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FINITE-ELEMENT SIMULATION OF GROUND-WATER FLOW IN THE VICINITY OF YUCCA MOUNTAIN, NEVADA-CALIFORNIA

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 84-4349

Prepared in cooperation with the
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By John B. Czarnecki and Richard K. Waddell

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Denver, Colorado
1984

UNITED STATES DEPARTMENT OF THE INTERIOR

WILLIAM P. CLARK, Secretary

GEOLOGICAL SURVEY

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CONVERSION FACTORS

Multiply SI units	*By*	*To obtain inch-pound units*
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
meter per second (m/s)	3.281	foot per second
meter per day (m/d)	3.281	foot per day
square meter (m^2)	10.764	square foot
meter squared per second (m^2/s)	10.764	foot squared per second
meter squared per day (m^2/d)	10.764	foot squared per day
square kilometer (km^2)	0.386	square mile
cubic meter per second (m^3/s)	35.315	cubic foot per second
cubic meter per second (m^3/s)	1.32×10^4	gallon per minute
cubic meter per day (m^3/d)	0.1527	gallon per day

FINITE-ELEMENT SIMULATION OF GROUND-WATER FLOW IN THE VICINITY OF YUCCA MOUNTAIN, NEVADA-CALIFORNIA

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ABSTRACT

A finite-element model of the ground-water flow system in the vicinity of Yucca Mountain at the Nevada Test Site was developed using parameter-estimation techniques. The model simulated steady-state ground-water flow occurring in tuffaceous, volcanic, and carbonate rocks, and alluvial aquifers. Hydraulic gradients in the modeled area range from 0.00001 for carbonate aquifers to 0.19 for barriers in tuffaceous rocks. Three model parameters were used in estimating transmissivities in six zones. Simulated hydraulic-head values range from about 1,200 meters near Timber Mountain to about 300 meters near Furnace Creek Ranch. Model residuals for simulated versus measured hydraulic heads range from -28.6 to 21.4 meters; most are less than ±7 meters, indicating an acceptable representation of the hydrologic system by the model. Sensitivity analyses of the model's flux boundary-condition variables were performed to assess the effect of varying boundary fluxes on the calculation of estimated model transmissivities. Varying the flux variables representing discharge at Franklin Lake and Furnace Creek Ranch has greater effect than varying other flux variables.

INTRODUCTION

Yucca Mountain, located on the western edge of the Nevada Test Site (fig. 1), is being studied by the U.S. Department of Energy as a potential site for a mined geologic repository for high-level nuclear waste. As a part of these studies, the U.S. Geological Survey has been investigating the ground-water flow system beneath Yucca Mountain and vicinity because of the potential of ground water in transporting radionuclides away from a repository to the accessible environment. The investigations, conducted in cooperation with the U.S. Department of Energy under Interagency Agreement DE-AI08-78ET44802, are part of the Nevada Nuclear Waste Storage Investigations. A principal technique has been the drilling of deep boreholes from which hydraulic-head data have been obtained. These data and additional head and flux data from various sources were used in conjunction with a finite-element parameter-estimation model to estimate transmissivities within the flow system and to generate a steady-state simulation of ground-water flow.

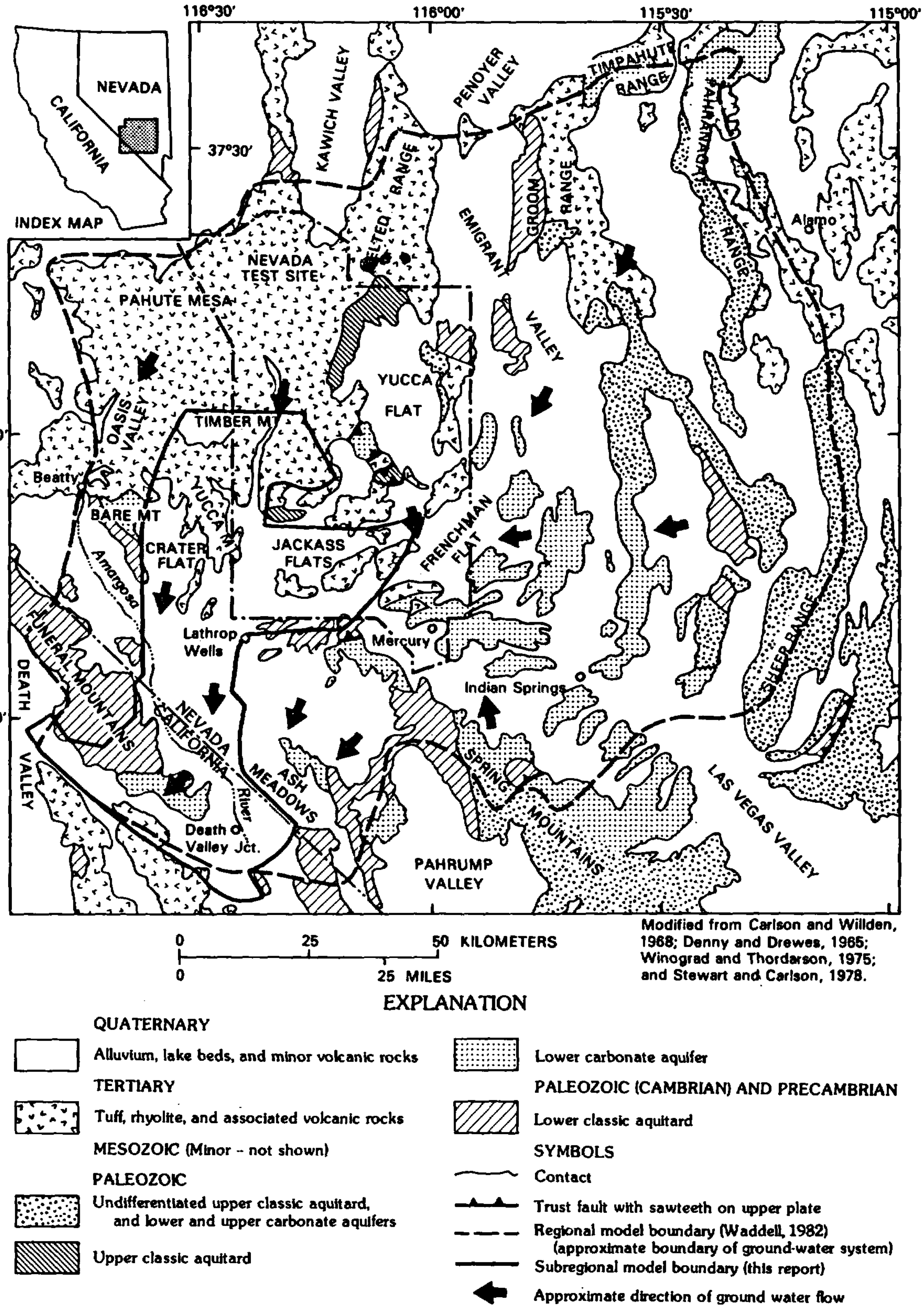

Figure 1.--Location of regional and subregional modeled areas, with generalized ground-water flow directions, and generalized geology (modified from Waddell, 1982, fig. 1).

Purpose and Scope

The purpose of this report is to present the results obtained from the application of a finite-element, parameter-estimation computer code to the analysis of the ground-water flow system beneath Yucca Mountain and its environs. This subregional model was developed in part to gain a better understanding of the ground-water flow system beneath the Yucca Mountain area, as well as for later use in simulating the change in position of the water table resulting from a change in future climatic conditions leading to increased precipitation and increased recharge. Model results also can be used as a basis for assessing the effect of future ground-water withdrawal for irrigation. This work can provide designers of the potential nuclear-waste repository with information that might affect the siting and design of the repository. Results from the present modeling effort may be used in modeling the potential transport of radionuclides from the proposed nuclear-waste repository at Yucca Mountain, and the results may be useful in siting additional boreholes that could be used to characterize the flow system further. Flow vectors of the ground-water movement presented in this report provide a preliminary basis for estimating the direction and time of travel of ground water.

This report includes a discussion of the assumptions and values of variables used in the model and estimates of transmissivity determined by the parameter-estimation procedure. It also includes analyses of the sensitivity of estimated transmissivity parameters used in the model to variations in flux boundary conditions. Results are for steady-state simulations only.

Previous Work

Flow modeling on a regional basis was performed for the regional flow system of the Nevada Test Site and vicinity (Waddell, 1982). This regional model includes the area shown within the dashed lines in figure 1, which also shows the areal coverage of the subregional model presented in this report. The regional model and its analysis provided information on various hydrologic parameters and the sensitivities of simulated hydraulic head to changes in parameters, such as boundary fluxes and transmissivities. Many of the initial parameters used in the subregional model were derived from this work.

The present model incorporates additional hydraulic-head data at Yucca Mountain and Franklin Lake playa not included in Waddell's (1982) report. The design of the present model was intended for use in future simulations of potential ground-water transport of radionuclides. Because of the increased number of equations involved, transport simulations of this type required a decrease of the area modeled by Waddell (1982), as well as a finer finite-element mesh to accommodate potential numerical problems.

Winograd and Thordarson (1975) wrote a comprehensive report on the hydrology of the Nevada Test Site and surrounding areas. Their report included: (1) A study of regional flow through carbonate rocks underlying much of the study area with discharge occurring at springs near Ash Meadows and Furnace Creek Ranch; (2) a study of volcanic rocks underlying Yucca Flat, a site of extensive underground nuclear-weapons testing; (3) a study of the hydrochemistry of waters throughout the study area; and (4) identification of potential hydrologic barriers (their lower and upper clastic aquitards; see pl. 1, this report) and their effects on ground-water flow.

Many geological studies have been conducted in the area. An overview of the general geology of the southern Great Basin is provided in Stewart (1980). The geology of the Nevada Test Site and vicinity was reported by Drewes (1963), Moench (1965), Byers and others (1976), Hoover and Morrison (1980), and U.S. Geological Survey (1984). Geologic and structural maps of the Nevada Test Site and vicinity were produced by McKay and Williams (1964), Lipman and McKay (1965), Orkild and O'Connor (1970), and R. B. Scott and R. W. Spengler (U.S. Geological Survey, written commun., 1981). Reports on analysis of core samples from boreholes drilled at Yucca Mountain are authored by Anderson (1981) and Caporuscio and others (1982). Carr and others (1984) have characterized the geology of Crater Flat.

Extensive geophysical investigations of the Nevada Test Site area have been conducted. Results from gravity and magnetic surveys are presented in Healey and Miller (1971), Kane and others (1981), Ponce (1981), Greenhaus and Zablocki (1982), Ponce and Hanna (1982), and Snyder and Carr (1982). Resistivity studies of the area were conducted by Smith and others (1981), Fitterman (1982), and Greenhaus and Zablocki (1982). Reconnaissance seismic-refraction studies are presented in Pankratz (1982). Of these studies, gravity and magnetic surveys provide the most useful information for delineating different lithologies in the study area, particularly for differentiating volcanic rocks from carbonate rocks.

