2.2.4 Regional Geochemistry

In addition to hydraulic observations, an understanding of regional flow systems can be ascertained from interpretations of the regional hydrogeochemistry. The application of hydrogeochemical and isotopic methods make it possible to reduce some uncertainties concerning regional groundwater flow patterns and flow rates. They also provide some bounds on the magnitude and timing of recharge of saturated zone groundwater.

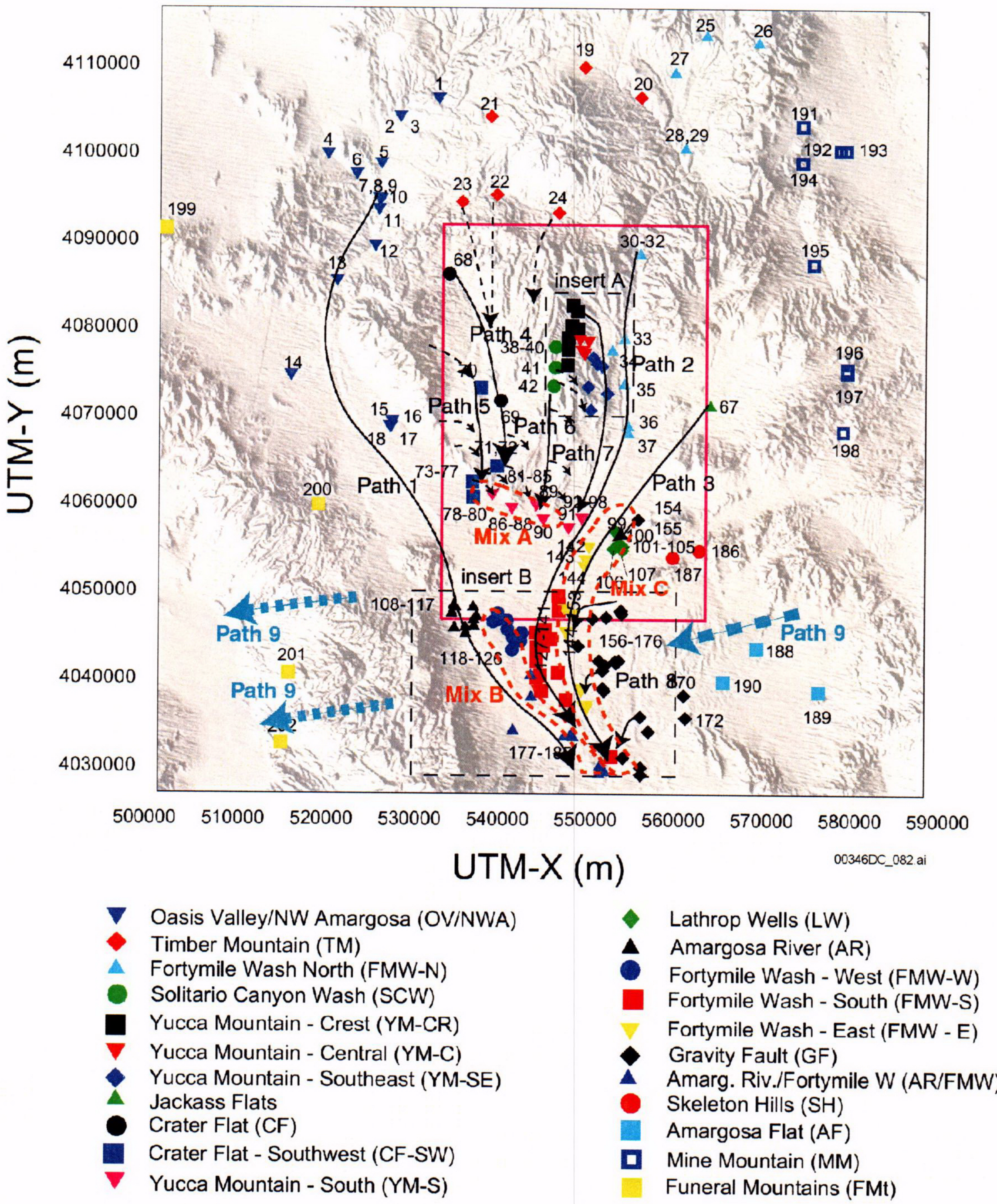
The main processes that control groundwater chemistry are:

- Precipitation (atmospheric) quantities and compositions
- Soil-zone processes in recharge areas
- Rock-water interactions in the unsaturated zone between the zone of infiltration and the water table
- Rock-water interactions in the saturated zone along the flow path from the recharge location to the point where the water is sampled
- Mixing of groundwater from different flow systems.

Groundwater is influenced to differing degrees by these processes, and as a result, groundwater extracted from different places (and therefore traveling by different pathways) can attain different chemical signatures that reflect individual pathway histories. The first three of the main processes do not affect the composition of groundwater after it enters the aquifer. However, input compositions differ in the recharge area because of evapotranspiration (which affects ion concentrations), recharge temperatures (which affect δ-deuterium and $\delta^{18}O$), precipitation compositions, soil-zone mineral dissolution, and precipitation reactions.

After entering an aquifer, chemical characteristics can be affected by interactions between the groundwater and the rocks. Conservative geochemical constituents (i.e., those that show the least effects of interactions with water and rocks) are particularly important for delineating flow paths because these concentrations primarily reflect inputs and processes that operate in recharge areas. Generally, conservative constituents, for which analytical data are available, include chloride, sulfate, δ-deuterium, and $\delta^{18}O$. Where a lack of downgradient continuity in chemical and isotopic compositions was observed, the possibility of groundwater mixing was evaluated and quantified with inverse geochemical mixing and reaction models.

Areal distribution maps of groundwater solutes and isotopes were used in *Geochemical and Isotopic Constraints on Groundwater Flow Directions and Magnitudes, Mixing, and Recharge at Yucca Mountain* (BSC 2003f) to obtain initial estimates of groundwater flow paths. Water type locations and the corresponding observation points used to evaluate geochemical signatures are depicted in Figure 2-10. Figure 2-11 illustrates the same information while showing chloride concentrations in the identified boreholes. Table 2-3 summarizes the basis for the flow paths illustrated on Figure 2-11. Similar plots for sulfate and δ-deuterium were also used in interpreting these flow paths (Figures 2-12 and 2-13, respectively).

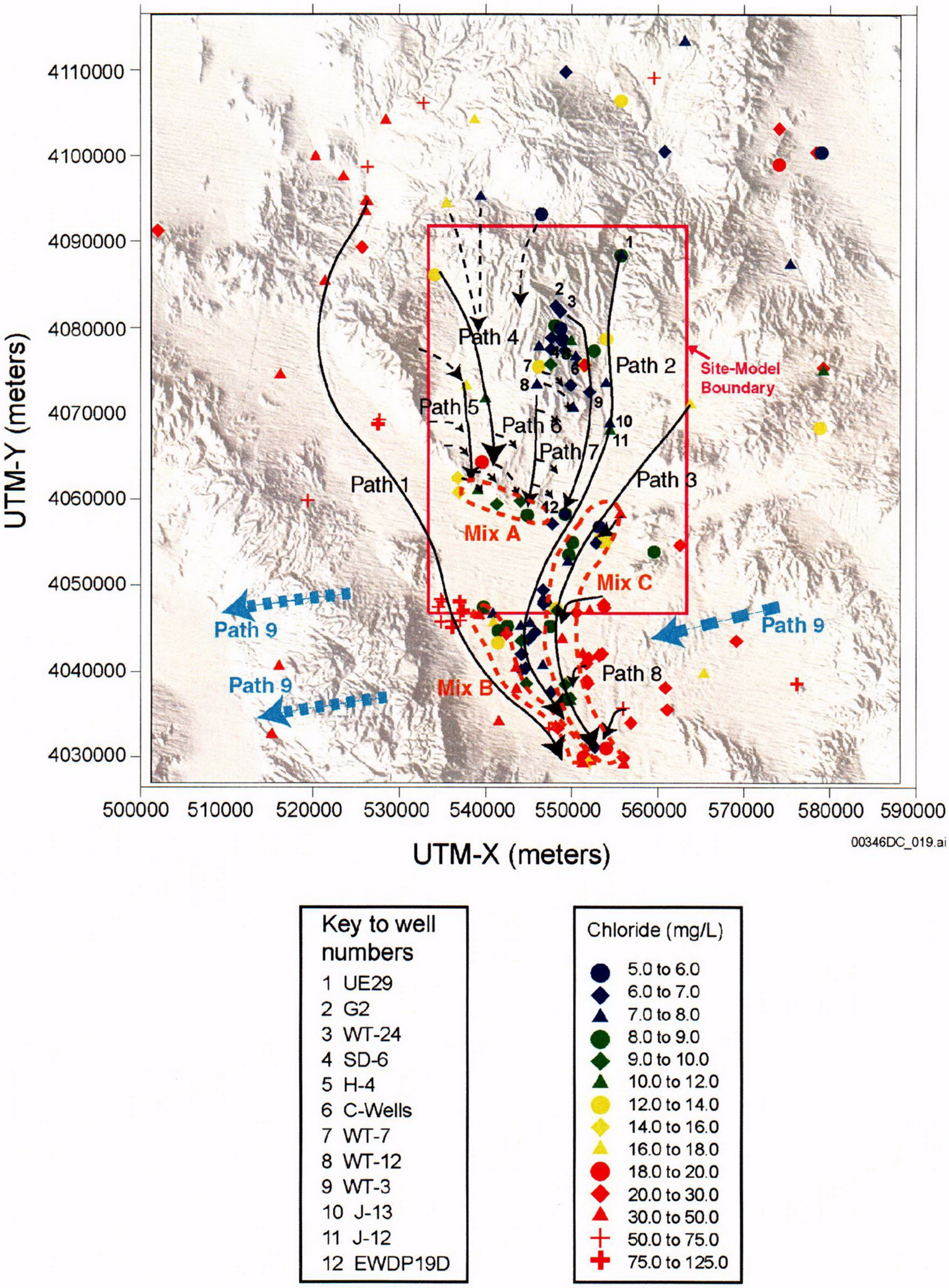


Source: BSC 2003f, Figure 62.

