RAI Volume 3, Chapter 2.2.1.3.6, Second Set, Number 9:

> Explain how water table temperature data support predictions for the distribution of unsaturated flow reaching the water table.
>
> Basis: Depending on the flux rate, percolating water should depress the geothermal gradient in the unsaturated zone, and perturb the temperature at the water table. Zones of high percolation flux should lead to lower water table temperatures compared to zones with lower percolation flux because water entering the unsaturated zone is cooler than water at depth. Thus, the spatial pattern of water table temperatures should reflect the spatial distribution of percolation flux. Temperatures at the water table could reflect the (i) localized and high flux rates predicted by the unsaturated zone model in faults, (ii) low flux reaching the water table below zeolitic rocks, which predominate in the northern half of the repository, or (iii) intermediate fluxes focused by decreasing areal extent of vitric Calico Hills Formation with depth, which predominates in the southern half of the repository.
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> Interpolations of water table temperature include those presented in the SAR (Figure 2.3.2-37) and SNL, 2008 (Figure 6.3.1-7), and an interpolation based on the data in Sass, et al. (1988).

1. RESPONSE

An examination was performed of the spatial distribution of temperatures at the water table and the relationship of water table temperature to depth to the water table (thickness of the unsaturated zone), percolation flux through the unsaturated zone, faults, and vertical groundwater flow in the saturated zone. Use of water table temperature data to support predictions for the distribution of unsaturated flow is generally precluded by the complexity of other processes and features influencing the temperature at the water table, particularly at individual borehole locations. Measured water table temperatures are used in the development of percolation flux distributions for the total system performance assessment (TSPA) (SNL 2007a, Section 6.8 and Appendix J). However, no relationship between water table temperature and percolation flux, and a process model for predicting water table temperature based on underlying factors, has been developed or used in TSPA. Scatter plots of water table temperature and percolation flux at the water table, water table temperature and unsaturated zone thickness, and water table temperature and saturated zone vertical flux show no interpretable relationships. Similarly, a scatter plot of average temperature gradient in the unsaturated zone and percolation flux at the water table shows no interpretable relationship. The conclusion is that water table temperature is not a sensitive indicator of percolation flux in the unsaturated zone and is not suitable to support predictions for the distribution of unsaturated zone flow reaching the water table.

1.1 FACTORS THAT AFFECT WATER TABLE TEMPERATURES

Temperature at the water table may be influenced by percolation flux in the unsaturated zone, with higher percolation flux resulting in a lower temperature at the water table. However, temperature at the water table is more greatly affected by several other factors, and these may obscure the effects of variability in percolation flux through the overlying unsaturated zone. These other factors include:

- Thickness of the unsaturated zone – The water table temperature is a function of depth below the ground surface, with greater depths corresponding to higher temperatures. The depth to the water table in the area near Yucca Mountain varies from less than 300 to greater than 700 m, primarily in relation to topographic relief.

- Vertical groundwater flow in the saturated zone – Vertical groundwater flow can impact temperatures at the water table by altering the conductive geothermal gradient in the underlying saturated zone. Near Yucca Mountain, upward groundwater flow would increase temperatures at the water table while downward groundwater flow would decrease temperatures at the water table. The magnitude and variability of the vertical component of groundwater flow in the saturated zone can be large relative to the magnitude of percolation flux through the unsaturated zone.

- Thermal conductivity in the unsaturated zone – Differences in the geology of the unsaturated zone can result in variability in the effective thermal conductivity of the unsaturated zone. The thermal conductivity of non-welded tuff and alluvium is significantly lower than for welded tuff. Greater thickness of geologic units with lower thermal conductivity in the unsaturated zone would result in higher temperatures at the water table.

