ELECTRIC POWER RESEARCH INSTITUTE

Long-Term Climate Modeling and Hydrological Response to Climate Cycles in the Yucca Mountain Region

1018714

Long-Term Climate Modeling and Hydrological Response to Climate Cycles in the Yucca Mountain Region

1018714

Technical Update, June 2009

EPRI Project Managers

A. Sowder
J. Kessler

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Monitor Scientific, LLC

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

CITATIONS

This document was prepared by

Monitor Scientific, LLC
3900 S. Wadsworth Blvd.
Denver, CO 80235

Principal Investigator
M. Apted

This document describes research sponsored by the Electric Power Research Institute (EPRI).

This publication is a corporate document that should be cited in the literature in the following manner:

Long-Term Climate Modeling and Hydrological Response to Climate Cycles in the Yucca Mountain Region. EPRI, Palo Alto, CA: 2009. 1018714.

REPORT SUMMARY

Climate and its influence on hydrological conditions are important considerations in the evaluation of the Yucca Mountain (YM) site as a geologic repository for disposal of U.S. commercial spent nuclear fuel and defense high level radioactive wastes. This report updates previous EPRI studies (reports 1013445 and 1015045), which produced a quantitative and paleo-climate-calibrated/verified model of how climate, infiltration, and YM flow properties might appear in the future. The studies also supported assessment of the impact of climate/infiltration change on the large regional flow system at YM.

Background

Most previous attempts to predict future hydrological conditions in the YM site vicinity, including groundwater recharge and deep percolation, have focused on relating net hydrological surface balance conditions to climate parameters. These parameters were either observed within the modern instrumental record or reconstructed based on a chain of inferences from paleo-environmental proxy data. Observations of modern climate at sites deemed analogous to the paleo-climate reconstructions have been used as boundary conditions in assessments of past and future climate, near-surface hydrology, and infiltration in the YM region.

Objectives

- To develop a new proxy record for paleo-infiltration independent of prior approaches.
- To establish whether a full earth system model—including a global general circulation model representation of the ocean-atmosphere-land surface—can accurately predict net recharge (infiltration) in the present and in the past, and then be used to forecast the future.

Approach

The project team took a new approach, validating the regional predictions produced by the National Center for Atmospheric Research Community Climate System Model using modern climate and hydrological observations. They conducted further validation with the paleo-environmental record of past hydrological balance during the last glacial maximum (LGM) and at 130 thousand years before present (kyr BP), near the inception of the last interglacial period. Finally, the team used that paleo-climate-validated model to predict future conditions.

Results

Consistent with previous studies, EPRI has found that infiltration was maximized during the LGM. However, EPRI has also found that substantial recharge during the glacial maximum was likely to have been brief and that the long glacial period preceding it was likely not to have been as “wet” as previously reconstructed. EPRI has found that the last interglacial interval was typically near the upper range of modern and recent (past 6000 kyr) infiltration estimates, and that termination of the penultimate glaciation had higher infiltration rates than even LGM.

Based on published predictions—which show that anthropogenic climate change would prevent global climate from slipping into the next glacial interval and potentially the next several glacial cycles—EPRI conjectured that conditions in the YM region would probably be as dry or drier than modern conditions for at least 60,000 years and as much as 400,000 years. If indeed anthropogenic climate change prevents the transition into glacial cycles in the future, then the

substantial decreases in infiltration shown in this study could be considered quasi-permanent features. Such an occurrence could in turn skew the distribution of likely infiltration rates further to the dry side because peak glacial values would occur infrequently, and the interglacial mean itself could be smaller than the modern mean.

Based on the above climate and infiltration studies, a regional flow model was used to explore the transient behavior of a large regional flow system at YM resulting from the significant variability in Pleistocene and Holocene climates. Simulations involved a 39 km slice of the Death Valley flow system through YM toward the Amargosa Desert. The long time scale over which infiltration had changed (tens of thousands of years) was matched by the large physical extent of the flow system (many tens of kilometers). Flow and ^{14}C transport simulations showed that the flow system changed markedly as a function of paleo-climate. At YM, transient changes in infiltration and recharge exert a dominant control on groundwater ages that explain why no systematic increases in ages are evident along a present day flow path. It is also clear that simple geochemically based interpretive tools cannot synthesize the complex flow history that gives rise to measured ^{14}C age distributions.

EPRI Perspective

The relevant U.S. Nuclear Regulatory Commission regulations in 10 CFR 63 for the YM repository site impose a fixed range of conservative percolation rates at the repository horizon for the 1 million year compliance period. It is worth noting, however, that the climate/infiltration analyses presented in this report suggest that global warming will likely produce a future that is drier than the present in the YM region, and that such conditions could persist for another 100,000 to 400,000 years. If such dry conditions remain in place over this relatively long time period, then the YM flow system has the potential to achieve steady state with low recharge conditions that are far outside the range of behavior for much of the past 180,000 years and far below the post-10,000-year infiltration values mandated by 10 CFR 63. The residence time for water in the YM flow system of the future would be much longer, and the infiltration rates much lower, than present day conditions, enhancing the isolation performance of a nuclear waste repository located at YM. Consequently, the existing mandated values are conservative.

Keywords

Yucca Mountain
Infiltration
Regional Hydrology
Paleo-Climate
Transient Flow

ACKNOWLEDGMENTS

The work presented in this report was supported by the Electric Power Research Institute through Monitor Scientific, LLC. EPRI is grateful to the following authors of this report:

Dr. Matthew Huber, Purdue University (climate and infiltration)

Drs. Franklin Schwartz and Edward Sudicky, Groundwater Simulations Group (hydrological modeling)

In addition, Dr. Huber's work on climate and hydrology in the southwest was supported by National Science Foundation (NSF) Grant EAR-0450221. Dr. Huber's work was also made possible by the provision of climate model output by NSF and DOE through the Earth System Grid and through NSF support of the National Center for Atmospheric Research (NCAR) and the CCSM Paleoclimate Working Group. Dr. Sudicky also acknowledges the support of the Natural Sciences and Engineering Research Council of Canada (NSERC) through the Tier I Canada Research Chair to E.A. Sudicky. Thanks are given to Dr. Stuart Childs for sharing ideas during this effort.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Yucca Mountain, Nevada (YM) is the proposed site for a geological repository to dispose of US commercial spent nuclear fuel and defense high-level radioactive wastes. A license application for the Yucca Mountain geological repository has been submitted by the US Department of Energy (DOE, 2008) to the US Nuclear Regulatory Agency (NRC) and is currently under review. Throughout the more than 20-year history of the DOE's Yucca Mountain Project, EPRI has performed independent assessments of key technical and scientific issues to facilitate an understanding of and to provide a third party perspective on overall repository performance and site suitability. Climate and its influence on hydrological conditions are a key component in the evaluation of the site as a repository. Net infiltration into the deep unsaturated zone of YM is largely governed by climate and surface hydrological processes. These processes, along with the response of the regional flow system at YM to changes in infiltration are especially important in the evaluation of possible future release of radionuclides from a potential YM Nuclear Repository Site. This report updates previous EPRI studies evaluating climate variability and infiltration and their impact on the large regional flow system at Yucca Mountain, Nevada (EPRI, 2006; EPRI, 2007).

1.1 Background

Southwestern North America has been less arid in the past and appears to be poised to become more arid in the near future. Determining the future hydrological conditions in the vicinity of YM is necessary to evaluate the suitability of the site as a potential repository for nuclear waste. Most previous attempts to predict future hydrological conditions, including groundwater recharge and deep percolation in the YM Site vicinity, have focused on relating net hydrological surface balance conditions to climate parameters, either observed within the modern instrumental record or reconstructed based on a chain of inferences from paleo-environmental proxy data. Observations of modern climate at sites deemed analogous to the paleoclimate reconstructions have been used as boundary conditions in assessments of past and future climate, near surface hydrology and infiltration in the YM region.

EPRI's approach to assessing infiltration has been to avoid the use of this indirect paleoclimate analogue method as much as possible by creating a proxy for paleo-infiltration itself and to ascertain whether climate models can accurately reproduce these paleo-infiltration estimates as an obligatory step to modeling future infiltration. Thus the primary objective of EPRI's climate/infiltration study was to develop a new proxy record for paleo-infiltration independent of prior approaches and further to establish whether a full Earth System model, including global general circulation model representative of the ocean-atmosphere-land surface, could accurately predict net recharge (infiltration) in the present and in the past, and then be used to forecast the future.

Initial EPRI studies analyzing proxies for past infiltration at the Yucca Mountain site (YM) indicated the possibility that infiltration is (or has been for ~6,000 years) at or near 0, whereas for a brief interval near the last glacial maximum (LGM), infiltration was higher (EPRI, 2006). Additional work, using climate models to directly simulate past infiltration with the ultimate goal of validating model performance for predicting future infiltration, was conducted by EPRI in 2006 (EPRI, 2006). In 2007, a more complete version of the climate model with dynamic (model-predicted) interactive vegetation was utilized to update the previous studies and resulted in a major improvement in parts of the modeled soil hydrology. In addition, longer time series of past infiltration were developed to better characterize the history of infiltration at YM and to validate the climate model predictive capabilities via direct comparison of model predictions with proxy records. Preliminary analyses to address the impact of global warming forecasts on the evolution of climate/infiltration at YM, and to establish infiltration during paleo-climates from the last interglacial as a means of constraining existing paleo-climate analysis for the future also were conducted. The goal of these studies was to produce a quantitative and paleo-climate calibrated/verified model of what climate, infiltration, and YM flow properties might look like in the future. The initial results of these studies were documented in EPRI (2007). The final results of these climate/infiltration studies are presented in this report.

In conjunction with its climate/infiltration studies, EPRI conducted complementary studies on hydrologic flow models for Yucca Mountain (EPRI, 2006; 2007). EPRI's climate-related hydrologic studies initially were driven by the performance assessment (PA) reported in the Final Environmental Impact Statement (FEIS) by the DOE (DOE, 2002). In the FEIS, the PA showed several "spikes" in calculated doses at the regulatory compliance point for a 10^6-year post-closure period. The largest spikes in dose were about four times the mean dose value, indicating sensitivity in one or more of the uncertain parameters in the probabilistic performance assessment. The main question raised by this observation was whether these calculated "spikes" reflected the expected response of the YM hydrological setting to abrupt changes in climate, or whether such "spikes" were an artifact of the modeling approach and assumptions used in the DOE's FEIS.

The initial EPRI study was designed to examine the above question by analyzing patterns of flow and the transport of a hypothetical tracer within the hydrological setting of YM under conditions of changing climate. The overall objective was to determine the pattern of potential contaminant release (and therefore, dose) at the outflow end of the YM hydrological flow system as a function of increased recharge due to credible future climate transitions. In the study, EPRI constructed an advanced two-dimensional, dual permeability, dual porosity model with fully coupled flow and transport of the Yucca Mountain hydrological setting that contained the key hydrostratigraphic units and adjusted initial estimates of flow parameters and current recharge rates until the predicted and observed water table positions matched quite closely. Steady-state flow and transport scenarios were first analyzed using this model to provide an estimate of the long-term migration of a conservative solute from the proposed repository under current climatic conditions (unchanging), and to provide a base case that could be used to gauge the impact of the climate change. Then, to assess the effects of changing climate, a fully transient flow and transport simulation was conducted analyzing response to changes in infiltration. Results of this initial study indicated that climate transitions (*i.e.*, changes in infiltration), when analyzed by a model that accounts for transients, were not expected to produce significant "spikes" in mass flux at YM and that the "spikes" reported in the FEIS (DOE, 2002) might be the artifacts of modeling assumptions such as the instantaneous adjustments in flow used in the FEIS simulation approach. This initial study was documented in EPRI (2006).

At YM, the size and the complexity of the groundwater flow system and the variability in infiltration from the last interglacial to present made transient flow and transport analyses difficult. However, EPRI's work in 2006 (EPRI, 2006) suggested that the basin time constant was sufficiently large that flow was dominated by transient readjustments. Thus in 2007, EPRI conducted studies to understand the transient behavior of the large regional flow system at YM due to a significant decline in infiltration caused by the waning of pluvial rainfall related to the last glaciation. The study had two main objectives: (i) to calibrate the transient regional flow and transport model using present-day measurements of hydraulic head and measured ^{14}C values, and (ii) to examine the system state with varying conditions of future infiltration. It extended the previous work (EPRI, 2006) with calibrations based on assumed steady state conditions. It was felt that the YM hydrological flow model simulations could be improved with more accurate initial and boundary conditions derived from this infiltration data set. Furthermore, EPRI concluded that these potential improvements could be diagnosed by comparing flow-model predicted age tracers (mimicking ^{14}C age) with the substantial "age" data that has been collected at YM. The preliminary results of this study were documented in EPRI (2007). The final results of these hydrologic flow and transport modeling studies are also presented in this report.

1.2 Report Organization

In this report, a final update on EPRI's work on climate and infiltration variability is presented in Section 2.0. Initial and bounding infiltration rates established through the climate study are then used to improve and update EPRI's YM hydrologic flow model. The YM hydrologic flow and transport modeling work is presented in Section 3.0. Section 4.0 provides a brief summary of the conclusions for both studies, and cited references are presented in Section 5.0.

2
LONG-TERM CLIMATE MODELING

Yucca Mountain (YM) is situated in the arid climate of southwestern Nevada and has been extensively characterized and evaluated as a potential repository for commercial spent nuclear fuel and spent fuel and high-level radioactive waste from defense programs. Climate and its influence on hydrological conditions are a key component in the evaluation of the site as a repository. Observations of modern rainfall varies spatially from < 130 mm/yr at low elevations in the south to > 200 mm/yr at higher elevations to the north (Flint *et al*., 2001) and also temporally as a result of natural climate variability. Southwestern North America, including the YM region, has been less arid in the recent past and appears to be poised to become more arid in the near future (Seager *et al.*, 2007; Barnett and Pierce, 2008; CCSP, 2008). Because the YM site is so arid, modern net infiltration (recharge) rates are small: typical estimates are on the order of 5 mm/yr (Flint *et al.*, 2001). Net infiltration into the deep unsaturated zone of YM is largely governed by climate and surface hydrological processes, and these processes are especially important for future dose levels at the planned YM Nuclear Repository Site. For example, Mohanty *et al.* (2004) found that current infiltration is the single most important parameter in assessing dose levels in the far future, and the second most important variable is precipitation increase at the glacial maximum. However, both future climate and the link between climate and infiltration are also uncertain aspects.

This section is structured as follows. In Section 2.1, the overall approach is described. In Section 2.2, a description of the climate model used is provided. A model-data comparison for the Recent (past 6000 years) is presented in Section 2.3 along with paleo-climate simulations for the Last Glacial Maximum (LGM) and a comparison with proxies and previous simulations. In Section 2.4, the context for, and conceptual model of a direct proxy for paleo-infiltration using the Juniper pollen record from Owens Lake is presented and then compared with climate model predictions, most importantly at the termination of the penultimate glaciation and inception of the Last Interglacial (~130 thousand years before present (kyrbp)). Model predictions for the future within the context of the emerging consensus view of future global hydroclimatological change are presented in Section 2.5 and summary/conclusions in Section 2.6.

2.1 Approach

Although in-mountain flow models of enormous sophistication have been applied to the problem of assessing flow through YM (Wu *et al.*, 2006, 2007; BSC, 2004; Wilson and Guan, 2004), the upper several meters and their associated interactions with climate and vegetation have usually been treated quantitatively but crudely (BSC, 2001, 2004; Flint et al, 2001b; Faybishenko, 2007). Recently, though, this situation has been improved (SNL, 2007; Stothoff and Walker, 2007). However, in nearly all of these studies essentially the same future climate scenario is used, as derived by Sharpe (Sharpe 2003a,b) or the USGS (2001a,2001b) by assuming that future climate is like past climate as represented by paleo-environmental diatom and ostracode records from Owens Lake, California, and that these paleo-environmental conditions are best represented by analogy with modern day climatologies from regions well outside the YM region. Stothoff and Walter (2007) have used a very simple climate model (based on Paillard, 1998) to simulate past and future climate evolution based on known orbital variations, but their model assumes that climate in the YM vicinity is entirely predicted by insolation at 65°S, which is a large assumption. On the other hand, in the field of global climate modeling, enormous progress has been made in simulating the spatial pattern and temporal evolution of past, present and future climates with an ever improving basis in the representation of essential physics (Meehl *et al.*, 2007) and its interaction with soils, vegetation, and hydrology. Such models could provide essential insights into present past, present, and future characterization of net infiltration in the YM region, although that has not been the route taken by most previous work. Indeed, this approach has been specifically disallowed as part of the YM site review process and consequently this important approach has languished after some early pioneering studies (Schelling *et al.*, 1997).

As a route to better understanding past and future hydroclimatology and infiltration in the YM region, EPRI employs a synergistic combination of data and Earth System Models. The goal of this study is first to establish if such global models can produce values of modern net infiltration in the range observed today in this region, and then to test if they can reproduce the likely dynamic range of infiltration indicated by paleo-environmental reconstructions. To accomplish this validation, a long reference infiltration proxy data time series is generated from published juniper pollen records from Owens Lake (Woolfenden, 2003). A key distinction between EPRI's approach and that taken in some previous work (Sharpe 2003a; Stothoff and Walter, 2007) is that regional paleo-environmental records should be used to estimate paleo-infiltration in the YM, not global ice volume records or the insolation curves with which they roughly correlate. This work is discussed in detail in the following section. As shown below, the models perform excellently in these regards and EPRI therefore takes the next step, and uses them to forecast the likely evolution of net infiltration in the future.

EPRI's approach is intentionally different in many fundamental ways from that taken in the USGS, DOE, or USNRC (U.S. Nuclear Regulatory Commission) studies of this subject. While, as documented below, EPRI finds that its approach is physically well-justified and likely to be reasonably accurate, no 'gold standard' proxy record of infiltration exists to demonstrate with certainty that this method is better than other estimates. EPRI attempts here to create a proxy record that, we argue does a better job of directly recording net hydrological balance in the Yucca Mountain Region in the past than previous approaches, but there is enough uncertainty in any such attempt that further refinements may be necessary. Regardless, EPRI believes that utilizing new proxy records and new modeling frameworks has intrinsic value since it provides insights into the robustness of previous methodologies and may arguably be more accurate given the methodology we present here is innovative because of its self-consistent, objective physical basis. The methodology used here, however cannot resolve the spatial inhomogeneity and lateral flow processes that likely are important to determine the finest scales of infiltration and in-mountain flow. Nevertheless, by comparing the gross features produce in this study and previous work, EPRI finds that reconstructions of modern and past infiltration of various methods are generally congruent and that major differences are introduced in future predictions primarily from different assumptions about the evolution of future climate and the likelihood of future glaciations.

The goal of this component of the study is to test whether an Earth System Model representing the full dynamical interactions between ocean-atmosphere-land-sea ice and vegetation that is self-consistent from first principles can make accurate predictions of net infiltration (into the deep unsaturated zone) in the YM region. The first validation stage consists of comparison of the Community Climate System Model (CCSM) (Collins et al., 2006) simulation results against modern and Recent observations and previous modeling results. As a second validation stage, a comparison against qualitative and quantitative records of past infiltration and other variables relevant to net hydrological balance from the paleo-environmental record is made. This is performed for the LGM because there are a wide variety of existing quantitative proxy and modeling estimates of infiltration for this interval and because most other approaches have also been calibrated for LGM (*i.e.,* Sharpe, 2003a; BSC 2004). To further explore the model's response throughout its dynamic range, a further validation is performed at 130 kyrbp, the inception of the Last Interglacial (LIG)-end of the penultimate glaciation period. This stage of validation required the development of a new quantitative proxy for past infiltration because model simulations are sparsely distributed in the past, and there is no existing long quantitative infiltration proxy record for comparison for this. As a context, the model and paleo-infiltration proxy is also compared with prior modeling results of past infiltration and paleo-environmental variables. At any stage, either the model or the long proxy record can fail; *i.e.,* lack of congruence between the two would suggest that one or the other is in error, and if both lie well outside the range of existing quantitative and qualitative projects, then that also would render the results questionable. The CCSM is shown to pass this multi-stage validation process. Finally, after it is shown that the model produces modern and paleo-observations well, the simulations are carried into the future and used to estimate future net infiltration.

2.2 Description of the Earth System Model

In this study, results from the CCSM version 3 are analyzed. This is a comprehensive Earth System Model that includes full dynamical models for the atmosphere, ocean, sea ice, land surface, and vegetation. CCSM is a community-wide effort funded by the NSF, DOE, and NASA, and is one of the U.S. models featured in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2007). The model is exceptionally well characterized and described in many publications (see AMS, 2006).

Documentation of the model as a whole for the paleo-climate simulations that form the basis for this study, as well as for the vegetation model, can be found in AMS (2006), Collins *et al.* (2006), Kiehl *et al.* (2006), Levis et al (2004), Bonan *et al.* (2003), and Oleson *et al.* (2008). These models are computationally demanding, requiring approximately six months of computing on a massively parallel supercomputer to perform one simulation. For that reason, existing experiments available through the various working groups of the National Center for Atmospheric Research (NCAR) including the Paleo-climate Working Group and simulations of the modern and future, available through www.earthsystemgrid.org, are utilized. The atmospheric component of the model is referred to as CAM (version 3). Results from these simulations are analyzed using T31, T42, and T85 spectral resolution. These spectral resolutions translate into higher spatial resolution (3.75°, 2.8°, and 1.4°, respectively) which enables both depiction of topographic variation and the regional and microclimates associated with topography to be better represented. Three simulations at T31 resolution are analyzed: present, Holocene (~6 kyrbp), and a long transient Holocene simulation beginning at 6 kyrbp. Six T42 simulations are analyzed: present, Holocene (6 kyrbp), Last Glacial Maximum (21 kyrbp), the Last Interglacial inception (130 kyrbp), and future simulations stabilized at 2x and 4x pre-industrial carbon dioxide concentrations. The paleo-climate experiments are conducted by the Paleo-climate Working Group of the NCAR CCSM project. Results from three T85 simulations also are analyzed: one for the present and for stabilization at 2x and 4x modern carbon dioxide concentrations, respectively. The long-term atmospheric concentrations of carbon dioxide are likely to fall and decrease slowly but smoothly within this wide range for at least tens of thousands of years after a substantial anthropogenic carbon emission (Archer, 2005; Archer and Ganopolski, 2005; Montenegro *et al.*, 2007; Uchikawa and Zeebe, 2008).

One of the major limitations of using a global climate model to predict changes at a specific location is the discrepancy in scale between the smallest resolved scale of a climate model (e.g. ~2°x2°) and the scale of interest (~10km x 10km). One way to address this discrepancy may be to use a regional climate model, which employs the same sort of physical treatment as the global scale model but operates at a much finer scale (fed at its boundaries by output from a global scale model). Whereas temperature is a relatively smooth field, which may allow even a global scale model to produce meaningful results when applied at finer scales, precipitation is variable in both space and time, thus necessitating a fine scale model to make accurate predictions at smaller scales. In the past several years, a suite of studies performed using different models by different groups has been applied to the climate and hydrological cycle of the West with a focus on California and Nevada (Snyder *et al.*, 2002; Diffenbaugh, 2004). These studies suggest that the high resolution associated with these models leads to significant improvements of the ability of climate models to predict precipitation when compared with point observations collected at individual weather stations (Snyder *et al.*, 2002). This same model configuration has been applied to both future global climate change and past climate change (in the Holocene). The model is able to simulate important aspects of Holocene climate as derived from paleo-environmental proxies, which gives some faith in its ability to predict climate change as well as modern climate (Diffenbaugh, *et al.*, 2004). When applied to a future climate change scenario with doubled carbon dioxide values, the simulation shows very little change in seasonal or annual mean precipitation in the YM region, but warmer conditions lead to high net evaporation, soil moisture, and presumably less net recharge, just as in the global simulations used to drive them. Based on these experiences, it is believed that a global model is sufficient to perform at least this initial attempt at predicting past and future infiltration even at the sub-regional scale, although it is acknowledged that the results are likely to be refined utilizing a higher resolution model. To fully represent the finest scale features important for determining the spatial focusing of infiltration (*i.e.,* within ditches, or on ridge crests) would require the further downscaling of such model results to a even finer highly resolved model (~10m x10m)—this study is merely the first, necessary step in that direction. Nevertheless the relative changes are well-captured by the large scale models as used in this report. In Section 3 of this report, an evaluation of the potential consequences on the history (and future) of infiltration reconstructed here for within-mountain flow are described.

2.3 Model-data Intercomparison for Recent and LGM

A validation of CCSM results for the Recent past climate and infiltration simulations for the Yucca Mountain region is presented by comparing a synthesis of existing records against model results (Figures 2-1, 2-2, 2-3). This is followed by a further validation for infiltration in the distant past climate for which this synthesis has been extended and a new high resolution, long, continuous proxy record for infiltration has been created (Figure 2-4).

