Chapter 4
Saturated Zone

I. Overview

The saturated zone contributes as a natural barrier in two ways: (1) It delays the transport of radionuclides to the accessible environment (increases the travel time) and (2) It reduces the concentration of radionuclides that entered from the UZ before they reach the accessible environment (causes dilution).[1] Characterization of the SZ has been influenced to a certain extent by the regulations that existed in the past. Under the previous release-based standard, dilution in the SZ did not play a significant role. Only the delay aspect of the SZ was important because of the requirement for a minimum groundwater travel time at the site (10 CFR 60). Now that a change is anticipated from a release-based to a dose- or risk-based standard, the SZ is a more important natural barrier because of its potential to decrease radionuclide concentration (DOE 1998). Dilution is particularly important for reducing the peak dose from very-long-lived radionuclides (e.g., ^{237}Np), where delay does not result in significant radioactive decay.

The flux of water percolating (flowing) down through the UZ at Yucca Mountain is small (on the order of 7 mm/yr in the current climate) in comparison to the groundwater flux laterally in the SZ below Yucca Mountain. Although there is a large spatial variability of the lateral flux in the SZ, the average flux is thought to be on the order of 1 meter/yr, more than 100 times the estimated downward flux in the UZ. The UZ flow is expected to “mix” to a certain depth and thus be diluted by the larger volume of water flowing in the SZ (Sevoughian et al. 1995). However, the amount of dilution through mixing is highly uncertain and difficult to verify. There are no data at Yucca Mountain to determine the amount of mixing that could occur at the SZ-UZ interface. There also are no data to substantiate how much the radionuclide-contaminated plume will spread as water flows from the repository to the accessible environment.

Radionuclide dilution and travel times are directly related to repository performance. They address the “How much will arrive?” and “How long will it take?” aspects of the SZ. Other aspects also can be important, even though they might not directly influence the computed dose. One is “Where will the radionuclides arrive?”—i.e., the present and paleo-discharge points. Another can be the total water budget in the flow system and its relation to withdrawal in Amargosa Valley. Thus, characterization of the SZ should not be limited to information deemed necessary to performance assessment.

II. Regional SZ Groundwater Flow

A. Stratigraphy

The SZ at Yucca Mountain lies between 500 and 700 meters below the surface. The dominant recharge of water to the SZ occurs north of Yucca Mountain at higher elevations, where precipitation is greater and

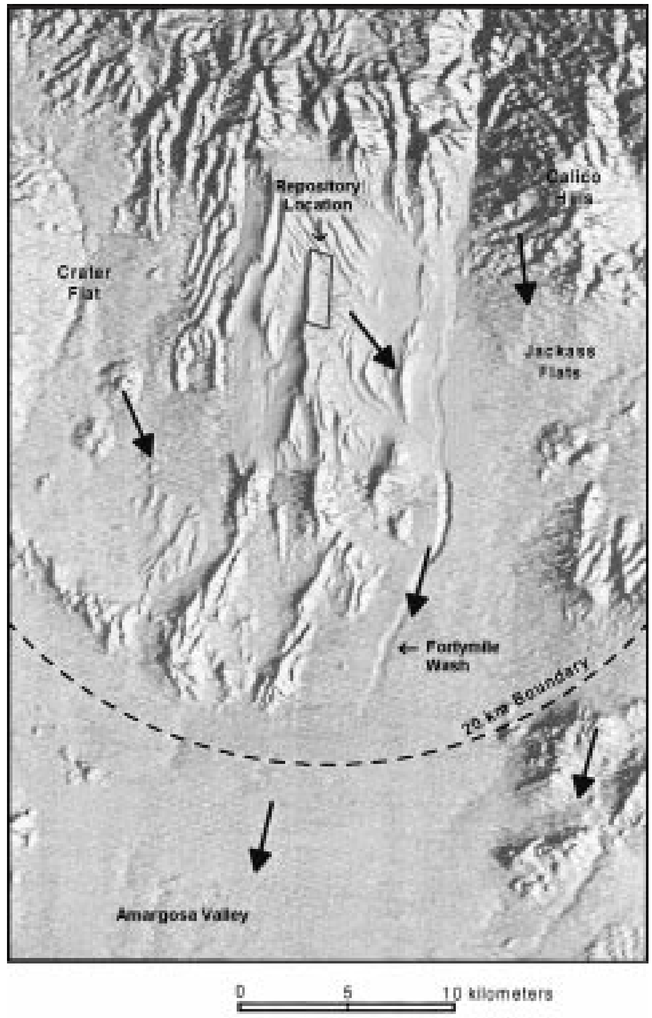
1. The dilution factor for the SZ is defined as the ratio of the average radionuclide concentration in groundwater entering the SZ from the UZ to the average radionuclide concentration being withdrawn from the SZ for human use.

