Sandia National Laboratories Estimates of Infiltration

Presented to:
Nuclear Waste Technical Review Board

Presented by:
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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**
- **Joseph Kanney (SNL) – Regional recharge estimates**
- **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 (AMRs) related to net infiltration titled:**
    - ***Simulation of Net Infiltration for Present-Day and Potential Future Climates* (MDL-NBS-HS-000023 REV 00)**
    - ***Analysis of Infiltration Uncertainty* (ANL-NBS-HS-000027 REV 01)**
- **BSC produced nine data qualification reports to support the new model**
  - **Site maps; bedrock, soil, and vegetation properties; and site weather data (SNL)**
- **A new model (MASSIF) has been developed and documented as MDL-NBS-HS-000023 REV 01; this report is currently in the checking and review stage**
- **Because the new AMR is not finalized, all information presented in this presentation is preliminary**

Goals for New Modeling Approach

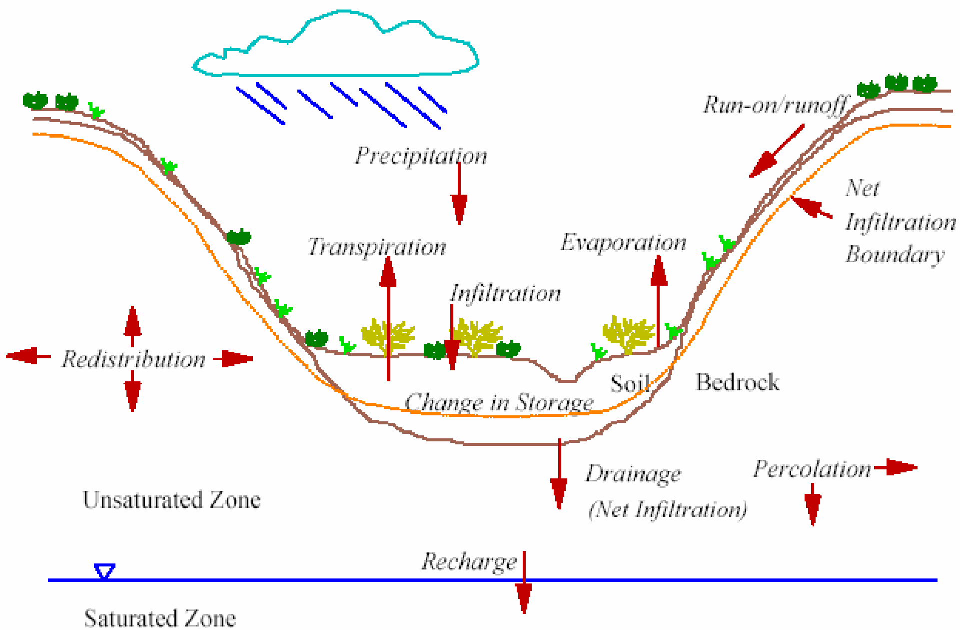
- **Use INFIL 2.0 conceptual model**
  - **Mass-balance approach, similar grid and domain, field capacity approach, etc.**
  - **Evaluate INFIL 2.0 submodels with available documentation**
- **Quality assurance objectives were integrated with the model development process**
  - **Documentation to be sufficient, traceable, and transparent**
  - **Calculations to be accurate, reproducible, retrievable, and testable**

Goals for New Modeling Approach (continued)

- **We chose to use Mathcad software in order to create a calculation environment with the following features**
  - Calculation algorithm and routines are extensively documented
  - Inputs and results are presented and archived in context with the calculations
  - The calculation is transparent such that any 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)**



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

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

MASSIF Conceptual Model
Precipitation and Snow Processes

- Daily precipitation is stochastically simulated
- Ten representative years are selected for each realization
- Precipitation is lapse-corrected for elevation
  - Reference elevation is top of YM, 1,524 m above sea level
- Snowfall occurs when average daily temperature is below 0°C
- Water from snow enters the soil as snowmelt (function of average daily temperature)
- Sublimation losses are represented

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

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 model used to represent evapotranspiration (ET)**
  - **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 penetrate bedrock)**

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

MASSIF Conceptual Model
Subsurface Water Movement and Storage (continued)

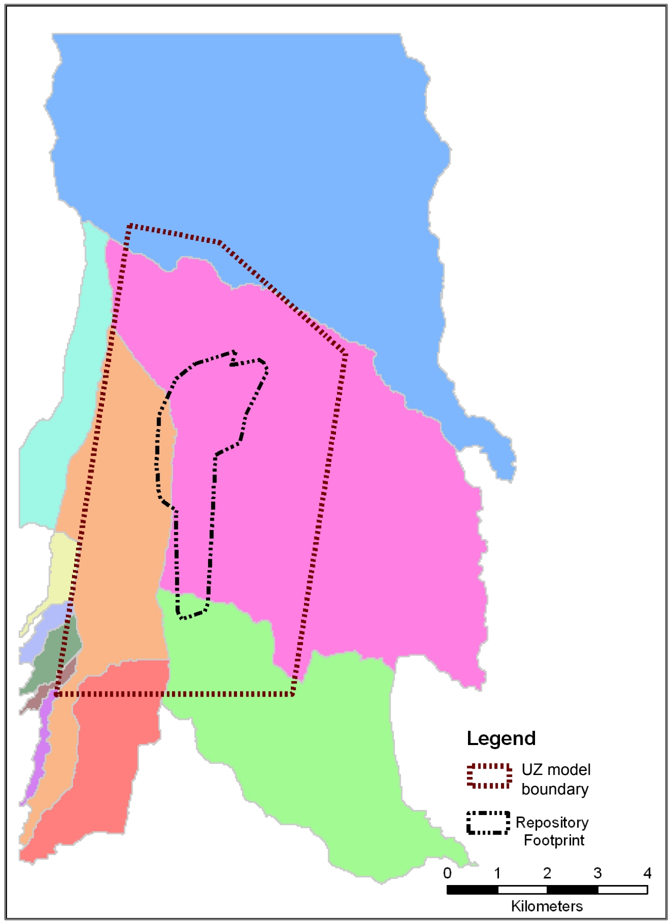
- Water flows from upper to lower layers when field capacity is exceeded in the upper layer; flow is limited by soil conductivity
- Net infiltration occurs once soil layer contacting bedrock exceeds field capacity
- Daily net infiltration limited by bedrock conductivity

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



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

MASSIF Conceptual Model
ET Model

- **FAO-56—An internationally accepted set of guidelines to calculate ET**
- **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

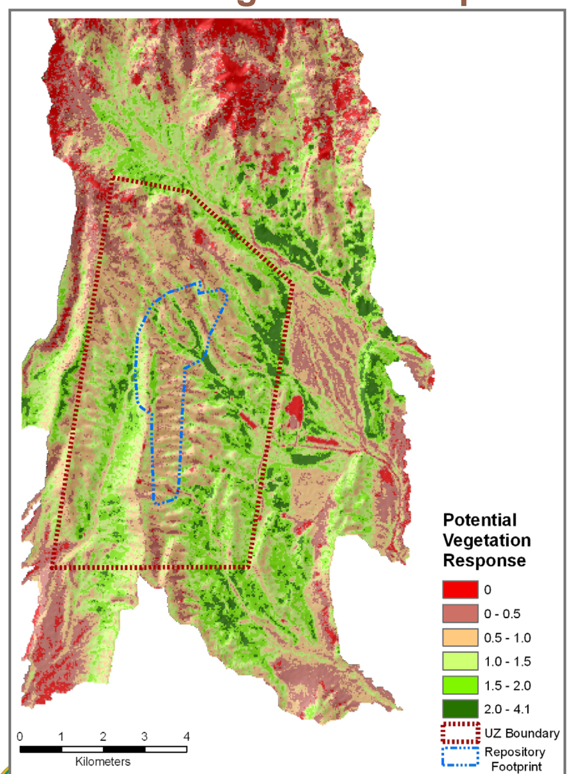
- **Penman-Monteith equation used to estimate reference ET**
  - **Solar radiation**
    - **Estimated on a horizontal surface from Hargreaves equation (based on temperature difference)**
    - **Slope-azimuth correction applied**
    - **Approach validated by comparison to direct measurements**
  - **Minimum and maximum temperature modeled separately on wet and dry days**
  - **Wind speed derived from present-day site measurements and varies with day of year**

