CNWRA 95-019

CONCEPTUAL AND MATHEMATICAL MODELS OF THE DEATH VALLEY REGIONAL GROUNDWATER FLOW SYSTEM

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ABSTRACT

Yucca Mountain, Nevada, is located within the Death Valley regional groundwater flow system, in which the hydrogeologic regime is controlled by thick sequences of highly permeable Paleozoic carbonate rocks that provide a hydraulic connection between more than 15 topographically closed structural basins. The saturated zone hydrology at Yucca Mountain is consequently affected by recharge derived from mountain ranges 100 to 150 km to the north and northeast. Although the water table at Yucca Mountain presently lies approximately 300 m below the level of the proposed repository, there is abundant evidence that the water table has been between 85 to 115 m higher during the past. Models used to determine the long-term performance of the proposed repository must be able to predict the changes to the site saturated flow regime that may occur if the climate returns to the cooler-wetter full-glacial regime characteristic of the Pleistocene. This report examines a number of mathematical and conceptual models that have been developed for all or portions of the Death Valley regional groundwater system in order to assess their usefulness for predicting the evolution of the hydrogeologic regime at Yucca Mountain. Most of the conceptual models are markedly similar, reflecting a gradual evolution in the understanding of the region's hydrogeology. While most of the conceptual models could be used to develop a numerical model that can approximate the effects of increased recharge, none incorporate the three-dimensional (3D) nature of the flow regime caused by the complex hydrostratigraphy resulting from Mesozoic compressional and Tertiary extensional tectonism.

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ACKNOWLEDGMENTS

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the Nuclear Regulatory Commission (NRC) under Contract No. NRC-02-93-005. The activities reported here were performed on behalf of the NRC Office of Nuclear Regulatory Research, Division of Regulatory Applications. The report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

This report was greatly improved by thorough technical and programmatic reviews provided by H. Lawrence McKague and Budhi Sagar. Staff from the Publications Office at Southwest Research Institute conducted a thorough editorial review that greatly improved this report. Richard Klar devoted considerable time and effort to developing and refining the figures depicting the regional physiography and the location of system and sub-basin boundaries. Finally, the careful formatting, checking of references, and preparation of tables performed by Rebecca Sanchez is greatly appreciated.

QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: CNWRA-generated original data contained in this report meet quality assurance requirements described in the CNWRA Quality Assurance Manual. Sources for other data should be consulted for determining the level of quality for those data.

ANALYSES AND CODES: No computer codes were used for analyses contained in this report.

1 INTRODUCTION

Yucca Mountain (YM) has been proposed as a potential high-level nuclear waste (HLW) repository in part because of the favorable geochemical and hydrologic environment provided by its 700-m-thick unsaturated zone. Siting the repository in the unsaturated zone may significantly reduce the potential for water to contact the waste canisters and subsequently the waste itself. Moreover, the low water flux rates that are presumed to exist in the unsaturated zone reduce the likelihood that radionuclides that are dissolved will be rapidly transported to the accessible environment. Mechanisms that may saturate the repository horizon, and thus compromise favorable conditions provided by the YM site, include increased infiltration of water from the surface through highly conductive fracture networks to form localized saturated zones and an increase in the elevation of the regional water table due to change in climate or geologic structure. The first mechanism is a site-scale or subregional issue and is not addressed by this research project. Elevation of the water table may occur due to increased recharge to the regional carbonate system along stream channels and mountain fronts in topographically closed basins 100 km to the north and northeast of YM, or by disruption of the barrier that effects the steep hydraulic gradient at YM. Even if elevation of the regional water table does not saturate the repository block, the reduced thickness of the unsaturated zone has the potential to diminish travel times within the vadose zone. Travel times in the saturated zone, and the location of potential discharge areas for dissolved radionuclides downgradient from YM, are performance related issues addressed by this research project. The primary objectives of this research project are to: (i) analyze existing conceptual models and if appropriate, develop new conceptual models of the regional hydrogeologic flow regime in the Death Valley region that contains YM, and (ii) construct numerical models of regional flow that may be used to assess the potential for the water table beneath YM to rise in response to wetter climatic conditions and disruption of the steep hydraulic gradient.

Predictions made with numerical models will be used by the U.S. Department of Energy (DOE) in their license application to demonstrate that the YM site meets the overall performance standards outlined in 10 CFR 60.112 and the geologic subsystem performance standard defined in 10 CFR 60.113(a)(2). In addition, the DOE may choose to use numerical models to demonstrate the absence or influence of potentially adverse conditions including: the effects of future pumping on the regional flow system [10 CFR 60.122(c)(2)]; the potential for deleterious changes to the hydrologic system [10 CFR 60.122(c)(5)]; the potential for changes to the hydrologic conditions resulting from climate change [10 CFR 60.122(c)(6)]; the potential for water table rise [10 CFR 60.122(c)(22)]; and the presence and influence of favorable conditions, including the clear absence of fully saturated pathways connecting the repository to the water table [10 CFR 60.122(b)(8)(ii)]. Understanding of the regional hydrogeologic system developed from this project will be used to guide the review of the DOE license application and to assess the adequacy of the models used by the DOE to demonstrate compliance with the regulatory requirements and environmental standards.

1.1 OUTLINE OF REPORT

This report contains a review of literature related to the development and application of conceptual and mathematical flow models of the Death Valley regional groundwater system. Since its inception in May 1993, the primary efforts in this research project have been directed toward accomplishing the goals outlined in Task 1 on the Collection and Analysis of Data and Existing Models, and Task 2 on the Construction of Alternative Conceptual Models of Key Hydrogeologic Processes. The specific goals of Task 1 are to: (i) review existing literature; (ii) conduct an inventory of hydrogeologic data in the immediate vicinity of the proposed YM repository and the Death Valley region; and

(iii) compile relevant hydrogeological, hydrochemical, and mineralogical data into an integrated Geographic Information System (GIS) database. The specific goals of Task 2 are to develop conceptual models to address key issues related to the saturated flow system at YM including: (i) the steep hydraulic gradient, (ii) the location and magnitude of recharge and discharge zones, (iii) the potential for fast pathways to develop along fault zones, (iv) groundwater travel time (GWTT) in the saturated zone, (v) the evolution of the regional water table under conditions of increased recharge, and (vi) the influence of heterogeneity and anisotropy on the construction of flow direction maps. The development of the regional hydrogeology GIS database is reported in Wittmeyer et al. (1995a), development of an alternative conceptual model of the steep hydraulic gradient is described in Wittmeyer et al. (1995b), the estimation of the spatial distribution of recharge is addressed in Wittmeyer and Klar (1995), the potential for fast flow pathways is described in Murphy (1995), and an assessment of the effects of anisotropy of transmissivity on regional flow directions is addressed in Wittmeyer et al. (1994b).

This report is divided into two sections: (i) a review of literature on the Death Valley regional flow system, and (ii) an evaluation of the models in terms of their utility for assessing the effects of water table rise due to climate change or disruption of the steep hydraulic gradient on the proposed YM repository. Some of the modeling studies reviewed in Section 2 have been previously reviewed by Wittmeyer et al. (1994a,b; 1995a,b), and Wittmeyer and Klar (1995). Studies reviewed in Section 2 include those of Schoff and Moore (1964), Rush (1970), and Winograd and Thordarson (1975), which examine the Nevada Test Site (NTS) groundwater system using a combination of hydrochemical facies data, hydrostratigraphic data, and hydraulic data. Waddell (1982) and Rice (1984) developed numerical models of the NTS and Greater Death valley regional flow systems. Studies by Czarnecki and Waddell (1984), and Czarnecki (1985, 1989) outline the results of numerical and conceptual modeling studies of the YM flow system conducted to assess the effects of neotectonism and climatic change on the proposed repository. Ahola and Sagar (1992) developed regional and subregional numerical flow models based on Rice (1984) to evaluate the effects of increased recharge, neotectonism, and dike or sill emplacement. Feeney et al. (1987) and Sadler et al. (1992) developed numerical models of the western NTS and Death Valley system flow systems, respectively, using deuterium calibrated mixing cell models. Also reviewed in this section are conceptual and mathematical models of the subsurface flow regime in the carbonate province of eastern Nevada, western Utah, and southern Idaho developed by Dettinger (1989, 1992), and Burbey and Prudic (1991).

1.2 REGULATORY BASIS FOR REVIEWING CONCEPTUAL MODELS OF THE DEATH VALLEY FLOW SYSTEM

Understanding of the regional hydrogeologic system gained from reviewing the existing literature and compiling relevant hydrogeologic data will be used to construct specific Compliance Determination Methods (CDMs) outlined in the License Application Review Plan (LARP) (Nuclear Regulatory Commission, 1994). Information contained in this report will provide data that may be directly used to assess the description of individual systems and characteristics of the site (LARP section 3.1) and, in particular, the description of the hydrologic and geochemical systems (LARP sections 3.1.2 and 3.1.3, respectively). Evidence gleaned from these and other literature reviews and data analyses, in conjunction with conceptual and numerical models of the regional flow regime developed in other tasks within this research project, will be directly used to determine if the applicant has provided convincing evidence of the presence or absence of favorable hydrogeologic conditions and potentially adverse hydrogeologic conditions (LARP sections 3.2.1.1, 3.2.2.1, 3.2.2.3, 3.2.2.6, 3.2.2.8, 3.2.2.9, 3.2.2.11, and 3.2.4.2). Flow models developed in this project will also be used to confirm that velocity fields and travel times within the saturated zone estimated by the DOE are accurate enough to demonstrate compliance with the GWTT performance objective (LARP section 3.3).

Compliance Determination Strategies (CDSs) for the LARP sections listed previously have been developed in draft form and are in review. The Regional Hydrogeology Research Project will be instrumental in resolving specific technical uncertainties identified during the CDS development process. Key Technical Uncertainties (KTUs) that pose a high risk of noncompliance with the total-system or subsystem performance requirements may require that the Nuclear Regulatory Commission (NRC) conduct independent research to resolve the issue. Development of a conceptual groundwater flow model that is representative of the YM site groundwater system has been identified as a KTU that must be addressed in LARP sections 3.2.2.1, 3.2.2.9, and 3.3. Understanding of the regional hydrogeologic system gained from this research project will also be used to construct specific CDMs outlined in the LARP (Nuclear Regulatory Commission, 1994). Literature reviews and hydrogeologic data gathered in Task 1 of the project will provide information that directly may be used to assess the description of individual systems and characteristics of the site (LARP section 3.1) and, in particular, the description of the hydrologic and geochemical systems (LARP sections 3.1.2 and 3.1.3, respectively). Evidence gleaned from literature reviews and data analyses in conjunction with conceptual and numerical models of the regional flow regime developed in this research project will be directly used to determine if the applicant has provided convincing evidence of the presence or absence of favorable hydrogeologic conditions and potentially adverse hydrogeologic conditions (LARP sections 3.2.1.1, 3.2.2.1, 3.2.2.3, 3.2.2.6, 3.2.2.8, 3.2.2.9, 3.2.2.11, and 3.2.4.2). Flow models developed in this project will also be used to confirm that velocity fields and travel times within the saturated zone estimated by the DOE are accurate enough to demonstrate compliance with the GWTT performance objective (LARP section 3.3).

2 REVIEW OF EXISTING FLOW MODELS OF THE DEATH VALLEY SYSTEM

Hydrogeologic studies in the Death Valley region were first undertaken in the early 1960s to assess the potential for radionuclides released from underground tests of nuclear devices to contaminate groundwater at the NTS and to estimate the amount of water available for use at the NTS. Although many of the early reports on the hydrogeology and water resources of the NTS were prepared by the U.S. Geological Survey (USGS), these reports received little circulation outside of the Atomic Energy Commission (AEC). This review is focused on those reports that attempt to define the regional hydrogeologic setting for the Death Valley system or explain the intricacies of the saturated flow regime at YM. Particular emphasis is paid to those reports in which the boundaries for the regional system were delineated. Studies reviewed in this section include those of Schoff and Moore (1964), Rush (1970), and Winograd and Thordarson (1975), which examine the NTS groundwater system using a combination of hydrochemical facies data, hydrostratigraphic data, and hydraulic data. Waddell (1982) and Rice (1984) developed numerical models of the NTS and Greater Death Valley regional flow systems. Studies by Czarnecki and Waddell (1984), and Czarnecki (1985, 1989), outline the results of numerical and conceptual modeling studies of the YM flow system conducted to assess the effects of neotectonism and climatic change on the proposed repository. Feeney et al. (1987) and Sadler et al. (1992) developed numerical models of the western NTS and Death Valley system flow systems, respectively, using deuterium calibrated mixing cell models. Ahola and Sagar (1992) developed regional and subregional models to assess the effects of increased recharge, neotectonism, and dike or sill emplacement on YM. Also reviewed in this section are conceptual and mathematical models of the subsurface flow regime in the carbonate province of eastern Nevada, western Utah, and southern Idaho developed by Dettinger (1989, 1992), and Burbey and Prudic (1991).

The figures presented in this section depict the general physiography and topography of the Death Valley region using gray-scale shaded relief maps as the background coverage. In Figure 2-1 the names of major mountain ranges and valleys are added so that the reader can locate physiographic features identified in the report. Figures 2-7 through 2-10 show the boundaries of the flow systems considered in each of the studies reviewed. The names on these maps (Figures 2-2 through 2-10) correspond to hydrographic areas [Rush (1968); Wittmeyer et al. (1995a)] and are not equivalent to those on Figure 2-1.

2.1 SCHOFF AND MOORE (1964)

Schoff and Moore (1964) presented one of the earlier conceptual models of groundwater flow in the vicinity of the NTS. Their study did not cover the entire Death Valley flow system, but was principally limited to basins within the boundaries of the NTS. The primary analytical tool used by Schoff and Moore to infer the direction of flow at the NTS was detailed analysis of hydrochemical facies. Based on major chemical element analyses of well and spring waters, Schoff and Moore (1964) identified three types of waters:

(i) Na+K waters that the authors related to tuff aquifers or samples collected from tuffaceous alluvium. For these waters, the authors used an operational definition where Na+K makes up to 60 percent or more of total cations. In all cases, Na is the dominant cation, with only small amounts of K.

(ii) Ca+Mg waters were assumed to reflect sources in carbonate aquifers or carbonate-bearing alluvium. As with Na+K waters, the authors developed an operational classification such that Ca+Mg makes up more than 60 percent of the total cations. Unlike the Na+K waters, either Ca or Mg can be the dominant cation, and they are typically present in subequal amounts.

(iii) Mixed types where neither cation pair constitutes more than 60 percent of total cations, but both pairs amount to more than 40 percent. These waters were found predominantly in carbonate rocks, with some occurrence in alluvium. The authors observed that either cation pair might predominate.

In most cases, HCO_3^- and CO_3^{2-} were identified as the dominant anions in the waters, although isolated occurrences of elevated SO_4^{2-} were reported in some areas. Schoff and Moore (1964) hypothesized that these waters might occur through either (i) movement of water from tuffs into carbonate rocks, acquiring Ca+Mg through dissolution of carbonates; (ii) movement of water from carbonate to tuff, acquiring Na+K through mineral dissolution or ion exchange; or (iii) mixing of the two end-member Na+K and Ca+Mg waters.

Water samples taken from wells in Indian Spring Valley (36° 45′N, 115° 45′W) (Figure 2-1) were relatively dilute [Total Dissolved Solids (TDS) of about 200 to 300 ppm] and cluster near the $Ca+Mg+HCO_3^-+CO_3^{2-}$ end-member. The topographically closed basins in Yucca and Frenchman Flats contained all three water types. In most cases, Na+K waters were associated with tuff aquifers or basin-fill aquifers composed of tuffaceous detritus, while Ca+Mg waters were associated with Paleozoic dolomites at the north end of Yucca Flat. The dominant anions in Yucca and Frenchman Flats were $HCO_3^-+CO_3^{2-}$, although some elevated SO_4^{2-} concentrations were observed in wells penetrating fractured zones in the Climax stock granodiorite at the north end of Yucca Flat. Jackass Flat also contained both Na+K tuff waters and Ca+Mg carbonate waters. A unique $Na+Ca+SO_4^{2-}$ water sample was also obtained from an unspecified tuff unit in Jackass Flat that was hydrothermally altered to a sulfate assemblage, according to Schoff and Moore (1964). Water samples from carbonate aquifers in the Amargosa Desert were generally of the mixed type and had higher TDS levels (400 to 600 ppm) than the basins located on the NTS. In general, higher Ca+Mg concentrations were found in the western part of the Amargosa Desert, and Na+K increased westward at sampling locations farther from recharge in the Spring Mountains.

The conceptual flow model developed by Schoff and Moore (1964) was based on distinguishing different valleys and basins on the basis of water chemistry. In defining the subsurface hydraulic regime, Schoff and Moore (1964) did not divide the NTS stratigraphy into regional aquifers and aquitards as was done in later studies, other than to identify the three water types and relate them to the predominant aquifer material (tuff, carbonate, and alluvium). In the hydrostratigraphic definitions used by Schoff and Moore, Paleozoic rocks were identified together as limestone and dolomite units with siliceous interbeds, while the Tertiary and Quaternary tuffs at the NTS were lumped together into a single hydrostratigraphic unit. Groundwater solute concentrations were assumed to increase due to dissolution of the host rock, and acquisition of Na+K through ion exchange with clays and zeolites. In general, solute concentration was assumed by Schoff and Moore (1964) to relate to increased interaction with aquifer minerals, implying longer, slower flow paths.

Water from springs (largely at Rainier Mesa) tended to be from perched water zones. The dilute concentrations of these Na+K tuff waters suggested little water-rock interaction and that recharge to the springs was from local precipitation. From the low measured TDS and the low Na concentrations, Schoff and Moore (1964) also inferred that water in Indian Spring Valley had not interacted with much tuffaceous rock, ruling out this basin as a discharge point for waters from the NTS. The Ca+Mg waters in Indian

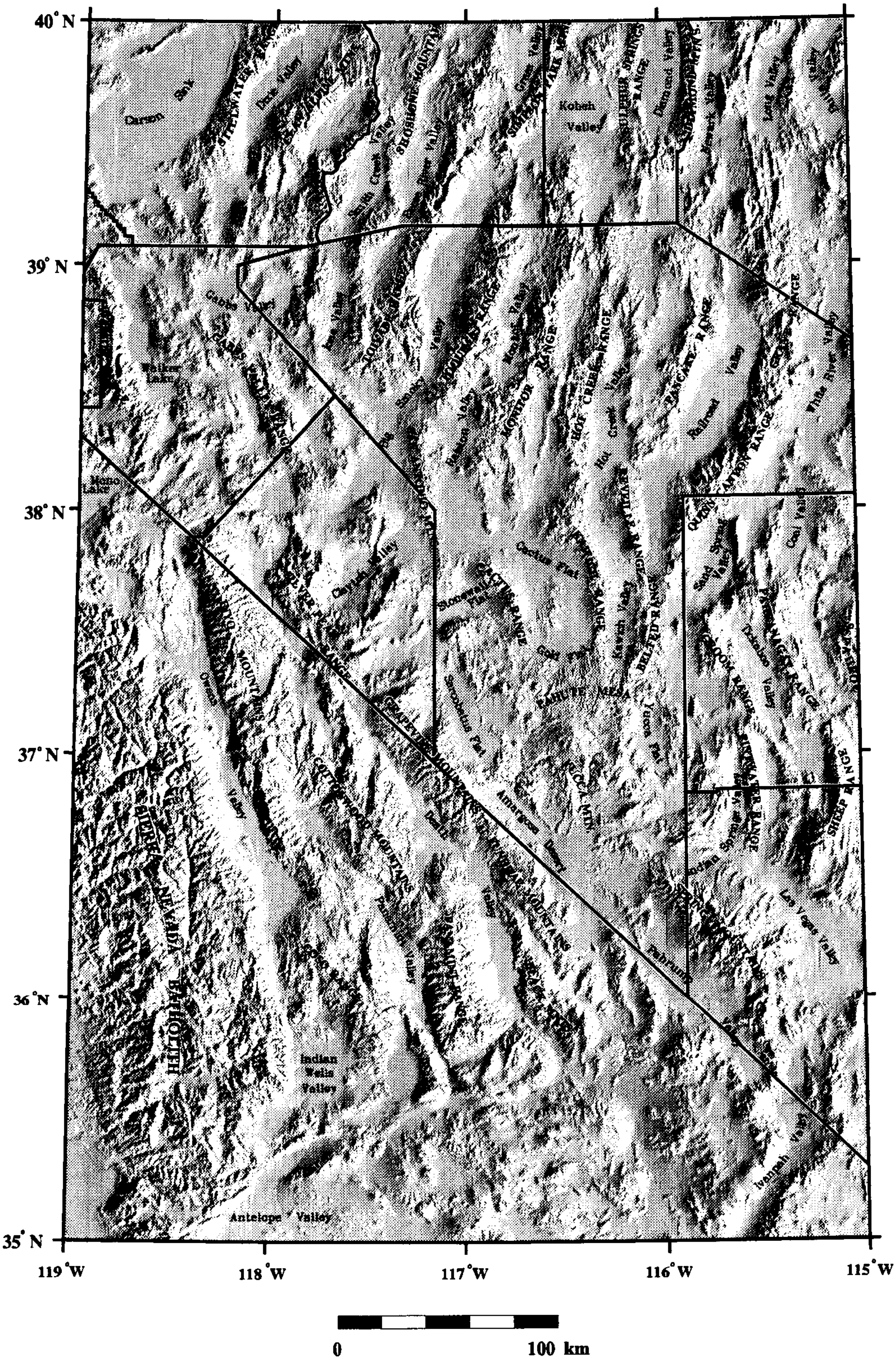

Figure 2-1. Physiographic map of the Death Valley region with political boundaries

Spring Valley suggested to Schoff and Moore (1964) that recharge occurs in the Paleozoic carbonates cropping out in the Spring Mountains to the south-southwest. Based on trends in Na concentrations, flow from Indian Spring Valley is either to Mercury Valley to the west or north into Frenchman Flat. Schoff and Moore (1964) also suggested that recharge in the Yucca Flat, Frenchman Flat, and Emigrant Valley basins is from local precipitation in the surrounding highlands. Based on Na distribution and on the earlier work of Winograd (1962a,b) at Yucca Flat, Schoff and Moore (1964) suggested that water does not move between these basins in the tuffaceous aquifers, but rather percolates down through the alluvium and tuff units into the underlying carbonates, with interbasin fluid flow occurring in the limestones and dolomites.

