipitation (mm/yr)	Infiltration (mm/yr)
10th%	144.1	3.9
30th%	160.6	7.3
50th%	189.3	13.0
90th%	212.7	26.8



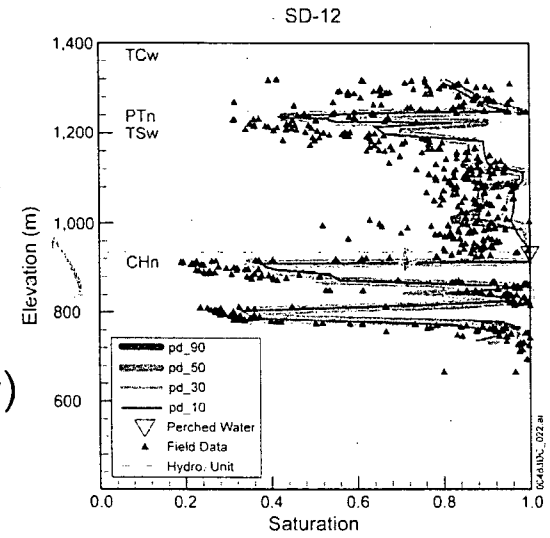
Source: Adapted from MDL-NBS-HS-000023 REV01 AD01, *Figure 6.5.7.1-6[a] (right) and Figures 6.5.7.1-2[a], 6.5.7.1-4[a], and 6.5.7.1-5[a] (below)*

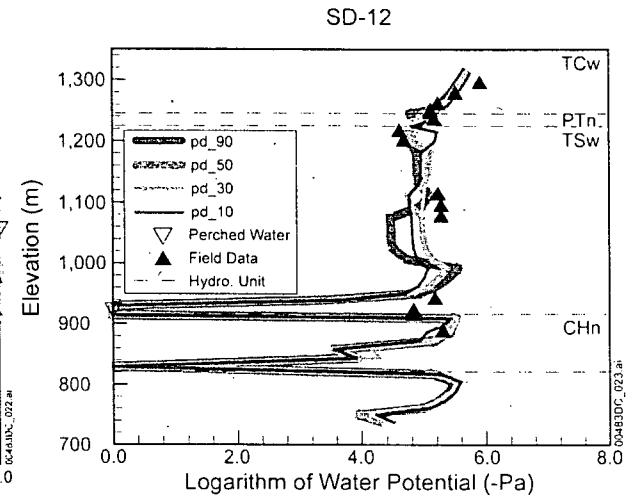


Calibration of the UZ Flow Model to Water Saturation and Potential Data

- **1-D calibrations**
  - Using data from 16 boreholes
  - Matrix permeability, fracture and matrix van Genuchten α, and active fracture model parameter (γ)
- **3-D calibrations**
  - Lateral flow
  - Perched water
- **Calibrations are conducted for each uncertainty case implemented for present-day climate**

3-D Calibrations for SD-12





Source: MDL-NBS-HS-000006 REV02 AD01, Figures 6.2-3 and 6.2-4

UZ Model Domain Infiltration Rates for Present-Day

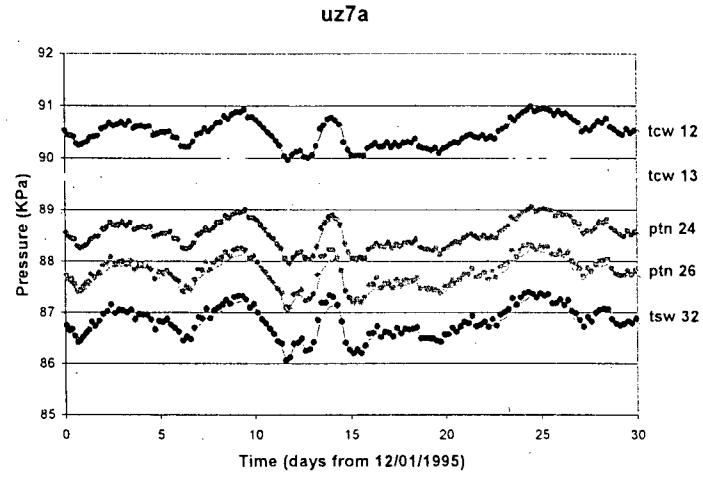
	Infiltration (mm/yr)
10th Percentile	3.03
30th Percentile	7.96
50th Percentile	12.28
90th Percentile	26.78