NOTE: The termination of flow paths implies that the flow paths could not be traced from geochemical information downgradient from these areas because of mixing or dilution by more actively flowing groundwater; flow path terminations do not imply that groundwater flow has stopped.

Figure 2-10. Location of Geochemical Groundwater Types and Regional Flow Paths Inferred from Hydrochemical and Isotopic Data

C11



Source: Based on BSC 2003f; chloride from Figure 15; flow paths from Figure 62.

NOTE: The termination of flow paths implies that the flow paths could not be traced from geochemical information downgradient from these areas because of mixing or dilution by more actively flowing groundwater; flow path terminations do not imply that groundwater flow has stopped.

Figure 2-11. Regional Groundwater Chloride Concentrations and Inferred Regional Flow Paths

c12

Table 2-3. Summary of Bases for Regional Flow Paths and Mixing Zones Derived from Geochemistry Observations

Flow Path or Mixing Zone (Figure 2-10)	Geochemical Flow Path or Mixing Zone Description	Geochemical Evidence of Flow Path or Mixing Zone
1	Oasis Valley through the Amargosa Desert along the axis of the Amargosa River to the confluence with Fortymile Wash	Areal plots of chloride and scatterplots of SO_4 versus Cl. Groundwater along this flow path becomes more dilute to the south as it becomes increasingly mixed with groundwater near Fortymile Wash. Upstream of this mixing zone, high groundwater ^{14}C activities and variable δD and $\delta^{18}O$ compositions indicate the presence of relatively young recharge in the groundwater due to runoff or irrigation in the area
2	Fortymile Canyon area southward along the axis of Fortymile Wash into the Amargosa Desert	Similar anion and cation concentrations along the flow line and dissimilarities compared to regions to the east and west. Groundwater along the northern part of this flow path is distinguished from groundwater at Yucca Mountain by δD and $\delta^{18}O$ compositions that are heavier or more offset from the Yucca Mountain meteoric water line than the groundwater found under Yucca Mountain. Based on the observation that ^{14}C activities do not decrease systematically southward in the northern or southern segments of the wash, some part of the groundwater along Fortymile Wash may also be derived from recharge due to runoff or irrigation in the area.
3	Jackass Flats in the vicinity of well UE-25 J-11 southward along the western edge of the Lathrop Wells area and southward through boreholes in the FMW-E area	High SO_4 and low $\delta^{34}S$ characteristics of groundwater from well UE-25 J-11 distinguish it from the high SO_4 and high $\delta^{34}S$ groundwater characteristic of the Gravity fault and the low SO_4 and low $\delta^{34}S$ groundwater of the Fortymile Wash. A scatterplot of $\delta^{34}S$ versus $1/SO_4$ indicates a mixing trend involving well UE-25 J-11 as an end member, with wells in the Lathrop Wells and FMW-E groups having up to 20 percent of a UE-25 J-11-like groundwater. These mixing relations were confirmed with PHREEQC inverse models involving selected boreholes in these groups.
4	Lower Beatty Wash area into northwestern Crater Flat. This groundwater flows predominantly southward in Crater Flat past borehole USW VH-1 and NC-EWDP-3D.	Scatterplots and PHREEQC inverse models show that a mixture of groundwater is required to account for the Cl, δD, and $\delta^{18}O$ compositions characteristic of this flow path. East of Flow Path 4, the extremely light $\delta^{13}C$ and high $\delta^{87}Sr$ of groundwater in northern Yucca Mountain compared to Timber Mountain groundwater, indicates that groundwater from the Timber Mountain and Beatty Wash areas is not the dominant component of groundwater at Yucca Mountain north of Drill Hole Wash.
5	SW Crater Flat Group	Chemically and isotopically distinct from groundwater that characterizes Flow Path 4, with higher concentrations of most major ions (but lower concentrations of F and SiO_2), and relatively high $\delta^{18}O$ and δD. Groundwater in Oasis Valley has some of the lightest oxygen and hydrogen isotopic compositions in the Yucca Mountain area, eliminating flow from Oasis Valley under Bare Mountain as a possible source of groundwater in southwest Crater Flat. A more likely source for groundwater along this flow path is local recharge at Bare Mountain, a source suggested by the similarly heavy δD and $\delta^{18}O$ compositions of perched water emanating from a spring at Bare Mountain (Specie Spring) and groundwater in southwest Crater Flat. This similarity indicates that local recharge and runoff from Bare Mountain may be the source of groundwater along this flow path, as schematically indicated by the dashed nature of the beginning of this flow path in Figure 2-10.

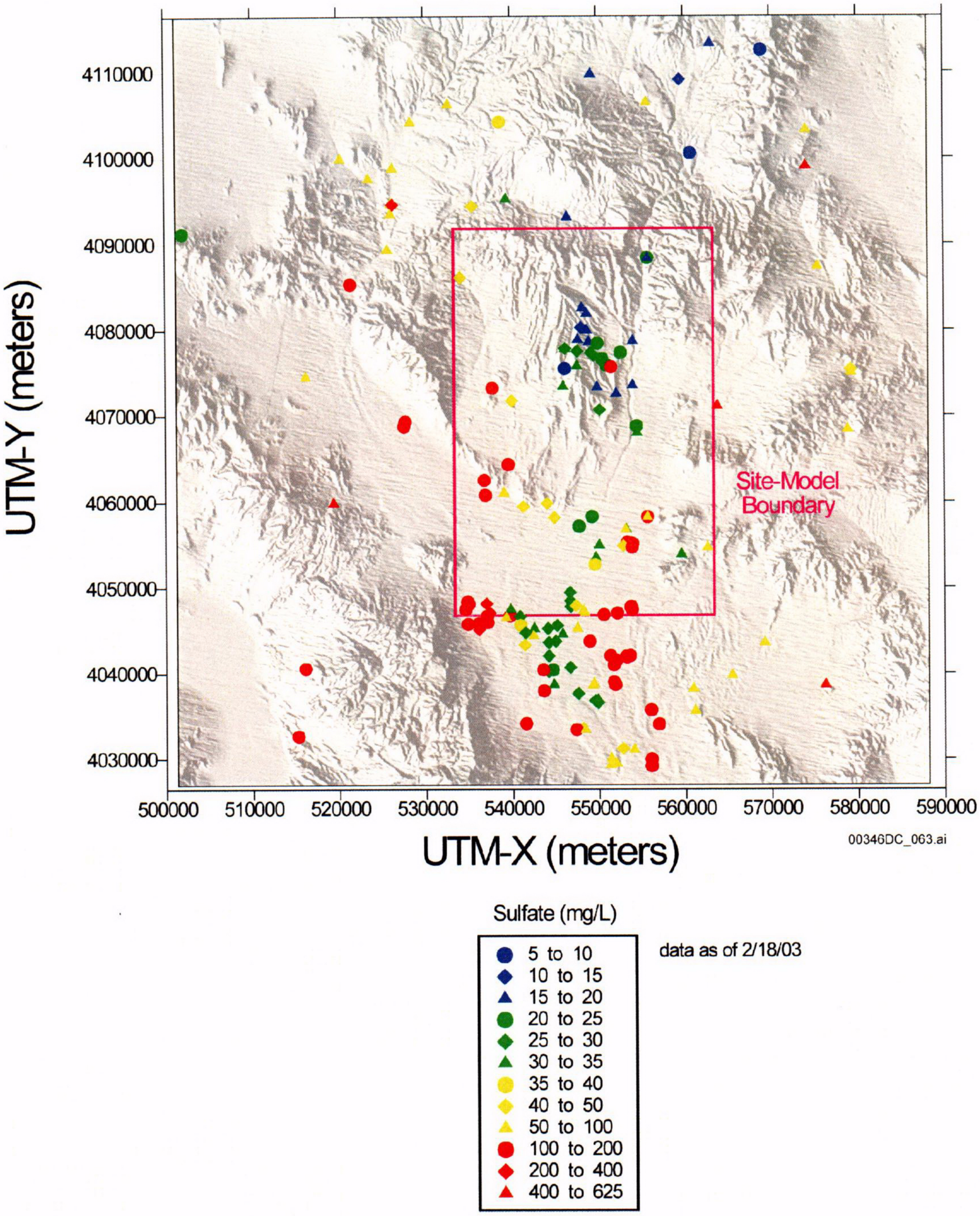
Table 2-3. Summary of Bases for Regional Flow Paths and Mixing Zones Derived from Geochemistry Observations (Continued)