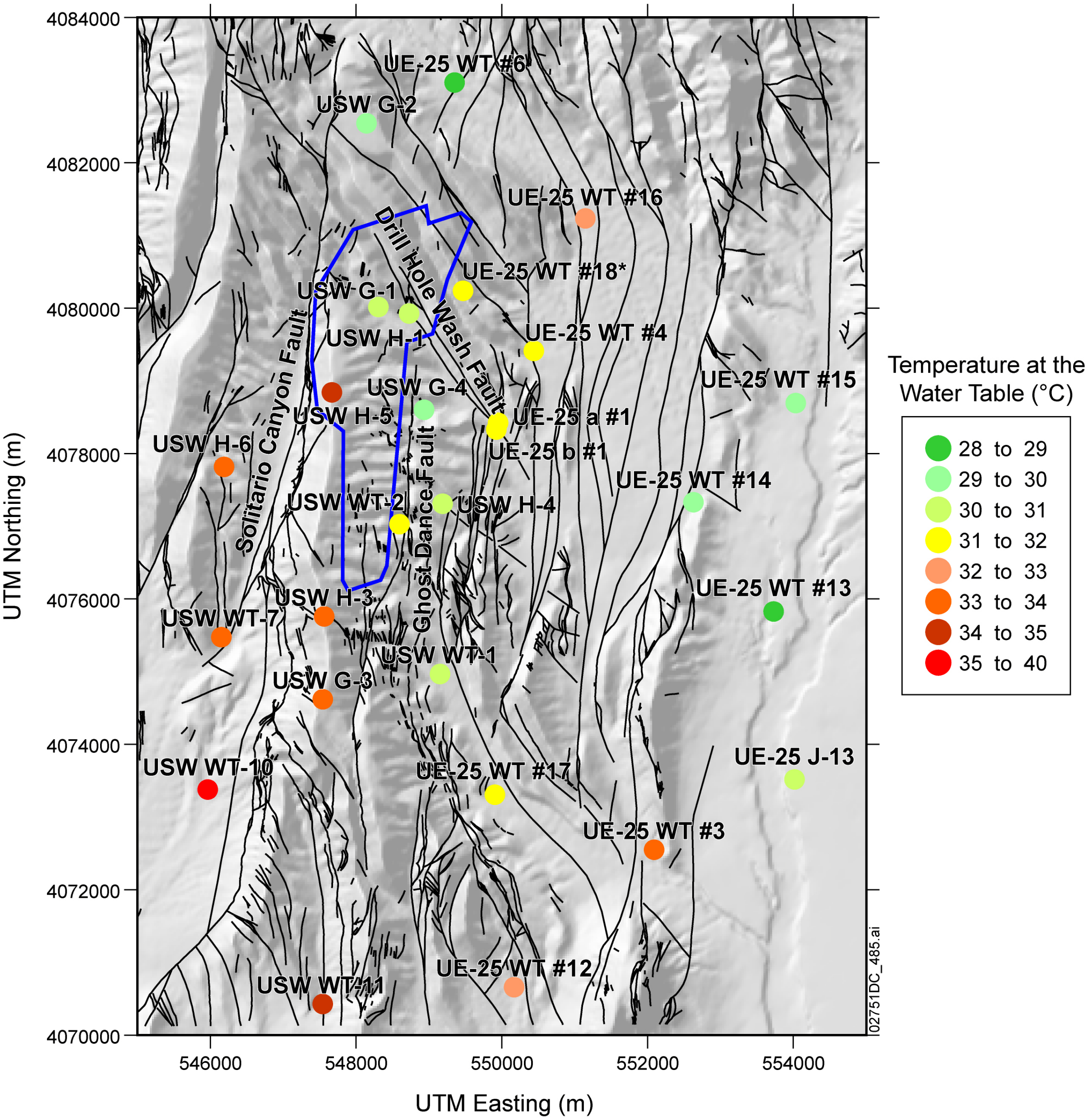
- Average surface temperature – The average annual temperature at the ground surface is a function of topographic elevation and varies by several degrees Celsius in the area near Yucca Mountain. A lower average surface temperature would lead to a lower temperature at the water table.

- Deep subsurface heat flux – The conductive heat flux from the deep subsurface can vary as a function of heat production rate in crustal rocks, variations in thermal conductivity at depth, and tectonic setting. Although most of these variations are expected to occur at scales larger than the area near Yucca Mountain, some local variations may also influence temperatures at the water table.

Considering these multiple factors that can influence the temperature at the water table, it is difficult to interpret the potential relationship between percolation flux in the unsaturated zone and the observed temperature at the water table at specific locations. Consequently, an empirical approach is taken in this analysis. The data at multiple locations are examined for possible relationships between predicted values of unsaturated zone thickness, percolation, and saturated zone fluxes.

1.2 COMPARISONS OF WATER TABLE TEMPERATURES WITH UNSATURATED ZONE THICKNESS AND COMPUTED PERCOLATION FLUXES

Before evaluating possible relationships, the distributions of saturated zone vertical flux, unsaturated zone thickness, and percolation are examined. There are 27 boreholes with both temperature measurements and water table elevation measurements in the vicinity of Yucca Mountain (SNL 2007a Section J3.1). Figure 1 shows the locations of these boreholes and the corresponding measurements of temperature at the water table. Temperatures range from about 28°C to greater than 38°C and trend from higher temperatures to the west of Solitario Canyon fault and along the crest of Yucca Mountain to cooler temperatures to the east and north of Yucca Mountain.