Many reports on various aspects of the hydrology of the study area have been published. Thordarson and Robinson (1971) compiled data on wells and springs within 160 km of a point on the Nevada Test Site. Eakin and others (1963), Rush (1970), and Waddell (1982) summarized the regional hydrology of the study area. More specific areal studies include: Amargosa Desert hydrology (Walker and Eakin, 1963; Johnston, 1968; Naff, 1973; Claassen, 1983); Ash Meadows hydrology (Dudley and Larson, 1974; Naff and others, 1974; Winograd and Thordarson, 1975; Winograd and Pearson, 1976; Carson, 1979); Furnace Creek Ranch hydrology (Pistrang and Kunkel, 1964; Hunt and others, 1966; Miller, 1977); and Yucca Mountain hydrology (Waddell and others, 1984). Geohydrologic data on individual drill holes at Yucca Mountain are given in Benson and others (1983), Bentley and others (1983), Craig and others (1983), Lobmeyer and others (1983), Thordarson (1983), Bentley (1984), Rush and others (1984), and Thordarson and others (1984).

To calibrate a ground-water flow model, measurements of hydraulic head at numerous points throughout the flow system are required; then these data are interpreted on the basis of hole construction, use, and lithology. Data of this type were compiled by Walker and Eakin (1963), Thordarson and Robinson (1971), Winograd and Thordarson (1975), and Robison (1984); some data are stored in the U.S. Geological Survey WATSTORE files (Hutchinson, 1975).

Acknowledgments

William J. Oatfield of the U.S. Geological Survey helped in compiling many of the hydraulic-head measurements used in the model and in preparing data sets for the model. Richard L. Cooley of the U.S. Geological Survey provided the computer code used in the study.

CONCEPTUAL MODEL

Components of the Model

Major components of the conceptual model of the ground-water flow system are recharge/discharge fluxes, boundary fluxes, and distribution of hydrologic properties of geohydrologic units within a three-dimensional framework. The conceptual model used in this study is based largely on the model proposed by Winograd and Thordarson (1975); it has been refined by additional data, not available to them, especially data obtained from recently drilled holes. The types of data used in developing the conceptual model include: (1) Geologic information; (2) water-level information (obtained from drill holes and spring altitudes); (3) precipitation data; (4) measurements of discharge at springs; (5) aquifer-test data; (6) water-chemistry data; and (7) surface and subsurface geophysical information.

The modeled area is about 6,000 km^2 and extends from Timber Mountain in the north to discharge areas at Alkali Flat (Franklin Lake playa) in the south and Furnace Creek Ranch in the southwest. Recharge occurs north of the modeled area at Pahute Mesa and is assumed also to occur along Fortymile Canyon. The model includes an area about one-third the size of the area in the model developed by Waddell (1982).

Alkali Flat-Furnace Creek Ranch Ground-Water Basin

The study area was restricted to part of the Alkali Flat-Furnace Creek Ranch ground-water basin defined by Waddell (1982). A basin is defined as an area that contributes or transmits water to the basin's discharge areas; it includes recharge and discharge areas, and areas under which water must flow from one to the other. The boundaries for this basin are not well known but were estimated from hydraulic-head data, geology, location of discharge areas, and hydrochemistry. Hydrologic aspects of the basin are summarized in this report; greater detail is included in the report describing the regional-flow model (Waddell, 1982). Generalized ground-water-flow directions and generalized geology in and around the modeled area are shown in figure 1. The location of the boundary of the modeled area and nearby geographic features are shown in figure 2.

The northern part of the basin is underlain by volcanic rocks associated with several caldera systems as indicated by the geologic section (pl. 1), extending from Timber Mountain to Alkali Flat and Eagle Mountain. Both Basin-and-Range type faults and faults associated with caldera formation are present. South of Yucca Mountain the volcanic rocks thin and presumably wedge out. The Amargosa Desert is underlain by alluvial, lacustrine, and eolian deposits, which are assumed to overlie rocks of Paleozoic age, probably limestone and dolomite.

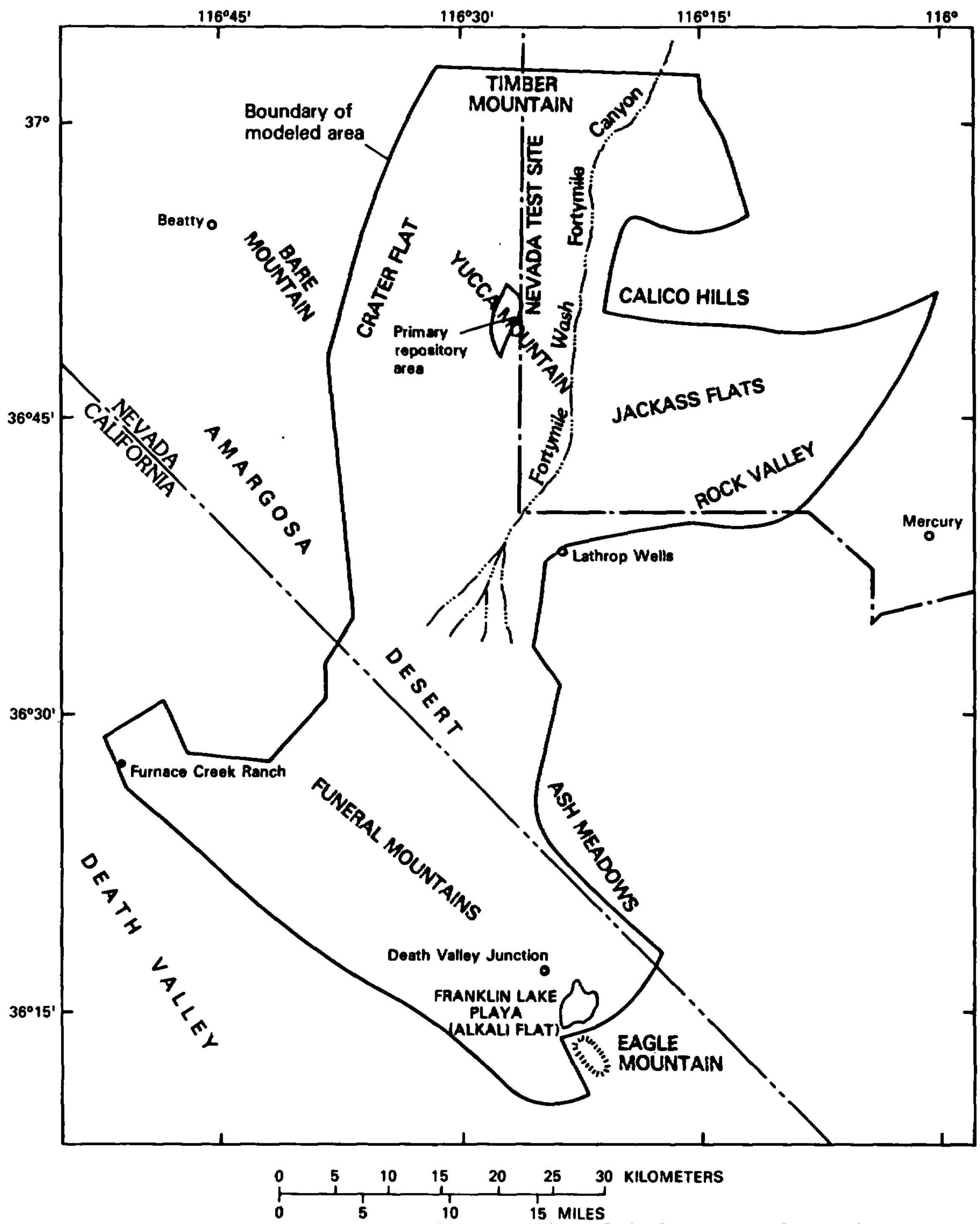

Figure 2.--Location of subregional modeled area and nearby geographic features.

The basin was named after the two major discharge areas near its southern end. Alkali Flat (one of several such named playas within Nevada, also known as Franklin Lake) is an area where ground-water discharge occurs almost entirely through evapotranspiration, the principal component of which is bare-soil evaporation. A few marsh areas occur. Along the central axis of the playa, hydraulic heads measured in drill holes penetrating to depths of 5 to 15 m are near or above land surface (J. B. Czarnecki, unpublished data, 1983-84). Discharge in the Alkali Flat area has been estimated to be about 0.39 m^3/s, or 3.37×10^4 m^3/d (Walker and Eakin, 1963).

The other major discharge is from springs near Furnace Creek Ranch, near the headquarters of Death Valley National Monument. The origin of the water discharging from the springs is incompletely known. The springs issue from either carbonate rocks or alluvium overlying carbonate rocks at altitudes tens to hundreds of meters above the floor of Death Valley. Winograd and Thordarson (1975) present several types of evidence that indicate that the majority of the ground-water discharge in the Furnace Creek Ranch area does not originate in the Funeral Mountains, but must have been recharged elsewhere. The two most likely sources of water (although not necessarily recharge areas) are alluvium that underlies the Amargosa Desert immediately northeast of the Funeral Mountains, and carbonate rocks that probably underlie that alluvium.

Upgradient from the discharge areas, water flows through alluvial sediments underlying the Amargosa Desert. The alluvium probably overlies carbonate rocks, but no drill holes fully penetrate the alluvium to provide confirmation. Fine-grained lakebeds, playa deposits, or marsh deposits occur within the alluvium, principally near Ash Meadows southeast of Lathrop Wells (Walker and Eakin, 1963; Naff, 1973; Claassen, 1983).

The juxtaposition of less transmissive sediments (lacustrine or eolian deposits or both) against very transmissive carbonate rocks along a gravity fault on the eastern edge of the Amargosa Desert near Ash Meadows is, in part, responsible for the presence of springs in this area (Winograd and Thordarson, 1975). The areal extent of these sediments is not known precisely, but is indicated by the presence of gravity lows in the area (Healey and Miller, 1971; Healey and others, 1980). Some lateral recharge of ground water from the Ash Meadows basin into the Alkali Flat-Furnace Creek Ranch basin in the Amargosa Desert area probably occurs through these lakebeds, but the rate of recharge is unknown. The model boundary in the Ash Meadows area represents the westernmost extent of these less transmissive units.

In the vicinity of Timber Mountain, Yucca Mountain, Crater Flat, and Jackass Flats, volcanic tuffs and rhyolitic lava of Tertiary age were derived from several different calderas and smaller eruptive centers. Thicknesses of these rocks exceed several thousand meters within the calderas. Elsewhere, volcanic rocks are thinner; hence, underlying rocks of Paleozoic age may be hydrogeologically important. Argillite in the Eleana Formation, which occurs along the western edge of Yucca Flat, locally beneath Calico Hills, and in the Bare Mountains (west of Crater Flat), commonly is a barrier to ground-water flow. The regional model (Waddell, 1982) indicates that flow within the Eleana argillite near Calico Hills is not significant in the flow system, because water can flow more easily through volcanic rocks to the west. Model boundaries were specified in such a manner that flow within the Eleana argillite was not modeled; an estimated, minor boundary flux into Jackass Flats from the Eleana argillite was specified.

The area north of Timber Mountain, which is a large caldera whose resurgent dome is still well exposed, was not included in the subregional model; this area (Pahute Mesa) consists of tuffs and rhyolite lavas of the Silent Canyon caldera. North of Pahute Mesa, volcanic rocks are thinner, and alluvium, pre-Mesozoic carbonates, and clastic rocks again dominate the section.