Flow Path or Mixing Zone (Figure 2-10)	Geochemical Flow Path or Mixing Zone Description	Geochemical Evidence of Flow Path or Mixing Zone
6	From borehole USW WT-10 southward toward borehole NC-EWDP-15P	This flow path is identified from PHREEQC models that indicate that groundwater from borehole NC-EWDP-15P is formed from subequal amounts of groundwater from boreholes USW WT-10 and USW VH-1, and a small percentage (less than 5 percent) of groundwater from the carbonate aquifer. Although the predominant direction of flow from the Solitario Canyon area is southward along the Solitario Canyon fault, evidence for the leakage of small amounts of groundwater eastward across the fault is provided by similarities in the concentrations of many ions and isotopes between boreholes in the Solitario Canyon Wash and Yucca Mountain Crest areas. This chemical and isotopic similarity indicates that groundwater as far east as borehole USW H-4 may have some component of groundwater from the Solitario Canyon Wash area and possibly NC-EWDP-19D. The short southeast-oriented dashed lines from boreholes in the Solitario Canyon Group schematically illustrate this leakage.
7	From northern Yucca Mountain southeastward toward YM-SE boreholes in the Dune Wash area, then southwestward along the western edge of Fortymile Wash	The upper segment of this flow path is motivated by the high groundwater $^{234}U/^{238}U$ activity ratios found in the northern Yucca Mountain and Dune Wash areas. High $^{234}U/^{238}U$ activity ratios (greater than 7) typify perched water and groundwater along and north of Drill Hole Wash but not groundwater along Yucca Crest at borehole USW SD-6 or perched water at borehole USW SD-7. Based on the conceptual model for the evolution of $^{234}U/^{238}U$ activity ratios, congruent dissolution of thick vitric tuffs that underlie the Topopah Spring welded tuff along Yucca Crest south of Drill Hole Wash would be expected to decrease the $^{234}U/^{238}U$ activity ratios of deep unsaturated-zone percolation south of the wash. High $^{234}U/^{238}U$ activity ratios are expected only where these vitric tuffs are absent, as in northern Yucca Mountain.
8	Leakage of groundwater from the carbonate aquifer across the Gravity fault	Hydrogeologists and geochemists have recognized leakage across the fault (Winograd and Thordarson 1975; Claassen 1985). The carbonate aquifer component in this groundwater is recognized by many of the same chemical and isotopic characteristics that typify groundwater discharging from the carbonate aquifer at Ash Meadows. These characteristics include high concentrations Ca and Mg, low SiO_2, heavy $\delta^{13}C$ values, low ^{14}C activity, and $\delta^{18}O$ and δD values comparable to Ash Meadows groundwater.
9	Deep underflow of groundwater from the carbonate beneath the Amargosa Desert and Funeral Mountains to discharge points in Death Valley	The similarity in the chemical and isotopic characteristics of groundwater found in the Gravity fault area and groundwater that discharges from Nevares and Travertine springs support this interpretation. The dissimilarity in Cl, Mg, and SiO_2 concentrations in these springs compared to the groundwater from the alluvial aquifer along the Amargosa River suggests that this alluvial groundwater is not the predominant source of the spring discharge in Death Valley.
Mix A	Samples from the Nye County and SW Crater Flat boreholes along U.S. Highway 95	The zone is demonstrated by groundwater compositions of samples that are intermediate between the compositionally distinct groundwater of the carbonate aquifer and dilute groundwater of the volcanic aquifer that is interpreted to have originated in the Yucca Mountain area (see discussion of flow paths 6 and 7).

Table 2-3. Summary of Bases for Regional Flow Paths and Mixing Zones Derived from Geochemistry Observations (Continued)

Flow Path or Mixing Zone (Figure 2-10)	Geochemical Flow Path or Mixing Zone Description	Geochemical Evidence of Flow Path or Mixing Zone
Mix B	Samples from the FMW-W and AR/FMW groups, plus a few samples from the FMW-S group	The zone highlights groundwater with compositions that are intermediate between the distinct and consistent groundwater compositions of the Amargosa River Group and the dilute groundwater of the FMW-S group.
Mix C	All samples from the Lathrop Wells and FMW-E groups, a few of the more westerly samples form the Gravity fault group, and at least one sample (#141) from the FMW-S group	Characterized by small percentages of the distinctively high SO_4 groundwater from Well UE-25 J-11. Groundwater with this distinctive signature is mixed to variable degrees with dilute water from the FMW-S group to the west or with groundwater from the carbonate aquifer (Gravity fault group) to the east.

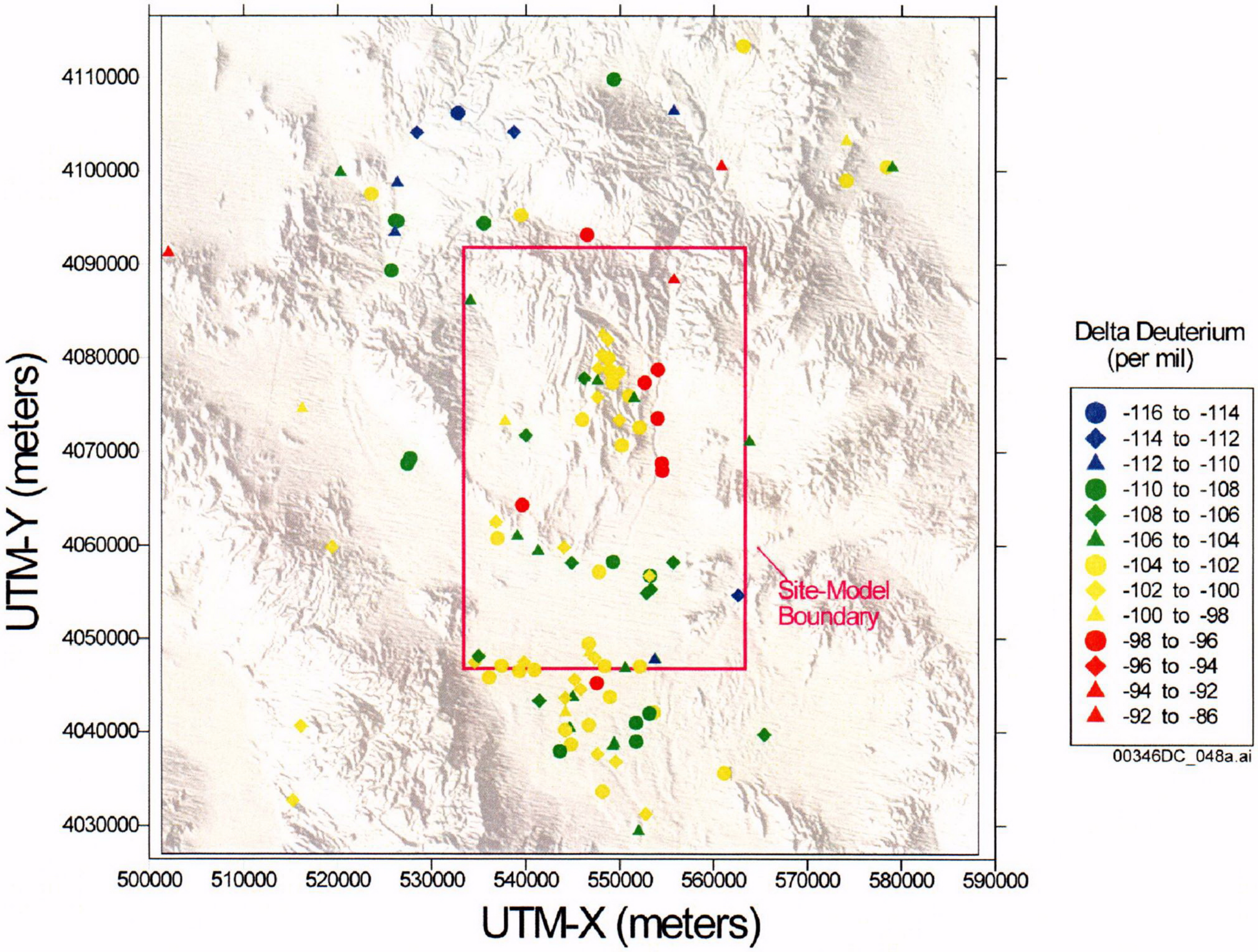
Source: BSC 2003f.



Source: BSC 2003f, Figure 16.

Figure 2-12. Areal Distribution of Sulfate in Groundwater

C13



Source: Based on BSC 2003f, Figure 24.

Figure 2-13. Regional Groundwater δ-Deuterium

Flow paths were interpreted based on a number of approaches, including examination of areal distribution plots for spatial trends (e.g., Figures 2-11, 2-12, and 2-13), examination of scatterplots between chemical or isotopic variables that indicate relationships (including mixing) between groundwater from the different geographic areas (identified in Figure 2-10), and inverse geochemical models used to estimate the mixing fractions of various upgradient groundwaters present in a downgradient groundwater, recognizing that groundwater composition can be a result of mixing and water-rock interactions (BSC 2003f). The first two approaches focus on patterns and relationships displayed among relatively nonreactive species (e.g., chloride, sulfate, and δ-deuterium). The potential groundwater sources and mixing relationships suggested by the first two approaches were examined quantitatively by inverse mixing and reaction models that also considered the evolution of more reactive species through water-rock interaction. The first approach is essentially two dimensional, but the second and third approaches incorporate the effects of three-dimensional mixing with local recharge or with groundwater upwelled from the deep carbonate aquifer.