MASSIF Conceptual Model

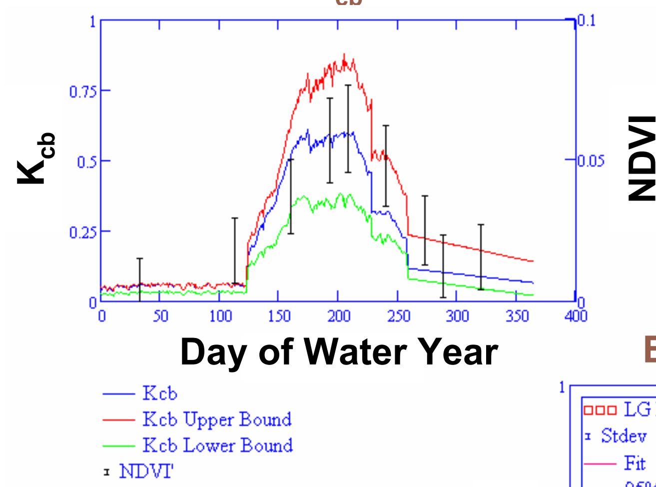
Estimating K_{cb}

- **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 YM**

Potential Vegetation Response

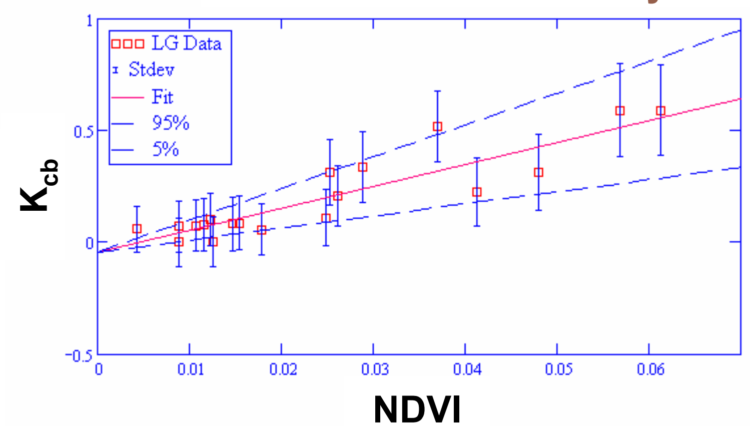


Wet Year K_{cb} and NDVI



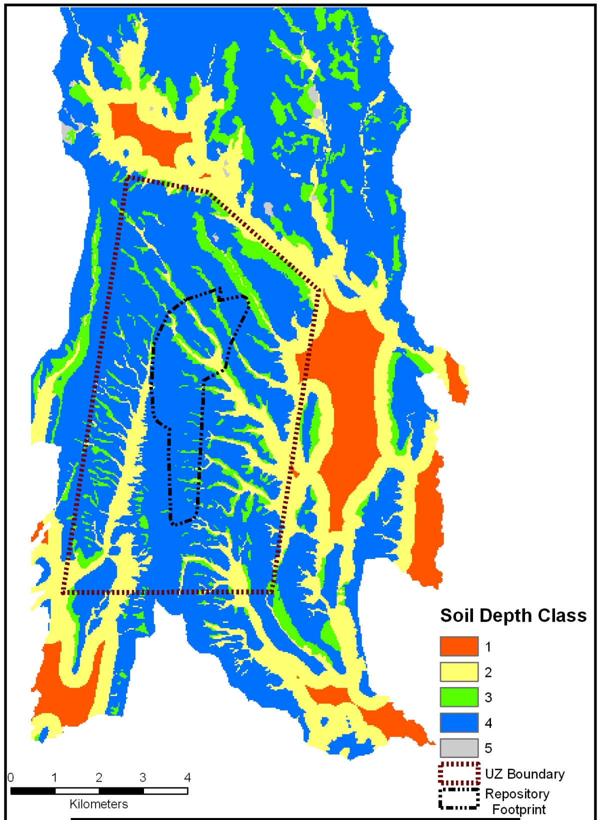
$$NDVI = \frac{NIR - Red}{NIR + Red}$$

NVDI vs. K_{cb}
Error bars show uncertainty



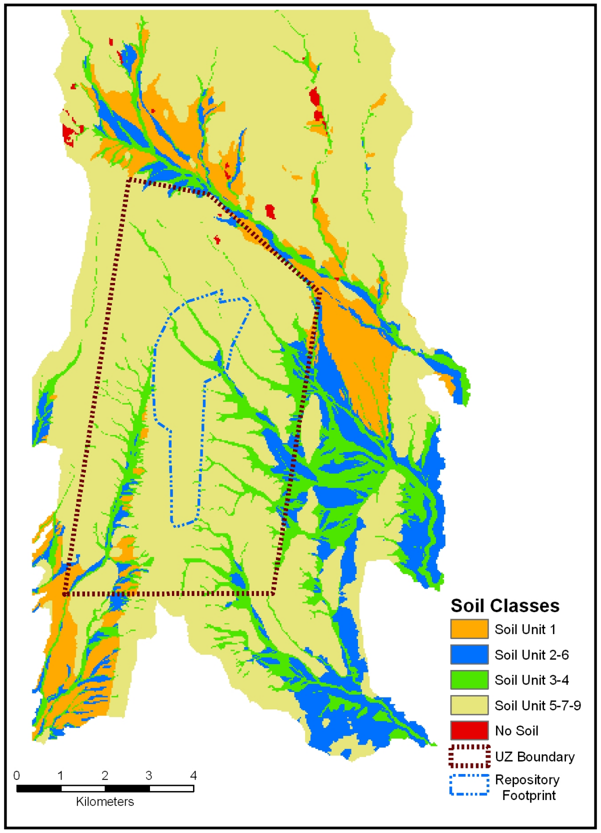
Soil and Bedrock Maps

Soil Depth Class

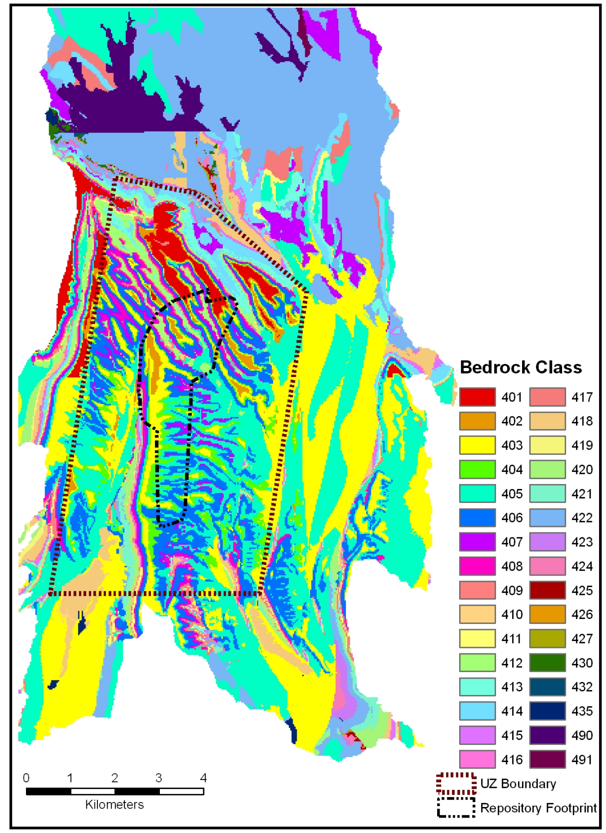


Soil Depth	Value (m)
Depth Zone 1	95
Depth Zone 2	16
Depth Zone 3	3
Depth Zone 4	0.1 – 0.5
Depth Zone 5	0