The geology, and hence the hydrology, of the region is complex, and the model can only approximate this complexity. In addition, much of the permeability is secondary (fractures in the volcanic rocks and fractures and dissolution features in carbonate rocks), so that wells might provide inaccurate indications of permeability. Waddell (1982) discusses other sources of uncertainty and stresses the importance of sensitivity studies of models of ground-water flow in the region.

MODELING TECHNIQUE

Parameter-Estimation Procedure

The numerical techniques used in this study were developed by Cooley (1977, 1979). The basic equation describing flow of ground water in porous media is given by:

$$\frac{\partial}{\partial x_i}\left(T_{ij}\frac{\partial h}{\partial x_j}\right) + R\,(H-h) + W = 0,\ j = 1,\ 2\ , \qquad (1)$$

where T_{ij} = transmissivity (L^2/T);
- R = hydraulic conductivity divided by thickness of a confining bed (L/T);
- W = source-sink term (positive for source) (L/T);
- h = hydraulic head (L);
- H = hydraulic head on the distal side of the aquitard (L); and
- x = Cartesian coordinate (L).

The repeated subscript i or j without parentheses indicates summation on that subscript. The source-sink term is composed of two different parts: The first is areally distributed recharge or discharge, depending on sign; the second is a point source or sink, described by pumping or injection wells. This equation is solved using a finite-element code written by R. L. Cooley (U.S. Geological Survey, written commun., 1979).

Internal boundary conditions between elements require that both specific discharge normal to the boundary and hydraulic head remain unchanged as the boundary is crossed. External boundaries may be either known flux or known head boundaries.

The code used in this study uses a parameter-estimation technique described by Cooley (1977, 1979, 1982) that derives values for the parameters a_k, k = 1, 2, ... K, where a_k represents any of T_{ij}, R, W, and constant head or flux boundary conditions for zones or nodes defined throughout the modeled area. The a_k are determined to minimize the weighted sum of squared residuals of simulated head:

$$\sum_{\ell=1}^{I} w_\ell e_\ell^2 = \sum_{\ell=1}^{I} w_\ell \, (h_\ell^m - h_\ell)^2 \, , \tag{2}$$

where h_ℓ = simulated head (L);

h_ℓ^m = measured hydraulic head (L);

w_ℓ = weighting factor;

I = the number of nodes; and

e_ℓ = residual.

The weighting factor is zero, if no measurement is available; it is set equal to one, if measurement is available. The value $h_\ell^m - h_\ell$ is the residual for the node. An iteration process, using a linearized-regression model, is used to minimize the weighted sum of squared residuals by successive approximations to model parameters. Development of a sensitivity matrix is implicit in the algorithm. Because all fluxes and transmissivities cannot be determined from a given head distribution, some parameters used in the model need to be specified as known.

One major goal in the calibration of the model was to minimize the error variance:

$$s^2 = \sum_{\ell=1}^{I} \frac{w_\ell \, (h_\ell^m - h_\ell)^2}{J - K + L} \, , \tag{3}$$

where J = number of observations;

K = number of parameters being estimated; and

L = number of parameters for which estimates of value exist.

Another major goal was to adjust aquifer zonation and values of parameters, so that residuals were distributed randomly throughout the modeled area.

Success of a modeling effort is dependent on knowledge of the system, including both geometry of hydrologic units within the system and values of parameters. The better the parameters are known, the more successful the modeling effort is likely to be. Within a system, parameters may exist for which minor changes in their values do not cause significant changes in simulation results. Parameter-estimation techniques are not successful in estimating precise values of these parameters. Some parameters are very important to the simulation of heads; for these parameters, the parameter-estimation technique produces precise estimates. The standard error of estimated parameters reflects the ability of the model to determine these parameters (the precision of the estimates); this error is directly dependent on the sensitivity of the model to these parameters.

Model-Mesh Design

The design of the finite-element mesh allowed for complex geometries in the modeled area, including barriers, aquifers, and recharge and discharge areas. An automated mesh-generation program was used to construct the initial mesh. Different transmissive zones were considered in the selection of control blocks used by the mesh-generation program. Triangular elements were generated because they could be easily rearranged manually and still maintain a proper element-aspect ratio (length:width). Denser nodal spacing in the area near Yucca Mountain was selected to accommodate steep hydraulic gradients present there.

The finite-element mesh used in this model may later be used in a transport model to evaluate the potential migration of radionuclides through the ground-water system near Yucca Mountain. One restriction in transport modeling is to insure that the characteristic length (d) of a given element divided by the dispersivity (α) is less than 10 (Huyakorn and Pinder, 1983, p. 206). The ratio ($d:\alpha$) is referred to as a Peclet number; the ratio is a measure of the stability of the solution process. The smaller the dispersivity value is, the smaller the characteristic length of a given element must be, necessitating more elements closer to the source of the transported material (Yucca Mountain). As material is transported farther and farther away from the source, larger dispersivities are encountered, allowing for the use of larger elements. This scale dependency for dispersivities was acknowledged by Fried (1975). A representative length for the elements of the mesh immediately downgradient from the potential repository block (pl. 1) is about 800 m, allowing for dispersivities as small as 80 m.

Boundary Conditions

Boundary conditions used in the model consist of three types: flux, no-flow, and constant head (pl. 2). A constant-head boundary was placed at the northernmost boundary of the model. Fluxes into the flow system were applied (pl. 2): (1) Along the northern boundary of Jackass Flats; (2) along the western edge of the Amargosa Desert (accounting for flow from the northwest); (3) along the eastern edge of the Amargosa Desert, west of Ash Meadows; and (4) as a distributed flux through elements in the area corresponding to a reach along Fortymile Canyon (zone 8; pl. 1). At northern Jackass Flats, two different fluxes were applied: a small flux from the Eleana argillite, and a greater one from the carbonates underlying Rock Valley (1×10^{-6} m^2/s), based on Waddell (1982). Fluxes out of the flow system were applied along a line east of Furnace Creek Ranch and as a distributed areal discharge out of Alkali Flat north of Eagle Mountain (Franklin Lake playa, zone 2; pl. 1). All other external boundaries were treated as no-flow boundaries.

The flux specified for Furnace Creek Ranch discharge is based on the value used by Waddell (1982) in his model. The principal discharge along this line sink occurs at Nevares Spring [1.7×10^{-2} m^3/s (1.47×10^3 m^3/d)]. The total flux from this line discharge is 0.22 m^3/s (1.9×10^4 m^3/d).

Additional minor fluxes were specified as: throughflow from the Amargosa Desert [2.2×10^{-4} m^3/s (19 m^3/d)]; flow across lakebeds at Ash Meadows [8.9×10^{-4} m^3/s (76.9 m^3/d)]; and flow into Jackass Flats from the Eleana Formation from the north [1.4×10^{-2} m^3/s (1.21×10^3 m^3/d)]. These flux values are not well-known.

The above flux boundary conditions are depicted on plate 2. Flux values are given in table 1.

Hydraulic-Head Measurements

Measurements of hydraulic head need to be supplied in the model for the parameter-estimation problem to be solved. Water levels from wells and springs are the basis for hydraulic-head data. Several sources of published and unpublished hydraulic-head data concerning the study area were available for use. These data and their sources are listed in table 5 in the "Supplemental Data" section at the end of the report.

When entering hydraulic-head measurements into the parameter-estimation procedure, the node closest to a given measurement site was assigned the hydraulic-head value at that site. In instances where several measurement sites surrounded a given node, an average value of the surrounding hydraulic heads was applied to a central node (see "Supplemental Data" section at the end of the report). In several instances, nodes were moved to coincide with measurement sites. This commonly was done with wells near Yucca Mountain. Location of nodes having assigned hydraulic-head values, and contours of these values are shown in figure 3; the hydraulic-head data are given on plate 1 and in the "Supplemental Data" section (table 5) at the end of the report.

Errors in hydraulic-head data can have two principal sources: (1) Inaccuracy in measurements of depth to water, and (2) inaccuracy in determination of altitude of land surface. Waddell (1982) discusses various types of error that can be encountered and the degree of accuracy expected for hydraulic-head data obtained. In general, hydraulic-head data from wells at the Nevada Test Site are considered quite accurate (Waddell, 1982). Considering the range in hydraulic head encountered throughout the subregional-model area (more than 1,200 m), maximum measuring errors of 1 m in wells at the Nevada Test Site are considered insignificant for modeling at this scale (Waddell, 1982), but are significant for detailed evaluation of flow east of Yucca Mountain (Robison, 1984). Errors in measurement in other locations off the Nevada Test Site result principally from inaccuracies in determining measuring-point altitudes. Estimated errors in measurements of hydraulic head are ±3 m for wells in the Amargosa Desert and ±12 m for springs in Death Valley (Waddell, 1982). Additional sources of error associated with using hydraulic-head data stem from assigning hydraulic-head values to the closest node, averaging head values and assigning the average value to a central node, and using head data collected at different times.

Table 1.--*Values of model variables and standard errors*

[T, transmissivity, in meters squared per second; Q, flux, in cubic meters per second; number following letter T in model variable column is zone number; jf, Jackass Flats; rv, Rock Valley; fc, Furnace Creek; wa, western Amargosa Desert; am, Ash Meadows; fl, Franklin Lake playa (Alkali Flat); fm, Fortymile Canyon; m^2/d, meters squared per day; m^3/d, cubic meters per day; values in parentheses are in terms of days; dashes indicate that value was held constant]

Model variable	Parameter number	Value	Standard error	Coefficient of variation	Dominant lithology
T1,T2	1	0.1546×10^{-1} (1.336×10^{3} m^2/d)	0.3694×10^{-3} (31.92 m^2/d)	0.024	Alluvium
T3, T4a	2	$.1484 \times 10^{-2}$ (1.282×10^{2} m^2/d)	$.2802 \times 10^{-4}$ (2.421 m^2/d)	.019	Volcanic rocks
T4b	2	$.1385 \times 10^{-2}$ (1.197×10^{2} m^2/d)	$.2616 \times 10^{-4}$ (2.260 m^2/d)	.019	Carbonate rocks
T5	1	0.1353 (1.169×10^{4} m^2/d)	$.3232 \times 10^{-2}$ (2.792×10^{2} m^2/d)	.024	Carbonate rocks
T6,T7,T8	1	$.3866 \times 10^{-1}$ (3.340×10^{3} m^2/d)	$.9235 \times 10^{-3}$ (79.79 m^2/d)	.024	Tuff
T9	3	$.1110 \times 10^{-2}$ (95.90 m^2/d)	$.3138 \times 10^{-5}$ (.2711 m^2/d)	.003	Tuff
T10	---	$.9100 \times 10^{-3}$ (78.62 m^2/d)	-----------------	----	Tuff
T11	---	$.4500 \times 10^{-4}$ (3.888 m^2/d)	-----------------	----	Tuff
T12	---	$.100 \times 10^{-6}$ (8.64×10^{-3} m^2/d)	-----------------	----	Lakebeds
Q_{jf}	---	$.1835 \times 10^{-2}$ (1.585×10^{2} m^3/d)	-----------------	----	Argillite
Q_{rv}	---	$.1249 \times 10^{-1}$ (1.079×10^{3} m^3/d)	-----------------	----	Carbonate rocks
Q_{fc}	---	-.2236 (-1.932×10^{4} m^3/d)	-----------------	----	Carbonate rocks
Q_{wa}	---	$.2244 \times 10^{-3}$ (19.39 m^3/d)	-----------------	----	Alluvium
Q_{am}	---	$.8990 \times 10^{-3}$ (77.67 m^3/d)	-----------------	----	Lakebeds/ carbonate rocks
Q_{fl}	---	-.4120 (-3.560×10^{4} m^3/d)	-----------------	----	Lakebeds
Q_{fm}	---	.2563 (2.214×10^{4} m^3/d)	-----------------	----	Alluvium/ tuffs