C14

The regional flow paths and mixing zones, identified based on the groundwater geochemical signatures, are consistent with the general flow directions and recharge-discharge relationships discussed in Section 2.2.2. For example, the southwesterly flow in the deep carbonate aquifer across the Amargosa Desert is consistent with recharge in the Spring Mountains and Sheep Range and with discharge in the springs around Death Valley. Similarly, the relatively shallow southerly flow through tuff and alluvium from recharge in the Rainer Mesa area along the Fortymile Canyon and under Fortymile Wash discharges in the wells in Amargosa Valley or at natural discharge areas such as Franklin Lake Playa. All of these figures illustrate a general southerly flow of regional groundwater in the vicinity of Yucca Mountain and a mixing of different groundwater types in the alluvial aquifer underlying the Amargosa Valley.

2.2.5 Groundwater Flow Model and Results

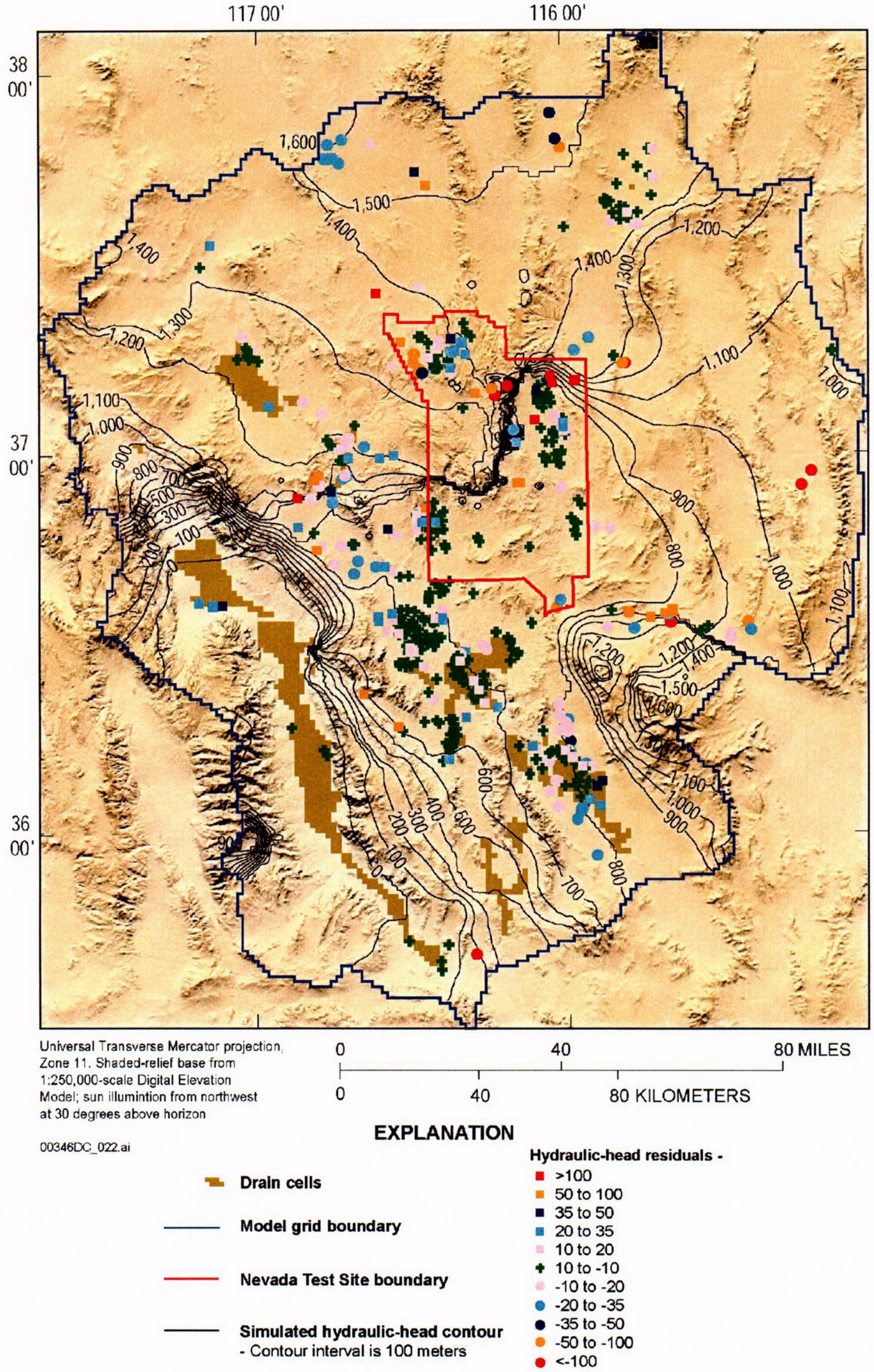
Several models have been constructed over the past decade to describe the hydrogeology in the Death Valley region. The current three-dimensional digital hydrogeologic framework model developed for the Death Valley regional flow system contains elements from both of the hydrogeologic framework models used in previous investigations: the 1997 Death Valley regional flow system model (D'Agnese et al. 1997) and the Under Ground Test Area regional model (DOE 1997).

The Death Valley regional flow system has been analyzed by the USGS using a three-dimensional steady-state model. The required model parameter values were supplied by discretization of the three-dimensional hydrogeologic framework model and digital representations of the remaining conceptual model components. The three-dimensional simulation and corresponding sensitivity analysis supported the hypothesis of interactions between a relatively shallow local and subregional flow system and a deeper dominant regional system controlled by the carbonate aquifer.

Model calibration was completed to estimate hydraulic parameters that best fit observed hydraulic data and evaluate alternative conceptual models of the flow system. The results of the model are illustrated in Figure 2-14, where the residual difference between the simulated and observed heads is plotted. Acceptable matches to observed hydraulic heads generally occur in areas of low hydraulic gradients. Poorer fits generally occur in areas with a steep hydraulic gradient. Although some of the observed and simulated heads differ by more than 100 m, the general flow directions and recharge and discharge relationships are preserved.

Figure 2-14 indicates that in some parts of the regional flow model, the data are too sparse to sufficiently constrain the model. That is, the model attempts to reduce the hydraulic head residual with equal weight applied to all observations. In areas where more boreholes exist to constrain the predicted hydraulic heads, the residuals generally are lower. This is the case in the Amargosa Farms area, Yucca Flat, Oasis Valley, and in the vicinity of Yucca Mountain. In areas with less hydraulic constraint, such as north of Indian Springs and along the Eleana Range, the residuals generally are greater.

Although considerable uncertainty exists in the observed and predicted hydraulic heads in the regional flow model, the general trends indicate major recharge and discharge areas that are consistent with the observed areas presented in Figures 2-2 and 2-3.



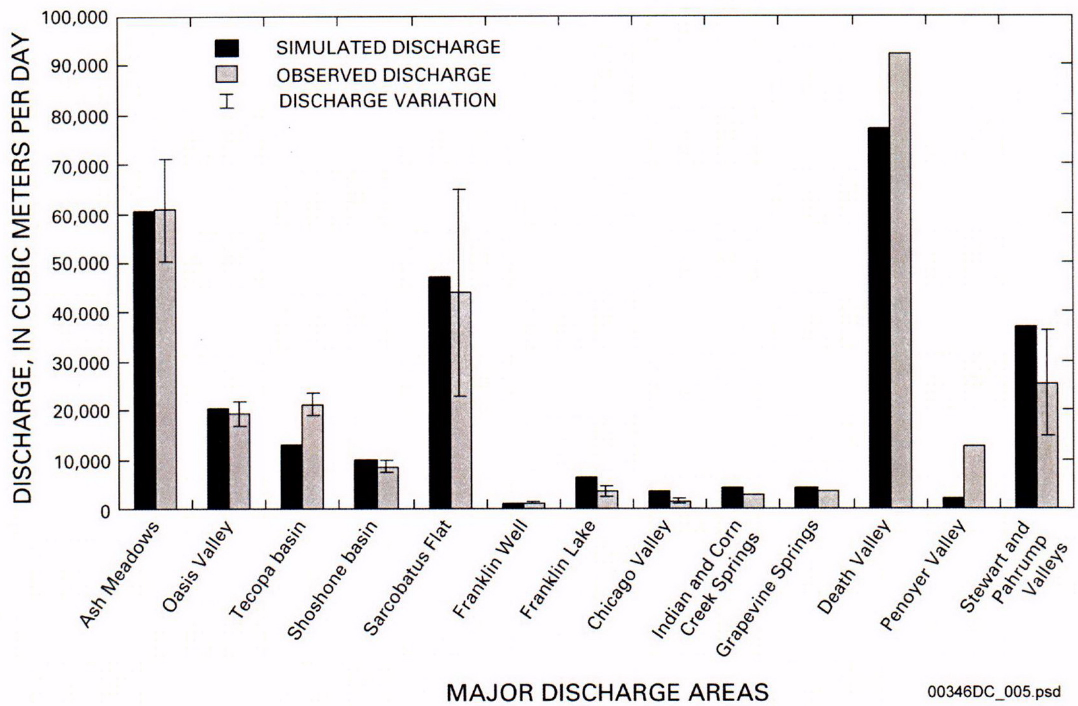
Source: Based on D'Agnese et al. 2002, Figure 40.