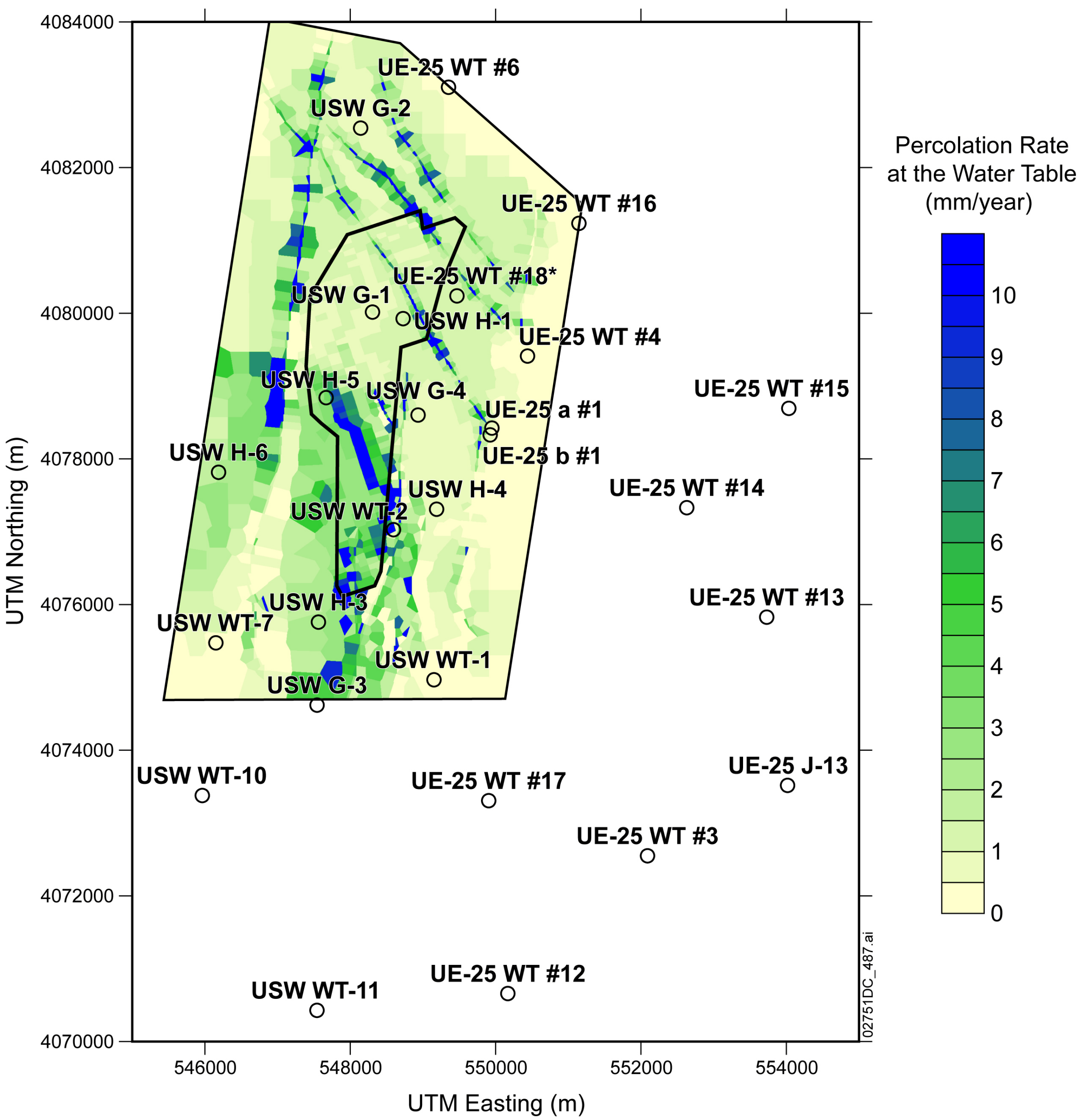


NOTE: Faults are shown as black curves and the repository outline is in blue.

Figure 1. Borehole Locations and Measured Water Table Temperatures

Variations in depth to the water table and proximity to the major block-bounding Solitario Canyon fault system explain some of the general spatial trend in temperatures at the water table evident in Figure 1. The higher temperatures in the boreholes along the crest of Yucca Mountain (H-5, H-3, and G-3) may be associated with relatively greater depth to the water table at these boreholes. Boreholes to the east and north of Yucca Mountain tend to have lower temperatures and lesser depths to the water table. Boreholes H-6, WT-7, WT-10, and WT-11 have higher than average temperatures at the water table and are located near the Solitario Canyon fault or the branching Iron Ridge fault to the west and south of Yucca Mountain.