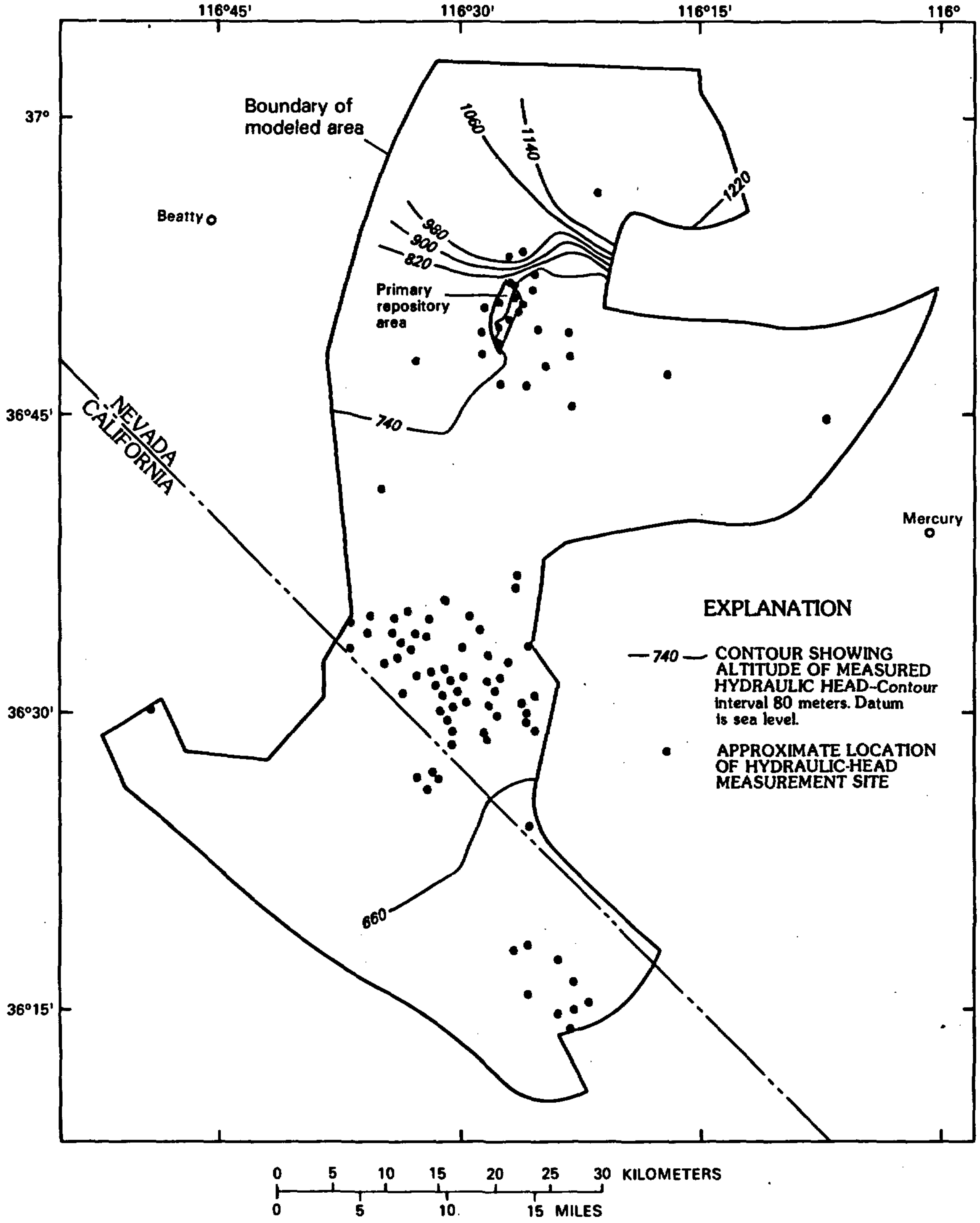

Figure 3.--Hydraulic head and location of measurement sites.

Assumptions Made During the Study

Several simplifications and assumptions regarding geology and hydrology were made to develop the model; many of these simplifications were necessary because of lack of data. These assumptions and simplifications are:

1. Ground-water flow is strictly horizontal.
2. Hydrological parameters (transmissivities, rates of recharge and discharge) do not change with time, and hydraulic heads now are at steady-state conditions.
3. The rocks (except in zone 6) are isotropic with respect to hydraulic conductivity. Although deposition and subsequent fracturing of sedimentary and tuffaceous rocks create anisotropy with respect to transmissivity, insufficient data are available from aquifer tests to evaluate the degree of anisotropy.

The above assumptions commonly are made in modeling two-dimensional ground-water flow in complex flow domains such as in this study area. The primary reason for making these assumptions is the absence of sufficient data to define spatial variability of aquifer properties.

Modeling Sequence and Model Parameters

Initial attempts at modeling the flow system involved supplying the model with estimates of transmissivities based on previously reported values. Many runs were performed with various arrangements of transmissivity zones to form a given parameter. In this model, a parameter is defined as an assemblage of transmissivity variables that are significantly correlated, and whose values are estimated using the parameter-estimation procedure. Convergence of the model depends to a large extent on how parameters have been selected and combined. Significant correlation among parameters can cause convergence problems, so that it is commonly helpful either to hold one or more parameters constant (in which case it is no longer a parameter), or combine it with other parameters. In this study, parameters that were significantly correlated were combined. However, transmissivities of zones 10 and 11 were held constant rather than being treated as parameters. Generally, zones with parallel flow paths were lumped to form one parameter zone. Estimates of transmissivities for various runs were saved and used as initial estimates in subsequent runs, resulting in faster convergence of the solution.

Several model variables were selected as parameters for optimization at various points in the modeling effort. Fluxes (both areally and linearly distributed), constant-head nodes, and transmissivities were included as parameters, with mixed results. Simulations involving constant-head and transmissivity parameters, transmissivity parameters only, and one areally distributed flux parameter (Franklin Lake playa evapotranspiration) successfully converged. Simulations made with both transmissivity and flux parameters failed to converge. The correlation depends on the magnitude of flux and the geometrical arrangement of transmissivity zones, with respect to both explicit and implicit flux terms.

The final selection of parameters involved only transmissivities. The groupings of the specific transmissivity zones appear in table 1 and are illustrated in figure 4. Parameter 1 incorporates the transmissivities of the flow systems of Rock Valley, Jackass Flats, and the Amargosa Desert; parameter 2 incorporates the transmissivities of the flow system of the Funeral Mountains and Furnace Creek Ranch; and parameter 3 incorporates the transmissivities of western Yucca Mountain, Timber Mountain, and Crater Flat (pl. 1). For a given parameter involving multiple transmissivity zones of differing initial estimates, the ratio of these is maintained in subsequent estimations.

MODEL RESULTS

Simulated Hydraulic Heads

Simulated hydraulic-head altitudes range from 1,279.3 m near Timber Mountain to 284.6 m at Furnace Creek Ranch in Death Valley. Head gradients range from a high of 0.19 in the east-west oriented barrier north of Yucca Mountain to a low of 1×10^{-5} in the Rock Valley area. Gradients in western Jackass Flats and the Amargosa Desert are about 0.001; near Furnace Creek Ranch, gradients are about 0.01. Residuals of the 93 hydraulic-head measurements range from -28.6 to 21.4 m (pl. 1). Generally, absolute values of residuals are less than 7 m.

Simulated ground-water flow vectors are shown on plate 2. Each vector is drawn with its tail located at the center of a given element. Contours of simulated hydraulic head near Yucca Mountain are shown in figure 5 and may be compared to contours based on measured values in figure 3. Error variance is 50.6 m^2, resulting in a standard error of 7.1 m. The standard error divided by the range in measured head values is 0.008. Thus, although an individual residual may be large (almost 29 m in one instance), overall agreement between measured and simulated heads is good. The correlation coefficient between measured and simulated heads for the final simulation is 0.997, indicating an acceptable representation of the hydrologic system by the model.

Estimates of Parameters

Description

Values of variables used in simulation and estimates of standard errors for parameters are listed in table 1. Standard errors were calculated by the parameter-estimation procedure; they are a function of sensitivities of simulated head to changes in parameters. Generally, the more sensitive the model is to changes in the parameter, the better the parameter can be estimated. The standard errors are measures of the range throughout which parameters may be varied without greatly changing simulated-head distribution.

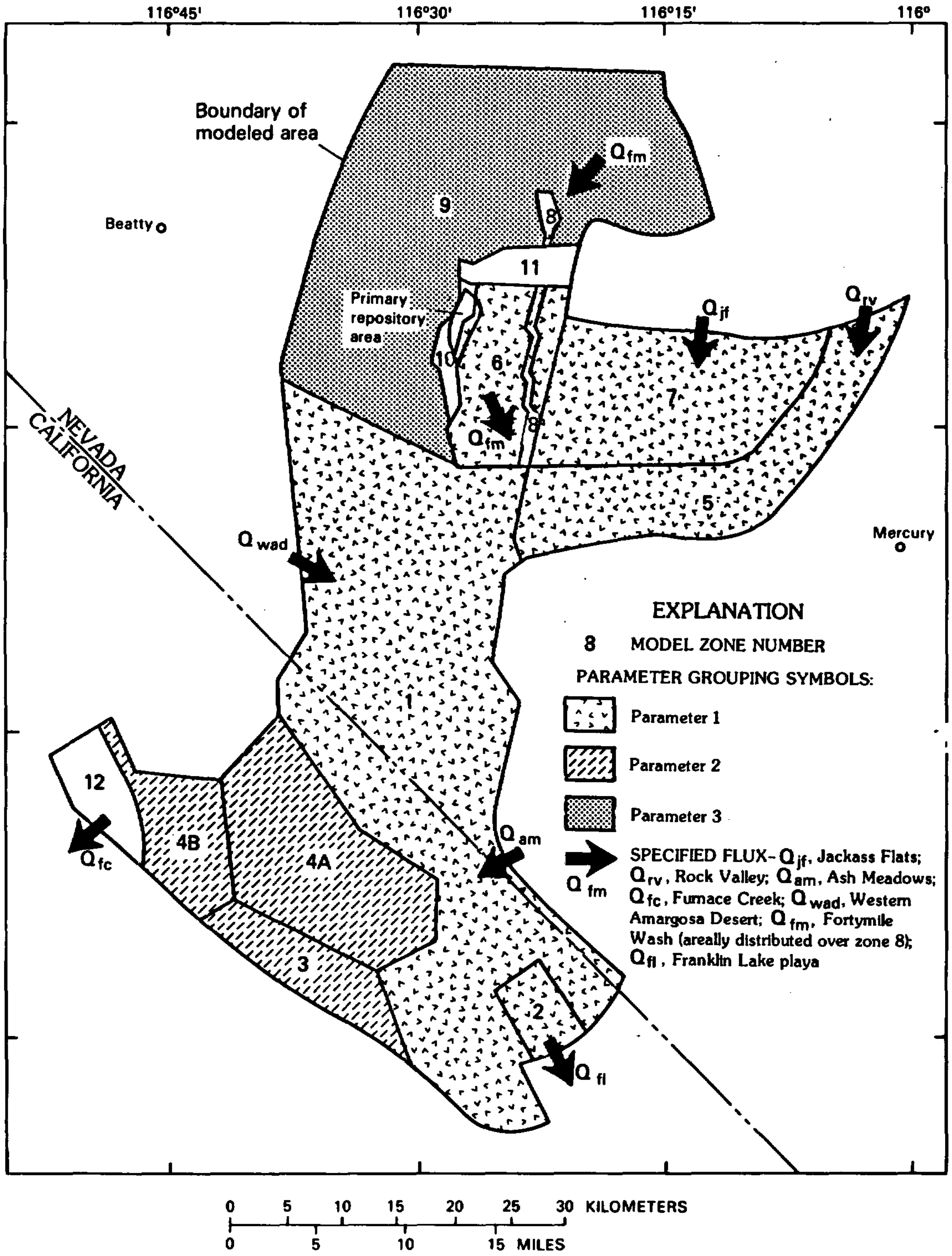

Figure 4.--Model zone numbers, parameter groupings, and model boundary fluxes.