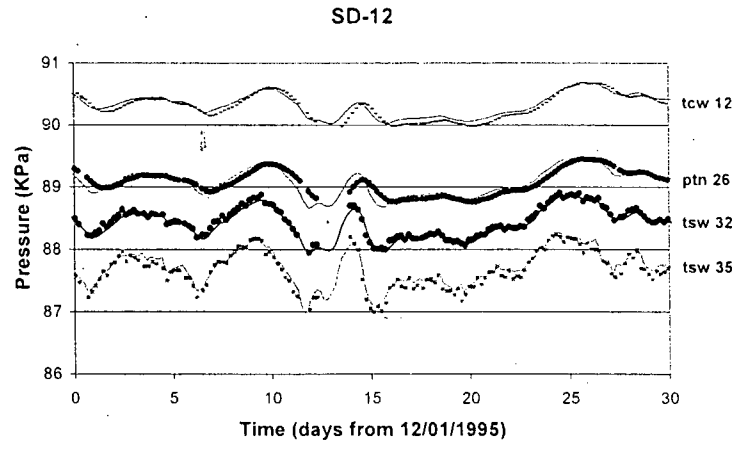
Source: MDL-NBS-HS-000006 REV02 AD01, Table 6.1-2

Calibration of the UZ Flow Model to Pneumatic Data

- **Natural barometric pressure fluctuations**
- **1-D calibrations**
  - Using data from 4 boreholes
  - Fracture permeability
- **3-D calibrations**
  - Using data from 2 boreholes
  - Account for high-flux pathways accessible in the 3-D fracture network

3-D Calibration Results

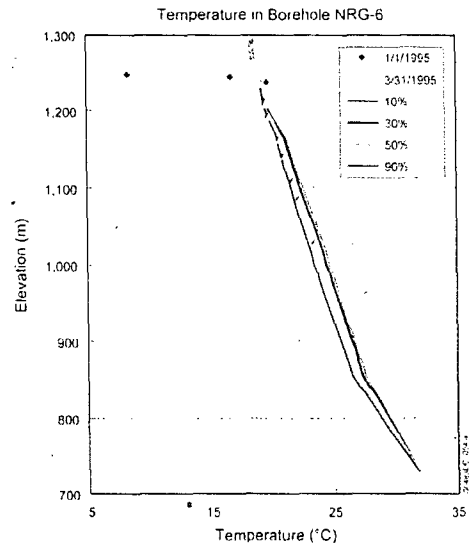


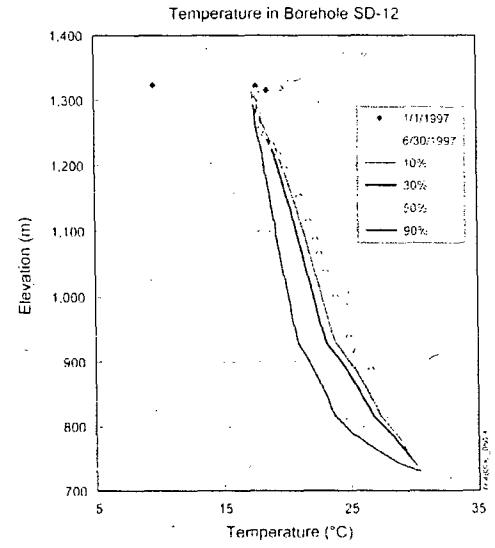


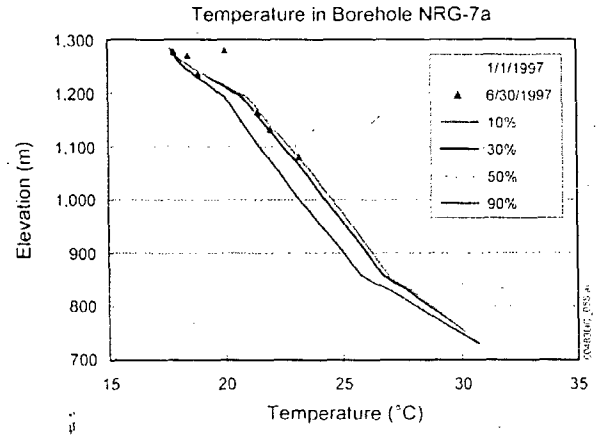
Source: MDL-NBS-HS-000006 REV02 AD01, Figures 6.4-1 and 6.4-2

Comparison to Measured Temperature

- Infiltration rates for present-day climate have little effect on temperature for locations with low infiltration flux and/or small changes in infiltration flux
- At locations with sufficiently high infiltration flux, increases in infiltration result in reductions in the predicted temperatures







Local infiltration rates (mm/yr) for Present-Day

Borehole	10th%	30th%	50th%	90th%
NRG-6	0.5	2.2	3.8	9.7
NRG-7a	1.4	3.8	6.0	14.0
SD-12	3.2	8.5	12.8	30.5