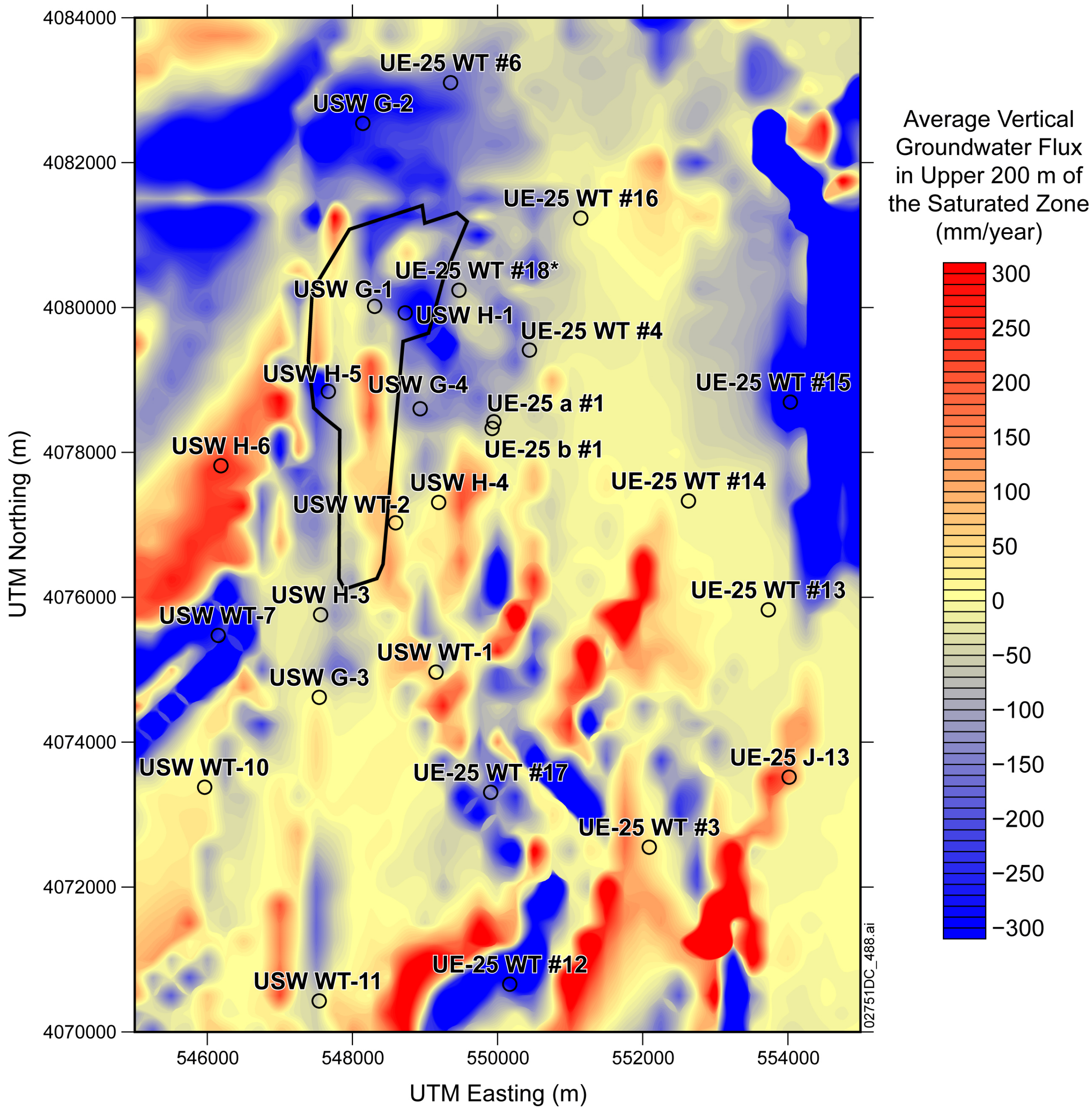
Simulated percolation flux at the water table taken from the unsaturated zone model (SNL 2007a) is shown in Figure 2. Percolation fluxes generally range from zero to 10 mm/yr below the unsaturated zone model footprint, with a maximum percolation value of 2,967 mm/yr, and an area-weighted average of 3 mm/yr. The maximum value occurs in a fault near the projected intersection of the Solitario Canyon and Drill Hole Wash faults. The focusing of groundwater flow and resulting higher values of percolation flux along some of the major faults in the unsaturated zone flow model are shown in Figure 2. The lower temperatures at the water table in boreholes H-1, a#1, b#1, and WT-2 may be related to the higher percolation rate simulated to occur in the nearby Drill Hole Wash and the Ghost Dance faults.



NOTE: Borehole locations are indicated with the open circles and the repository outline is in black.

Figure 2. Unsaturated Zone Model Percolation Fluxes at the Water Table for the 10th Percentile Infiltration Scenario for the Present-Day Climate

Output from the saturated zone site-scale flow model (SNL 2007b) was post-processed to extract layer-thickness-weighted vertical fluxes at nodes within 200 m of the water table, and results are shown in Figure 3. Fluxes range from $-7{,}800$ to 15,600 mm/yr, although the color scale from ± 300 mm/yr shows the results most effectively because the averages are -160 and 200 mm/yr. The larger values of upward groundwater flow shown in Figure 3 are generally to the south and west of Yucca Mountain. There is significant variability in upward and downward simulated groundwater flow evident at the local scale, but there is an overall pattern of more upward flow to the south and west of Yucca Mountain, consistent with an upward gradient observed in USW H-1 and H-3 (SNL 2007b, Section 6.3.1.5). Visually comparing Figures 1 and 3, however, suggests no distinct relationship.



NOTE: Borehole locations are indicated with the open circles and the repository outline is in black. A positive value of flux indicates upward flow and a negative value indicates downward flow.