Figure 2-14. Comparison of Predicted and Observed Hydraulic Heads in the Death Valley Regional Groundwater Flow Model

C15

Comparison of modeled and inferred discharge is presented in Figure 2-15. Given the large uncertainty in the hydraulic characteristics and the sparseness of the observations, the match is acceptable for understanding the overall flow system and estimating the flow rates in the vicinity of Yucca Mountain.

Uncertainties in the regional flow model can be attributed to uncertainties in the hydrogeology represented in the framework model, water levels being represented as static rather than perched, and resolution of detailed hydrostratigraphy in the coarse grid of the regional model. Considering these constraints, the regional representation of groundwater flow is sufficiently characterized to define a general southerly flow direction in the vicinity of Yucca Mountain.



Source: D'Agnese et al. 2002, Figure 43.

Figure 2-15. Simulated and Observed Groundwater Discharge for Major Discharge Areas

2.3 SITE-SCALE GROUNDWATER FLOW SYSTEM

To better represent the groundwater flow system at the scale of interest for the repository, it is necessary to develop a more refined estimate of the groundwater regime than is possible using only the regional characterization. The regional groundwater flow characterization provides the context of the site-scale representation by constraining the likely groundwater flow paths (through regional understanding of recharge, discharge, hydraulic potentials, and geochemistry) and the average volumetric flow rates (through regional understanding of the hydraulic characteristics and the regional water budget). The regional representation is not suitable for evaluating the details of the groundwater flow rates (e.g., specific discharge) or the distribution of flow rates along the paths of likely radionuclide migration from Yucca Mountain to the compliance point specified in regulations.

C16

Figure 2-1 depicts the location and scale of the site-scale groundwater flow representation. This model encompasses an area of 30 by 45 km and extends from the top of the water table to the lower clastic confining unit. Although the site-scale model resides within the regional-scale representation and must be consistent with the regional characterization, details of the flow paths and hydrogeology at the scale of hundreds of meters to kilometers necessitates a finer resolution of understanding than the scale of kilometers to tens of kilometers used in the regional model.

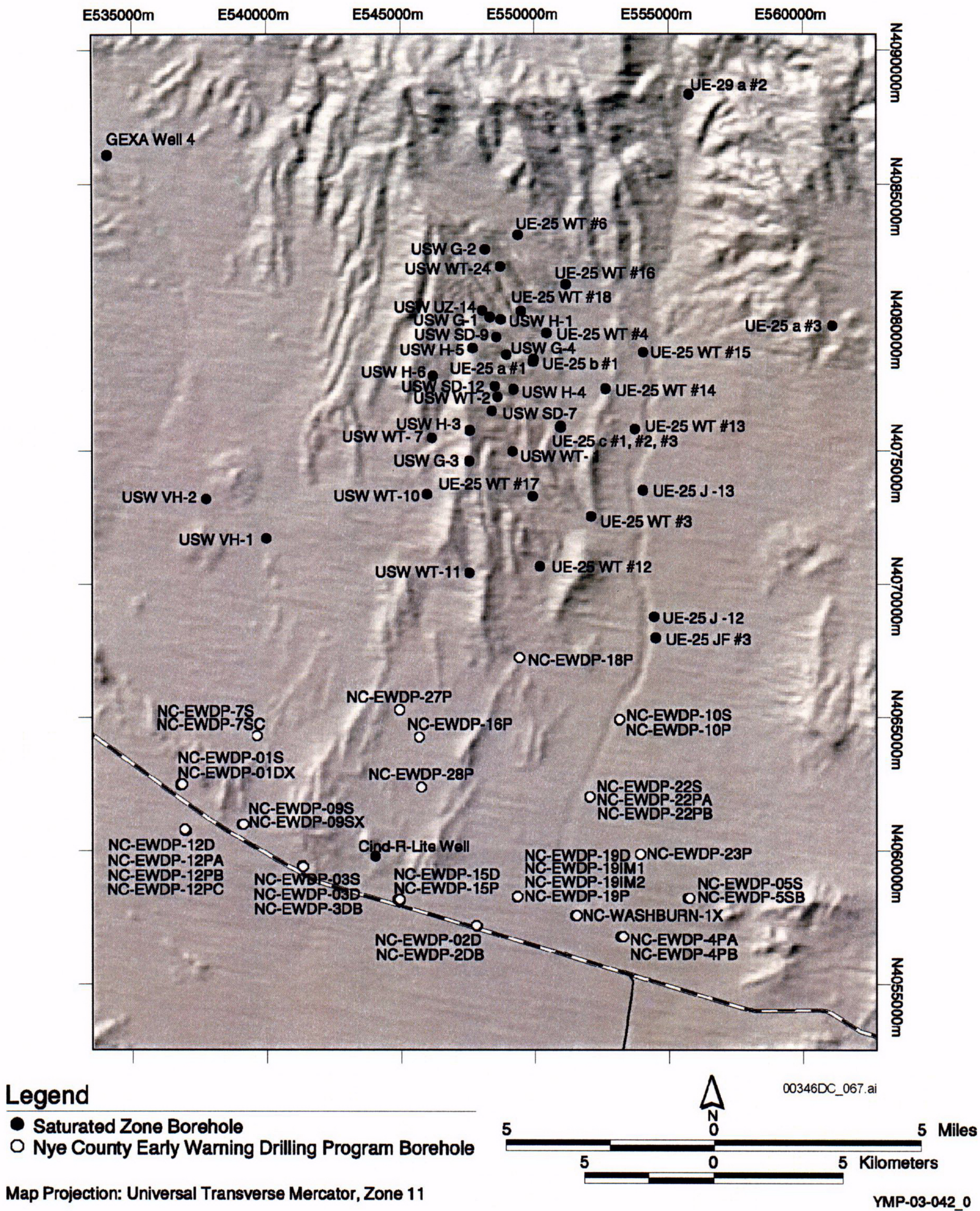
2.3.1 Site Characterization and Data Collection

Drilling to evaluate the Yucca Mountain site began in 1978, and the first hydrologic test borehole was completed in 1981. Detailed site characterization commenced in 1986. Water levels were measured as each borehole was completed, and long-term water-level monitoring commenced in 1983. Periodic measuring of water levels continues through the present. The network of monitoring boreholes has evolved over the years and continues to increase as boreholes are installed as part of the ongoing Nye County Early Warning Drilling Program. The boreholes provide measurements at various depths, and a number of boreholes monitor more than one depth interval.

The location of monitoring boreholes used to characterize the groundwater flow system in the vicinity of Yucca Mountain are illustrated in Figure 2-16. This figure includes boreholes drilled and tested by the DOE in support of the Yucca Mountain Site Characterization Project and those drilled and tested by Nye County as part of the Nye County Early Warning Drilling Program.

2.3.2 Site-Scale Recharge and Discharge

Within the scale of the site model of saturated zone groundwater flow, the bulk of the recharge and discharge occurs along the lateral boundaries with the regional model (Figure 2-17a). Inflow generally occurs along the northern and eastern boundaries, and discharge generally is along the southern boundary (Table 2-4). Figure 2-17a shows the segments of the north, east, and west boundaries listed in Table 2-4. Inflow from the north generally is the result of regional recharge that occurs at Timber Mountain, Pahute Mesa, and Rainer Mesa. Inflow from the east is generally the result of regional underflow in the carbonate aquifers that were recharged in the Specter Range. Outflow to the south is the result of carbonate underflow and flow in the alluvial aquifers that ultimately discharges to wells in Amargosa Valley or naturally at Ash Meadows. Table 2-4 shows the site-scale base-case flow model and the 1997 Death Valley regional flow system model. Appendix D also compares the 2001 Death Valley regional flow system model. Local recharge due to infiltration along Yucca Mountain and, to a lesser extent, along Fortymile Wash is also considered. The distributions of vertical recharge in the site-scale model are depicted in Figure 2-17b.



Source: CRWMS M&O 2000a, Figure 3-7. DTNs: MO0105GSC01040.000, MO0106GSC01043.000, MO0203GSC02034.000, and MO0206GSC02074.000.

Figure 2-16. Location of Boreholes used to Characterize the Site-Scale Groundwater Flow System

C17

Of the total volumetric recharge and discharge in the regional flow basin (on the order of 100 to 300 million m^3/year), about 10 to 30 percent (depending on the assumed regional flow balance) flows through the site-scale model boundaries. The bulk of the flow is within the carbonate aquifers that are recharged to the east and north of the site model area. Groundwater flows into and across the site model boundaries, and it ultimately discharges to the south of the site model.