Soil Group



Bedrock Type

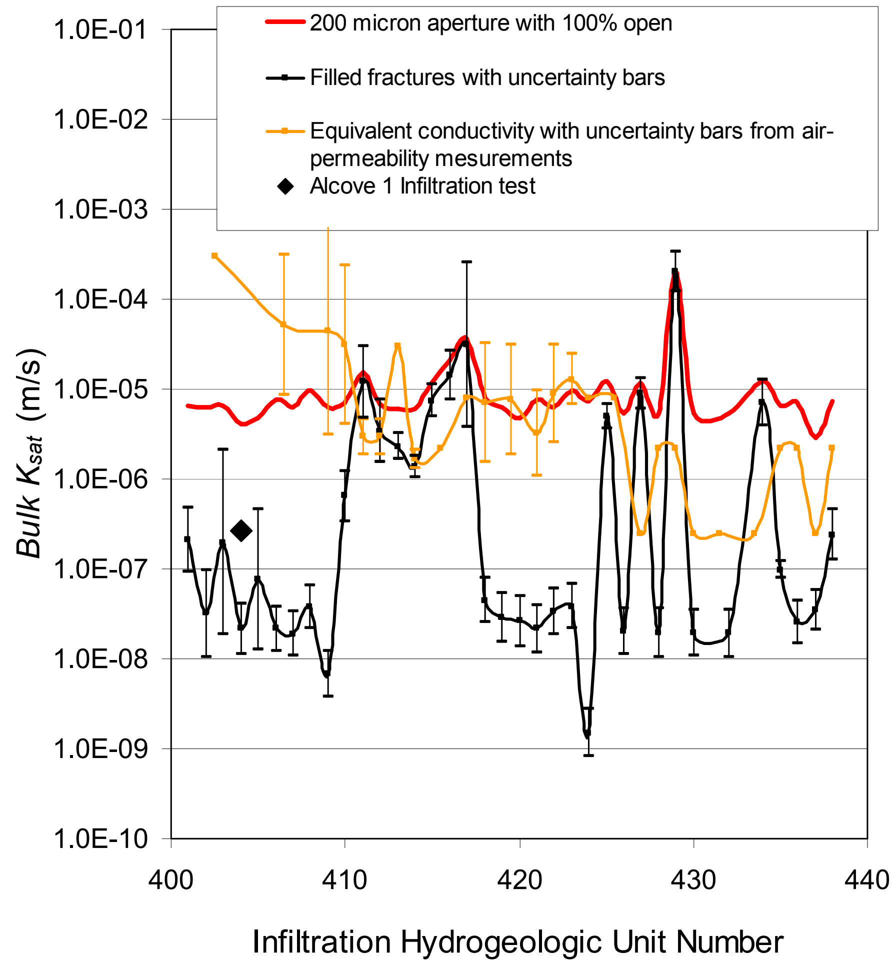


Soil Properties

- **Not all soil properties used for INFIL 2.0 calculations could be independently reproduced from available records**
- **New infiltration model used soil texture data collected at YM to estimate soil properties using a pedotransfer approach**
  - **Nonparametric approach identified similar soils (based on textural characteristics) 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**

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



Uncertainty Analysis Calculation Set Up

- **Parameter uncertainty distributions defined for all parameters (> 200 parameters)**
- **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 Preliminary 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
50th	13.0	22.9	28.6
90th	26.8	52.6	47.0

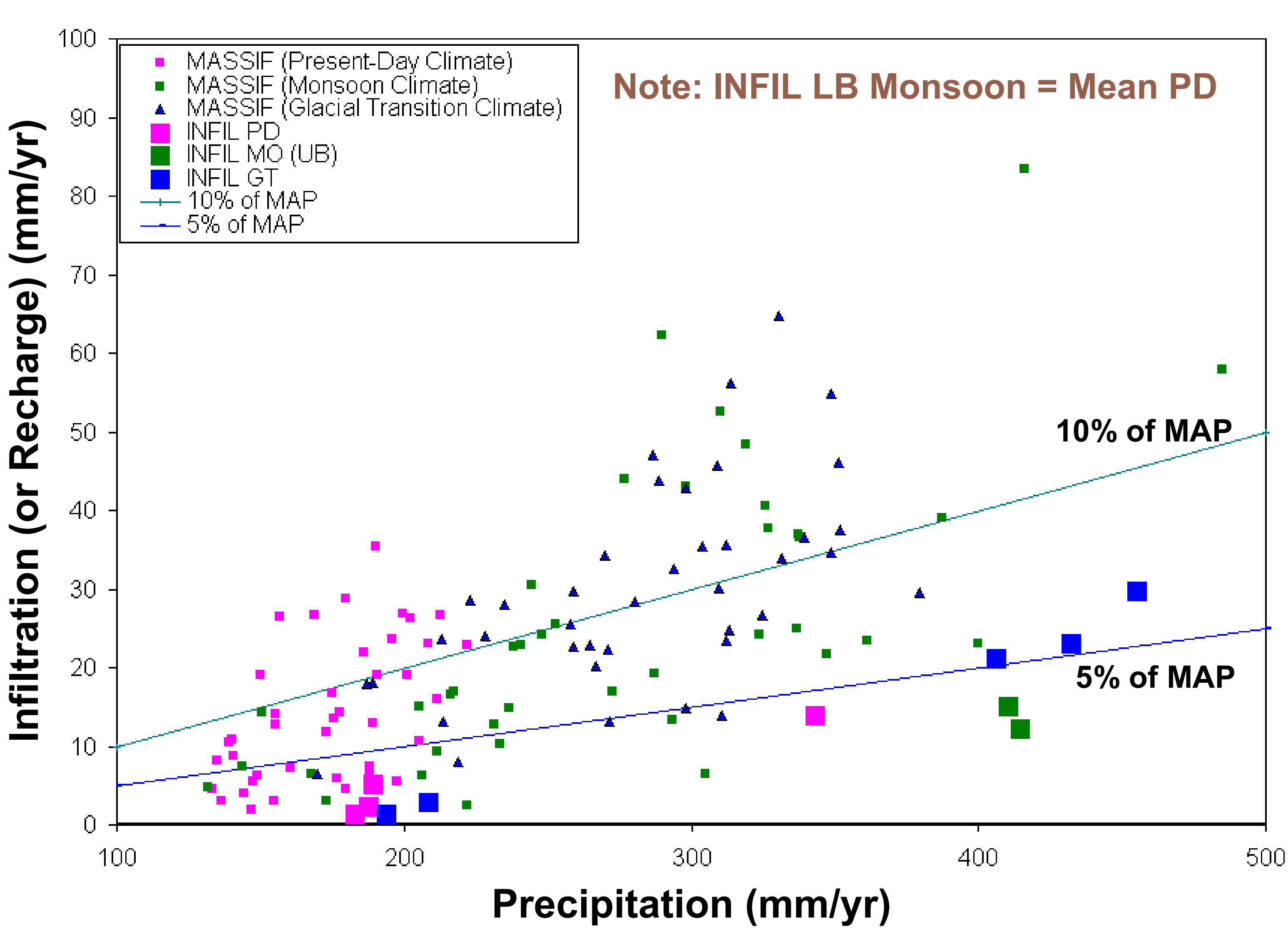
INFIL Net Infiltration Results

	Present Day (mm/yr)	Monsoon (mm/yr)	Glacial Transition (mm/yr)
Lower Bound	1.2	3.6	2.2
Mean	3.6	8.6	13.4
Upper Bound	8.8	13.6	24.6