2.3.1 CCSM Results for the Recent

First, the model predicted infiltration/recharge for the YM region is summarized in Table 2-1. The YM region is defined here as the nearest neighboring grid cells to the present location of YM. The model produces a range of values from 1.5 to 14.0 mm/yr with the variation largely being a function of resolution for the Recent (modern and Holocene) period. Whereas some uncertainty exists about the exact temporal and spatial variation in the transition from the pluvial conditions of the last glacial and the generally dryer conditions of the Holocene, a series of studies (e.g., Tyler *et al.*, 1996; Walvoord *et al.*, 2002a; 2002b; 2004) have established that this transition began about 14 kybp and was nearly complete by 8 kyrbp. Several lines of evidence, including pollen records and paleo-lake levels, indicate several resurgences of near-glacial pluvial episodes (*e.g.,* at ~9 kyrbp) but by ~6 kyrbp it appears that the near-modern effective moisture regime had begun. Consequently, the modern and Holocene results are lumped together because, in general, paleo-climate data indicate that surface hydrological conditions have been roughly constant.

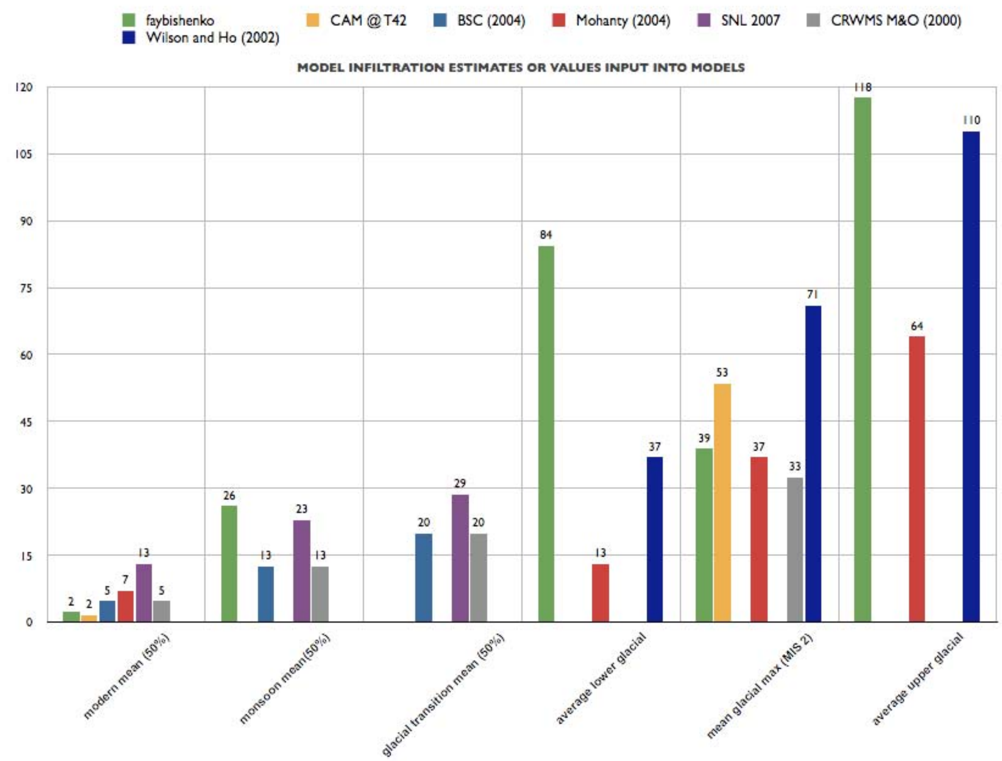

Figure 2-1
Published Infiltration Estimates for the Yucca Mountain Region Derived from or Input into Models. The labels refer to references cited in the main text.

Higher resolution models that capture more details of the YM region produce smaller values both for modern and Holocene conditions than the same model at lower resolution (Table 2-1). The highest infiltration/recharge values for the Recent are in the long-transient, low-resolution simulation including a wide variety of forcings, including a stochastic representation of volcanic activity. All of these infiltration/recharge values are well within the range measured for modern day or Recent conditions (summarized below). This demonstrates the fidelity of the model for predicting infiltration/recharge rates for Recent conditions. In addition, the higher resolution model is interpreted as having greater fidelity because it entails a more detailed representation of the local conditions at YM. Therefore, the lower range of infiltration values is considered to be more realistic and where possible results from the higher resolution simulations are utilized.

Table 2-1
CCSM3/CAM Experiments for the Yucca Mountain Region

Experiment	**Net infiltration mm/yr**
Present T42	1.50
Present T31	3.30
Holocene T42	1.90
Holocene T31	6.60
Transient Holocene T31	14.00
T42 Glacial Max	53.45
T42 130 kyrbp	61.40

2.3.2 Comparison of Recent to Other Infiltration Models

The results from these simulations are compared with the wide array of existing published model simulations of past infiltration. All the studies summarized in Figure 2-1, excluding EPRI's, are based at some level on the paleo-climate analogues developed or adopted by the USGS (Thompson *et al.*, 2001; Sharpe 2003a,b; Sharpe, 2007) and DOE (BSC, 2004), which have minor differences. Thus, the main differences in those results are due to differences in model formulation or the application of the same basic climatic boundary conditions. The CCSM simulations for the present fall within the range of Recent simulation predictions. At the preferred resolution in this study (T42), the simulation is within 3 mm/yr of all the existing simulations, except the recent results using MASSIF (SNL, 2007). Indeed, the latest MASSIFF (SNL, 2007) results are higher than all the other approaches with the exception of the recent study of Stothoff and Walter (2007) that is described separately below because it is substantially different than previous work. As a further validation of the model, EPRI's results can be compared in a gross sense against a wide range of other previous studies (Figure 2-3) that are not built around the same paleo-climate analogue approaches. Here, several of the most important modern and Recent estimates of infiltration/recharge interpreted from observational or proxy records or from models tightly constrained by proxies or modern observations have been combined (Flint *et al.*, 2002; Zhu *et al.*, 2003; Bagtzoglou, 2003; Constanz *et al.*, 2003). The range of these published values extends from approximately zero to 15 mm/yr, but the average is near 6 mm/yr. EPRI's high resolution simulation-based estimates are between 1.5 and 2. Averaging EPRI's shorter low resolution time series with the several thousand year long mid-

Holocene CCSM simulations that EPRI analyzed yields an average value of ~10 mm/yr. Thus, CCSM simulated values span essentially the same range for modern and Recent as previous studies grounded in data and have about the same mean value, *i.e.,* ~5 mm/yr.

2.3.3 Model Comparison for LGM

The only other time interval for which CCSM simulations have been performed and for which independent paleo-infiltration estimates exist is the glacial maximum conditions represented by the LGM. Many direct constraints on terrestrial conditions in the YM region are available from the LGM. As summarized by Tyler *et al.* (1996), the transition to glacial conditions during Marine Isotope Stage (MIS) 2/4 was characterized by wet, marshy periods with widespread standing water from 6060 to 4040 and 30 to 15 kybrp. While Owens Lake was at a high stand from at least 27 kyrbp to 20 kyrbp, open conifer woodland dominated the region (Thompson and Anderson, 2000). Juniper wetlands and steppe became widespread from at least 45 to 10 kyrpb. All proxy records indicate high effective moisture conditions in the YM region during the LGM, but whether the high effective moisture (here defined as strong net precipitation minus evaporation) conditions were caused predominately by decreases in temperature (and hence evaporation) or increases in precipitation is an unresolved question.

If, however, the goal is to estimate net infiltration, separation of the underlying variables may not be necessary; in fact it might introduce apparent ranges of uncertainty (since the range of combinations of temperature and precipitation are so large) that do not exist when considering just one variable. As summarized in DOE (2004; 2007), plant macrofossil records found in packrat middens allow climates during the LGM and subsequent intervals to be directly estimated. The DOE found that mean annual precipitation was in the range of 266 to 321 mm/yr and Mean Annual Temperature (MAT) was 7.9 to 8°C. It also is interesting that this estimate—which is based on direct proxy evidence from the YM region—produces maximum precipitation values that are much less than the maximums that are an outgrowth of the series of analogy-driven steps based on ostracode and diatom data (Sharpe, 2003a,b; Sharpe, 2007). A significant body of independent evidence supports the interpretation that there may have been little increase in annual average precipitation during the LGM. Indeed, it is even mentioned as a possibility in interpretations that discount it, *e.g*., Forester *et al.* (1999), who find that the LGM conditions, as indicated by the presence of limber pine but the absence of white fir, could be well explained by cooling in the absence of increases in annual average precipitation.

The NCAR CCSM simulations carried out for the LGM boundary conditions produced temperature and precipitation values in agreement with paleo-climate proxies, validating the model's climate performance in the YM region (See Figure 2-2). The model is slightly cooler (0.4°C) than the minimum proxy value, but the values are well within the uncertainties of the data. The precipitation is somewhat less (20 mm/yr) than the minimum proxy values, but given the slight bias to low temperatures, the net impact on effective water balance between the two biases is probably small.

A further consistency check on the model prediction can be made by utilizing water balance modeling of the glacial lakes Lahontan and Bonneville that achieved significant size during the LGM. Matsubara and Howard (2007) conducted a water balance lake modeling investigation of the conditions consistent with varying lake levels that was used in this study to evaluate model fidelity. The CAM simulations produce precipitation values slightly less than modern (246 mm/yr compared to 292 mm/yr = ~15 percent less), whereas temperatures are 6°C cooler than modern. In this parameter space of temperature versus precipitation explored by Matsubara and Howard (2007, their Figure 5) CCSM results occupy potential climate states that could reproduce the lake levels of Lake Lahontan or Bonneville at the LGM. Thus, although CCSM does not produce more precipitation than modern for LGM, it has significantly greater effective moisture and is consistent with the presence of large lakes in the Great Basin during LGM.

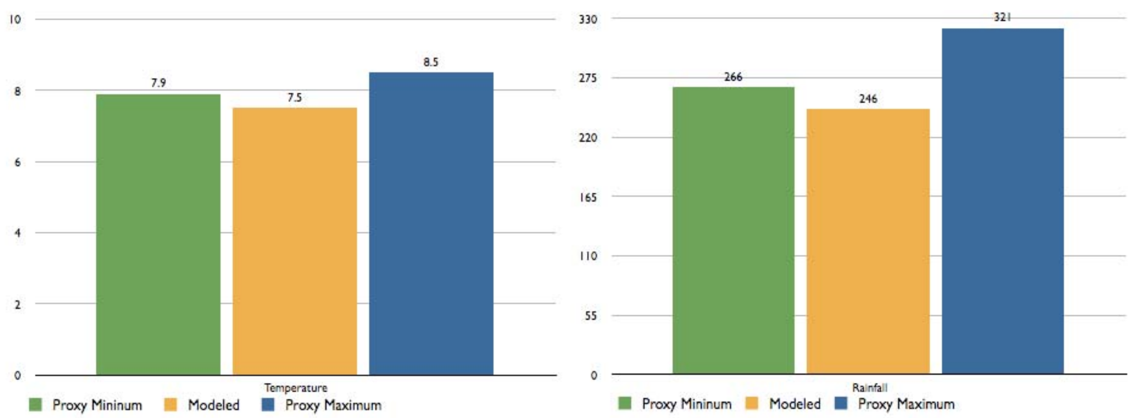

Figure 2-2
LGM Temperature and Precipitation Estimates in the Yucca Mountain Region (A, left) LGM Temperature (°C) proxies vs. model. (B, right) LGM precipitation (mm/yr) proxies vs. model.

The climate model data are consistent with the hypothesis that annual mean precipitation did not increase above modern at the LGM, but that the significant increases in effective moisture were largely caused by decreases in temperature. Both temperature and precipitation are in reasonable agreement with independent estimates for the LGM. If it is correct that glacial maximum pluvial conditions are primarily caused by cool temperatures and not by increased precipitation, this has major implications for the parameter range propagation as currently implemented in the projections of future infiltration that vary precipitation to very high values and then propose sampling of recharge percentages within that range (*e.g.* Mohanty *et al.*, 2004). The separate reconstruction of temperature and precipitation estimates followed by the propagation of parametric uncertainty separately is likely to introduce spuriously large ranges of potential parameter values. Given that CCSM produces climate results in line with direct paleo-climate proxies, it is suitable for the next stage of evaluation, which is the comparison of estimated infiltration with other simulations.

Previous simulations of infiltration at YM during the LGM have produced mean values that span from approximately 33 to 71 mm/yr (Wilson and Ho, 2002; CRWMS M&O, 2000/1998; summarized in Figure 2-1). The CCSM produces values of ~53 mm/yr during the peak LGM, which lasts for only several thousand years. Most of the existing mean model-derived infiltration estimates for glacial maximum conditions cluster around 35 mm/yr, but the several analogue climates that go into producing that mean value introduce a range of infiltrations from ~5 mm/yr to ~70 mm/yr. It is also noteworthy that, in these studies, there is an even wetter category, which corresponds generally to the conditions associated with MIS 6, typifying the upper bound glacial category, distinct from the glacial maximum category on which this study has focused.

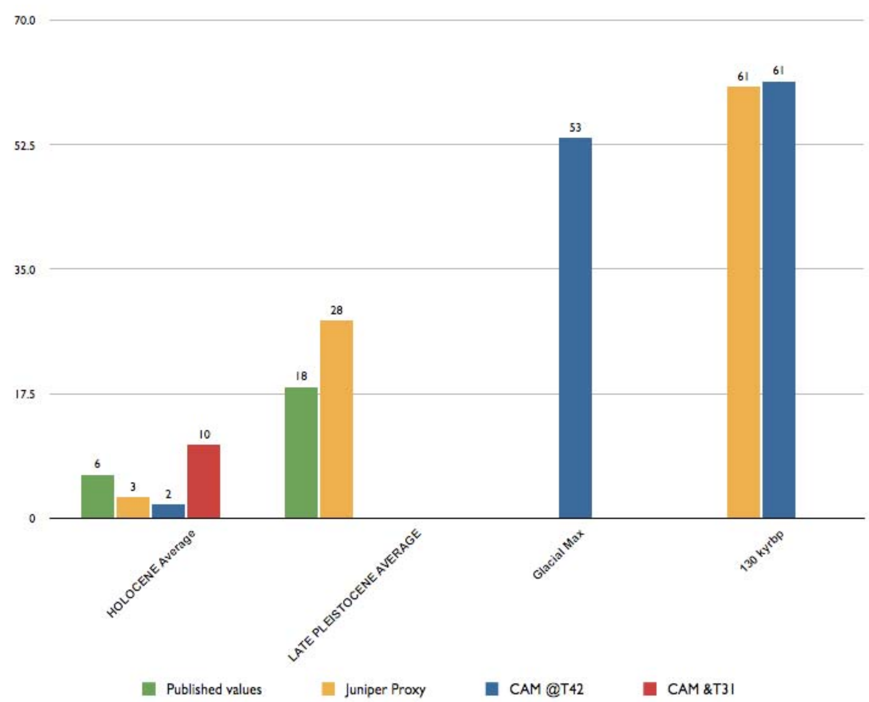

Figure 2-3
Published Infiltration/Recharge Estimates (mm/yr) vs. Results for the Yucca Mountain Region for this Study

There are direct data-derived infiltration estimates for comparison. As much of the water sampled in YM is 'old' —the age has been established to range to greater than 21,000 years—various attempts have been made at estimating the infiltration rate when the old water was emplaced (*e.g.* Flint *et al.*, 2002; Zhu *et al.*, 2003). Following the conventions of previous papers, this old water is referred to as late Pleistocene water, although those papers never defined exactly what age range ‘late Pleistocene’ encompassed. Based on the discussion of ages in Zhu *et al.* (2003) and Meijer and Kwicklis (2000, Table 9), EPRI assumed that late Pleistocene corresponds to the time period between 10 kyrbp to 25 kyrbp. Previous work has identified a range of late Pleistocene infiltration rates ranging from 7.8 to 40 mm/yr (Flint *et al.*, 2002; Zhu *et al.*, 2003), with a mean value of 18.4 mm/yr. If it is assumed that this mean value represents an average between low values, *e.g*., near 5 mm/yr at 10 kyrbp and peak values near 50 mm/yr at 21 kyrbp, then the previously estimated values are consistent with the high peak LGM value and low Recent values predicted by the CCSM.

Concentrating specifically on the maximum values at LGM, the climate model suggests values as high as ~53 mm/yr. As summarized in Flint *et al.* (2002), late Pleistocene infiltration values for Borehole SD-7 are reconstructed to be as high as 40 mm/yr, although the period of time under consideration remains poorly defined. Keeping this caveat in mind, the 53 mm/yr model estimate appears to be within 25 percent of some existing proxy records, although slightly higher. In the recent analysis prepared by Mohanty *et al.* (2004), the mean value of infiltration during their maximum glacial conditions was 37 mm/yr (but this value is assumed to hold for ~40 kyrs). This is discussed further below.

2.4 Proxy Records for Validating Model Results Over the Past 180 kyr

Remarkably few constraints on paleo-infiltration rates exist previous to 23 kyrbp. Summarizing what has been learned directly relevant to net infiltration into the YM region over the past 120 kyr, based on proxy records and chlorine mass balance (CMB)-constrained model results, Tyler *et al.* (1996) found that the major periods of groundwater and surface water discharge occurred during the glacial maxima at ~150-120 kyrbp and 35-15 kyrbp. The Tyler *et al.* study, in conjunction with some more recent studies (Scanlon *et al.*, 2003; Walvoord *et al.*, 2002a; 2002b) represents the most detailed depiction, with the most accurate chronology currently available, for conditions nearest to the proposed YM repository site (synthesizing results from Nevada Test Site and other nearby time series). These direct approaches to estimating past infiltration are not used directly in most published YM studies (although they are used as corroboration of the climatic conceptual models), because they likely only apply over deep alluvium, which is of limited utility in the YM setting.

Typical modeling approaches utilize either analogue-derived mean paleo-temperature and paleo-precipitation conditions for various past intervals to drive infiltration models (*i.e.*, the common approach used by DOE); or less commonly, an arbitrary percentage of precipitation is assumed to be converted to net infiltration. In the former approach, the proxies used are not direct, quantitative proxies for MAT or MAP such as are utilized for LGM, instead they are proxies for which a wide combination of possible climate states might exist for the same record and modern climate data from analogues localities are used. To EPRI’s knowledge, in no study has a proxy record of infiltration been used to drive YM flow models or performance analysis models. Furthermore, in no study has a model been used to self-consistently prognose temperature, precipitation, and infiltration through a long paleo-climate time interval.

The qualitative paleo-climatic and paleo-hydrological data that have been used to characterize the long-term behavior of the YM region have mostly come from Owens Lake records (Forester *et al.*, 1999; BSC, 2004; USGS 2001; Bradbury 1997; Li *et al.*, 2004). Other long records, for example from Death Valley (Yang *et al.*, 1999; Forester *et al.*, 1999; BSC, 2004), have also been used to corroborate or inform interpretations from the Owens Lake record. Most of the proxy records used in the existing YM site characterization have been based on the diatom and ostracode records from the Owens Lake cores (Bradbury 1997; Forester *et al.*, 1999; BSC 2004). In the most common approach, central to the entire DOE process of estimating past and future infiltration (BSC, 2004; SNL 2007), and also intimately related to the approach taken in other studies (Faybishenko, 2008; Stothoff and Walter, 2007), the ostracode record is used to define potential historical trajectories of annual mean precipitation and annual mean temperatures, even though ostracode assemblage data are not strong or specific proxies for either quantity. As Sharpe (2003a) and BSC (2004) put it, "Unlike common plant species (Thompson *et al.* 1999a; 1999c) however, the biogeographic distributions of lacustrine ostracodes are not mapped, so can not be quantified in climate terms." And so consequently,

> …the occurrence of various ostracode species does provide a paleo-geographic sense (polar, tropical, or temperate) of the nature of past climates. Actual climate parameters, however, do not have to be generated from the microfossil species profiles to reconstruct long-term climate, as long as the characteristics of, for example, a given glacial or interglacial climate can be properly evaluated relative to others. [Sharpe (2003a) and BSC 2004)]

In practice therefore, calibration tie-points are necessary to utilize this approach, and those tie points are modern climatic observations and the quantitative MAT and MAP proxy records (Thompson *et al.*, 1999) from middens at LGM and all inferences about climate are defined relative to LGM values. This ostracode-proxy approach has been used either explicitly or implicitly in most subsequent research to generate MAP and MAT historical scenarios with the exception of Stothoff and Walter (2007) who curiously chose to calibrate their model with the penultimate glacial (MIS 6) as their glacial end member even though there are no proxy records for MAP or MAT for that interval to base that calibration on. The ostracode-based approach has its strengths but EPRI believes it also has its weaknesses and it is informative to attempt a different approach.

Proxy records that reflect conditions within a lake are not ideal for understanding the hydrological conditions on the land surface. Lakes, especially large ones such as Owens Lake during pluvials, integrate over a range of temporal and spatial scales. This introduces several important factors that make interpretation of the records difficult. First, because of this integration effect (or inertia), the timing of events in a lake record may be expected to lag with respect to the net surface hydrological forcing that drives the change. Similarly, some rapid climate-driven shifts may be filtered out. In addition, changes may be due to non-local effects such as changes in stream flow into or out of the region, or 'fill-and-spill' thresholds between closed and overflowing lake levels. Consequently, these records do not directly reflect the local net surface hydrological balance changes that are expected to dominate infiltration.

To complicate matters, since these are not direct climate proxy records, analogies are made between the conditions that certain diatom or ostracode species live in today and the likely conditions in the past. This is necessarily subjective and depends on expert judgment because these species actually span wide ranges of temperature and precipitation conditions today and, therefore, determinations are necessarily subject to varying interpretations.

This approach also can give rise to questions of subjectivity and circularity. Because the actual environmental tolerances of these species is quite large, expert judgment has been used to limit the range of environmental parameters (temperature and precipitation) and modern climate analogue stations considered. But if the range of environmental parameters and modern climate analogue stations is picked by expert judgment, in what sense is the method objective? If independent proxy records are used to corroborate the reconstructions guided by expert judgment then objectivity can be restored. That is one benefit of utilizing the completely independent approach taken in this study.

For these reasons, records of land surface conditions (rather than lake conditions which have been used before) that are not affected by these processes may be more useful for understanding past infiltration. Furthermore, the avoidance as much as possible of the use of hand-picked modern analogues may reduce the subjectivity and circularity of the process of characterizing past infiltration. Nevertheless, the Owens Lake records provide a wealth of multi-proxy information that provides significant context to understanding the broader pattern of regional climatological and hydrological change..

The approach of this study is that some existing paleoclimatic records reflect terrestrial effective moisture and that effective moisture is more directly tied to infiltration than its separate temperature and precipitation components. Consequently, such records can be used directly as infiltration/recharge proxies if they can be calibrated. To this end, the Juniper pollen record from Owens Lake is used, because it appears to be a sensitive recorder of effective moisture changes that are generally in agreement with other proxies (Woolfenden, 2003). As Woolfenden (2003) describes, the Juniper record is highly correlated with existing ice volume records and orbital insolation values and thus the timing and magnitude and change it reflects is just as likely to represent past climatic evolution accurately as other methods which rely on those parameters (*e.g*. BSC (2004), SNL (2007), and Stothoff and Walter (2007)). It is also terrestrially derived and, therefore, more likely to reflect infiltration than proxies that are complicated by lake, stream, and spring hydrology. The Juniper record is next described in depth and then compared with other paleo-environmental records to provide a conceptual model for considering it a direct proxy for net infiltration.

2.4.1 Conceptual Model for Juniper Paleo-infiltration Proxy and Paleo-climate Context over 180 kyr

The pattern of environmental change in the Owens Lake core is that of warm, drier intervals dominated by xeric, scrub vegetation alternating with cool, temperate, open woodlands. The percentage of juniper is a straightforward indicator of the varied pattern of changes across many taxa that encapsulates the main sense of the changes, *i.e.,* between warm-dry and cool-wet conditions. Notably, even most of the warm-dry conditions were still wetter than today and they were associated with enough mean annual precipitation (probably largely falling in winter months) to allow for juniper growth. Junipers have a wide tolerance for precipitation variation (between approximately 250 and 400 mm/yr). Thus, even the long intervals with dry conditions were characterized by rain rates at the high end of modern values in the region, but conditions were still generally arid to semi-arid.