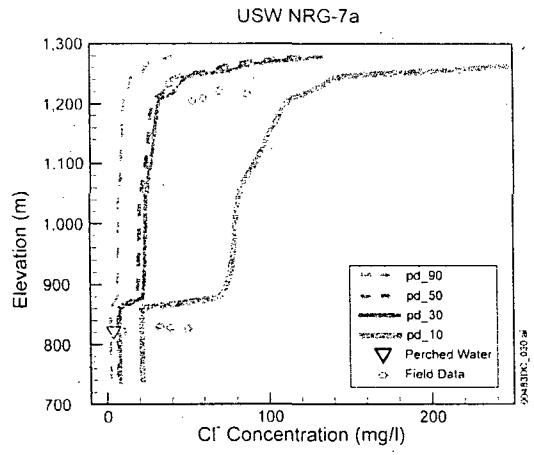
ANL-NBS-HS-000058 REV 00, Table 6-3

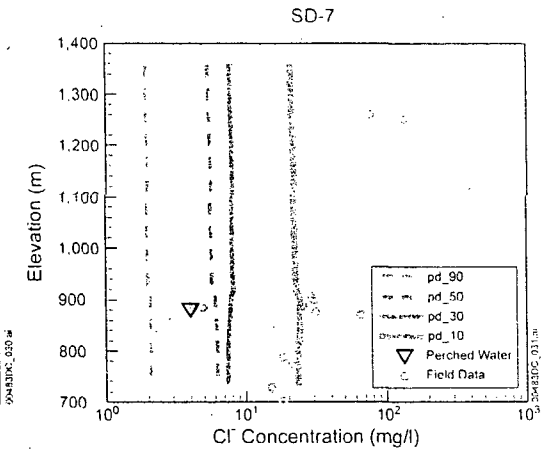
Source MDL-NBS-HS-000006REV03 AD01 Figures 6.3-2 through 6.3-5

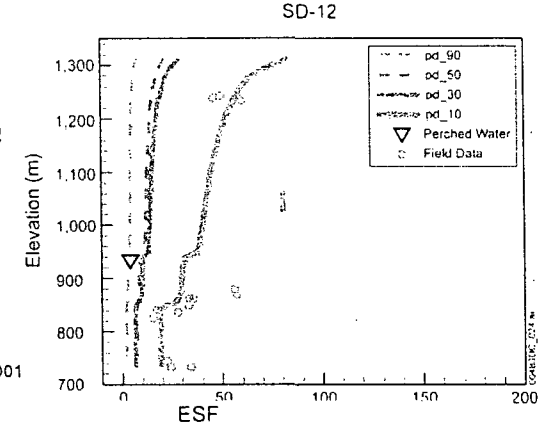
Chloride Comparisons

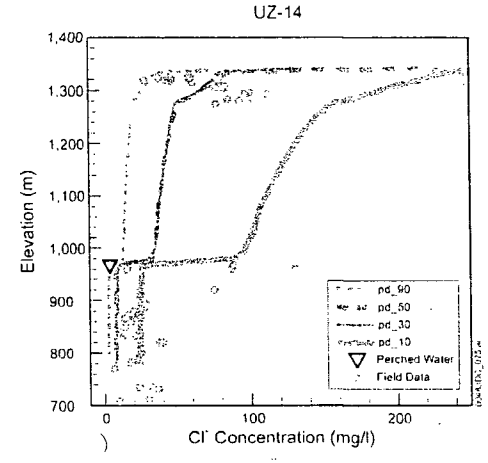
- Chloride levels along boreholes vary with depth in response to lateral flow and diffusion
- Chloride concentrations across the ESF and ECRB show less spatial structure, suggesting that variability in surface concentrations are homogenized during transport from the ground surface

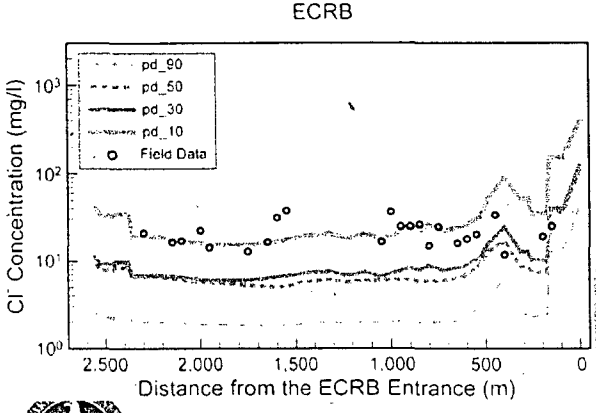
Source: MDL-NBS-HS-000006 REV02 AD01
Figures 6.5-1, 6.5-4 through 6.5-8