MASSIF Mean Water Flux Fractions

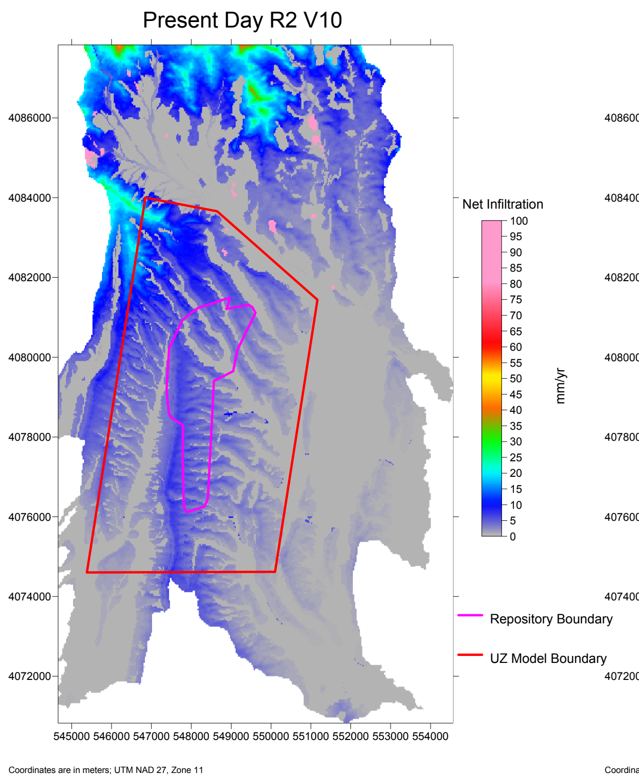
	Present Day (% precip)	Monsoon (% precip)	Glacial Transition (% precip)
%Infil	8	9	10
%ET	88	85	86
%Runoff	2	5	1
%Storage	2	1	2
%Sub	0	0	1

Net Infiltration Preliminary Results (continued)