Local terrestrial paleo-environmental conditions near Owens Lake are reflected in the juniper pollen record Woolfenden (2003) and correlate well with the Martinson *et al.* (1987) 'stacked' oxygen isotope chronostratigraphy (*i.e.,* SPECMAP). The strong correlation between the juniper pollen percentage record and global oxygen isotope record is important because it indicates that the apparent environmental changes reflected in juniper pollen percentage may actually reflect synchronous global, or at least hemispheric, trends. For example, the Woolfenden (2003) record corresponds well with the landmark Shackleton *et al.* (2003) paper that provided the first clear linkage between marine isotope records and terrestrial records of climatic change through the Last Interglacial. These records were the first, and still are probably the best, to allow the chronology of major events in the marine and terrestrial realm to be established. The Shackleton *et al*. (2003) record clearly reveals a substantial lead (~6 kyr) of the benthic $\delta^{18}O$—probably reflecting Arctic ice volume—compared to sea surface temperature (SST) proxies. On the other hand, the terrestrial records are in phase with the local SST changes. In other words, the major Northern Hemisphere ice sheets melted significantly before the rest of the world warmed, and it is also clear that this warmth continued after ice sheets began to re-accumulate. Intriguingly, the pollen records in Shackleton *et al.* (2003) reflect very similar variations as the juniper pollen records of Woolfenden (2003)—what is key is that the synchroneity is indicative of the fact that these various records are reflecting global hydrological cycle variability coupled to SST changes that are driven by, but may not be directly in phase with, orbital forcing or ice sheet volume.

Furthermore, a qualitative interpretation of the juniper pollen percentage record compares well with trends in the low resolution Bradley (1997) record of saline diatoms, $CaCO_3$, and smectite from Owens Lake core over the past 200 kyr (their Figure 6). The percentage saline diatoms record shows a clear peak in the Recent (~6-10 kyrbp), a broad peak from ~130-50 kyrbp, and indications of saline conditions before 180 kyrbp. Fresher conditions dominated from ~15 to 50 kyrbp, 95-110 kyrbp, and 130-170 kyrbp. The juniper record of Woolfenden (2003) also shows that the time period from 180 kyrbp to 130 kyrbp was a wet interval, apparently approximately as wet as the LGM (near 20 kyrbp), although there appears to be an approximately 10 kyr drying interval centered at ~170 kyrbp. This brief drying period is also apparent in the diatom record.

The juniper record reveals that drying in earnest began at ~130 kyrbp—the beginning of Marine Isotope Stage 5e (MIS 5e)—and effective moisture values stayed near the values characteristic of early Holocene values for much of the next 50 kyr. Again the slight lag between terrestrial changes in the YM region and the isotope record is noted. This again compares well with the diatom record which shows a broad peak in saline conditions between 130 kyrbp and 50 kyrbp that lies within MIS 5 and includes the Last Interglacial (LIG) that began at ~130 kyrb and extended to ~110 kyrbp as well as the frequently occurring interstadials noted for this stage. The dating on this core was not as high resolution as, for example, that of the Devil's Hole chronology, so the age control is not sufficient to be precise. Substantial variability exists in these records that becomes apparent at higher resolution (See Figure 7 of Li *et al*, (2004)), but the overall conclusion is the same—periods of warming correspond well with periods of decreasing lake levels—indicating that interglacials and interstadials correspond, generally, with intervals with drier effective moisture conditions.

Beginning around 80 kyrbp and extending to ~30 kyrbp, juniper pollen values are in an intermediate range indicating conditions wetter than early Holocene values but not as wet as glacial maximum conditions. Whereas there is a gradual trend in the benthic $\delta^{18}O$ record through this interval reflecting the gradual growth of polar ice, the transition in pollen percentage is much sharper. At ~25 kyrbp, juniper pollen percentage dramatically increases indicating a return to conditions of extreme effective moisture. This period is brief—less than 10 kyr—and by the beginning of the Holocene, the record indicates strong drying. Beyond the length of the record, conditions continued to dry as described above.

In this study, EPRI argues that the juniper pollen record is an excellent indicator of the net surface hydrological state of the land surface and a sensitive indicator of factors that affect infiltration. Juniper lives in an annual mean precipitation range of 250-400 mm/yr, which spans the likely range of precipitation values from slightly wetter than modern to full glacial conditions. It is conjectured here that between these precipitation limits of the percentage of juniper pollen scales linearly with infiltration from the base of the soil layer. As described further below this assumption is likely to be true over a large range of environmental conditions. Furthermore, linearity between proxy records and forcing is implicitly or explicitly utilized in prior YM region estimate of paleoenvironmental conditions and is a useful starting point.

EPRI's conceptual model is based on the observation that within the wide range of precipitation values at which juniper thrives,, the main factor that juniper pollen percentage reflects is temperature, either directly through a biophysiological parameter such as "growing degree days" (GDD), or through the control of temperature on evaporation. Given that the indices of effective moisture are strongly correlated with GDD and the cold month mean temperature (MTCO) for this vegetation type in the YM region, the assumption of a tight correlation in the past is reasonable (*cf*. Figure 6 of Thompson and Anderson, 2000). This covariance indicates that there is a very strong linkage between cooler temperatures and higher effective moisture conditions, *i.e.,* the same nearly saturated conditions at the base of the rooting-zone that lead to infiltration and recharge.

This assumption of a linkage between juniper pollen percentage, temperature and infiltration needs to be considered in context with the fact that changes in vegetation may also play a key role in mediating infiltration. Studies have advanced the interesting concept that vegetation dynamics modulated the purely climate driven nature of past transitions (Walvoord *et al.*, 2002a, 2002b; Wolfsberg and Stauffer, 2003). These studies are based on the observation that the current hydrological and geochemical features, such as dissolved Cl in Southwestern alluvial basins with thick vadose zones, are not in equilibrium with modern climatological/infiltration conditions. Instead, they reflect past pluvial conditions. Within these deep, thick alluvial layers, it has been proposed in these studies that it is vegetation type that plays a fundamental role in mediating soil moisture transitions from pluvial to interpluvial conditions. This is because xeric, desert shrub vegetation is extremely efficient at pulling water out of the ground by generating extremely low water potentials in the rooting zone. On the other hand, mesic woodlands are less resistant to water loss, and their deep rooting structures provide conduits for subsurface flow. So, as the large-scale climate transitions from high surface effective moisture to low effective moisture conditions, vegetation type provides a strong positive feedback on soil moisture.

As this rapid transition occurs, the extremely low water potentials generated by xeric vegetation prevents downward infiltration past the root zone and creates pressure gradients that effectively draw water and vapor upward for large distances below the rooting zone. At some distance below a region of weakly upward flow, water that has entered the deep alluvium during the last (or previous) pluvial period continues to flow downward. In this way, deep recharge may be positive even in regions where the infiltration at the base of the rooting zone is upward. Model results driven by multiple data constraints indicate that the transition from pluvial conditions with net recharge and this interpluvial dry state with upward water fluxes in the upper alluvium occurred 9.5-6.5 kyrbp (with some indication that the early result is more likely, Kwicklis *et al.*, 2006). These findings support the approach in this study—it is consistent with the interpretation of juniper pollen percentage as being directly related to infiltration. It also suggests the importance of including fully dynamic vegetation models in attempts to simulate these changes and transitions.

It is important to note, however, that net discharge is only likely to be seen in deep alluvial deposits. In regions where the primary mode of infiltration is through a thin veneer of alluvium into bedrock, upward water flxues driven by plants are unlikely. Heilweil *et al.* (2006) recently demonstrated that in the sandstone bedrock of Sand Hollow, the extremely low matric potential found by Walvoord *et al.* (2002a; 2002b) and Scanlon *et al.* (2003) did not occur, and the vegetation was relatively unimportant in maintaining upward fluxes, and a substantial downward infiltration occurred through the bedrock. Flint *et al.* (2002), also summarize data showing a ten fold variation in apparent infiltration (from ~0.1 mm/yr to ~1 mm/yr) between sites with thin alluvium and those with little cover (Flint *et al.*, Table 1). Thus, the phenomenon of upward infiltration (discharge) due to water scavenging by xeric plants may only be important to prognosing recharge in some regions. Current estimates are that less than 30 percent of the recharge entering the YM repository footprint is sourced from thick alluvial surface deposits. It is for this reason that the paleo-infiltration estimates of Tyler *et al.* (1996) are not discussed quantitatively in detail here. Subsequent work by others (e.g. Scanlon *et al.*, 2003, 2005; Heilweil *et al.*, 2006) also is not discussed in detail because the actual values (rather than trends) do not apply materially to the recharge of the region of interest. On the other hand, such time series can still be of use in ascertaining the qualitative pattern of change through time and space and have been used as context for this purpose. It also provides clear evidence for biological-physical feedbacks and their importance for understanding net infiltration.

This is clear, for example, from the work of Sandvig and Phillips (2006) who analyzed a transect across an ecotone in New Mexico and compared key hydrological and geochemical data across ecological and climatic gradients while attempting to sample over as little alluvial variation as possible. A key finding in Sandvig and Phillips (2006) was that the soil matric potential measured under flora found in arid climates (grasses, creosotes) is much higher than under flora with an affinity for moister conditions (juniper, ponderosa pine). Furthermore, juniper, in particular, created deep conduits for flow via their rooting behavior. These features combined to create conditions with much greater moisture at depth in the soils and a net downward flow under junipers and ponderosa pine, and a much reduced chloride load as compared to the xeric floras (*cf.,* Figure 12 of Sandvig and Phillips (2006)). In their study, Sandvig and Phillips calculated infiltration rates and accumulation durations and infiltration were found to vary from 2.26 mm/yr and accumulation time of 2 kyr in the wettest flora (ponderosa pine) to upward flow (discharge) with an accumulation time of 22 kyr in the driest flora.. Juniper in this case was associated with an infiltration rate of 0.439 mm/yr and an accumulation time of ~5 kyr. These values are for New Mexico and within alluvium and are not direct analogues for the YM site, but they do demonstrate the physical and biological mechanisms by which flora characteristics might directly correlate with infiltration. Sandvig and Phillips (2006) provided an excellent basis for a simple parameterization of infiltration as a function of vegetation type by noting (their Figure 14) the simple dependence of the chlorine accumulation time (which may be thought of as being directly related to infiltration rate) on aridity index as mediated by vegetation type.

Junipers thrive within the range of hypothesized higher-than-modern precipitation values for these time intervals and this simplifies the interpretation of the record. When conditions get as dry as modern conditions, juniper pollen percentage decreases to near zero, providing a solid tie point for calibration. At precipitation much greater than 400 mm/yr, it is expected that juniper will be out-competed, which provides a solid upper range for validity of the proxy. Based on existing paleo-precipitation estimates it is unlikely that precipitation was much above 400 mm/yr in this region (BSC, 2004).. Within this range it is expected that most of the proxy variation is due to temperature variations through their affect on effective moisture and water stress on juniper. This decomposition is not necessary, however, if juniper pollen percentage is interpreted as a direct proxy of effective moisture within its precipitation toleration thresholds.

We note that the EPRI approach does not rely on deep alluvium assumptions to estimate paleo-infiltration at Yucca Mountain itself. Only the relative variation in infiltration, which reflects large scale patterns of net evaporation minus precipitation, is used important for this estimation. The juniper proxy record is used here to calculate the relative changes in infiltration in past climates. The absolute values are assigned by calibrating the proxy time series against climate model results for modern and Last Glacial Maximum, after verifying that the climate model results and proxy time series are in qualitative agreement. The resulting calibrated juniper based proxy is then compared with the climate model results for time intervals outside of the calibration time series.

This approach assumes a linear scaling between juniper pollen percentage and infiltration. There are several reasons to make this assumption. The ecophysiological study described above demonstrates a solid basis for a positive correlation of juniper pollen percentage with infiltration. In the activities addressed in this section, these lines of evidence are utilized to suggest that the same climatic features that shape infiltration also govern vegetation distributions (and that the interaction may even be two-way) and—assuming other factors are locally constant—that variations in the success of a suitable flora with time is proportional to the variations in expected infiltration. The results of Sandvig and Phillips (2006, their figure 14) provides some evidence that this relationship might be linear, but it is not clear if it provides a guarantee that the percentage of any given flora is linearly correlated with infiltration variations. The results of Thompson and Anderson (2000) suggest this may be the case, but the results are not definitive. Here a linear dependence is assumed to make predictions about periods of time for which there are model simulations. Consistency with climate model simulations is used as a check on the viability of the linear assumption (see below). EPRI's approach is very similar to existing approaches that use modern and LGM as calibration tie-points and utilize a linear relationship between a variable such as ice volume or insolation at a given latitude to estimate climate in the YM region (Sharpe, 2003a,b; BSC, 2004; Stothoff and Walter, 2007).

Verification of this new proxy record comes from three avenues. First, the reconstructed history of infiltration is compared with existing qualitative- or analogue-based methods to verify that there are no substantial differences. If major differences are found, a careful analysis of the specific causes would be necessary because there is little a priori reason to value one paleo-estimate over another. Second, some quantitative modeling utilizing analogue-derived precipitation and temperature parameters to drive infiltration models can be used to decide whether there are major differences at the qualitative level. Again, it is noted that there is no obvious reason to consider any of these models more or less valid than our attempt at a model-calibrated proxy reconstruction, but differences might highlight flaws in either set of analyses or their underlying conceptual model. Third, a consistency check of the proxy results from the coupled climate model studies to prognose infiltration and climate directly from first principles and within a self-consistent framework can be performed. This must, of course, be performed for periods of time outside of the calibration period. In this study, such a check is performed by focusing on predictions for the 130 kyrpb with a lesser focus on predictions for the Holocene.

2.4.2 Methodology: A Calibrated Continuous Proxy for Infiltration

A calibration is necessary to make juniper pollen percentage into a quantitative proxy for infiltration. The approach in this study is to assume a linear relationship and to scale the relationship so that at 0 percent juniper pollen, infiltration equals its base value for the Recent period. The next tie point is the LGM, which all proxy records and prior work demonstrate was a local maximum in infiltration within the last full glacial cycle. The infiltration/recharge value (52.5 mm/yr) produced by a climate model experiment conducted for the LGM conditions by the NCAR CCSM Paleo-climate working group is selected for this tie point. Alternatively, the Flint *et al*., (2002) or Mohanty *et al.,* (2004) net infiltration estimates of 40 mm/yr or 37 mm/yr, respectively, could be used without substantially changing EPRI's conclusions, although it would reduce all of the paleo-infiltration estimates, making the current EPRI approach conservative.

To create a calibrated time series, first a smooth spline curve is fit to interpolate the juniper pollen percentage data of Woolfenden (2003) into 1 kyr segments. After demonstrating that the juniper paleo-infiltration proxy and the simulation agree qualitatively at LGM (both indicate very wet conditions compared to Recent), the model-predicted value ((52.5 mm/yr) for the LGM is used to calibrate the linear relationship between juniper pollen percentage and infiltration by setting the value of infiltration in the proxy series at 52.5 mm/yr at 21 kyrbp. Model results can then be compared within this proxy record (Figure 2-4) at the key intervals for which there are model results (excluding the LGM so as to avoid circularity) to check for consistency (Figure 2-5).

A summary comparison of paleo-infiltration estimates based on the calibrated juniper pollen percentage proxy as compared to estimates using current documentation and guidance available from other sources is shown in Figures 2-3 and 2-5. Because EPRI's approach uses a high resolution continuous proxy record for the past, as opposed to idealized snapshots as in the other studies, some translation is necessary between the two.

In this study, a Holocene Mean infiltration value is defined that for the juniper-based time series, refers to an average over the last 10 kyrs. EPRI's juniper pollen percentage proxy estimate yields approximately 3 mm/yr averaged over the past 10 kyr. This infiltration value is approximately the same as that which other studies include, although some are snapshots of modern values or integrals over thousands of years. The infiltration values are very close to the mean (5 mm/yr) of these prior estimates using independent methods (~3 mm/yr as compared to ~5 mm/yr). However, in this study that prediction is not truly independent of the model estimates, given that the calibration presumes that the proxy value equals that of the modern model value near 0 kyr and assumes a smooth approach to that value in the Holocene from peak LGM values.

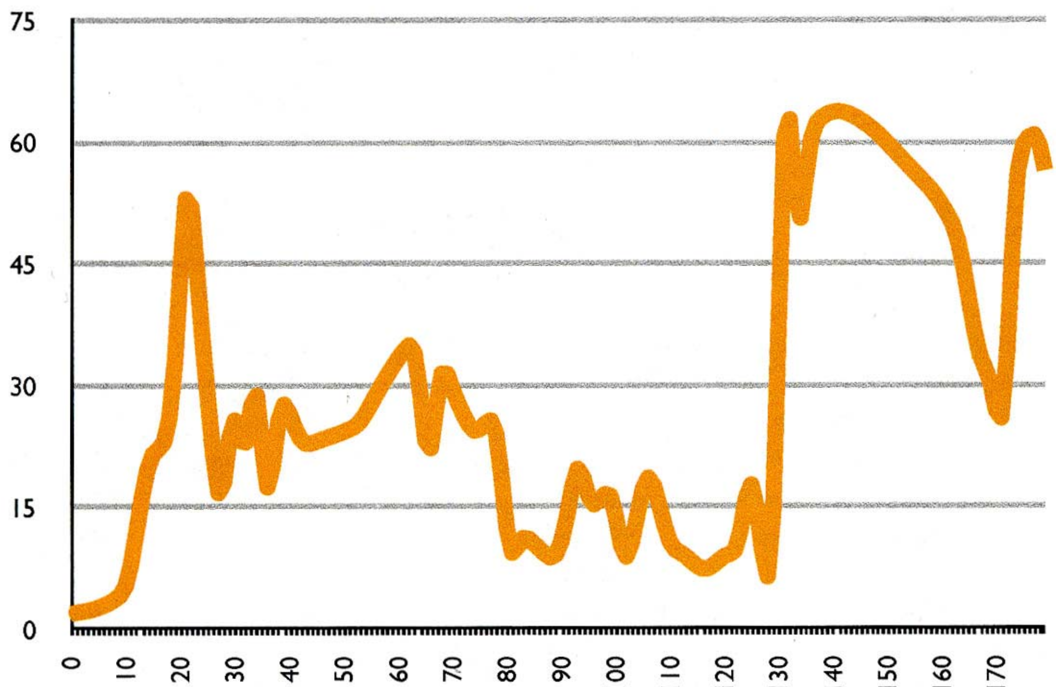

Figure 2-4
A Juniper % Proxy-based Infiltration (mm/yr) Record versus kyrbp Based on the Record of Woolfenden (2003)

The existing estimates of late Pleistocene infiltration can be used for a meaningful consistency check (Figure 2-3). If we define late Pleistocene average as being the mean of the juniper time series paleo-infiltration (Figure 2-4) from 10 to 25 kyrbp then EPRI's estimate is at the high end of the published range, 28 mm/yr, but part of this is due to the ambiguity of the actual age range being considered. If late Pleistocene water is defined as including only the interval from 10 kyrbp to 20 kyrbp, which is consistent with the corrected ages in Meijer and Kwicklis (2000, Table 9, 4th column), then the corresponding juniper-proxy estimate is only 20.8 mm/yr, *i.e.,* nearly identical to the mean of published values (~18 mm/yr) summarized in Figure 2-3).1). Infiltration rates were likely changing rapidly during the transition into and out of the LGM around 21 kyrbp and any estimate is likely to be sensitive to underlying assumptions about timing. The agreement between EPRI's proxy reconstruction and existing data is considered to be good for the late Pleistocene, which encompasses the LGM. It is noted that the maximum value during this interval is reached at ~21 kyrbp in the juniper-based record, and this maximum is very sharp and abrupt. Values were higher than Recent long before the LGM, but the LGM peak itself is short lived.

Predictions for infiltration for "Glacial Mean" conditions (which is a category with a standing in the current YM process) can be meaningfully compared (Figure 2-5). "Glacial Mean" is defined here as referring to the mean value of the past Glacial interval, which spans from approximately 10 kyrbp to 80 kyrbp (until the beginning of MIS 5) in the juniper proxy record. In the BSC (2004) prescription, "Glacial Mean" refers to approximately the same length of time, but is fixed at an infiltration of approximately 37 mm/yr on average as compared to our record that indicates lower mean values (26 mm/yr, the average value of Figure 2-4 from 10kyrbp to 80kyrbp). The main difference between these two estimates is that the BSC (2004) methodology combines the Predictions for infiltration for "Glacial Mean" conditions (which is a category with a standing in

the current YM process) can be meaningfully compared (Figure 2-5). “Glacial Mean” is defined here as referring to the mean value of the past Glacial interval, which spans from approximately 10 kyrbp to 80 kyrbp (until the beginning of MIS 5) in the juniper proxy record. In the BSC (2004) prescription, “Glacial Mean” refers to approximately the same length of time, but is fixed at an infiltration of approximately 37 mm/yr on average as compared to our record that indicates lower mean values (26 mm/yr, the average value of Figure 2-4 from 10kyrbp to 80kyrbp). The main difference between these two estimates is that the BSC (2004) methodology combines the sharp peak at the LGM (here referred to as previous glacial mean) with the long increase in infiltration associated with the overall cool conditions of the glacial period.

Taking the entire 180 kyr record, a mean infiltration of 29 mm/yr (as compared to the long-term mean of ~22 mm/yr combined from BSC (2004) analyses (Figure 2-5) is constructed. The mean of the whole record is not actually the proper value for the sake of comparison because the proxy time series is short and includes the strong glacial period at its beginning that skews the values. Instead, our best estimate is made over one full glacial cycle, from the end of the penultimate glacial to today. This produces a mean value of 19 mm/yr, which is extremely close to the mean value of the other methodologies (Figure 2-5).

A review of the probabilities of these various states is informative. The probability density function of proxy-based infiltration estimates for the past 130 kyr (one full climate cycle) shows that high infiltration values are very rare, but that values at the high end of Recent values are common (Figure 2-6).

2.4.3 Model Data Comparison for 130 kyr and Characterization of the LIG

The LIG was a time transgressive event and the strong interpluvial (dry event) associated with it in the Southwest began at 129 kyrbp in the juniper time series. The transition from the penultimate glaciation to the LIG occurred over an approximately 2 kyr period at 131-130 kyrbp in that record. This was the period simulated by the NCAR Paleoclimate Working group and that simulation is used in this analysis. Consequently, the simulation captured the end of the penultimate glaciation, which was a strong pluvial. (MIS 6, Stothoff and Walter, 2007; Sharpe, 2003a,b; Sharpe, 2007) As noted earlier, the proxy record and model produce identical values at 130-131 kyrbp. This is a validation of the approach of assuming a linear relationship between juniper percentage and infiltration. Beginning at 129 kyrbp, the proxy record shows a prolonged dry period. The infiltration during the LIG period as a whole (approximately MIS 5 here) is estimated to be 12 mm/yr. Although higher than this study’s modern value (Figure 2-5), it still within the range of modern and recent values reconstructed using other techniques. The spread of values during the LIG is somewhat smaller than the modern spread (Figure 2-7). There is less evidence of very dry conditions and no evidence for much wetter conditions at the level of resolution that the record provides. Thus, while this study’s present interglacial may be slightly drier than past interglacials, the differences are relatively small, and it is clear that at least the ~50 kyr of the LIG was characterized by infiltration values within the upper range predicted by many published studies for the last 10 kyr (Figure 2-7).

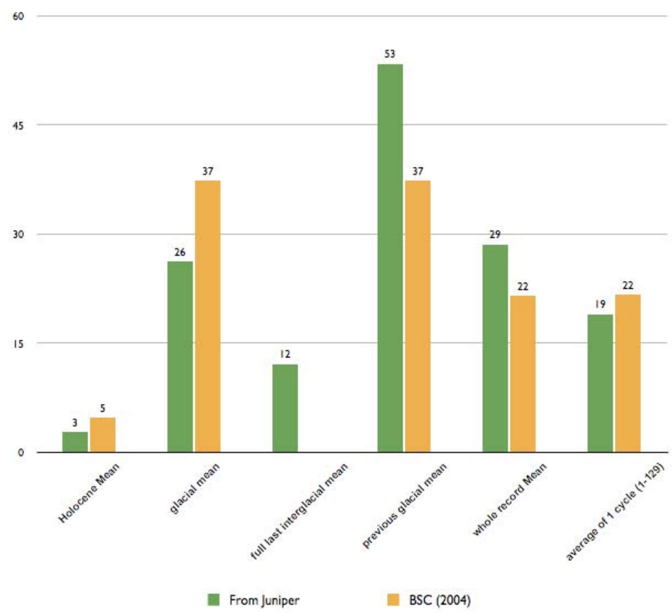

Figure 2-5
Comparison of This Study's Proxy Infiltration Mean Estimates ("From Juniper") to BSC (2004) Estimates (mm/yr)

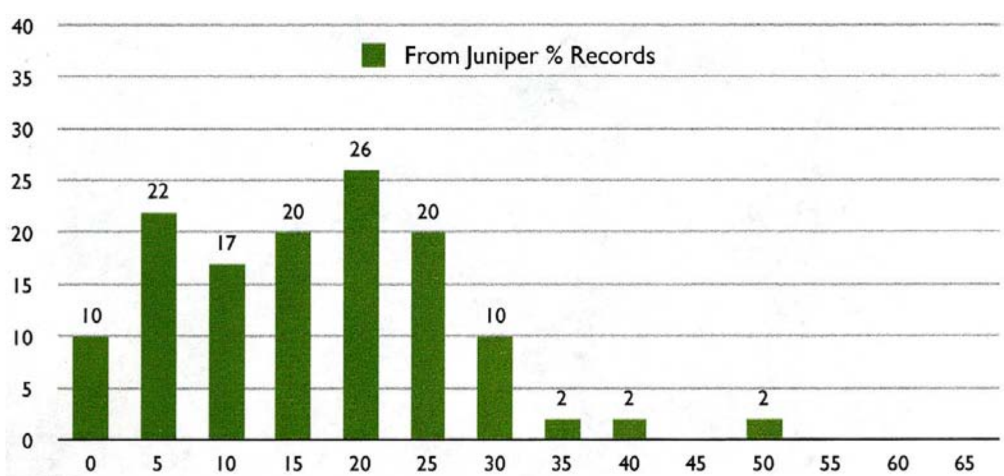

Figure 2-6
Histogram (probability density function) of Calculated Infiltration (mm/yr, x-axis) from Calibrated Proxy Records Over the Past 130 kyr. The bar heights represent the number of kyrs the specified infiltration rate occurred over the 130 kyr period.