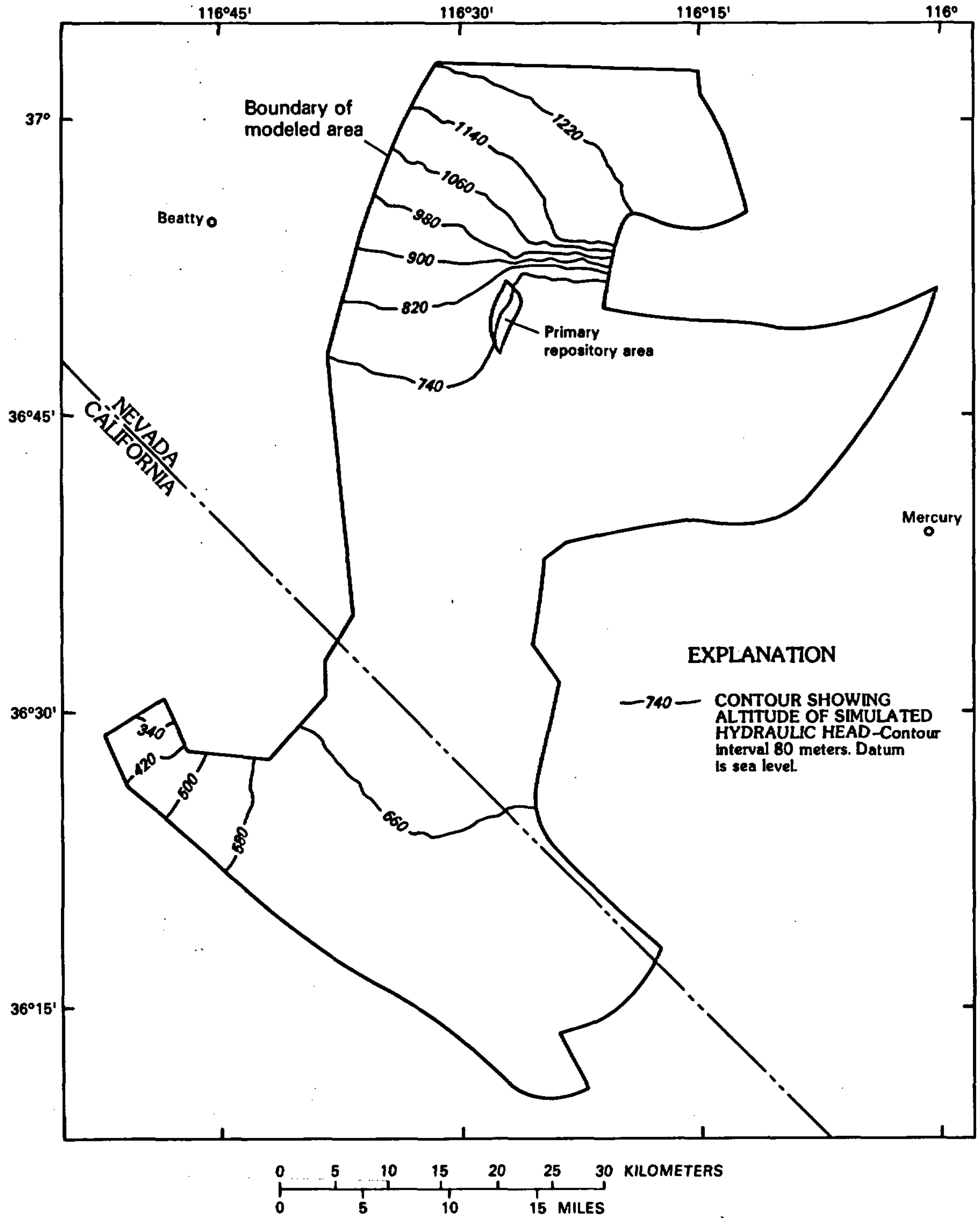

Figure 5.--Simulated hydraulic heads.

Transmissivities

Zones were grouped according to the dominant lithology (alluvium, carbonate, tuff) in a zone. Because of the general lack of transmissivity data throughout the modeled area, initial estimates of transmissivity values were assumed to be uniform throughout areas where lithologies were believed to be the same, or where information was lacking to indicate that transmissivities throughout a given area differed.

Rocks underlying the Amargosa Desert

Zones 1 and 2 (pl. 1) represent transmissivity zones resulting from the combination of various lithologies (carbonate and tuffaceous rocks, lakebeds, and alluvium). Beneath much of the Amargosa Desert, alluvium is an important aquifer. No wells penetrating rocks of Paleozoic age are known except near Ash Meadows. Major transmissive units to the south include alluvium and, probably, carbonate rocks. Carbonate rocks crop out near Ash Meadows, at Eagle Mountain, and in the Funeral Range, and presumably underlie the alluvium at depths greater than several hundred meters. The Eleana Formation is not known to occur south of U.S. Highway 95. Because the estimated transmissivity in these zones is greater than regional transmissivity for tuffaceous rocks to the north, the tuffaceous rocks within zones 1 and 2 either are more transmissive than those to the north, or they are of minor hydrologic significance beneath the Amargosa Desert. Byers and others (1968) mapped the zero-thickness line for tuffs associated with the eruption of Timber Mountain near the southern boundary of the Nevada Test Site. Greenhaus and Zablocki (1982) indicate that strongly magnetized tuffs are not present in significant quantities beneath the Amargosa Desert. Magnetized tuffs again are present south of the Furnace Creek fault zone. Bedded and reworked tuffs are present along margins of the Amargosa Desert south of Ash Meadows and east of the Funeral Mountains (Denny and Drewes, 1965). However, they probably are not hydrologically significant on a regional scale.

Tuffaceous rocks

The northern one-half of the modeled area is underlain principally by tuffaceous rocks. Transmissivity of these rocks is largely controlled by the number and properties of fractures (Blankennagel and Weir, 1973). Because of the complexity of stratigraphy and structure within tuffaceous rocks, hydraulic conductivities may vary greatly within short distances. Values listed are representative of averages of transmissivities of large volumes of rock; these values may be different from those determined by borehole techniques.

Rocks east of Yucca Mountain (zones 6, 7, and 8; pl. 1) were estimated to have greater values of transmissivity [3.9×10^{-2} m^2/s (3.36×10^3 m^2/d)] than rocks west and north of Yucca Mountain, which have lesser values of transmissivity [1.1×10^{-3} m^2/s (95 m^3/d), zone 9]. Thordarson (1983) calculated transmissivities ranging from 110 to 850 m^2/d from pumping tests for well J-13, which is located on the southeastern edge of Yucca Mountain near Fortymile Wash. Moench (1984) calculated a transmissivity of 3.3×10^{-3} m^2/s for late time data (greater than 1,000 minutes) from a pumping test of well UE-25b#1 located near the easternmost edge of the primary repository area (fig. 2). Evidence for this difference in transmissivities is indicated by the difference in hydraulic-head gradients in each area. The zone east of Yucca Mountain in western Jackass Flats has a relatively slight gradient (0.002), indicating a greater transmissivity than in the zones west and north of Yucca Mountain (gradient 0.13).

Hydraulic barriers occurring in the tuffaceous rocks at Yucca Mountain are represented by zones 10 and 11 (pl. 1). Transmissivity in each zone was estimated by repeated simulations, using a range of values for each zone. Initially, simulations were attempted using these zones as separate parameters; however, these simulations failed because these barrier zones and other surrounding parameters were very correlated. As indicated by the actual hydraulic-head gradient across both zones, the transmissivity in zone 10 might be greater [9.1×10^{-4} m^2/s (78.6 m^2/d)] than the transmissivity in zone 11 [4.5×10^{-5} m^2/s (3.89 m^2/d)]. Transmissivities of these zones were held constant during the parameter-estimation runs. The causes for the existence of these barriers may be related to any of the following: (1) Decrease in the number of open fractures; (2) faulting, resulting in fault-gouge sealing or the juxtapositioning of transmissive against nontransmissive tuff units; or (3) the presence of a different type of lithology (rhyolite or argillite).

Carbonate rocks

Rocks underlying the Rock Valley area (zone 5; pl. 1) were assigned transmissivities corresponding to carbonate rocks [0.14 m^2/s (1.21×10^4 m^2/d)]. These are the largest transmissivities in the model; however, because gradients are so slight in this area, hydraulic-head values are only slightly affected by changes in transmissivity.

The other area in which carbonates appear is in zone 4 (Funeral Mountains, pl. 1). The transmissivity value calculated by the model for this zone is 1.4×10^{-2} m^2/s (1.21×10^3 m^2/d). This value is small, in order to produce the actual hydraulic gradient from the Amargosa Desert to Furnace Creek Ranch. No hydraulic-head data are available within the carbonates of the Funeral Mountains.

Lakebeds

Lakebeds occur within zone 12 (near Furnace Creek Ranch). The steep hydraulic gradient across this zone, and the springs that occur along its upgradient border, are evidence for the minimal transmissivity of this zone. By assigning a transmissivity of 1×10^{-7} m^2/s (8.64×10^{-3} m^2/d) to this zone, it effectively was removed from the model and functions as a no-flow boundary. Discharge nodes were placed along the upgradient side of this zone, simulating springs or seeps.

Fluxes

Principal fluxes specified in the model are the distributed areal fluxes at Franklin Lake playa, occurring as evapotranspiration; at Fortymile Canyon, occurring as infiltration; and as linearly distributed flux at Furnace Creek Ranch, occurring as seeps and springs. The evapotranspiration flux estimate of 1.3×10^{-8} m/s (1.12×10^{-3} m/d), applied throughout an area of 31.7 km^2 at Franklin Lake playa (0.42 m^3/s, or 3.63×10^4 m^3/d, throughout total area), was obtained by allowing the model to optimize on this flux as the only model parameter. Significant correlation of this flux parameter with upgradient transmissivity parameters prevented convergence to a solution, hence the need to solve for this parameter individually. By holding all other parameters constant, this procedure produced only a local-minimum error variance. This model-estimated flux was used in subsequent simulations. Although not obtained in the most optimal manner, this estimated value of flux is in agreement with the value for evapotranspiration of 0.39 m^3/s (3.37×10^4 m^3/d) estimated by Walker and Eakin (1963), which they noted was "crude." Because of the importance of this flux to the regional-scale model developed by Waddell (1982), analysis of the sensitivity of the present model to changes in this and other flux parameters was performed and is discussed in a subsequent section of this report.

