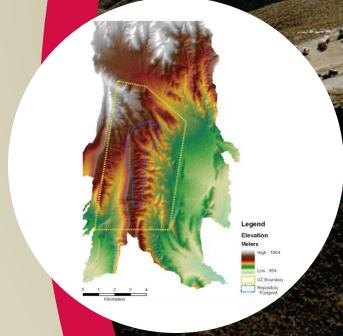
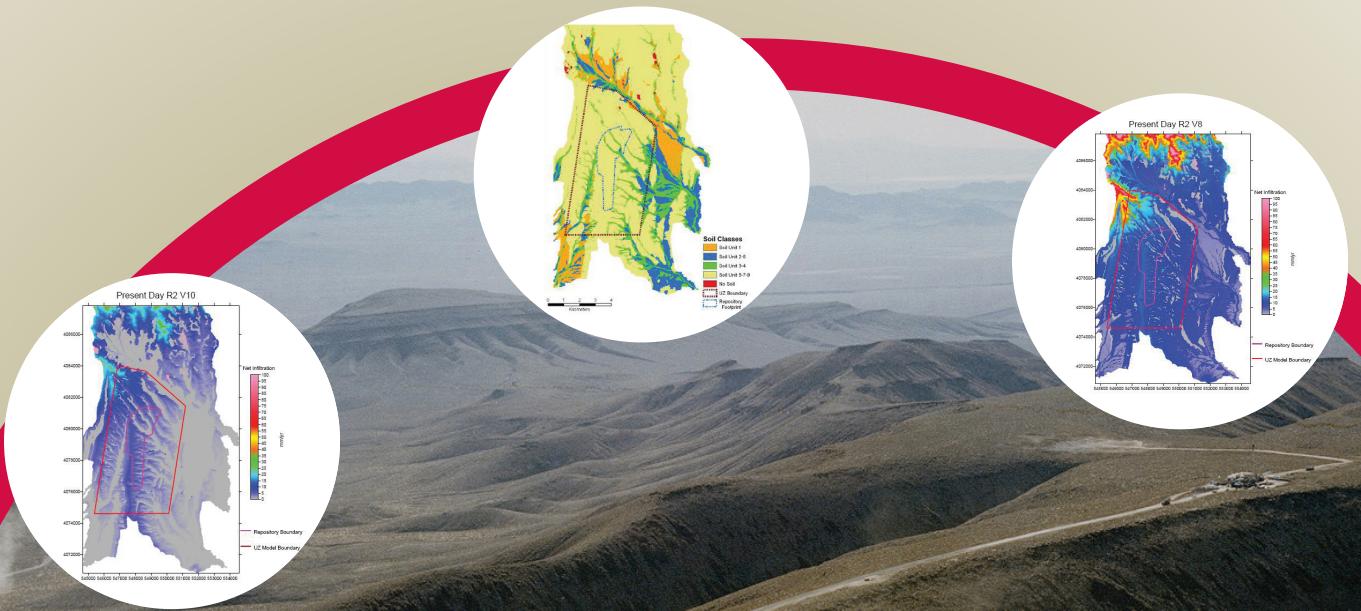


Independent Review of Simulation of Net Infiltration for Present-Day and Potential Future Climates

(MDL-NBS-HS-000023, Rev. 01)

April 2008



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Independent Review of
***Simulation of Net Infiltration for Present-Day and
Potential Future Climates***

MDL-NBS-HS-000023, Rev. 01

Yucca Mountain Project

April 2008

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Simulation of Net Infiltration for Present-Day and Potential Future
Climates
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Yucca Mountain Project

SUMMARY

The DOE Office of Civilian Radioactive Waste Management (OCRWM) tasked Oak Ridge Institute for Science and Education (ORISE) with providing an independent expert review of the documented model and prediction results for net infiltration of water into the unsaturated zone at Yucca Mountain. The specific purpose of the model, as documented in the report MDL-NBS-HS-000023, Rev. 01, is “to provide a spatial representation, including epistemic and aleatory uncertainty, of the predicted mean annual net infiltration at the Yucca Mountain site ...” (p. 1-1)

The expert review panel assembled by ORISE concluded that the model report does not provide a technically credible spatial representation of net infiltration at Yucca Mountain. Specifically, the ORISE Review Panel found that:

- A critical lack of site-specific meteorological, surface, and subsurface information prevents verification of (i) the net infiltration estimates, (ii) the uncertainty estimates of parameters caused by their spatial variability, and (iii) the assumptions used by the modelers (ranges and distributions) for the characterization of parameters. The paucity of site-specific data used by the modeling team for model implementation and validation is a major deficiency in this effort.
- The model does not incorporate at least one potentially important hydrologic process. Subsurface lateral flow is not accounted for by the model, and the assumption that the effect of subsurface lateral flow is negligible is not adequately justified. This issue is especially critical for the wetter climate periods. This omission may be one reason the model results appear to underestimate net infiltration beneath wash environments and therefore imprecisely represent the spatial variability of net infiltration.
- While the model uses assumptions consistently, such as uniform soil depths and a constant vegetation rooting depth, such assumptions may not be appropriate for this net infiltration simulation because they oversimplify a complex landscape and associated hydrologic processes, especially since the model assumptions have not been adequately corroborated by field and laboratory observations at Yucca Mountain.

The review panel noted that the model is well documented in the simulation report and the derivation of its results is transparent and traceable. However, because of the

lack of site-specific data and the use of an oversimplified model, the review panel was unable to confirm whether the model uses parameter values, assumed ranges, probability distributions, and bounding assumptions that are technically defensible, reasonably account for uncertainties and variabilities, and do not result in an underestimation of the long-term net infiltration.

The spatially averaged net infiltration estimates that result from the modeling effort (summarized in Table 6.5.7.8-1 in the model report), along with their uncertainty ranges, may or may not accurately capture the value of net infiltration at Yucca Mountain for the modeling domain as a whole. The fact that the results are generally consistent with other regional estimates for mean net infiltration is not proof they are correct for Yucca Mountain. More importantly, in the opinion of the review panel, calculated spatial averages may be less relevant than identification of areas where sustained infiltration may exceed the averages, along with characterization of the likely distribution of such areas over the modeling domain.

Statements in the report indicate a general lack of confidence in the spatial distribution of net infiltration values produced by the model. Maps of mean annual net infiltration suggest distinct spatial patterns of infiltration, but they do not compare well with limited field observations, and the limited discussion of spatial variability suggests the variance within map colors may greatly exceed the difference between colors. Not enough field data are available to adequately constrain and characterize the spatial variability and patterns. It is not possible to confirm with existing information that there are not areas for which infiltration is underestimated. Even with a wide uncertainty range, the infiltration at a given location could be underestimated because of soil and root depths, subsurface lateral flow, and other heterogeneities such as fracture properties and fracture distribution that vary differently than the assumed (but largely unknown/untested) values. For example, the modeling simulation does not show significant infiltration beneath ephemeral stream channels; the report's authors caution that "this result raises some important questions about the predicted spatial distribution of net infiltration produced by the model" (p. 6-203).

The ORISE Review Panel concludes, along with the report authors, that "more field work would have to be performed in order to evaluate the accuracy of the spatial distribution of net infiltration in the current maps" (p. 6-203). For quantification of the uncertainty range of the spatial distribution of the net infiltration, collection of sufficient site-specific data will be required to better characterize such critical parameters as soil hydraulic properties, soil depth, fracture distributions, and vegetation rooting depth and to test the underlying assumptions of the modeling effort, most notably, the assumed negligible effect of subsurface lateral flow. The report's authors are in agreement: "Sensitivity analyses ... suggest that there may be insufficient characterization of soil properties (depth, holding capacity, and hydraulic conductivity) over the modeling domain to obtain accurate and detailed maps of net infiltration" (p. 8-11). Only with adequate field data can the modeling effort accomplish its purpose of credibly describing the spatial distribution and associated uncertainty bounds for net infiltration of water at Yucca Mountain.

Independent Review of
Simulation of Net Infiltration for Present-Day and Potential Future
Climates
MDL-NBS-HS-000023, Rev. 01

Yucca Mountain Project

1.0 PURPOSE

The purpose of this independent review is to assess whether the model and results documented in MDL-NBS-HS-000023, Rev. 01, *Simulation of Net Infiltration for Present-Day and Potential Future Climates*, credibly meet their intended purpose. The specific purpose of the model is to provide a spatial representation, including its uncertainty, of the predicted mean annual net infiltration at the Yucca Mountain site for present-day and potential future climate scenarios. The model applies “a simple water mass-balance approach to the near-surface layer that is influenced by evapotranspiration” (p. 1-1) for predicting net infiltration of water into the unsaturated zone (UZ). The UZ, including the soil and rock above the water table, is one of the natural barriers classified as “Safety Category” because of its importance to waste isolation at the Yucca Mountain site (p. 2-1).

2.0 BACKGROUND

The U.S. Department of Energy (DOE) Office of Civilian Radioactive Waste Management (OCRWM) is preparing an application for submittal to the U.S. Nuclear Regulatory Commission (NRC) for authorization to construct a repository for nuclear waste at Yucca Mountain in Nevada. In preparation for the application, a Total System Performance Assessment (TSPA) is being prepared that predicts the flow of water through the mountain over time. Infiltration of water is one of the parameters in the TSPA, with the results of the net infiltration model being fed to the TSPA through the UZ flow model for the fractured bedrock enclosing the waste repository footprint. The predicted spatial distribution of mean annual net infiltration at the soil-bedrock interface is used as the top boundary condition, or potential recharge, for the UZ flow model.

Net infiltration is the result of several distinct processes occurring in different portions of the site, including mountain block, mountain front, ephemeral stream channels, and interdrainage areas of the basin floor. As pointed out by the authors of the report, the processes controlling net infiltration in arid and semiarid regions are “highly variable in both time and space, and the dominant mechanisms may vary throughout the basin” (p.-6-4).

An early net infiltration model was used to simulate the spatial distribution of water infiltration at Yucca Mountain, and a report was issued, along with associated maps. However, in March 2005, OCRWM became aware of emails exchanged by employees of

the U.S. Geological Survey (USGS) that indicated a lack of compliance with Yucca Mountain Project Quality Assurance (QA) requirements. The emails pertained to the infiltration model developed by the USGS and the development of the site-specific net infiltration rate estimates for present and future climates. In response, OCRWM conducted (1) a technical evaluation that determined the USGS net infiltration rate estimates are corroborated by independent studies of infiltration and recharge in semi-arid environments and (2) a programmatic evaluation that examined the QA issues but was unable to resolve whether conditions adverse to quality had occurred. A report of these evaluations, issued in February 2006, noted that while the science seemed sound, QA concerns remained. To allay these concerns, OCRWM directed Sandia National Laboratories (SNL), the Lead Laboratory for Repository Systems, to create a new infiltration model and associated climate maps while ensuring traceability, transparency, and full compliance with OCRWM QA requirements.