Trends in water chemistry indicate that the Amargosa Desert acts as the ultimate discharge point for much of the groundwater in the NTS. Higher overall solute concentrations and increasing TDS from the northern edge of the Amargosa Desert Basin near Lathrop Wells to the south both support this interpretation. Schoff and Moore (1964) noted that the NTS groundwaters are a relatively small contribution to the total discharge in the Amargosa Desert (<8 percent), citing the work of Eakin et al. (1963).

2.2 RUSH (1970)

Rush (1970) collated information contained in earlier published reports by Eakin et al. (1963), Winograd and Thordarson (1968), and Winograd (1963), as well as numerous unpublished investigations to develop a conceptual model of the regional flow system at the NTS. Rush (1970) divided the regional groundwater system within a 17,000 km^2 area containing the NTS into three separate interbasin flow systems: (i) the Ash Meadows groundwater flow system in the eastern portion of the region, (ii) the Pahute Mesa groundwater flow system in the central portion, and (iii) the Sarcobatus Flat groundwater flow system in the extreme west-northwest. As shown in Figure 2-2, the Ash Meadows flow system extends from the Timpahute and Groom ranges to the north, the Pahranagat and Sheep ranges to the east, the Spring range to the southwest, and the Kawich Range to the west. Rush (1970) estimated the recharge due to precipitation for each hydrographic basin in the study area using the empirical formulae developed for the Great Basin by Walker and Eakin (1963) and Eakin (1966). Based on these estimates, the primary areas of recharge to the Ash Meadows flow system are Tikaboo Valley, Las Vegas Valley along the western slopes of the Sheep Range, southern Three Lakes Valley, and Indian Springs Valley. Water in the Ash Meadows flow system flows predominantly from the north-northwest to the south-southwest where it is discharged in the Amargosa Desert, primarily along the Ash Meadows spring line.

The Pahute Mesa flow system (Figure 2-2) includes the Gold Flat and Kawich Valley hydrographic basins to the north, Oasis Valley to the west, the highlands of Pahute Mesa and Buckboard Mesa in the central region, and Crater Flat, the portion of Jackass Flat west of Fortymile Wash, and the Amargosa Desert to the south. According to Rush (1970), flow in the Pahute Mesa flow system is predominantly north to south; the primary areas of recharge being Gold Flat and Kawich Valley in the north with some underflow to Kawich Valley from the southern terminus of Reveille Valley. Although some water from the Pahute Mesa system is discharged from springs in Oasis Valley, Rush (1970) believes that most discharge occurs by evapotranspiration (ET) in the Amargosa Desert west of the Ash Meadows fault, although some of the water may discharge as far west as Death Valley.

Because Rush did not define the northern or western boundaries of the Sarcobatus Flat flow system, it is difficult to determine which hydrographic basins are included in its definition other than Cactus Flat to the north, the eastern portion of Stonewall Flat, and Sarcobatus Flat to the south. According

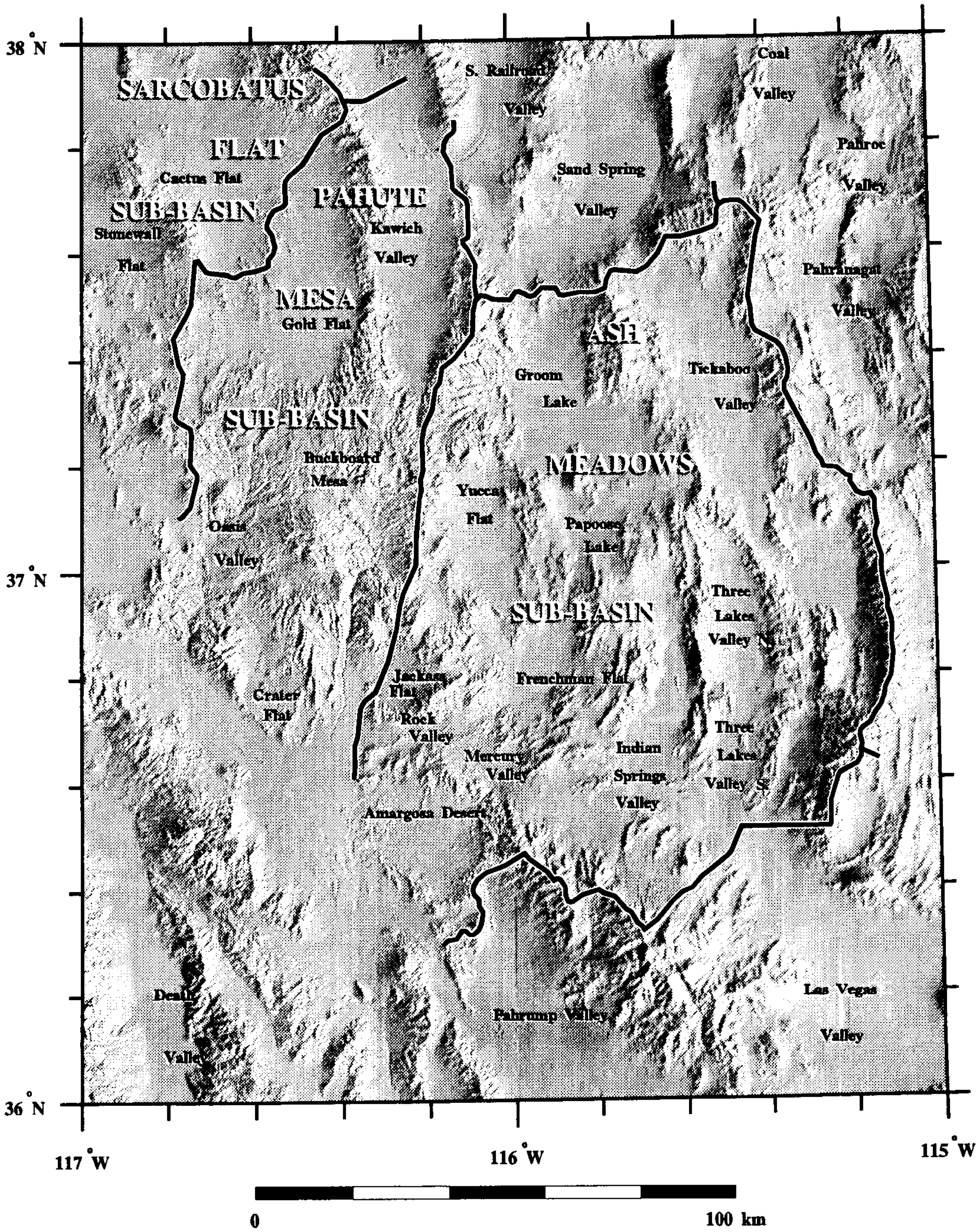

Figure 2-2. Map showing the general region and groundwater sub-basin boundaries of Rush (1970)

to Rush's estimates, 50 percent of the recharge to the Sarcobatus Flat system occurs within Sarcobatus Flat itself, with the remaining recharge occurring in Cactus Flat, Stonewall Flat, and Lida Valley. Most of the water from the Sarcobatus Flat system is discharged by ET in Sarcobatus Flat, although a small portion (< 15%) may discharge to the west through Grapevine Canyon in northern Death Valley. Based on Rush's work it appears that water from the Ash Meadows and Pahute Mesa flow systems may mix in the western portion of the Amargosa Desert, west of the Ash Meadows fault. However, it appears that the Sarcobatus Flat system is not connected to either the Ash Meadows or Pahute Mesa flow systems.

Because Rush's study represents a compilation of many reports, some of which are unpublished, it is difficult to determine the exact type of data used to delineate the flow system. It appears that the sole line of evidence used to separate the Pahute Mesa flow system from the Ash Meadows flow system is the relatively great difference in water levels (>600 m) that occur between Pahute and Buckboard Mesas to the west and Yucca Flat to the east in the central portion of the region, a region coincident with the north-trending, low-permeability clastic units of the Eleana Range. It should be noted, however, that according to Rush (1970), large differences in heads are also observed across faults within and between hydrographic basins which are presumed to be hydraulically connected at depth by a thick sequence of highly permeable, fractured Paleozoic carbonate rocks. Thus, large head differences alone are clearly insufficient to delineate flow system boundaries.

2.3 WINOGRAD AND THORDARSON (1975)

Although most of the data used in the 1975 report by Winograd and Thordarson were collected between 1957–1964, this report remains the seminal work on the overall hydrogeologic framework of the regional groundwater flow system at the NTS. Much of this report is devoted to an in-depth description of the hydrostratigraphy of the NTS regional flow system based on detailed analyses of cores, drilling records, geophysical logs, surface geologic maps, and drill stem and pumping tests which will not be reviewed here. For this report the most important aspects of their work are the delineation of the regional flow system and its major subsystems, and the types of data used by the authors to support their conceptual model of the flow system. It is important to note that many of the documents used by Schoff and Moore (1964) and Rush (1970) in their reports were prepared during the extensive hydrogeologic investigation conducted by the USGS in support of Winograd and Thordarson (1975), and thus there are many similarities between these conceptual models.

Winograd and Thordarson (1975) present a meticulously crafted picture of the regional hydrogeologic regime starting from detailed descriptions of the principal aquifers and aquitards found within the NTS area, defining the areal extent and saturated thickness of these aquifers and aquitards for each of the major hydrographic basins, determining the intrabasin flow of water for each of the major hydrographic basins, determining the interbasin transfer of water, and finally delineating individual groundwater basins with the regional NTS flow system. Within the NTS, Winograd and Thordarson (1975) identified six aquifers and five aquitards. From the bottom of the hydrostratigraphic section, these hydrogeologic units are: (i) the lower clastic aquitard consisting of Precambrian to Lower Cambrian quartzites, shales, and siltstones; (ii) the lower carbonate aquifer consisting of middle Cambrian to Devonian limestones and dolomites; (iii) the upper clastic aquitard consisting of Devonian to Mississippian argillite and quartzite; (iv) the upper carbonate aquifer consisting of Pennsylvanian to Permian limestone; (v) local aquitards composed of Cretaceous granitic stocks, dikes, and sills; (vi) the tuff aquitard composed of Oligocene to middle Miocene zeoblitized interbedded, nonwelded to welded ash-flow and ash-fall tuffs; (vii) the lava-flow aquitard composed of upper Miocene lava flow and interflow breccia; (viii) the bedded tuff aquifer consisting of upper Miocene ash-fall and fluvially rework tuff; (ix) the welded tuff aquifer consisting of upper Miocene to middle Pliocene nonwelded to densely welded ash-fall and ash-flow tuffs; (x) the lava flow aquifer composed of upper Pliocene basaltic and rhyolitic flows; and (xi) the valley fill aquifer consisting of upper Pliocene to Holocene alluvial, fluvial, and lacustrine deposits. Winograd and Thordarson (1975) note that the surface and subsurface extent of the principal hydrogeologic units vary from basin to basin due to the complex structural and erosional history of the rocks. However, some generalizations were drawn by Winograd and Thordarson regarding the distribution and saturation of the principal hydrogeologic units. The lower clastic aquitard and lower carbonate aquifer are present throughout the eastern two-thirds of the NTS, and are saturated except in outcrops and buried structural highs. The tuff aquitard generally separates the welded-tuff aquifer from the lower carbonate aquifer; however, in areas where the Tertiary volcanics do not occur, Cenozoic alluvial deposits are hydraulically connected directly to the lower carbonate aquifer. Based on the great depths to water measured in many of the topographically and structurally closed basins within the NTS area, as well as the absence of wet or discharging playas, Winograd and Thordarson (1975) concluded that groundwater recharged along the fronts of the basin bounding mountains flows downward through the Cenozoic aquifers and Tertiary tuff aquifers (where present) and into the underlying lower carbonate aquifer. The evidence for this downward flow is particularly strong in Yucca Flat and Frenchman Flat where extensive drilling of deep boreholes for the weapons testing program indicated a general decrease in hydraulic head with depth. Winograd and Thordarson (1975) note that in the Amargosa Desert, southern Indian Springs Valley, and eastern Jackass Flat, groundwater may flow upward from the lower carbonate aquifer into the overlying Cenozoic deposits.

According to Winograd and Thordarson (1975), the interbasin flow of groundwater is not significantly influenced by the topographic boundaries of the individual basins but rather by the presence and relative positions of the lower carbonate aquifer and the upper and lower clastic aquitards. From water level measurements made in wells penetrating the lower carbonate aquifer in Yucca and Frenchman Flats, Mercury Valley, and the Amargosa Desert, Winograd and Thordarson (1975) infer a relatively mild (<1 m per km) regional gradient from northern Yucca Flat toward Devils Hole at Ash Meadows. Additional evidence for the interbasin movement of water through the lower carbonate aquifer cited by Winograd and Thordarson includes: (i) the areal extent of the Paleozoic carbonate units; (ii) similarity of water levels in alluvial aquifers in adjacent, topographically closed basins; (iii) the hydrochemical facies of the groundwaters; and (iv) the disparity between the large spring discharge at Ash Meadows and the relatively small catchment area of the local hydrographic basin.

Based on a regional groundwater contour map covering an area of approximately 11,700 km^2, Winograd and Thordarson (1975) deduced that groundwater flowing beneath the NTS is discharged at three major areas: (i) Ash Meadows to the southeast, (ii) Oasis Valley along a reach of the Amargosa River just north of Beatty, and (iii) Franklin Lake Playa (Alkali Flat) to the southwest. Winograd and Thordarson (1975) believe that two distinct groundwater basins transmit the groundwater which discharges at Ash Meadows and Oasis Valley. The Ash Meadows basin is the larger of these two groundwater basins and extends from the Timpahute and Pahranagat Ranges to the north and northwest, to the Sheep Range in the east, to the Belted Range, Shoshone Mountain, and near Fortymile Wash in Jackass Flat to the west, and the Spring Range and Amargosa Desert near Ash Meadows and Franklin Lake Playa to the south. As shown in Figure 2-3, the precise location of the northeastern boundary of the Ash Meadows system defined by Winograd and Thordarson (1975) has not been determined due to the absence of definitive hydrologic or geologic data. However, on the basis of isohyetal maps, hydraulic head contour maps in both the Cenozoic and lower carbonate aquifers, and structural geology, Winograd and Thordarson (1975) appear to be confident that Tikaboo (Desert or Tikapoo) Valley, Three Lakes Valley, Indian Springs

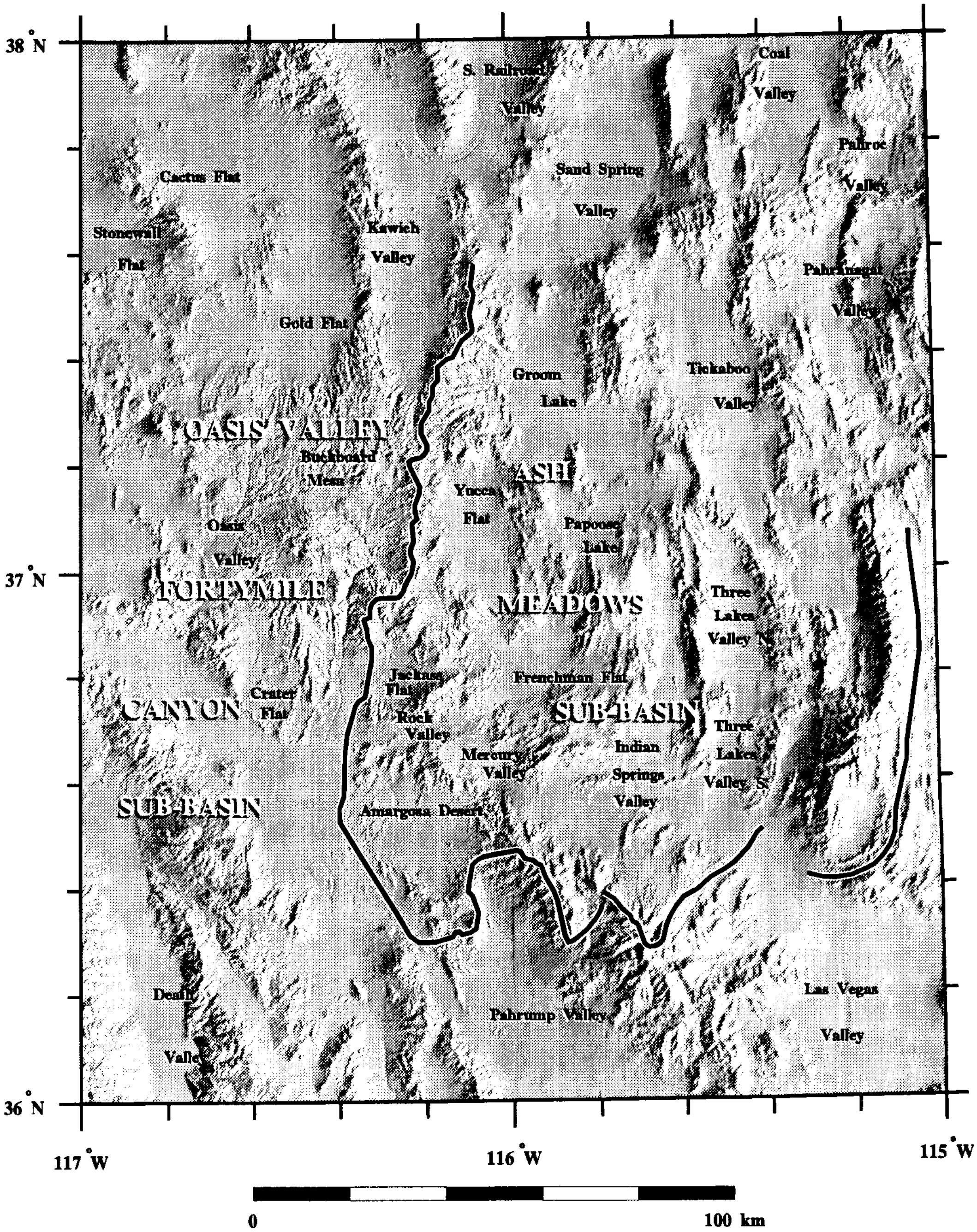

Figure 2-3. Map showing the general region and groundwater sub-basin boundaries of Winograd and Thordarson (1975)

Valley, Emigrant Valley (Groom Lake and Papoose Lake), Yucca Flat, Frenchman Flat, eastern Jackass Flat, Mercury Valley, Rock Valley, and the unnamed valley northeast of the Ash Meadows spring line are part of the Ash Meadows basin. On the basis of the measured spring discharge at Ash Meadows, Winograd and Thordarson (1975) estimated that recharge to the lower carbonate aquifer within the Ash Meadows system is less than 3 percent of the precipitation. However, based on deuterium data, they estimated that as much as 35 percent of the total discharge at Ash Meadows may be underflow from Pahranagat Valley, which is part of the White River regional groundwater flow system, and thus recharge may be significantly less than 3 percent of precipitation.

The second groundwater system at the NTS, informally named the Oasis Valley-Fortymile Canyon groundwater basin, is much less well defined than the Ash Meadows groundwater system. The Oasis Valley-Fortymile Canyon basin lies immediately to the west of the Ash Meadows basin and includes Kawich Valley, the western portion of Pahute Mesa, Oasis Valley, western Jackass Flat, Buckboard Mesa, and Crater Flat. The eastern extent of the basin is largely defined by the low permeability upper clastic aquitard which outcrops along the Belted Range and Eleana Range. Unlike the Ash Meadows basin, interbasin flow is primarily through the thick sequences of Tertiary volcanics in Pahute Mesa, Silent Canyon caldera, and Timber Mountain caldera. Blankennagel and Weir (1973) note that, while the Paleozoic carbonates may underlie the volcanic rocks beyond the ring fractures of the calderas, they probably do not underlie the volcanics within the centers of the calderas, and thus do not form a continuous, highly permeable conduit for interbasin flow. Groundwater generally moves south-southwest beneath Pahute Mesa, through Oasis Valley, Crater Flat, and western Jackass Flat toward the Amargosa Desert. Recharge to the Oasis Valley-Fortymile Canyon basin is largely derived from precipitation on the highlands of Pahute Mesa, Rainier Mesa, and the Kawich Range. In addition, Blankennagel and Weir (1973) estimate that as much as 38 percent of the total water entering the basin may be derived from underflow to the north into Kawich Valley and Gold Flat. Approximately 30 percent of total basin flow is discharged through springs in Oasis Valley, while the remaining flow moves south into the Amargosa Desert through Crater Flat and western Jackass Flat.