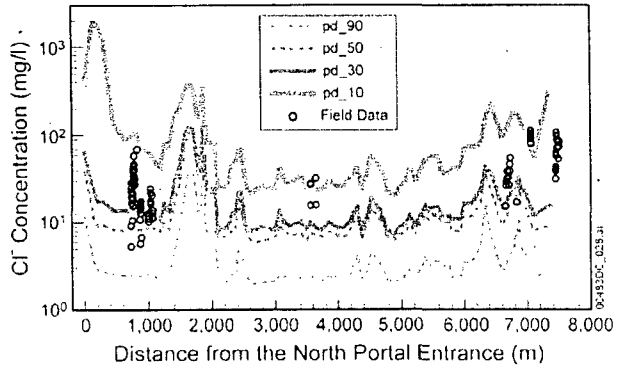












Local Infiltration Rates (mm/yr) for Present-Day

Borehole	10th%	30th%	50th%	90th%
NRG-7a	1.4	3.8	6.0	14.0
SD-7	3.4	9.0	15.0	34.6
SD-12	3.2	8.5	12.8	30.5
UZ-14	1.9	4.8	6.9	16.4

ANL-NBS-HS-000058 REV 00, Table 6-3

Need for Integration of the Infiltration Model with the UZ Flow Model

- Net infiltration estimates by the infiltration model were based on information about climate and surface hydrological conditions that are subject to uncertainty
- UZ model predictions for temperature and chloride, using median results from the infiltration model, deviate from observations of temperature and chloride
- Calibration of the top boundary condition using subsurface data (e.g., temperature and chloride) provides additional constraints for the infiltration results

Why Use Temperature and Chloride Data?

- Temperature profiles along boreholes are controlled by boundary conditions at the ground surface and the water table, percolation flux, and heat redistribution processes (advection and thermal conduction) within the UZ. Percolation is strongly influenced by surface infiltration at locations with sufficiently high infiltration rates
- Chloride is a nearly ideal natural tracer for the study of water movement in geologic systems, and chloride porewater concentrations result from upper boundary conditions on chloride concentration and water flux and mass redistribution processes (advection and diffusion) within the UZ. Chloride concentrations are sensitive to the chloride concentration boundary condition at ground surface

Methodology for Infiltration-UZ Flow Integration

- Generalized Likelihood Uncertainty Estimate (GLUE) methodology was used, with multiple likelihood functions to account for uncertainty in the assignment of a likelihood function
- The residuals between UZ model calculations of temperature or chloride concentration and measured values were used as inputs to likelihood functions
- For temperature, the residuals for each borehole are averaged and then implemented in each likelihood function. Then the likelihoods across the different scenarios are scaled to provide the weights
- For chloride, the residuals for each borehole are averaged and then the residuals over all the boreholes are averaged. The residuals within the ESF and ECRB are separately averaged for use in the likelihood functions. Then the likelihoods for a given infiltration scenario are summed over the boreholes, ESF, and ECRB. Finally, the cumulative likelihoods across the four infiltration scenarios are normalized such that the sum is 1

Multiple Likelihood Functions

normal distribution (s1) (Carrera and Neuman, 1986)

$$L_{1i} = \prod_{j=1}^{K} \left(2\pi\sigma_j^{\,2}\right)^{-0.5} \exp\left\{-\frac{(x_{ij} - X_j)^2}{2\sigma_j^{\,2}}\right\}$$

inverse square sum (s2) (Beven and Binley, 1992)

$$L_{2i} = \left\{\sum_{j=1}^{K} \frac{W^*_j}{(x_{ij} - X_j)^2}\right\}^N$$

inverse square product (s3) (Beven and Binley, 1992)

$$L_{3i} = 1 \Big/ \left(\prod_{j=1}^{K} \left(x_{ij} - X_j\right)^2\right)$$

fuzzy measure (s4) (Beven 2006)

$$L_{4i} = \sum_{j=1}^{K} \left(1 - \frac{\left|x_{ij} - X_j\right|}{\varepsilon}\right)$$