The new infiltration model has been termed MASSIF (Mass Accounting System for Soil Infiltration and Flow). MASSIF, along with its results, has been documented in Revision 01 of the model report, which is the subject of this review. MASSIF is a collection of Mathcad “routines” that was designed to provide an estimate of the net infiltration of water into the fractured rock that underlies the soil at Yucca Mountain. The core of MASSIF is a daily water balance for each 30 m × 30 m cell in the modeling domain, the dimensions corresponding to the high spatial resolution of Landsat images.

The daily water balance for the soil in each cell is:

$$R_{off} = P_{rain} + R_{on} + SM - \Delta\theta - ET - NI$$

where

- R_{off} = surface runoff
- P_{rain} = precipitation as rain
- R_{on} = surface run-on
- SM = snowmelt
- $\Delta\theta$ = change in water storage in the soil
- ET = actual evapotranspiration
- NI = net infiltration

The water balance is written as a calculation for the runoff from the cell, in which all the quantities to the right of the equals sign are computed from submodels (pp. 6-23 – 6-24).

Such a determination of net infiltration in arid and semiarid regions is inherently difficult for two primary reasons. First, the infiltration depends on a water balance in which actual evapotranspiration is almost equal to precipitation. The net infiltration is thus mainly determined by subtracting two relatively large numbers (precipitation and evapotranspiration) to find a small number (infiltration). So even when precipitation and evapotranspiration can be determined with small uncertainty bounds, large uncertainty remains for the infiltration (Gee and Hillel, 1988). The second reason is the large spatial and temporal variability of water fluxes in arid environments (Scanlon et al., 1997). The

MASSIF approach deals with these issues by using small grids (30 m × 30 m) and small time steps (one day).

Simulations of net infiltration using MASSIF were conducted over the 125 km² domain encompassing Yucca Mountain under three climate scenarios: Present-Day, Monsoon, and Glacial Transition. These climates represent the likely range of states for the Yucca Mountain region and are reasonably justified for the 10,000 years in this study.

3.0 REVIEW PROCESS

To ensure the highest quality and objectivity of the science and technology supporting the Yucca Mountain Project, OCRWM has adopted a policy of “trust, but verify,” in which external experts in appropriate technical disciplines independently verify and validate key project work as a matter of routine, before and as part of the acceptance process. In April 2006, OCRWM selected the Oak Ridge Institute for Science and Education (ORISE) at Oak Ridge Associated Universities in Tennessee to perform this work.

For the MASSIF model developed by SNL, ORISE was tasked with performing an independent, objective review of the model report and associated results. ORISE would accomplish this task by engaging the services of recognized experts in infiltration modeling, climate, and predictive modeling to determine whether the model report and supporting documentation provide (1) a credible analysis of the infiltration rates associated with the Yucca Mountain repository for current and future climates and (2) a transparent and traceable presentation of the infiltration model and associated data sets to allow outside experts to reproduce the results from the model.

ORISE assembled a review panel of five recognized experts in hydrology, infiltration modeling, climate, and predictive modeling. Each expert comes from a distinguished university in the arid Southwestern states surrounding the Yucca Mountain site. Brief qualifications of the five reviewers are given in Appendix A. The review panel was charged by ORISE with giving their expert opinion on whether the model report (1) credibly meets its intended purpose; (2) is transparent, traceable, and reproducible; and (3) adequately meets nuclear regulatory standards and requirements, as well as (4) identifying additional work or research that may be needed. The detailed Charge to Reviewers is given in Appendix B.

The review panel studied the subject report and several supporting documents (listed in Appendix C) and discussed issues, concerns, and recommendations in a series of conference calls and at a meeting in Las Vegas. ORISE staff facilitated the interactions and a technical editor compiled reviewer contributions and comments into report drafts for circulation and revision by the review panel. The report represents a consensus opinion of the panel members that emerged through the review process.

The scope of this review included only the Rev 01 infiltration modeling report by Sandia National Laboratories—the review did not evaluate linkages or relationships with the

unsaturated zone (UZ) modeling efforts or the Total System Performance Assessment (TSPA). It also did not consider the Rev 00 infiltration modeling report by the USGS.

During the effort leading to this final report, the review panel received comments on a draft from DOE, along with an addendum to the infiltration model report (MDL-NBS-HS-000023 Rev 01 AD 01) that provides some new soil depth data and also compares MASSIF results with infiltration estimates in the recent NRC report, *Long-Term-Average Infiltration at Yucca Mountain, Nevada: Million-Year Estimates* (CNWRA 2007-003, Stothoff and Walter, 2007). In addition, DOE provided a section of the recently approved TSPA model report (MDL-WIS-PA-000005 Rev 00) that explains how the infiltration model results are used as input to the UZ flow model and the TSPA. The review panel has considered the DOE review comments and exclusively the new soil depth information in the addendum and has incorporated minor revisions when appropriate to clarify statements in this final report. However, the panel found that the additional soil depth information presented in the addendum did not change its conclusions as presented in this review report.

4.0 ANSWERING THE CHARGE

A. Does the subject report, *Simulation of Net Infiltration for Present-Day and Potential Future Climates*, credibly meet its intended purpose of “providing a spatial representation, including epistemic and aleatory uncertainty, of the predicted mean annual net infiltration at the Yucca Mountain site”...for present-day and potential future climate scenarios?

The ORISE Review Panel concluded that the simulation report does not credibly meet its intended purpose to provide spatial representation of the predicted mean annual net infiltration into Yucca Mountain. At the entire-domain scale, the model may adequately represent the regional water balance; its spatially averaged results and uncertainty bounds for the entire site are generally consistent with other regional estimates for mean annual net infiltration. However, this agreement among estimates does not necessarily mean that the spatially averaged results from the MASSIF model correctly represent long-term infiltration rates for the mountain as a whole or, more importantly, that infiltration for significant areas of the domain (such as upland convergent areas and upper reaches of ephemeral streams/washes) is not underestimated by the modeling approach, which assumed uniform conditions over large areas of heterogeneous soils. The spatial representation of the net infiltration at Yucca Mountain is acknowledged by the authors of the report to be of low confidence.

The one-dimensional representation of some important hydrologic processes and the lack of more detailed site-specific data for use in the model calculations compromise the reported spatial distribution of net infiltration. For example, the model was not capable of representing observed infiltration beneath washes and ephemeral streams without significant calibration and alteration of assumed hydraulic properties that were used for the final infiltration estimates. Infiltration under ephemeral washes, especially in upper reaches and under wetter meteorological and climatic conditions, is likely to lead to

significant recharge in those areas. For example, significant net infiltration beneath washes failed to be predicted under the monsoon climate scenarios, when significant net infiltration would likely occur. The inability of MASSIF to adequately capture infiltration under washes is likely due to lack of site-specific soil data for parameterization, the omission of subsurface lateral flow in the model, the “resetting” of soil moisture to dry conditions at the end of each water year, and the overestimation of soil depth in upper wash environments that leads to overestimation of evapotranspiration in the upper wash areas.

Figure 7.2.1.1-1 in the model report shows that the majority of soil depths assumed for MASSIF are larger than those from reported Yucca Mountain measurements. Soil depth class 2 seems to be very poorly predicted; this is the depth class likely to be in the washes. In particular, soil depths for soil depth class 2 show the most overestimation (only two MASSIF depths are less than the observed soil depths). This may explain the inability of MASSIF to accurately model runoff. Many of the boreholes are in soil depth class 2, where MASSIF consistently over predicts soil depth and therefore likely under predicts net infiltration.

In addition, the model results show an apparent lack of upland and interfluvue infiltration variability. This lack of upland variability likely results from the simplification, or “lumping,” of input parameters, such as the spatial aggregation of soil and geologic units and a constant rooting depth assumed for each soil type, and from the omission of the effect of subsurface lateral flow.

a. Was the methodology used appropriate and effectively applied?

The mass-balance approach used by MASSIF is appropriate for the time and space scales considered. MASSIF was competently applied, especially considering the limited amount of site-specific data used by the modeling team for parameterizing the model.

However, the characterization of the geologic inputs (hydraulic properties of soils, soil depths, and saturated hydraulic conductivity of bedrock) is questionable, given that the values for these parameters were derived without using measurements from Yucca Mountain either in the field or in the laboratory, with the exception of a few soil depth and bedrock K_{sat} measurements. The near absence of soil depth and soil hydraulic measurements from the site for validation is one of the primary weaknesses of the reported estimates.

For example, the Hanford-derived pedotransfer function is of questionable value for use at Yucca Mountain without extensive testing and comparison. Yet, the soil hydraulic properties calculated by the pedotransfer function have not been compared to site-specific Yucca Mountain soil properties measured directly as part of site-characterization activities. The panel reviewed the comparison of the Hanford-derived soil hydraulic properties to the measured water content/capillary pressure measurements from USDA, *Soil Survey of Nye County, Nevada, Southwest* (2004), as well as the reported measurements of hydraulic conductivity and data from Istok et al., both reported in *Data*

Analysis for Infiltration Modeling: Development of Soil Units and Associated Hydraulic Parameter Values (ANL-NBL-HS000055), but the review panel believes that the transfer function model needs to be compared to soil data collected at Yucca Mountain specifically for site characterization.

In addition, no scale adjustments are made from the point-scale values to the 30 m × 30 m model grids in the MASSIF application. The effect of upscaling to 30 meters depends strongly on the local topography that may vary widely for different cells across the modeling domain, which is acknowledged by the authors (p. 6-218). For such a large modeling region, upscaling of hydraulic parameters (e.g., Zhu and Mohanty, 2002; 2006; Mohanty and Zhu, 2007) for individual grid cells with site-specific conditions and complexities would be expensive and time consuming. However, some level of generalized linear or nonlinear bias correction (e.g., Jana et al., 2007) of soil hydraulic parameters, based on field-observed local distributions at Yucca Mountain, could have adjusted the point-scale soil hydraulic parameters to more accurately represent the 30 m × 30 m grid resolution.