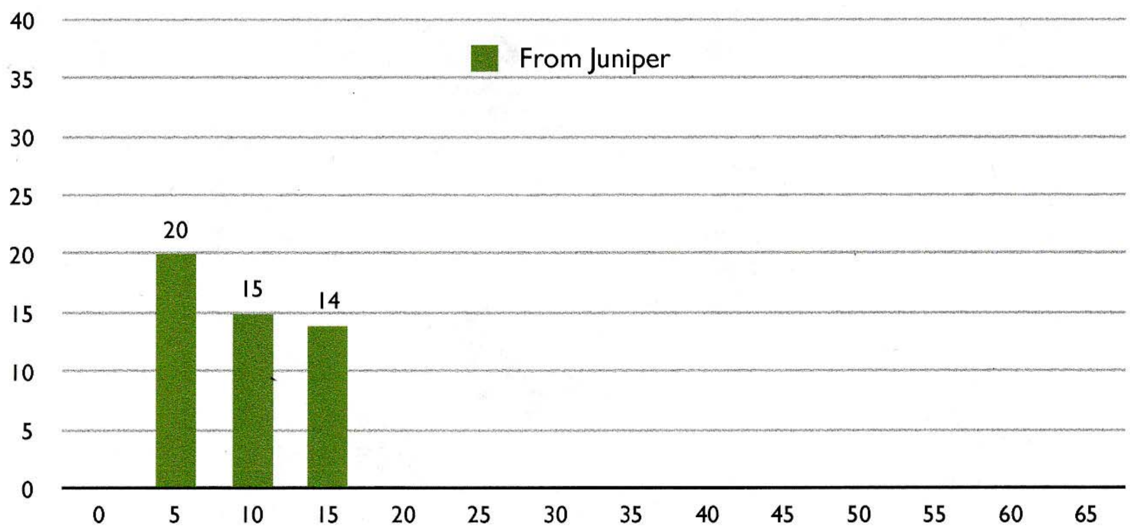

Figure 2-7
Histogram of Infiltration (mm/yr, x-axis) Proxies for MIS 5 (full interglacial, 80 kyrbp -130 kyrbp). The bar heights represent the number of kyrs the specified infiltration rate occurred over the 50 kyr period based on the juniper proxy in this study.

The implications of the different scenarios arising from these results and existing DOE (BSC 2004; SNL 2007) scenarios are summarized in Figure 2-8. If it is assumed that the next glacial cycle behaves as the past one (this is a conservative assumption given the likelihood that the current interglacial will be much longer and drier than past ones, as described below) the results of this study can be compared with current projections for the repository footprint. Dividing the results into quartiles is a standard way of providing robust quantifications of differences between two distributions. It diminishes the effects of small uncertainties and details of definition (*e.g.*, the assumed size of the repository footprint) and highlights the key differences in the distributions.

Clearly, the characterization based on the juniper proxy record for the last full climate cycle suggests a much greater percentage of time (37 percent compared to 17 percent) will be spent in the driest quartile. The 15-30 mm/yr infiltration quartile makes up 14 percent less of the total in the proxy record compared with the BSC (2004) prediction and a similar difference exists at the next wettest quartile. At the wettest end, the juniper pollen percentage-based record shows a very brief episode of high infiltration associated with glacial maximum conditions that is not reflected in current DOE predictions. So while the two different methodologies may have produced similar mean values in the long-term, the probabilities of key exceedences are different. The juniper proxy approach suggests that the highest infiltration events were very rare.

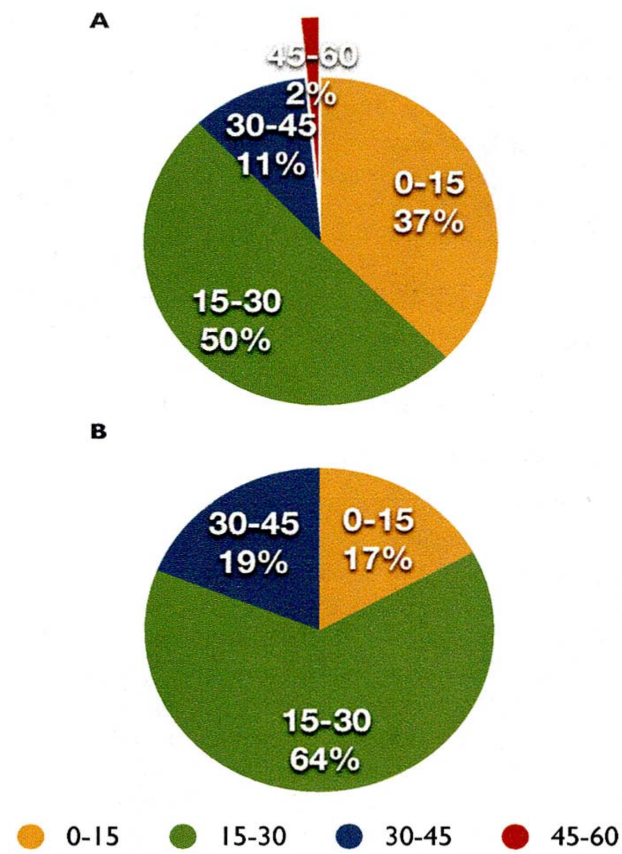

Figure 2-8
(A) Infiltration (mm/yr) Quartiles from the Juniper Pollen Percentage Method. (B) Infiltration Quartiles from DOE (BSC, 2004)

2.5 Future Scenarios

Having demonstrated the capability of the current generation of Earth System models to reproduce climate and infiltration for modern and paleo-climate conditions well within the acknowledged uncertainties of existing current observed and past inferred conditions, it is interesting to ask what predictions the models have for the future.

2.5.1 Simulation Methodology

A large suite of fully coupled CCSM simulations were carried out at NCAR as part of the U.S. contribution to the IPCC Fourth Assessment Report (FAR, 2007) on climate change. The simulations were carried out at T31, T42, and T85 resolutions and using a variety of boundary condition changes as forcing functions. The simulations are all described in the IPCC Fourth Assessment Report (IPCC, 2007) and in the papers found in AMS (2006). Two future climate change scenarios were selected for use in these simulations. The first assumes an approach to a steady-state concentration of atmospheric pCO_2 of 560 ppm (2x preindustrial), and the second assumes a steady-state concentration of pCO_2 of 1,120 ppm (4x preindustrial). The pCO_2 = 560 ppm cases were integrated with increasing pCO_2 until the pCO_2 reached its equilibrium value and then the simulations were continued for several hundred more years to allow climate to reach a quasi-equilibrium state for those boundary conditions. The pCO_2 = 1,120 ppm cases were branched off from the pCO_2 = 560 ppm simulations and run further with increased pCO_2 until 1,120 ppm was reached. At this point, the boundary conditions were fixed and the model integrated for several hundred more years to a quasi-equilibrium state. This is a stylized approach not intended to reproduce the exact trajectories of future CO_2 and climate because these are essentially unknowable, but to capture the essence of the likely rates of increase and their potential final values.

Neither set of simulations achieved true climatic equilibrium, but comparison with ‘slab’ ocean and long coupled integrations indicates that they are not very far from their final climatic state (Danabasoglu and Gent, 2009). The simulations can readily be considered to capture the essential changes of the next 1,000 years or so, and given the long residence time of atmospheric pCO_2 (Archer, 2005), the simulations should give a good indication of conditions beyond that for at least several thousand years. At some point, orbital variations may alter the moisture balance in the Southwest, establishing a potential limit for further projecting these results into the future (*cf*, Stothoff and Walter, 2007). An additional consideration is that the version of the CCSM used in the IPCC simulations did not have the same version of the land model that was used in the paleo-validation in this study. This affects the magnitude of infiltration in the modern case (the ‘control’ in this part of the study), but it should not affect the magnitude or direction of the changes with respect to this value. This is because the major changes are due to alterations in the large-scale patterns of evaporation and precipitation and these are robust to minor changes in land surface parameterization. For this reason, the infiltration projections relative to the modern control simulations are discussed in the following section.

2.5.2 Future Climate/Infiltration Modeling Results

The general pattern of predicted climate change using one case (the pCO_2 = 1,120 ppm T42 case) is discussed here as a general example. This simulation captures the future climate state approximately 1,000 years from now if the above-1950s anthropogenic greenhouse gas emissions continue for the next hundred years. Warming at high latitudes is substantial, >8°C (Figure 2-9), whereas the tropics warm by only 2-3°C. None of these simulations include positive feedbacks from large ice sheets melting or subsequent sea level rises. Since the anticipated drying increases with warming (Held and Soden, 2006), such positive feedbacks are likely to render our estimates conservative.

An emergent property of the climate system that has been discovered is that this warming appears to lead to an enhancement of the meridional hydrological cycle. In other words, it appears to be a robust, multi-model signal that global warming causes an increase in net evaporation in the subtropical regions and a net increase in precipitation in the mid-latitude and subpolar regions (Held and Soden, 2006). This pattern is borne out in the NCAR CCSM3 simulations at all resolutions, as indicated by comparing seasonal changes in precipitation (Figure 2-10). The simulations show a clear regional scale decrease in precipitation in both seasons due to global warming. Evaluation of evaporation-precipitation produces similar results.

This drying expresses itself in drainage/infiltration in the land surface model as shown in Figure 2-11 in simulations of pCO_2 = 560 ppm and pCO_2 = 1,120 ppm at T42 and pCO_2 = 1,120 ppm at T85 resolution. For each fixed resolution, infiltration decreases as global warming increases. Expressed as a fraction of the T42 case with dynamic vegetation described in previous sections, the decrease is 30% at pCO_2 = 560 ppm and 50% at pCO_2 = 1,120 ppm. At T85 resolution, the simulation shows somewhat more structure. There is some onshore flow producing a small monsoonal signal, but that impacts conditions to the south and east of YM, where drying occurs (~20% decrease). *It is reasonable to use these results to conjecture that the quasi-thousand year impact of global warming will be to diminish infiltration in the YM region by 20-50 percent.* There is certainly no evidence for global warming driving major increases in effective moisture and infiltration as has sometimes been claimed Musgrove and Schrag (2006) by analogies to past climate. On the contrary, the current consensus on future large scale hydrological change is clear and the few paleoclimate studies of past, massive global warmings that might apply as analogues (Pagani *et al.*, 2006; Bowen and Bowen, 2008) also tend to support this consensus view that global warming is associated with an enhancement of dry conditions in the dry regions.

This pattern of change, while only the result of one model (NCAR's CCSM) is representative of the consensus estimate from the full range of IPCC models as shown in Figure 2-12 from the IPCC Report, Chapter 10 (http://www.ipcc.ch/graphics/graphics/ar4-wg1/jpg/fig-10-12.jpg). The clear pattern from the full range of IPCC models is an increase in net evaporation in the arid regions which shows itself most clearly in a decrease in soil moisture in the North American Southwest in the vast majority of IPCC model simulations (as indicated by the stippling in Figure 2-12 (b)).

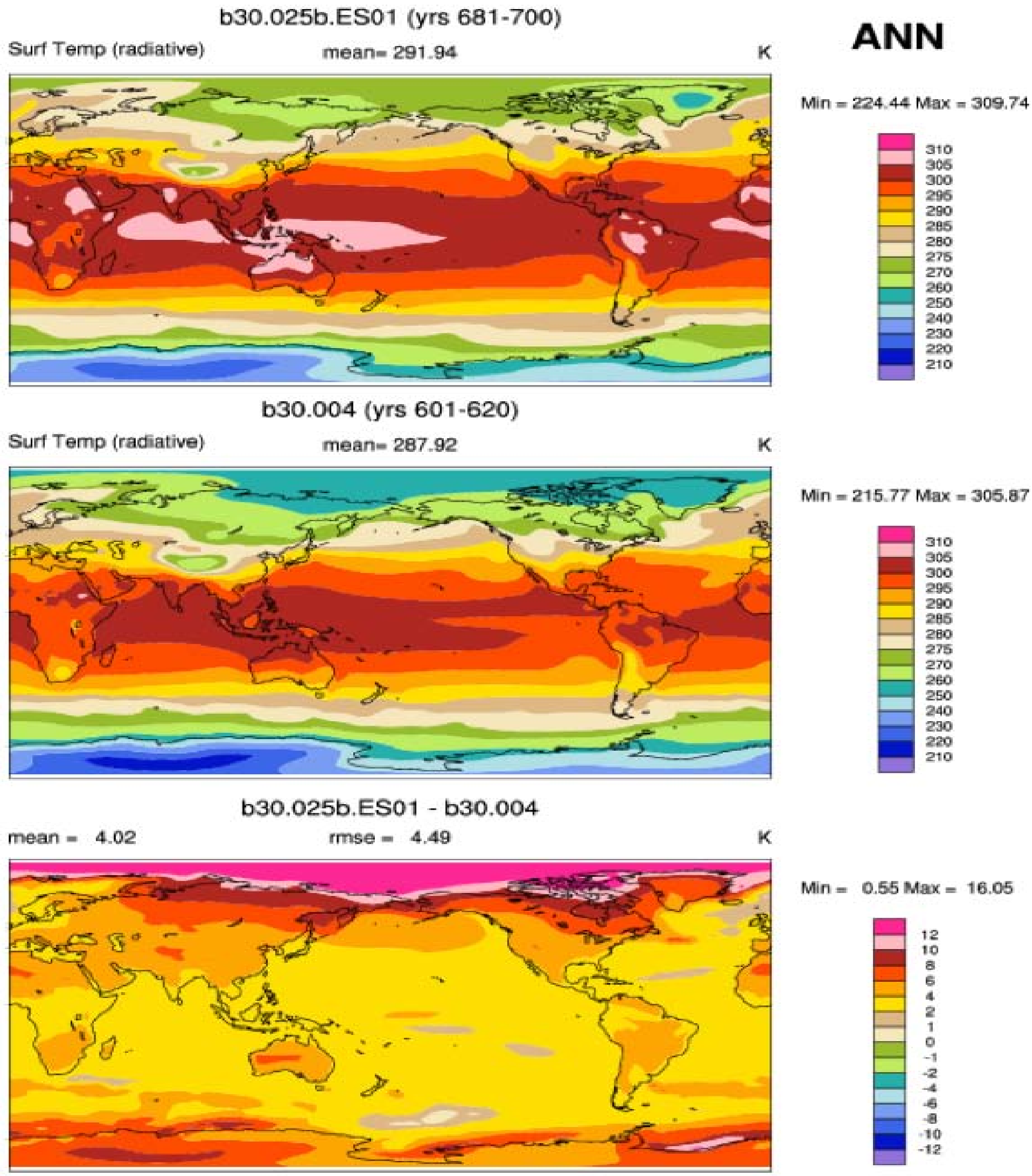

Figure 2-9
Annual Mean Surface Temperature (°K) Predicted for pCO_2 = 1,120 ppm (top, labelled b30.025b.ESO1), Modern Conditions (middle, labelled b30.004), and the Anomaly (future minus modern) (bottom)

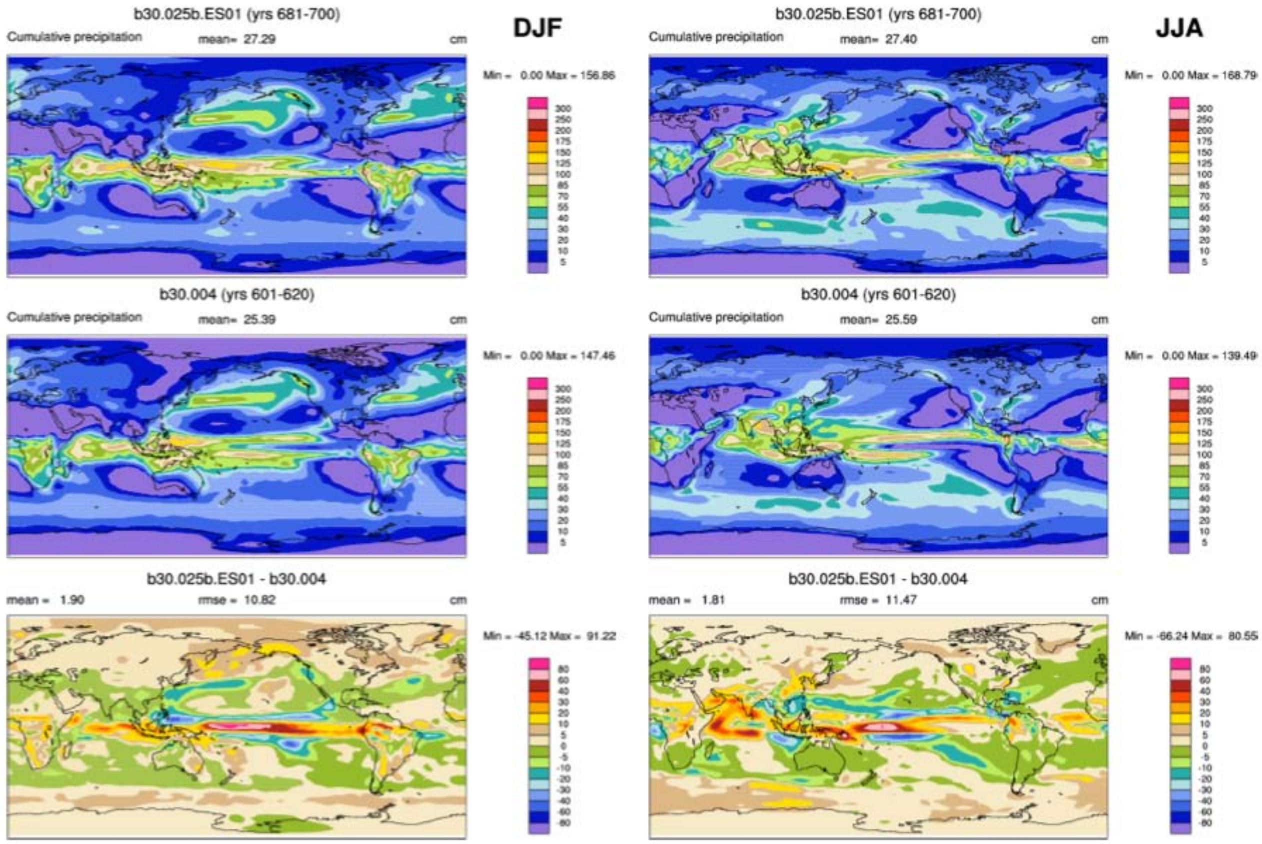

Figure 2-10
Model Predicted Precipitation (mm/yr) from a T42 Simulation at pCO_2. = 1,120 ppm (upper left) December through February and June through August (upper right) Means. The modern simulation fields are shown in the middle, left is December through February and right is June through August. Anomalies (difference of future simulation minus modern) are shown in the bottom figures.

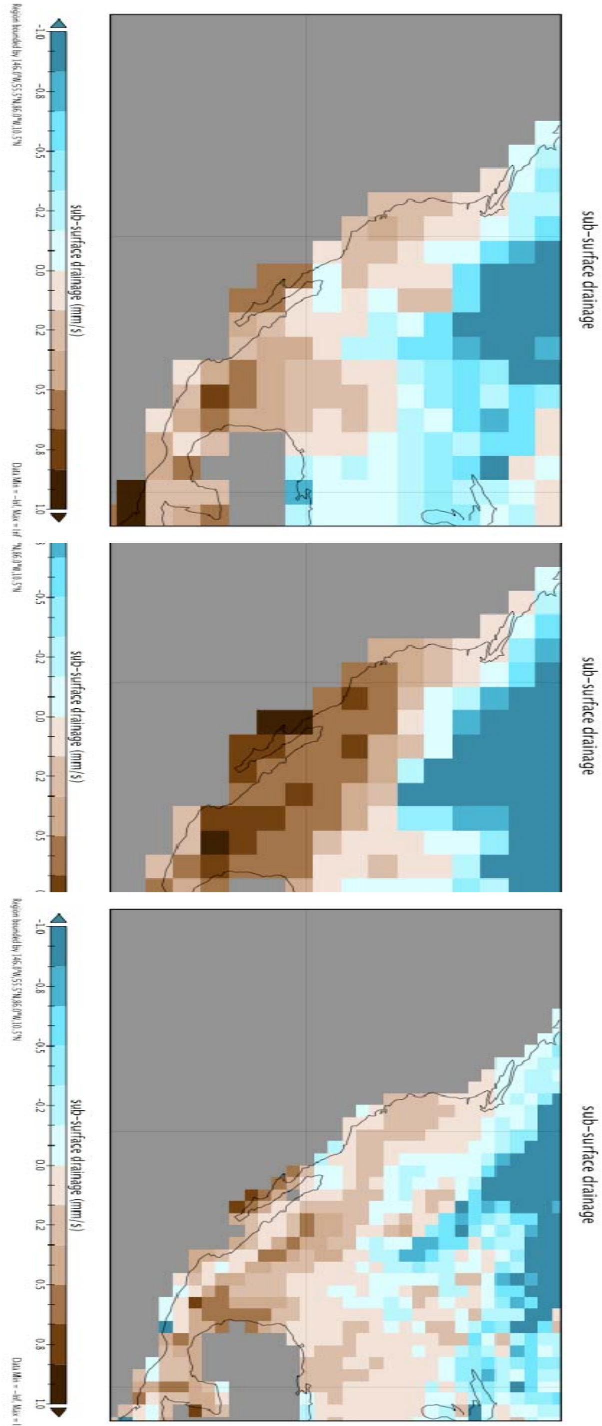

Figure 2-11
Model Predicted Infiltration/Recharge Expressed as a Fraction (see text) for the Future – A T42 Simulation

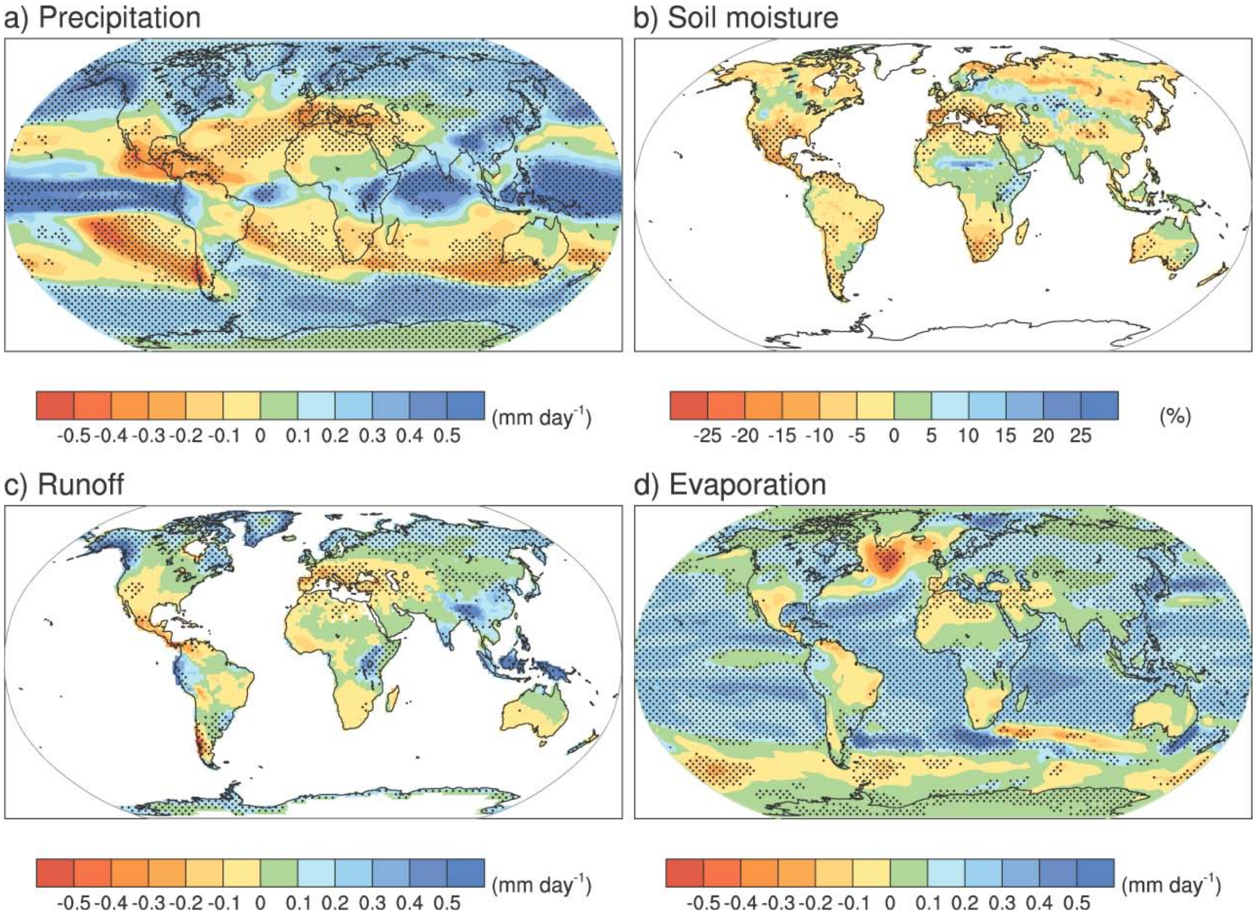

Figure 2-12
Changes in the Multi-model Ensemble Mean of (a) Precipitation (mm/day), (b) Soil Moisture content (%), (c) Runoff (mm/day) and (d) Evaporation (mm/day). Where at least 80% of models agree on the sign of the mean change the regions are stippled. Changes in annual means between the period 2080 to 2099 as compared to 1980 to 1999 are shown. From Meehl *et al.* (2007). Figure courtesy of IPCC.