Winograd and Thordarson (1975) identified five distinct hydrochemical facies in the regional groundwater system: (i) the calcium magnesium bicarbonate facies typical of waters discharged from perched springs and regional springs in the carbonate units, (ii) the sodium potassium bicarbonate facies typical of waters in the tuff aquifer, (iii) the calcium magnesium sodium bicarbonate facies typical of waters found in the east-central Amargosa Desert and at Ash Meadows, (iv) the sodium sulfate bicarbonate facies typical of waters discharged at Furnace Creek Wash and Nevares Springs in Death Valley, and (v) a playa facies, high in TDS, typical of waters discharged by ET at Franklin Lake Playa (Alkali Flat). Waters sampled from the lower carbonate aquifer at the NTS are of the calcium magnesium sodium bicarbonate type, which led Winograd and Thordarson (1975) to infer downward flow of water from the tuffaceous units into the Paleozoic carbonate aquifer. Waters discharging from the lower carbonate aquifer along the Ash Meadows spring line are also of the calcium magnesium sodium bicarbonate type. Waters in Pahrump Valley, which originate from recharge into carbonate rock which crop out in the Spring Mountains, are typical of the calcium magnesium bicarbonate facies. Because waters in Pahrump Valley contain less sodium and sulfate than those discharged at Ash Meadows, Winograd and Thordarson (1975) believe that little if any water flows from Pahrump Valley to the Ash Meadows area. Water from Indian Springs Valley, Three Lakes Valley, and northwest Las Vegas Valley has lower sodium, potassium, sulfate, and chloride concentrations than water from the NTS and Ash Meadows, suggesting that water does not flow eastward from the NTS.

The chemistry of water sampled from wells tapping the valley-fill aquifer in the east-central Amargosa Desert is different from water sampled from other valley-fill aquifers in the NTS area. While these waters have a lower ionic strength, they belong to the same hydrochemical facies as water discharging at Ash Meadows, suggesting that water flows upward from the lower carbonate aquifer and is then diluted by locally recharged water (Winograd and Thordarson, 1975). The chemical quality of water in the central Amargosa Desert varies considerably from place to place leading Winograd and Thordarson (1975) to infer that the water is derived from at least three sources. Water with the calcium magnesium sodium bicarbonate facies is probably derived from flow across the hydraulic barrier which causes the Ash Meadows spring line (Winograd and Thordarson, 1975). Water of the sodium potassium bicarbonate facies found southwest of Lathrop Wells is probably derived from Jackass Flat, and water in the west-central and northwestern portion of the Amargosa Desert is believed to come from Oasis Valley (Winograd and Thordarson, 1975).

Based on the observation that water discharging in the Furnace Creek Wash-Nevares Springs area in Death Valley is chemically similar to water from Ash Meadows, Hunt et al. (1966) postulated that the water was originally derived from Pahrump Valley. While Winograd and Thordarson (1975) do not refute the chemical similarity of Furnace Creek Wash-Nevares Springs and Ash Meadows waters, they note that there is a marked dissimilarity between the former and waters from Pahrump Valley. Because the chemistry of the Death Valley waters appears to be a mixture of Oasis Valley and Ash Meadows, Winograd and Thordarson (1975) suggest that this water is derived from the valley-fill aquifer in the central and northwestern portions of the Amargosa Desert.

2.4 WADDELL (1982)

Waddell (1982) constructed a two-dimensional (2D), steady-state, finite element model of the groundwater flow system of the NTS and surrounding areas in Nye and Clark Counties, Nevada, and Inyo County, California, to determine regional groundwater velocities for use in predicting radionuclide transport, and assessing the effects of parameter uncertainty on these estimates. The conceptual model of the flow system developed by Waddell (1982) is largely based on the work of Winograd and Thordarson (1975); however, it was refined using data acquired from boreholes drilled after the completion of Winograd and Thordarson's report. The area of the region considered by Waddell was approximately 18,000 km^2. Waddell defined three groundwater sub-basins within the study area on the basis of readily identifiable recharge locations connected to discharge areas by inferred principal flow paths. These groundwater sub-basins are: (i) the Oasis Valley system, (ii) the Alkali Flat-Furnace Creek Ranch system, and (iii) the Ash Meadows flow system.

As defined by Waddell (1982), the Ash Meadows groundwater basin consists of all areas that contribute flow to the springs in Ash Meadows and is roughly the same system identified by Winograd and Thordarson (1975). Because groundwater does not discharge in Fortymile Wash, but flows south through the central Amargosa Desert where it is discharged at Alkali Flat (Franklin Lake Playa) and in Death Valley near Furnace Creek, Waddell (1982) divided the Oasis Valley-Fortymile Wash system into the Oasis Valley groundwater basin and the Alkali Flat-Furnace Creek Ranch basin (Figure 2-4). The discharge areas in the Oasis Valley and Ash Meadows basins are both caused by low permeability rocks that form "dams" forcing water to the surface to create springs (Waddell, 1982). Although most of the water discharged at these springs is lost to ET by native vegetation or irrigated fields, some of the water may re-enter the local valley-fill aquifers.

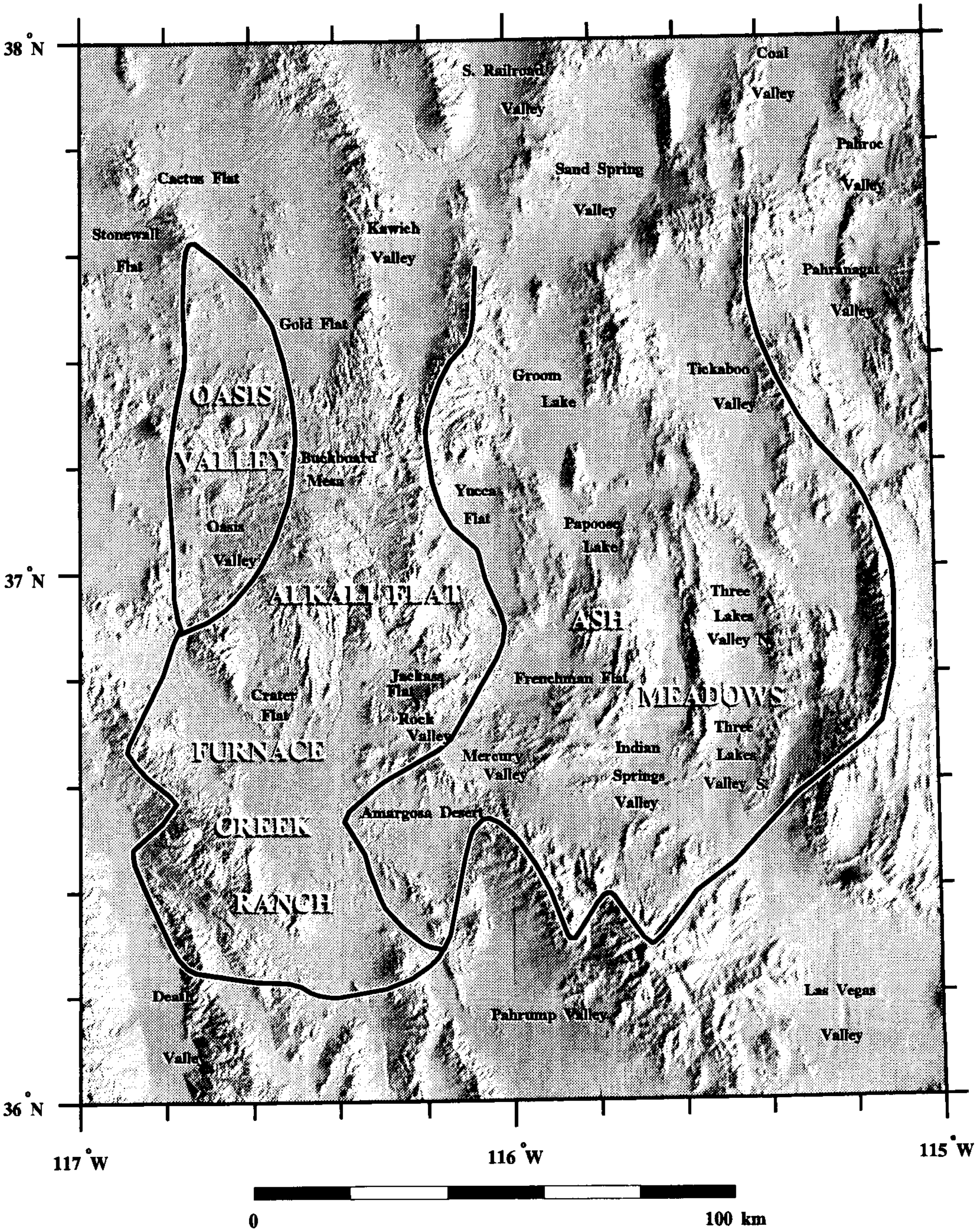

Figure 2-4. Map showing the general region and groundwater sub-basin boundaries of Waddell (1982)

Waddell's Oasis Valley basin extends approximately 70 km from the southern end of the Cactus Range and Gold Flat in the north to Beatty in the south, and 20 km from eastern Pahute Mesa, Timber Mountain, and Beatty Wash in the east to western Gold Flat, western Pahute Mesa, and eastern Sarcobatus Flat in the west. The Oasis Valley flow system receives recharge from the highlands of western and central Pahute Mesa. Discharge in Oasis Valley comes from springs that are forced to the surface by a region of low permeability rocks down gradient of Beatty, Nevada.

The Alkali Flat-Furnace Creek Ranch basin is bounded on the north by the Cactus, Kawich, and Reveille Ranges and on the south by the Black Mountains in Death Valley, and the northern ends of the Greenwater and Resting Spring Ranges. The eastern boundary of the Alkali Flat-Furnace Creek Ranch basin parallels the Reveille and Belted Ranges in the north, Rainier Mesa, the Eleana Range, the southwestern margin of Yucca Flat in the central portion, and the Ash Meadows spring line to the south. Waddell notes that the eastern boundary of the Alkali Flat-Furnace Creek Ranch basin is not well constrained in the south. Based on Plate 1 of Waddell (1982), it appears that recharge to the Alkali Flat-Furnace Creek Ranch system occurs in southern Kawich Valley, northeastern Pahute Mesa, along the Belted Range, and in the Rainier Mesa area. Water discharges by ET at Alkali Flat (Franklin Lake Playa) where water appears to be forced to the surface by the damming effect of low permeability rocks that crop out at Eagle Mountain. At Alkali Flat, ET was estimated to be 0.39 m^3/s, and spring discharge at Furnace Creek Ranch was estimated to be 0.20 m^3/s.

The Ash Meadows groundwater basin lies in the eastern portion of Waddell's model area and includes the following hydrographic areas: (i) Tikaboo Valley (Desert Valley), (ii) the southern tip of Pannier Valley (Sand Spring Valley), (iii) Groom Lake (northern Emigrant Valley), (iv) Papoose Lake (southern Emigrant Valley), (v) northern Three Lakes Valley, (vi) southern Three Lakes Valley, (vii) Indian Springs Valley, (viii) eastern Frenchman Flat, and (ix) the southeastern portion of the Amargosa Desert. Ash Meadows groundwater basin is bounded on the north by the Groom, Timpahute, and Pahranagat Ranges, and on the south by the Funeral and Black Mountains, the northern end of the Resting Spring Range, and the Spring Range. The western boundary of the Ash Meadows basin is coincident with the eastern boundary of the Alkali Flat-Furnace Creek Ranch basin, while the eastern boundary is parallel to the Pahranagat and Sheep Ranges, and coincident with a low, northeast to southwest oriented topographic divide between the southern Sheep and the northern Spring Ranges. Recharge to the Ash Meadows system was assumed to be derived from the Pahranagat and Timpahute Ranges to the north, the Sheep Range to the east, and the Spring Mountains to the south. Some water was also assumed to enter the system as underflow from Pahranagat Valley into Tikaboo Valley. This system discharges at the spring line in Ash Meadows, which is believed to result from the juxtaposition of low permeability Tertiary lake deposits on the western downthrown side of a north-trending normal fault against the highly permeable Paleozoic carbonate aquifer. Total discharge from the Ash Meadows springs was estimated to be 0.655 m^3/s. Waddell notes that just up-gradient of the Ash Meadows spring line, water is forced through a narrow zone beneath the Specter Range, which is laterally confined by clastic units that crop out at the northern end of the Spring Mountains and the northern end of the Specter range. Contrary to the conceptual model of the Ash Meadows system presented by Winograd and Thordarson (1975), Waddell believes that water beneath Rock Valley flows southwest rather than southeast. Evidence for southwestward flow is twofold. First, water from Lathrop Wells is saturated with respect to both calcite and dolomite suggesting it is derived from carbonate units to the east. Second, water samples from Lathrop Wells show high concentrations of sulfate ion suggesting interaction with alteration products from the Wahmonie intrusive 32 km to the northeast.

According to Waddell, uncertainty in the conceptual model of the Death Valley flow system arises from: (i) the wide variation and complex spatial distribution of transmissivity; (ii) the complex hydrostratigraphic structure caused by Basin and Range normal faulting, folding, and thrust faulting in Paleozoic and Precambrian rocks, and complex volcanic stratigraphy from at least five eruptive centers; and (iii) determining the location of recharge and discharge boundaries and estimating associated flow rates. To simplify the conceptual model, Waddell assumed that: (i) flow was predominantly horizontal and the system could be modeled as a 2D, confined system, (ii) steady-state conditions prevail, and (iii) the hydraulic properties of the rocks are isotropic and homogeneous within a given zone. The simplified conceptual flow model was evaluated by constructing, calibrating, and conducting sensitivity analyses of the corresponding mathematical model. Waddell used the inverse procedure developed by Cooley (1977, 1979), which is based on minimizing the variance of the head residuals. The 2D finite element mesh was refined in areas where the amount of hydrogeologic information was greatest, such as the NTS, and coarsened in regions where few data were available. Subsequent sensitivity analysis suggested that the coarse mesh used in the area east of the NTS and north of Las Vegas Valley had little effect on the estimated heads and fluxes. Parameters that were estimated using the inverse procedure included transmissivity, discharge, and recharge. Note that the discharge rate at Ash Meadows was held fixed during the calibration process as were initial estimates of transmissivity for the clastic units.

Estimated head gradients predicted by the calibrated model ranged from 0.04 in clastic rocks on the upstream margins of Yucca Flat and Death Valley, to 0.03 to 0.005 in tuffaceous rocks, to 0.00016 in the highly transmissive Paleozoic carbonate rocks. Estimated transmissivities in the carbonate rocks had a geometric mean 0.0022 m^2/s, with the largest values occurring beneath the Specter Range and Amargosa Flat (Amargosa Desert). Although the Funeral Mountains, which form the eastern boundary of Death Valley, were designated to be a carbonate zone, very low transmissivities were estimated, suggesting that either the clastic rocks are thicker than assumed or an undetected fault is present. For the tuff zones, the geometric mean of the estimated transmissivities was 0.00056 m^2/s. However, within the Fortymile Canyon zone, transmissivity was 0.01 m^2/s, which correlates well with the intense fracturing observed in these tuff units. The geometric mean transmissivity for the clastic units was 0.000054 m^2/s.

Head residuals from the final calibration run ranged from −61.0 to 85.2 m with the largest head residuals occurring at Pahute Mesa and Jackass Flat. Boreholes in Pahute Mesa are generally very deep (>2,000 m) and penetrate several water bearing units. Because the vertical gradients in these boreholes vary with depth, the use of a single, composite head value to represent the mean potential in the borehole is a poor approximation and was probably the cause of the large residuals. Waddell did not venture an explanation of the large residuals obtained in Jackass Flat. However, Waddell suggested that the largest contribution to the head residuals comes from simulation errors rather than errors in measured heads, and that these simulation errors were primarily the result of errors in the conceptual model. A statistical analysis of calibration errors indicated that the best determined parameters were the transmissivities for zones beneath Fortymile Canyon and along Furnace Creek Ranch, recharge or underflow through Pahute Mesa, and discharge at Death Valley. The least well-determined parameters were transmissivities for zones at Oasis Valley, the Belted Range and Emigrant Valley, the Eleana Formation, carbonates beneath the Amargosa Desert, and along the Las Vegas shear zone.

Waddell concluded that, despite the difficulties posed by the complexity of the region's hydrogeology, uncertainty about the distribution and magnitude of transmissivities and fluxes, and the absence of potentiometric data in the eastern portion, the model is probably reasonably accurate for the NTS area. The marked variation in magnitude and direction of both measured and simulated hydraulic gradients within the study area appear to be the result of the complex spatial distribution of the low permeability clastic and high permeability carbonate units rather than the result of the location and magnitude of recharge. However, recharge at and underflow beneath Pahute Mesa did appear to have a significant effect on the hydrogeologic regime within Oasis Valley, YM, and Jackass Flat.

2.5 RICE (1984)

Rice (1984) developed a 2D hydrogeologic model covering a region of some 41,000 km^2. The modeled region is roughly triangular in outline with the boundaries set on topographic highs in the region, except along the southwestern edge which runs through Death Valley and along the Amargosa River, and is used as a discharge boundary (Figure 2-5). The boundaries extend from the Grant, Quinn Canyon, Reveille, Kawich, and Cactus Ranges in the north, to the Spring Mountains, Saddle Hills, and the Kingston Range in the south. The eastern boundary of the model runs along the crests of the Sheep, Pahranagat, and Golden Gate Ranges. No new field data were presented in the report, and the groundwater chemistry was based on earlier work by Schoff and Moore (1964), Winograd (1971), and Winograd and Thordarson (1975), while the hydrostratigraphy of Rice's model was based on the terminology of Winograd and Thordarson (1975).

Hydrochemical facies were used to define general groundwater flow patterns of the model. Flow is generally from north and northeast to the south and southwest. Groundwater flow from beneath the NTS was assumed to move toward the Ash Meadows Spring discharge region in the Amargosa Desert. Groundwater was also inferred to flow from the Pahranagat Valley, and possibly Garden and Coal Valleys, to Ash Meadows. Pahrump and Stewart Valleys to the south were thought to make only a small contribution to discharge in Ash Meadows. Also, groundwater flow from the Amargosa Desert is identified as a major source for discharge in east-central Death Valley. The conceptual model developed by Rice (1984) was one of interbasin flow through the lower Paleozoic carbonate aquifer of Winograd and Thordarson (1975). Although the basins are topographically separated, interbasin flow can be significant. Recharge is assumed to occur predominantly in the mountain ranges where these carbonate units are exposed at the surface. Precipitation can also occur where recharge is through the tuff and the alluvium to the carbonate aquifer. Most of the discharge was assumed to occur in the basins either through springs, ET, or pumping.

To model flow in the hydrogeologic region, Rice (1984) used the 2D Variable Thickness Transient (VTT) finite difference flow code developed at Pacific Northwest Laboratories (PNL) (Reisenauer, 1980). Because the code represents regional flow in two dimensions assuming a single transmissive layer, a number of simplifying assumptions were made in the conceptual model. The regional hydrogeologic model was represented by a 70×80 node grid, in which each computational cell was 3.8 km square. The regional system was modeled as one layer, lumping together carbonate, tuff, and alluvium aquifers into a single transmissive unit. The flow system was assumed to be at steady state, and the transmissivity of the aquifer was presumed to be isotropic. The flow system was also modeled under confined conditions. A constant head boundary was assumed for most of the region, with discharge conditions assumed along the southwestern boundary in Death Valley, and recharge in the mountain ranges. Assumed no-flow conditions were limited to the area between the Pahranagat and Sheep Ranges, the Sheep Range and the Spring Mountains, and Fish Lake Valley at the northwest end of Death Valley. No structural surface was assumed.