Figure 3. Saturated Zone Model Vertical Fluxes

The thickness of the unsaturated zone is another factor that has a relatively straightforward influence on the temperature at the water table (i.e., a thicker unsaturated zone insulates the water table and elevated temperatures would be expected). This relationship is examined by plotting the depth to the water table versus the temperature at the water table for the boreholes near Yucca Mountain in Figure 4. This plot shows no interpretable relationship between temperature at the water table and depth to the water table. Boreholes WT-10, WT-11, WT#12, and WT#3 seem anomalously warm in Figure 4 and are all located furthest south of Yucca Mountain. If these boreholes are not included, there is a distinct trend of increasing water table temperature with depth. While no single-parameter relationships appear to explain all the data in the analyses presented here, thermal modeling has demonstrated how variations in temperature in the saturated zone are primarily controlled by the combination of thermal conduction and depth, accounting for about 80% of the variation in the observed temperatures (Arnold et al. 2003). Similar results were also found by Painter et al. (2003) where the effects of unsaturated zone thickness on thermal conduction and, to a lesser extent, vertical flow in the saturated zone were identified as the main factors affecting water table temperature.

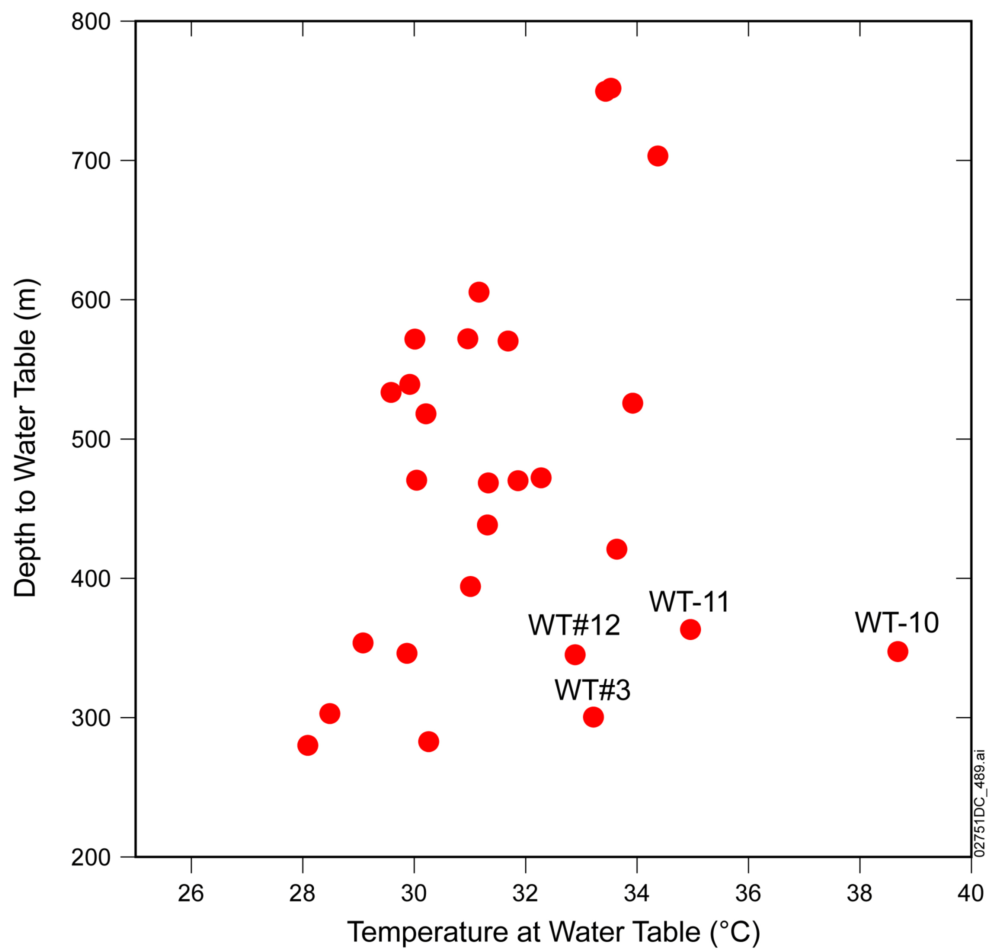


Figure 4. Depth to the Water Table versus Observed Temperature at the Water Table

Percolation flux and temperature at the water table are examined by plotting simulated percolation flux versus the measured temperature at the water table for 15 boreholes in Figure 5. This is a subset of the 27 boreholes used in Figures 1 through 4 that lie within the domain of the unsaturated zone flow model. It is important to note that the temperature at the water table could be impacted by the vertical percolation flux throughout the unsaturated zone and not only by the percolation flux at the water table because the water will warm as it flows through the unsaturated zone. Area-weighted percolation fluxes from the 10th and 90th percentile infiltration cases from the unsaturated zone model were extracted from within 100 m of each water table temperature measurement. Although there is some trend in the data indicating higher water table temperature with increasing percolation flux, this relationship may be spurious because increased percolation flux is expected to lead to lower water table temperatures. The map of unsaturated zone model percolation fluxes for the 10th percentile infiltration scenario is presented in Figure 2.