2.6 Summary and Conclusions

Infiltration/recharge and other climatic variables from the fully coupled CCSM 3 model simulations for modern, Holocene, LGM, LIG, and two future projections conditions were analyzed. A preliminary history of recharge from 25 kyrbp to the present was produced using climate model output from the LGM and the Holocene after comparison of absolute values and trends from proxy records. These calculations provided quantitative, high resolution, and modern-calibrated/verified prediction of the near-term changes in conditions at YM. A long-term proxy record for effective moisture was derived, based on the Woolfenden (2003) juniper pollen from the Owens Lake core. After demonstrating a qualitative match between model results and the juniper proxy record, the proxy was calibrated to match model infiltration predictions at the LGM. Then the calibrated, continuous proxy record-based estimate was compared with both model-predicted estimates of recharge for other intervals and other previous estimates of recharge. The new juniper pollen percentage-derived proxy record matched model results well outside of the calibration period, demonstrating the general efficacy of this technique. This continuous calibrated time series also agreed well in magnitude and timing with existing compilations.

Fully coupled climate model simulations were performed for the ~130 kyrbp interval. Investigating the past hydrological conditions of the YM region during this interval extended the analyses to time scales approaching those expected in the final EPA standard for YM (*i.e.,* >100,000 years) and made direct predictions of infiltration for this interval without assuming empirical relationships or using paleo-climate analogue approaches. Most importantly, paleo-climate/ paleo-environmental data in the YM region existed for comparison to model predictions for this time interval. Comparison of model-predicted and proxy-derived infiltration revealed nearly identical predictions at 130 kyrbp, confirming the ability of the model to capture the major features of infiltration in past climates.

Results show a decrease in model-predicted infiltration in the YM region of 20-50 percent from modern values over the next several hundred to 1,000 years. The range of values reflects differences in atmospheric pCO_2 scenarios and differing resolutions of the model. *In none of the simulations examined is there an increase in infiltration or in hydrological conditions leading to increased infiltration..*

The new results have implications for the interpretation of previous work. In the base case considered by Mohanty *et al.* (2004), which extended for 100,000 years, a prescribed gradual transition from dry modern values to wet pluvial conditions was imposed and the resulting mean infiltration values varied from 8 mm/yr to full pluvial (glacial) conditions with a mean value of 37 mm/yr. This analysis seems to have been a key factor in the prescribed future glacial infiltration conditions implemented in NRC's 10 CFR Part 63, in which for all times greater than 10,000 years following repository closure, constant percolation rates of groundwater at the repository horizon at YM are assumed to range from 10 mm/y to 100 mm/y, with a mean value of 41 mm/y.. The simulations with prescribed temperature and precipitation forcing generated approximately 40,000 years of conditions with this high infiltration value, and in general 74,000 of the next 100,000 years were inferred to have conditions much wetter than modern.

EPRI's results certainly indicate that 41 mm/yr is a reasonable estimate for peak glacial pluvial conditions (the CCSM model results indicate a brief glacial maximum value of ~52 mm/yr and the juniper proxy results suggest a glacial mean value of ~28 mm/yr). But, this study's results indicate that infiltration values this high have not characterized much of the past full glacial-interglacial cycle (past 130kyr). Instead, 87% of the past cycle was characterized with values less than 30 mm/yr (and 37% with infiltration less than 15 mm/yr). This value is also consistent with prior work by DOE and USGS. *So while higher values did occur in the past, EPRI finds that much of the last full glacial cycle experienced conditions biased to drier, low infiltration values and that the mean value is 19 mm/yr. This in contrast to recent modeling results by Stothoff and Walter (2007) that indicate mean infiltration values of ~41 mm/yr for the next million years.* Taken within the context of the juniper proxy records discussed in this report, this means that their model predicts conditions wetter than have occurred in >90% of the past 130 years will be the average condition for the next million. EPRI believes this discrepancy has a simple explanation. Comparison of local paleo-environmental records such as juniper pollen (Woolfenden, 2003) or others from Owens Lake (Menking *et al.*, 1997; Bischoff *et al.*, 1997) with the global ice volume record show substantially different patterns of change, although the main peaks and troughs are similar. While the isotope record has a strong linear trend toward greater ice volume from the beginning of MIS 5 through the end of MIS 3, the juniper record does not. Since EPRI's technique is based on the latter and the other techniques are based directly or indirectly on the former, EPRI believes that its approach is more likely to reflect conditions in the Yucca Mountain region. This difference biases methods that utilize global ice volume records or insolation curves rather than local paleo-environmental records to much 'wetter' higher infiltration values. While differences in methods are likely to lead to differences in results between EPRI's study and theirs, it is noted that at no point was their study quantitatively validated against any proxy record for MAP, MAT, or infiltration in the Yucca Mountain region. Since Stothoff and Walter (2007) used MIS6, not LGM as their calibration tie point, their model could have been validated using the relatively well constrained MAP, MAT, and infiltration estimates for LGM, but that exercise was not conducted, so, at the present time, it is not possible to ascertain which methodology is more accurate.

Anthropogenic global warming is likely to have a large drying affect throughout the North American Southwest, including in the YM region (Wang, 2005; Barnett and Pierce, 2008; CCSP, 2008; Cook *et al.*, 2007). This affect is not likely to be transitory since simple climate model results indicate that the present interglacial will probably extend for at least 100,000 years, and perhaps as long as 400,000 years (Archer, 2005; Archer and Ganopolski, 2005; Montenegro *et al.*, 2007; Uchikawa and Zeebe, 2008). If that is the case, the substantial decreases in infiltration shown in this study could be considered quasi-permanent features, thus skewing the distribution of likely infiltration rates further to the dry side because peak glacial values would occur infrequently and the interglacial mean itself may be smaller than modern. Therefore, based on EPRI's independent analyses, the range and mean value expressed in NRC's 10 CFR Part 63 appear to result in higher, more conservative infiltration values than are likely to occur at YM under future glacial conditions.

3 HYROLOGIC RESPONSE TO CLIMATE CYCLES IN THE YUCCA MOUNTAIN

Transient flow systems are manifested by hydraulic head distributions that change as a function of time. Such behavior is clearly well understood, for example, in terms of drawdowns due to the extraction of ground water from wells. Although it is obvious that transient flow conditions could exist in regional flow systems, most studies take a steady-state view. For relatively short periods of time, for example years to decades, patterns of natural recharge and discharge could be considered reasonably constant with fluctuations around some average or steady condition. Freeze and Witherspoon (1966) invoked this idea to justify their assumption of a steady water table in their classic paper on the analysis of regional ground-water flow. Now, there is an increasing awareness of just how variable climate can be over a variety of different time scales and the concomitant influence of these changes on the spatial and temporal extent of infiltration (Lemieux *et al.*, 2008). Thus, there is some point at which regional flow needs to be examined in a transient context to account realistically for marked changes in the spatial and temporal patterns of recharge.

A transient conceptualization of regional ground-water flow also brings with it complexity which is often not recognized or understood. For example, hydraulic heads or fluxes at different places in the flow system can be adjusting at a different rate in response to transient forcings. Thus, a hydraulic head measurement taken in a piezometer today may in fact reflect recharge conditions prevailing centuries or millennia in the past. This is a point made by Toth (1978) in explaining under-pressures in deep formations in the Red Earth area of Alberta. Complexities in transient flow systems may also be manifested in the interpretation of age dates. For example, ages determined at various points in a flow system exhibiting continuous transient changes may not be interpretable in the normal context in which age dating is used.

The purpose of this study then is to elucidate the complexities of continuous transients in a large regional flow system. Of particular interest is application of this approach to the past, present and future flow conditions for the proposed YM, Nevada site for disposal of the US spent nuclear fuel and high-level radioactive waste in a geological repository. By using information from paleo-climatic models, an attempt is made to compare how modeled changes in transient flow may or may not be manifested in the present-day flow system at YM. Results from such a history matching exercise, in turn, could prove useful in assessing how future climatic changes might affect long-term changes in regional flow conditions for the YM site.

The well-studied, large, regional flow system at YM in Nevada (e.g., Luckey *et al.*, 1996; CRWMS, 2001; BSC, 2003; Eddebbarh *et al.*, 2003; Winterle, 2004) provides a suitable basis for this analysis. In general, the hydrology and hydrogeology of the southwestern United States is influenced by cyclical glaciation of North America that produced colder and wetter conditions in California and Nevada (Benson *et al.*, 2002; Woocay and Walton, 2006). During these wetter times, a number of large lakes appeared (Snyder and Langbein, 1962; Anderson and Wells, 2003) and ground-water recharge increased (Winograd and Thordarson, 1975; Quade *et al.*, 1995; Zhu *et al.*, 2003). EPRI uses a regional flow model to explore the transient behavior of a large regional flow system due to significant variability in Pleistocene and Holocene climates. Specifically, the system of interest is a 39 km slice of the Death Valley Flow System through YM toward the Amargosa Desert. What makes this flow system interesting is that the long time scale over which infiltration to the subsurface has changed (tens-of-thousands of years) is matched by the large physical extent of the flow system (many tens-of-kilometers).

This analysis is conducted in two steps. First, the spatial behavior in lag times in hydraulic head/flux as a function of recharge rates and position in the flow system is studied and its implications for interpreting hydraulic head measurements in the field evaluated. Second, the coupling between time lag and ground-water age, as well as understanding the complexities in interpreting ages with a flow system that is adjusting in a transient manner is investigated.

3.1 Physical Setting of the Study Area

YM is located in southwestern Nevada about 200 km northwest of Las Vegas. This site is presently under consideration as a potential repository for US spent nuclear fuel and high-level radioactive waste (DOE, 2001; BSC, 2003). The climate is arid to semi-arid. Present-day rainfall varies from < 130 mm yr^{-1} at low elevations in the south to > 200 mm yr^{-1} at higher elevations to the north (Flint *et al.*, 2001). Mesas north of YM receive about 200-250 mm yr^{-1}.

Briefly, Precambrian and Paleozoic basement rocks are overlain by Miocene silicic ash flows and ash-fall tuffs. It is this latter sequence of tuffs that are being considered as the potential host rocks for the proposed repository. Extensive faulting disrupts the continuity of units and produces the topography characteristic of the Basin and Range. YM itself consists of a group of north-south trending ridges comprised of a two km thick sequence of tuffs (Eddebbarh *et al.*, 2003). Valleys typically contain alluvium and playa lake deposits.

Given the present-day aridity of the YM site, infiltration and recharge are relatively low. Field and model studies find net infiltration values at YM averaging about 6 mm yr^{-1} (Figure 3-1). The greatest infiltration occurs along the crest of YM with little to no infiltration at lower levels (Flint *et al.*, 2001). Higher rainfall coinciding with continental glaciation promoted higher infiltration and ground-water recharge. There are certain surface manifestations of higher infiltration in the past, which are represented by dormant springs and other indicators (Winnograd and Thordarson, 1975).

This study depends on an assessment of patterns of infiltration and recharge for the late Pleistocene to modern times. Section 2 of this report has presented a detailed reconstruction of infiltration/recharge back to 185 kyrbp, beyond the LIG. The reconstruction is based on the juniper pollen record from Owens Lake (EPRI, 2007). Figure 3-1 shows the function for YM (from Figure 2-4 in Section 2 of this report). Paleo-climate archives, such as percent Juniper pollen, reflect the quantity of effective moisture present, and that effective moisture is closely tied to infiltration rate. Moreover, Juniper pollen is terrestrially derived, and therefore more likely to reflect infiltration rates better than other proxies that are complicated by lake, stream, and spring hydrology. A linear relationship between percent Juniper pollen and infiltration rate is assumed and the function is calibrated by assuming that 0% Juniper pollen corresponds to an observed present day infiltration rate of about 2 mm/yr and that the peak percentage of Juniper pollen value observed at the Last Glacial Maximum at 21 kyrbp corresponds to an infiltration rate of about 53.5 mm/year (see Section 2.4 for further discussion).

At the present time, the depth to the water table averages 510 m at YM (Flint *et al.*, 2001). A map of the water table (Figure 3-2) describes flow approximately north to south along the Death Valley regional flow system. Recharge in this large regional flow system occurs at higher elevations where precipitation is greater. Flow occurs through permeable units to discharge areas in the Amargosa Desert, Franklin Lake Playa and Death Valley (Eddebbarh *et al.*, 2003). The regional hydrostratigraphy is described by Luckey *et al.* (1996). The saturated zone is subdivided into four main units, the Upper Volcanic Aquifer and Confining Unit (UVA and UVCU), and the Lower Volcanic Aquifer and Confining Unit (LVA and LVCU).

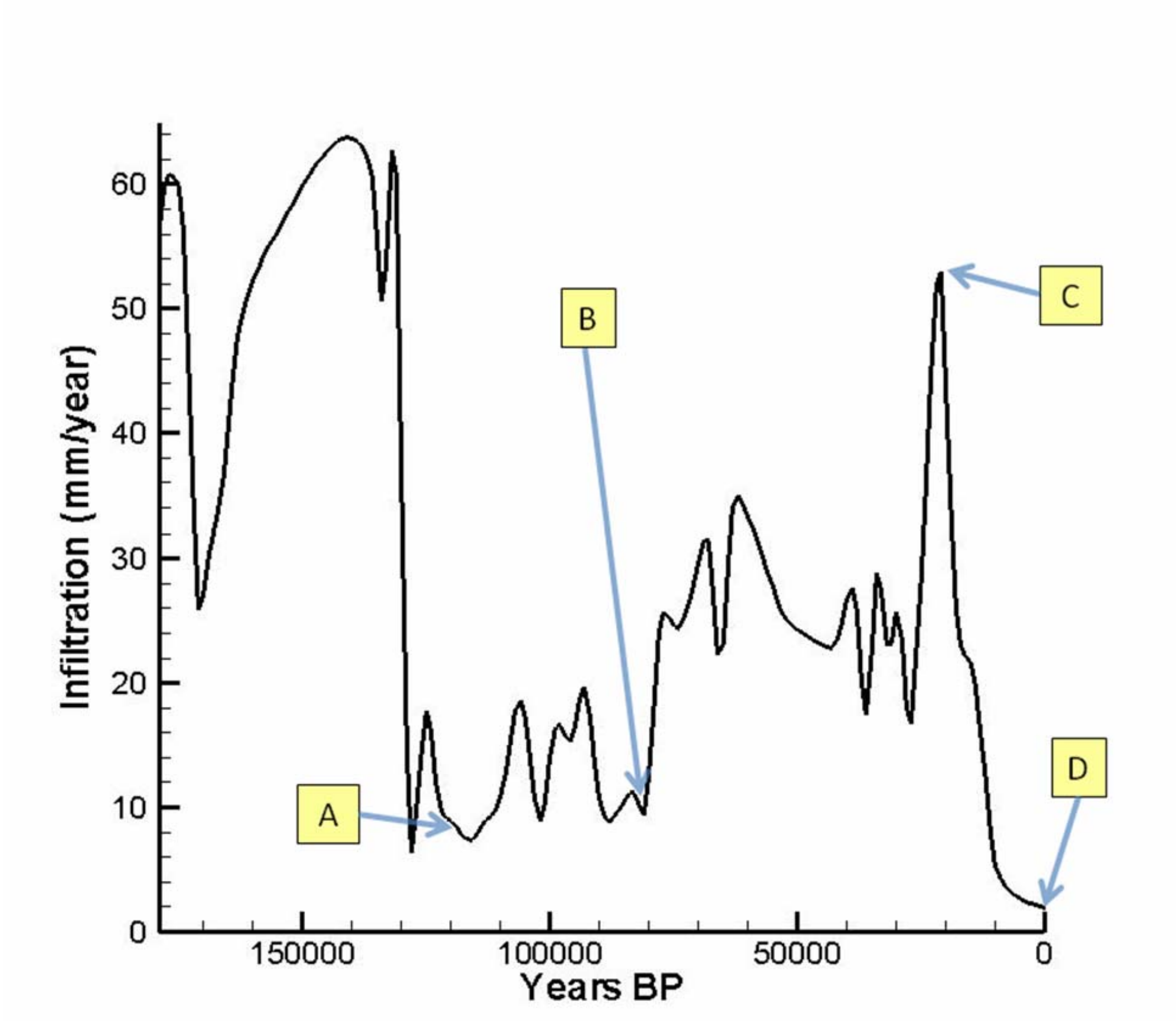

Figure 3-1
Infiltration Function Based on Paleoclimate Reconstruction Data as Interpreted from Juniper Pollen Data from Nearby Cores. Points shown correspond to (a) start of LIG (b) end of LIG (c) LGM and (d) present.

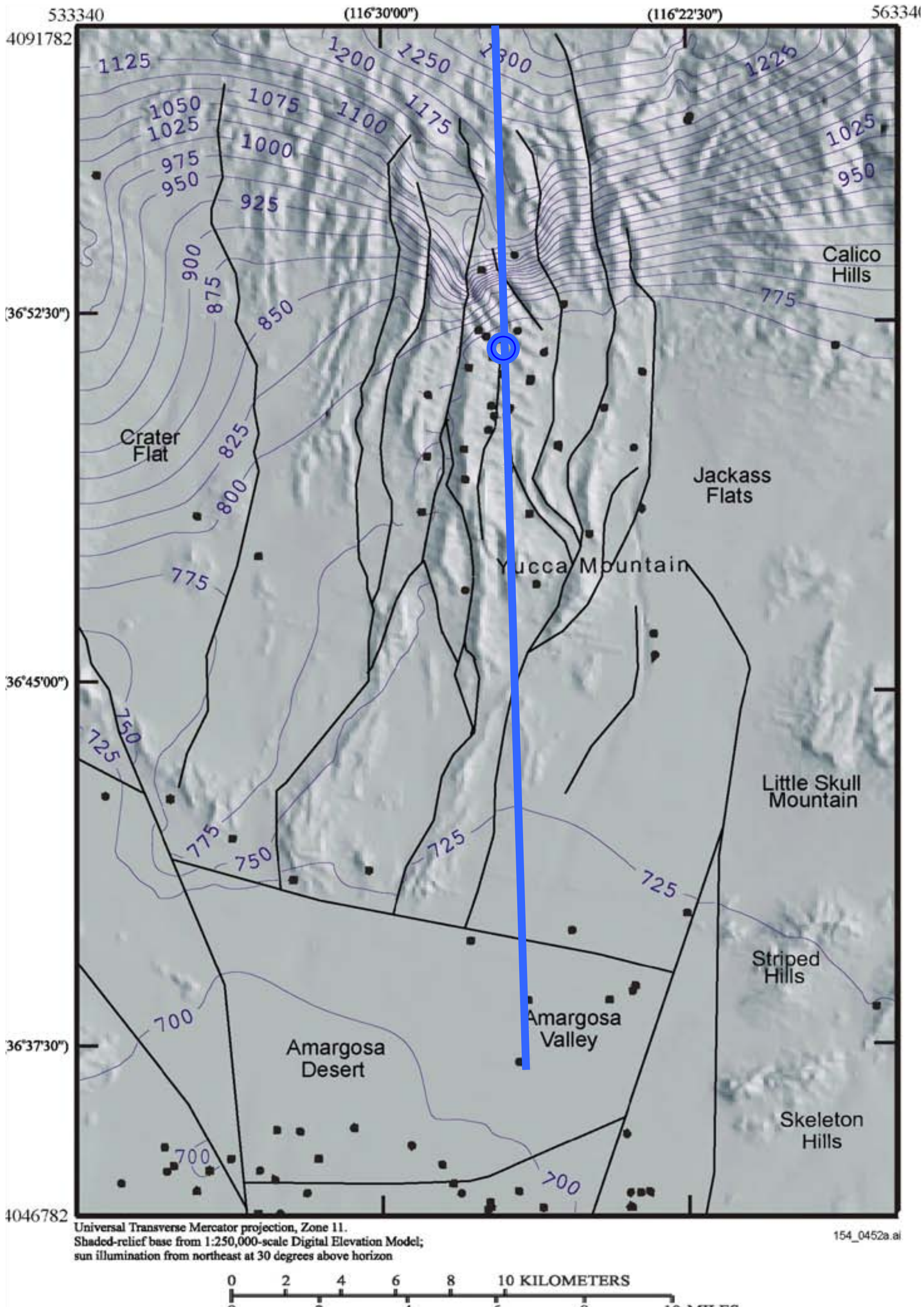

Figure 3-2
Shaded Relief Map of Study Region at Yucca Mountain (from BSC, 2003) Showing the Water-table Elevation (blue contours), the Approximate Location of the Proposed Repository (circle), and the Location of the Cross-section

The distribution of these key units is shown on a cross-section, oriented nearly north-south, approximately coinciding with a regional flow path, one segment of which passes beneath the proposed repository (Figure 3-3). The hydrogeologic framework used in this study is based generally on Winterle (2004). The cross-section shows ten hydrostratigraphic units defined on the basis of different hydrologic properties (Table 3-1). Upstream of the proposed repository site, the Caldera zone has been subdivided to provide a permeability decrease with depth, with horizontal boundaries at 1,000 and 1,200 meters above sea level (MASL). The rationale for subdividing these units is discussed in more detail in Section 3.4 of this report, but is based on a conceptual model designed to capture the steep water-table gradient north of the proposed repository and to provide capacity to carry pluvial recharge. The top of the Lower Volcanic Confining Unit (LVCU) is generally considered as the bottom of the simulation domain or an implied no-flow boundary (Figure 3-3).

Table 3-1
Final (calibrated) Flow Parameters from EPRI (2007)

Parameter	Hydrostratigraphic Unit					
	AL	UVA	UVCU	CB	LVA	C
Porous matrix						
Permeability (m^2)	5×10^{-12}	5.71×10^{-18}	4.23×10^{-19}	4.23×10^{-19}	1.57×10^{-16}	1.57×10^{-16}
Specific storage (1/m)	1×10^{-6}	1×10^{-6}	1×10^{-6}	1×10^{-3}	1×10^{-6}	1×10^{-3}
Porosity	0.38	0.112	0.288	0.288	0.286	0.286
Volume fraction	1.0	0.99984	0.99984	0.99984	0.99903	0.99903
Van Genuchten:						
α (Pa^{-1})	1×10^{-4}	3.55×10^{-6}	3.38×10^{-7}	3.38×10^{-7}	2.67×10^{-6}	2.67×10^{-6}
m	0.85	0.38	0.51	0.51	0.369	0.369
Residual saturation	0.072	0.05	0.12	0.12	0.11	0.11
Fracture						
Permeability (m^2)		1.14×10^{-7}	6.36×10^{-11}	6.36×10^{-11}	1.82×10^{-10}	3.63×10^{-11}
Specific storage (1/m)		1×10^{-7}	1×10^{-7}	1×10^{-7}	1×10^{-7}	1×10^{-7}
Porosity		1	1	1	1	1
Volume fraction		1.6×10^{-4}	1.6×10^{-4}	1.6×10^{-4}	9.7×10^{-4}	9.7×10^{-4}
Van Genuchten:						
α (Pa-1)		1.4×10^{-3}	1.4×10^{-3}	1.4×10^{-3}	1.6×10^{-3}	1.6×10^{-3}
m		0.633	0.633	0.633	0.633	0.633
Residual saturation		0.005	0.005	0.005	0.005	0.005
Spacing (m)		0.25	10.0	10.0	5.0	5.0
Interface						
Permeability (m^2)		3.63×10^{-13}	3.63×10^{-13}	3.63×10^{-13}	3.63×10^{-13}	3.63×10^{-13}
Van Genuchten:						
α (Pa^{-1})		2.67×10^{-6}	2.67×10^{-6}	2.67×10^{-6}	2.67×10^{-6}	2.67×10^{-6}
m		0.369	0.369	0.369	0.369	0.369
Residual saturation		0.1	0.1	0.1	0.1	0.1
Fluid exchange coefficient		76.8	0.048	0.048	0.192	0.192

AL, Alluvium; UVA, Upper Volcanic Aquifer; UVCU, Upper Volcanic Confining Unit; CB, Caldera Barrier; LVA, Lower Volcanic Aquifer; C, Caldera.