Hydraulic head data for the model were obtained from hand-contoured, unpublished USGS maps digitized at PNL. The head distribution was also determined using universal kriging assuming a zero-order drift model. Both distributions are similar, with roughly a regional north-south gradient to YM, which

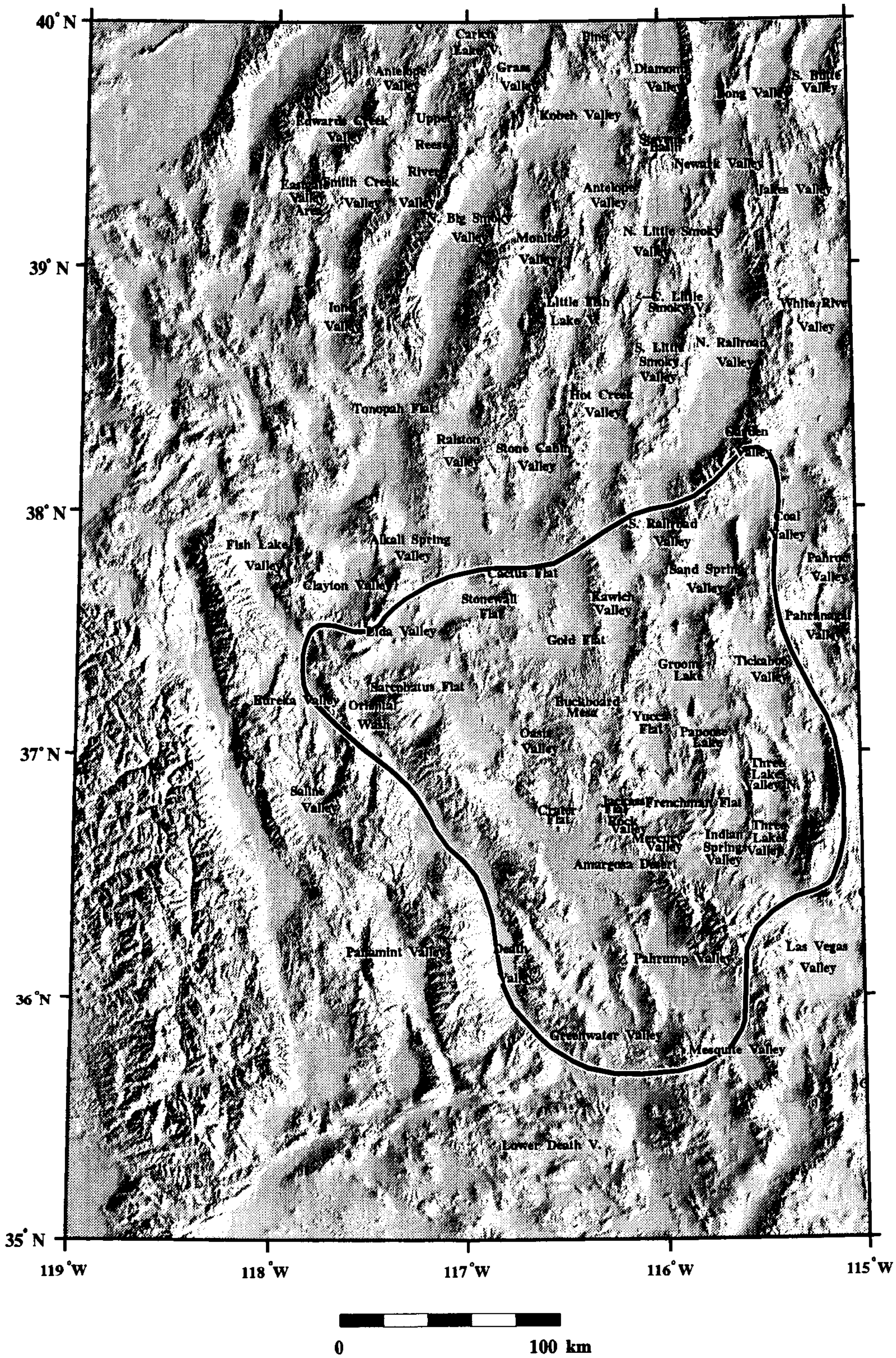

Figure 2-5. Map showing the boundary of the groundwater model of Rice (1984)

swings to the southwest toward Death Valley. Because most of the wells on which the head distributions are based are located in the basins, it is not surprising that error estimates show the most uncertainty in the mountains where the data are much sparser. In these areas, uncertainty in head estimates may be greater than 100 m.

Recharge was calculated by water balance over the root zone of vegetation, including average monthly precipitation, runoff, actual ET, and change in soil moisture storage. Potential evapotranspiration (PET) was calculated using the empirical Blaney-Criddle relationship (Blaney and Criddle, 1950) and converted to actual ET based on soil moisture content. Data on soil type, vegetation type, root zone depth, and runoff were all included in the calculation. Based on these relationships, a recharge of 1.64×10^8 m^3/yr was estimated for the model, although sensitivity analyses showed a range of 6.5×10^7 to 2.6×10^8 m^3/yr. This was in good agreement with estimates for the region using the Walker-Eakin method. Discharge areas were digitized from maps, and assigned to nodes based on geographic locations. Discharge rates were assigned to each node based on measured and estimated values from pumping records, spring flow rates, and estimated ET. Total discharge estimated from springs, pumping, and ET data was estimated at about 1.16×10^9 m^3/yr. Pumping (51 percent) and springs (32 percent) dominated the total discharge. Transmissivity data were taken from the USGS regional model of Waddell (1982). Gaps were filled in assuming reduced transmissivity in the mountain ranges. Transmissivity varied from less than 10 m^2/d near YM to 500,000 m^2/d in Ash Meadows.

During model calibration, transmissivity was adjusted to match calculated and measured hydraulic heads. The best steady-state model simulation matched reasonably well with the observed head distribution, with a residual error of as much as 30 to 70 m. In the YM region, residual errors were between 12 to 24 m. Water balance from the calibrated model suggests that there is significant underflow into the model from the north and east, and outflow to Death Valley to the southwest.

2.6 CZARNECKI AND WADDELL (1984)

Czarnecki and Waddell (1984) developed a finite-element model of groundwater flow in the vicinity of the NTS. The region is smaller than that of Rice (1984) and Waddell (1982) and roughly corresponds to the YM groundwater basin (Figure 2-6). The model covers about 3,000 km^2 (The authors report the model area to be about 6,000 km^2, however planimetry indicates the area is 2,950 km^2) extending from Timber Mountain in the north to the Funeral Mountains and Death Valley in the southwest. The eastern boundary is Lathrop Wells, Rock Valley, and Jackass Flat, while the western limit of the model region is coincident with Bare Mountain. A smaller subregional model was investigated to allow for finer discretization of the finite element mesh that was thought likely to be necessary for future detailed flow and transport modeling.

The basic conceptual model of Winograd and Thordarson (1975) was adopted by Czarnecki and Waddell (1984) for the subregion model. Additional, more recent data were included to refine the initial model, including depth to water, precipitation, discharge/recharge estimates, water chemistry, and geophysical data. The resulting subregion is made up of 12 zones based on three rock types; alluvium, volcanics, and Paleozoic carbonate. For the purposes of modeling, the groundwater system is assumed to be at steady state, and the rocks are assumed to be isotropic with hydrologic parameters that remain constant through time. A constant-head boundary was assumed at Timber Mountain, assuming that recharge was occurring in Pahute Mesa to the north of the modeled region. A flux boundary was specified with recharge in Fortymile Canyon within the model. Underflow into the model was effected using specified flux boundaries from Jackass Flat, Rock Valley, Western Amargosa Desert, and from Ash

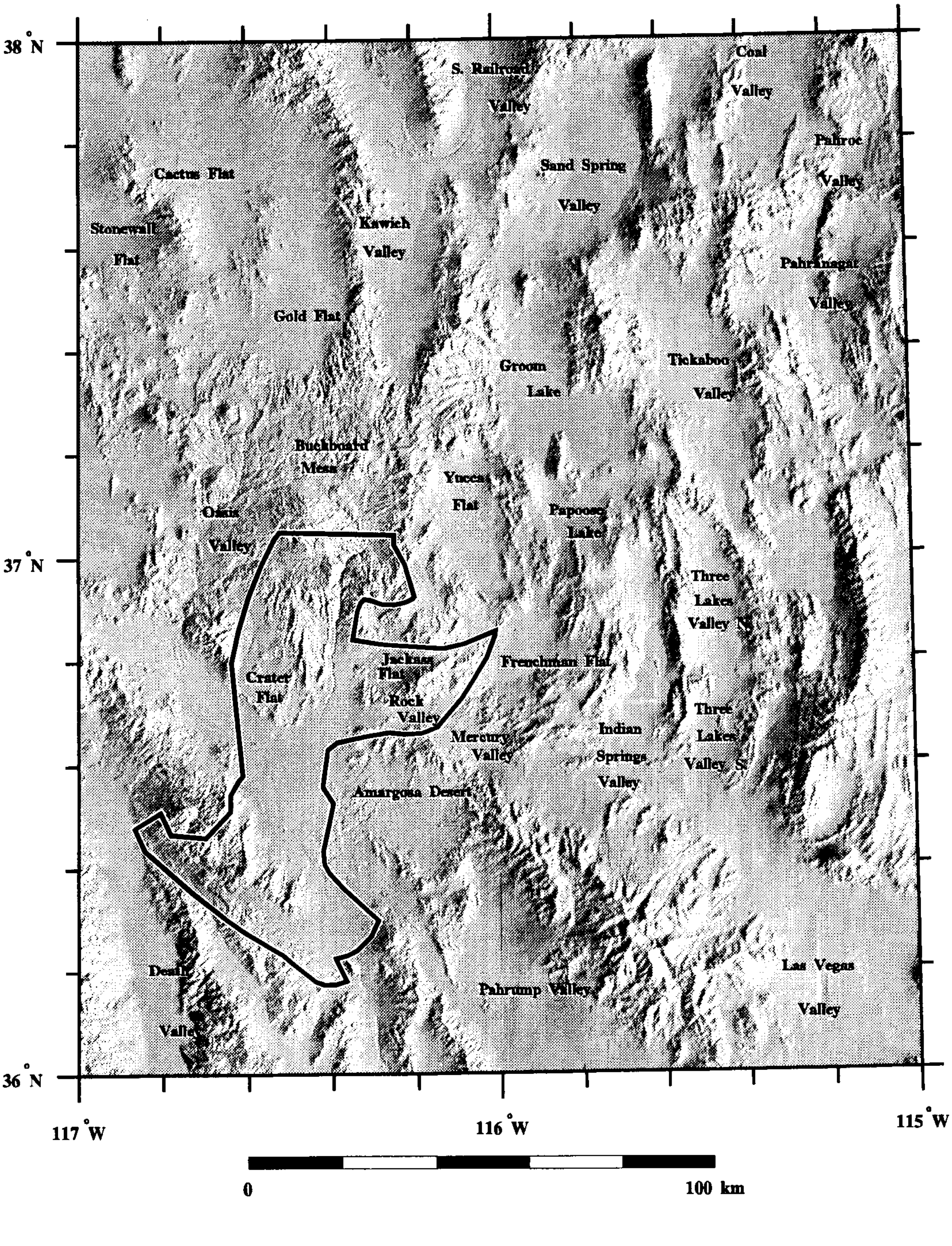

Figure 2-6. Map showing the boundary of the groundwater models of Czarnecki and Waddell (1984) and Czarnecki (1985)

Meadows. Based on the conclusions of Winograd and Thordarson (1975), discharge from the model was assumed to be by ET at Franklin Lake Playa in Alkali Flat. An additional discharge flux, based on the earlier work of Waddell (1982), was specified at the southwestern corner of the model to account for spring flow near Furnace Creek Ranch. The Ash Meadows discharge region used in other models lies outside of the model boundaries of Czarnecki and Waddell (1984) and was not explicitly considered. All other boundaries were assumed to be no-flow.

Because a transmissivity type model was used, the implicit assumption in the model is that fluid flow is lateral only, with no vertical component. To accommodate the steep hydraulic gradients observed north of the proposed repository site, two model zones were specified as hydrologic barriers to flow and were placed north and west of YM. A third barrier zone (low transmissivity lake bed sediments) was assumed in the southwest corner of the model to represent the observed steep hydraulic gradient and spring discharge near Furnace Creek Ranch.

One goal of this modeling exercise was to use statistical procedures to determine best-fit values for the different model parameters. As mentioned above, the 12 zones of the model were initially grouped according to whether the dominant rock type was alluvium, carbonate, or volcanics, and assigned initial uniform estimates of transmissivity. Volcanic rock underlies the northern half of the model. In addition to the hydrologic barriers assumed for the model, Czarnecki and Waddell (1984) also estimated that volcanic rocks to the east of YM were more transmissive than those to the west and north. The lithology of the southern part of the model in the Amargosa Desert was assumed to be a mix of alluvium, carbonate, and volcanic rock types. Carbonate rocks were assumed to underlie Rock Valley and the Funeral Mountains to the south.

Parameter estimation techniques of Cooley (1977, 1979, 1982) were used to calculate values for transmissivities, fluxes, and constant head nodes. The model was calibrated by minimizing the error variance between the calculated and measured hydraulic head data. Parameter values were adjusted so that the variance was randomly distributed throughout the modeled region to avoid the problems of systematic overprediction or underprediction of head distributions. Ultimately, Czarnecki and Waddell (1984) achieved the best model results by fixing fluxes and constant-head nodes and estimating only the transmissivity. The 12 original transmissivity zones were recombined into three parameters due to strong correlation among the transmissivity estimates. The first parameter included the transmissivities of Rock Valley, Jackass Flat, and the Amargosa Desert. The second parameter included the Funeral Mountains and Furnace Creek Ranch, while the third parameter included the transmissivities of YM, Timber Mountain, and Crater Flat. Although the parameters were statistically correlated, they did not necessarily represent the same rock type.

The simulated hydraulic head distribution for the modeled region agreed reasonably well with the measured values. The calculated maximum hydraulic head was 1,279.3 m near Timber Mountain to 284.6 m at Furnace Creek Ranch. Comparison to measured hydraulic heads indicated residuals ranged from about −29 to 21.4 m, with an average absolute residual value of 7 m. Residuals were generally greater where there was likely to be a vertical component to flow or a steep measured hydraulic gradient. Following model calibration, sensitivity analyses were performed to test the effect of estimated flux values on transmissivity. The fluxes estimated for Jackass Flat, underflow from western Amargosa Desert and Ash Meadows, upflow from carbonate rocks in Rock Valley, discharge from Franklin Playa (by ET), and spring discharge near Furnace Creek Ranch were varied by factors of 0.25, 0.5, 1, 2, and 4, and the effects on estimated transmissivities for Furnace Creek Ranch, Amargosa Desert, and YM were compared. In general, transmissivity estimates were most sensitive to discharge from the Furnace Creek Ranch and from

Franklin Lake Playa. Transmissivity near YM was particularly sensitive to flux variations at Franklin Lake. The fact that the discharge from the springs at Furnace Creek Ranch is much better constrained by historical records suggests that effort is needed to reduce uncertainty in ET at Franklin Lake Playa. Finally, Czarnecki and Waddell (1984) investigated the effects of anisotropy on model results, and concluded that although increased transmissivity in a north-south direction (i.e., through north-south oriented fractures) produces faster travel times, the model uncertainty increased suggesting that an assumption of isotropic behavior may be reasonable at a large scale.

2.7 CZARNECKI (1985, 1989)

The purpose of the investigation conducted by Czarnecki (1985) was to predict the effects of increased precipitation due to climate change on the water table in the western section of the NTS and, in particular, beneath YM. The modeled region is the same as that used in the earlier parameter-estimation efforts of Czarnecki and Waddell (1984). Czarnecki (1985) also relied on conceptual models for the subregional flow system developed by Winograd and Thordarson (1975), Waddell (1982), Czarnecki and Waddell (1984), and Waddell et al. (1984) to define the hydrogeologic structure. The computer code used to model the region was the finite element groundwater flow code FEMOD, which, unlike the modeling work of Waddell (1982) and Rice (1984), was unconfined.

Most of the boundaries were specified as no-flow, with some areas as specified lateral flux, either positive or negative. Positive inflow into the model includes flow from Timber Mountain, Jackass Flat, Rock Valley, the western Amargosa Desert, and Ash Meadows. An additional flux was specified within the model at Fortymile Wash. There was no specified lateral flux out of (negative flux) the model region. Incoming fluxes were based on the results of the parameter-estimation modeling results of Czarnecki and Waddell (1984). Discharge from the model was assumed by Czarnecki (1985) to occur through ET, and was represented by the use of an ET coefficient of 10^{-5} m/s per unit area at the land surface. The coefficient was assumed to decrease linearly with depth, reaching zero at 5 m, the depth which was assumed to be the maximum depth for bare-soil evaporation. For the purposes of evaluating the effect of increased recharge, the ET coefficient was set at a high value to prevent the water table from rising above the ground surface. Head-dependent sinks were assigned to individual nodes in contrast to the earlier work of Czarnecki and Waddell (1984) where a constant flux boundary was established at the northern end of the model, only two constant head nodes were specified by Czarnecki (1985) at the southern end of the modeled region. The first, at Furnace Creek Ranch was set at –68 m, and the second at Franklin Lake Playa was set at 606 m. In both cases, the hydraulic head was set at the estimated altitude of the land surface.

The hydraulic conductivities used by Czarnecki (1985) were taken from Czarnecki and Waddell (1984) and directly assigned as constant values based on the predominant lithology. The 12 transmissivity zones of Czarnecki and Waddell (1984) were also used, although the Amargosa Desert transmissivity zone was divided into three zones to attain a better match between measured and predicted heads. A low transmissivity zone immediately north of the proposed repository was inferred as a possible explanation for the high hydraulic gradient observed north of the proposed repository site. Saturated thickness was estimated at 1,000 m from drill hole information and resistivity surveys. Prior to evaluating the effect of increased precipitation/recharge, a baseline was established assuming that current groundwater conditions represent a steady state. Hydraulic heads calculated in Czarnecki (1985) for the baseline case agreed with the earlier work of Czarnecki and Waddell (1984) within about 10 m in the Amargosa Desert and within about 1 m in the vicinity of YM.

Methods developed by Eakin et al. (1951) and Rush (1970) were used to estimate current recharge conditions in the vicinity of the hydrologic model. Three precipitation zones were identified based on historical precipitation records. Recharge estimates using the method of Rush (1970) were based on determining the area within each hydrographic basins corresponding to a given elevation range and assuming a corresponding precipitation rate and percentage of that precipitation as infiltration. The recharge for precipitation Zone 1 was assumed to occur principally within Gold Flat and Buckboard Mesa, and estimated at 2.6 to 2.8 mm/yr. For Zone 2, recharge was estimated at 0.7 mm/yr within Jackass Flat and Crater Flat. For Zone 3, recharge was principally within the Amargosa Desert, but was assumed to be only minor. In spite of all of the effort involved in the recharge calculations, Czarnecki (1985) acknowledged the limitations and uncertainties in the method of Rush (1970) and used conservative values of 2 mm/yr, 0.5 mm/yr, and trace for recharge in Zones 1, 2, and 3, respectively.

Once the baseline was established, precipitation in the region was assumed to increase by 100 percent and the additional recharge was calculated, again using the methods of Eakin et al. (1951) and Rush (1970). A doubling of annual precipitation was estimated to result in an average increase in recharge for all three precipitation zones by a factor of 13.7. For the modeling exercise, this was rounded up to a 15-fold increase in recharge. Czarnecki (1985) noted that this approach assumed that all precipitation was available for infiltration and recharge and did not address the possibility of increased surface runoff. Huntington Valley in northern Nevada was investigated as an analogue to the increased precipitation model. Water balance in Huntington Valley suggested that as much as two-thirds of the potential recharge ended as surface runoff. For this reason, it is suggested that the conceptual model as presented is a conservative prediction of the effects of increased precipitation on water table rise.

For a doubling of precipitation (and a 15-fold increase in recharge) from the baseline conditions, the water table was estimated to rise by about 130 m near the proposed repository. Additional discharge zones developed in the northern reaches of Fortymile Canyon, and southeast of Lathrop Wells. Sensitivity analyses suggested that the calculated water table rise was relatively insensitive to changes in the recharge flux for Zones 1 and 2, and most sensitive to influx across the northern boundary of the model and especially to infiltration in Fortymile Wash. The direction of vertically integrated groundwater flux vectors was generally to a more strongly north-south orientation, while the flux magnitude increased to as much as 27 times the baseline case under the increased precipitation scenario.

Czarnecki (1989) developed an enhanced conceptual model of the flow regime for the portion of the Alkali Flat-Furnace Creek sub-basin that includes YM, but did not attempt to develop a computational model (Figure 2-7). The steep hydraulic gradient north of YM was assumed to be caused by a low permeability barrier, although no particular cause for this barrier (e.g., fault gouge, cross-fault juxtaposition of low and high permeability strata) was favored by the author. The gentle hydraulic gradient through the Amargosa Desert was assumed to be due to a proposed Tertiary carbonate aquifer at a depth of about 150 m. Although vertically upwards gradients indicate discharge at Franklin Lake Playa, there is also a suggestion of continued through-flow toward and beneath the Amargosa River. Water level and temperature data from deep drillholes in the Amargosa Desert indicate that there is an upward component of flow from the carbonate rocks into the overlying units. A potentiometric high (875 versus 620 m in the Amargosa Desert) in the Greenwater Range suggests recharge to the local groundwater system, which suggests that a similar local recharge zone may exist in the Funeral Mountains. However, based on the hydrochemical analysis of Winograd and Pearson (1976), Czarnecki (1989) proposed that discharge near Furnace Creek Ranch may be from a deeper, confined system of Paleozoic carbonates, rather than the shallower tuff and alluvium groundwater system.