Source: Adapted from MDL-NBS-HS-000006 REV02 AD01, Section 6.8

Steps for Determining Weighting Factors

- To integrate the UZ flow and infiltration models for use in TSPA, use the GLUE methodology to calculate the weighting factors for the *k*th infiltration map
  - Determine the prior weights (P_i)
  - Calculate the likelihood values based on chloride data (L_{kci}) and temperature data (L_{kti}) and UZ model predictions, for the *k*th infiltration map, and
  - Calculate the final weighting factors P_{ki}^f for the *k*th infiltration map

$$P_{ki}^{f} = \frac{P_i L_{kci} L_{kti}}{\sum_{i=1}^{4} P_i L_{kci} L_{kti}}$$

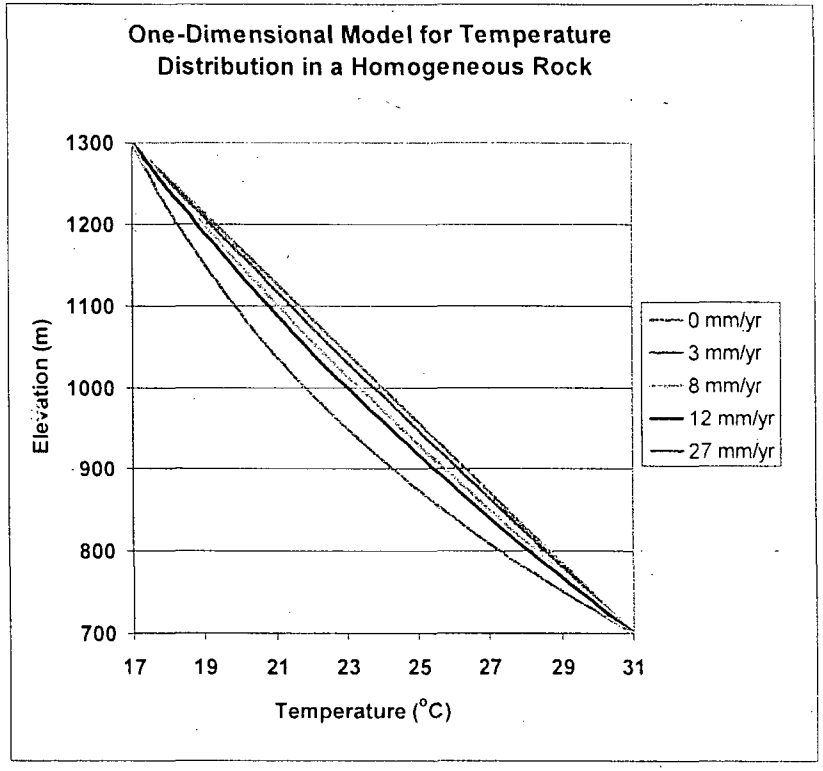
- Calculate the final weighting-factor values
  - $P(L = L_k)$ is the probability for L_k to be the true likelihood function and assigned the same value for all the four likelihood functions

$$P_i^f = \sum_{k=1}^{4} P_{ki}^{f} P(L = L_k)$$

Source: Adapted from MDL-NBS-HS-000006 REV02 AD01, Section 6.8

Sources and Uncertainty of Temperature Data

- All qualified temperature data available from various depths along 5 boreholes: NRG-6, NRG-7a, SD-12, UZ#5, and UZ-7a
- Near ground surface observed temperatures show significant seasonal variations. However, these seasonal changes in surface temperature have little impact on essentially steady-state heat flow or temperature profiles in the deeper (more than 20 m) unsaturated zone, because measurement uncertainty is small (less than 0.1 °C) and measurements below 20 m are stable
- Only measurements 40 m or more below ground surface were considered, resulting in a total of 50 temperature data points for comparison
- Thermal conductivity uncertainty range is ±15%
- Thermal diffusion (~4×10^{-7} m^2/s) leads to thermal equilibrium over 10,000 years. The process also leads to reduced sensitivity of temperature to flux at low rates



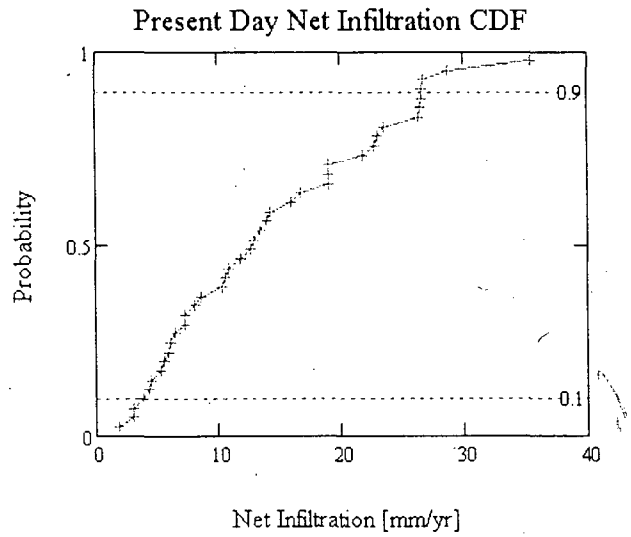
Source: MDL-NBS-HS-000006 REV02 AD01, Sections 6.3.4 and 6.8.3