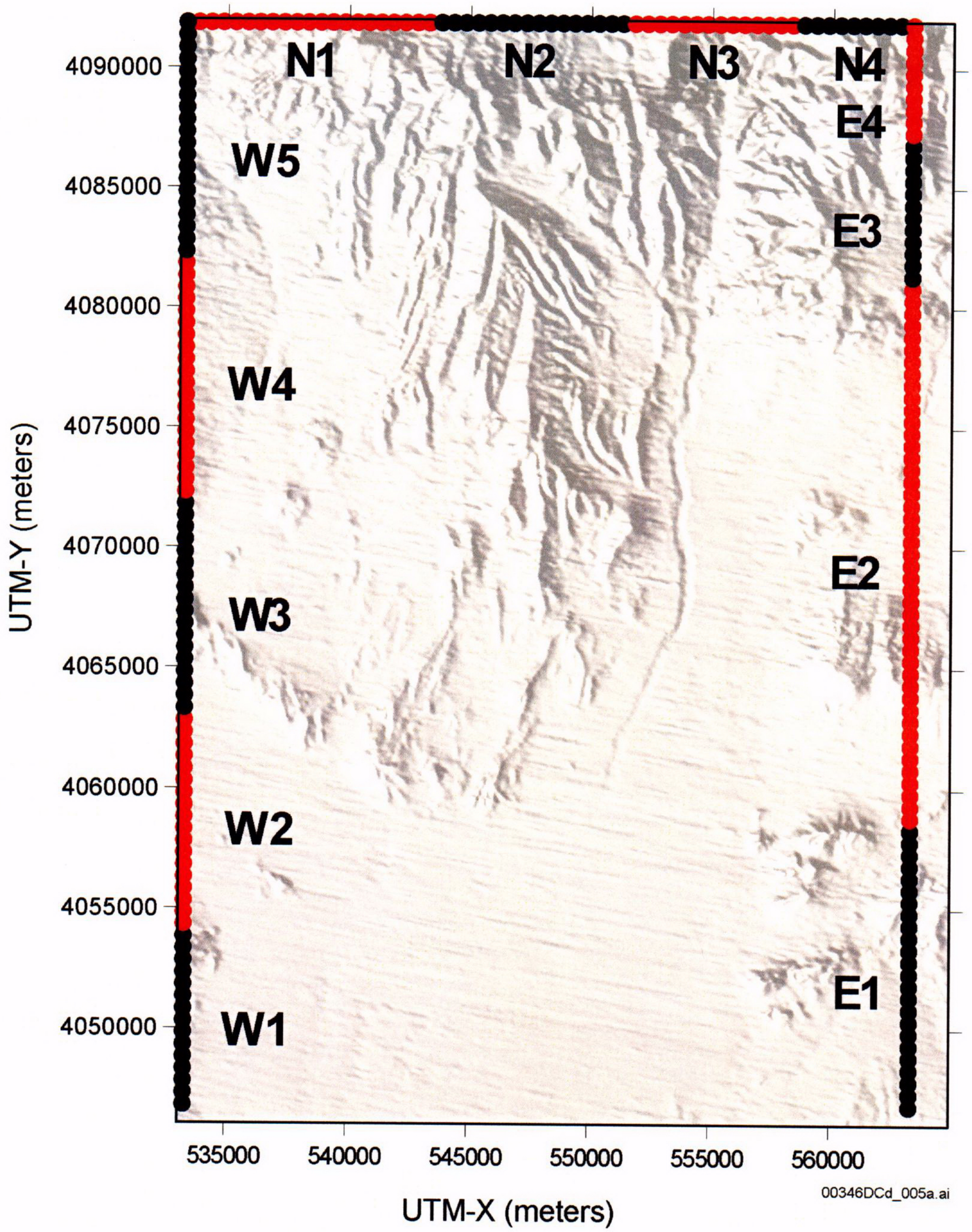
Table 2-4 compares the regional and site-scale model fluxes for an evaluation of consistency. Based on the discussion of uncertainty in the regional potentiometric surface, the uncertainty and variability in regional aquifer characteristics, and the uncertainty in regional recharge and discharge amounts and distribution, the uncertainty in the boundary fluxes (which is not quantified on this table) is considerable. All three types of information (hydraulic heads, hydraulic conductivity, and recharge-discharge amounts) are integrated into the site-scale model to develop an integrated and self-consistent representation of the overall flow system. Although uncertainty exists in each type of information, the integrated representation appropriately reflects all three observations.

Table 2-4. Comparison of Regional and Site-Scale Fluxes

Boundary Zone	Regional Flux (million m^3/year)	Site-Scale Flux (million m^3/year)
N1	-3.2	-1.9
N2	-0.5	-1.1
N3	-1.7	-1.0
N4	-0.6	-1.4
Subtotal of North Boundary Fluxes	-6.1	-5.4
W1	0.1	0.1
W2	-2.2	<<0.1
W3	-0.2	<<0.1
W4	0.1	<<0.1
W5	-1.5	-0.2
Subtotal of West Boundary Fluxes	-3.7	-0.1
E1	-17.5	-17.5
E2	-0.2	0.1
E3	0.1	0.5
E4	-0.1	0.5
Subtotal of East Boundary Fluxes	-17.7	-16.4
S	28.9	22.8

Source: Based on BSC 2001a, Table 14.

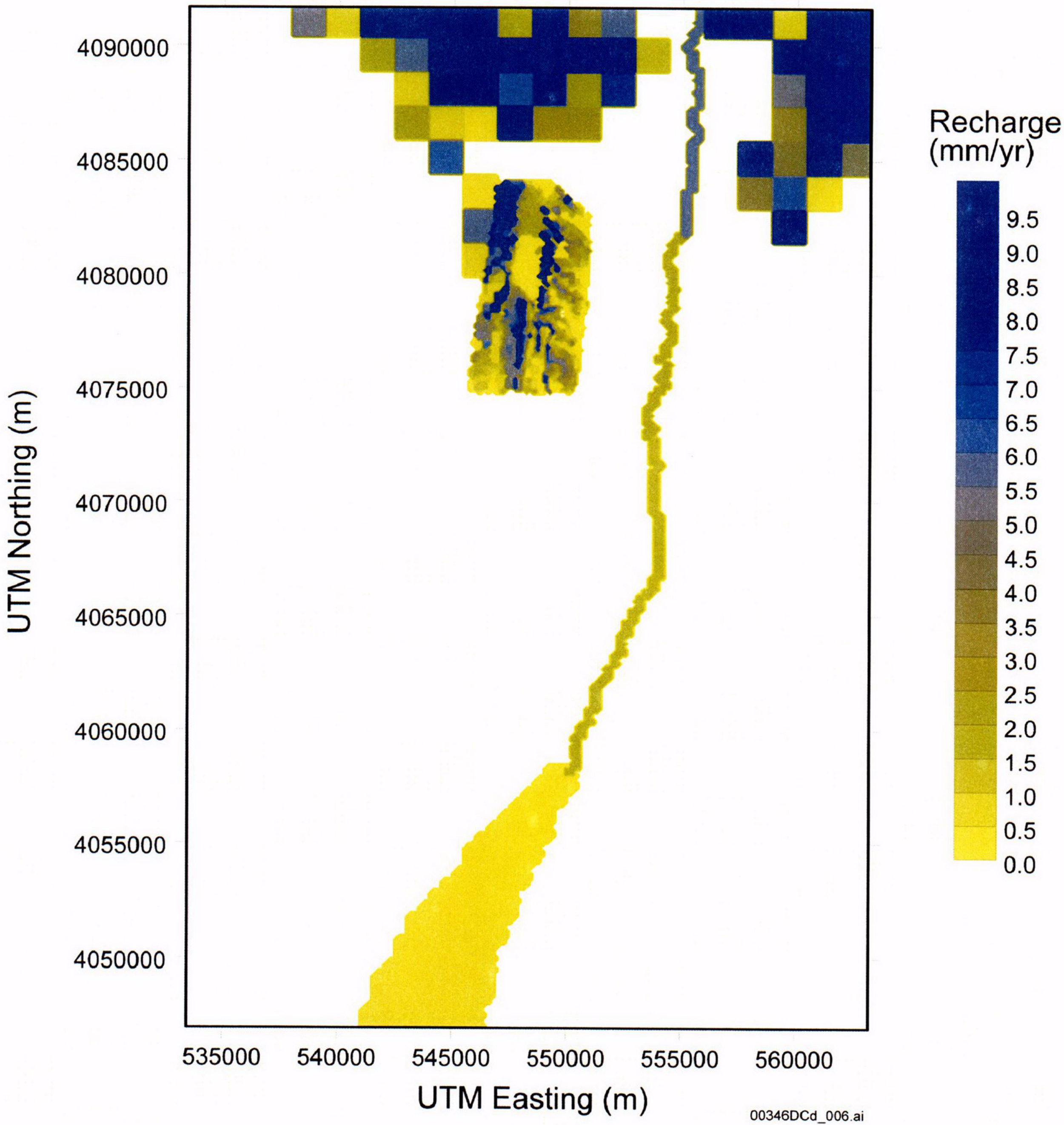
NOTES: Negative values indicate flow into the model. Values were converted from mass flux to volumetric flux and rounded to the nearest 0.1 million m^3/yr.



Source: BSC 2001a, Figure 16.

NOTE: Locations indicate discrete places where boundary fluxes from the regional model are applied to the site-scale flow model. The southern boundary is not coded S because it is one segment.