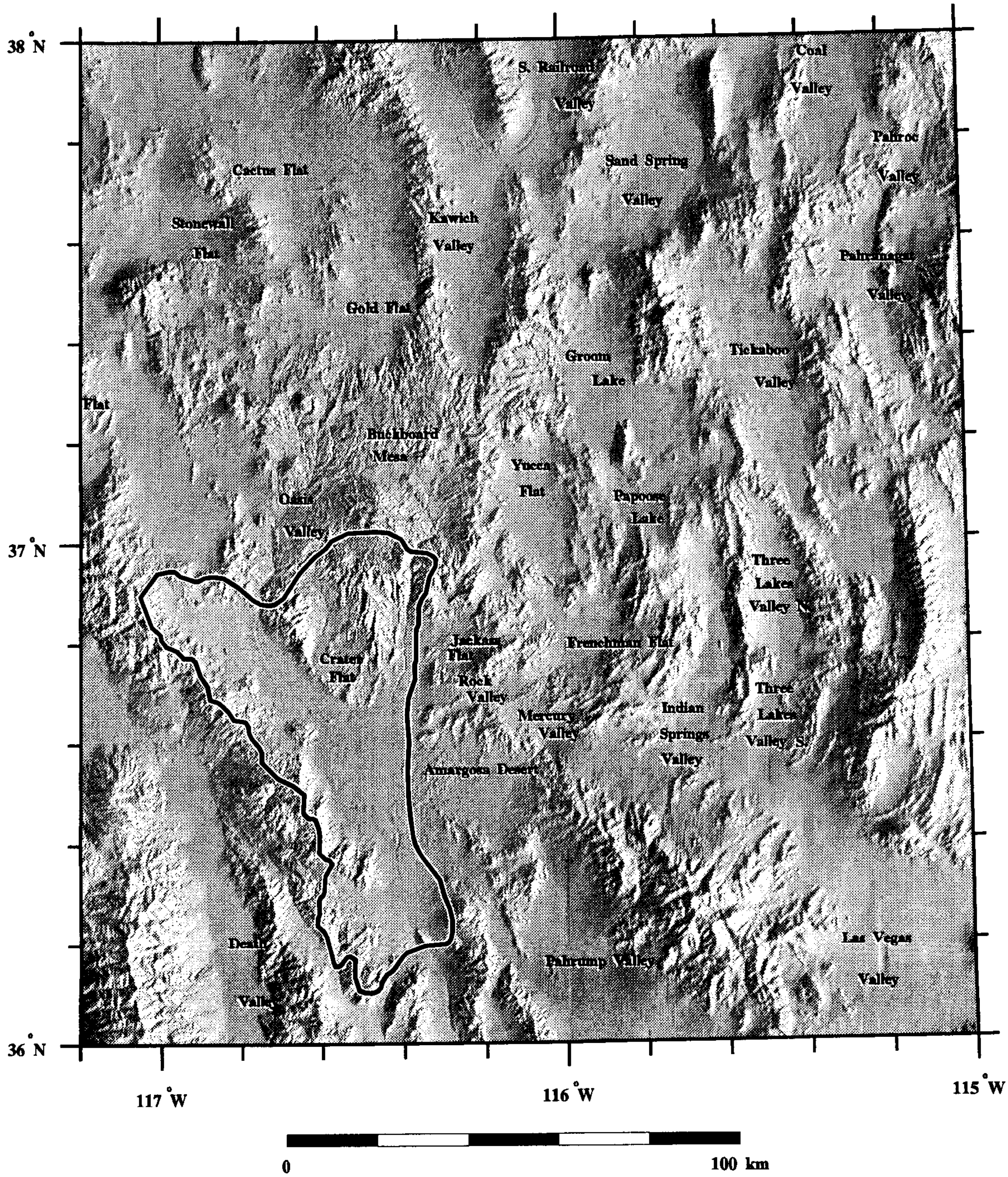

Figure 2-7. Map showing the boundary of the conceptual flow model of Czarnecki (1989)

2.8 FEENEY, CAMPANA, AND JACOBSON (1987)

Feeney et al. (1987) used a discrete state compartment (DSC) model to simulate groundwater flow for a 3,700 km^2 region in the vicinity of the NTS that extends from the highlands of Pahute Mesa south to Ash Meadows. The DSC model does not calculate groundwater flow explicitly; fluxes between cells are indirectly determined by balancing the mass of a conservative tracer. The stable isotope deuterium was chosen as a nonreactive tracer because of the relatively low temperatures of the groundwaters in the vicinity of the NTS.

The hydrogeology of the study area was largely taken form the earlier work of Winograd and Thordarson (1975). Feeney et al. (1987) assumed that three types of lithology controlled groundwater flow: (i) alluvium, (ii) volcanic rocks, and (iii) carbonate rocks. The authors further assumed that within the study area (Figure 2-8) carbonates exist in significant thickness only beneath the Amargosa Desert. Groundwater flow was assumed to be controlled by secondary porosity such as fractures and dissolution features in the volcanic and carbonate rocks, with primary porosity controlling flow through the alluvium. Structural features such as the northwest trending Walker Lane and ring fractures in the caldera complexes are also assumed to control the groundwater to some extent, although it was beyond the intended scope of the modeling to consider these features in a quantitative way.

The area considered by Feeney et al. (1987), roughly equivalent to the Oasis Valley and Alkali Flat-Furnace Creek Ranch sub-basins of Waddell (1982), extends from Pahute Mesa in the north to the Amargosa Desert and Ash Meadows to the south. The southern boundary of the model region runs northwest to southeast, approximately along the Nevada-California state line at the base of the Funeral Mountains. The western boundary of the model is Oasis Valley, and extends to roughly the eastern side of Fortymile Canyon/Wash. The first cell network was based on the transmissivity regions of Waddell (1982), resulting in a 14-cell model. Recharge was considered for Oasis Valley, Pahute Mesa, Fortymile Canyon, Timber Mountain, and the Amargosa Desert. Subsequent iterations reduced the number of cells to improve agreement between model results and the observed δD values. The final model consisted of nine cells, with the boundaries drawn based on field deuterium measurements. A third dimension was investigated by adding another layer of cells, identical in shape to those at the surface, but subsequent sensitivity analysis indicated that the "best" model results were obtained when the communication between the two model layers was rendered insignificant.

Application of a mixing cell model requires an estimate of the water volume of each cell. The saturated thickness, used by Feeney et al. (1987) to calculate the water volume of the cell, was generally assumed to be the total well depth minus depth to water. In the Amargosa Desert, Feeney et al. (1987) had to estimate the saturated thickness using a combination of carbonate (Winograd and Thordarson, 1975) and alluvium (Walker and Eakin, 1963) thicknesses because most water wells in the Amargosa Desert are quite shallow. Effective porosities, another parameter used to calculated water volume, were initially based on the bulk porosity ranges given by Blankennagel and Weir (1973) and Winograd and Thordarson (1975), but during calibration of the model, porosity was varied to produce the best fit to the observed data. The resulting effective porosities were significantly less than bulk porosity for all cells (1 to 3 percent for model-derived effective porosity as compared to 0 to 52 percent for bulk porosity), but Feeney et al. (1987) indicated that the DSC model could not be calibrated assuming higher porosity.

To calibrate the model, Feeney et al. (1987) used observed deuterium data (64 analyses) to assign a steady-state δD value to each cell. Generally the most depleted values were selected on the assumption

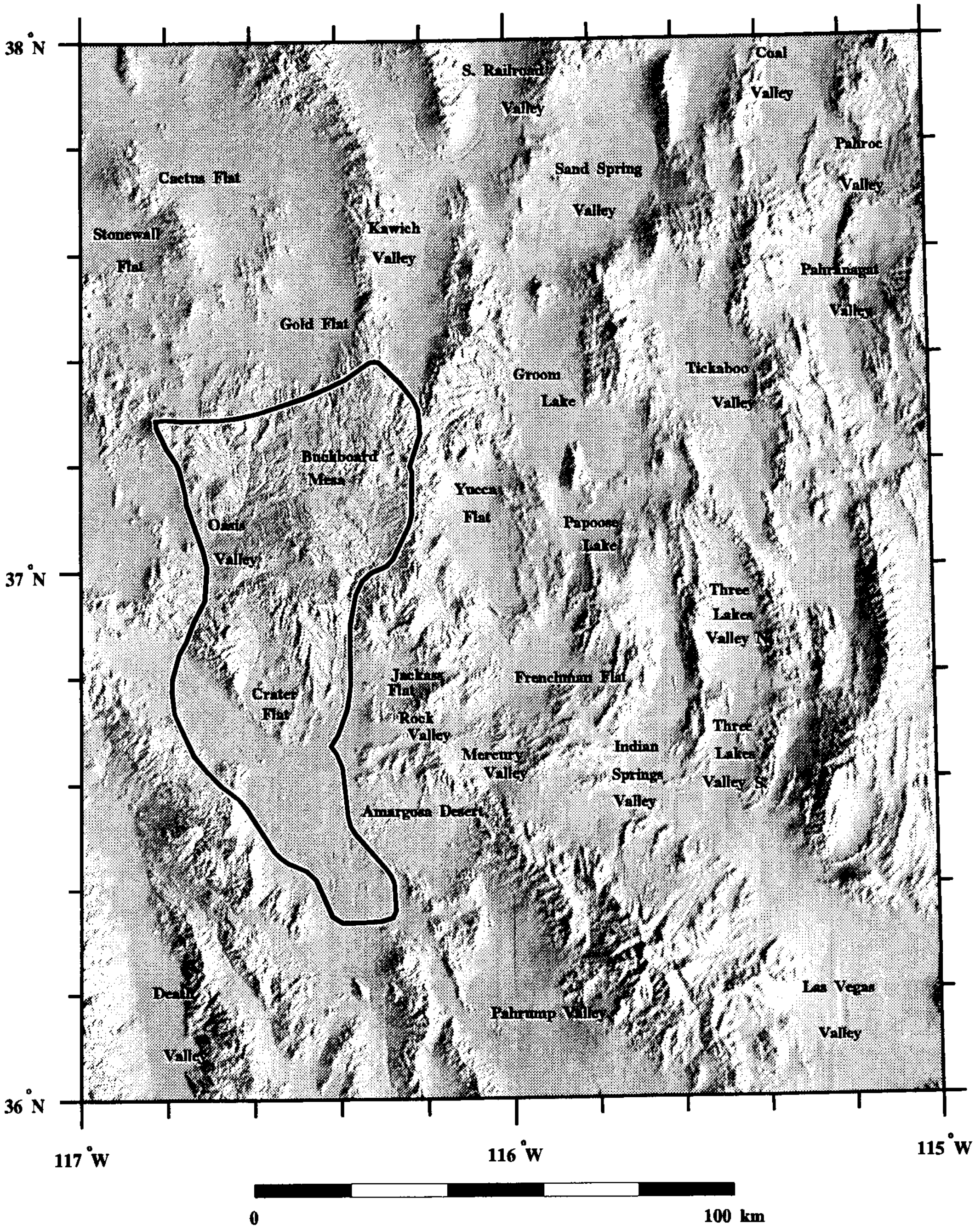

Figure 2-8. Map showing the boundary of the DSC model of Feeney et al. (1987)

that more enriched values represented local effects rather than regional groundwater flow. The most depleted values were found at the higher elevation of Pahute Mesa (−110 to −114‰), generally decreasing to −102 and −104 permil in the two cells representing the Amargosa Desert. Although the two values for Northwestern Amargosa Desert (−102‰) and Southeast Amargosa Desert/Ash Meadows (−104‰) were very close given an analytical uncertainty of ± 1 permil, Feeney et al. (1987) preserved the differences because other geochemical evidence (e.g., Schoff and Moore, 1964) indicated different sources of recharge for these two cells. Based on water sample data from wells J-12 and J-13 in Jackass Flat, Fortymile Wash was assigned a relatively enriched δD value (−97‰). This is thought to be due to the fact that most of the recharge in Fortymile Wash occurs during runoff from summer thunderstorms, which are enriched in deuterium relative to the winter precipitation, which is the primary source of recharge to the regional system.

The DSC mixing cell model also requires a deuterium concentration for recharge to the system. Where possible, recharge values of δD were estimated using data from springs up-gradient of the modeled region. Where such data were not available, values were assigned based on springs at the same latitude thought to receive recharge in the same fashion as the cell (e.g., snowmelt, summer thunderstorms). For recharge in Pahute Mesa and discharge in Ash Meadows, there may be more than one source of fluid input to the cell. For Pahute Mesa recharge may come from deep underflow from Kawich Valley or Gold Flat to the north as well as from precipitation. Because the DSC model in Feeney et al. (1987) only provides for one input value, end-member δD from different recharge sources were assumed to mix in proportion, yielding an average value for input into the model.

After setting up the boundary and initial conditions, the DSC was calibrated by allowing the model to reach steady state and comparing the predicted values against measured δD values. Model results were improved, principally by adjusting the system boundary recharge volumes. Other adjustable model parameters included cell δD and cell volumes as discussed in the preceding paragraph.

Agreement between the model and the observed values is generally exact, except for one of the cells representing the eastern part of Pahute Mesa, where the predicted δD value is 4 permil heavier than the reported value (−110 versus −114‰). The authors proposed that this may be due to isotopically distinct inflow from Kawich Valley that was not accounted for in assigning the recharge δD values for this cell, or precipitation and underflow in different proportions than those assumed in setting up the boundary condition.

Although the DSC approach as implemented by Feeney et al. (1987) cannot distinguish between different types of inflow, for those model cells where system recharge was through vertical recharge of precipitation or runoff alone, estimates of percent of precipitation involved in deep infiltration was made using precipitation estimates of Blankennagel and Weir (1973) and the fluxes calculated by the model. The highest calculated vertical infiltration was for Fortymile Canyon/Wash and Stockade Wash where 5 to 12 percent of the precipitation was estimated to recharge. For Timber Mountain, Crater Flat, and eastern Pahute Mesa, only 1 to 2 percent of available precipitation reached the water table through deep infiltration.

In general, the model results for flow direction and flux rates are consistent with previous work (Blankennagel and Weir, 1973; Czarnecki and Waddell, 1984; Walker and Eakin, 1963). Inflow into the model volume is from Pahute Mesa in the north towards discharge in Ash Meadows in the south. Minor outflow from the model is westward into Oasis Valley from western Pahute Mesa, and eastward into Yucca Flat from Stockade Wash through the Eleana Range. Flow into the Amargosa Desert includes underflow from Pahute Mesa and flow from the Amargosa River and Fortymile Wash. In addition to recharge from underflow through the model, Ash Meadows receives input from the Spring Mountains to the east. The two largest discharge points from the model are at Ash Meadows and underflow beneath the Funeral Mountains towards Death Valley. The model also suggests that there is very little east-west connection between the water system beneath YM/Jackass Flat and Fortymile Canyon/Wash. Instead, most of the outflow from Fortymile Wash is south into the Amargosa Desert.

Feeney et al. (1987) also used the fluxes in the model results to estimate mean ages. Although the ages are in the range of 2,700 (Ash Meadows) to 9,200 yr (Pahute Mesa), the ages were generally considered to be too young due to the restriction requiring an age of zero for recharge. It is likely, however, that some of the underflow into a given cell (e.g., Pahute Mesa, Ash Meadows) may in reality be much older. Feeney et al. (1987) proposed comparing these calculated ages against ^{14}C age dates in future research.

2.9 DETTINGER (1989, 1992)

To evaluate the possibility of developing new water sources for Las Vegas, Dettinger (1989, 1992) provided survey reports of the water resources available in the carbonate aquifers of southern Nevada. In addition to reviewing earlier work done in the region, Dettinger (1989) presented a summary of work done as part of a State of Nevada/U.S. Department of Interior funded program for the study and testing of carbonate-rock aquifers in eastern and southern Nevada. The region of detailed study was limited to the Nevada state boundary south of the latitude of Tonopah and Pioche. The work as presented in Dettinger (1989) is not a groundwater flow modeling study, but describes a general conceptual model of the regional groundwater flow system in southern Nevada. The report emphasizes issues relevant to water resource management including: (i) how much water is in the carbonate aquifer system, (ii) how much water can potentially be produced from the system, and (iii) what are the potential effects of developing these water resources.

Dettinger (1989) focused on a north-south trending "corridor" of Paleozoic carbonate rocks centered under Pahranagat Valley, the Sheep and Spotted Ranges, and the Spring Mountains. Thicknesses of these carbonates range from 910 to 5,800 m with significant variations in thickness and lateral discontinuities due to structural faulting (Tertiary normal faulting, Mesozoic thrust-faulting), stratigraphic thinning, volcanism, and erosion. A zone of low quality water (high TDS) was identified along the eastern margin of the corridor near the Black Mountains and Mormon Mesa. In this area, Permian and younger units with abundant evaporite interbeds are believed to have contributed to saline waters from springs and oil-test wells. Three cross sections based on the work of Scott and Whitney (1987), Guth (1980, 1988), Wright et al. (1981), and Smith et al. (1987) show significant continuous thicknesses of carbonate beneath Coyote Spring Valley, the Pintwater and Spotted Ranges, the Mormon Mountains, the Sheep Range, and Pahrump Valley and the Spring Mountains. Precambrian units crop out in several areas providing barriers to underflow between basins. For example, Cambrian and Precambrian units along the west side of the Sheep Range forces most of the recharge from these mountains to flow to the north and east towards the Muddy River Springs. Flow through the central carbonate corridor is largely focused through high transmissivity along fractures and dissolution features in the carbonates. This type of flow is particularly true near regional springs where aquifers are 25 times more transmissive within a radius of 19 km relative to farther away. Dettinger (1989) proposed that these zones remain transmissive only as long as large volumes of water flow through them, otherwise mineralization will gradually seal the fractures.

The qualitative conceptual model presented by Dettinger (1989) is one of recharge at the higher elevations, with interbasinal flow through the highly transmissive, interconnected carbonates. Interbasinal flow is assumed to be generally from north to south. In addition to recharge in the mountains, there is some underflow from the valleys (especially the White River basin) to the north. Based on earlier work (Scott et al., 1971; Harrill, 1976, 1986; Harrill et al., 1988), Dettinger (1989) reported that average annual recharge in the mountains of southern Nevada to the carbonate corridor is some 1.36×10^8 m^3/yr. The single largest recharge area is in the Spring Mountains, with about 8.9×10^7 m^3/yr of annual recharge into Pahrump Valley, Indian Springs Valley, and at Las Vegas Springs. Regional underflow from east-central Nevada to the north of the study area is about 2.6×10^7 m^3/yr, with 8.6×10^6 m^3/yr of the total flowing south towards discharge at Ash Meadows, and the remaining 1.7×10^7 m^3/yr flowing southeast towards Muddy River Springs (Thomas, 1988). Direct discharge from the carbonate aquifers is through springs, and outflow towards Lake Mead and into carbonates in California. Spring discharge (Hess and Mifflin, 1978; Dettinger, 1989) occurs at Ash Meadows (2.1×10^7 m^3/yr), Rogers Spring (1.5×10^6 m^3/yr), and Muddy River Springs (4.4×10^7 m^3/yr). Regional groundwater outflow is through the Amargosa Desert into California (2.6×10^7 m^3/yr), and towards Lake Mead (2.6×10^6 m^3/yr). To maintain water-balance (assuming steady state), the remaining discharge of about 6.6×10^7 m^3/yr is assumed to be leakage from the carbonates into the basin-fill of alluvium and volcanics, and subsequent discharge through springs, pumping, and ET.

Dettinger (1989) estimated the total amount of water stored in the carbonate aquifers south of Tonopah and Pioche at about 99 million ha-m, assuming an areal extent of about 26,000 km^2 for the carbonates, an average thickness of 3,700 m, and an average connected porosity of 1 percent. In the top 30 m alone, Dettinger (1989) estimated approximately 74,000 ha-m. Production of these stored waters might have adverse effects on discharge in other areas. Dettinger (1989) reported on historical records to discuss the impact of development of the water resources in the carbonate aquifers. Based on water levels at Devils Hole in Ash Meadows, pumping from 1969 to 1972 resulted in about 60 cm of drawdown. After pumping was stopped in 1972, the water level recovered slowly to its former level over 15 yr. However, extensive pumping for irrigation only resulted in minimal changes in the water levels at Muddy River Springs.

Finally, Dettinger (1989) proposed an expanded regional study of the Paleozoic carbonate province extending from Salt Lake City through northern and eastern Nevada into the southern Nevada study region. Described only in a general sense, Dettinger (1989) identified recharge from east-central Nevada moving south, but with a component of outflow to the northeast into Utah. Regional flow in northeastern Nevada was suggested to move eastward toward the Great Salt Lake Desert (Harrill et al., 1988).

For a similar study region to Dettinger (1989), Dettinger (1992) presented a qualitative rating system to identify those geographic units of Rush (1968) within about 160 km (100 mi) of Las Vegas that merited a more detailed study of water resources and potential development. The eight criteria used in this rating system included:

- Interbasinal groundwater flow—the amount of inflow and outflow for a given geographic unit was felt to indicate renewable water resources. Amargosa Desert, Yucca and Frenchman Flats, Mercury, Rock, Indian Springs, Pahranagat, Coyote Spring, Pahrump, and Tikaboo Valleys were all estimated to have significant amounts of interbasinal flow.

- Areal extent of carbonate aquifers—This was difficult to estimate in some areas due to heavy basin and volcanic cover. Some of the extent was inferred from estimates of structural and stratigraphic barriers to groundwater flow.

- Stratigraphic and structural thinning of carbonate units—The thickest original stratigraphic sections of carbonate aquifer were inferred for Pahranagat Valley. Subsequent thickening through Mesozoic thrusting, and thinning into "broken terrain" due to Basin and Range normal faulting were also considered. Under these conditions, the stable terrain in Coyote Spring Valley and Kane Spring Valley were favored.

- Continuity among carbonate units—In evaluating this criterion, Dettinger (1992) considered structural complexity (less complex structures were assumed to be more continuous) and abundance of carbonate in outcrop. Valleys such as Muddy River Springs, Hidden, Garnet, Mesquite, and Three Lakes all ranked high against this criterion. Due to lack of significant carbonate outcrop or complex structure, areas such as Pahranagat Valley, Pahrump Valley, Emigrant Valley, Jackass Flat, and Buckboard Mesa were ranked low.

- Distances to discharge areas and pumping centers—Discharge in the study region was largely confined to a few regional springs (Ash Meadows, Muddy River Springs, Ivanpah Valley, and Hiko, Crystal and Ash Springs in Pahranagat Valley) and a few pumping centers (Las Vegas, Amargosa Desert, Pahrump Valley, and Mesquite Valley). All other regions scored relatively high in this category due to either lack of natural discharge points or low population density.