Sources and Uncertainty of Chloride Data

- The evaluation used measured chloride porewater concentrations from the Exploratory Studies Facility (ESF), the Enhanced Characterization of Repository Block (ECRB), and 12 boreholes: G-2, NRG-6, NGR-7a, SD-12, SD-6, SD-7, SD-9, UZ-14, UZ-16, UZ-7a, UZ-N55, and WT-24
- Large spatial variations in chloride concentration due to variable surface evapotranspiration and subsurface flow conditions
- Water diffusion rates are low (~ 10^{-10} m^2/s) such that equilibrium with present-day climate is not expected
- The chloride method used here accounts for fracture and matrix pathways as well as fracture-matrix interaction
- Chloride concentration variations for present-day climate scenarios cover a range of about one order of magnitude for the flux-weighted average chloride concentration

Scenario Case	Infiltration over UZ model domain (mm/yr)	Flux-weighted average chloride concentration (mg/L)
Present-Day, 10th%	3.03	29
Present-Day, 30th%	7.96	10
Present-Day, 50th%	12.28	8
Present-Day, 90th%	26.78	3

Prior Weights from the Infiltration Model

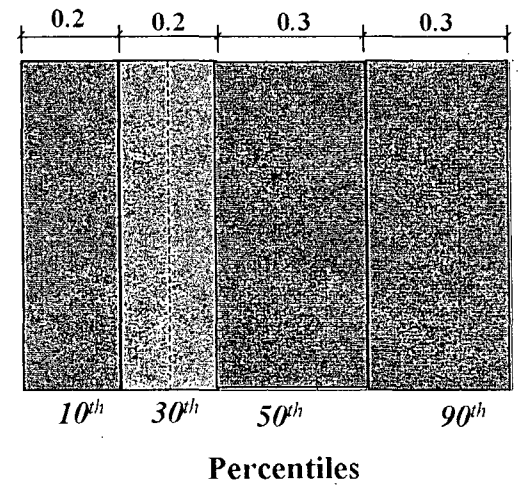


Source: Adapted from MDL-NBS-HS-000023 REV01 AD01, Figure 6.5.7.1-6[a]

Precipitation and Net Infiltration over Infiltration Model Domain for Present-Day (MDL-NBS-HS-000023 EV 01, Section 6.5.7.1)

Case	Precipitation (mm/yr)	Infiltration (mm/yr)
10th%	144.1	3.9
30th%	160.6	7.3
50th%	189.3	13.0
90th%	212.7	26.8

- Uncertainty in UZ flow fields is evaluated by using probabilistic scenarios for the upper boundary conditions
- 4 infiltration maps (10th, 30th, 50th, and 90th percentile) selected for evaluation of uncertainty in the UZ flow fields in TSPA
- Prior weights for the maps are 20%, 20%, 30%, and 30% respectively



Source: Adapted from MDL-NBS-HS-000006 REV03 AD01, Figure 6.8-1

Calculated Weighting Factors Using Both Chloride Data and Temperature Data

- The average weight is highest for the 10th percentile case, with similar average weights for the 30th and 50th percentile cases and the lowest for the 90th percentile case
- The results confirm that it is important to consider uncertainty in the likelihood function

Calculated Weighting Factors Using Both Chloride Data and Temperature Data

Summary of Final Weights From All The Methods				
Infiltration map	**10th%**	**30th%**	**50th%**	**90th%**
Prior weights	20%	20%	30%	30%
S1	100%	0%	0%	0%
s2_a1_N=1	59%	21%	17%	3%
s2_a1_N=0.5	40%	24%	26%	11%
s2_a2_N=1	47%	24%	25%	4%
s2_a2_N=0.5	34%	24%	30%	12%
s3_a1	97%	3%	0%	0%
s3_a2	94%	6%	1%	0%
s4_sum	26%	24%	32%	18%
Average final weighting factors	62%	16%	16%	6%

Output DTN: LB0701PAWFINFM.001, *factors.doc.*

Source: Modified from MDL-NBS-HS-000006 REV02 AD01, Table 6.8-1

Calculated Weighting Factors Using Chloride and Temperature Data Separately

Calculated Weighting Factors Using Chloride Data Only

Infiltration map	10th%	30th%	50th%	90th%
Prior weights	20%	20%	30%	30%
S1	100%	0%	0%	0%
s2_a1_N=1	48%	25%	21%	6%
s2_a1_N=0.5	34%	25%	28%	14%
s2_a2_N=1	41%	27%	25%	8%
s2_a2_N=0.5	30%	25%	29%	16%
s3_a1	72%	21%	7%	0%
s3_a2	62%	27%	11%	0%
s4_sum	24%	23%	32%	21%
Average Final Weights	51%	22%	19%	8%