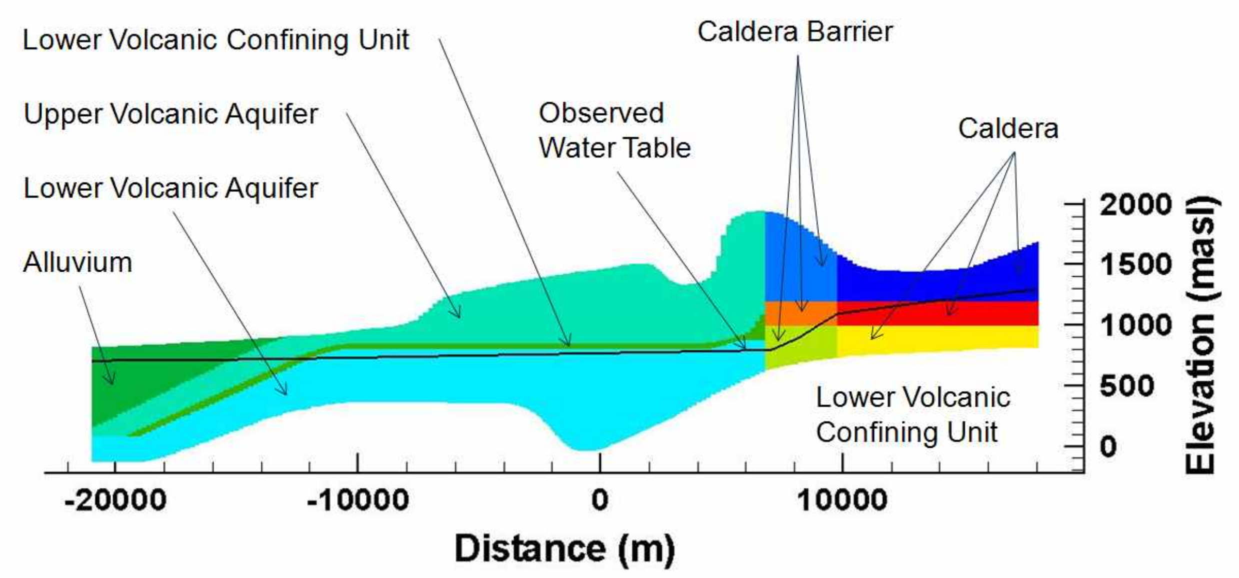

Figure 3-3
Model Domain and Hydrostratigraphy

The observed water table in Figure 3-3 is indicated on the cross-section by a heavy black line. It is developed from the water-table map, where elevations are given by points of intersection of the water-table contours along the line of section. The left boundary of the cross-section is located at the regulatory boundary, located 18 km away from the proposed repository. The right boundary coincides approximately with a ground-water divide north of YM.

3.2 Theoretical Approach

This study makes use of the concept of a *basin time constant*, which is a parameter characterizing the time required for the hydraulic head in a flow system to readjust to an imposed stress. For example, if the recharge to a flow system is discontinued, the discharge of springs at the downstream end will eventually be depleted. The development of a basin time constant assumes that the change in hydraulic head in such a system has an exponential form, or

$$h(t) = h_o + \left(h_\infty - h_o\right)\left[1 - e^{-t/\tau}\right] \qquad \text{Eq. 3-1}$$

where: h = hydraulic head (L),

h_0 = hydraulic head at t = 0 (L),

h_∞ = hydraulic head at t = ∞

t = time (T), and

τ = time constant (T).

The diffusional form of the ground-water flow equation provides the validity of the form of Equation 3-1. The time constant (τ) essentially describes how fast an exponential function decays. For example, when t = τ, or a period of one time constant, approximately 63% of the head change will have occurred has decayed and 37% remains. When t = 3τ, 95% of the head change will have taken place.

Domenico and Schwartz (1990) suggest the possibility of calculating time constants for a ground-water basin; however, the calculation is not common. The basin time constant is related to parameters in the ground-water flow equation as:

$$\tau = \frac{L^2 S_s}{K} \qquad \text{Eq. 3-2}$$

where: L = characteristic length (e.g. of basin) (L),

S_s = specific storage (1/L), and

K = hydraulic conductivity (L/T).

Equation 3-2 is helpful because it shows that the time constant for a ground-water basin is maximized when L, the basin size, is large, when S_s is large, and hydraulic conductivity is small. Thus, a large-scale flow system might be likely to exhibit relatively large time constants.

3.3 Flow and Transport Modeling

The HydroGeoSphere code at the University of Waterloo (Therrien *et al.*, 2005) is used to model flow and transport of ^{14}C along the regional flow system. ^{14}C is a useful tracer because many actual age measurements have been made with ground-water samples from YM, and because it is a commonly used approach to compare changes to the flow system as a function of recharge. The code is able to accommodate both fractures and the porous matrix as two overlapping continua. The dual-permeability, dual-porosity conceptualization used in HydroGeoSphere is based on the formulation of Gerke and van Genuchten (1993). The dual formulation allows the capturing of fluid and solute exchanges between the fractures and the rock matrix, including the retardation effect induced by matrix diffusion. The fractures comprising the fracture continuum are taken to be open features without infilling material. Thus, the porosity of an individual fracture is unity, and the value of the fracture porosity (*i.e.,* volume of fractures per unit volume of the rock mass) is interpreted as the volume fraction of the fracture continuum shown in Table 3-1. Furthermore, the fracture permeability in HydroGeoSphere is defined as a product of the fracture permeability and the fracture-continuum volume fraction.

The cross-section (Figure 3-3) is discretized into 8-node finite-element blocks typically 200 m by 1 m by 5 m in the x-, y-, and z-directions, respectively. Although modeled as a two-dimensional, cross-section, the flow domain has a unit thickness in the y-direction. This discretization produces a mesh consisting of 94,196 nodes and 46,283 elements. Because a dual-porosity, dual-permeability approach is used, two degrees of freedom exist at each mesh node, with one representing the matrix and the other representing the fractures (Therrien *et al.*, 2005; GSG, 2004).

Figure 3-4 shows the present recharge conditions, which are similar, but slightly wetter than other estimates of current climate (Figure 3-1), as developed in Section 2 of this report. This set of infiltration values is used in a steady-state analysis, and facilitates comparisons with studies by other modeling groups in the YM Project and EPRI's previous results (EPRI, 1996). Note that small infiltration fluxes (0.15 mm/yr) are applied in lower elevation areas as a practical matter. Simulation trials show that zero recharge at lower elevations effectively causes 'old' water to persist at shallow depths. This situation is not observed at YM, which implies small non-zero recharge.

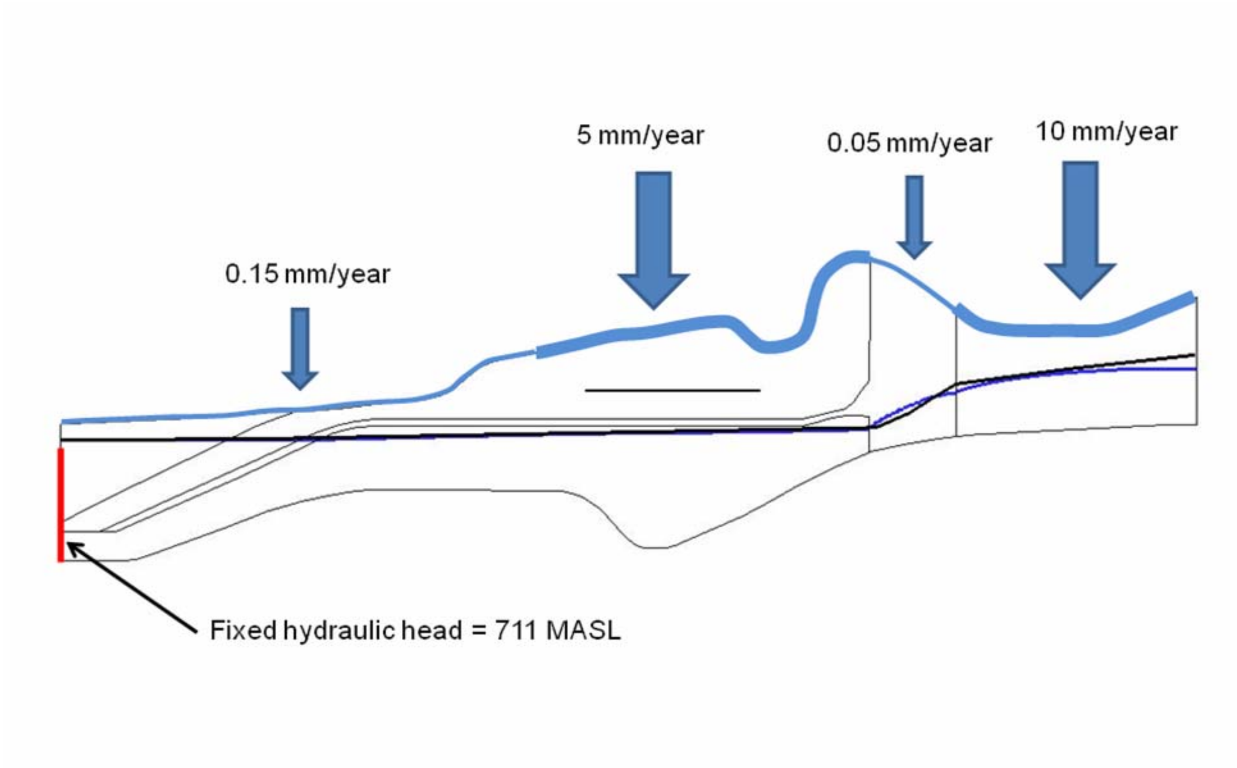

Figure 3-4
Steady-state Flow Scenario Boundary Conditions

All other boundaries on the model domain are considered to be either no-flow or prescribed-head boundaries. The bottom boundary is located at the top of the LVCU, which has a very low permeability, here assumed to be zero. The right-hand side boundary is located at a ground-water divide. The left boundary above the water table is located in the unsaturated zone and is assumed to be a zone of vertical flow. Below the water table on the left, the hydraulic head is specified to equal 711 MASL such that ground water can discharge across the outflow boundary under hydrostatic conditions.

Other simulation trials with the code involve transient runs where recharge is assumed to vary with time due to past climate changes. For these simulation trials, the recharge function in Figure 3-1 is applied at the surface. At each time step, the average fluxes in Figure 3-1 corresponding to the time step are partitioned along the ground surface to maintain the average values and the relative magnitude of recharge rates implied in Figure 3-4. Thus, it is always assumed that recharge north of YM is always a factor of two higher than at YM.

Another requirement for a transient run is a set of initial conditions. With simulations being performed over long time frames, it is usually not possible to define the initial conditions far in the past. Thus, as a model is started up, there are uncertainties regarding initial conditions. With time, the impact of uncertain initial conditions diminishes as the flow and transport solutions become less and less dependent or sensitive to the initial conditions. In this study, errors have been minimized in the model spin-up by beginning the historical simulations at 120 kyrbp, a time when the infiltration rates are quite similar to present-day dry conditions (Figure 3-1).

In the transport simulation, the infiltrating water is assigned a nominal activity of 100% modern carbon for all times. This is a simplifying assumption because the atmospheric production of ^{14}C varied somewhat from late Pleistocene to Holocene (Bard, 1997). The solute properties are those of ^{14}C, which has a half-life of 5,230 ± 40 years. The transport code does not include other processes that cause ^{14}C exchanges. This detail is not necessary because the numbers calculated are comparable to corrected age dates. In principle, other processes besides decay are accounted for in correction of the age dates. Table 3-2 lists the transport parameters that are assigned to the various hydrostratigraphic units.

Table 3-2
Transport Parameters

Parameter	Hydrostatigraphic Unit					
	AL	UVA	UVCU	CB	LVA	C
Porous matrix						
Longitudinal dispersivity (m)	10	10	10	10	10	10
Transverse dispersivity (m)	1	1	1	1	1	1
Tortuosity	1	1	1	1	1	1
Fracture						
Longitudinal dispersivity (m)		10	10	10	10	10
Transverse dispersivity (m)		1	1	1	1	1
Interface						
Mass exchange coefficient (m^2/year)		0.6048	3.78×10^{-4}	3.78×10^{-4}	1.512×10^{-3}	1.512×10^{-3}
Solute						
Free-solution diffusion coefficient (m^2/year)	0.0315	0.0315	0.0315	0.0315	0.0315	0.0315
Decay constant (1/year)	1.21×10^{-4}	1.21×10^{-4}	1.21×10^{-4}	1.21×10^{-4}	1.21×10^{-4}	1.21×10^{-4}

3.4 Results

EPRI's analysis differs in several respects from a conventional model study. Most importantly, EPRI is not intent on developing a simulation model to explicitly reproduce details of regional flow at YM. Rather, EPRI is using key features of the hydrogeologic setting at YM as an illustrative case that can be analyzed to learn about the temporal response of large flow systems undergoing significant climatic fluctuations. This approach thus implies a limited scope in calibration of the model. EPRI relies on existing data compilations and modeling, for example Winterle's (2004) cross-section, as the foundation for the modeling in this study.

In a sequence of steady-state simulations, initial estimates of the hydraulic properties for the various hydrostratigraphic units are adjusted to simulate the approximate configuration of the water table under current climate conditions. Values of infiltration are assumed that correspond to present-day dry conditions (Figure 3-4). The resulting set of hydraulic parameters is then tested to see how well the model performs under 'wet' climate conditions, or, in other words, infiltration conditions representative of pluvial conditions.

For the 'wet' climate simulation, the peak infiltration value of 53.5 mm/yr is partitioned to the upstream and downstream infiltration zones at rates of 72 and 35 mm/yr respectively. When these infiltration values are tested with a preliminary parameter set, they produced hydraulic heads that are excessively high relative to the ground surface in the upstream zone of recharge. Thus, it was necessary to alter the model. The Caldera and Caldera Barrier units are subdivided vertically into three subunits, as indicated on Figure 3-3, and the fracture permeability is adjusted using a trial and error approach. The final parameter set allows higher rates of infiltration to be accommodated without resulting in excessively high heads and maintains the original good fit with the water table with much lower recharge rates. The final calibrated values of fracture permeability of the subdivided Caldera and Caldera Barrier units are given in Table 3-3. Generally, the topographically higher units are assigned larger fracture permeabilities in order to eliminate the excess heads.

Table 3-3
Final Calibrated Values of Fracture Permeability of the Subdivided Caldera Barrier and Caldera Units

Parameter	Hydrostratigraphic Unit	
	C	CB
Fracture Permeability (m^2)		
Below 1000 m	6×10^{-11}	3×10^{-12}
1000 to 1200 m	6×10^{-10}	3×10^{-11}
Above 1200 m	2×10^{-8}	1×10^{-9}

3.4.1 Steady-State Simulation – Present-day Climate

The results of a steady-state simulation are presented in Figures 3-5a and 3-5b. With the imposed boundary conditions (Figure 3-4), flow generally proceeds from right to left. The predicted position of the water table matches the observed position of the water table well. It should be noted that several different conceptual models have been proposed to explain the large gradient in the water table at YM. Only one of these possibilities, a low permeability zone effectively damming the flow, has been implemented in the modeling.

The variation in ^{14}C activity shown in Figure 3-5a is in keeping with the pattern of flow with highest activities found in areas with relatively large infiltration rates. In Figure 3-5b, the apparent age of the waters is computed from the ^{14}C activity as:

$$Age = -\frac{1}{\lambda}\ln\left(\frac{C}{C_0}\right) \qquad \text{Eq. 3-3}$$

where: λ = decay constant for ^{14}C, and

C/C_0 = activity of ^{14}C as a fraction.

The ^{14}C results point to a complex pattern of mixing in regional flow as water from the two key recharge areas commingle. Commonly, calculated water ages are >10,000 years with a tendency for water to become older with depth and laterally in the deepest part of the regional aquifer.

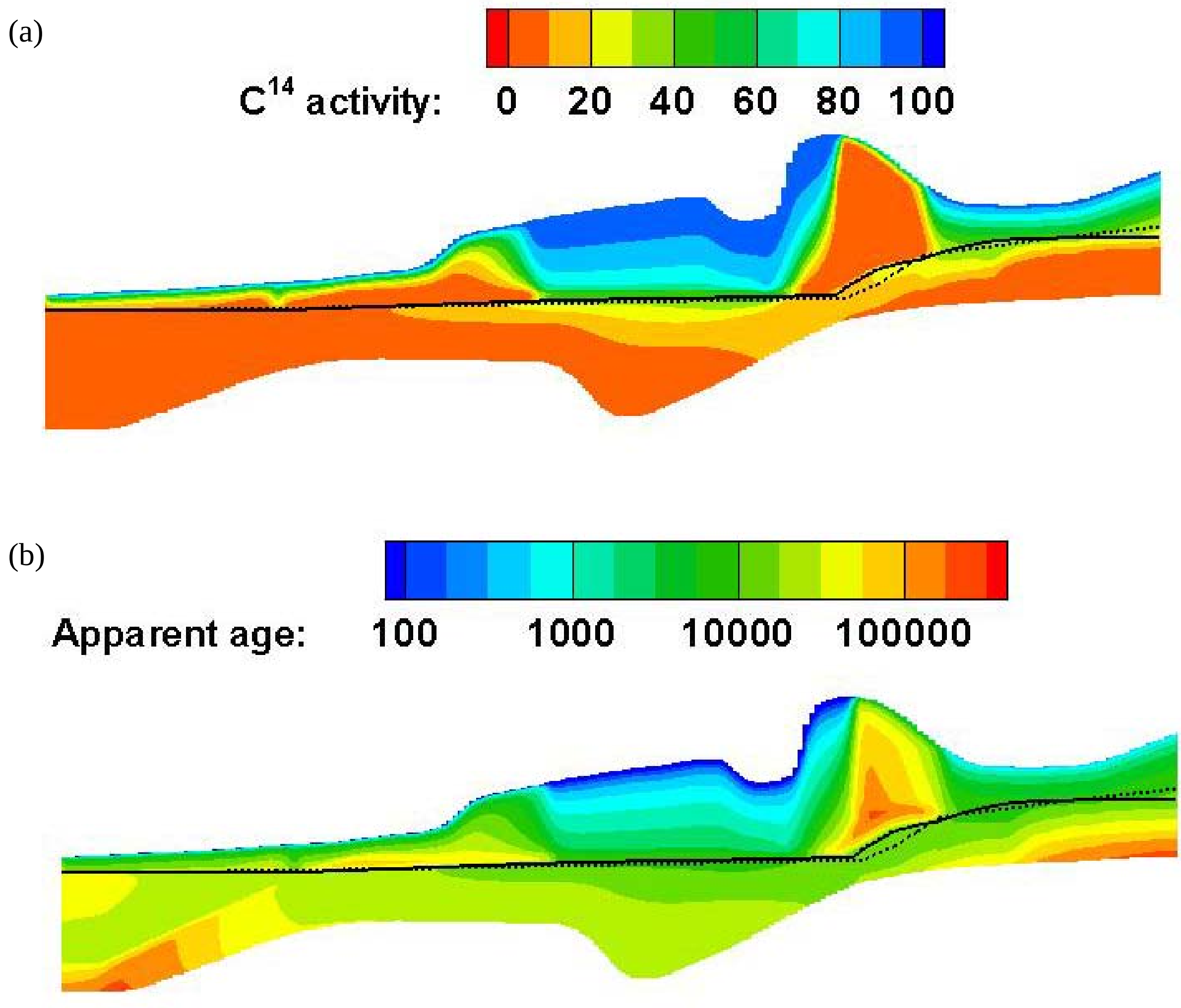

Figure 3-5
Steady-state Flow Scenario Showing (a) ^{14}C Activity and Positions of the Observed (dashed black line) and Predicted (solid black line) Water Table and (b) Apparent Age

3.4.2 Time Constants

This section examines the concept of a basin time constant through an illustrative calculation using the steady-state flow field for the cross-section. The steady-state flow-field is perturbed by an abrupt decline in infiltration. Two different cases are simulated; (i) a step decrease in the infiltration rate by 50% along the upper boundary, and (ii) a step reduction in infiltration to zero. Once the infiltration is reduced, the flow system responds through by a transient readjustment of hydraulic heads and fluxes back to a new steady state. By accounting for these adjustments in flows or hydraulic heads, at different places in the system, it is possible to estimate the basin time constants. Figure 3-6a shows three locations where fluid fluxes are calculated (i) in the

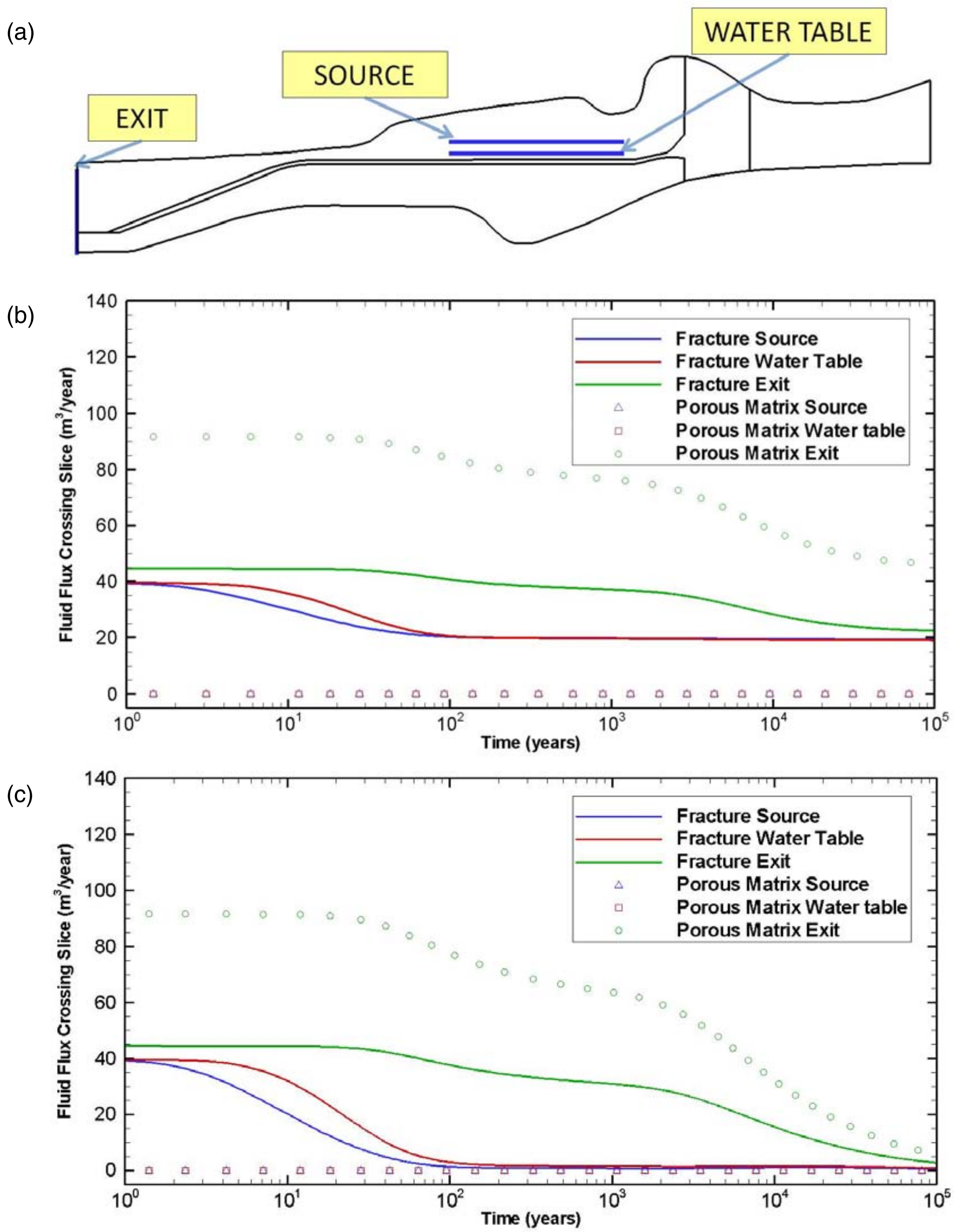

Figure 3-6
(a) Positions in the Flow System where Fluxes are Calculated; (b) Flux History with a 50% Reduction in Recharge; (c) History with Zero Recharge

unsaturated zone above the water table, (ii) in the saturated zone below the water table, and (iii) in the saturated zone at the outflow. Fluxes are calculated in both the fractures and the porous media. The value of τ is determined graphically on the figures as the time at which 63% of the change in flux has occurred.