- Depth to water—The expense of lifting water during development of pumping centers was also considered in the evaluation. In those valleys where natural discharge points are found, a depth of zero was assigned. In all other cases, the maximum depth was about 270 m in Delamar Valley, ranging to less than 15 m in Ivanpah, Jean Lake, and Mesquite Valley. With the exception of Yucca and Frenchman Flats, the deeper levels were in the higher elevation northern valleys, with depth to water decreasing towards the south.

- Groundwater development in basin fill (alluvium, volcanics)—The evaluation of this criterion was based on the State Engineer designation of the different areas. Those areas that were designated as limited due to groundwater mining or for no future development were downgraded in the evaluation. These areas were concentrated in the southern part of the region near Las Vegas and Pahrump Valley. The Amargosa Desert was also designated as a region of groundwater mining.

- Water Quality—Water quality was generally quite good over the entire study region. High dissolved solids, including dissolved sulfate, were reported in the eastern part of the region for Mormon Mesa and the Black Mountains. The NTS was downgraded due to the potential for radionuclide transport from the nuclear testing.

Many of the criteria, such as thickness and complexity of structural relations, were applied in a qualitative sense. Some criteria such as inflow, recharge, and outflow could be quantified based on earlier work. Based on these criteria, seven geographic basins to the north of Las Vegas, Coyote Spring Valley, Three Lakes Valley, Las Vegas Valley (northern), Pahranagat Valley, Indian Springs Valley, Tikaboo Valley, and Delamar Valley, were identified as those regions most favorable for more detailed study.

2.10 BURBEY AND PRUDIC (1991)

Burbey and Prudic (1991) describe the results of a USGS Regional Aquifer-System Analysis (RASA) study conducted to evaluate the hydrogeologic regime of the carbonate rock province of the Great Basin, which extends from Death Valley and Las Vegas in the southwest to southeastern Idaho and Salt Lake City in the northeast and covers an area of 363,000 km^2. The boundaries for this extensive region include the Wasatch Range and Colorado Plateau to the east, and the Snake River drainage divide to the north. The southern boundary is established by the mountain ranges south of Las Vegas, which are primarily composed of Precambrian rock, and the drainage divides for the Colorado and Virgin Rivers. The western boundary of the modeled region is demarcated by the general north-northeast zone of transition from carbonate to clastic rocks. Although most wells in this region tap only the overlying alluvial aquifers, Burbey and Prudic, like previous researchers, assumed that the 17 primary shallow alluvial flow systems within the region are hydraulically connected through the underlying highly transmissive Paleozoic carbonate aquifer. While the depositional thickness of the Paleozoic carbonate units was relatively uniform throughout this vast region, post-depositional compression, extension, as well as the effects of intrusive and volcanic episodes, have greatly altered its thickness and distribution. The continuity of the carbonate aquifer has been further altered by the presence of low-permeability metamorphic core complexes. In developing the general conceptual model for the region, Burbey and Prudic used aeromagnetic and gravity data to infer the location of intrusive bodies and near-surface basement rock that may act as hydraulic barriers. Gravity data were also used to estimate the thickness of alluvial cover within the valleys.

Burbey and Prudic constructed a steady-state, quasi three-dimensional (3D) model of the carbonate province using the USGS MODFLOW computer program. The computational grid consisted of 62 columns aligned from southwest to northeast, 60 northeast to southwest rows, and two layers. Each computational cell was 12.1 km long (aligned southwest to northeast) and 8 km wide. The computational domain was rectangular in shape and had a total area of 361,000 km^2 of which only 238,000 km^2 was included in the computationally active portion of the grid. The upper layer, which represented the basin fill deposits, had an assumed thickness of a 1,000 m. Since MODFLOW uses transmissivity, cell or layer thickness need not be specified. The lower layer was used to account for flow beneath the basin-fill and mountain ranges. In general, the boundaries of the computational model were extended to mountain ranges composed of low permeability material so that no-flow boundary conditions could be imposed. Specific boundaries included: (i) the Snake River drainage divide, which was assumed to be a no flow boundary; (ii) the Great Salt Lake, which was treated as a prescribed head boundary; (iii) the western extent of carbonate province, which was defined as no-flow boundary; (iv) the Sevier and Humbolt Rivers, both treated as head-dependent source boundaries; and (v) the Virgin River, Utah Lake, Lake Mead, and Death Valleys, which were also treated as head-dependent sources or sinks. Recharge to the model was simulated by prescribing a recharge flux at each of the major mountain ranges in the carbonate province. Discharge by ET in marshes and playas was simulated using a head-dependent sink condition from the upper layer, while discharge from regional springs was simulated as a head-dependent sink tapping the lower layer.

Burbey and Prudic (1991) manually calibrated the computational model by adjusting transmissivities until: (i) simulated water levels approximated regional gradients inferred from measured heads, (ii) model estimates of ET matched estimates from other studies, and (iii) simulated spring discharge matched measured discharge. Initial estimates of transmissivities were based on the predominant geology within a computational cell. Three basic hydrogeologic units were assumed: (i) basin fill deposits including Tertiary tuffs, and alluvial and lacustrine deposits; (ii) thick sequences of carbonate rock; and (iii) low permeability volcanics, metamorphic rocks, crystalline rocks, Precambrian basement rocks, and locally thick Tertiary clays and silts. The initial estimates of the transmissivities, based on reported values from other studies, were 2.2×10^{-8} m^2/s for the basin fill, 2.7×10^{-7} m^2/s for the carbonate rocks, and 1.0×10^{-9} m^2/s for the low permeability rocks. The initial vertical leakance coefficient was 1.0×10^{-11} per second. Although the calibration was performed manually, sophisticated routines were developed to estimate the changes required for the cell transmissivities and leakances based on the difference between measured and computed values of heads and discharge.

In summarizing the results of the carbonate province flow model, Burbey and Prudic note that the regional steep hydraulic gradient, which parallels the 36th parallel, is roughly coincident with a particular east-west lineament referred to as the transverse crustal boundary (Eaton, 1975). Burbey and Prudic note that these east-west lineaments tend to be associated with the termination of mountain ranges, stratigraphic discontinuities, mineral belts, caldera boundaries, volcanic boundaries, and aeromagnetic and gravity anomalies. The transverse crustal boundary, which is associated with an abrupt north-south change in elevation of the valley floors from 1,200 to 600 m, and left-lateral shear zones such as the Pahranagat, may also demarcate a zone of low permeability rocks that effects the regional steep gradient. However, Burbey and Prudic also assert that igneous intrusive rocks are more likely to be the cause of the abrupt changes in the head gradients than are the lineaments.

In addition to the 17 shallow flow systems, Burbey and Prudic identified five deep flow regions based on the occurrence of five zones of terminal discharge from the lower layer. The deep regional flow system that discharges in Death Valley includes all or part of eight of the shallow flow systems. As defined by Burbey and Prudic, the Death Valley regional flow system covers an area of 52,000 km^2, which extends from Pahrump Valley and the Shoshone area in the south to Big Smoky Valley in the north, and from Death Valley in the west to the Pintwater and Groom Ranges in the east (Figure 2-9). Most of the recharge to the Death Valley region occurs in the Toiyabe, Toquima, southern Monitor, and Hot Creek Ranges to the north. Of the 1.3×10^{11} m^3 of water that is estimated to recharge the Death Valley system each year, 7.58×10^{10} m^3 is derived from the northern mountain ranges. Because Burbey and Prudic's definition of the Death Valley system does not extend east of the axis of the Groom and Pintwater Ranges, they do not include underflow from Pahranagat Valley or recharge from the Sheep Range as was done in models by Waddell (1982) or Rice (1984). Discharge in the Death Valley system is primarily the result of ET from shallow water tables in wet playas or from spring discharge. Areally distributed ET primarily occurs in northern Big Smoky Valley and northern Clayton Valley, although some ET also occurs in Pahrump Valley, Death Valley, Sarcobatus Flat, and the Amargosa Desert. Spring discharge from the deep carbonate system occurs at Ash Meadows and at Furnace Creek Ranch in Death Valley.

Based on inspection of the simulated flow directions in the Death Valley, Burbey and Prudic inferred the presence of a groundwater divide along the eastern part of Pahute Mesa extending north through the Kawich Valley. This subregional flow system boundary roughly coincides with the boundary between the Oasis Valley-Fortymile Canyon system to the west and the Ash Meadows system to the east, as defined by Winograd and Thordarson (1975). However, the Ash Meadows flow system as delineated by Burbey and Prudic differs significantly from that of Winograd and Thordarson (1975) in that its eastern boundary is coincident with the axis of the Pintwater and Groom Ranges rather than the Sheep and Pahranagat Ranges, which lie approximately 50 km farther to the east. According to Burbey and Prudic, water discharged at Ash Meadows is primarily derived from recharge that occurs in the mountain ranges

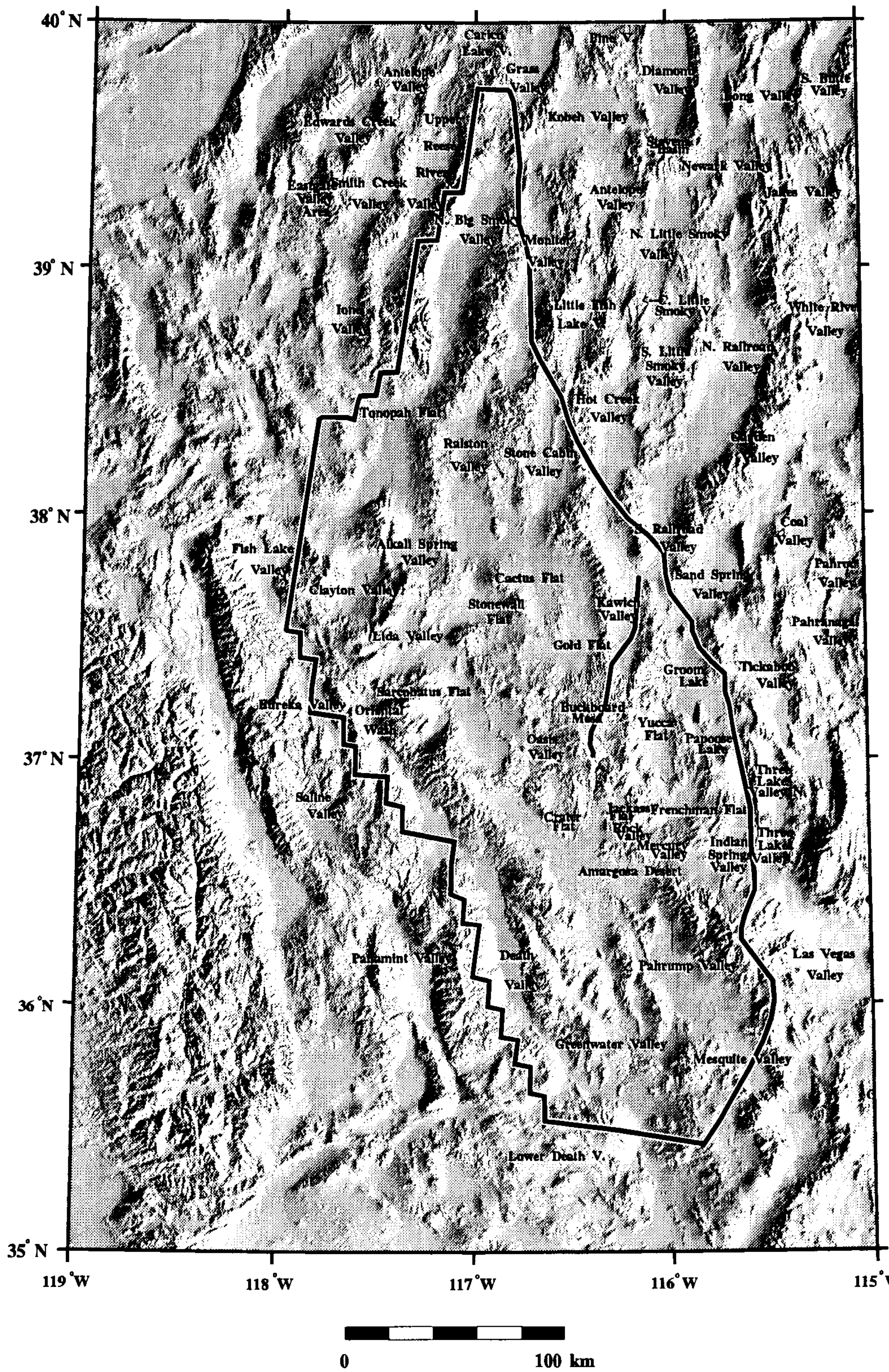

Figure 2-9. Map showing the general region and boundary for the Death Valley flow model of Burbey and Prudic (1991). The north-south line segment running from Jackass Flat to Kawich Valley represents an inferred groundwater divide.

in the eastern portion of the NTS. An additional 2.37×10^9 m^3 of water is simulated to enter the Ash Meadows system as underflow from the southern Hot Creek and Monitor Ranges, and 3.16×10^9 m^3 is derived from the Spring Mountains annually.

Two aspects of Burbey and Prudic's model distinguish it from most other conceptual models of the Death Valley flow system: (i) the northern extension of the system boundary to include recharge from the Toiyabe, Toquima, Monitor, and Hot Creek Ranges; and (ii) the placement of the eastern boundary along the axes of the Pintwater and Groom Ranges rather than the Sheep and Pahranagat Ranges, which lie 50 km farther to the east. The authors did not discuss the implications of the extreme northern extent of their system, but they did conduct additional model simulations to investigate the effects of altering hydrogeologic properties along the eastern boundary. The apparent groundwater divide that coincides with the Groom and Pintwater Ranges is probably caused by the simulated recharge mound beneath the Spring Mountains, which inhibits direct, southward flow. This recharge mound diverts flow either to the southeast into the Colorado River region or to the southwest toward Death Valley. In effect, the Spring Mountain recharge mound produces a north-trending ridge of high hydraulic potential that happens to be coincident with the axes of the Pintwater and Groom Ranges. Because the paucity of hydraulic head data in the area of the Pintwater and Groom Ranges required calibration target heads to be interpolated from surrounding areas, this groundwater divide may be an artifact of the interpolation process. Burbey and Prudic note that the presence of low permeability Precambrian rock outcrops in the Desert Range to the east, as well as higher heads measured in Three Lakes Valley also located to the east, suggest that the groundwater divide may instead be located along the axis of the Desert Range. Burbey and Prudic tested several alternative hydrogeologic models to see if the resulting flow field could be made to conform to earlier conceptual models. Lowering the transmissivity east of the Sheep Range did induce westward flow. However, the groundwater divide was moved eastward only to the Desert Range. Increasing transmissivities to the west of the Sheep Range did initiate westward flow, but also caused water levels to rise to the surface in Frenchman and Yucca Flats. It was postulated that the use of very small transmissivities along the Las Vegas shear zone would push the Spring Mountain recharge mound to the south, which would in turn remove the mound under the Pintwater Range and permit westward flow from the Sheep Range. However, while the Spring Mountain recharge mound was moved to the south, significant westward flow did not occur until the transmissivities north of the shear zone between Yucca Flat and Pahranagat Valley were greatly increased. Although this last change did induce underflow from Pahranagat Valley to the Ash Meadows subregion, the groundwater divide was still located to the west of the Sheep Range. Further testing of the model was limited by: (i) the sparsity of head data in the region east of Yucca Fault, west of the Sheep Range, and north of the Spring Mountains; (ii) lack of understanding of the hydraulic properties of the Las Vegas shear zone; (iii) uncertainty about the possible westward extension of the Pahranagat shear zone, and (iv) uncertainty regarding the role played by the Precambrian units in the Desert Range and west of the Sheep Range.

2.11 AHOLA AND SAGAR (1992)

Ahola and Sagar (1992) developed a 2D unconfined flow model of the Death Valley groundwater flow system that was based on the conceptual flow models of Rice (1984) and Waddell (1982). A 2D planar finite-difference grid was constructed for the 40,000 km^2 area that consisted of 13,161 computational cells, each of which was 2.5 km on a side. Boundary conditions specified along the irregularly-shaped boundary (Figure 2-5) consisted of either prescribed heads or no-flow conditions as given by Rice (1984). Within the interior of the flow domain, no-flow conditions were imposed by setting the corresponding directional permeabilities to very small values.

Unlike Rice (1984), Ahola and Sagar (1992) assumed that the flow regime was unconfined and employed a numerical model that explicitly incorporated the free surface boundary condition. Hydraulic conductivities for the model were estimated by dividing the transmissivity values obtained by Rice (1984) by an assumed uniform saturated thickness of 1,000 m. The hydraulic conductivity zones used by Ahola and Sagar were generally based on the transmissivity zonation used by Rice (1984), although several of the smaller transmissivity zones were merged where a more detailed model parameter structure did not appear to affect the regional flow patterns. Hydraulic conductivity values ranged from 5.8×10^{-8} m/s in the low permeability area north of YM to 3.5×10^{-3} m/s in the Ash Meadows area. High hydraulic conductivity values were also used where water level contours indicated relatively flat hydraulic gradients within Jackass Flat, Frenchman Flat, Indian Springs Valley, and Three Lakes Valley.

Areas where the water table is shallow and discharge occurs by direct ET through the vadose zone, such as at Franklin Lake Playa in the southern Amargosa Desert, were modeled using prescribed head conditions. Recharge in the higher elevations areas of the Spring Mountains, Sheep Range, Pahranagat Range, Kawich Range, and Pahute Mesa was modeled using prescribed flux conditions. Ahola and Sagar (1992) did not calibrate their flow model, since the hydraulic conductivity values, boundary conditions, and recharge and discharge values were extracted directly from the model of Rice (1984), which had been calibrated.

The primary purpose of Ahola and Sagar's modeling study was to assess the effects of increasing recharge, disrupting the hydraulic barrier that causes the steep hydraulic gradient, and emplacing intrusive bodies, such as dikes or sills on the flow regime at YM. Within the immediate vicinity of YM, Ahola and Sagar (1992) found that ten-fold, twenty-fold, and thirty-fold increases in recharge led to water table rises of approximately 40, 85, and 125 m, respectively. These increased recharge scenarios were conducted using a transient analysis, from which the authors determined that maximum water table rises did not occur until 400 to 700 yr after recharge was increased. Additional analyses were conducted to assess the effects of increasing recharge not only in the higher elevation areas, but also along Fortymile Wash to the east of YM. Increasing recharge in the highlands and Fortymile Wash by a factor of 10 led to a water table rise in the YM area of between 75 to 100 m. Raising the level of the primary discharge area for YM at Franklin Lake Playa by 10 m caused only a 3 m water table rise beneath YM.

Ahola and Sagar (1992) also investigated the changes to the YM hydraulic regime caused by the emplacement of a 20 km long, east-west oriented volcanic sill located to the southeast of YM. The region chosen for the volcanic sill coincides with a high permeability zone through which much of the groundwater flow from Yucca and Frenchman Flats is channelled toward Ash Meadows. Simulations conducted by Ahola and Sagar (1992) suggested that the water table at YM may rise from 175 to 200 m under ambient climatic conditions in response to the emplacement of this sill.

Ahola and Sagar also conducted flow simulations to investigate changes to the water table at YM that may occur from neotectonic disruption of the presumed structural feature that causes the steep hydraulic gradient at the north end of the proposed repository. Under ambient conditions this structural feature was assumed to effect a dramatic decrease in the permeability along an east-west transect located at the northern end of YM. When the permeability was increased, simulated water levels rose 275 m beneath YM and fell 300 m in the vicinity of Pahute Mesa.

Ahola and Sagar (1992) conducted additional simulations using a subregional-scale model centered on YM, which was extracted from the larger regional-scale model. This rectangular subregion, which was 50 km on a side, used a computational grid that was coarse near the boundaries and refined in the center near YM. Boundary conditions for all four sides of the subregional model consisted of prescribed heads obtained from the regional model. This subregional-scale flow model was used to simulate the hydraulic effects of volcanic dikes of varying orientation. Based on the regional tectonic regime the preferred orientation for possible basaltic dikes is N 15° E. A single 4 km dike emplaced at this orientation through the repository area resulted in a rise in the water table of 79.3 m. When a second 4 km dike was emplaced at right angles to the first the water table rose a total of 103.4 m. Eight additional single-dike intrusion scenarios at various orientations and locations were also considered, but all of these simulations resulted in smaller water table rises.

2.12 SADLER, CAMPANA, JACOBSON, AND INGRAHAM (1992)

Using the techniques described by Feeney et al. (1987), Sadler et al. (1992) developed a more detailed mixing cell model calibrated with hydrogen isotope (deuterium) data for the hydrogeologic regime of the Death Valley Flow system. The modeled region is much larger (19,000 km^2) than the earlier mixing cell model of Feeney et al. (1987). The southern and western boundaries of the modeled area (Figure 2-10) were taken from Waddell et al. (1984) for groundwater basins in southern Nevada. The northern and eastern boundaries correspond to those of the model of Harrill et al. (1988) for the Death Valley System. However, calibration of the model using deuterium data indicated small input from southern Railroad Valley to Kawich Valley. Therefore, the boundary from the Harrill et al. (1988) model was modified to exclude southern Railroad Valley from the northern edge.