temperatures are lower. The dominant flow direction in the SZ from the Yucca Mountain site is southeast toward and below Fortymile Wash, then south to Amargosa Valley, as shown in Figure 4-1.

The primary hydrogeologic units that carry and influence the flow are the volcanic aquifer (consisting of the Upper Tram, Bullfrog, and Prow Pass formations), the volcanic aquitards (confining units) of the Calico Hills formation, the underlying and more permeable Paleozoic carbonate aquifer, and, to the south, the valley-fill alluvium. An idealized geohydrologic cross section from Yucca Mountain to Amargosa Valley is shown in Figure 4-2.

Based on data showing that the water pressure in the carbonate is higher than in the overlying volcanic aquifer and on numerical modeling, the general belief (SZEE 1997, D'Agnese et al. 1996) is that the downgradient flow paths emanating from Yucca Mountain primarily stay within the volcanic aquifer and, farther south, within the valley-fill alluvium. These flow paths probably do not penetrate the carbonate aquifer close to Yucca Mountain.[2] However, insufficient hydrologic and stratigraphic data downgradient between Yucca Mountain and Amargosa Valley make the models and their interpretations uncertain.

Figure 4-1. Plan View of Flow System (after D'Agnese et al. 1996)



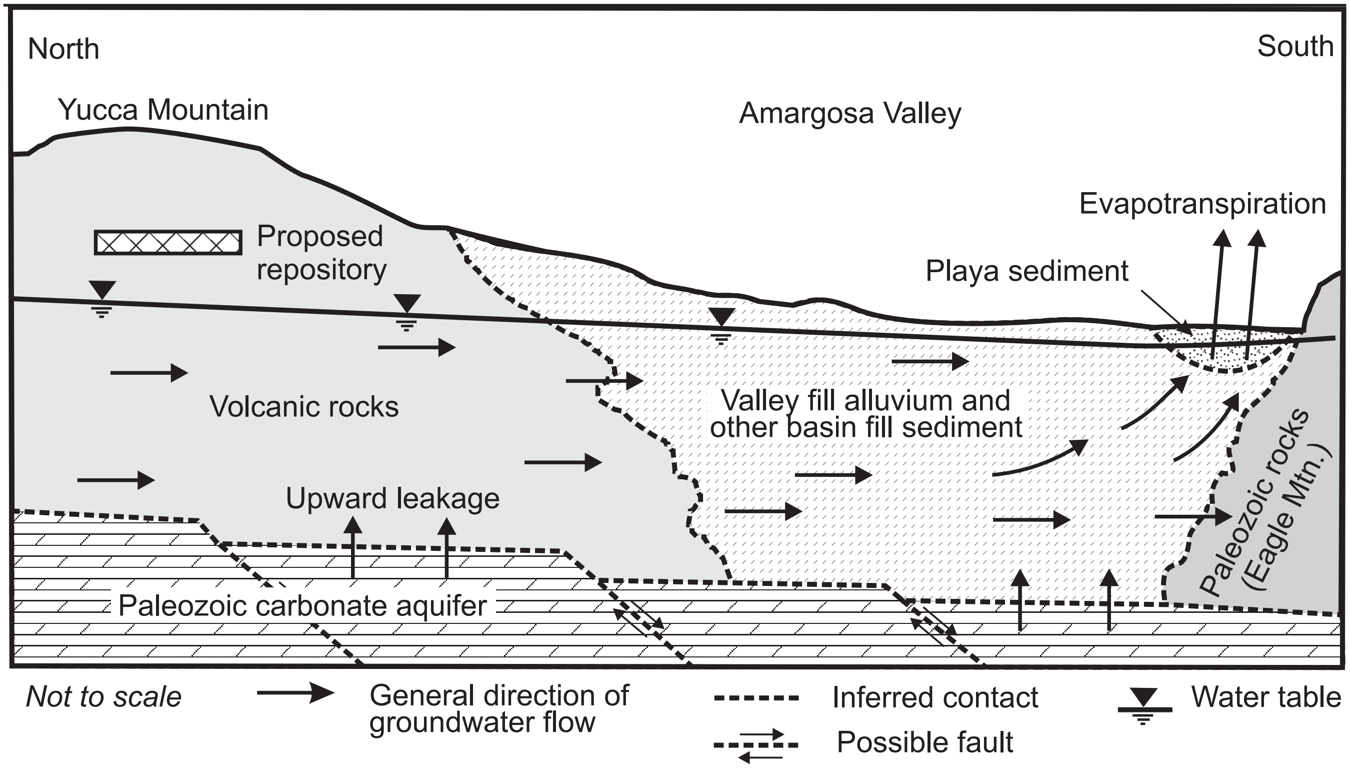
B. Hydraulic Conductivity

An important factor in the TSPA is the magnitude of groundwater flux at the top of the SZ beneath Yucca Mountain (Sevougian et al. 1995). At the water table beneath the site, the dominant aquifer carrying the flow is a volcanic aquifer consisting of the Prow Pass, upper and lower Bullfrog, and Tram units,[3] the lower Bullfrog being the most transmissive. To estimate the groundwater flux in a unit, one must know the spatial distribution of hydraulic conductivity of that unit and the hydraulic gradient.

The primary uncertainty is in the estimation of hydraulic conductivity because relatively few data at the appropriate scale are available. The most reliable data come from the recent testing at the C-well complex (Geldon et al. 1997). The C-well data are from multiple-well pumping tests, which are generally more reliable than single-well tests. The C-well tests were designed to test the Bullfrog unit; single-well test results are available for the other units. Continuing the C-well pumping tests longer so that hydrologic