Measurements are being made throughout the year and at various locations at Franklin Lake playa to evaluate evapotranspiration rates and to refine this flux. Initial measurements of evapotranspiration at Franklin Lake playa produced rates of about 3×10^{-3} m/d during June 1983 and 1×10^{-3} m/d during January 1984 (D.I. Stannard, U.S. Geological Survey, written commun., 1983-84).

The flux occurring as infiltration at Fortymile Canyon was set as a parameter; however, setting that flux as a parameter did not allow model convergence, because of significant correlation with parameter 3. Estimates of this flux were varied for individual runs until a minimum error variance was achieved. As for the case of estimating the evapotranspiration flux at Franklin Lake playa, this produced only a local-minimum error variance.

Standard Errors

Standard errors in parameters were estimated by the parameter-estimation procedure (Cooley, 1979, p. 606; R. L. Cooley, U.S. Geological Survey, written commun., 1981). As stated by Cooley (1979, p. 606), "Standard errors * * * are measures of the ranges over which the respective parameters may be varied and produce a similar solution for the head distribution as that obtained by using $\hat{a}$ [the value of the parameter]." Uncertainty in the parameters normally is larger than that indicated by the estimated standard errors.

Standard errors range from 0.3 to 2.4 percent of the associated parameter value (table 1). This fit was obtained after many simulations and recombinations of parameters. Additional uncertainty occurs because of uncertainty in flux terms that were assumed to be known exactly.

Sensitivity Analysis

The calculation of transmissivities by the parameter-estimation procedure is dependent, in part, on fluxes specified in the model. Because several flux values used in this model are estimates, sensitivity analyses of calculated transmissivity values to changes in flux values were made to help assess the importance of knowing a particular flux value.

Transmissivities in zones forming three separate parameters were calculated using a range of values of fluxes from north of Jackass Flats (jf); from the carbonates underlying Rock Valley (rv); from Ash Meadows (am); from the western Amargosa Desert (wa); from Furnace Creek Ranch (fc); and from Franklin Lake playa (fl). These calculated values are presented in table 2. The relationship of these calculated transmissivities to specific fluxes is shown in figures 6 through 8. Of all the fluxes specified in the model, the best-known is the spring discharge near Furnace Creek Ranch. The next best estimate is that for the evapotranspiration flux at Franklin Lake playa. The remaining flux values are estimates.

Flux values were varied independently in multiples of 0.25, 0.50, 1, 2, and 4 times a baseline value. The estimate of transmissivity near Furnace Creek Ranch is affected only by changes in flux at Furnace Creek Ranch. The possible isolation of ground-water flow to Furnace Creek Ranch from ground-water flow beneath the Amargosa Desert (pl. 2; flow-vector diagram) may explain the insensitivity of this transmissivity calculation to changes in other fluxes. Estimated transmissivity values in the Amargosa Desert are linearly dependent (1 to 1 correspondence) with respect to changes in flux values specified for Franklin Lake playa (fig. 7). The manner in which this calculation is affected by changes in other fluxes is shown in figure 7. Changes in the flux at Furnace Creek has the second largest effect on this calculation, but the effect is only large when this flux is quadrupled.

The effect of changes in flux on the estimation of transmissivity near Yucca Mountain is shown in figure 8. Again, changes in the flux at Franklin Lake playa have the greatest effect on this calculation, followed by changes in the flux at Furnace Creek Ranch.

When the flux into either Rock Valley or into Jackass Flats (fig. 8) is increased, less water is required to move from the constant-head nodes along the northern boundary of the model through the zone near Yucca Mountain to provide the specific discharges at Franklin Lake playa and Furnace Creek Ranch. Therefore, the resulting estimated transmissivity at Yucca Mountain, is less when these flux terms are increased.

Table 2.--*Results of sensitivity analysis based on changes in estimated transmissivity to changes in flux boundary conditions*

Flux	Flux multiplier	Transmissivity (meters squared per second)		
		Furnace Creek Ranch	Amargosa Desert	Yucca Mountain
Jackass Flats	0.25	0.1485E-2	0.1420E-1	0.3493E-1
	.5	.1487E-2	.1425E-1	.3455E-1
	1.0	.1485E-2	.1425E-1	.3375E-1
	2.0	.1485E-2	.1429E-1	.3217E-1
	4.0	.1488E-2	.1455E-1	.2806E-1
Rock Valley	.25	.1487E-2	.1409E-1	.3983E-1
	.5	.1486E-2	.1411E-1	.3780E-1
	1.0	.1485E-2	.1425E-1	.3375E-1
	2.0	.1484E-2	.1463E-1	.2565E-1
	4.0	.1481E-2	.1784E-1	.9511E-2
Ash Meadows	.25	.1485E-2	.1431E-1	.3396E-1
	.50	.1485E-2	.1429E-1	.3389E-1
	1.0	.1485E-2	.1425E-1	.3375E-1
	2.0	.1485E-2	.1416E-1	.3347E-1
	4.0	.1485E-2	.1398E-1	.3290E-1
	16.0	.1485E-2	.1300E-1	.2951E-1
Western Amargosa Desert	.25	.1486E-2	.1432E-1	.3413E-1
	.50	.1486E-2	.1432E-1	.3407E-1
	1.0	.1485E-2	.1425E-1	.3375E-1
	2.0	.1485E-2	.1430E-1	.3374E-1
	4.0	.1485E-2	.1428E-1	.3330E-1
Furnace Creek Ranch	.25	([1])	([1])	([1])
	.50	.0739E-2	.1365E-1	.2706E-1
	1.0	.1485E-2	.1425E-1	.3375E-1
	2.0	.2991E-2	.1633E-1	.4580E-1
	4.0	.6013E-2	.2031E-1	.7087E-1
Franklin Lake playa	.25	.1501E-2	.5238E-2	.9229E-2
	.50	.1493E-2	.8626E-2	.1906E-1
	1.00	.1485E-2	.1425E-1	.3375E-1
	2.00	.1479E-2	.2669E-1	.6553E-1
	4.00	.1473E-2	.5284E-1	.1291E+0

[1]Solution unstable.

The slopes of the lines in figure 8 can be used to estimate the effects of erroneously estimating the flux at Franklin Lake playa on the estimation of model transmissivities. For example, the difference between the baseline estimate of flux at Franklin Lake playa (0.42 m^3/s) with the published value (0.39 m^3/s, Walker and Eakin, 1963) is 0.03 m^3/s, which, when multipled by the slope of the line (0.032) for changes in estimated transmissivities at Yucca Mountain, gives a value of 9.6×10^{-4} m^2/s. This value is about 2 percent of the Yucca Mountain estimated transmissivity (T6, table 1) obtained using 0.42 m^3/s as the flux out of Franklin Lake playa.

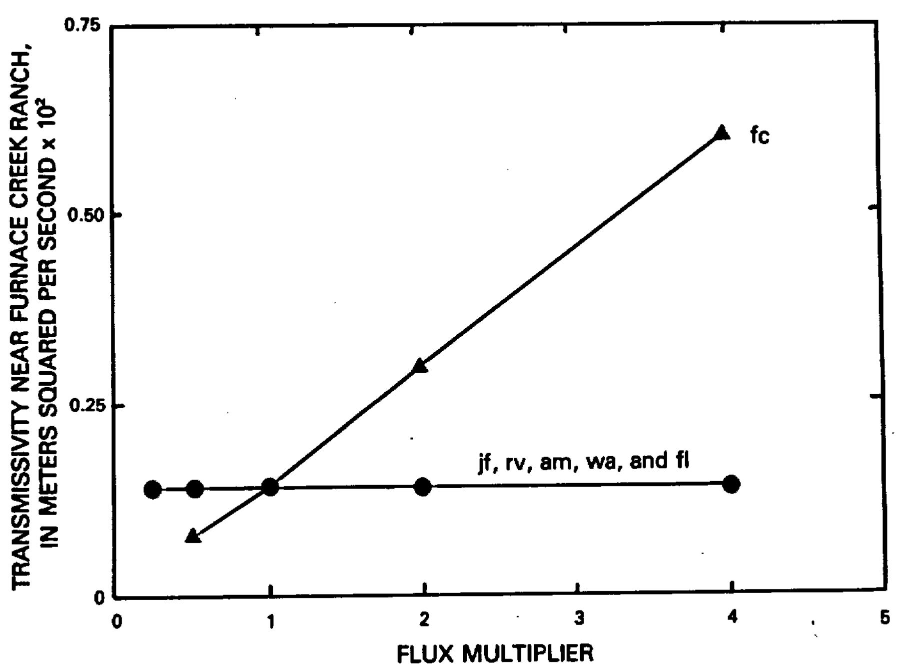

Figure 6.--Sensitivity of calculated transmissivity near Furnace Creek Ranch to changes in flux boundary conditions at Jackass Flats (jf), Rock Valley (rv), Ash Meadows (am), western Amargosa Desert (wa), Furnace Creek Ranch (fc), and Franklin Lake playa (fl).