Close to the water table, the time constant is short, several tens of years (Figures 3-6b, c), with equilibrium reestablished to the new recharge after about 100 years (5τ). All of the flux is occurring within the fractures. At the discharge end of the system, the time constant is about 10,000 years in both the fractures and matrix with a time to equilibrium of 50,000 years. The readjustment approximates an exponential function (Figure 3-6b, c), although the form is more complex. Not shown here are estimates of the time constant determined for the time variation in hydraulic head. The curve shapes are quite similar to those for flux, and the time constants are comparable at ~8,000 years.

3.4.3 Flow System Response to Climate Change

Transient simulations are performed to examine the behavior of the flow system to changes in infiltration over the last 120,000 years (*i.e.,* one complete cycle of glaciation). The start time of the simulation is chosen at 120 kyrbp (point A, Figure 3-1). This starting point is close to the beginning of the LIG, but lags by a period of several thousand years to allow the system to respond to the lower infiltration conditions that characterized the LIG. The state of the flow system at that time would have been similar to the steady-state flow system shown in Figure 3-5, which provides the initial condition for this simulation.

The infiltration fluxes applied to the top boundary of the domain are allowed to vary with time as defined by the percent Juniper curve in Figure 3-1. However, the Juniper values are averages developed for the Yucca Mountain region. These averages are used as a basis for assigning elevation-dependant infiltration rates along the cross-section (Figure 3-4). Higher recharge rates are assigned to higher elevations. For the purpose of this analysis, infiltration in the Yucca Caldera is assumed to be two times that at Yucca Mountain. These rates are obtained with 1.34 times percent Juniper value for upstream zone, 0.66 times for downstream zone, 1% of upstream value for region between upstream and downstream zones and 3.5% of downstream value for region between downstream and exit boundary). These locations are the same as those of Figure 3-4 for the steady-state flow scenario. In the transport simulation, the infiltrating water is again assigned a^{14}C activity equal to 100%.

The results of this long-term simulation trial are presented in Figure 3-7, which provides the estimates of apparent age from the ^{14}C activity distribution. Because the activities and age distributions are directly related, only the age distribution results are shown. The three different times at which results are presented correspond to the end of the LIG (85 kyrbp , point B Figure 3-1), the last glacial maximum (LGM) (20 kyrbp, point C Figure 3-1) and the present (point D, Figure 3-1). The observed position of the water table is shown to help illustrate how the flow system is changing in response to variations in the infiltration rate.

The age distribution in Figure 3-7 shows how markedly the flow system changes as a function of paleo-climate. At the LGM (20 kyrbp), the flux of water through the flow system is much greater with much greater recharge. Consequently, ground water in the upper part of the Lower Volcanic Aquifer is relatively young, only several thousand years old (Figure 3-7b). The water table rise in the central part of the cross-section is simulated to be approximately 111 meters above levels observed presently. Such an increase coincides well with independent estimates of water-table rise provided in earlier EPRI studies (EPRI, 1996).

(a)
(b)
(c)

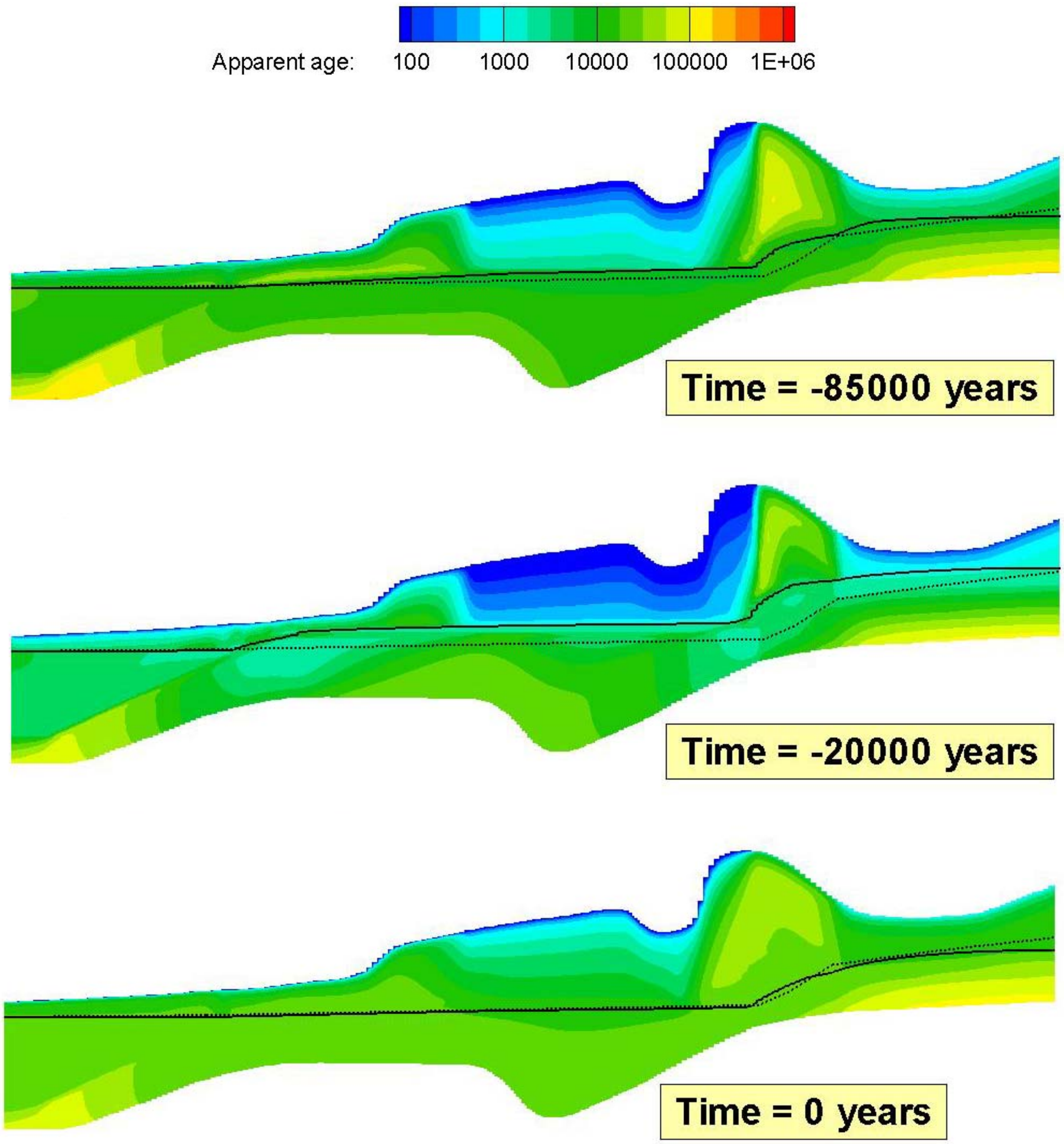

Figure 3-7
Results from the Transient Flow Simulation Show Apparent Ages at (a) End of LIG (b) LGM and (c) Present

By comparison, the lower infiltration during the LIG (85 kyrbp) and the present day produces more sluggish flow systems. For example, with the decline to the present-day infiltration rates, the lowest in the past 120,000 years, water ages along the water table appear to be >10,000 years (Figure 3-7c). The slope of the water table has become much flatter, especially in the down-gradient half of the flow system.

3.5 Discussion

3.5.1 Basin Time Constant

The calculated time constants suggest that for the complex infiltration/recharge fluxes applied to the YM system, parts of the flow system readjust quickly and are essentially always in equilibrium with the infiltration occurring at the surface. Other parts of the system are likely never in equilibrium because of the much shorter frequency of fluctuations in infiltration rates. With maximum τ values of about 10,000 years, the heads and fluxes that are calculated at some locations in the flow system carry a relatively significant imprint of conditions that existed during pluvial times.

Time constants are extremely variable spatially for the YM flow system, ranging from decades to many thousands of years. The largest time constants are associated with parts of the system most distant from the major recharge areas. This result suggests that care should be exercised in defining the basin time constant at the YM site and elsewhere. It is likely that simply substituting parameter values in Equation 3-2 may or may not yield a good estimate. It is suggested that sensitivity simulations of the type used in this study may be required to provide an estimate of a basin-scale time constant at a regional discharge area.

3.5.2 120,000-year Transient Case

The long and complex climate history beginning shortly after the start of the LIG, 120 kyrbp translates to a complex history of infiltration and recharge. During the LIG, the average minimum infiltration rate was about 8 mm/yr over the flow system (Figure 3-1). Values fluctuated up to a maximum of about 19 mm/yr. At the LGM, 20 kyrbp, the average infiltration reached a high of about 54 mm/yr. From the LGM to present, the average infiltration rate declined steadily to the lowest value in the last 120,000 years (Figure 3-1).

One of the questions that this study set out to address is whether the interpretations of ^{14}C data from YM field measurements are being conditioned by an implicit assumption that the flow system is steady. Expressed in a different way, is there an expectation that ^{14}C dates along a flow line from recharge to discharge areas should be progressively older? The YM case study is instructive in this respect. The simulated ^{14}C age distribution in the ground water is actually being controlled by the transient behavior of the flow system, in addition to dispersive mixing. Thus, “point” age dates along the flow path are complex and essentially un-interpretable using simplified steady-state assumptions and approaches based on examining patterns of variation in corrected water ages.

To make this point, the present-day results from the steady-state and transient simulations are examined. For convenience of comparison, these simulated age distributions are shown together in Figure 3-8. With the steady-state case (Figure 3-8a), simulated ^{14}C ages become progressively older along a hypothetical flow path from the proposed repository toward the discharge area. Near the downstream end of the system, the location of the confining bed produces localized younger water. Thus, while complicated, one should still be able to make a reasoned

(a)

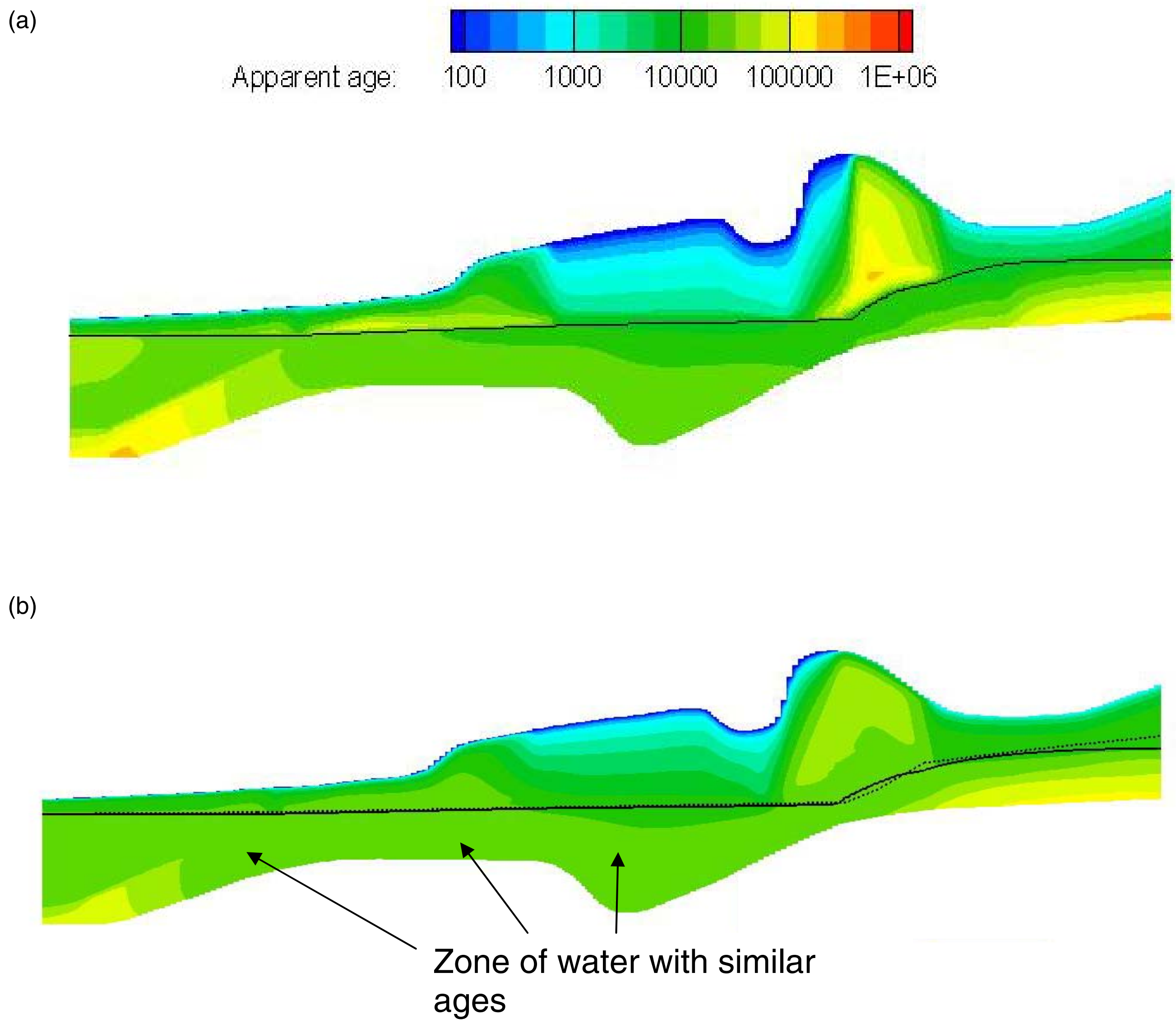

Figure 3-8
Comparison of Simulated ^{14}C Age Distributions. Panel (a) shows ages based on a steady-state conceptualization of the flow system. Panel (b) shows the age distribution simulated using a transient recharge function. Highlighted on Panel (b) is a large zone with water of the same age.

interpretation from a collection of ^{14}C age dates in this flow system. The transient case is distinguished by the observation that most of the deeper ground water (indicated on Figure 3-8b) is the same age, approximately 20 kyrbp. During the glacial maximum, the recharge was so rapid and pervasive along the entire cross-section that young water reset the ^{14}C clock in a spatially complex manner. The diminishing recharge through the Holocene to present superimposed a new pattern of ^{14}C on this pattern related to the LGM. A straightforward interpretation of the age distributions in Figure 3-8b then becomes problematic and would essentially require an *a priori* knowledge of the flow transients in order to perform the deconvolution. The geochemically-based interpretive tools for correcting ^{14}C activities in water effectively account for carbon transfers in various processes but not for complexities in flow histories that gives rise to the mass transport (Figure 3-8b).

The interpretation above is borne out by an examination of the measured ^{14}C data. ^{14}C measurements on samples taken from the unsaturated zone provide information on the age of water backward in time to perhaps 15 to 20 kyrbp. Much of the existing ^{14}C information is described in CRWMS (2001). More recent analytical results are available in electronic data summaries maintained by the Nye County Nuclear Waste Repository Project Office (http://www.nyecounty.com/LSN/index/EWDP/water_data.htm).

The interpreted ages for perched water collected from the unsaturated zone range from 7,000 to 14,000 years (CRWMS, 2001). These ages correspond with other samples from the unsaturated zone. Overall, water in the unsaturated zone is quite old, as suggested by EPRI's transient simulation trials (Figure 3-7c). Water dates from the saturated zone commonly do not exhibit obvious spatial trends in ages. At the water table, ground water has a corrected maximum age of about 15,000 years (*e.g.*, in WT-10). Interpretations based on ^{14}C as well as inferred ages from stable isotopes, suggest that ground water beneath YM was infiltrated between 10 and 19 kyrbp (CRWMS, 2001). However, little is revealed concerning any large changes in the patterns of groundwater flow. The model results provided in Figure 8b suggest that no major age changes occur along a flow path, which is in line with the actual field measurements.

3.5.3 Beyond Simple Systems

The regional hydrological system analyzed for the well-characterized YM site exhibits realistic complexity, especially in terms of recharge and its transient response. A system in a state of constant transient transition implies that hydraulic heads are always changing with time along with the fluxes and streamline configurations. With large basin time constants, flow is complicated because hydraulic heads at one place might be reflecting conditions of the past, but in another, the system may reflect present conditions. This complexity is also manifested by processes that depend on flow, for example ^{14}C transport. Without a model that accounts for the historical transients for at least the last the last 20,000 years, there may be no simple way to interpret the ^{14}C dates to explain patterns of flow.

3.6 Conclusions

Over the past 185,000 years at YM in Nevada, paleo-climatic and hydrological studies indicate that there has been tremendous variability in the infiltration rates as a function of time (Snyder and Langbein, 1962; Winnograd and Thordarson, 1975; Quade *et al.*, 1995; Benson *et al.*, 2002; Zhu *et al.*, 2003; Anderson and Wells, 2003; Woocay and Walton, 2006). From LGM approximately 20 kyrbp to the present, infiltration has declined significantly from in excess of 50 mm/yr to about 2 to 5 mm/yr. The model described in this report is specifically designed to examine the implications of this complex pattern of infiltration to evaluate if and how well present-day measurements are consistent with modeling of climate-induced transient flow.

The results are instructive in several different ways. First, the results indicate a huge dynamic range in the vigor and variability of the flow system. For the regional flow system at YM, cycling between glacial and interglacial periods changed infiltration and recharge rates by a factor of ten or more. These variations have produced significant changes in the character of the groundwater flow system as measured and monitored today. As infiltration rates declined from the LGM to present-day levels, the simulated water table fell about 110 m and travel times for water through the flow system increased substantially. Thus, it is important to understand the implications of transient changes on flow systems due to changes in the past and future.

Notably, during the past 120,000 years, there is almost no time period during which the flow system at YM might be considered to be at steady state. There exist nearly continual transient readjustments as this large flow system responds to climate fluctuations, a situation that could apply to sites other than YM as well. With the time lag required for basin-scale readjustments, the hydraulic head distribution is complex, because at any time the flow system locally may be reflecting influences from the past. The complexity of transient readjustments also extends to mass transport processes. EPRI's analysis suggests that complex transients can severely diminish the possibilities of interpreting ^{14}C data with simplified interpretive models. At YM, transient changes in infiltration and recharge exert a dominant control on groundwater ages that explain why no systematic increases in ages are evident along a present-day flow path. Nor can simple geochemically-based interpretive tools synthesize the complex flow history that gives rise to measured ^{14}C age distributions.

The newest generation of models has given researchers a means for envisioning the inherent complexity of hydrologic systems. However, progress in fully understanding the complexity of real systems is slow because of severe limitations in the availability of data and inherent uncertainty, especially with respect to future climatic conditions.

Given uncertainty in future climatic changes, it is reasonable for the pertinent U.S. NRC regulations in 10 CFR 63 (NRC, 2008) to have eliminated the need to conduct detailed modeling of complex hydrological response to future climate change by imposing a fixed range of increased percolation rates at the repository horizon, and assuming a return to glacial conditions 10,000 years after repository closure. It is worth noting, however, that recent independent analyses presented in Section 2 of this report suggest that global warming will likely produce a future that is drier than present in the YM region, and that such conditions could persist for another 100,000 to 400,000 years. If such dry conditions remain in place over this relatively long time period, then the YM flow system has potential to achieve steady state with low recharge conditions that are far outside the range of behavior for much of the past 180,000 years, and far below the post-10,000 year infiltration values assumed in NRC (2008). The residence time for water in the YM flow system of the future would be much longer, and the infiltration rates much lower, than present-day conditions, enhancing the isolation performance of a nuclear waste repository located at YM.

4
SUMMARY

Southwestern North America has been less arid in the past and appears to be poised to become more arid in the near future. Future hydrological conditions in the vicinity of Yucca Mountain (YM) are a crucial issue for evaluating the stability of the site as a potential repository for nuclear waste. Most previous attempts to predict future hydrological conditions, including groundwater recharge and deep percolation, in the YM vicinity have focused on relating net hydrological surface balance conditions to climate parameters, either observed within the modern instrumental record or reconstructed based on a chain of inferences from paleo-environmental proxy data. Observations of modern climate at sites deemed analogous to the paleo-climate reconstructions have been used as boundary conditions in assessments of past and future climate, near surface hydrology and infiltration in the YM region.

In this study, EPRI's approach was to avoid the use of indirect paleoclimate analogues as much as possible by creating a proxy for paleo-infiltration itself and to ascertain whether climate models can accurately reproduce these paleo-infiltration estimates as an obligatory step to modeling future infiltration. The objectives of this study were to develop a new proxy record for paleo-infiltration independent of prior approaches and further to establish whether a full Earth System model, including a global general circulation model representation of the ocean-atmosphere-land surface, can accurately predict net recharge (infiltration) in the present and in the past, and then be used to forecast the future. Here a new approach has been presented: (1) the regional predictions produced by the NCAR Community Climate System Model were validated utilizing modern climate and hydrological observations, (2) further validation was conducted with the paleo-environmental record of past hydrological balance during the Last Glacial Maximum (LGM) and at 130 kyrbp, near the inception of the Last Interglacial; and (3) finally that paleo-climate validated model was used to predict future conditions. Consistent with previous studies, EPRI has found that infiltration was maximized during the LGM. However, EPRI has also found that this period of substantial recharge was likely to have been brief and that the long glacial preceding it was likely to have been not as 'wet' as previously reconstructed. EPRI has found that the Last Interglacial interval was typically near the upper range of modern and recent infiltration estimates and that the termination of the penultimate glaciation had higher infiltration rates than even LGM. EPRI's studies have also found that, over the next several thousand years, it was likely that conditions would be substantially drier (less infiltration) than current values. *Based on published predictions, which show anthropogenic climate change would prevent global climate from slipping into the next glacial interval, and potentially the next several glacials, it was conjectured that conditions in the YM region would probably be as dry or drier than modern for at least 60,000 years and as much as 400,000 years.* If that was to be the case, the substantial decreases in infiltration shown in this study could be considered quasi-permanent features, thus skewing the distribution of likely infiltration rates further to the dry side because peak glacial values would occur infrequently and the interglacial mean itself may be smaller than modern.

Based on the above climate and infiltration studies, a regional flow model was used to explore the transient behavior of a large regional flow system at Yucca Mountain resulting from the significant variability in Pleistocene and Holocene climates. Simulations involved a 39 km slice of the Death Valley Flow System through Yucca Mountain toward the Amargosa Desert. The long time scale over which infiltration had changed (tens-of-thousands of years) was matched by the large physical extent of the flow system (many tens-of-kilometers). Paleo-infiltration rates were estimated using a juniper pollen percentage (the juniper pollen proxy developed in the climate / infiltration studies) that extended from the last interglacial (LIG) period (approximately 120 kyrbp) to present. Flow and ^{14}C transport simulations showed that the flow system changed markedly as a function of paleo-climate. At the LGM (20 kyrbp), the recharge to the flow system was about an order-of-magnitude higher than present and water table was more than 100 meters higher. With large basin time constants, flow was complicated because hydraulic heads at a given location reflected conditions of the past, but at another location the flow may have reflected present conditions. This complexity was also manifested by processes that depend on flow, for example ^{14}C transport. Without a model that accounted for the historical transients in recharge for at least the last the last 20,000 years, there was no simple way to deconvolve the ^{14}C dates to explain patterns of flow. At YM, transient changes in infiltration and recharge exert a dominant control on groundwater ages that explain why no systematic increases in ages are evident along a present-day flow path. Nor can simple geochemically-based interpretive tools synthesize the complex flow history that gives rise to measured ^{14}C age distributions.

The governing NRC regulations for the proposed YM repository (NRC, 2008) appropriately obviate the need to conduct detailed modeling of complex hydrological responses to future climate change by imposing a fixed range of increased percolation rates at the repository horizon, and assuming a return to glacial conditions 10,000 years after repository closure. It is worth noting, however, that the climate / infiltration analyses presented of this report suggest that global warming will likely produce a future that is drier than present in the YM region, and that such conditions could persist for another 100,000 to 400,000 years. If such dry conditions remain in place over this relatively long time period, then the YM flow system has the potential to achieve steady state with low recharge conditions that are far outside the range of behavior for much of the past 180,000 years, and far below the post-10,000 year infiltration values assumed in NRC (2008). The residence time for water in the YM flow system of the future would be much longer, and the infiltration rates much lower[1], than present-day conditions, enhancing the isolation performance of a nuclear waste repository located at YM.