2. This conclusion is based on a single measurement of the pressure head in the carbonate aquifer.
3. These units are part of the Crater Flat undifferentiated rock group shown in Figure 1-1.

Figure 4-2. North-South Cross Section of SZ (after Czarnecki 1989)



information could have been obtained on a larger scale would have been fruitful. Upon evaluating the set of available data, the Saturated Zone Expert Elicitation (SZEE) Panel assessed an average uncertainty of two orders of magnitude for hydraulic conductivity for the upper and lower volcanic aquifers (SZEE 1997). This uncertainty carries over to the uncertainty about the flux beneath the site.

Additional tests at the C-well complex or other field studies, perhaps on the main block, would reduce this uncertainty and greatly increase the confidence of the SZ site-scale modeling. These tests could be carried out in several distinct units of the volcanic aquifer and over sufficient time-space intervals. The data could be obtained within the next several years. Having these test plans reviewed by an outside group, such as the panel that was convened for the expert elicitation project (SZEE 1997), before the plans are implemented also would be useful. Such a review would add confidence that the testing will obtain the required information on the SZ.

C. Channeled Flow

Because the region has been tectonically active, the regional hydrogeologic environment is structurally complex and characterized by locally high permeabilities that are due to faults and fractures. Most of the flow appears to be channeled in preferential flow paths, which, on the basis of flowmeter data obtained from boreholes, appear to represent only 5 to 20 percent of the thickness of the hydrostratigraphic units.

The role of the major faults and fracture systems is judged very important, although to what extent these features need to be—or accurately can be—included explicitly in the hydrologic model is not clear (SZEE 1997). Because the location and hydrologic properties of the faults are poorly known, model predictions of transport will have a large uncertainty (i.e., the pathway taken by the radioactive plume will be difficult to predict). In the past, little effort has been made to characterize the hydraulic conductivities of faults and fault zones, despite their potential significance. The DOE plans to evaluate the hydraulic significance of the Solitario Canyon fault zone as well as other possible faults.