Review of over 300 deuterium measurements on groundwater and precipitation samples revealed that young waters (e.g., precipitation and upland spring waters) with δD values generally between −92 and −101 permil are less depleted than groundwater in the regional (interbasin) groundwater system with δD generally between −99 and −117 permil. These data were interpreted to imply that the regional groundwater was recharged under different climatic conditions in the past and/or that it was recharged outside the boundaries of the modeled system. The data also indicate decreasing deuterium depletion from northwest to southeast, with increasing depletion with elevation in surface water in the Spring Mountains. The discrete cell model was developed assuming underflow of deuterium depleted water into the system from the north and northeast with gradual deuterium enrichment by mixing with local recharge.

The regional system was divided into 30 cells in one horizontal layer based on conventional hydrogeologic criteria from the literature and deuterium data. Each cell has similar hydrogeological conditions and deuterium values. Where data permitted, each cell was assigned a regional and/or a surface recharge value of δD.

Recharge was introduced in areas of high elevation and discharge placed at mapped discharge areas. Initial estimates of recharge were based on elevation distribution within each cell, precipitation distribution, and the Maxey-Eakin recharge estimation method. The study focused on regional flow systems discharging at southern Amargosa Desert (Ash Meadows and Franklin Lake Playa), Death Valley, and Oasis Valley, and the local groundwater flow system discharging at Indian Springs Valley.

Potentiometric and transmissivity maps in the literature were used to estimate flow routing and flow rates between cells. The system boundary was open to input by underflow from the north and east. For each cell receiving underflow a deuterium value was assigned corresponding to the most depleted measurement observed in the cell. The system boundary was also assumed to be open to ET in discharge areas and to outflow toward Death Valley on the northwest and southwest sides.

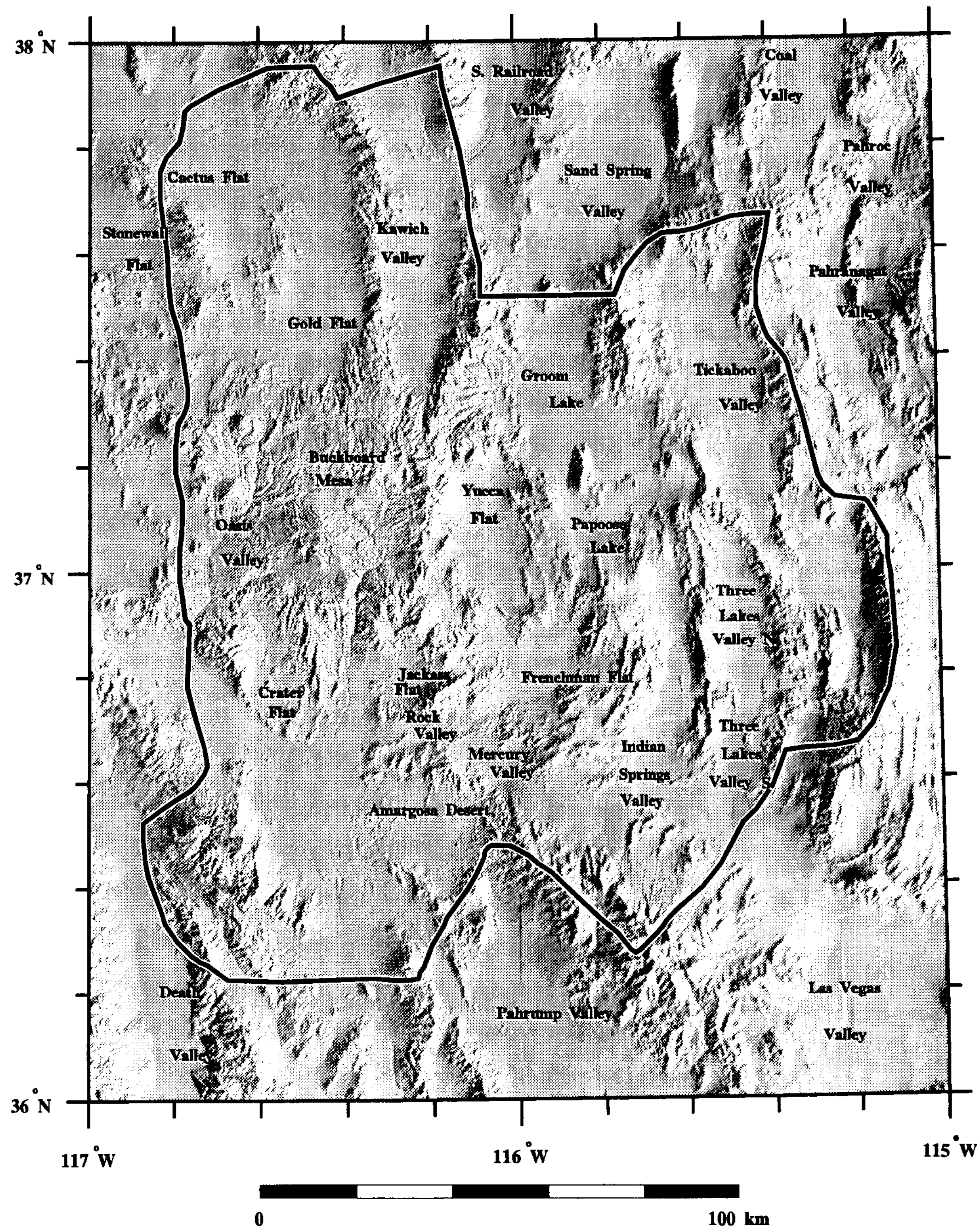

Figure 2-10. Map showing the boundary of the DSC model of Sadler et al. (1992)

Given initial estimates for surface recharge, flow directions, and flow rates, the model was calibrated by adjusting horizontal regional flow volumes and surface recharge to reproduce regional δD values by mixing recharge with throughflow. Several basic conclusions were derived from the modeling. A large amount of throughflow relative to recharge is required to maintain the depleted deuterium values in the regional aquifer; 43 percent of flow in the model was underflow through the system. Absolute recharge and throughflow values are not constrained by the deuterium values, only their ratio. Much of the area requires little or no recharge to match regional deuterium values. However, significant recharge is required along the axis of Fortymile Canyon to account for relatively enriched deuterium values. In contrast, the initial recharge estimation technique indicated minimal recharge in this area.

3 SUMMARY AND COMPARISON OF EXISTING CONCEPTUAL MODELS AND IMPLICATIONS FOR YUCCA MOUNTAIN

As was described in Section 1.2, the primary purpose of this review is to summarize the current understanding of the Death Valley flow system, and to examine in detail the hydrogeologic features incorporated into each conceptual model that are likely to have a significant effect on the saturated flow regime beneath YM. YM has been proposed as a HLW repository because of the favorable geochemical and hydrologic conditions provided by its 700-m unsaturated zone. Favorable hydrologic conditions would be compromised by an increase in the water table elevation, which may significantly reduce the thickness of the unsaturated zone below the repository. Presently, the saturated zone lies approximately 300 m below the proposed repository. The water table may rise in response to: (i) increased recharge in the mountains ranges to the north, and (ii) disruption of Mesozoic thrust faults or Tertiary normal faults that control both the regional steep hydraulic gradient and the steep gradient located at the north end of the proposed repository. There is evidence [Paces et al. (1993), Marshall et al. (1993), Quade (1994)] that the water table has been between 85 to 115 m higher in the past. Fluctuations in the apparent water table elevation correlate well with the geochronological record, suggesting that they are the result of long-term cycling between cool-wet and warm-dry climates. Czarnecki (1985) estimated, that if precipitation in the Death Valley region were to double, recharge would be increased by a factor of 15 and cause the water table beneath YM to rise 115 m and produce new areas of discharge along Fortymile Wash. Several researchers have developed hypotheses regarding the cause of the local steep hydraulic gradient north of YM and the regional steep hydraulic gradient, which runs from northeast of Bare Mountain, eastward under YM, across Shoshone Mountain, north along the Eleana Range to Oak Spring Butte, and eastward near the Groom Range [Czarnecki (1989), Fridrich et al. (1994), Wittmeyer et al. (1995b)]. Numerical modeling studies performed by Ahola and Sagar (1992) suggest that disruption of the hypothetical hydraulic barrier responsible for the steep hydraulic gradient may induce a water table rise of 275 m beneath YM. Because the model of Ahola and Sagar (1992) did not account for attenuation of the vertical rise of the water table due to creation of new surface discharge areas along Fortymile Wash or within Crater and Jackass Flat, the actual water table rise would probably be less than predicted.

The recently released National Academy of Sciences (NAS) (National Research Council, 1995) report on the development of a performance standard for YM recommends that the Environmental Protection Agency (EPA) replace the current release-based standard with a standard based on the risk to a critical group of individuals of adverse health effects from released radionuclides. Findings outlined in the NAS report indicate that peak risk may not occur until several tens to hundreds of thousands of years after closure of the repository. The saturated flow regime may play a significant role in forming estimates of repository performance in accordance with the proposed NAS recommendation for at least two reasons. First, dose-to-man calculations must include the dose received via radionuclide contaminated water which is either pumped from the fractured tuff aquifer or is discharged to a surface water body, such as Franklin Lake Playa. Clearly, the drinking water dose will be affected by the transport properties of the tuff aquifer and perhaps the lower carbonate aquifer. Second, extending the risk-based analysis to a performance period of a million years or more would require accounting of climatic cycles which include a cooler-wetter full glacial climate. Performance assessment models of flow and transport in the saturated zone would be required to simulate the effects of increased recharge under a full-glacial pluvial climate on: (i) the direction of flow beneath the repository, and (ii) the corresponding travel time and mixing potential.

While a conceptual model of the saturated flow system that is suitable for assessing the long-term safety of the proposed repository has not yet been synthesized from the suite of models reviewed here, it is possible to identify attributes of these models that have the potential to affect performance predictions. With the ultimate focus of this research being the saturated flow regime at YM, it is necessary to understand how YM fits into the regional flow regime described by these models. Some of the models reviewed in Section 2 are focused specifically on YM, while others describe the flow system for the NTS, the Death Valley system, or the carbonate province.

3.1 COMPARISON OF THE ALTERNATIVE CONCEPTUAL MODELS OF THE DEATH VALLEY AND YUCCA MOUNTAIN GROUNDWATER FLOW SYSTEMS

The conceptual flow models reviewed in Section 2 can be classified by the region, area or sub-basin considered. Three scales based on the region, area, or sub-basin of interest can be identified: (i) hydrogeographic province scale, (ii) regional groundwater flow system scale, and (iii) groundwater basin scale. The hydrogeographic province scale refers to those studies which consider all or part of the carbonate province of eastern Nevada, western Utah, and southeasternmost Idaho. Hydrogeographic province scale models include those of Dettinger (1989, 1992) and Burbey and Prudic (1991). Mifflin (1968) defines a regional groundwater flow system to be "...a large ground-water flow system which encompasses one or more topographic basins...[and]...may include within its boundaries several ground-water basins." Studies by Rush (1970), Winograd and Thordarson (1975), Waddell (1982), Rice (1984), Ahola and Sagar (1992), and Sadler et al. (1992) were focused on the Death Valley regional groundwater flow system. As defined by Mifflin, a groundwater basin usually represents "...only a part of ground-water system," but may include "...more than one [regional or local] ground-water flow system." Investigations by Czarnecki and Waddell (1984), and Czarnecki (1985, 1989), were focused on the YM and Amargosa Desert basins, while Feeney et al. (1987) developed a model for the western portion of the NTS. Table 3-1 shows the geographic setting and the area of the region considered in each of the studies reviewed in Section 2.

While the groundwater basin scale models reviewed here allow the hydrogeologist to define accurately the hydrogeologic setting of YM, and to assess precisely the effects of increased recharge or neotectonic disruption on the water table beneath YM, somewhat artificial boundary conditions must be imposed to adequately match predicted to measured head contours. For example, Czarnecki and Waddell (1984) imposed a prescribed head condition at Timber Mountain to account for recharge to the YM groundwater system from the Pahute Mesa area, although there are no surface water features that could impose a constant head. Similarly, regional scale models by Waddell (1982) and Rice (1984) used prescribed flux boundary condition to incorporate the effects of underflow from Pahranagat valley to the Ash Meadows sub-basin. The Death Valley groundwater flow system is composed of a number of topographically closed basins that are hydraulically connected at depth by the highly transmissive Paleozoic carbonate aquifer. The physical extent of the Death Valley system can be precisely defined if a boundary across which no water is transported can be delineated. If these zero-flux boundaries can be identified, the nature of the hydrogeologic regime can be largely determined by the location of internal recharge and discharge zones. Hydrogeographic province scale models, such as those by Dettinger (1989, 1992) and Burbey and Prudic (1991), are of great enough areal extent that their boundaries can be located along zero-flux, regional groundwater system divides. As such, hydrogeographic province scale models can be used to directly assess the effects of increased or decreased recharge on the water levels throughout the region.

Table 3-1. Hydrogeologic study areas

Hydrogeologic Study	Geographic Setting	Specified Boundaries	Setting Area (km^2)
Czarnecki and Waddell (1984)	YM/NTS	Yes	3,000
Czarnecki (1985)	YM/NTS	Yes	3,000
Feeney et al. (1987)	Western NTS	Yes	3,740
Czarnecki (1989)	YM/NTS Amargosa Desert	Yes	4,900
Schoff and Moore (1964)	NTS	No	NA
Winograd and Thordarson (1975)	Death Valley/NTS	Yes	11,700
Rush (1970)	Death Valley/NTS	Yes	17,000
Waddell (1982)	Death Valley/NTS	Yes	18,000
Sadler et al. (1992)	Death Valley	Yes	19,000
Dettinger (1989,1992)	Carbonate Province of Nevada	No	NA
Rice (1984) and Ahola and Sagar (1992)	Death Valley	Yes	41,000
Burbey and Prudic (1991)	Carbonate Province/Death Valley	Yes	52,000

In several of the studies, separate groundwater sub-basins or subsystems were delineated on the basis of distinct water chemistry or the presence groundwater divides inferred from potentiometric data. Rush (1970) identified the Ash Meadows, Pahute Mesa, and Sarcobatus Flat sub-basins. The boundaries of these sub-basins (Figure 2-2) indicate that YM lies within Rush's Pahute Mesa sub-basin. Winograd and Thordarson (1975) identified the Ash Meadows, and Oasis Valley-Fortymile Canyon sub-basins (Figure 2-3). Winograd and Thordarson did not delineate the boundaries of the Oasis Valley-Fortymile Canyon sub-basin; however, it appears that YM must lie within this flow system. As noted in Section 2.4, Waddell (1982) identified the Ash Meadows, Alkali Flat-Furnace Creek Ranch, and Oasis Valley sub-basins by the locations of principal discharge areas (Figure 2-4). YM lies within Waddell's Alkali Flat-Furnace Creek Ranch sub-basin. Later modeling studies of the YM saturated flow regime by Czarnecki and Waddell (1984) and Czarnecki (1985) considered the central portion of Waddell's Alkali Flat-Furnace Creek Ranch sub-basin (Figure 2-6). This YM subregion extends from Timber Mountain south to the Furnace Creek Ranch discharge area in Death Valley, and excludes the northwest arm of Frenchman Flat. The western NTS subregional flow system considered in the DSC model developed by Feeney et al. (1987) includes the YM area and appears to be roughly coincident with Waddell's Alkali Flat-Furnace Creek Ranch sub-basin (Figure 2-8). However, rather than being extended to the Furnace Creek Ranch discharge area in Death Valley, the model constructed by Feeney et al. (1987) terminates immediately to the west of the Ash Meadows area. The YM subregional system considered by Czarnecki (1989) extended the western boundary of the region delineated by Czarnecki and Waddell (1984) to include the northern Amargosa Desert, but excluded eastern Jackass Flat and Rock Valley (Figure 2-7).

Additional hydraulic head data obtained from mining company boreholes in the Greenwater range indicated a groundwater divide between the southern Amargosa Desert and Death Valley. On the basis of this groundwater divide, Czarnecki (1989) hypothesized that the primary discharge area for the Alkali Flat-Furnace Creek Ranch sub-basin is Franklin Lake Playa (Alkali Flat) and therefore elected to exclude the Furnace Creek Ranch discharge area from his conceptual model. Burbey and Prudic (1991) infer the presence of a groundwater divide that parallels eastern Pahute Mesa and extends north through Kawich Valley (Figure 2-9). Although this Pahute Mesa flow boundary extends only as far south as Timber Mountain in Figure 2-9, it appears that YM lies to the west when this boundary is extrapolated farther to the south. Burbey and Prudic's groundwater divide appears to closely follow the boundary between Waddell's Alkali Flat-Furnace Creek Ranch and Ash Meadows sub-basins.

For those conceptual and mathematical models which either subdivide the Death Valley system into sub-basins or explicitly consider the saturated zone setting of YM, it is apparent that YM is always included in the sub-basin that discharges at Franklin Lake Playa in southern Amargosa Desert rather than in the sub-basin discharging at Ash Meadows. However, the northern extent of these conceptual models vary greatly and extend from as close as Timber Mountain (Czarnecki and Waddell, 1984) to as far away as Big Smoky Valley (Burbey and Prudic, 1991), which is bounded on the east and west by the Toquima and Toiyabe ranges, respectively. Those conceptual models that include the more northern mountain ranges in the YM saturated zone setting imply increased sub-basin recharge due to the general increase in altitude and precipitation from south to north. Burbey and Prudic's (1991) model suggests that as much as 58 percent of the total recharge to the Death Valley regional flow system occurs in the Toiyabe, Toquima, southern Monitor, and Hot Creek Ranges. However, it is not clear if increased recharge to the YM saturated zone setting implies that north to south flow in the tuff or carbonate aquifers beneath YM is also increased.

3.2 IMPLICATIONS FOR WATER TABLE RISE DUE TO INCREASED RECHARGE

As noted earlier, there is abundant evidence that the water table in the Death Valley regional flow system, including the immediate YM vicinity, has been higher in the past. Winograd and Szabo (1986) performed uranium-series disequilibrium dating of calcitic veins located at elevations as much as 50 m above the present water table in Ash Meadows and Amargosa Flat, and as much as 200 to 600 m above the present water table in Furnace Creek Wash. Apparent ages of the youngest laminae deposited in these veins ranged from 510 ka in Ash Meadows to more than 1,000 ka at Furnace Creek Wash. Assuming that the water table has declined at a constant rate during the middle and late Pleistocene, Winograd and Szabo estimated that rates of water table decline range from 0.03 to 0.08 m/1,000 yr in Ash Meadows and Amargosa Flat, to 0.2 to 0.6 m/1,000 yr in Furnace Creek Wash. Rates of crustal offset estimated by Carr (1984) for the Black Mountains suggest that tectonic uplift may explain the high apparent water table decline rates observed in Furnace Creek Wash. However, crustal offset in the Ash Meadows area indicates that tectonic uplift in the Ash Meadows area is less than half of the apparent rate of water table decline. Winograd and Szabo (1986) note that climate change during the Pliocene and Quaternary may partially explain the apparent water table decline. The Sierra Nevada are estimated to have been uplifted 950 m during the past 3 million years, which would have caused a marked decrease in the precipitation in the southern Great Basin due to the increased rain shadow effect.

Paces et al. (1993) examined uranium compositions of carbonate-rich material from three fossil spring deposits located in the southern end of Crater Flat and near the town of Amargosa Valley (Lathrop

Wells). Uranium and Thorium isotopic analyses of samples taken from the Quaternary Crater Flat and Horse Tooth deposits indicate that discharge occurred at 18±1, 30±3, and 45±4 ka. Uranium-series isotopic evolution patterns indicate that the carbonates precipitated from the groundwater discharging at these sites is isotopically distinct from pedogenic carbonates and probably originated from the Tertiary tuff aquifer. The $^{234}U/^{238}U$ measurements appear to preclude the possibility of significant addition of surface waters from Crater Flat to the paludal environment during pluvial periods. The ages of the deposits were also found to correlate well with dated high water stands in Brown's Room in Devil's Hole. Present-day water surface elevations range from 713 to 719 m at the Horse Tooth deposit to 716 to 734 m at the Crater Flat deposit, which indicate present-day depths to water of 79 to 85 m and 98 to 116 m, respectively. Based on the present water table configuration between YM and southern Crater Flat, Paces et al. (1993) estimated that the water table beneath the proposed repository would have been 80 to 115 m higher. Inasmuch as similar spring deposits have not been found at higher elevations within the vicinity of YM, Paces et al. (1993) concluded that these spring deposits reflect the maximum water surface elevation attained during the past 45,000 yr.