The assumption that subsurface lateral flow is unimportant for this modeling effort is not tested nor is it convincingly justified. Subsurface lateral flow may be important or maybe not. The statement that “most of the model domain is characterized by relatively low slopes” is not supported by the reported median slope for the domain of ~10 degrees and the statement that 90% of the domain has a slope of less than 25 degrees (p. 5-1). Slopes of >10 degrees likely contribute to the lateral head gradient. In addition, variations in soil layering, soil depth, rooting depth, bedrock topography, and fracture connectivity all may contribute to development of subsurface lateral flow (Zaslavsky and Sinai, 1981a and b; Yeh et al., 1985c), which is likely to lead to redistribution of recharge and strongly affect the spatial distribution of calculated net infiltration. For example, subsurface lateral flow can reduce vertical percolation of water and increase evapotranspiration, thus reducing net infiltration. Or, lateral flow may increase net infiltration by diversion of water to washes or other likely flow paths to the deep subsurface, such as head slopes, where water is converging, in first order drainage basins. As a result, it is important to consider the impact on net infiltration of subsurface lateral flow that possibly occurs at specific locations experiencing extreme fluxes, rather than assuming the flux is distributed uniformly across a grid cell, hillslope, or catchment.

An additional question in the methodology is the use of a fracture/matrix volume fraction weighted approach to estimate the saturated hydraulic conductivity of the fractured bedrock (p. 6-96). In the opinion of the review panel, a flow-weighted approach would have been more realistic.

b. Were alternative modeling approaches and their results and limitations appropriately considered?

The alternative models selected for consideration (Sec. 6.2.4) were HYDRUS-1D and HELP (Hydrologic Evaluation of Landfill Performance). HYDRUS-1D solves the Richards' equation for variably saturated water flow. The report states that this

alternative model was not used because (1) it is unable to simulate runoff between cells and (2) the previous model used for net infiltration was a mass-balance model and the available data were more compatible with that approach. However, the report acknowledges (p. 6-15) that the inability to simulate runoff could have been overcome by examining two- or three-dimensional versions of HYDRUS, but “other models and methods were easier to implement.” The report also acknowledges that “the strength of a Richards’ equation approach is that it can simulate the spatial and temporal details of unsaturated water movement in soil” and that “appropriate properties could have been estimated and developed for a Richards’ equation approach...” This was not pursued because it requires “substantial and detailed information” and “the available soil property dataset was limited.”

HELP incorporates a quasi-two-dimensional water balance model to simulate water movement in the unsaturated zone. HELP was not used “primarily because it was developed for a different type of application” (landfill systems). To be used in this modeling effort, “HELP would require substantial modifications.”

The reasons given for not using such alternative modeling approaches are not sufficient. A more realistic two- or three-dimensional model that can simulate the details of unsaturated water movement in soil is what is needed to capture the subsurface lateral flow that likely affects the spatial distribution of the net infiltration or, at least, to develop simple but more realistic routines for improved simulation of subsurface lateral flow. For example, results from a 3-D Richards’ equation are more realistic than those from a 1-D Richards’ equation, even when the same hydraulic properties (or data) are used. Lack of data or the need for substantial modifications of existing numerical simulators is not sufficient justification for using the one-dimensional MASSIF model.

c. Are bounds of uncertainty adequately defined?

The uncertainty reported at the aggregated domain level for the spatially averaged, mean annual results may be adequately defined; but given the lack of field measurements and the omission of subsurface lateral flow, this is impossible to confirm. The reported uncertainty is based on parameter uncertainty; however, the discussion in Section 6.6.3 suggests that model uncertainty “may be of a comparable magnitude to parameter uncertainty” (p. 6-219). Whether the two uncertainties may be additive, multiplicative, or otherwise, is not addressed.

Discussion of spatial distribution uncertainty is limited. Spatial uncertainty is not characterized in the report by soil depth class, bedrock type, or other key-variable spatial aggregation. The color differences on the net infiltration maps suggest there are significant differences in infiltration by location on the landscape, but data that support this are not presented. The different map colors shown may not be statistically significant, since the discussion of spatial uncertainty in Section 6.6.2 suggests that variability within map colors may be greater than the differences between map colors. If it is unrealistic to characterize uncertainty within a map color for an area as large as Yucca Mountain, then it makes little sense to show such a delineation. The report states

that local uncertainty by pixel may be a factor of 50 or more (p. 6-217) and that local infiltration uncertainty in areas with shallow soils may be approximately 6 (p. 6-218). These issues place in doubt the proposition that the reported spatially averaged, mean annual infiltration estimates (and the associated uncertainty) for the aggregated domain do not underestimate net infiltration for some areas of the mountain.

Uncertainty of the infiltration process due to spatial variability of unsaturated hydraulic properties (epistemic uncertainty) has been intensively investigated using a three-dimensional Richards' equation (Gelhar, 1993; Mantoglou and Gelhar, 1987; Yeh et al., 1985a, b, and c). Results of these studies have shown that the uncertainty in infiltration depends on means, variances, and correlation scales (average thickness and lateral extent of soil layers) of the saturated hydraulic conductivity and pore-size distribution parameters and the average moisture contents as well as uncertainty in boundary conditions (e.g., Ferrante and Yeh, 1999). It is well-known and well-documented that spatial variability in soil properties is not spatially independent but, rather, spatially correlated due to natural processes (e.g., Russo and Bouton, 1992; Russo et al., 1997). It appears that the epistemic uncertainty in this report mainly deals with the variance of the saturated hydraulic conductivity and some other parameters but not spatial correlations. Specifically, the probability distributions assigned to the parameters (p. 6-220) should have been joint probability distributions (i.e., the parameters should have been treated as spatially random fields)—the lack of site-specific data perhaps contributed to this approach. The omission of lateral interaction of vertical soil columns (i.e., subsurface lateral flow) further undermines the uncertainty analysis.

Finally, the validation cases in the simulation report are not sufficient to show that the range of uncertainty has been captured. In most instances, the validation cases required calibration of MASSIF parameters in order to reproduce the observed behavior (the need to calibrate raises doubt about the realism of the spatial patterns shown). The review panel is not convinced that the bounds of uncertainty have been fully defined, due to the lack of inclusion or comparison with site-specific data; without sufficient data for validation, there is no assurance that the distributions fully capture the ranges of uncertainty.

B. Is the presentation of the infiltration model and associated data sets transparent and traceable to allow outside experts to reproduce the results of the model?

The work presented in the model report is transparent and traceable. The overall conceptual model and the mathematical models for the individual components are well documented in the main report as well as in the extensive appendices and supporting documents. The modeling is described in sufficient detail for reproducibility of the results, although the evapotranspiration discussion could be improved so that an outside expert can more easily reproduce the results.

C. Adequacy in meeting nuclear regulatory standards and requirements as they pertain to the subject of this review [refer to subject report (*Simulation of Net Infiltration for Present-Day and Potential Future Climates*) Section 4.2, pages 4-6 to 4-9, for applicable requirements]

The nuclear regulatory standards and requirements are stated in 10 CFR Part 63, “Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada.” The acceptance criteria that will be used by the NRC to determine whether those requirements have been met are defined in *Yucca Mountain Review Plan, Final Report*, Section 2.2.1.3.5.3 (NUREG-1804). The infiltration-model report’s authors repeat these requirements in Section 4.2 and address each in Section 8.3.

The review panel determined that its assessment of key issues regarding the model’s technical credibility is sufficiently presented throughout this review report and chose not to repeat these issues here by specifically addressing each acceptance criterion. Overall adequacy and acceptability of the infiltration model will be determined by NRC review.

D. Additional work or research needs that may be identified.

a. Describe any near-term or long-term key knowledge gaps. Are any of these gaps important to current decision making?

The spatial distribution of net infiltration that results from this modeling effort is not adequately represented. If a smaller uncertainty range and/or a more credible spatial distribution of the net infiltration is needed for the subsequent UZ model, the research suggested below is recommended to help resolve issues and knowledge gaps identified by this review panel. The unresolved issues addressed by this suggested research are discussed in detail in Appendix D.

1. **Critically limited site-specific data.** A systematic and coordinated data collection and monitoring effort is needed for parameterization, uncertainty analysis, and validation of the MASSIF model, which would lead to a more credible determination of the spatial distribution of net infiltration at Yucca Mountain. The current report clearly shows the need for additional site-specific data on soil hydraulic properties and rooting depths, as well as soil distribution and soil thickness across Yucca Mountain. Without a reliable independent dataset to verify the parameters used as input to MASSIF, validation and uncertainty analyses will be inadequate. Combining remote sensing (aerial photos, satellite imagery) and field measurements with geophysical methods (electromagnetic induction, ground-penetrating radar) and analysis of terrain attributes should result in much more reliable maps of soil depths, soil hydraulic properties, and rooting depths. A considerable amount of information is available on the “digital soil mapping” approach (Lagacherie et al., 2007; Lamotte et al., 1994; McBratney et al., 2003).

2. Subsurface lateral flow excluded by the modeling approach. The potential for capturing the impact of subsurface lateral flow is excluded by the one-dimensional mass-balance modeling approach used. Extension of the MASSIF model to include subsurface lateral flow, or at a minimum, comparison to models that account for subsurface lateral flow, is needed to better understand the predicted lack of net infiltration in the wash environments during wetter climates and the lack of variability of infiltration in upland areas. Such an analysis is necessary to quantify the spatial distribution of net infiltration into Yucca Mountain.
3. Incompletely defined bounds of uncertainty. The bounds of uncertainty have not been fully defined due to the lack of site-specific data for determining uncertainty in parameters due to spatial variability, as well as comparison of the model results with site-specific data and with alternative modeling predictions. Comparison with a more realistic, coupled surface-subsurface model would be helpful. Such a comparison could focus on a small-scale representative watershed, or just a hillslope, comparing the net infiltration predicted by MASSIF with the net infiltration from a more conceptually realistic model capable of capturing interactions between adjacent columns. Such a comparison would test the impact of the assumption that the effect of subsurface lateral flow is negligible.
4. Limited validation examples. The validation cases are not sufficient to show that the range of uncertainty has been captured. Additional validation can come from two sources: (1) validation experiments (i.e., actual infiltration testing) and (2) existing site-specific data that has apparently not been used for parameterization in this modeling effort. If quality assurance issues prevent the use of existing data in the model simulations, those measurements still represent a valuable dataset that could be used for validation of the infiltration model.
5. Parameters estimated in a lumped manner. A number of parameters were estimated in a lumped manner, such as assumed constant rooting depth and constant soil depth, whose variability likely affects the spatial distribution of net infiltration. Additional site-specific data will lead to better resolution of these parameters. Accounting for the variability in soil depth and rooting depth will likely result in more precise predictions of the spatial distribution of net infiltration. Resolution of Soil Group 5/7/9 back to its constituent soils is warranted to provide a more precise spatial distribution of net infiltration. The effect of surface soil thickness in the MASSIF model needs to be better evaluated, especially in bare soils and in vegetated soils during non-growing periods.
6. Cubic convolution possibly truncating the range of evapotranspiration values. It is not clear why cubic convolution was used during the geocorrection process to resample data from the Landsat TM images in the evapotranspiration submodel. Using cubic convolution results in the original pixel values being replaced by weighted means of sixteen pixels, which results in considerable smoothing of the data and may average out the smallest and largest evapotranspiration values. While cubic convolution resampling is often used to make images more attractive, it compromises subsequent

analyses: “Images altered in this manner by resampling should be examined carefully before they are used for subsequent analysis” (Campbell, 2007). In quantitative hydrology remote sensing, nearest-neighbor resampling is typically used, where each georeferenced pixel receives its value from the nearest point on the reference grid. In this way, the original values are maintained for further analysis.