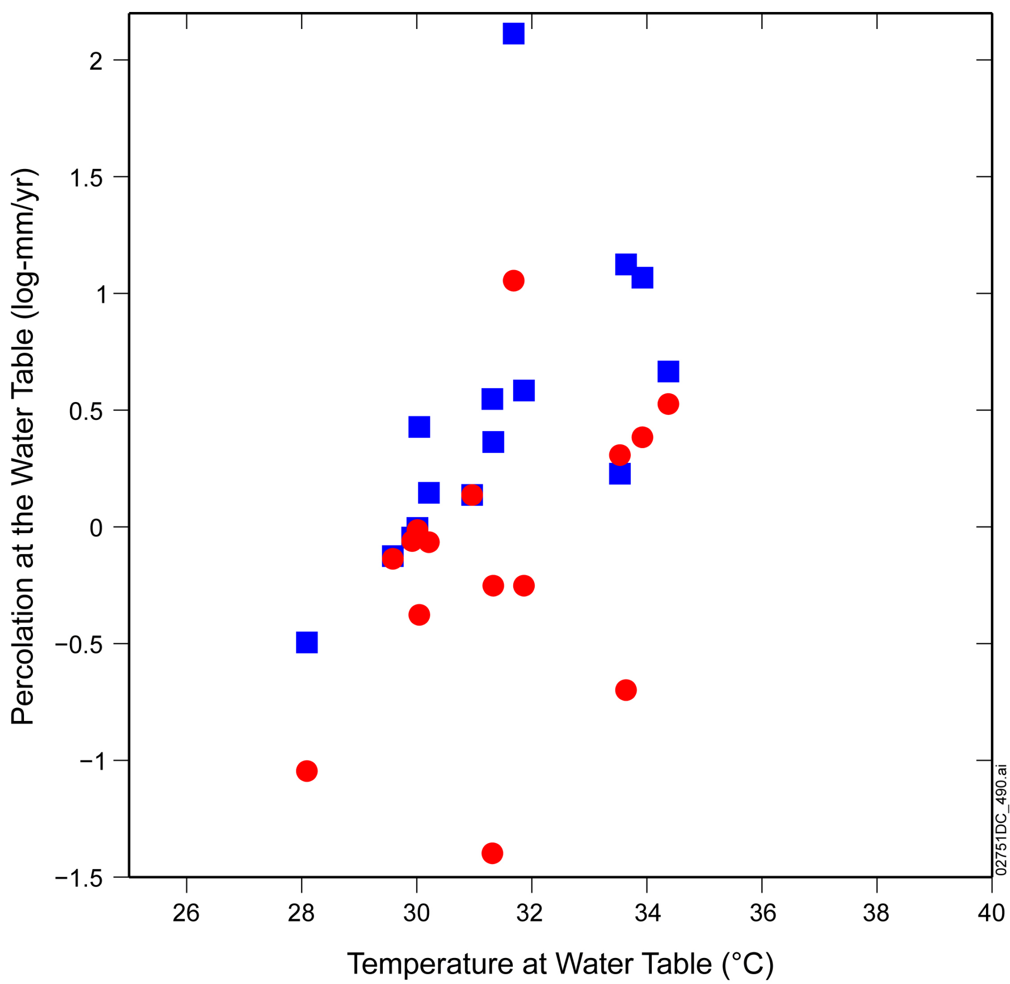


Figure 5. Unsaturated Zone Model Area-Weighted Percolation Fluxes within 100 m of Each Water Table Temperature Measurement for the 10th (circles) and 90th (squares) Percentile Infiltration Scenarios

An alternative, shown in Figure 6, is to make a plot similar to Figure 5 in which percolation flux for the 10th and 90th percentile infiltration cases are plotted versus the average temperature gradient in the unsaturated zone (the *y*-axis is presented in log scale). The average temperature gradient is calculated as the difference between the temperature at the water table and the average surface temperature, divided by the thickness of the unsaturated zone. The average temperature gradient in the unsaturated zone thus effectively "normalizes" the temperature at the water table for the impacts of variations in unsaturated zone thickness and average surface temperature. As shown in Figure 6, there is no interpretable relationship between temperature gradient and percolation flux at the water table.