Quade (1994) studied the sedimentologic and paleontologic characteristics of fine-grained paludal deposits from Three Lakes Valley and Indian Springs Valley, as well as from six other areas outside of the Death Valley regional groundwater system. Valley cross sections show that gravels on the upper portions of alluvial fans abruptly grade into fine grained sediments where phreatophyte growth prevents transport of coarse materials to the valley bottom. Because phreatophyte growth is initiated where the depth to water is less than 6 to 7 m below the surface, the abrupt transition to fine-grained sediments can be used to reconstruct the position of the water table during the last full-glacial period (17 ka). The areas of phreatophyte growth grade downslope into pale-green to white muds, which accumulate in wet meadows and marshes. Accordingly, the presence of mudstone also can be used to mark the elevation of the water table during the full-glacial period. The presence of full-glacial marsh deposits in southern Three Lakes Valley and western Indian Springs Valley indicate that water levels were 30 to 40 m, and 60 to 70 m higher, respectively. Although Three Lakes and Indian Springs Valleys are part of the Death Valley regional flow system, the configuration of the last full-glacial water table was not projected north-northwest to YM. Quade (1994) also used radiocarbon dating to determine the age of organic-rich black mats, which, in some of the spring deposits, overlie the green clay indicative of the full-glacial period. The ^{14}C ages of the black mats, which cluster around 10 to 11 ka, support the stratigraphic evidence that they postdate the full-glacial (17 ka). Quade (1994) believes that these black mats indicate renewed spring discharge in response to the Younger Dryas cooling event. Moreover, the strong correlation of the ^{14}C ages of the black mats with accurately determined ages of the Younger Dryas event obtained from Greenland ice cores, led Quade to infer that the aquifers that discharged in these meadows responded very rapidly (10's to a few 100's of years) to increased recharge. The work of Quade et al. (1995) elaborates in much greater detail the sedimentologic and paleontologic analyses used to reconstruct the habitat of the southern Great Basin spring deposits; however, the conclusions reached in this paper are substantially the same as those of Quade (1994).

Within the Alkali Flat-Furnace Creek Ranch sub-basin evidence of higher past water levels consists of the Quaternary Crater Flat and Horse Tooth fossil spring deposits and the mid to late Pleistocene calcitic vein deposits in Furnace Creek Wash. The Furnace Creek Wash vein deposits may reflect crustal offset rather than water table decline. However, there does not appear to be evidence of a water table rise associated with the Younger Dryas cooling event within this sub-basin. The height of water table rise under conditions of increased recharge depends upon many factors including: (i) the magnitude of recharge, (ii) the spatial extent of the recharge area, (iii) the duration of the period of increased recharge, (iv) the absolute values of transmissivity throughout the Alkali Flat-Furnace Creek

Ranch sub-basin, (v) the capacitance or storativity of the aquifers, (vi) the diffusivity of the aquifers, (vii) spatio-temporal changes in extent and location of discharge zones, and (viii) the lateral and vertical extent of the sub-basin. Unfortunately, these factors will likely prove to be difficult to quantify throughout the system. Moreover, where hydraulic data make it is possible to quantify the forcing functions and parameters of the flow system, interpolated and extrapolated numerical estimates may be very uncertain. Future climate scenarios, including estimates of precipitation during full-glacial periods, can be inferred from past climates, which may be determined by reconstructing past vegetation from plant macrofossils preserved in packrat middens (Spaulding, 1985). However, precipitation estimates cannot be directly used to determine recharge except by conducting detailed water budget studies in groundwater basins with analogous climatic and hydrogeologic regimes. Czarnecki (1985) used Huntington Valley in northern Nevada as an analog to the Alkali Flat-Furnace Creek Ranch sub-basin under a full-glacial climate and estimated that a doubling of precipitation would lead to a 15-fold increase in recharge. The duration of future full-glacial pluvial periods in the Death Valley region may, perhaps, be estimated by applying the various dating methods outlined in Spaulding (1985), Paces et al. (1993), Quade (1994), and Quade et al. (1995). Transmissivity, storativity, and aquifer diffusivity can be estimated from pump tests; however, the expense of drilling boreholes and conducting tests in deep aquifers greatly limits the areal coverage that can be obtained. The hydraulic properties of the aquifers can also be estimated from the spatio-temporal distribution of measured heads using inverse methods; however, absolute values of transmissivity cannot be obtained unless independent estimates of recharge or discharge rates are available. The work of Paces et al. (1993), Quade (1994), and Quade et al. (1995) can clearly be used to directly estimate the location and probable areal extent of future discharge areas in the Death Valley region. Volumetric water flow rates beneath YM depend on the width and depth of the transmissive regions in the Alkali Flat-Furnace Creek Ranch sub-basin, which connect the upland recharge areas to the discharge areas in Crater Flat and Franklin Lake Playa. If the increased upland recharge is funnelled beneath Timber Mountain and YM (e.g., Figure 2-6), the presence of low transmissivity zones could induce a rise in the elevation of the water table.

Of primary concern in this review are the implications of each conceptual model on the potential for water table rise at YM under a full-glacial or pluvial climate. As noted earlier, most of these models suggest that YM lies wholly within the Alkali Flat-Furnace Creek Ranch sub-basin; YM would, therefore, presumably be unaffected by changes to the hydrogeologic regime of the adjoining Ash Meadows sub-basin. Accordingly, recharge occurring to the northeast in Pahranagat, Tikaboo, Sand Spring, Railroad, Groom Lake, and Papoose Lake Valleys may be assumed to have little or no effect on the water table at YM. However, this assertion assumes that the boundary separating the Ash Meadows and Alkali Flat-Furnace Creek Ranch sub-basin, which was delineated primarily using hydraulic data and hydrogeochemical facies data taken from boreholes that tap the upper tuffaceous and alluvial aquifers, also reflects the hydraulic regime in the lower carbonate system. At YM there is both hydraulic and thermal evidence of vertical flow between the tuffaceous aquifer and the lower carbonate aquifer [Czarnecki (1989); Fridrich et al. (1994)], so additional data are clearly required to unequivocally establish that YM lies within the Alkali Flat-Furnace Creek Ranch sub-basin as presently defined.

Assuming that YM does indeed lie within the Alkali Flat-Furnace Creek Ranch sub-basin, it is clear that the groundwater basin scale models of Czarnecki and Waddell (1984), and Czarnecki (1985, 1989) cannot be used to assess the consequences of increased recharge north of Timber Mountain except by imposing a larger specified flux along their northern boundaries. The regional groundwater flow system scale models by Rush (1970), Winograd and Thordarson (1975), Waddell (1982), Rice (1984), and Sadler et al. (1992) all appear to include Kawich Valley, Gold Flat, and southern Cactus Flat in the Alkali Flat-Furnace Creek Ranch sub-basin, thus allowing increased recharge to be incorporated by specifying areal recharge zones for the Belted, Reveille, Kawich, and Cactus Ranges, as well as for Pahute Mesa. Deuterium data described by Feeney et al. (1987) confirm that there is southward flow of water from at least Kawich Valley to Pahute Mesa. The deuterium calibrated DSC model of Sadler et al. (1992) indicates that there is little inflow to Kawich Valley from Railroad Valley, which receives runoff from the Quinn Canyon, Grant, and Pancake Ranges, suggesting that Kawich Valley may be the most northern hydrographic basin influent to the Alkali Flat-Furnace Creek Ranch sub-basin. As shown in Figure 2-9, Burbey and Prudic (1991) appear to extend the Alkali Flat-Furnace Creek Ranch sub-basin northward to include Alkali Spring Valley, Ralston Valley, Stone Cabin Valley, Tonopah Flat, and Big Smoky Valley. According to Burbey and Prudic (1991), southward flow of water from the northern mountain ranges bordering these valleys can be inferred from the relatively light deuterium values ($\delta D = -110$) found in Reveille Valley. This northward extension of the Alkali Flat-Furnace Creek Ranch sub-basin may imply greater groundwater flow rates beneath YM during pluvial climatic regimes due to increased recharge from the northern mountain ranges. Indeed, according to Mifflin (1988), early work by Meinzer (1916) indicated the former presence of pluvial lake in Big Smoky Valley. While evidence of the former presence of a pluvial lake does indicate that significantly higher recharge rates may occur in northern Alkali Flat-Furnace Creek Ranch sub-basin under a full-glacial climate, the evidence also suggests that Big Smoky Valley is hydrogeologically cloud and thus not a part of a larger groundwater flow system.

It is apparent that each model of the Alkali Flat-Furnace Creek Ranch sub-basin will need to be quantitatively evaluated with the results then compared to the results from other models in order to assess the potential for water table rise at YM due to increased recharge under a full-glacial climate. The conceptual model of Burbey and Prudic (1991) appears to have significant implications for the potential for water table rise at YM. Additional effort must be devoted to understanding the hydraulic connection between the thick volcanic sequences within this sub-basin and the Paleozoic carbonate aquifer to determine if the Alkali Flat-Furnace Creek Ranch sub-basin and the Ash Meadows sub-basin are indeed distinct flow systems in the vicinity of YM. If the Ash Meadows sub-basin contributes flow to the YM site groundwater system through the lower carbonate aquifer, increased recharge from the Pahranagat, Groom, and Sheep Ranges, and perhaps the Spring Mountains under a full-glacial climate will also have to be considered.

3.3 IMPLICATIONS FOR WATER TABLE RISE DUE TO DISRUPTION OF THE STEEP HYDRAULIC GRADIENT AT YUCCA MOUNTAIN

A saturated zone feature that may compromise repository performance is the relatively steep (300 m in 2 km) (Fridrich et al., 1994) hydraulic gradient located at the northern extreme of the perimeter of the proposed YM repository. If this steep hydraulic gradient is formed by the juxtaposition of high- and low-permeability units across a fault zone, there is concern that future tectonism may alter the throw across the fault and permit water levels to rise beneath YM. Numerical modeling studies performed by Ahola and Sagar (1992) suggest that disruption of the hydraulic barrier that forms the steep hydraulic gradient may cause a water table rise of 275 m beneath YM. Inasmuch as current construction plans call for the repository to be located approximately 300 m above the water table, a 275-m water table rise would dramatically decrease unsaturated zone travel times and may cause the repository to fail the overall system performance standards (10 CFR 60.112). It has been noted by Winograd and Thordarson (1975) and Fridrich et al. (1994) that the steep hydraulic gradient at YM appears to be part of a regional hydraulic feature that extends from just northeast of Bare Mountain, westward to Shoshone Mountain, northward along the Eleana Range, and then eastward across Oak Spring Butte, at the north end of Yucca Flat, and into the Groom Lake area. According to Winograd and Thordarson (1975), the steep eastward hydraulic gradient between the Eleana Range and Yucca Flat is due to thrust faulting that has placed portions of the highly permeable Paleozoic carbonate unit over the low-permeability argillite units of the Eleana Formation and thus effectively compartmentalized the Paleozoic carbonate unit. Whether a similar geologic structure is responsible for the steep hydraulic gradient north of YM is an open question.

The presence of the steep hydraulic gradient at YM is inferred from measured water levels from boreholes UE25-WT#6 and USW G-2, which are located approximately 300 and 1,600 m to the south of Yucca Wash, respectively. Borehole UE25-WT#6 was drilled to a depth of 372 m, while borehole USW G-2 was drilled to a depth of 1,831 m. Water surface elevations in UE25-WT#6 and USW G-2 are 1,034 and 1,029 m above mean sea level, respectively (Ciesnik, 1995). The low hydraulic head portion of the steep gradient is derived using data from wells UE25-WT#16, UE25-WT#18, and USW H-1, which have water levels of 738.2, 730, and 730.9 m, respectively (Fridrich et al., 1994). Approximately 2,000 m to the southeast, water surface elevations decline to around 730 m, which yields a gradient of 0.15 (300 m in 2 km). Except for a north-trending region with a moderate hydraulic gradient of 0.024 (40 m in 1.7 km) paralleling Solitario Canyon, the gradient within the immediate vicinity of the repository is 0.0001. Perched water bodies are fairly prevalent in the immediate vicinity of the repository horizon. However, the 531-m saturated thickness penetrated by USW G-2 suggests that the high water surface elevations measured in the two wells do not indicate the presence of a perched zone.

Czarnecki (1989) noted that the "cause and nature of the large hydraulic gradient are unknown." However, he did propose three possible explanations including: (i) faults that juxtapose high-permeability units to the north and northwest against low-permeability units to the south or southeast or fault zones filled with low-permeability gouge; (ii) the presence of units that are resistant to fracturing such as argillite, or the presence of a volcanic dike or other intrusive rocks; and (iii) a change in the local stress regime that effects a spatial change in fracture frequency, aperture, or orientation across the steep gradient region. In his 2D vertically integrated, subregional-scale numerical model of the YM flow system, Czarnecki (1989) effected the steep gradient by implementing a low-permeability barrier that diverts water around the western flank of the barrier, and then back to the southeast through the repository area. He noted that his model yields flow directions that are not perpendicular to the observed potentiometric contours. This observation is hardly surprising given his decision not to extend the barrier along the entire length of the steep hydraulic gradient. Moreover, if the structural or stratigraphic feature causing the steep gradient forces water to flow vertically downward, a 2D areal model, such as used by Czarnecki (1989), cannot correctly reproduce the observed potentiometric contours.

Fridrich et al. (1994) presented a very detailed description and analysis of possible structural and stratigraphic features that could give rise to what they refer to as the "large hydraulic gradient." This paper was prefaced by the authors' recognition that existing data are insufficient to prove that the inferred steep hydraulic gradient does indeed drive flow from the north to the south, rather than representing the relative potentiometric levels in two separate flow systems. However, after assuming that the steep gradient is a feature of a single flow system, Fridrich et al. (1994) undertook an in-depth analysis of the hydrogeology of the Tertiary volcanics, which form the upper 1 to 2 km of the YM section. Within the volcanic units at YM, the degrees of hydrothermal alteration and lithostatic loading increase with depth. In addition, Fridrich et al. (1994) pointed out that alteration increases strongly to the north, and the ratio of the horizontal to vertical *in situ* stresses decreases to the south, which suggests a southward decrease in shear stress. Taken together, the spatial trends in the degree of alteration and the stress regime suggest that the bulk permeability in the tuff units decreases with depth, and increases from the north to the south, which is consistent with the presence of the steep gradient. The hydrostratigraphic units at YM consist from bottom to top of: (i) an aquitard formed by the nonwelded Lithic Ridge and older tuffs; (ii) a moderately productive aquifer formed by the variably welded Crater Flat Tuff; (iii) an aquitard formed by the bedded tuffs of the Calico Hills; and (iv) a very productive aquifer formed by the highly fractured, densely-welded Topopah Spring member of the Paintbrush Tuff.

These hydrostratigraphic units are cut by a series of north-trending, steeply dipping normal faults such as the Solitario Canyon Fault, the Ghost Dance Fault, the Bow Ridge Fault, and the Midway Valley Fault. Fridrich et al. (1994) contend that these faults may form the most permeable features within the tuffs, although their permeability is probably controlled by the lithology of the dissected unit. Across this series of normal faults, the throw is great enough in some areas to have juxtaposed the highly permeable Topopah Spring member against the bedded tuffs of the Calico Hills. Fridrich et al. (1994) prepared a detailed map of the geology at the water table under YM, which suggests very abrupt changes in bulk permeability along both west-east and north-south transects within the region in which the hydraulic gradient is small (0.0001). The extreme flatness of the gradient within this region indicates that the overall hydraulic regime is not controlled by the shallow tuff units, suggesting the presence of an extremely permeable unit, such as the lower carbonate aquifer, at depth.

Since the hydrogeology and structure of the upper tuff units do not appear to be the cause of the steep gradient, Fridrich et al. (1994) examined the influence of deeper units and structures, such as those formed by the buried contact between the Eleana Formation and the Paleozoic carbonate unit. They speculate that the geometry of the large-scale Mesozoic folds and thrusts in the Paleozoic rocks, as truncated by the Tertiary unconformity, control the large-scale Mesozoic clastic-carbonate contact. Fridrich et al. (1994) note that an aeromagnetic high that parallels the regional steep gradient and extends into the YM steep gradient zone is probably caused by the magnetite-bearing Eleana Formation. There are additional lines of evidence that indicate a hydraulic connection between the shallow tuff units and the lower carbonate aquifer. A heat flow low measured in the unsaturated zone above the steep gradient area may be caused by local downwelling of water from the tuffs to the lower carbonate aquifer. Linear thermal highs measured to the south of the steep gradient may be caused by water upwelling from the lower carbonate aquifer. Carbon isotope data appear to support the theory that water flows upward from the lower carbonate aquifer into the tuff units in the low-gradient area. As additional evidence to support this upwelling theory, the authors point out that when borehole UE25 P#1 penetrated the tuff-carbonate contact, an upward gradient was detected. These data taken together suggest that the clastic-carbonate contact is at least coincident with the steep hydraulic gradient, and may, in fact, be its cause.

The evidence for the coincidence of the steep hydraulic gradient and the clastic-carbonate contact cannot be used to determine the exact structure and stratigraphy in this area. However, by using gravity measurements and detailed information on north-south stratigraphic changes in the deep volcanics, Fridrich et al. (1994) are able to construct two alternative flow models. The presence of a gravity low immediately to the south of the steep hydraulic gradient suggests a downward deflection (0.5 km) of the denser clastic and carbonate strata. Fridrich et al. (1994) speculate that this downward deflection of the clastic and carbonate strata formed a graben, which was subsequently buried by less dense volcanic material. Lithologic data from six boreholes drilled to the south of the steep gradient indicate an abrupt stratigraphic thickening (50 to 100%) in the area of the steep gradient. This stratigraphic thickening clearly supports the authors' model of a graben that has been covered with less dense tuffaceous rock.

Fridrich et al. (1994) argued that because the lower carbonate aquifer at YM is buried by approximately 2 km of tuff units, the Paleozoic rocks have a different effect on the hydraulic regime at YM than they do elsewhere along the regional steep gradient. They asserted that even if the Paleozoic rocks are critical to the hydraulic system, they can only be so if the structure of the Tertiary tuff units effects an hydraulic connection to the lower carbonate aquifer. Accordingly, their first conceptual model of the steep gradient provides a vertical path along the fault on the northern boundary of the graben that drains water from the brecciated lavas to the lower carbonate aquifer. The downwelling of water along this fault is consistent with the local heat flow low. In their second conceptual model, a spillway is formed on the upthrown side of the fault by the juxtaposition of highly altered tuffs against the northern extent of the welded tuff aquifer. The abrupt transition from relatively impermeable units to very permeable units across the fault zone gives rise to the steep gradient.

Other than the work of Czarnecki (1989) and Ahola and Sagar (1992), none of the models reviewed here have explicitly addressed the consequences of disrupting the hydrogeologic feature that gives rise to steep hydraulic gradient. As described in Section 2.10, Burbey and Prudic (1991) noted the coincidence of the regional steep gradient with the transverse crustal boundary identified by Eaton (1975). Burbey and Prudic did not attempt to describe geologic structures along this transverse crustal boundary that may cause the steep gradient. However, they do note that the transverse crustal boundary may demarcate a general north-south transition from high permeability to low permeability rocks. The mathematical models reviewed here are generally one-layer or two-layer areal models, which are clearly incapable of capturing the complex 3D hydrogeologic structures that are probably the cause of the steep hydraulic gradient. The north-trending portion of the regional steep hydraulic gradient, which parallels Shoshone Mountain, the Eleana Range, and Rainier Mesa, is roughly coincident with the boundary between the Alkali Flat-Furnace Creek Ranch sub-basin and the Ash Meadows sub-basin. Therefore, new explanations for the cause of the steep hydraulic gradient may consequently affect the boundary and hydraulic relationship between the two sub-basins. New conceptual models that capture the 3D hydrostratigraphy of YM as well as that of the Death Valley region clearly need to be constructed in order to accurately assess the consequences of disrupting the YM or the regional steep hydraulic gradient.

3.4 SELECTION OF A CONCEPTUAL MODEL FOR THE DEATH VALLEY REGIONAL FLOW SYSTEM

Most of the conceptual flow models reviewed herein may be used to assess the potential for the water table to rise beneath YM in response to increased recharge under a full-glacial or pluvial climatic regime. However, the northern extent of the Alkali Flat-Furnace Creek Ranch sub-basin, in which YM is located, is not well-established, so predicted flow rates and consequent water surface elevation changes may be expected to vary among these models. Evidence of vertical flow between the tuffaceous aquifer and the underlying Paleozoic carbonate aquifer at YM suggests that 3D flow models may be required to properly simulate the transient response of the water table to increased recharge. Moreover, it appears that 3D models will be needed to accurately capture the complex hydrogeologic structure that causes the steep hydraulic gradient. The general concept of regional-scale interbasin flow through the lower carbonate aquifer is common among these models. These conceptual models are also in general agreement that the basic hydrologic regime consists of recharge in the northern highlands flowing south-southwest toward discharge areas at Ash Meadows, Oasis Valley, Franklin Lake Playa (Alkali Flat), and Furnace Creek Ranch in Death Valley. In the final analysis it is difficult to select one of these models as the correct model since they reflect the evolution of understanding of the regional system rather than independent lines of thought. The work of Burbey and Prudic (1991) is the only conceptual model that clearly diverges from the basic understanding. However, their model of the Death Valley system appears to spring from the analysis of results from a much larger numerical model, rather than the synthesis a new conceptual model from newly acquired data. For the purpose of assessing the performance of the proposed repository, it appears that the concepts introduced by Burbey and Prudic (1991) must be considered. It is also apparent that while a 2D areal flow model may be sufficient for those portions of the Death Valley flow system that are outside the NTS and Alkali Flat-Furnace Creek Ranch sub-basin area, a 3D model will be needed to incorporate the complex hydrostratigraphy in the general YM area. Until 3D hydrostratigraphic models for the Death Valley region are developed it is difficult to say whether or not the current conceptual models of the flow system will be needed to be completely reworked. However, within the immediate area of YM appears that 3D models are needed to describe the hydrogeologic structure that give rise to the steep hydraulic gradient. Even if a 3D model can be constructed efforts would be made to see whether or not portions of the flow domain can still be accurately simulated using a vertically averaged model.

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