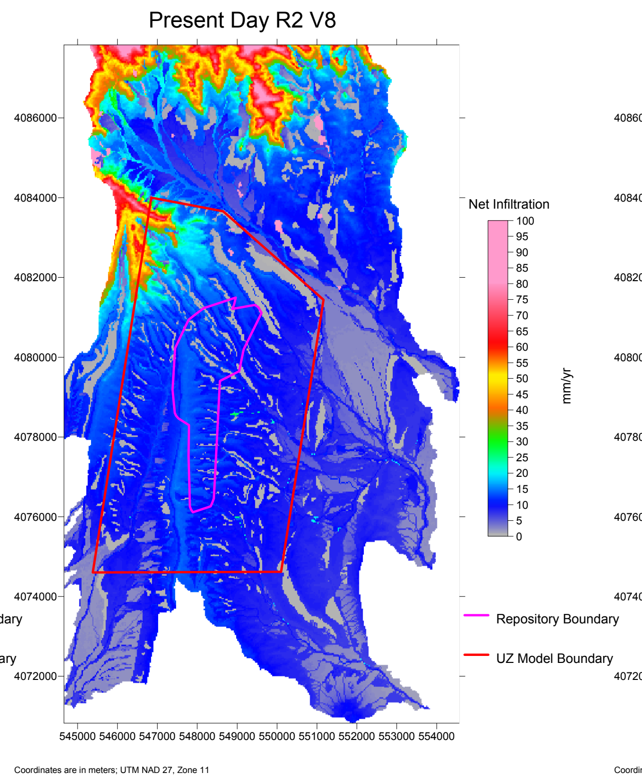


Net Infiltration Preliminary Results
Present-Day Climate

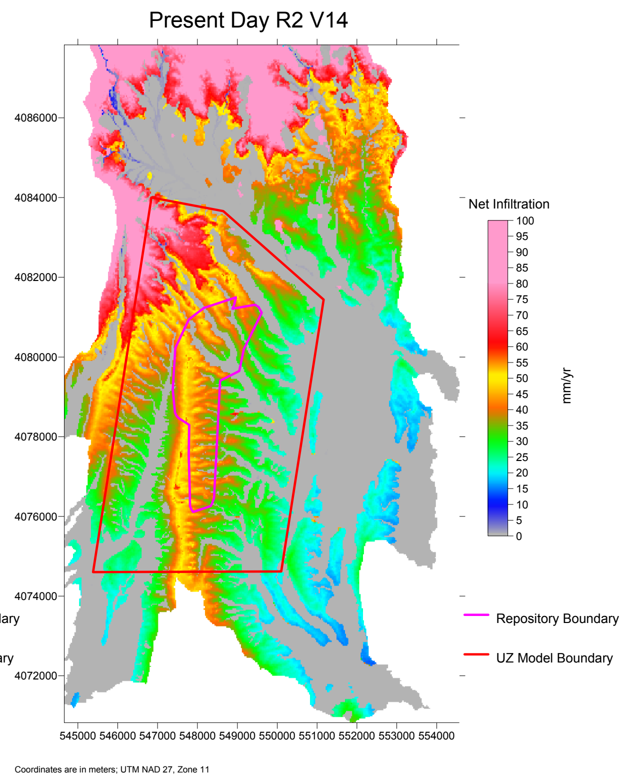
10th Percentile



50th Percentile

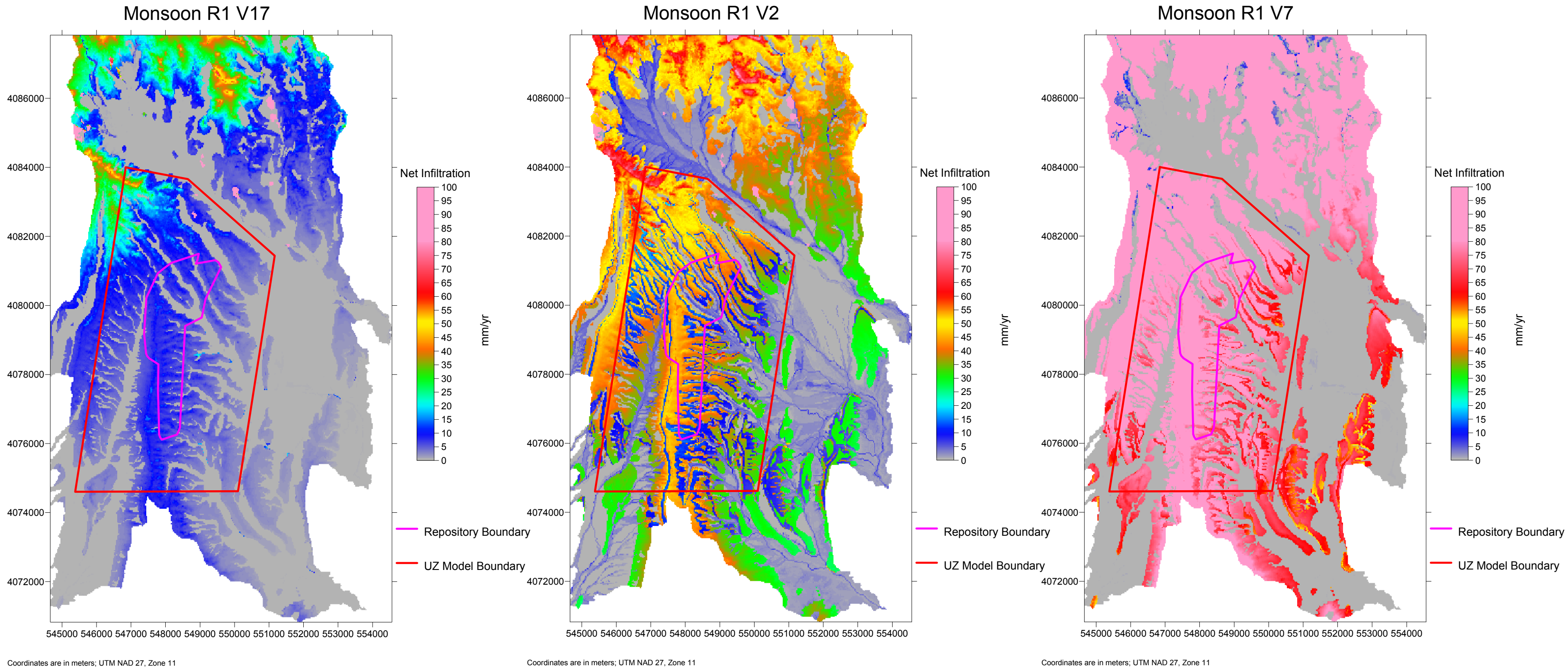


90th Percentile



Net Infiltration Preliminary Results
Monsoon Climate

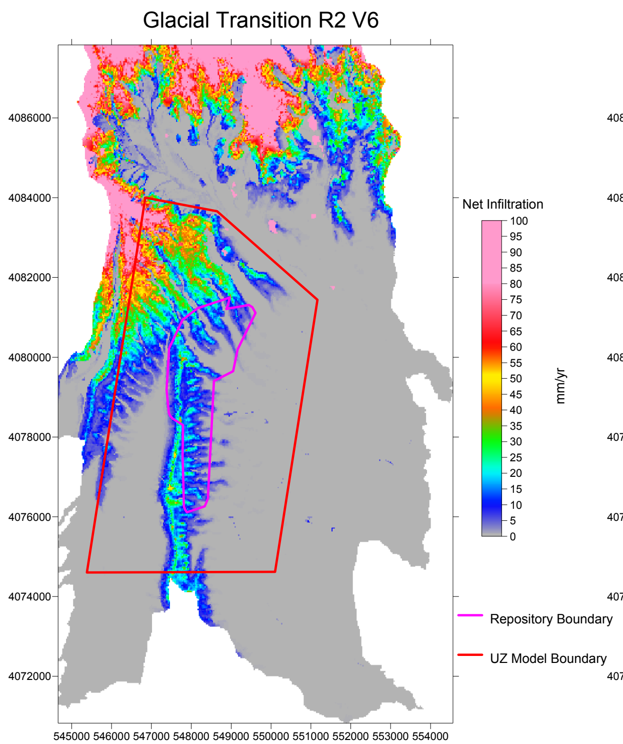
10th Percentile | 50th Percentile | 90th Percentile



Net Infiltration Preliminary Results

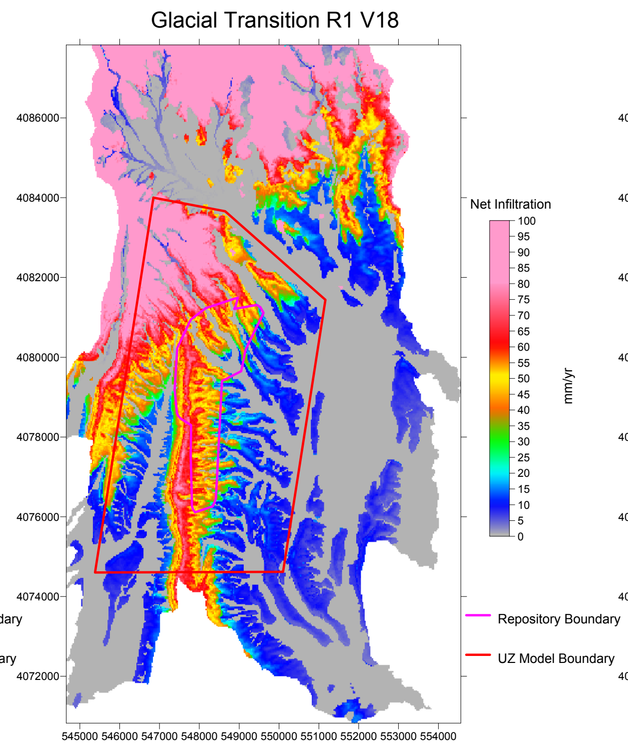
Glacial-Transition Climate

10th Percentile



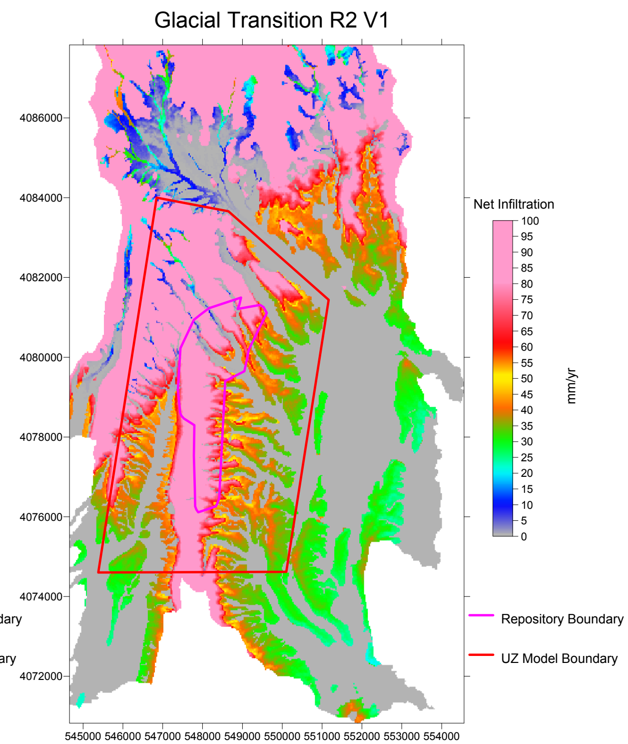
Coordinates are in meters; UTM NAD 27, Zone 11

50th Percentile



Coordinates are in meters; UTM NAD 27, Zone 11

90th Percentile



Coordinates are in meters; UTM NAD 27, Zone 11

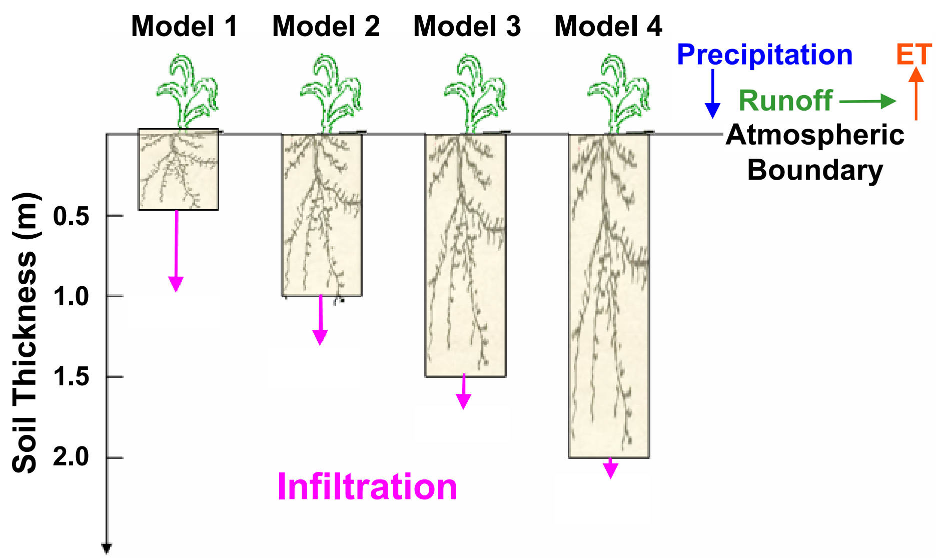
Sensitivity Analysis

- **Stepwise regression method applied**
  - **Analysis 1—40 realizations per climate**
  - **Analysis 2—Alternative analysis done by fixing precipitation inputs for all realizations**
    - **Focus on physical property uncertainties (epistemic) rather than uncertainties related to future weather patterns (aleatory)**
  - **Analysis 3—Extended analysis (42 uncertain parameters, 200 realizations**
  - **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**