7. Initial conditions reset each year. Water years were considered independently in the simulations. Initial conditions were reset for each year, precluding possible accumulation of moisture in successive wetter years and eliminating any impact of previous wet years on the following year’s infiltration. Under the potential tendency of hydrometeorological persistence, where high precipitation years tend to be followed by high precipitation years (Fiering and Jackson, 1971), the elevated soil moisture from the previous year could produce significantly more net infiltration the following year. Additional evaluations are needed in which 400-year sequential simulations are conducted to assess the importance of serial correlation in precipitation and soil moisture.
8. Little to no net annual infiltration predicted for wash environments. The lack of predicted infiltration in washes, which is contrary to currently accepted recharge behavior, likely results from several sources: (1) the omission of subsurface lateral flow between model cells, (2) incorrect representation of the soil hydraulic properties in cells within washes, (3) “resetting” the soil moisture to dry conditions at the end of each water year, and (4) overestimation of soil depth in wash environments that leads to overestimation of evapotranspiration in the washes. Each of these issues is addressed by one or more research options in this list. In addition, the largest drainage to the north of Yucca Mountain (Yucca Wash) was partially cut off from the study due to “lack of detailed information on soil and bedrock properties in this region” (p. 6-61). Given the general lack of measured values elsewhere, this removal of part of the hydrologic basin appeared arbitrary to the review panel since it was not adequately justified in the report. As washes do provide concentrated recharge (Goodrich et al., 2004, pp. 77-99; Hogan et al., 2004, p. 294), this catchment could be included in the study while assuming conservative properties.

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I have reviewed the Yucca Mountain infiltration-modeling document MDL-NBS-HS-000023, Rev. 01 and was able to access its supporting materials (listed in Appendix C of this review report). I contributed to writing this ORISE review report and have had opportunity to comment on and revise this report's text. I agree with the statements and conclusions of this ORISE review report. I reassert that I do not have a conflict of interest in participation on this review panel.

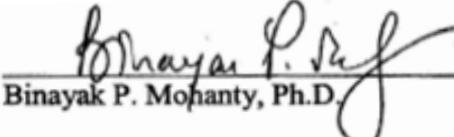
ORISE Yucca Mountain Review Panel Members:



April 24, 2008

Jan M. H. Hendrickx, Ph.D.

Date



Binayak P. Mohanty, Ph.D.

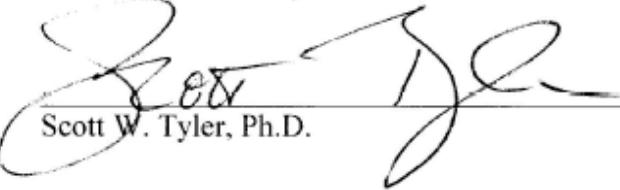
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Date

Soroosh Sorooshian, Ph.D., Panel Chair

April 22, 2008

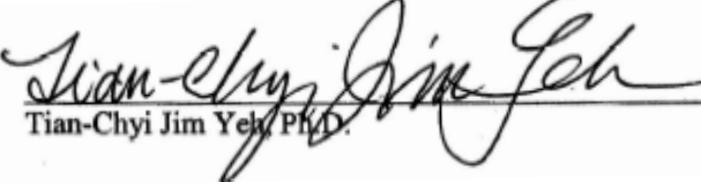
Date



Scott W. Tyler, Ph.D.

April 29, 2008

Date



Tian-Chyi Jim Yeh, Ph.D.

4/22/2008

Date

APPENDIX A

REVIEW PANEL MEMBERS

Jan M. H. Hendrickx, Ph.D., Professor of Hydrology at New Mexico Institute of Mining and Technology, Socorro, New Mexico. Dr. Hendrickx received his doctoral degree in 1984 from New Mexico State University, Las Cruces, New Mexico, majoring in Soil Physics. Current research includes the application of remote sensing for determination of actual evapotranspiration and soil moisture; and the process of water solutes movement through the vadose zone and the application of computer models to this process. While at the Netherlands Soil Survey Institute, Dr. Hendrickx completed a new modeling approach to model water flow through preferential flow paths caused by unstable wetting. In conjunction with the Mathematics Department at New Mexico Tech, Dr. Hendrickx and associates developed a stability model that is capable of predicting quantitatively unstable wetting and finger sizes in many different soils using readily available hydraulic soil properties for a wide range of precipitation rates.

Binayak P. Mohanty, Ph.D., Professor of Hydrology at Texas A&M University, College Station, Texas. Dr. Mohanty received his doctoral degree in 1992 from Iowa State University, Ames, Iowa, majoring in Soil and Water Engineering. Current research includes water, heat, and chemical transport measurement and modeling in variably saturated porous media; biogeochemical cycling in heterogeneous vadose zone; measurement, scaling, and estimation of effective soil hydraulic properties of shallow subsurface in the context of land-atmosphere interaction; spatial variability of soil hydraulic and transport properties in the context of deterministic/stochastic modeling; soil moisture measurement and scaling using ground-based, air-borne, and space-borne remote sensing techniques; and watershed-scale flow and transport modeling. Dr. Mohanty has developed adaptive geostatistical, exploratory, neural network, and data assimilation techniques and numerical forward and inverse models for geohydrological and geoenvironmental applications.

Soroosh Sorooshian, Ph.D., Distinguished Professor and Director of the Center for Hydrometeorology and Remote Sensing at University of California, Irvine, California. Dr. Sorooshian received his doctoral degree in 1978 from University of California, Los Angeles, majoring in Engineering, Water Resources, and Hydrologic Systems Analysis. Current research focuses on surface hydrology, primarily in the area of rainfall-runoff modeling. He has devoted much of his efforts to model identification and calibration issues and has developed special estimation criteria to account for the uncertainties of calibration data. Dr. Sorooshian also researched the application of remote sensing data for characterization of hydrologic parameters and fluxes and the implication of climate variability and change in water resources. Dr. Sorooshian served as chair for this Review Panel.

Scott W. Tyler, Ph.D., Professor of Hydrology and Hydrogeology at University of Nevada, Reno, Nevada. Dr. Tyler received his doctoral degree in 1990 from University of

Nevada, Reno, Nevada, majoring in Hydrology/Hydrogeology. Current research includes arid-region hydrology, vadose-zone hydrology, and moisture flux and groundwater recharge in arid environments. Dr. Tyler developed soil-atmosphere models of energy and water flux; studied groundwater/brine interactions in terrestrial environments; reconstructed paleoclimates from soil water chemistry; and researched the transport of contaminants in fractured, dual-porosity unsaturated media and mine waste materials.

Tian-Chyi Jim Yeh, Ph.D., Professor of Hydrology at University of Arizona, Tucson, Arizona. Dr. Yeh received his doctoral degree in 1983 from New Mexico Institute of Mining and Technology, Socorro, New Mexico, majoring in Hydrology. Current research includes stochastic/numerical analysis, stochastic analysis of effects of spatial variability on flow in unsaturated geologic media, and conditional simulations and inverse modeling of flow and transport processes in variably saturated geologic media. Dr. Yeh recently invented the sequential successive linear estimation technique as an innovation that overcomes difficulties of the traditional inverse modeling technique, which led to the development of robust hydraulic, tracer, electrical resistivity tomography and stochastic fusion methods to image the subsurface heterogeneity.

APPENDIX B

Oak Ridge Institute for Science and Education (ORISE)
Independent Review of the Yucca Mountain *Simulation of Net Infiltration for Present-Day and Potential Future Climates and Supporting Documents*

Charge to Reviewers

A. Does the subject report, *Simulation of Net Infiltration for Present-Day and Potential Future Climates*, credibly meet its intended purpose of “providing a spatial representation, including epistemic and aleatory uncertainty, of the predicted mean annual net infiltration at the Yucca Mountain site”...for present-day and potential future climate scenarios?

- a. Was the methodology used appropriate and effectively applied?
- b. Were alternative modeling approaches and their results and limitations appropriately considered?
- c. Are bounds of uncertainty adequately defined?

B. Is the presentation of the infiltration model and associated data sets transparent and traceable to allow outside experts to reproduce the results of the model?

From NUREG-1804, Yucca Mountain Review Plan

transparency: The ease of understanding the process by which a study was carried out, which assumptions are driving the results, how they were arrived at, and the rigor of the analyses leading to the results. A logical structure ensures completeness and facilitates in-depth review

C. Adequacy in meeting nuclear regulatory standards and requirements as they pertain to the subject of this review [refer to subject report (*Simulation of Net Infiltration for Present-Day and Potential Future Climates*) Section 4.2, pages 4-6 to 4-9, for applicable requirements]

D. Additional work or research needs that may be identified

- a. Describe any near-term or long-term key knowledge gaps. Are any of these gaps important to current decision making?

APPENDIX C

SUPPORTING DOCUMENTS

ANL-MGR-MD-000015, *Data Analysis for Infiltration Modeling: Extracted Weather Station Data used to Represent Present and Potential Future Climate Conditions within the Vicinity of Yucca Mountain*, Sandia National Laboratories, December 2006.

ANL-NBS-GS-000008, R1, "Future Climate Analysis," Bechtel SAIC Company, LLC, September 2004.

ANL-NBS-HS-000054, *Data Analysis for Infiltration Modeling: Bedrock Saturated Hydraulic Conductivity Calculation*, Bechtel SAIC Company, LLC, July 2006.

ANL-NBS-HS-000055, *Data Analysis for Infiltration Modeling: Development of Soil Units and Associated Hydraulic Parameter Values*, Bechtel SAIC Company, LLC, September 2006.