Figure 2-17a. Flux Zones used for Comparing Regional and Site-Scale Flux



Source: BSC 2001b, Figure 6.1.3-2.

Figure 2-17b. Recharge to the Saturated Zone Site-Scale Flow Model

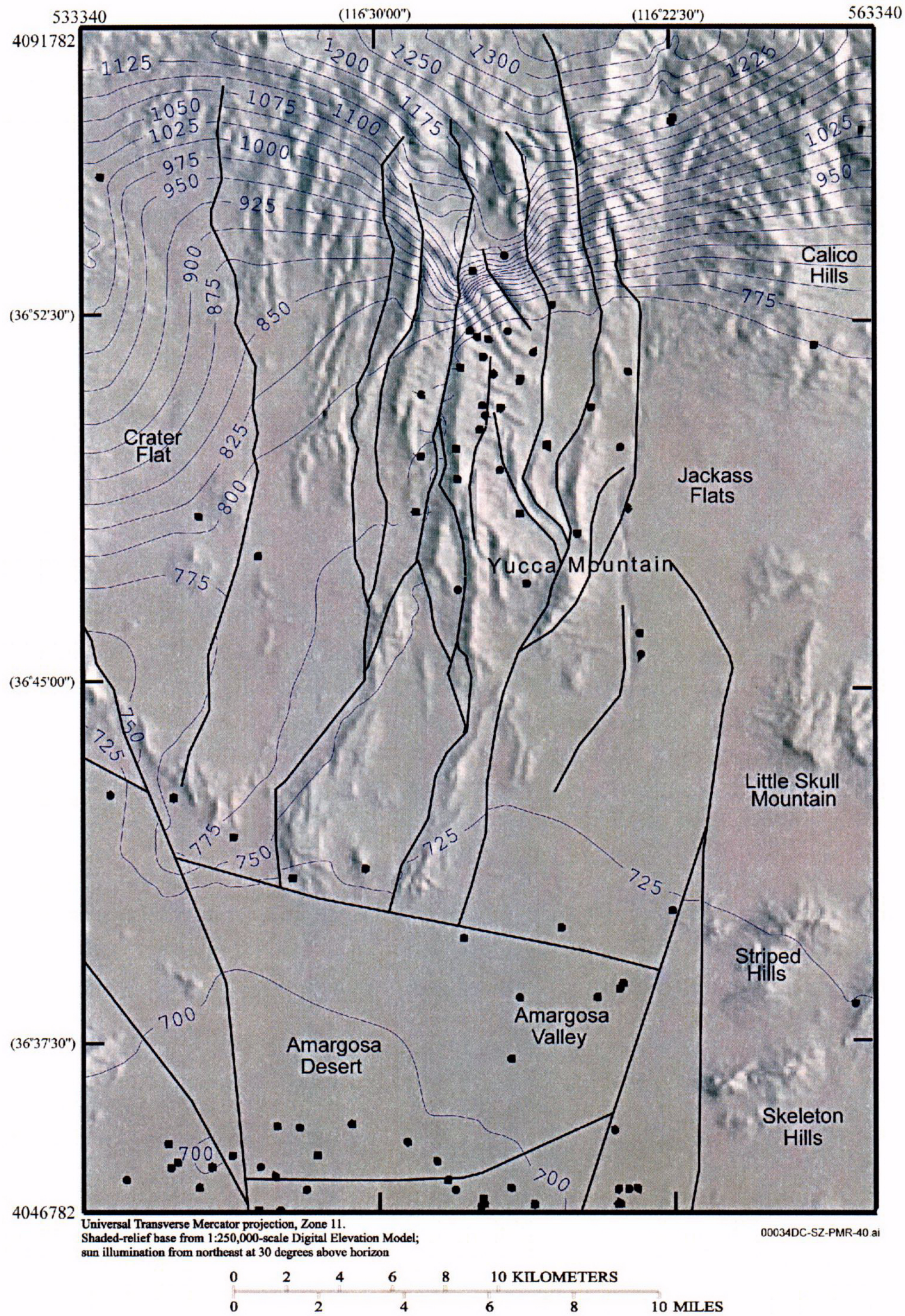
2.3.3 Site-Scale Potentiometric Surface

Figure 2-18 depicts the results of an analysis of water-level data prepared by the USGS to provide the potentiometric surface within the site-scale model domain and target water-level data for model calibration (USGS 2001b). During this analysis, the water-level data were used to generate a single representative potentiometric surface for the saturated zone site-scale model domain. When developing the potentiometric surface, water-level altitudes representing the uppermost aquifer system, typically the volcanic or alluvial system, were used. Water-level altitudes in some boreholes represent composite heads from multiple hydrogeologic units and fracture zones. Generally, water levels in the uppermost saturated zone appear to represent a laterally continuous, well-connected aquifer system. However, locally, it is possible that the observed uppermost potential represents a perched or semiconfined interval, or that a more transmissive unit deeper in the borehole controls the local potential. The faults depicted in Figure 2-18 are described in *Site-Scale Saturated Zone Flow Model* (BSC 2003c) and *Water-Level Data Analysis for the Saturated Zone Site-Scale Flow and Transport Model* (USGS 2001b).

The USGS (2001a) provided an updated analysis of water-level data (Figure 2-19). This analysis included water-level data collected through December 2000, including water-level data obtained from the expanded Nye County Early Warning Drilling Program and data from borehole USW WT-24. In addition to the inclusion of new water-level data, the primary difference in the approach taken to generate the revised potentiometric surface was the assumption that water levels in the northern portion of the model domain (boreholes USW G-2 and UE-25 WT #6) represent perched conditions and are not representative of the regional potentiometric surface. As a result, the revised potentiometric surface map represents an alternate concept for the large hydraulic gradient area north of Yucca Mountain.

Comparison of Figures 2-18 and 2-19 indicates that the potentiometric surface maps are similar. Although differences can be noted in these two conceptualizations, both potentiometric surfaces indicate a predominately southerly component of groundwater flow in this area.

Based on the potentiometric surface map, three distinct hydraulic gradient areas in the vicinity of Yucca Mountain have been identified: a large hydraulic gradient between water-level altitudes of 1,030 m and 750 m at the northern end of Yucca Mountain, a moderate hydraulic gradient west of the crest of Yucca Mountain, and a small hydraulic gradient extending from Solitario Canyon to Fortymile Wash.

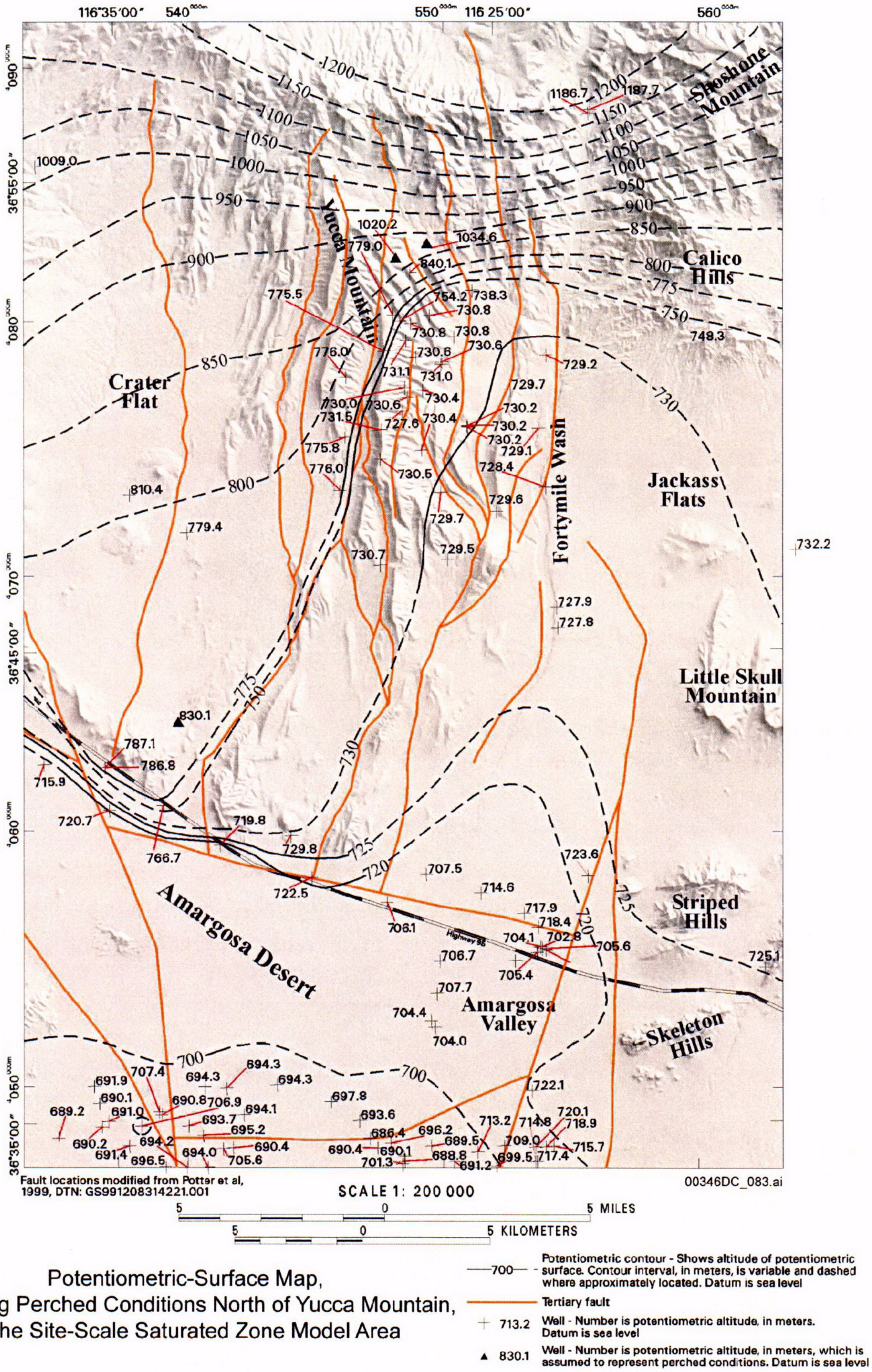


Source: USGS 2001b, Figure 1-2.