D. Water Budget

The main recharge to the SZ comes from farther north, as well as from Fortymile Wash, but there is uncertainty about the total volumetric recharge of groundwater to the regional groundwater system. The discharge areas of the regional flow system are known, but the volumetric discharge from the regional system is not well constrained. Recently, efforts have been made to estimate evapotranspiration in the Ash Meadows and Franklin Lake Playa areas more accurately, but the magnitude of discharge is still considered approximate within Oasis Valley, Death Valley, and Amargosa Valley (Paces et al. 1996). The total recharge and discharge of water into and out of the groundwater system is an important constraint on the regional and site-scale groundwater models. Currently, water usage in Amargosa Valley is a significant fraction (~20 percent) of the estimated total water budget and can be expected to increase in the future.

E. Nye County Early Warning Drilling Program

DOE funding has been allocated for Nye County's proposed system of wells approximately 5 km downgradient of Yucca Mountain. Twenty-one wells are contemplated: 15 wells in the 500- to 1,000-ft depth range and 6 deeper wells for penetrating the carbonate aquifer and determining the hydraulic heads there. The 21 wells will be distributed roughly perpendicular to the direction of anticipated groundwater movement from Yucca Mountain, approximately at the interface of the volcanic rocks and the alluvium (see Figure 4-2). Considerable data will be obtained from these wells over the next 3 years (and beyond) that will form a baseline of the present conditions in the SZ at this location and that will fill in key data gaps for the SZ regional flow system. The gathered data, including geology and stratigraphy, pressure head, water chemistry, and isotopic data, should substantially increase confidence in the regional-scale modeling effort.

III. Conceptual Model of Radionuclide Transport in SZ

A. Groundwater Travel Times

Highly transmissive zones controlled by faults are believed to exist in the SZ (Geldon et al. 1997), as evidenced by the regional distribution of paleo-spring deposits and modern springs that are associated with known faults (Paces et al. 1996). In such highly heterogeneous systems, groundwater travel times are highly variable and the first arrival times can be quite short (on the order of a few hundred years), but there are no direct data that support this estimate. The travel-time distribution through the volcanic aquifer to the accessible environment 20 to 30 km away is not known. In highly heterogeneous systems, the distribution of travel times can best be estimated by conducting a tracer test on the length scale of interest, or at least on a scale that is relevant to the model requirements.

Base-case TSPA-VA models predict travel times through the SZ that are comparatively short—e.g., for most calculations, the breakthrough curves for nonretarded technetium-99 show that 50 percent of the peak concentration at the accessible environment is reached between 500 and 2,000 years. Thus, the SZ travel times, as modeled in TSPA-VA, are significantly shorter than the likely regulatory period of 10,000 years. Current estimates indicate that the SZ by itself will not sufficiently delay the radionuclides in the event of juvenile (premature) failures of the waste packages.

B. Dilution Through Mixing and Diffusion-Dispersion

Two important natural processes in the SZ that reduce the radionuclide concentrations are (1) mixing of the UZ flux with SZ water at the UZ-SZ boundary and (2) spreading of the radionuclide plume by molecular diffusion and hydrodynamic dispersion during flow through the SZ to wells or natural discharge locations. The amount of dilution that will occur in the SZ has been one of the key uncertainties in assessing the performance of the natural barriers. The primary reason is that dilution factors cannot be measured directly and require model predictions.

TSPA-95 assumptions and models, including some mixing of groundwater during withdrawal from a well, yielded dilution factors for the SZ of about 1,000 to 10,000.

In post-TSPA-95 computations, the DOE-M&O's SZ transport model assumed that the UZ flux mixes instantaneously with the SZ water to a depth of 10 meters (the depth of a computational cell). The plume then was reduced further in concentration because of a large (assumed) transverse dispersion (spreading) as it moved through the SZ. Even though the maximum computed concentration in the plume was used for dose computations, these assumptions led to dilution factors in the range of 15 to 200 (Arnold 1998). Dilution due to water withdrawal was not included in these computations.