ANL-NBS-HS-000077, R1, *Data Analysis for Infiltration Modeling: Technical Evaluation of Previous Soil Depth Estimation Methods and Development of Alternate Parameter Values*, Bechtel SAIC Company, LLC, September 2006

AUZM32, "Infiltration Model Software Evaluation Project Closure Report," Idaho National Laboratory, February 2006.

CNWRA 2007-003, Long-Term-Average Infiltration at Yucca Mountain, Nevada: Million-Year Estimates, Center for Nuclear Waste Regulatory Analyses, August 2007.

CR 9213, "Representativeness of Uncertainty in Infiltration Related AMRs," April 5, 2007.

CR 9214, "Representativeness of Model Validation Approach Used in UZ Flow Model," August 20, 2007.

CR 10776, "Recommend Clarification of CR 9213 and Its Applicability to Infiltration Model Report # MDL-NBX-HS-000023," August 17, 2007.

CR 10783, "Technical Recommendations for Infiltration Report," June 7, 2007.

CR 10784, "Recommend Documenting Completeness of Lead Lab DPO-0001 Resolution," August 17, 2007.

DPO Number: 0001, (differing opinion between unsaturated zone flow modeling team and net infiltration modeling team), October 31, 2006.

LA-UR-07-3994, "INFIL vs. MASSIF: A Comparison of Yucca Mountain Infiltration Models," Daniel G. Levitt, Los Alamos National Laboratory, June 18, 2007

OQA-SNL-07-06, "Report for Audit OQA-SNL-07-06 of the Infiltration Model by the Office of Civilian Radioactive Waste Management at the Lead Laboratory Facilities, June 4-18, 2007," DOE OCRWM Office of Quality Assurance, August 9, 2007.

SCI-PRO-006, R5, Models (procedure), Yucca Mountain Project, August 14, 2007.

TDR-NBS-HS-000019, "Technical Evaluation and Review of Results, Technical Procedures, and Methods Related to the Collection of Moisture Monitoring Data Using Neutron Probes in Shallow Boreholes," Bechtel SAIC Company, LLC, April 2006.

TWP-NBS-HS-000012, R02, *Technical Work Plan for: Infiltration Model Assessment, Revision, and Analyses of Downstream Impacts*, Bechtel SAIC Company, LLC, August 2006.

APPENDIX D

UNRESOLVED ISSUES

The modeling effort as documented in the report is quite comprehensive in representing basic processes and hydrologic parameter uncertainties. However, several fundamental issues regarding the adequacy of the conceptual model, representation of spatial variability of different variables and parameters, and the alternative models used for validation of the modeling effort pose certain questions and uncertainties in the results presented in the report. In the following sections, these unresolved issues are discussed.

1. Critically Limited Site-Specific Data

The available dataset was critically limited in the number of samples and the types of measurements for parameterization of the model. It seems to the review panel that more effort should have been devoted to collection of data by direct or indirect methods for the model domain. Field capacity not only depends on the intrinsic soil hydraulic properties but also on the location of the soil in a profile (i.e., above or below a less permeable layer, just above bedrock, higher in the profile), which is determined primarily through the collection of field data.

The geologic inputs to MASSIF consist of parameters for Yucca Mountain soils and bedrock as well as spatial distributions for soil types, soil depth classes, and bedrock types over the modeling domain. A standard approach is to combine analyses of satellite imagery and aerial photographs with field observations and quick inexpensive measurements (such as texture, rock fragments percentage, carbonate content, color, structure) for the development of maps and databases. In addition, field and laboratory hydraulic measurements are taken in representative soil horizons and bedrocks to determine the relevant hydraulic parameters for the infiltration model. These measurements are then used for the development of pedotransfer functions that are used to estimate non-measured soil parameters from one or more measured ones (Bouma, 1989).

The initial USGS soil characterizations were developed from a map of surface deposits and resulted in 40 map units characterized primarily on extent of soil development, geomorphic character, and topographic position. These map units would have been appropriate for a first selection of representative field sites for measurement of hydraulic properties. Instead, useful information on spatial soil distribution was lost by combining the original 40 map units into 10 “base-case” soil units that then were further condensed into four soil groups. Instead of conducting hydraulic measurements in the field and the laboratory, the soil hydraulic properties for the four soil groups were derived from the pedotransfer function developed with soil texture data of the Hanford, WA site, which is located in a different geomorphological environment. Using pedotransfer functions outside of their development dataset introduces substantial uncertainty because their accuracy is not known (Schaap and Leij, 1998; Schaap et al., 2004). At least some

validation and calibration with actual hydraulic measurements at Yucca Mountain is needed before the uncertainty of hydraulic properties can be evaluated. Without hydraulic measurements at Yucca Mountain, the study has limited scientific basis.

Water content at field capacity is used as the threshold for water movement in MASSIF. Therefore, for each soil the water content at field capacity should ideally coincide with a negligible free drainage flux. Many factors influence field capacity: soil texture, type of clay minerals, organic matter content, soil structure, depth of wetting, previous water content, presence of impeding layers in the profile, evapotranspiration, water table depth, and temperature (Hillel, 1998; Kirkham, 2005). A typical approach is to identify a specific soil water pressure that identifies field capacity and then to determine the corresponding soil water content from the soil water retention curve. In the literature, soil water pressures of -330 cm (1/3 bar) and -100 (0.1 bar) have been typically used to identify field capacity. However, field capacities are reported to vary from -0.6 bar in a deep dryland soil to -0.005 bar in a highly stratified soil (Kirkham, 2005). Field capacities should be measured in the field since the effects of soil layering and hysteresis are difficult to mimic in the laboratory (Cassel and Nielsen, 1986; Romano and Santini, 2002). There is no definitive correlation between field capacity and soil texture (Bouma and Droogers, 1999; Ritchie et al., 1999), nor is there justification to associate field capacity with a specific soil water pressure (Stein et al., 2004). Therefore, the assumption is not correct that field capacity “is the soil moisture content at which internal drainage ceases based [on] correlation to matric potentials of -0.33 bar and -0.10 bar” (Section 5.3, p. 5-2 in “Data Analysis for Infiltration Modeling: Development of Soil Units and Associated Hydraulic Parameter Values,” ANL-NBS-HS-000055 REV 00). This assumption will lead to incorrect values for the field capacity and, therefore, water holding capacity of the soil. Until field measurements have been conducted, the uncertainties in field capacity and their effect on net infiltration cannot be quantified.

Use of a field capacity value higher (wetter) than -0.1 bar, perhaps as high as -0.04 bar, would lead to underestimation of the net infiltration since more water remains close to the soil surface where it can evaporate and transpire faster than at depth. Therefore, the lower value of -0.1 bar used in MASSIF would add conservatism to the model results by over-estimating net infiltration. On the other hand, if the field capacity value is indeed as high as -0.04 bar, then subsurface lateral fluxes on the slopes would increase by several orders of magnitude, possibly causing focused recharge in depressions and on head slopes with local net infiltration fluxes well above the ones predicted by MASSIF. Use of a field capacity lower (drier) than -0.33 bar, perhaps as low as -0.6 bar, would lead to higher net-infiltration since more water infiltrates faster to greater depths into the profile where it is out of reach for roots. For example, net infiltration in the washes might have been more realistic with a lower bound on field capacity. These considerations clearly demonstrate that “one should always try to measure field capacity in the field for each soil” (Kirkham, 2005).

Similarly, the number of soil-depth measurements is too few to allow reliable mapping of soil depth over the model domain. There also seem to be few measurements of bedrock

saturated hydraulic conductivity. Without further measurements, it is not possible to quantify the uncertainty in soil depths and bedrock conductivity.

A standard dew point offset is used for Yucca Mountain based upon Allen et al. (1998). However, actual values of the dew point offset can be derived from observed weather data. Relative humidity and temperature have been routinely collected at Yucca Mountain, and the offset could easily have been calculated for the years of data developed. Real data should be used when available.

2. Subsurface Lateral Flow Excluded by the Modeling Approach

While most processes are included that preserve the spatio-temporal variability of hydrologic fluxes/states, some hydrologic processes were assumed to be negligible because of the use of a simple vertical model. A significant process excluded by this approach is subsurface lateral flow that can occur as a result of vertical heterogeneity in soil hydraulic conductivity, conductivity differences along the soil-bedrock interface, and as a result of a lateral head gradient across model cells under saturated or unsaturated conditions on slopes as well as flat landscapes. In addition, variability and anisotropy in soil hydraulic properties, soil depth, rooting depth, and bedrock topography contribute to the lateral flow process. Subsurface topography (e.g., the soil-bedrock interface) may route the water laterally before it can build up vertically in a grid cell. This subsurface lateral flow ultimately affects the amount of surface runoff from each grid cell as well as the available soil water for root uptake and evapotranspiration.

Subsurface lateral flow can occur under both saturated and unsaturated conditions; the latter, of course, is more common in arid environments. The physical conditions that cause lateral flow under saturated conditions are completely different from those under unsaturated conditions.

Saturated lateral flow is caused by perched groundwater that develops at the interface between two layers where the top one has a higher hydraulic conductivity than that below; for example, a coarse sand overlying a finer-textured layer. A characteristic of perched systems is that they are underlain by unsaturated sediments. The development of perched groundwater and water table mounds in stratified alluvium occurring during flow in the Santa Cruz River, an ephemeral stream near Tucson, Arizona, contributed to groundwater recharge (Schmidt, 1995). Two saturated layers were clearly separated by an unsaturated zone with lower water content. Nevertheless, the hydraulic conductivity for this unsaturated transmission zone was sufficient to transmit vertical leakage from the perched system to the water table mound. Where wells are screened through a perched layer or where water leaks through casing joints at the perched layer, cascading water occurs. This is a common observation in arid alluvial basins and is evidence of saturated lateral flow in the vadose zone.

Unsaturated lateral flow is caused by perched water that develops at the interface between two layers of contrasting hydraulic conductivities or by anisotropy of the unsaturated hydraulic conductivity. Contrary to the case of saturated lateral flow in

layered profiles, coarse-textured layers now become the impeding layer for lateral flow because under unsaturated conditions the hydraulic conductivities of finer textured layers exceed those of coarse texture. Preferential lateral water movement through fine textured layers has been illustrated using laboratory tank experiments where water infiltrated from a point source into alternating layers of coarse and fine-textured materials. Lateral unsaturated flow occurred in the fine rather than the coarse layers (Palmquist and Johnson, 1962; Stephens and Heerman, 1988). These experiments also imply that under unsaturated conditions fractures filled with fine-textured gouge have a higher hydraulic conductivity than those with open apertures.