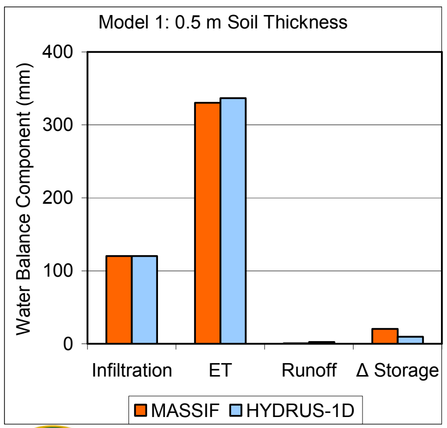
Model Validation Comparisons

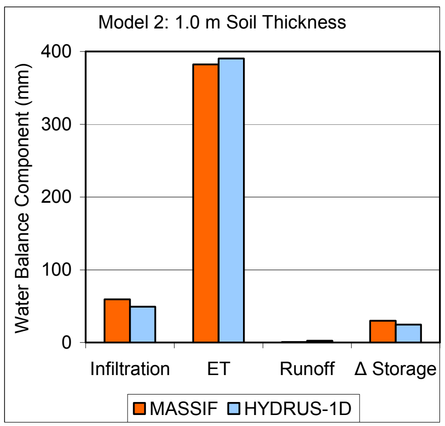
- **Confidence building during model development**
  - Precipitation submodel validated with comparisons to weather records
  - ET submodel validated by simulating weighing lysimeter datasets from Nevada Test Site (NTS) and Reynolds Creek, ID
  - Runoff results validated by simulating YM (1994 to 1998)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

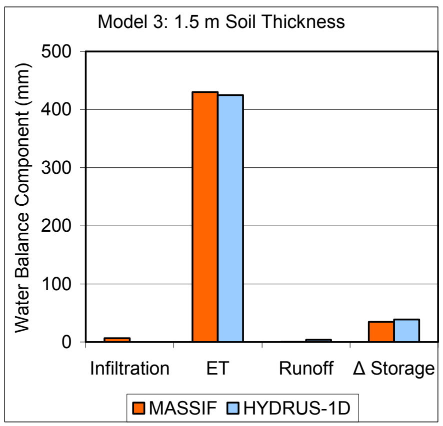
Alternative Model Comparisons

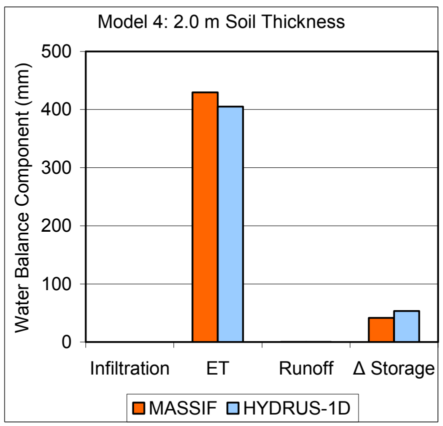


- MASSIF simulations were compared to HYDRUS-1D (Richards equation model) simulations at four locations
- Transient responses to precipitation and events and drying periods were somewhat different between models, however cumulative responses were quite similar