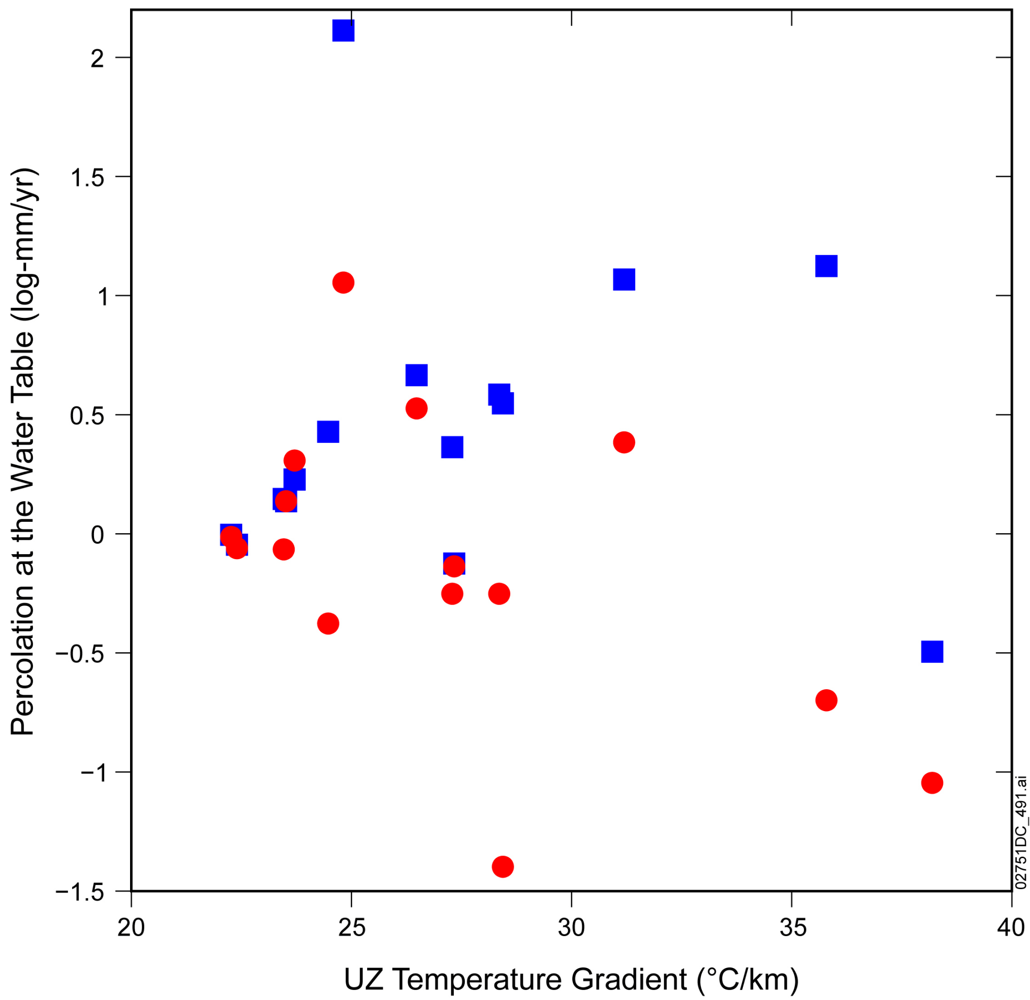
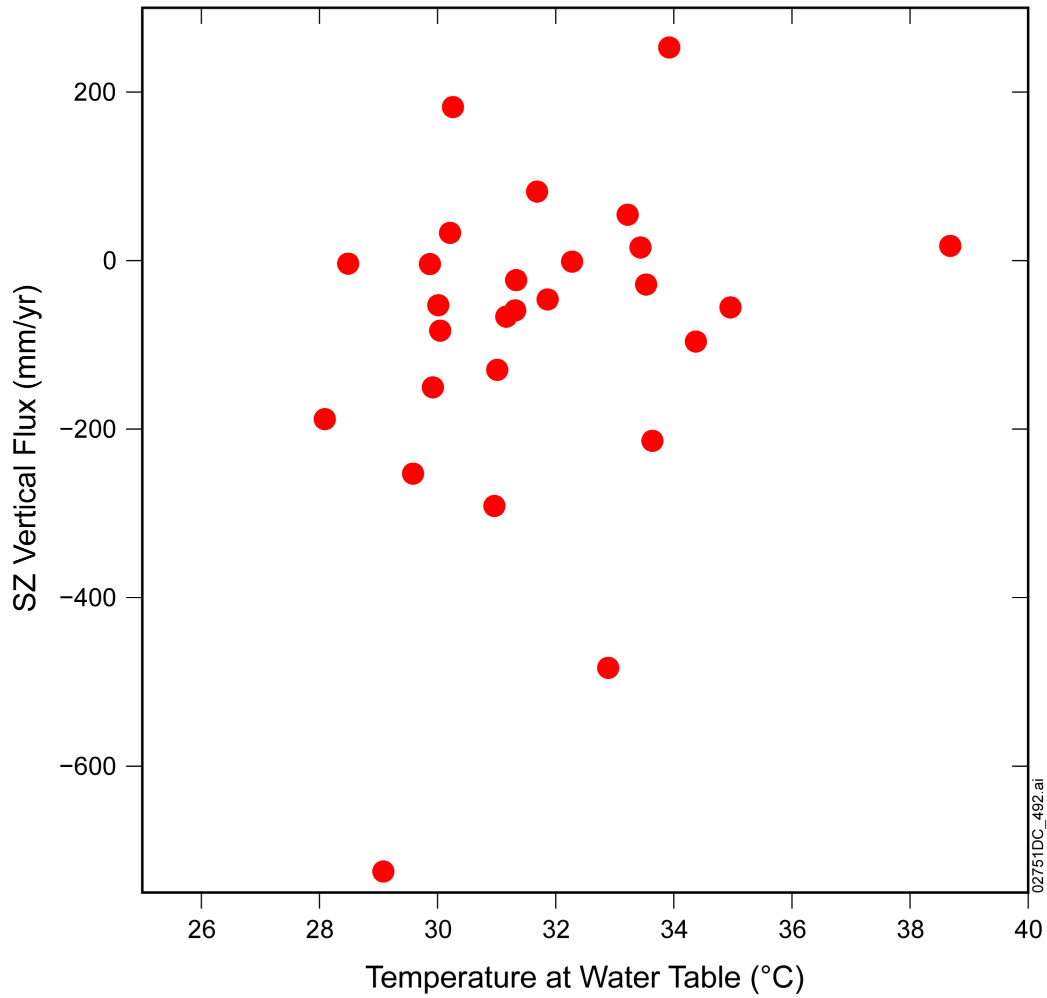