[1] Based on EPRI's independent analyses presented in Section 2 of this report, the range and mean value expressed in NRC's 10 CFR Part 63 seems skewed to much higher infiltration values than are likely to occur at YM under future glacial conditions.

5
REFERENCES

AMS, 2006. Special Issue on the Community Climate System Model, *J. Clim.*, 19, American Meteorological Society.

Anderson, D.E., and S.G. Wells, 2003. Latest Pleistocene lake highstands in Death Valley, California, in *Paleoenvironments and Paleohydrology of the Mojave and Southern Great Basin deserts*. edited by Y. Enzel, S.G. Wells, and N. Lancaster, The Geological Society of America: 115-128.

Archer, D., 2005. Fate of fossil fuel CO_2 in geologic time, *J. Geophys. Res*., 110, C09S05, doi:10.1029/2004JC002625.

Archer, D., and A. Ganopolski, 2005. A movable trigger: Fossil fuel CO_2 and the onset of the next glaciation, *Geochem. Geophys. Geosyst.*, 6, Q05003, doi:10.1029/2004GC000891.

Bagtzoglou, A.C., 2003. Perched water bodies in arid environments and their role as hydrologic constraints for recharge rate estimation: Part 2. The Case of Yucca Mountain, *Environmental Forensics*, 4, 47-62.

Bard, E., 1997. Geochemical and geophysical implications of the radiocarbon calibration. *The Geochemical News*, 93, 6-7.

Barnett, T. P., and D. W. Pierce, 2008. When will Lake Mead go dry?, *Water Resour. Res*., 44, W03201, doi:10.1029/2007WR006704.

Benson, L., M. Kashagarian, R. Rye, S. Lund, F. Paillet, J. Smoot, C. Kester, S. Mensing, D. Meko, and S. Lindstrom, 2002. Holocene multidecadal and multicentennial droughts affecting northern California and Nevada. *Quaternary Science Reviews* 21: 659-682.

Berger, A., and M.F. Loutre, 2002. An exceptionally long interglacial ahead?, *Science*, 297, 1287–1288.

Bischoff, J.L., K. M Menking, J. P. Fitts, and J. A. Fitzpatrick, 1997. Climatic Oscillations 10,000–155,000 yr B.P. at Owens Lake, California Reflected in Glacial Rock Flour Abundance and Lake Salinity in Core OL-92. *Quaternary Research*, 48, 313-325.

Bonan, G.B., S. Levis, S. Sitch, M. Vertenstein, and K.W. Oleson, 2003. A dynamic global vegetation model for use with climate models: concepts and description of simulated vegetation dynamics, *Global Change Biol*., 9, 1543-1566.

Bonan, G.B., and S. Levis, 2006. Evaluating aspects of the Community Land and Atmosphere Models (CLM3 and CAM3) using a dynamic global vegetation model. *J. Clim*., 19, 2290-2301.

Bowen, G. J., and B. B. Bowen, 2008. Mechanisms of PETM global change constrained by a new record from central Utah, *Geology*, 36; 379-382, DOI: 10.1130/G24597A.1.

Bradbury, J.P., A diatom record of climate and hydrology for the past 20ka from Owens Lake, California with comparison to other great basin records, Quaternary Science Reviews, 16, 203-219, 1997.

Branstetter, M.L., and D.J. Erickson III, 2003. Continental runoff dynamics in the Community Climate System Model (CCSM2) control simulation, *J. Geophys. Res*., 108, doi:10.1029/2003JD003212.

BSC, (Bechtel SAIC Company), 2001. *Simulation of Net Infiltration for Modern and Potential Future Climates.* ANL-NBS-HS-000032 Rev 00 ICN 02.

BSC, 2003. Technical Basis Document No. 11: *Saturated Zone Flow and Transport: Revision 2*. Las Vegas, Nevada, Bechtel SAIC Company.

BSC, 2004. *Simulation of Net Infiltration for Present-Day and Potential Future Climates*. MDL-NBS-HS-000032 Rev 00.

Collins, W.D., C.M. Bitz, M.L. Blackmon, G.B. Bonan, C.S. Bretherton, J.A. Carton, P. Chang, S.C. Doney, J.J. Hack, T.B. Henderson, J.T. Kiehl, W.G. Large, D.S. McKenna, B.D. Santer, and R.D. Smith, 2006. The Community Climate System Model Version 3 (CCSM3). *J. Clim.*, 19, 2122-2143.

CCSP, 2008. *Abrupt Climate Change. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research* [Clark, P.U., A.J. Weaver (coordinating lead authors), E. Brook, E.R. Cook, T.L. Delworth, and K. Steffen (chapter lead authors)]. U.S. Geological Survey, Reston, VA, 459 pp.

Constantz, J., S.W. Tyler, and E. Kwicklis, 2003. Temperature-profile methods for estimating percolation rates in arid environments, *Vadose Zone Journal*, 2, 12-24.

CRWMS, 2001. *Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing, and Recharge at Yucca Mountain, Nevada.* ANL-NBS-HS-000021 REV 00, Las Vegas, Nevada: CRWMS.

Dickinson, R.E., K.W. Oleson, G. Bonan, F. Hoffman, P. Thornton, M. Vertenstein, Z.-L. Yang, and X. Zeng, 2006. The Community Land Model and its climate statistics as a component of the Community Climate System Model, *J. Clim.*, 19, 2302-2324.

DOE (U.S. Department of Energy), 2001. *Supplemental Science and Performance Analyses, Volume 1: Scientific Bases and Analyses, Revision 00*, TDR-MGR-000007.

DOE, 2002. Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada. DOE/EIS-0250, 2002.

DOE, 2004a. *Yucca Mountain Site Description*, TDR-CRW-GS000001 Rev 02 ICN 01.

DOE, 2004b. *Future Climate Analysis*, ANL-NBS-GS-000008-Rev 01, p. 6-34, Las Vegas, NV.

DOE, 2008. *Yucca Mountain Repository License Application Safety Analysis Report, DOE/RW-0573, Rev. 0* June 2008 Office of Civilian Radioactive Waste Management, Las Vegas, NV.

Domenico, P.A., and F.W. Schwartz, 1990. *Physical and chemical hydrogeology*. John Wiley & Sons, New York.

Eddebbarh, E.E., G.A. Zyvoloski, B.A. Robinson, E.M. Kwicklis, P.W. Reimus, B.W. Arnold, T. corbet, S.P. Kuzio, and C. Faunt, 2003. The saturated zone at Yucca Mountain: an overview of the characterization and assessment of the saturated zone as a barrier to potential radionuclide migration. *Journal of Contaminant Hydrology* 62-63:477-493.

EPRI (Electric Power Research Institute), 1996. *Yucca Mountain total system performance assessment, Phase 3*. Electric Power Research Institute, Final Report, TR-107191, 3055-02.

EPRI, 2006. *Program on Technology Innovation: EPRI Yucca Mountain Spent Fuel Repository Evaluation, 2006 Progress Report*, Technical Report No. 1013445, EPRI, Palo Alto, CA.

EPRI, 2007. *Program on Technology Innovation: EPRI Yucca Mountain Spent Fuel Repository Evaluation, 2007 Progress Report,* Technical Report No. 1015045, EPRI, Palo Alto, CA.

Flint, A.L.; J. A. Hevesi; and L. E. Flint, 1996. *Conceptual and Numerical Model of Infiltration for the Yucca Mountain Area, Nevada. Milestone 3GUI623M*. Denver, Colorado: U.S. Geological Survey.

Flint, A.L.; Flint, L.E.; Bodvarsson, G.S.; Kwicklis, E.M.; and J. M. Fabryka-Martin, 2001. Evolution of the conceptual model of unsaturated zone hydrology at Yucca Mountain, Nevada. *Journal of Hydrology*, 247, 1-30.

Flint, A. L.; L.E. Flint; E.M. Kwicklis; G.S. Bodvarsson; and J.M. Fabryka-Martin, 2001. Hydrology of Yucca Mountain, Nevada. *Reviews of Geophysics*, 39:4, 447-470.

Flint A.L., L.E. Flint, E.M. Kwicklis, J.T. Fabryka-Martin, G.S. Bodvarsson, 2002. Estimating recharge at Yucca Mountain, Nevada comparison of methods, *Hydrogeology Journal*, 10, 180-204.

Forester, R.M., J.P Bradbury, C. Carter, A.B. Elvidge-Tuma, M.L. Hemphill, S.A. Lundstrom, S.A. Mahan, B.D. Marshall, L.A. Neymark J.B., Paces, S.E. Sharpe, J.F. Whelan, and P.E. Wigand, 1999. *The Climatic and Hydrologic History of Southern Nevada During the Late Quaternary,* U.S. Geological Survey Open-File Report 98-635, 63 p.

Freeze, R.A., and P.A. Witherspoon, 1966. Theoretical analysis of regional ground-water flow. I, Analytical and numerical solutions to the mathematical model. *Water Resources Research* 2: 641-656

Gee, G.W., and D. Hillel, 1988. Groundwater recharge in arid regions: Review and critique of estimation methods, *Hydrologic Processes,* 2, 255-266.

Gerke, H.H. and M.T. Van Genuchten, 1993. A Dual-Porosity Model for Simulating the Preferential Movement of Water and Solutes in Structured Porous Media, *Water Resources Research* 29, no. 2: 305-319.

GSG (Groundwater Simulations Group), 2004. *HydroGeoSphere: A Three-dimensional Numerical Model Describing Fully-integrated Subsurface and Surface Flow and Solute Transport, User's Guide,* University of Waterloo, Waterloo, Ontario, Canada.

Heilweil, V.M., D.K. Solomon, and P.M. Gardner, 2006. Borehole environmental tracers for evaluating net infiltration and recharge through desert bedrock, *Vadose Zone Journal*, 5, 98-120.

IPCC, 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., and Miller, H.L. (eds.)]. Cambridge University Press, Cambridge, United 26 Kingdom and New York, NY, USA, 996 pp, 2007.

Kiehl, J. T., C. A . Shields, J. J. Hack, and W. D. Collins, 2006. The Climate Sensitivity of the Community Climate System Model Version 3 (CCSM3), *J. Clim.*, 19, 2584-2596.

Kwicklis, E.M., A.V. Wolfsberg, P.H. Stauffer, M.A. Walvoord, and M.J. Sully, 2006. Multiphase, multicomponent parameter estimation for liquid and vapor fluxes in deep arid systems using hydrologic data and natural environmental tracers, *Vadose Zone Journal,* 5, 934–950.

Lemieux, J.-M., E.A. Sudicky, W.R. Peltier, and L. Tarasov 2008. Dynamics of groundwater recharge and seepage over the Canadian landscape during the Wisconsinian glaciation, *J. Geophys. Res.*, 113, F01011, doi:10.1029/2007JF000838.

Levis, S., Bonan, G., Vertenstein M., and Oleson, K. W., 2004. *The Community Land Model's dynamic global vegetation model (CLMDGVM): Technical description and user's guide*. NCAR Technical Note, NCAR/TN-459+IA.

Li, H.C., J.L. Bischoff, T.L. Ku, Z.Y. Zhu, 2004. Climate and hydrology of the Last Interglaciation (MIS 5) in Owens Basin, California: isotopic and geochemical evidence from core OL-92," *Quaternary Science Reviews*, 23, 49-63.

Luckey, R.R., P. Tucci, C.C. Faunt, E. M. Ervin, W.C. Steinkampf, E.A. D'Agnese, and G.L. Patterson, 1996. *Status of understanding of the saturated-zone ground-water flow system at Yucca Mountain Nevada, as of 1995*. U.S. Geological Survey Water-Resources Investigations Report 96-4077.

Martinson, D.G., N. G. Pisias, J.D. Hays, J. Imbrie, T.C. Moore Jr., and N.J. Shackleton, 1987. Age dating and the orbital theory of the ice ages; development of a high-resolution 0 to 300,000-year chronostratigraphy, *Quaternary Research,* 27, 1–29.

Matsubara, Y. and A.D. Howard, 2009. "Spatially-explicit modeling of modern and Pleistocene runoff and lake extent in the Great Basin region, western United States," *Water Resources Research*, submitted.

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J., and Zhao, Z.-C. 2007. Global Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., and Miller, H.L. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.

Meijer, A., and E. Kwicklis, 2000. *Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing, and Recharge at Yucca Mountain, Nevada*, Rep. ANL-NBS-HS-000021, 131 pp., Office of Civilian Radioactive Waste Management, Dep. of Energy, N. Las Vegas, NV.

Mohanty, S., R. Codell, J.M. Menchaca, R. Janetzke, M. Smith, P. LaPlante, M. Rahimi, and A. Lozano, 2004. *System Level Performance Assessment of the Proposed Repository at Yucca Mountain Using the TPA Version 4.1 Code*, CNWRA 2002-05, Rev 2. Center for Nuclear Waste Regulatory Analyses, San Antonio TX.

Montenegro, A., V. Brovkin, M. Eby, Archer, D., and A. J. Weaver, 2007. Long term fate of anthropogenic carbon, *Geophys. Res. Lett*., 34, L19707, doi: 10.1029/2007GL030905.

Musgrove, M. and D.P. Schrag. 2006. *Climate Change at Yucca Mountain: Lessons from Earth History, in Uncertainty Underground: Yucca Mountain and the Nation's High-Level Nuclear Waste,* edited by Allison M. Macfarlane and Rodney C. Ewing, The MIT Press, Cambridge, Massachusetts, 149-162.

NRC, 2008. Nuclear Regulatory Commission, "Final Rule: 10 CFR Part 63, Implementation of a Dose Standard After 10,000 Years," (RIN 3150-AH68) November 4, 2008 SECY-08-0170

Oleson, K.W., Y. Dai, G. Bonan, M. Bosilovich, R. Dickinson, P. Dirmeyer, F. Hoffman, P. Houser, S. Levis, G.-Y. Niu, P. Thornton, M. Vertenstein, Z.-L. Yang, and X. Zeng, 2004. Technical description of the Community Land Model (CLM). NCAR Technical Note NCAR/TN-461+STR. National Center for Atmospheric Research, Boulder, Colorado. 173 pp.

Oleson, K.W., G.-Y. Niu, Z.-L. Yang, D.M. Lawrence, P.E. Thornton, P.J. Lawrence, R. Stöckli, R.E. Dickinson, G.B. Bonan, S. Levis, A. Dai, and T. Qian, 2008. Improvements to the Community Land Model and their impact on the hydrological cycle. *J. Geophysical Research,* 113, G01021, doi:10.1029/2007JG000563.

Otto-Bliesner, B.L., E.C. Brady, G. Clauzet, R. Tomas, S. Levis, and Z. Kothavala, 2006: Last Glacial Maximum and Holocene climate in CCSM3. *J. Clim.*, 19, 2526-2544, 2006.

Pagani, M., N. Pedentchouk, M. Huber, and 7 others, 2006. Arctic hydrology during global warming at the Paleocene/Eocene thermal maximum, *Nature*, 442, doi:10.1038/nature05043, 671-675.

Polyak, V. J. and Y. Asmeron, 2005. Orbital control of long-term moisture in the southwestern USA, *Geophys. Res. Lett*., L19709, doi:10.1029/2005GL023919.

Quade, J., M.D. Mifflin, W.L. Pratt, W. McCoy, and L. Burckle, 1995. Fossil spring deposits in the southern Great Basin and their implications for changes in water-table levels near Yucca Mountain, Nevada during Quaternary time. *Geological Society of America Bulletin*107, no. 2: 213-230.

Sandvig, R.M. and F.W. Phillips, 2006. Ecohydrological controls on soil moisture fluxes in arid to semiarid vadose zones, *Water Resources Research*, 42, W08422.doi:10.1029/ 2005WR004644.

Scanlon, B.R. 1991. Evaluation of moisture flux from chloride data in desert soils, *Journal of Hydrology,* 128, 137-156.

Scanlon, B.R., S.W. Tyler, and P.J. Wierenga, 1997. Hydrologic issues in arid, unsaturated systems and implications for contaminant transport, *Reviews of Geophysics,* 35, 461-490.

Scanlon, B.R., K. Kesse, R.C. Reedy, J. Simunek, and B.J. Andraski, 2003. Variations in flow and transport in thick desert vadose zones in response to paleoclimate forcing (0–90 kyr): Field measurements, modeling and uncertainty, *Water Resources Research*, 39, doi:10.1029/2002WR001604.

Scanlon, B. R., D Levitt, R.C. Reedy, K. Keese, and M Sully, 2005. Ecological controls on water-cycle response to climate variability in deserts, *Proceedings Nat. Acad. Sci.*, 102, 6033-6038.

Schelling, F. J., S. L. Thompson, 1997. *Future climate modeling scenarios*, SLTR97-0001, Department 6850 Letter Report.

Schwartz, F. W., E. A Sudicky, R. G. McLaren, Y. J. Park, M. Huber, and M. Apted, 2009. Transient 120,000-year response of the large regional flow system at Yucca Mountain, Nevada to complex cyclical variability in paleoclimate. *Ground Water,* submitted.

Seager, R., M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H-P. Huang, N. Harnik, A. Leetmaa, N-C. Lau, C. Li, J. Velez, and N. Naik, 2007. Model projections of an imminent transition to a more arid climate in southwestern North America, *Science*, 316, 1181-1184.

Shackleton, N.J., M.F. Sanchez-Goni, D. Pailler, Y. Lancelot, 2003. Marine isotope Substage 5e and the Eemian Interglacial, *Global and Planetary Change*, 36, 151-155.

Sharpe, S.E., 2007. Using modern through mid-Pleistocene climate proxy data to bound future variations in infiltration at Yucca Mountain, Nevada, in Levich, R.A., and Stuckless, J.S., eds., *The Geology and Climatology of Yucca Mountain and Vicinity, Southern Nevada and California: Geological Society of America Memoir* 199, p. 155-205, doi: 10.1130/2007.1199(05).

Sharpe, S. 2003a. *Future Climate Analysis—10,000 Years to 1,000,000 Years After Present*. MOD-01-001 REV 01. Reno, Nevada: Desert Research Institute, 2003a.

Sharpe, S., 2003b. *Yucca Mountain Climate: Past Present and Future.* Harry Reid Center Report. TR 03-001 Rev.00.

SNL, 2007. Simulation of Net Infiltration for Present-Day and Potential Future Climates. MDL-NBS-HS-000023 REV 01, Sandia National Laboratory, Albuquerque, NM.

Snyder, C.T., and W.B. Langbein, 1962. The Pleistocene lake in Spring Valley, Nevada, and its climatic implications. *Journal of Geophysical Research* 67: 2385-2394.

Stothoff, S. and G. Walter. 2007. *Long-Term-Average Infiltration at Yucca Mountain, Nevada: Million-Year Estimates.* CNWRA 2007-003. San Antonio, Texas: CNWRA.

Therrien, R., R.G. McLaren, E.A. Sudicky and S.M. Panday, 2005. *HydroGeoSphere: a three-dimensional numerical model describing fully-integrated subsurface and surface flow and solute transport.* Groundwater Simulations Group, University of Waterloo, Waterloo, Ontario, Canada, 322p.

Thompson, R.S. and K.H. Anderson, 2000. Biomes of western North America at 18,000, 6000 and 0 14C yr BP reconstructed from pollen and packrat midden data, *Journal of Biogeography*, 27, 555-584.

Tyler, S.W., J.B. Chapman, S.H. Conrad, D.P. Hammermeister, D.O. Blout, J.J. Miller, M.J. Sully, and J.M. Ginanni, 1996. Soil-water flux in the southern Great Basin, United States: Temporal and spatial variations over the last 120,000 years, *Water Resources Research*, 32, 1481– 1499.

Tóth, J., 1978. Gravity-induced cross-formational flow of formation fluids, Red Earth region, Alberta, Canada: Analysis, patterns, evolution. *Water Resources Research* 14, no. 5: 805-843.

Uchikawa, J., and R. E. Zeebe, 2008. Influence of terrestrial weathering on ocean acidification and the next glacial inception, *Geophys. Res. Lett.*, 35, L23608, doi:10.1029/2008GL035963, 2008.

USGS, 2001a. *Future Climate Analysis*. ANL-NBS-GS-000008 REV 00 ICN 01. Denver, Colorado: U.S. Geological Survey.

USGS, 2001b. *Simulation of Net Infiltration for Modern and Potential Future Climates*. ANL-NBS-HS-000032 REV 00 ICN 02. Denver, Colorado: U.S. Geological Survey.

USNRC (U.S. Nuclear Regulatory Commission) 1997. *Issue Resolution Status Report on Methods to Evaluate Climate Change and Associated Effects at Yucca Mountain (Key Technical Issue: Unsaturated and Saturated Flow Under Isothermal Conditions).* Washington, D.C.: U.S, Nuclear Regulatory Commission.

Walvoord, M.A., M.A. Plummer, F.M. Phillips, and A.V. Wolfsberg, 2002a. Deep arid system hydrodynamics: 1. Equilibrium states and response times in thick desert vadose zones, *Water Resources Research*, 38, doi:10.1029/2001WR000824.

Walvoord, M.A., F.M. Phillips, S.W. Tyler, and P.C. Hartsough, 2002b. Deep arid system hydrodynamics 2. Application to paleohydrologic reconstruction using vadose zone profiles from the northern Mojave Desert, *Water Resources Research*, 38, doi:10.1029/2001WR000825.

Walvoord, M.A., D.A. Stonestrom, B.J. Andraski, R.G. Striegl,2004. Constraining the inferred paleohydrologic evoution of a deep unsaturated zone in the Amargosa Desert, *Vadose Zone Journal*, 3, 502-512.

Wang, G., 2005. Agricultural drought in a future climate: results from 15 global climate models participating in the IPCC 4th assessment, *Climate Dynamics*, 25, 739–753, DOI 10.1007/s00382-005-0057-9.

Wilson, J.L., and H. Guan, 2004. Mountain-block hydrology and mountain-front recharge. p. 113–137. In J.F.Hogan et al. (ed.) *Groundwater recharge in a desert environment: The southwestern United States. Water Sci. and Appl. Ser. 9.* Am. Geophys. Union, Washington, DC.

Wilson, M.L., and C.K. Ho, 2002. TSPA model for the Yucca Mountain unsaturated zone, *WM'02 Conference*, February 24-28, Tucson, AZ.

Winterle, J., 2004. CNWRA Modeling of Site-scale Saturated Zone Flow at Yucca Mountain: Presentation to Nuclear Waste Technical Review Board Meeting, March 10, 2004, Las Vegas Nevada, available, http://www.nwtrb.gov/meetings/march%202004/winterle.pdf.

Winnograd, I.J., and W. Thordarson, 1975. *Hydrogeologic and hydrochemical framework, south-central Great Basin, Nevada-California with special reference to the Nevada Test Site*, U.S. Geological Survey Professional Paper 712-C: C1-C126.

Wolfsberg, A., and P. Stauffer, 2003. *Vadose-Zone Fluid and Solute Flux: Advection and Diffusion at the Area 5 Radioactive Waste-Management Site*, Report LA-UR-03-4819. Los Alamos National Laboratory, Los Alamos, NM.

Woocay, A., and J.C. Walton, 2006. Climate change effects on Yucca Mountain region groundwater recharge. *IHLRWM 2006*, Las Vegas, Nevada: 191-198.

Woolfenden, W.B., 2003. A 180,000-year pollen record from Owens Lake, CA: terrestrial vegetation change on orbital scales, *Quaternary Research*, 49, 430-444.

Wu, Y.S., S. Mukhopadhyay, K. Zhang , and G.S. Bodvarsson, 2006. A mountain-scale thermal–hydrologic model for simulating fluid flow and heat transfer in unsaturated fractured rock, *J. Contaminant Hydrology*, 86, 128-159.

Wu, Y. S., G. Lu, K. Zhang, L. Pan, and G. S. Bodvarsson, 2007. Analyzing unsaturated flow patterns in fractured rock using an integrated modeling approach, *Hydrogeology Journal*, 15, 553-572.

Yeager, S., C. Shields, W. Large, and J. J. Hack, 2006. The low resolution CCSM3. *J. Climate*, 19, 2545–2566.

Zhang, K, Y. S. Wu, and L. Pan, 2006. Temporal damping effect of the Yucca Mountain fractured unsaturated rock on transient Infiltration pulses, *Journal of Hydrology*, 327, 235– 248.

Zhu, C., J.R. Winterle and E.I. Love, 2003. Late Pleistocene and Holocene groundwater recharge from the chloride mass balance method and chlorine-36 data, *Water Resources Research*, 39, doi:10.1029/2003WR001987.

The Electric Power Research Institute Inc., (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI's members represent more than 90 percent of the electricity generated and delivered in the United States, and international participation extends to 40 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together…Shaping the Future of Electricity

Printed on recycled paper in the United States of America

1018714

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com