The dilution factor was discussed thoroughly by the expert panel during the SZEE meeting in 1997; their findings are summarized in their report (SZEE 1997; individual expert commentaries). The consensus of the panel members was that mixing and hydrodynamic dispersion probably are not as effective in spreading the plume as the models had predicted. The numerous faults and the complex stratigraphy make predicting the flow path of the plume and the amount of mixing that might occur along this path very difficult. The experts' interpretation was that the concentration within the plume will not significantly decrease, but rather that the uncertainty about where the plume will emerge is high (i.e., the probability of it being at a specified location is low). The average estimate for the dilution factor from the expert panel was ~10, considerably lower than the 15 to 200 range in the initial TSPA-VA computations.

Because of the lack of data and the unsubstantiated assumptions, radionuclide transport in the SZ is being modeled for TSPA-VA by a one-dimensional stream-tube model. The dilution factors for each stream tube will be sampled randomly from the elicited expert probability distribution functions (range of 1 to 100, expected value of 10) for the dilution factor (Andrews 1998a).

There is some potential that dilution could occur because of infiltration in Fortymile Wash. As the recharged water percolates downward and reaches the water table, it could mix with the underlying plume that would leave Yucca Mountain, lowering its concentration. Conceptually, this process appears possible, but it would be difficult to verify quantitatively.

A shift to a dose-based regulatory standard, as has been recommended by the National Research Council (NAS / NRC 1995), would make estimating how much dilution could occur during SZ transport more important. The current lack of data over the 20- to 30-km distance to the accessible environment (as anticipated in the forthcoming regulatory criteria for a Yucca Mountain repository) makes estimating dilution with any confidence difficult. Thus, the TSPA-VA SZ model relies primarily on the expert elicitation estimates of the dilution factor (average dilution factor of 10). The present estimates of dilution in the SZ (base-case TSPA-VA) could be too pessimistic, just as the earlier TSPA model predictions were too optimistic.

C. Retardation

The SZ is highly variable in its hydraulic properties, and highly transmissive (fractured) regions are known to exist (Geldon et al. 1997). Estimating how much retardation will occur in these fractures is difficult. A considerable fraction of the flow might bypass the sorptive minerals in the volcanic material of the SZ by staying in the highly transmissive (permeable) regions. In that case, if retardation is to be an effective process, matrix-diffusion (the transfer of radionuclides from fractures to the matrix by diffusion) will have to occur.

Retardation may not be as effective in the field as it is when measured in the laboratory in batch experiments, especially where fracture- and fault-controlled flow dominates. Tracer tests at the C-well complex were designed specifically to quantify the processes of retardation and matrix-diffusion in the Bullfrog unit. The experiments provided initial information about the transport of simulated colloids and retarded and nonretarded dissolved species through the fractured Bullfrog unit.

Retardation in the alluvium farther away from Yucca Mountain could be more significant than retardation in fractured tuff. Currently, there are no data that corroborate this hypothesis, although experiments using the proposed Nye County wells could be used to acquire such data.

D. Colloids

The role of colloids in radionuclide transport is discussed in the UZ chapter of this report. Additional data that can be extrapolated to transport of colloids in the SZ are expected from the new experiments planned for the UZ at Busted Butte.

E. SZ Geochemistry

The solubilities of some of the elements in HLW and SNF, including Np and uranium, are sensitive to the oxidizing or reducing potential of groundwater. In the UZ, where water will be oxidizing, these elements may be relatively soluble. However, if the dissolved species are transported into areas of the SZ where conditions are reducing, they will become much less soluble and will precipitate in the same way uranium naturally precipitates to form uranium ore deposits. The precipitated species would be permanently removed from groundwater, with a consequent reduction in predicted radiation doses at the biosphere.

It seems likely that at least some parts of the SZ between Yucca Mountain and the biosphere will have reducing groundwater chemistry. Evidence of reducing conditions would include the presence in groundwater of dissolved methane, H_2S, or Fe^{++}; the absence of dissolved oxygen; and measured Eh (redox potential) values. Geochemical studies of groundwater in the Nye County wells (and possibly at other sites closer to Yucca Mountain) are needed to determine the extent to which reducing conditions may exist in SZ groundwater.