Output DTN: LB0704UZWFINFM.001, file: *summary_chloride only.xls.*

Calculated Weighting Factors Using Temperature Data Only

Infiltration map	10th%	30th%	50th%	90th%
Prior weights	20%	20%	30%	30%
S1	100%	0%	0%	0%
s2_a1_n=1	31%	21%	30%	19%
s2_a1_n=0.5	25%	21%	30%	24%
s2_a2_n=1	26%	21%	35%	18%
s2_a2_n=0.5	23%	21%	33%	24%
s3_a1	89%	8%	2%	0%
s3_a2	83%	11%	5%	0%
s4_sum	22%	21%	31%	27%
Average Final Weights	50%	15%	21%	14%

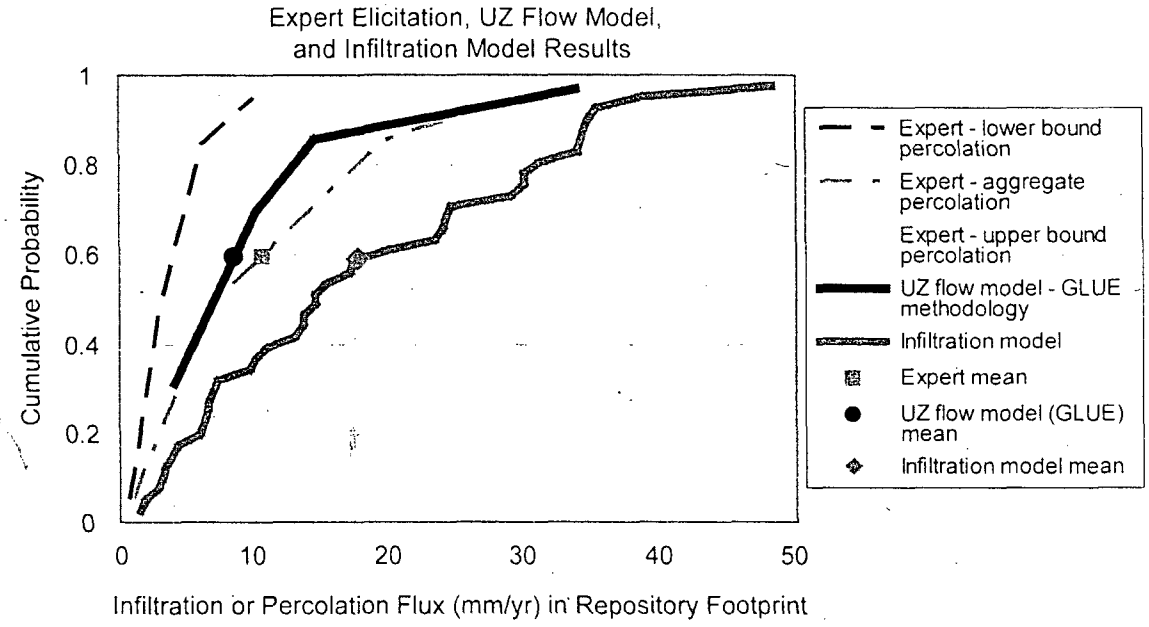
Output DTN: LB0704UZWFINFM.001, file: *summary_temperature only.xls.*

Source: Modified from MDL-NBS-HS-000006 REV02 AD01, Tables 6.8-4 and 6.8-5

- **Similar weighting factors were obtained from independent calculations using temperature and chloride data sets which represent different physical processes**