Following are a number of other studies examining the occurrence of both saturated and unsaturated subsurface lateral flow:

Where alternating layers of coarse and fine material have been deposited on a hillslope, unsaturated lateral water movement may be considerably enhanced. The dramatic effect of a relatively thin inclined coarse sand layer in a fine sand profile on water movement under unsaturated conditions has been demonstrated during a field experiment where uniform downward unsaturated water flow in the top 1.2 m of a sandy profile was observed until it started to flow laterally along the boundaries of inclined coarse sand lenses (Kung, 1990). Laboratory experiments (Kung, 1993) and computer simulations (Ju and Kung, 1993) revealed that such funnel flow is most distinctive under dry conditions with a flow rate into the profile that is less than 2% of the saturated hydraulic conductivity for the fine layer. Higher flow rates would cause water to leak into the coarse layer and diminish the funnel effect. Vadose zones in semi-arid regions apparently have a greater propensity for funnel flow than in more humid environments.

Anisotropy of the unsaturated hydraulic conductivity in horizontal and vertical directions is another factor causing lateral flow under unsaturated conditions in homogeneous soils. Laboratory experiments under unsaturated conditions demonstrated the dependence of anisotropy on soil water content and pressure head. An increase in anisotropy was measured from 1 at pressure -5 cm to 18 at -20 cm (Stephens and Heermann, 1988). Field measurements in a uniform sand dune revealed an anisotropy of approximately 1 at saturation to 20 at a pressure head of around -40 cm. A tracer experiment was conducted to demonstrate that lateral flow components occurred after only 26 mm of precipitation. The importance of such lateral flows for net recharge is that the soil water remains relatively close to the surface resulting in higher evaporation and/or transpiration losses (McCord et al., 1991).

Using a chloride mass-balance approach, Scanlon (1991; 2000) evaluated the recharge flux in several desert soils of the semi-arid western U.S. for drainage and inter-drainage areas. By using chloride tracer data, she inferred that lateral flow mechanisms, including preferential flow and runon, are important and provide higher net water flux in inter-drainage areas. In addition to desert soils, subsurface lateral flow has been observed as an important mechanism in semi-arid forested hillslopes.

For example, with designed field experiments, Wilcox et al. (1997) found subsurface lateral flow accounts for up to 20% of snowpack/snowmelt drainage. They discovered that when antecedent soil moisture was high, subsurface lateral flow was highly responsive to snowmelt and rainfall events and was dynamic in nature. They attributed the development of a shallow zone of saturation to a combination of occasional very wet conditions with the presence of a shallow restrictive horizon, while a network of macropores facilitated this type of subsurface lateral flow.

In a similar hillslope scale study in Japan, which would be relevant for the future monsoon climate, Sidle et al. (2001), using a three-dimensional conceptual subsurface hydrologic modeling framework and experimental data, showed the significance/dominance of subsurface lateral preferential flow and associated hydrologic attributes, such as pore distribution, length, diameter, density, tortuosity, connectivity, orientation, soil layering, and bedrock topography. An interesting study supporting subsurface lateral flow in semi-arid desert environments of the U.S. was provided by McCord and Stephens (1987). Using data from a site intensively monitored for soil moisture, soil water potential, and tracer experiments on a sandy hillslope to delineate the flow paths of vadose water, they found a strong lateral component to unsaturated flow, even in the absence of apparent impeding layers of much lower permeability.

A study from southern California (annual precipitation 380 mm) describes a toposequence of soils along a slope about 150 m long with an average slope of 10% (Nettleton et al., 1968). Three different soils formed along this slope with soil and vegetation characteristics that differ with topographic position. Soil water content measurements indicated that the downslope soils receive more soil moisture than the upslope soil due to surface runoff and “seepage” (i.e., subsurface lateral flow), which was observed by the authors along a road-cut through the downslope soil. The increased weathering of the downslope soils signifies that surface runoff and subsurface lateral flow along this slope occur regularly.

Soil water fluxes in a first-order drainage basin in New Mexico (annual precipitation 300 mm) are determined by the geometry and orientation of a hillslope (Gutiérrez-Jurado et al., 2006; McMahon and Harrison, 2003). The geometry influences water fluxes through the creation of convergent and divergent zones of surface runoff and subsurface throughflow. In this case study, the major soil differences were not so much correlated with hillslope position but more with hillslope orientation. The drier south-facing slope is characterized by Creosote grassland, the north-facing slope by Juniper grassland, and the head slope, where water is converging, by grassland. Taking the soil characteristics into consideration, the investigators estimated that the “infiltration water” on the north-facing slope has been about double that on the south-facing slopes, while the lowest part of the head slope received more than five times the amount of infiltration water than on the north slope (McMahon and Harrison, 2003). These studies indicate that subsurface lateral flow—especially during wet periods in current and future climates favorable for infiltration below the root zone—

probably occurs at some locations of Yucca Mountain on a scale that exceeds a 30 × 30 m pixel.

Many field studies in arid environments have found a strong correlation between vegetation, soil and terrain characteristics, and net infiltration (e.g., Guan, 2005; Gutierrez Jurado et al., 2006; Sandvig and Phillips, 2006). Since only a very small part of Yucca Mountain has been disturbed by human activities, there is a high likelihood for detection of subsurface lateral flow settings using a “digital soil mapping” approach (Lagacherie et al., 2007; Lamotte et al., 1994; McBratney et al., 2003). Those experimental studies corroborate and emphasize the presence of a significant subsurface lateral flow component in semi-arid hillslopes that needs specific attention during vadose-zone flow modeling.

Recently, Kampf and Burges (2007) provided an exhaustive review of available conceptual and computer models for surface and subsurface hydrologic modeling, at hillslope and catchment scale. The review discusses the significance of various coupled surface-subsurface hydrologic process models that are one-, two-, and three-dimensional. They show that, depending on need and computational burden, complex multi-dimensional hydrologic models may be adopted in part of the modeling domain and important findings extrapolated to the entire region.

Another model is the new Integrated Landscape Hydrology Model (ILHM) used to integrate widely available hydrologic and landscape data in a synergistic and computationally efficient manner to assess temporal and spatial changes in important hydrologic processes (Hyndman et al., 2007). The Soil Moisture Distribution and Routing Model (SMDR) was developed for humid, well-vegetated areas with steep to moderate slopes with shallow soils and high infiltration capacity soils (Soil and Water Laboratory, 2003). Both models take subsurface lateral flow into account and are evidence that the inclusion of subsurface lateral flow in infiltration models is a standard practice in hydrology today.

Guan, 2005 (Chapter 5) compares—among other aspects of mountain block recharge—estimates of net infiltration at a semi-arid soil-bedrock interface using HYDRUS-1D and HYDRUS-2D. Simulations were carried out to compare net infiltration on north- and south-facing 20-degree slopes with soil thickness of 30 cm and 100 cm, hillslope conditions not uncommon at Yucca Mountain. For these specific conditions, the net infiltration of the 1D simulations is between that from the 2D top-slope and mid-slope simulations. Since 1D simulations can only represent vertical infiltration and not subsurface lateral flow, they underestimate along the entire slope consisting of top slope and mid-slope. For the 20-degree slopes, the 1D simulation underestimated the net infiltration for the entire slope by about 15% compared to the geometric mean of 2D top-slope and mid-slope results. In general, the 2D simulations on mountain hillslopes yield different net infiltration rates than 1D simulations. Guan (2005) concludes that the magnitude of the difference between 1D and 2D simulations depends on slope aspect, slope steepness, and soil thickness (factors examined in the study), and probably also on soil type and bedrock

characteristics (factors not included in the study). Only on slopes with low steepness and/or thick soil cover are the 1D and 2D simulations expected to give similar results. These simulations suggest that neglecting subsurface lateral flow on the steeper slopes and shallow soils at Yucca Mountain may result in an underestimation of net infiltration on downhill slopes or other areas of water convergence, such as head slopes and local small topographic depressions.

Based on the above studies, the rationale provided in the MASSIF model report for ignoring subsurface lateral flow between the grid cells and assuming a one-dimensional vertical flow in the Yucca Mountain region appears to be an unjustified oversimplification. During infiltration-generating precipitation periods, the subsurface lateral flow from one cell to the others could be significant (Zaslavsky and Sinai, 1981a and b; Yeh et al., 1985c), considering the steep topography and soil layering at Yucca Mountain. It is well-known that vertical variations in the saturated hydraulic conductivity and pore-size distribution (i.e., the factors controlling the rate of reduction in the unsaturated hydraulic conductivity) and their lateral continuity (layering) prevent rapid vertical movement of moisture. The slope of the layering and capillary gradient then facilitate lateral spreading of moisture in the unsaturated zone. The report's statement that "most of the model domain is characterized by relatively low slopes" is not supported by the reported median slope for the domain of ~10 degrees and the statement that 90% of the domain has a slope of less than 25 degrees (p. 5-1). Slopes of >10 degrees would contribute to the lateral head gradient. These slopes are not small and need to be accounted for in the model, especially close to channels, or washes. Furthermore, the lumped soil type 5/7/9 (Figure 6.5.2.2-2) and soil depth class 4 (Figure 6.5.2.4-1) accounts for 90% of the total infiltration (Table 6.5.7.6-1) and covers most of the repository footprint. Distinguishing the spatial distribution of each of the constituent soils in these aggregated classes, including variations in soil depths, would better characterize the conditions facilitating the subsurface lateral flow across adjacent grid cells. Lateral flow in the subsurface could possibly prevent rapid downward migration of water and enhance evapotranspiration. Lateral flow, on the other hand, could quickly divert water to depressions (e.g., washes) or preferential flow paths to recharge the groundwater.

Another important trigger for subsurface lateral flow is the difference in saturated hydraulic conductivity of the bedrock versus the overlying soil in the region. Without accounting for spatial distribution, the average bulk bedrock conductivities (Figure 6-12, in report ANL-NBS-HS-000054) are quite similar or sometimes less than the average pedotransferred soil hydraulic conductivity used in this study (1.94×10^{-4} cm/sec per Rawls and Brakensiek, 1985, 2.23×10^{-4} cm/sec per ROSETTA, or limited measured K_{sat} values at the Yucca mountain site, 10^{-3} cm/sec, Table 6-19, in report ANL-NBS-HS-000055), which would trigger subsurface lateral flow. Moreover, higher precipitation rates during the projected monsoon climate scenarios may enhance this lateral flow because of possible bedrock fracture plugging, reducing the bulk K_{sat} (for bedrock) due to soil erosion, a process which is assumed negligible in this modeling study.