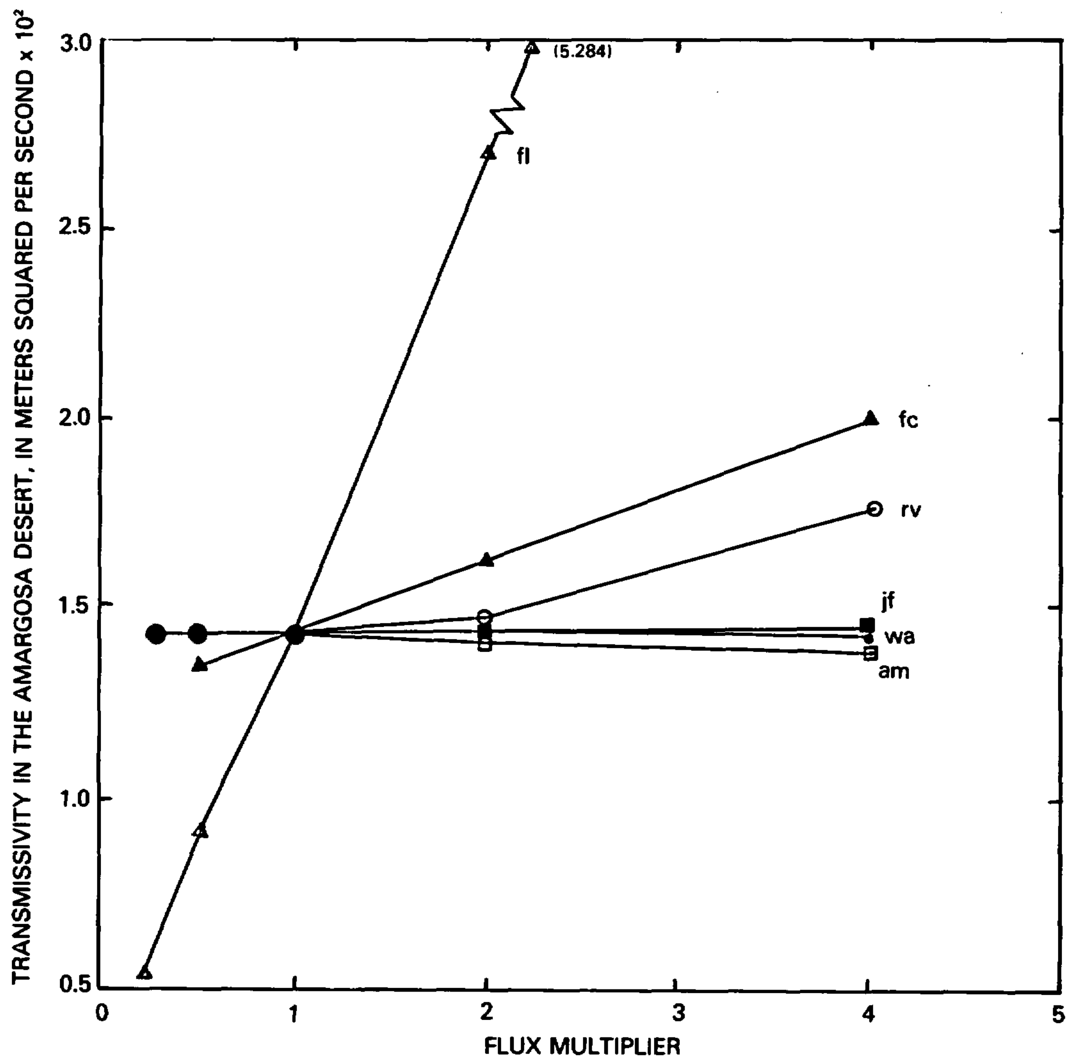

Figure 7.--Sensitivity of calculated transmissivity in the Amargosa Desert to changes in flux boundary conditions at Jackass Flats (jf), Rock Valley (rv), Ash Meadows (am), western Amargosa Desert (wa), Furnace Creek Ranch (fc), and Franklin Lake playa (fl).

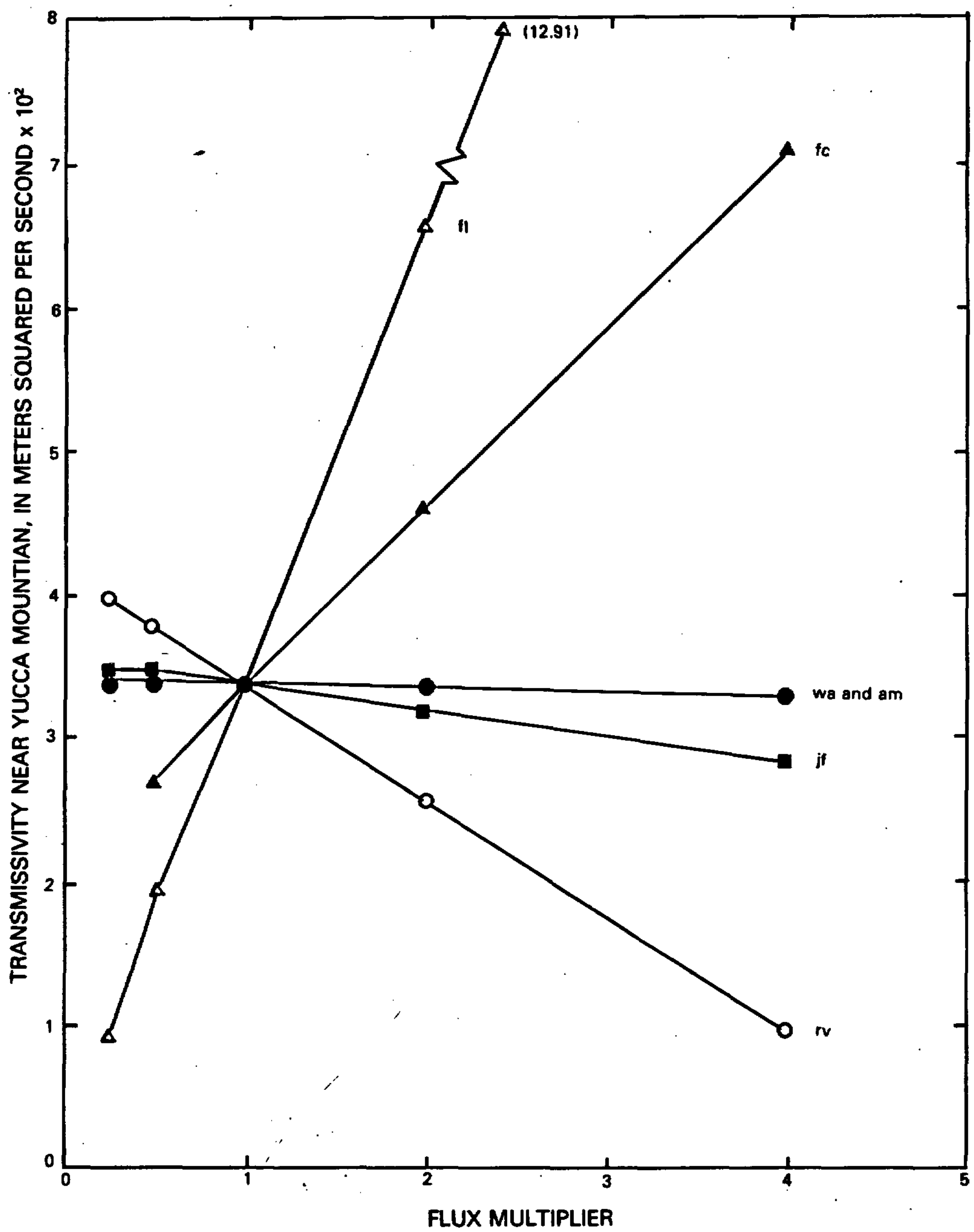

Figure 8.--Sensitivity of calculated transmissivity near Yucca Mountain to changes in flux boundary conditions at Jackass Flats (jf), Rock Valley (rv), Ash Meadows (am), western Amargosa Desert (wa), Furnace Creek Ranch (fc), and Franklin Lake playa (fl).

Model-Flux Calculations

For each element of the finite-element grid, a flux vector was calculated at the centroid of each element, using the technique presented by Waddell (1982, p. 55). The flow vectors calculated for each element for the modeled area are shown on plate 2. The length and head width of each vector is proportional to the magnitude of flux; the orientation is indicative of the direction of flux. Vector lengths are scaled; the maximum vector length is 12.7 mm, corresponding to a maximum flux of 9.36×10^{-5} m^2/s (8.09 m^2/d).

Such an illustration is useful for visualizing the direction and rate of flow throughout the modeled area. However, the density of vectors in a given area does not indicate the magnitude of flow in an area, rather the density of elements from which these vectors were derived.

Because transmissivity values are integral to the calculation of flux-vector magnitudes, adjacent zones with contrasting transmissivities may have flux vectors with contrasting lengths. Contrasting lengths also may occur where flow is forced around sharp corners of impermeable zones or boundaries, such as north of Yucca Mountain and south of Jackass Flats near Lathrop Wells.

Hydraulic-Head Analysis

Scaled sensitivity, S_k, may be expressed as

$$S_k = a_k \frac{\partial h}{\partial a_k} , \qquad (4)$$

where k = the parameter number;
a = a parameter value (transmissivity or flux); and
h = hydraulic head.

Waddell (1982) analyzed the relation between calculated hydraulic head and both transmissivity and discharge as parameters in terms of scaled sensitivities for simple, one-dimensional flow. From that analysis, several general conclusions were made:

1. Scaled sensitivity with respect to both discharge and transmissivity increases as distance from the point of constant head increases.
2. Absolute values of scaled sensitivities with respect to transmissivity and flux decrease as transmissivity increases.
3. Scaled sensitivities with respect to both types of parameters are functions of flux.

A summary of the scaled head sensitivities for all nodes is presented in table 3. Values of minimum and maximum sensitivities for each parameter and the sum of absolute values of the scaled sensitivities are included in this table. Minimum and maximum values give an indication of the sensitivity of head at individual nodes to variations in a parameter, whereas the sum of absolute values gives an indication of the sensitivity for the entire model.

Using the sum of absolute values performs a weighting based on the density of nodes within the study area. From the sum of absolute values listed in table 3, parameter 3 (transmissivity of zone 9) has the greatest effect. This parameter also had the smallest coefficient of variation (table 2). The large sensitivity of the model to this parameter is due to the line of constant-head nodes upgradient of zone 9. Because all flux terms were held constant, the flux entering the model across the northern boundary also is constant. Therefore, if the transmissivity of zone 9 were increased, the gradient across it would decrease in response and all simulated heads within and downgradient from the zone would increase.

Variations in parameter 2 (transmissivity of zone 4, beneath and near the Funeral Mountains) had the least effect on the sum of dissolute values. Simulated heads are most greatly affected within and downgradient from this zone. The affected area is a small part of the modeled area.

Table 3.--*Summary of scaled hydraulic-head sensitivities*

Parameter	Minimum (meters)	Maximum (meters)	Sum of absolute values (meters)	Area of maximum effect
1	-3.0	114.0	3.691×10^3	Amargosa Desert and Furnace Creek Ranch.
2	-.8	373.6	4.527×10^2	Furnace Creek Ranch.
3	8.1	435.2	3.911×10^4	Downgradient from Yucca Mountain.

Effect of Anisotropy

The ratio of transmissivity in the x-direction to transmissivity in the y-direction is a measure of anisotropy. For initial simulations, this ratio was kept equal to 1 for all zones. In subsequent simulations, transmissivities in zones 6 and 8 (pl. 1) were set so that the x-transmissivity (east-west orientation) was 0.5 and 0.25 that of the y-transmissivity (north-south orientation). Faults mapped in zone 6 trend predominantly northward, indicating that, if flow is through fractured rock in this zone, transmissivity in the north-south direction probably is greater than in the east-west direction.

The results of varying anisotropy in zones 6 and 8 are listed in table 4. The effect of varying this ratio on the fit of the calculated-versus-measured hydraulic heads can be determined by comparing the error variances. The error variance increases slightly as the anisotropy ratio is made smaller, indicating a poorer fit. The initial and estimated values of x- and y-transmissivities for zone 6 are listed in table 4. The estimated x- and y-transmissivities for zones 6 and 8 were constrained by including these zones in parameter 1 (fig. 4) rather than specifying the x- and y-transmissivities in these zones as separate parameters. This constraint was required because of significant correlation of these zones with other surrounding zones specified as parameter 1. As the anisotropy ratio is decreased, the estimated y-transmissivities increase. This relationship ultimately affects the calculation of the average cross-sectional flux vector along the flow line chosen for traveltime estimation. However, the calculation of traveltime along the flow line is little affected by the changes in the anisotropy ratio.