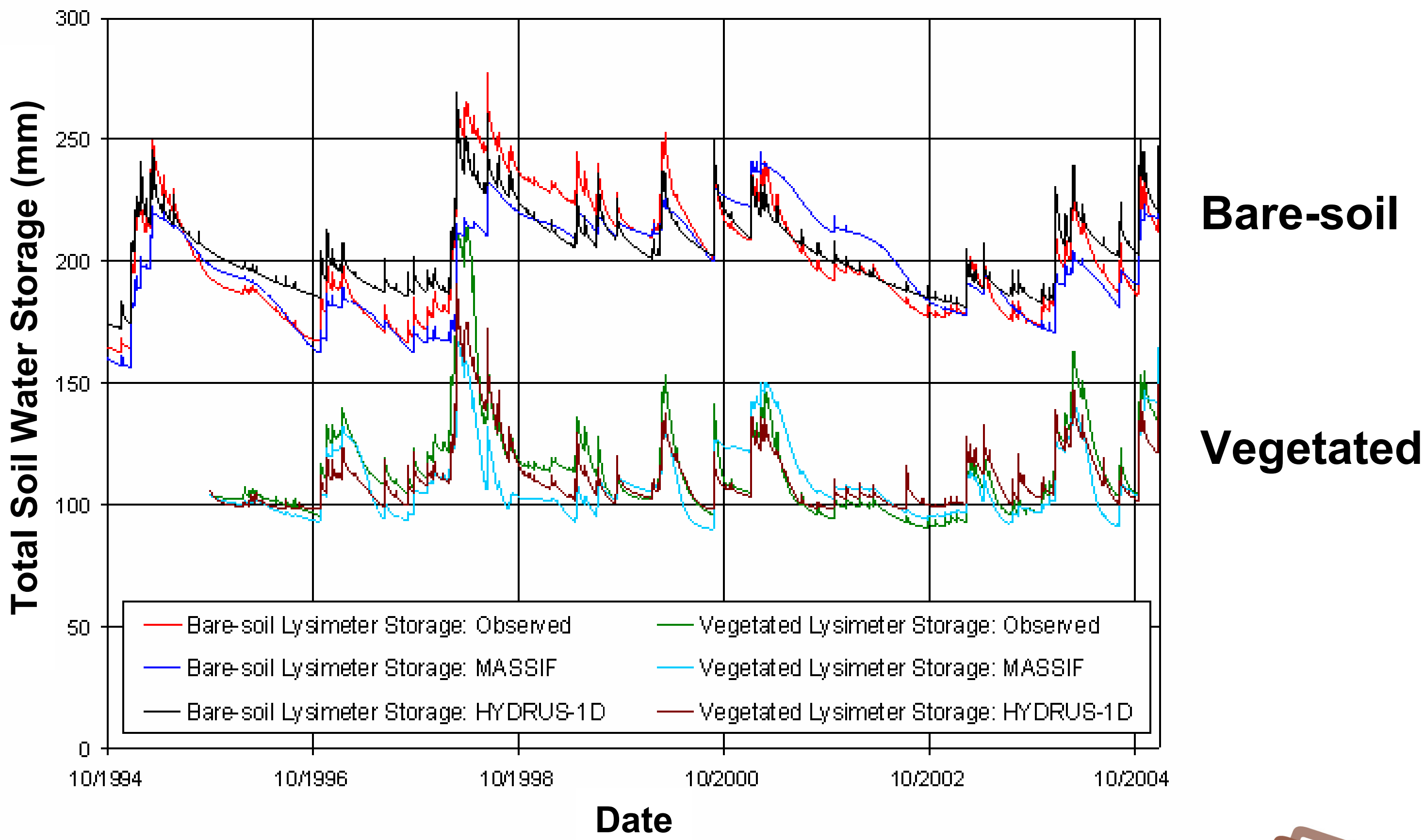






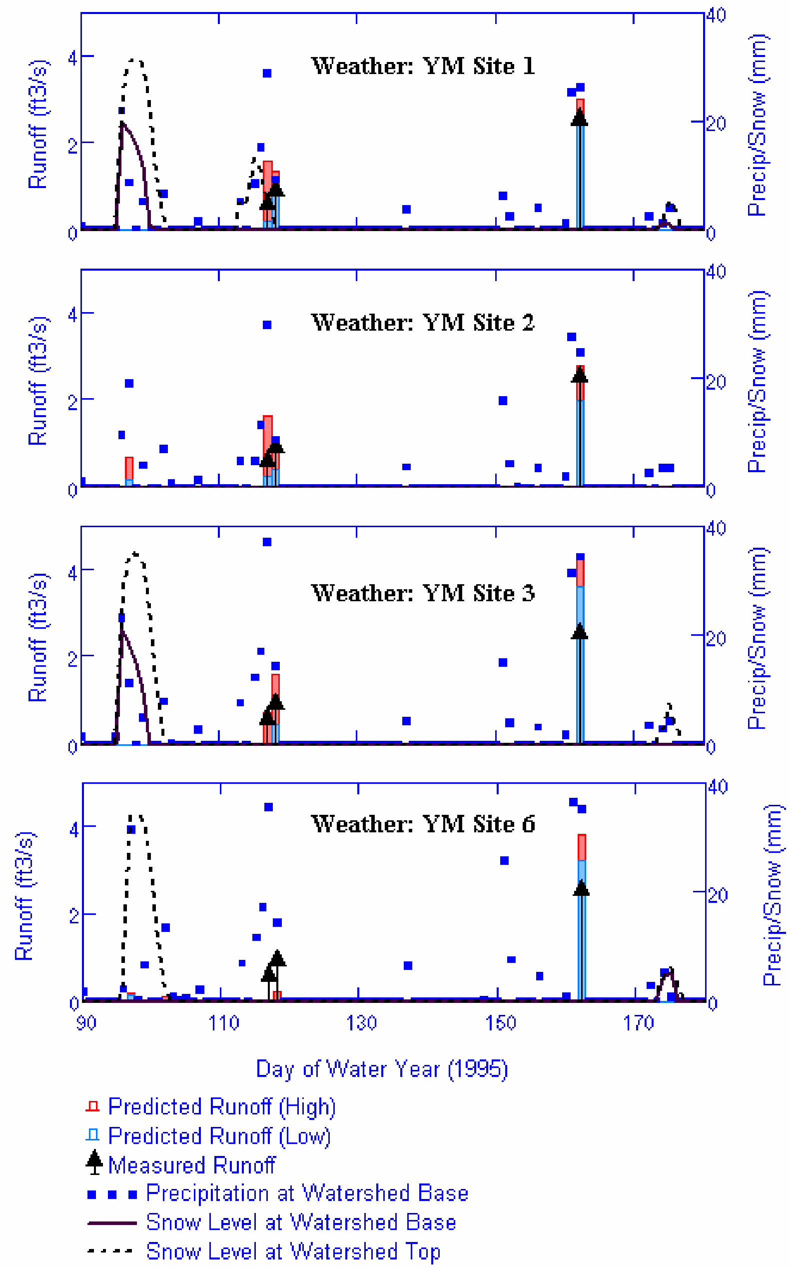
Model Validation Comparisons

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



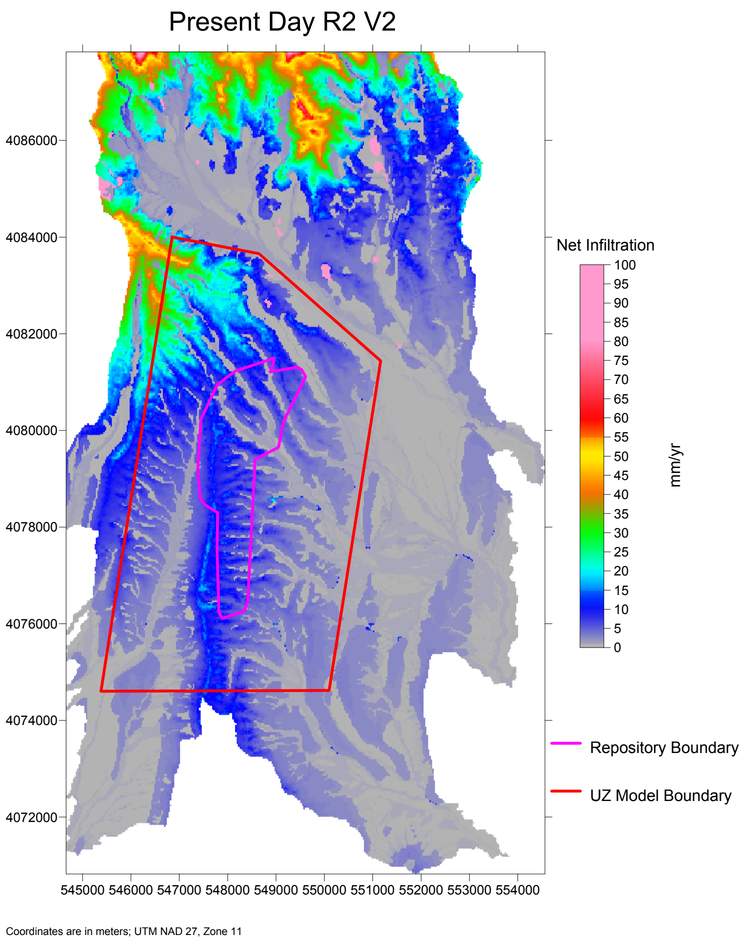
Model Validation Comparisons

- 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



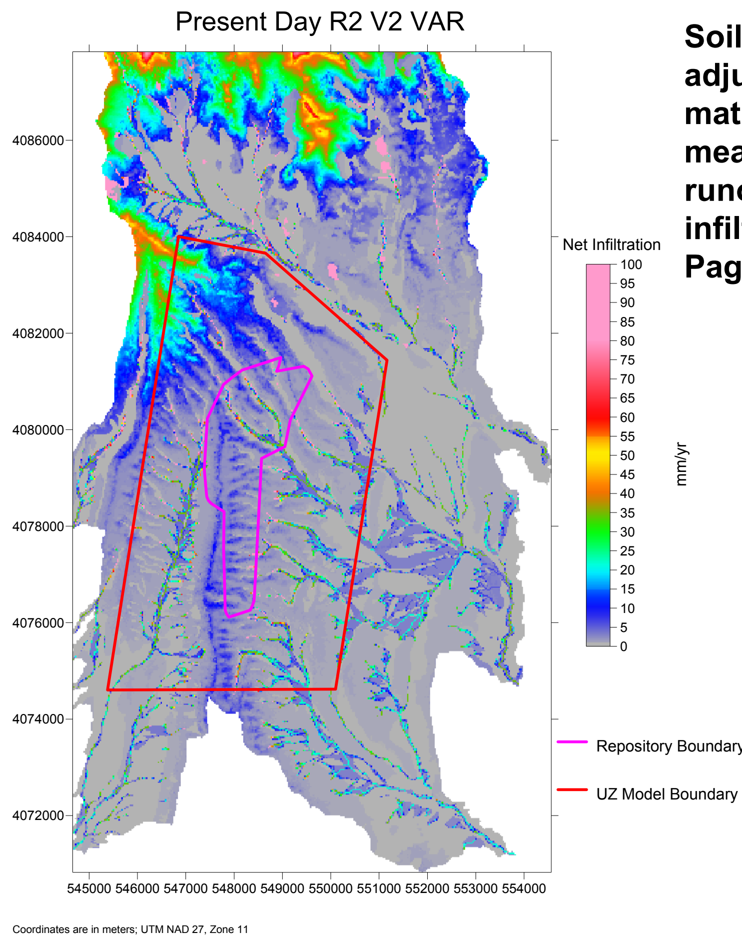
Example Model Comparisons

30th Percentile



Mean net infiltration = 7.3 mm/yr

Soil Conductivity Variation

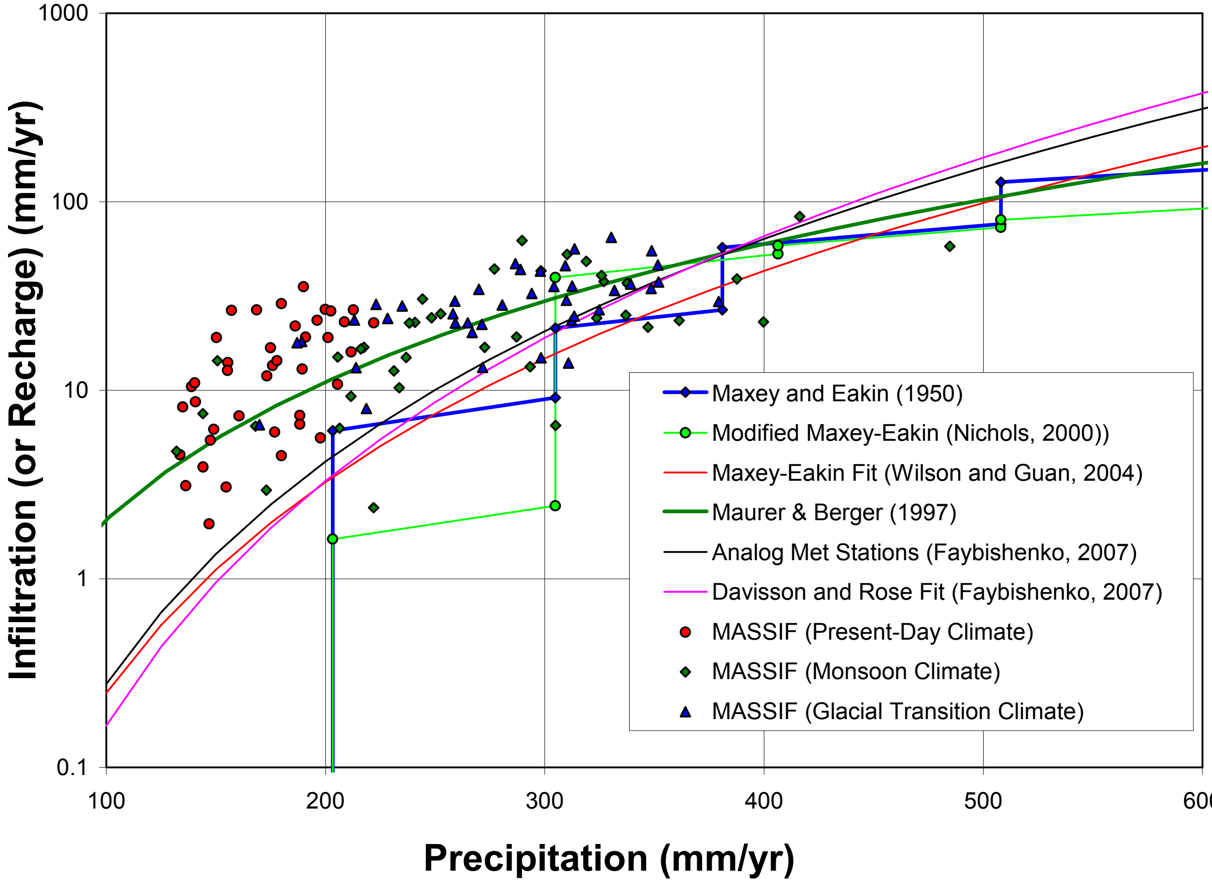


Mean net infiltration = 7.7 mm/yr

Soil Ksat adjusted to match measured runoff and infiltration in Pagany Wash.

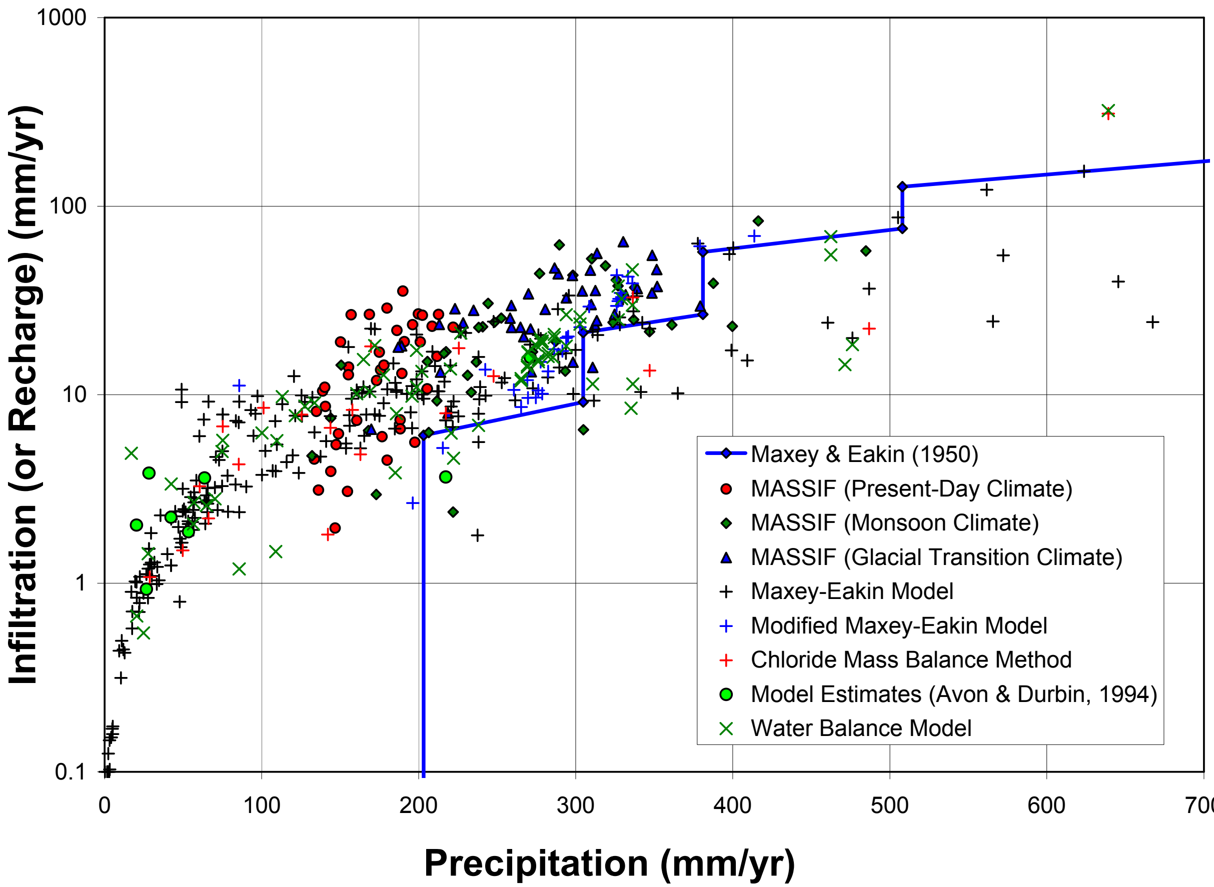
Example Model Comparisons (continued)

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



Example Model Comparisons (continued)

MASSIF Net Infiltration Estimates Compared with Selected Estimates for Nevada Hydrographic Areas



Summary and Preliminary Conclusions

- **MASSIF conceptual model is very similar to INFIL 2.0**
- **MASSIF net infiltration results are generally higher than INFIL 2.0 results**
  - **MASSIF accounts for parameter uncertainty**
    - **Soil depth, soil properties, and precipitation are most significant input parameters**
  - **MASSIF bedrock conductivity values are significantly higher than those used by INFIL 2.0**
  - **MASSIF does not consider removal of water from bedrock**
- **MASSIF predictions are validated with comparisons to field data, analog site estimates, and alternative model estimates**