The 30 m × 30 m grid-based vertical flow modeling without accounting for the subsurface lateral flow between the cells may not adequately describe the true spatio-

temporal distributions of net infiltration, including their extremes across the model domain. Subsurface lateral flow, including any preferential or funnel flow during saturated/unsaturated conditions, may occur at finer scale than 30 m × 30 m scale, depending on the local heterogeneity in soil and bedrock properties. As a result, the natural flow path should be better characterized (e.g., in a triangular irregular network rather than a regular square grid). Also, mean hydraulic properties of the bedrock (UZ), in comparison to the overlying soil layers, does not ensure that water will always move vertically downward through the bottom boundary in all soil cells. The panel agrees that subsurface lateral flow will provide further opportunity for extraction by ET in downstream soil cells; however, soil layers with contrasting hydraulic properties in the bedrock/soil interface, including the geometry of convergent/divergent flow zones with hit and miss fractures will dictate the ultimate subsurface flow routing. So there is concern about the accuracy of spatio-temporal variability and net infiltration extremes under saturated/unsaturated conditions during different projected climatic scenarios. The evidence of flow in the washes counters the suggested argument of no field evidence that subsurface lateral flow is important (unless the authors suggest this is only due to surface lateral flow). Only site-specific representative experimental/modeling studies will provide more insight on this unresolved issue.

In summary, not considering subsurface lateral flow resulting from topography, soil layering, and anisotropic hydraulic conductivity can distort the predicted spatial distribution of net infiltration at the soil-bedrock interface in the region. This may underestimate the upper bound for net infiltration to the top boundary of the UZ model in areas where subsurface pathways cause funneled or focused recharge. This hydrologic behavior will not be captured with the 30 m × 30 m uniform-grid, one-dimensional model used in this effort. A multi-dimensional model that is resolved spatially and temporally and captures the directional and interconnected subsurface flow, with supporting field data, would better serve the purpose of predicting net infiltration in the Yucca Mountain region.

3. Incompletely Defined Bounds of Uncertainty

In the uncertainty analysis, the choice of parameters to vary was based on their impact on net infiltration; parameters determined to vary insignificantly were eliminated from the analysis. Parameters that were varied in the simulation include daily rainfall, plant height, maximum rooting depth, soil depth class 4, bedrock conductivity for two units, readily available water, minimum transpiration coefficient, evaporation depth layer, and slope of the NDVI/crop coefficient function. The uncertainty ranges were based upon literature values in general, and distributions were taken to be, in general, limited to the range of distributions reported in the literature only. In this modeling effort, uniform distributions were used for most of the parameters, rather than the more traditional normal distributions for ecological parameters. This approach may result in an unrealistic sampling of outlier processes and prediction of the range of calculated infiltration.

Additionally, in the net infiltration modeling, most hydraulic transport properties (including hydraulic conductivities) were assigned log-uniform distributions rather than

the log-normal distribution routinely used in the field of hydrology. No convincing justification for the use of log-uniform was given in the documentation of the MASSIF model. Log-uniform distributions, to the review panel's knowledge, have not been reported previously for any subsurface hydraulic properties. It is the opinion of the review panel that a log-normal distribution is a more appropriate and realistic approximation of the variation of hydraulic properties. However, a uniform distribution is adequate if it extends far enough; it does increase the probability of sampling the extreme values compared to a normal distribution. Perhaps if more site-specific data were available, this issue could be resolved.

More importantly, it is well-documented that spatial variability in soil properties is not spatially independent, but rather correlated due to natural processes (e.g., Russo and Bouton, 1992; Russo et al., 1997; Jury et al., 1991). The epistemic uncertainty in this modeling report, however, mainly deals with the variance of the saturated hydraulic conductivity and some other parameters without spatial correlations. In other words, the soil properties in the study should have been treated as a spatial stochastic process; the probability distributions assigned to the parameters (p. 6-220) should have been joint probability distributions (i.e., the parameters should have been treated as spatially random fields). This oversimplified assumption leads to unrealistic estimates of net infiltration and uncertainty associated with the estimates.

In Sec. 6.5.2.3, "Soil Properties," field capacity, permanent wilting point, and saturated moisture content were determined from the moisture retention curves provided in the analogous database from Hanford, WA. A pedotransfer function using these derived parameters from Hanford is used to predict hydraulic properties. However, use of the Hanford-derived pedotransfer function is problematic, as acknowledged by the authors: "The pedotransfer approach introduces uncertainty due to the fact that the Hanford soil property database represents soils in a location and depositional environment that is different from Yucca Mountain" (p. 1-3). The measured data for all soil property development in the model is particle size distribution and fraction of rock fragments. The Hanford soils are fluvial, while Yucca Mountain soils are colluvial with a much larger rock fragment fraction and a much higher probability of the rock fragments being able to retain water. The predicted conductivities from the pedotransfer function do not appear to be compared with any measured data for verification, which represents a serious weakness in the approach for characterizing the site's soil properties.

The soil saturated and unsaturated hydraulic conductivities developed from the pedotransfer function model are quite similar or higher in magnitude to the bedrock conductivities used in the model simulation, particularly for the soils above the repository footprint. In addition, saturated hydraulic conductivity varies significantly with little change in porosity and pore size distribution. No sensitivity analyses have been conducted to show how saturated and unsaturated hydraulic conductivity would impact net infiltration when assumed constant, as opposed to its possible dynamic nature over 10,000 years at Yucca Mountain (because of pore plugging or enhancement due to hydrologic, geochemical, and biologic activities). This will be a key parameter for

infiltration uncertainty on a seasonal basis, as well as possibly a significant parameter over the duration of long-term MASSIF simulation.

In Sec. 6.5.4.2, “Input Parameters for Soil Water Balance Calculations,” there is an apparent arbitrary distribution of the nominal evaporation rate from dry soil, with a nominal value of zero. This is a fairly weak assumption, but probably conservative. The actual distribution of this parameter could be estimated from the lysimeter data, but this was not done; the only characteristic determined was that long-term evaporation from below the near surface did persist.

This section also provides an arbitrary value for the Soil Moisture Depletion Coefficient (p), a stress parameter for evapotranspiration, without solid justification or previous work. This may also be a conservative assumption, but it is not clear what the implications are.

The evaporation layer depth (Z_e)—the mean effective depth of the surface soil layer that is subject to drying by evaporation to dry air—has an arbitrary assignment of 0.15 m, with a uniform distribution between 0.1 and 0.2 meters. This is rather uncertain, particularly for coarse-textured soils. In addition, the report does not discuss how the thickness of the surface layer affects infiltration processes; in MASSIF, a thin surface layer will result in more infiltration than a thick layer, especially during periods when vegetation is not active or in bare soils.

Section 6.6, “Infiltration Prediction Uncertainties,” provides a lengthy mathematical analysis of parameter uncertainties in the MASSIF simulations. In the shorter discussion of model uncertainty, the report states that “The present study was unable to explicitly test the accuracy of the field capacity approach for representing subsurface water flow against field data from the Yucca Mountain site. However, a comparison was made against HYDRUS 1-D.... This comparison demonstrates that while the field capacity approach may not represent the transient nature of this flow accurately, it does an adequate job of representing the cumulative net infiltration over the year.” It is not possible for the Review Panel to assess the adequacy of calculation of prediction uncertainties when direct comparison to field infiltration or comparison to field measurements is not presented. The report goes on to suggest that “If the spatial distribution of neutron borehole locations is representative of the UZ modeling domain and the net infiltration estimates from the analysis of the neutron logs is representative of conditions away from the boreholes, this would suggest that the MASSIF model may underestimate actual net infiltration for this area by at least a factor of 2 ... It is not clear, however, that either of these criteria is met, and therefore it is not clear how these data can help to estimate model uncertainty.” The report concludes that “... model uncertainty may be of a comparable magnitude to parameter uncertainty. Given the complexity of modeling net infiltration over such a large and heterogeneous domain, such uncertainty is not unprecedented.” The panel does not have sufficient data (either in the report or supporting documents) to assess the accuracy of these statements.

4. Limited Validation Examples

Sec. 7.1.2, “Evapotranspiration and Storage,” describes the validation of MASSIF against two lysimeter facilities: Nevada Test Site and Reynolds Creek Experimental Watershed. This validation shows that MASSIF can predict trends in evapotranspiration and soil moisture storage reasonably well, if soil hydraulic properties are known. However, this does not necessarily mean that MASSIF will predict infiltration correctly since small errors in evapotranspiration, soil moisture storage, or precipitation will result in large errors in infiltration rates.

The lysimeter validations did not use measured soil textural data. Instead, specific water retention data measured on cores were used to generate K_{sat} and field capacity parameters. The soil depth, which should have been modeled as very deep, was not, due to the fact that the bottom boundary condition of a lysimeter is very different from a natural soil profile. For water to seep out of a lysimeter, the bottom soil water pressure has to become slightly positive, while in a natural soil profile, deep percolation will occur much sooner at negative soil water pressures.

No testing of the Hanford-derived pedotransfer function was conducted. Three parameters were calculated by using an optimization algorithm to get a good fit to observed storage (diffuse evaporation, canopy fraction, and growth curves). This was not a blind test, but a fitting of the predictions to observations. Optimal testing would have used blind soils. The overall Reynolds Creek evaluation also used some optimization to improve fits.

Section 7.1.3, “Run-on/Runoff,” describes the validation of model results by comparison to observed runoff events at Yucca Mountain in the 1990s as well as measured infiltration beneath wash environments. Six stream-flow gauge sites were used, along with data from an unsaturated borehole (UZ#4). MASSIF simulations were conducted on those watersheds where runoff data were collected, and the predicted runoff was compared with that observed. Using nominal values of soil hydraulic conductivity (i.e., those chosen from the distributions used for the final net infiltration estimates), MASSIF did not appear to predict the runoff (for example, see Figure 7.1.3-2 from Wren Wash). Additional simulations were conducted in which the nominal value of the soil hydraulic conductivity was reduced (to produce more overland flow). Reducing the nominal value of soil hydraulic conductivity by a factor of ~50% produced runoff that qualitatively matched that observed. Further study was made to compare to infiltration observed at the mouth of Lower Pagany Wash from UZ#4. To match the infiltration, the soil saturated conductivity needed to be increased by a factor of ~10 over the nominal value used in MASSIF. The report notes that this value is still below what was measured at the site by another order of magnitude.

Based upon these results, additional MASSIF simulations were conducted over the entire Yucca Mountain area using lessons learned from the validation cases. It was found that significant differences in the spatial distribution of modern recharge would occur by changing only the soil hydraulic conductivity of soils #3 and #4. Under this condition,

significantly more infiltration was found to occur beneath the wash environments (as much as 55%). The report concludes that the spatial distribution of net infiltration is “especially sensitive” to the spatial distribution of soil properties.