Table 4.--*Effect of varying the anisotropy ratio in western Jackass Flats*

[m^2/s, meters squared per second; m^2/d, meters squared per day; m^2, square meters; km, kilometers; m, meters]

Property affected	Anisotropy ratio		
	1:1	1:2	1:4
Estimated x-transmissivity	0.3866×10^{-1} m²/s (3.340×10^{3} m²/d)	0.1951×10^{-1} m²/s (1.686×10^{3} m²/d)	0.9832×10^{-2} m²/s (8.425×10^{2} m²/d)
Initial x-transmissivity	$.4 \times 10^{-1}$ m²/s (3.5×10^{3} m²/d)	$.2 \times 10^{-1}$ m²/s (1.7×10^{3} m²/d)	$.1 \times 10^{-1}$ m²/s (8.6×10^{2} m²/d)
Estimated y-transmissivity	$.3866 \times 10^{-1}$ m²/s (3.340×10^{3} m²/d)	$.3901 \times 10^{-1}$ m²/s (3.370×10^{3} m²/d)	$.3933 \times 10^{-1}$ m²/s (3.398×10^{3} m²/d)
Initial y-transmissivity	$.4 \times 10^{-1}$ m²/s (3.5×10^{3} m²/d)	$.4 \times 10^{-1}$ m²/s (3.5×10^{3} m²/d)	$.4 \times 10^{-1}$ m²/s (3.5×10^{3} m²/d)
Error variance	50.6 m²	52.0 m²	54.7 m²
Sum of squared errors----------	4.7097×10^{3} m²	4.8404×10^{3} m²	5.0858×10^{3} m²
Traveltime for 11.96 km; n = 0.001; b = 500 m.	86.55 years	86.65 years	86.7 years
Traveltime for 11.96 km; n = 0.10; b = 1,000 m.	17,313 years	17,329 years	17,342 years

Traveltime Estimation

The traveltime for a particle of water to move along the length of the flow line can be estimated by making several assumptions with respect to aquifer thickness, aquifer porosity, and average ground-water flux along a given flow line. If the saturated thickness, b, and the aquifer porosity, n, are known, then a ground-water velocity, $\underset{\sim}{V}$, may be obtained from the vertically integrated flux, $\underset{\sim}{q}$, at any point along the flow line, as:

$$\underset{\sim}{V} = \frac{\underset{\sim}{q}}{bn} , \tag{5}$$

An estimate of the traveltime, t_i, needed for a particle of water to move across the length, L_i, of the flow path across an individual element, i, can be calculated as:

$$t_i = \frac{L_i}{|\underset{\sim}{V}_i|} . \tag{6}$$

The total traveltime, t_{total}, along a flow line through several elements is the sum of the individual traveltimes:

$$t_{total} = \sum_{i=1}^{m} t_i , \tag{7}$$

where m is the number of elements along the flow line selected.

A flow line (or flow path) was selected to apply the above traveltime estimation equations. This flow line was selected as one possible route that radionuclides might move downgradient from the potential repository site. Flux vectors were used to approximate the location and extent of the flow line, which appears on plate 2 (flux-vector diagram). The length of the flow line was extended over 17 flow-line segments (L_i) for a total length of 11.96 km.

Values of saturated thicknesses and porosity are unknown for the zone of the selected flow line. Therefore, a range of values for each unknown was used to calculate a table of traveltimes. Saturated thicknesses were assumed to be between 500 to 1,000 m, based on the extent of permeable zones from pumping tests of wells at Yucca Mountain (Benson and others, 1983); primary porosities were assumed to range between 0.001 (fracture porosity) and 0.10 (matrix porosity). By varying both thickness and porosity throughout these ranges, a range in traveltime values was obtained. Traveltimes for the extremes of these calculations (n = 0.001; b = 500 m; n = 0.10; b = 1,000 m) throughout the length of the flow line selected are listed in table 4. The range in calculated traveltimes is about 100 to 20,000 years. This range reflects the large uncertainty in both the saturated thickness and porosity terms used to estimate traveltimes. Until better estimates of these terms are available, traveltimes need to be interpreted in the context of the reliability of the available estimates for saturated thickness and porosity.

CONCLUSIONS

Results obtained from model simulations of the ground-water flow system in the vicinity of Yucca Mountain provide a good match of simulated-to-measured hydraulic-head values throughout most of the modeled area, in spite of hydrogeologic complexities and lack of data in several areas. Exceptions to this good match occur in areas where vertical-flow components are present, such as Franklin Lake playa, and in areas where steep hydraulic gradients occur, such as directly north of Yucca Mountain. These conditions violate one of the principal assumptions made: That ground-water flow in the modeled area strictly is horizontal. In spite of these difficulties, the model probably is a good representation of the ground-water system in the vicinity of Yucca Mountain. Correspondingly, the model results indicate deficiencies in the understanding of the flow system and indicate areas where additional studies are needed. Sensitivity analyses performed with respect to various parameters versus different model variables highlight the need to know certain model variables better, such as the rate of evapotranspiration at Franklin Lake playa.

The presence of barriers in the model greatly affects the orientation of ground-water flow vectors. Few data are available regarding the shape, orientation, and extent of the barrier north of Yucca Mountain. Additional data related to the cause of this and other barriers are essential for a complete understanding of the ground-water flow beneath Yucca Mountain.

The traveltime-estimation procedure used to determine a possible range in traveltimes, while not entirely accurate, provides a means of comparing traveltimes resulting from different values of porosity and thickness. Although changing the anisotropy ratio in western Jackass Flats to achieve greater y-transmissivity versus x-transmissivity did produce faster traveltimes, it also led to larger error variance, indicating that the porous medium in this zone, although intensely fractured, might be similar to an isotropic porous medium on a large scale.

Results of this model need to be used with care, particularly with respect to the prediction of the transport of radionuclides. Fluxes provided by this model may be used in a detailed transport model, but results could be misleading if these fluxes are used out of the context of the assumptions and qualifications stated in this report.

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SUPPLEMENTAL DATA

Table 5.--*Summary of hydraulic-head data used in the model*

[Coordinates based on Central Nevada Coordinate System. Sources: 1, W.J. Oatfield (U.S. Geological Survey, written and oral commun., 1983); 2, Walker and Eakin (1963); 3, Waddell, 1982; 4, J.H. Robison (U.S. Geological Survey, written and oral commun., 1984); 5, J.B. Czarnecki (unpublished data, 1983-84)]

Node	East (feet)	North (feet)	Hydraulic head above sea level (meters)	Source
231	566,622.88	566,969.63	623	5
243	535,238.38	618,774.13	671	2
245	538,827.63	615,145.50	672	3
273	571,002.75	553,226.13	618	5
275	570,779.75	568,570.63	623	5
289	540,274.50	620,565.38	674	2
291	542,249.50	618,528.00	673	1
366	580,103.88	547,363.38	608	5
368	579,536.25	563,961.13	619	5
382	530,622.25	644,364.63	691	2
391	546,176.63	629,023.38	684	3
414	584,683.88	540,988.63	607	5
415	584,726.50	548,747.88	608	5
416	584,270.50	557,392.88	615	5
433	534,638.00	650,014.25	691	1,2
436	541,681.88	639,138.25	689	1
437	544,405.00	636,211.75	688	2
438	546,140.63	632,973.50	688	1
463	589,113.00	550,998.50	611	5
477	570,179.25	604,653.38	644	5
485	538,880.13	651,231.38	690	1
487	540,454.88	647,045.13	689	2
488	543,017.25	643,626.50	688	1
489	545,950.25	640,631.00	688	2
492	556,081.50	630,713.00	687	1
493	555,317.13	632,461.75	686	1
530	524,172.13	653,213.13	695	2
531	528,561.88	654,938.75	697	1
532	532,544.75	657,514.25	695	2
533	543,122.25	652,448.63	690	1
535	536,924.75	661,484.00	707	1,2
536	544,802.00	648,462.38	689	2
537	547,331.50	645,135.63	688	2
538	550,176.00	642,169.75	688	1
578	529,375.50	659,745.25	697	2

93 data pts

Table 5.--*Summary of hydraulic-head data used in the model*--Continued

Node	East (feet)	North (feet)	Hydraulic head above sea level (meters)	Source
579	533,489.63	662,553.63	702	1,2
583	538,069.75	667,219.00	697	5
584	549,129.38	649,902.75	690	1
587	556,888.63	640,916.50	685	1
588	558,824.38	637,862.00	679	1
616	526,225.88	662,307.50	693	2
620	548,256.75	658,518.13	692	1
626	555,799.38	648,308.25	689	2
627	558,388.00	645,480.13	689	2
633	567,715.38	636,470.88	677	1
634	567,843.38	638,803.63	677	1
653	514,198.38	657,734.00	693	2
655	519,444.44	662,327.25	693	2
657	526,931.25	667,215.75	708	1
658	531,006.13	669,361.38	696	2
659	555,848.63	656,100.25	691	3
663	543,118.88	672,993.25	699	3
668	559,916.88	650,007.63	689	2
671	566,550.75	641,854.75	690	1
674	570,412.25	633,675.63	674	2
697	519,769.25	667,888.25	695	1,2
702	553,223.88	663,997.13	687	2
703	550,041.50	668,219.63	699	1,3
710	561,872.25	654,453.25	691	1
714	570,057.88	644,207.13	678	2
735	513,365.00	667,251.75	695	3
772	568,571.75	659,751.75	699	2
825	451,941.13	640,378.38	285	5
850	563,296.13	677,159.88	704	2
871	563,939.13	681,129.75	706	1
882	522,042.88	706,805.63	711	5
1118	531,225.88	745,923.00	773	4
1169	556,951.00	739,607.38	731	4
1189 J-12	578,801.38	733,203.25	728	4
1255	551,294.75	748,439.50	776	4
1302	551,143.88	755,050.38	776	4
1312	564,559.25	739,358.13	729.2	4
1353	555,517.25	752,520.88	730	4
1429 J-13	577,367.63	748,495.25	728	4
1440	570,359.75	745,207.88	729	4
1451	551,721.25	762,803.00	779	4

Table 5.--*Summary of hydraulic-head data used in the model*--Continued

Node	East (feet)	North (feet)	Hydraulic head above sea level (meters)	Source
1455	556,068.38	756,972.88	732	4
1476	607,118.25	743,337.75	733	4
1509	558,975.25	759,098.88	730	4
1536	576,973.88	755,539.25	729	4
1558	555,924.00	764,069.38	775	4
1567	561,593.38	761,290.50	731	4
1617	558,965.38	770,034.00	754	4
1618	567,682.63	756,175.63	730	4
1621	563,168.13	763,698.63	730.1	4
1668	560,888.00	766,123.13	730.5	4
1671	561,183.25	769,312.13	730.1	4
1722	558,361.75	778,278.75	1,029	4
1762	657,512.00	730,411.25	732	4
WT4 — 1782	565,963.38	768,213.13	729.8	4
1787	566,380.13	773,321.38	738.5	4
1834	562,679.25	780,070.00	1,029	4
2050	584,139.25	798,574.00	1,187	4

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MAP SHOWING SIMULATED FLUX VECTORS & DESIGNATED BOUNDARY FLUXES FOR THE MODELED AREA, YUCCA MOUNTAIN & VICINITY, NEVADA-CALIFORNIA.

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D-1

THIS PAGE IS AN OVERSIZED DRAWING OR FIGURE,

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MAP SHOWING MEASURED HYDRAULIC HEADS, MODEL RESIDUALS, MODEL ZONES, MODEL FINITE-ELEMENT MESH, & SECTION SHOWING GENERALIZED GEOLOGY YUCCA MOUNTAIN & VICINITY, NEVADA-CALIFORNIA.

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