Figure 6. Unsaturated Zone Model Area-Weighted Percolation Fluxes Within 100 m Compared to the Unsaturated Zone Temperature Gradient for the 10th (circles) and 90th (squares) Percentile Infiltration Scenarios

Figure 7 is a cross plot of measured water table temperatures at 27 boreholes and vertical fluxes in the top 200 m of the saturated zone. Because of the 250-m node spacing in the saturated zone model, only the nearest node to the water table temperature measurement is presented. No interpretable relationship is evident.



NOTE: Only the flux from the nearest saturated zone node to the water table temperature measurement point is presented.

Figure 7. Saturated Zone Model Vertical Fluxes Compared to the Water Table Temperatures

1.3 REVISED WATER TABLE TEMPERATURE MAP

The response to RAI 3.2.2.1.3.6-008 outlines the technique used to develop an interpolated water table temperature map. The footprint for that map corresponds to the unsaturated zone thermal model domain and is smaller than Figure 1; the larger domain used in this response allows for examination of additional water table temperature data points. However, the measured borehole temperatures of Figure 1 are the same as those used to develop the water table temperature map shown in Figure 6 of the response to RAI 3.2.2.1.3.6-008.

1.4 SUMMARY

Measured water table temperatures are used in the development of percolation flux distributions for the TSPA (SNL 2007a, Section 6.8 and Appendix J). However, no relationship between water table temperature and percolation flux, and a process model for predicting water table temperature based on underlying factors, has been developed or used in the TSPA. Comparisons of various individual factors including unsaturated zone percolation flux relative to water table temperature, and the unsaturated zone average temperature gradient, do not have interpretable relationships. This leads to the conclusion that variations in water table temperature are not substantially explained by any one factor. Results given by Arnold et al. (2003) and Painter et al. (2003) suggest that water table temperature may be related to a combination of unsaturated zone thickness, thermal conductivity variations, and vertical flow patterns in the saturated zone. Therefore, water table temperature is not a sensitive indicator of percolation flux in the unsaturated zone and is not suitable to support predictions for the distribution of unsaturated zone flow reaching the water table.

2. COMMITMENTS TO NRC

None.

3. DESCRIPTION OF PROPOSED LA CHANGE

None.

4. REFERENCES

Arnold, B.W.; Zyvoloski, G.; Economy, K.; and Wallace, M. 2003. "Thermal Transport in the Saturated Zone Site-Scale Model at Yucca Mountain." *Proceedings of the 10th International High-Level Radioactive Waste Management Conference (IHLRWM), March 30-April 2, 2003, Las Vegas, Nevada.* Pages 301-306. La Grange Park, Illinois: American Nuclear Society.

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SNL (Sandia National Laboratories) 2007a. *UZ Flow Models and Submodels.* MDL-NBS-HS-000006 REV 03 AD 01. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20080108.0003; DOC.20080114.0001; LLR.20080414.0007; LLR.20080414.0033; LLR.20080522.0086; DOC.20090330.0026[a].

SNL 2007b. *Saturated Zone Site-Scale Flow Model.* MDL-NBS-HS-000011 REV 03. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070626.0004; DOC.20071001.0013; LLR.20080408.0261; LLR.20080512.0162; DOC.20080623.0001.

NOTE: [a]Provided as an enclosure to letter from Williams to Sulima, dtd 06/1/09, "Yucca Mountain – Request for Additional Information – Safety Evaluation Report, Volume 3 – Postclosure Chapter 2.2.1.3.6 – Flow Paths in the Unsaturated Zone, Set 1 – (Department of Energy's Safety Analysis Report Sections 2.3.2 and 2.3.3)."