F. Mixing at the Wellhead

Considerable dilution can occur during groundwater withdrawal from an extraction well or wells. The capture zone of a production well could be greater than the dimensions of a radioactive groundwater plume, thereby causing the plume to mix with a considerable amount of fresh water (e.g., the production could be from several stratigraphic intervals, but the contaminated water could be localized in a single interval). Another scenario could be that pumped water from several wells is mixed and distributed to a local population. Thus, even in the case where the plume is basically intact (not dispersed), the process of mixing at the wellhead could produce significant dilution—e.g., up to several orders of magnitude, depending on the specifics of withdrawal. It is plausible that dilution at the wellhead can be quantitatively greater than dilution that occurs through naturally occurring processes in the SZ. Present TSPA-VA estimates assume that the average dilution factor through natural processes is approximately 10, but the distribution of values is skewed to lower values.

Expanded groundwater withdrawal within the Amargosa Valley is almost certain. The carrying capacity of this aquifer will vary for various assumed rates of recharge, i.e., present climate, 1,000-year climate, and superpluvial climate. The USGS regional model is being extended to evaluate the transient effects of climate change and pumping in the Amargosa Valley so that the dose to a "critical group" under varying climatic conditions can be predicted.

TSPA-VA will not use a well-withdrawal scenario for additional dilution at the wellhead but will use the computed maximum concentration in the plume at a distance of 20 to 30 kilometers. Thus, the dilution due to SZ transport will be very small in TSPA-VA.

IV. Influence of Climate Change

The climate has changed in the past and will change during the next 10,000 years, most likely to wetter conditions. Increased precipitation will lead to greater infiltration and an increased percolation flux. The regional recharge will increase, as will the groundwater flow volume, and the water table will rise. Past increases in the water table, up to 100 meters above the present, have been documented through geochemical and paleo-discharge evidence. Thus, the effects of climate change on precipitation, infiltration, and percolation are conceptually understood, although the precise magnitude and timing of the changes are uncertain.

The effects of climate change on repository performance can be modeled in a TSPA as an assumed increase in the percolation flux, a rise in the water table, and an increase in the water flux in the SZ. The DOE's base-case analysis for TSPA-VA considers three climate states, as described in the UZ chapter of this report. As noted above, because of the lack of data, the SZ radionuclide transport is being modeled by one-dimensional stream-tube models. Climate change will be represented as an increased flux in the SZ (i.e., in each stream tube), a rise in the water table, and reactivation of paleo-discharge points.

V. Conclusions

The Board believes that the SZ is an essential natural component of a defense-in-depth repository design for Yucca Mountain. The following are the Board's conclusions about the SZ.

- Groundwater appears to move through the SZ from Yucca Mountain to the accessible environment 20 to 30 km away in less than the likely regulatory period of 10,000 years. Although retardation in fractured rocks may be ineffective because highly transmissive regions within the SZ may allow dissolved radionuclides to bypass sorptive minerals, retardation in the alluvium near Amargosa Valley may be greater. If so, the SZ could significantly delay transport of radionuclides between the repository and the accessible environment.

- Parts of the SZ may be a chemically reducing environment where some of the very-long-lived radionuclides, including Np and uranium, would precipitate, permanently removing them from the groundwater and reducing predicted radiation doses at the biosphere.

- More data are required to support modeling of the SZ, especially for the regional flow system between the repository and the accessible environment 20 to 30 km away. Key geologic, hydrologic, and geochemical data, including information about long-range colloid transport, have the potential to answer specific questions, such as the role of stratigraphy and structure, recharge and discharge locations, and possible ages of water. Obtaining these data is likely to improve the understanding of SZ characteristics much more than additional modeling efforts will.

- Current estimates of SZ dilution eventually may prove to be conservative, but supporting a larger dilution factor will be difficult unless new data are obtained to support the estimates produced by numerical models. The wells and experiments planned by Nye County should provide valuable information about the part of the SZ downgradient of Yucca Mountain. However, these wells may not provide sufficient data, and additional testing at other sites closer to Yucca Mountain may be needed.