Corroboration with Results of Expert Elicitation

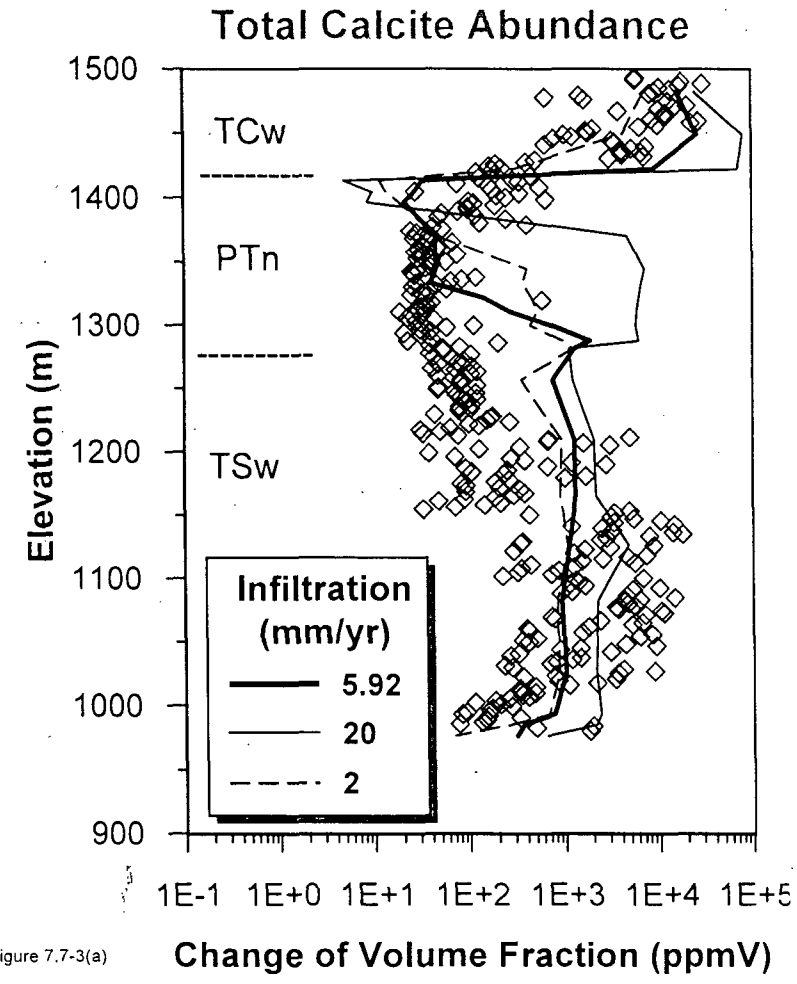
- **The probability distribution of area-averaged infiltration rate for the repository footprint, obtained using the modified GLUE methodology, is consistent with the aggregate percolation flux probability distribution from an expert elicitation by 7 experts (CRWMS M&O 1997. *Unsaturated Zone Flow Model Expert Elicitation Project.* ACC: MOL.19971009.0582.)**



Source: MDL-NBS-HS-000006 REV02 AD01, Figure 6.8-3[a]

Corroboration with Calcite Abundance Study

- The probability distribution for infiltration and percolation fluxes is also consistent with the result of a transport study of total calcite abundance from borehole WT-24
- It is recognized that the calcite data have limited sensitivity to infiltration rate, and are subject to poor resolution during the current interglacial (present-day) time period



Source:
MDL-NBS-HS-000006 REV03 AD01, Figure 7.7-3(a)

Weighting Factors for Future Climates

- The same weighting factors for present-day, monsoon, and glacial transition climates
- Basis: Given the similarity of modeling methods across climate states, any deviations between the UZ flow model results for temperature and chloride, and the infiltration model results for infiltration rates under present-day climate, are also comparable for future climates
- Additional evidence supporting the same weighting factors for future climates is provided by the calcite modeling study

Infiltration Case	Present-Day Infiltration (mm/yr)	Monsoon Infiltration (mm/yr)	Glacial-Transition Infiltration (mm/yr)	Post-10k Infiltration (mm/yr) [a]	Probability - Weighting Factors (All Climate States)
10th Percentile	3.03	6.74	11.03	16.89	0.62
30th Percentile	7.96	12.89	20.45	28.99	0.16
50th Percentile	12.28	15.37	25.99	34.67	0.16
90th Percentile	26.78	73.26	46.68	48.84	0.06

Source: MDL-NBS-HS-000006 REV03 AD01, Tables 6.1-2, 6.1-3, and 6.8-1

[a] Note that for the post 10,000-year period, the Infiltration cases differ and represent scaled versions of the present-day 90th percentile, the 50th percentile glacial- transition, the 90th percentile glacial-transition, and the 90th percentile monsoon maps, respectively.

Summary

- Integration of the infiltration and UZ flow models in TSPA is necessary because of deviations from subsurface measurements of temperature and chloride concentrations
- A probability distribution was evaluated using a modified GLUE methodology with measured temperature and chloride data, and is used to assign weighting factors for sampling the UZ flow fields in TSPA
- The analysis used measured temperature profiles from boreholes and measured chloride concentrations from boreholes, ESF and ECRB, because of their sensitivity to infiltration
- The modified GLUE methodology utilized multiple likelihood functions to account for uncertainty in the selection of likelihood functions
- The probability distribution obtained is consistent with the aggregate percolation flux probability distribution from an expert elicitation, and with estimated infiltration rates from an independent study of calcite deposition