Overall, the MASSIF model did not accurately reproduce the observed runoff or infiltration behavior at Yucca Mountain without substantial modification of the input hydraulic properties used for calculating the net infiltration over the entire Yucca Mountain area. The report is frank in acknowledgement of these differences, and clearly states “more detailed information” will be needed to reduce the uncertainty. The validation exercise showed that, due to a lack of information on soil hydraulic properties, significant uncertainty in the spatial distribution of net infiltration was likely.

5. Parameters Estimated in a Lumped Manner

Several of the multi-dimensional heterogeneous physical processes that influence net infiltration have been simplified in the modeling effort through the use of lumped parameters and threshold values. For example, the major soil unit used in the simulation is a lumping of three different soil classifications (5/7/9). Given that most of the infiltration occurs through this amalgamated soil, this grouping significantly removes complexity from the model, essentially claiming the domain mostly consists of a single soil type. The rationale for combining these soils is not convincing, and resolution of this soil back into several components is warranted in further study.

The Review Panel reviewed *Data Analysis for Infiltration Modeling: Development of Soil Units and Associated Hydraulic Parameter Values*, ANL-NBS-HS-000055 REV 00 (ACN 01 and ACN 2). However, because only limited site-specific data were used in the analysis of soil groupings, coupled with the importance of soil depth and soil texture on net infiltration, the panel believes that the combining of soil units leads to unnecessary additional uncertainty in the simulation of net infiltration.

In addition, the sensitivity analysis of the model shows that variation in soil depth plays an important role in the net infiltration estimate. However, a constant soil depth for each soil class was used without comparing the assumption to observed Yucca Mountain data for verification. Some additional soil depth data became available in an addendum to the model report (see Section 7.2.4[a], MDL-NBS-HS-000023 Rev 01 AD 01). While this new data corroborates the depth range used for one (shallow) soil class, this does not alleviate the concern that a large area of the domain is described as uniform for many key attributes because not enough spatial sampling was performed; the new data are from a small area of just one soil class of the larger domain.

Use of a constant rooting depth also seems to be an inadequately justified oversimplification. Rooting depths were chosen based upon literature reviews, with the exception that roots were limited to soil horizons when the soil depth is shallow. For each model run, one maximum rooting depth was selected for the entire model domain. Therefore, while the report acknowledges the potential importance of roots to deep water removal from the soil system at Yucca Mountain, the MASSIF model does not account

for spatial variability in rooting depth. The available data on root-depth distribution at Yucca Mountain appear inadequate for checking this assumption.

Also, roots can penetrate bedrock fractures where soil is present to extract stored water. However, this process was assumed to be negligible compared with the amount of water that roots can extract from the soil layer, and therefore was not included in the MASSIF model. Limiting root penetration into filled fractures in bedrock is likely a conservative assumption for some portions of Yucca Mountain where roots do likely penetrate into bedrock. However, the extent of root penetration is not well mapped across Yucca Mountain for comparison. Some experimental studies in the Mojave Desert (Hamerlynck et al., 2000) highlight the importance of detailed knowledge of soils, in addition to climate, for understanding desert-plant ecological function.

Recent research has also shown that water uptake by vegetation can be enhanced by ectomycorrhizal fungi extending from deep roots into the bedrock (Allen, 2006). For example, in shallow soils of southern California hillsides as much as 86% of the plant available water has been measured in the granite matrix below the soil (Bornyasz et al., 2005). Such numbers suggest that not including root uptake of water from the bedrock leads to infiltration estimates that are too high, indicating that uptake from the bedrock is too conservative in this modeling effort.

An additional issue is the use of a fracture/matrix volume fraction weighted approach to estimate the saturated hydraulic conductivity of the fractured bedrock. This approach may not be appropriate since water is known to percolate more rapidly through fractures compared to the rock matrix (e.g., Das Gupta et al., 2006); a flow-weighted approach would perhaps be more realistic for this multimodal behavior.

6. Cubic Convolution Possibly Truncating the Range of Evapotranspiration Values

The evapotranspiration model in MASSIF is an adaptation of the dual crop coefficient approach that was developed for irrigated agriculture by the Food and Agricultural Organization (FAO) of the United Nations (Allen et al., 1998) and has been extended for special applications (Allen et al., 2005a). This approach is standard practice for evaluation of actual evapotranspiration rates (Allen et al., 2005a; Allen et al., 2005b). Although it is not perfect (Wallace, 1995) and needs adaptations for arid ecosystems (Mata-González et al., 2005, 2006; Or et al., 2006), it is presently the only practicable approach for the derivation of best estimates of actual evapotranspiration for arid areas. The authors of the report are commended for their development of a new method for the derivation of basal crop coefficients combining satellite imagery with studies of native vegetation.

The authors resampled 28.5 m data from the original Landsat TM pixels into 30 m × 30 m grid cells of the model domain using the Environment for Visualizing Images (ENVI) cubic convolution algorithm. It is not clear why cubic convolution was used during the geocorrection process to resample data from the TM images. Using cubic convolution means that the original pixel values are replaced by weighted means of sixteen pixels, which results in considerable smoothing of the data and may yield pixel values without

physical significance. While cubic convolution resampling is often used to make images more attractive, it compromises subsequent analyses: “Images altered in this manner by resampling should be examined carefully before they are used for subsequent analysis” (Campbell, 2007). A rule in quantitative hydrology remote sensing is to use nearest-neighbor resampling where each georeferenced pixel receives its value from the nearest point on the reference grid. In this way, the original values are maintained for further analysis. The information provided in the report did not allow a quantification of the effect of cubic convolution resampling on the estimates of actual evapotranspiration. It is expected that the smallest and largest evapotranspiration values have been averaged out.

The effect of using cubic convolution on the evapotranspiration uncertainty is not known; otherwise, the bounds of uncertainty for evapotranspiration seem adequately defined. Of course, the problem is that annual evapotranspiration is nearly equal to annual precipitation while the annual infiltration (very small number) equals annual precipitation (large number) minus annual evapotranspiration (large number). So, even if the uncertainty of evapotranspiration is adequately defined, it almost definitely will amount to a rather large uncertainty in annual infiltration.

7. Initial Conditions Reset Each Year

The model methodology used 20 realizations, each containing 10 water-years, with variation in the uncertain parameters and two separate replicates of samplings. For each realization, a separate weather file was generated so that each year’s simulation was run independently; that is, no time series of continuous climate or soil/vegetation conditions was carried out. The approach of considering a water year independently eliminates any impact of previous wet years on the following year’s infiltration. For most years, this assumption is likely valid, because much of the soil moisture will be lost due to evapotranspiration by the beginning of the next year (October). However, for exceptional years under present climates, and more importantly under monsoon climates, where late summer storms can increase the soil moisture storage, the assumption of independent water years is neither physically appropriate nor conservative. Under the potential conditions of higher than normal precipitation years coming in sequence (Fiering and Jackson, 1971), the elevated soil moisture from the previous year can produce significantly more net infiltration the following year. This outcome, however, is precluded in the MASSIF simulations, and no alternative models were tested that would allow for a more realistic representation of sequential climate years. As a result, the bounds of uncertainty in the net infiltration may be underestimated during wetter meteorologic and climate scenarios.

Although Section 6.5.7.4 of the infiltration model report describes how an alternative set of simulations (IC 1 runs) was run with higher initial conditions that showed only a slightly higher net infiltration, the review panel does not believe that these simulations best represent the impact of sequential climate years for which multiple wetter-than-average years are simulated. Section 6.5.7.4 did not provide a clear justification for the values of “initially higher water contents,” a detailed analysis of how these values were chosen, or if these values were chosen to represent sequentially wet climate years. The

review panel is concerned that sequentially wet climate years may not have been realistically simulated by the approaches of MASSIF and believes that the impact of sequentially wet climate years has not been adequately tested.

8. Little to No Net Annual Infiltration Predicted for Wash Environments

The MASSIF simulations under the wettest (90%) of the monsoon climates (Figure 6.5.7.2-5) fails to produce significant annual infiltration beneath any of the major washes or ephemeral streams that drain Yucca Mountain. This is contrary to current thinking of recharge behavior under monsoon climates, in which more intense precipitation events will result in more repeated flooding of channels and hence, increased streambed infiltration. For example, Figure 6.5.7.1-2 shows little to no infiltration beneath the washes and even the larger watersheds show no net infiltration. Given that Yucca Wash is large in area, the lack of net annual infiltration in these environments is contrary to recent work by researchers, such as Scanlon (1991, 2000), who suggest that the washes are the primary source of infiltration in desert environments. At Yucca Mountain, washes may not be large sources of net infiltration under the current climate due to infrequent flooding (Flint and Flint, 1995), as they are in other environments. However, under glacial transition and most particularly in monsoon climates, wetter conditions and more intense precipitation events will produce more runoff and hence increase streambed recharge with a sufficient frequency to become major sources of net infiltration (Goodrich et al., 2004; Scanlon et al., 1999; Tyler et al., 1996).

From the model documentation, it appears several sources are likely responsible for this discrepancy: (1) lack of subsurface lateral flow between model cells, (2) incorrect representation of the soil hydraulic properties in cells within washes, (3) “resetting” the soil moisture to dry conditions at the end of each water year, and (4) overestimation of soil depth in wash environments, leading to overestimation of evapotranspiration in the washes. The latter issue may not be that MASSIF overestimates soil depth as much as it averages deep soils in lower washes with shallow soils in upper washes, resulting in a relatively deep soil in all washes, probably eliminating infiltration in the upper, shallow-soil washes because they have been assigned the average, uniform, deeper depth.

In addition, the largest drainage to the north of Yucca Mountain (Yucca Wash) was partially cutoff from the study due to “lack of detailed information on soil and bedrock properties in this region.” Given the general lack of measured values elsewhere, this removal of part of the hydrologic basin seems quite arbitrary. As washes do provide concentrated recharge (Goodrich et al., 2004, pp. 77-99; Hogan et al., 2004, p. 294), this catchment should be included in the modeling while assuming conservative properties.

The review panel concluded that infiltration is likely underestimated beneath the wash environments due to simplifications of parameters, limited data for parameterization, and the assumptions used to develop the model. When flow is concentrated in channels, or when there are focused preferential flow paths (e.g., sand columns, macropores), there will likely be sufficient water to overcome pore suction and upward thermal gradients to achieve recharge to the unsaturated zone (Hogan et al., 2004).