NOTE: Black lines indicate major faults, which are identified in the source document.

Figure 2-18. Nominal Site-Scale Potentiometric Surface

C20



Source: USGS 2001a, Figure 6-1.

Figure 2-19. Alternative Site-Scale Potentiometric Surface

C21

A number of explanations have been proposed to explain the presence of the large hydraulic gradient at the north end of Yucca Mountain (Czarnecki and Waddell 1984; Ervin et al. 1994). Explanations proposed for the large hydraulic gradient include:

- Faults that contain nontransmissive fault gouge
- Faults that juxtapose transmissive tuff against nontransmissive tuff
- The presence of a less fractured lithologic unit
- A change in the direction of the regional stress field and a resultant change in the intensity, interconnectedness, and orientation of open fractures on either side of the area with the large hydraulic gradient
- A disconnected, perched or semi-perched water body (i.e., the high water-level altitudes are caused by local hydraulic conditions and are not part of the regional saturated zone flow system).

The cause of the moderate hydraulic gradient generally is believed to be the result of the Solitario Canyon fault and its splays functioning as a barrier to flow from west to east due to the presence of low-permeability fault gouge or to the juxtaposition of more permeable units against less permeable units (Luckey et al. 1996, p. 25).

The small hydraulic gradient occupies most of the repository area and the downgradient area eastward to Fortymile Wash. Over a distance of 6 km, the hydraulic gradient declines only about 2.5 m between the crest of Yucca Mountain and Fortymile Wash. The small gradient could indicate highly transmissive rocks, little groundwater flow in this area, or a combination of both (Luckey et al. 1996, p. 27).

In addition to an understanding of the areal hydraulic potential gradient distribution, local vertical potential gradients have been observed in individual boreholes that have isolated test intervals. The results of these individual head observations are tabulated in Table 2-5. Depending on the location of the borehole, small vertical potential differences are probably not indicative of vertical flow but, instead, represent the degree of horizontal heterogeneity within the aquifer that is tested. However, large vertical potential differences, such as those between the carbonate aquifer and the overlying tuff or alluvial aquifers, are generally representative of more extensive flow field differences.

The vertical hydraulic gradients in the vicinity of Yucca Mountain are generally oriented upward (i.e., they are positive values in Table 2-5). These upward gradients effectively limit the downward potential for migration of water within the tuff aquifers or between the tuff aquifers and the underlying carbonate aquifer. Although locally downward hydraulic gradients are possible, these have been attributed to the presence of local recharge conditions and low permeability confining units. Additional details on observed vertical gradients in the vicinity of Yucca Mountain are presented in Appendix B.

Table 2-5. Summary of Vertical Head Observations at Boreholes in the Vicinity of Yucca Mountain

Borehole	Open Interval (m below land surface)	Potentiometric Level (m above sea level)	Head Difference deepest to shallowest intervals (m)
USW H-1 tube 4	573-673	730.94	54.7
USW H-1 tube 3	716-765	730.75	
USW H-1 tube 2	1097-1123	736.06	
USW H-1 tube 1	1783-1814	785.58	
USW H-3 upper	762-1114	731.19	28.9
USW H-3 lower	1114-1219	760.07	
USW H-4 upper	525-1188	730.49	0.1
USW H-4 lower	1188-1219	730.56	
USW H-5 upper	708-1091	775.43	0.2
USW H-5 lower	1091-1219	775.65	
USW H-6 upper	533-752	775.99	2.2
USW H-6 lower	752-1220	775.91	
USW H-6	1193-1220	778.18	
UE-25 b #1 upper	488-1199	730.71	-1.0
UE-25 b #1 lower	1199-1220	729.69	
UE-25 p #1 (volcanic)	384-500	729.90	21.4
UE-25 p #1 (carbonate)	1297-1805	751.26	
UE-25 c #3	692-753	730.22	0.4
UE-25 c #3	753-914	730.64	
USW G-4	615-747	730.3	-0.5
USW G-4	747-915	729.8	
UE-25 J-13 upper	282-451	728.8	-0.8
UE-25 J-13	471-502	728.9	
UE-25 J-13	585-646	728.9	
UE-25 J-13	820-1063	728.0	
NC-EWDP-1DX (shallow)	WT-419	786.8	-38.0
NC-EWDP-1DX (deep)	658-683	748.8	
NC-EWDP-2D (volcanic)	WT-493	706.1	7.6
NC-EWDP-2DB (carbonate)	820-937	713.7	
NC-EWDP-3S probe 2	103-129	719.8	-1.5
NC-EWDP-3S probe 3	145-168	719.4	
NC-EWDP-3D	WT-762	718.3	
NC-EWDP-4PA	124-148	717.9	5.7
NC-EWDP-4PB	225-256	723.6	
NC-EWDP-7SC probe 1	24-27	818.1	-77.9
NC-EWDP-7SC probe 2	55-64	786.4	
NC-EWDP-7SC probe 3	82-113	756.6	
NC-EWDP-7SC probe 4	131-137	740.2	
NC-EWDP-9SX probe 1	27-37	766.7	0.1
NC-EWDP-9SX probe 2	43-49	767.3	
NC-EWDP-9SX probe 4	101-104	766.8	
NC-EWDP-12PA	99-117	722.9	2.2
NC-EWDP-12PB	99-117	723.0	
NC-EWDP-12PC	52-70	720.7	
NC-EWDP-19P	109-140	707.5	5.3
NC-EWDP-19D	106-433	712.8	

Source: Based on USGS 2001a, Table 6-1.

NOTE: Negative values indicate downward gradient.

Only two boreholes, UE-25 p #1 and NC-EWDP-2D/2DB, provide information on vertical gradients between volcanic rocks and the underlying Paleozoic carbonate rocks. At borehole UE-25 p #1, water levels currently are monitored only in the carbonate aquifer; however, water-level data were obtained from within the volcanic rocks as the borehole was drilled and tested. At this borehole, water levels in the Paleozoic carbonate rocks are about 20 m higher than those in the overlying volcanic rocks. Borehole NC-EWDP-2DB penetrated Paleozoic carbonate rocks toward the bottom of the borehole (Spengler 2001a). Water levels measured within that deep part of the borehole are about 8 m higher than levels measured in volcanic rocks penetrated by borehole NC-EWDP-2D.

Water levels monitored in the lower part of the volcanic-rock sequence at Yucca Mountain also generally are higher than levels monitored in the upper part of the volcanics. For example, boreholes USW H-1 (tube 1) and USW H-3 (lower interval) both monitor water levels in the lower part of the volcanic rock sequence, and upward gradients are observed with head differences of 55 and 29 m, respectively. The gradient at USW H-3 is not completely characterized because the water levels in the lower interval had been continuously rising before the packer that separates the upper and lower intervals failed in 1996.

An upward gradient is also observed between the alluvial deposits monitored in borehole NC-EWDP-19P and underlying volcanic rocks monitored in borehole NC-EWDP-19D. The vertical head difference at this site is 5.3 m; however, levels reported for NC-EWDP-19D represent a composite water level for the alluvium and volcanics, so that the true head difference between those units is not completely known.

Several downward gradients have also been observed within the saturated zone site-scale flow and transport model area (Table 2-5). The largest downward gradient is observed between the deep and shallow monitored intervals at borehole NC-EWDP-1DX (head difference of 38 m) and NC-EWDP-7S (head difference of about 78 m). The depth to water at both of these locations is anomalously shallow and probably represents either locally perched conditions or the presence of a low permeability confining unit close to the surface that effectively impedes the downward migration of water to the more contiguous tuff and alluvium aquifers at greater depths.

2.3.4 Site-Scale Hydrogeologic Framework

The site-scale hydrogeologic framework represents site hydrostratigraphy at a scale commensurate with the scale of the flow system and sufficient to define the hydrogeologic units through which water may move from the repository block to a compliance point about 18 km south of Yucca Mountain. Understanding the various lithologic units through which water migrates is important due to the transport characteristics of the different lithologies in the vicinity of Yucca Mountain. In particular, the transport characteristics of fractured and porous welded tuffs are different from fractured nonwelded tuffs, which are both different from porous alluvium. Of particular interest to the behavior of the saturated zone barrier at Yucca Mountain are the effective porosity and retardation characteristics of the different lithologies, as well as the length of the flow path in the alluvial aquifer.