

SIMULATED EFFECTS OF INCREASED RECHARGE
ON THE GROUND-WATER FLOW SYSTEM OF
YUCCA MOUNTAIN AND VICINITY, NEVADA-CALIFORNIA

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 84-4344

Prepared in cooperation with the
U.S. DEPARTMENT OF ENERGY

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By John B. Czarnecki

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1985



UNITED STATES DEPARTMENT OF THE INTERIOR

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CONTENTS

	Page
Abstract-----	1
Introduction-----	1
Purpose and scope-----	3
Acknowledgments-----	3
Previous work-----	3
General hydrogeology of the modeled area-----	4
Modeling of the ground-water flow system-----	4
Description of computer program-----	4
Model variables-----	5
Boundary fluxes-----	5
Areally distributed fluxes-----	5
Land-surface altitudes-----	5
Evapotranspiration-----	6
Constant-head nodes-----	8
Hydraulic conductivities-----	8
Modeling results-----	8
Baseline simulation-----	8
Simulation of increased ground-water recharge-----	13
Recharge estimation-----	13
Hydraulic-head sensitivity analysis-----	21
Changes in water-table position-----	21
Changes in direction and magnitude of ground-water flux--	28
Summary and conclusions-----	32
References cited-----	32

ILLUSTRATIONS

	Page
Figures 1-9. Maps showing:	
1. Location of modeled area-----	2
2. Model boundary fluxes, constant-head nodes, and transmissivity zones-----	7
3. Simulated hydraulic head for the baseline-condition simulation-----	10
4. Measured hydraulic head and location of measurement sites-----	11
5. Difference in simulated hydraulic head between base- line-simulation results and parameter-estimation- simulation results-----	12
6. Location of head-dependent sinks for baseline simu- lation-----	14
7. Mean annual precipitation and model zonation for recharge-----	15
8. Difference in simulated hydraulic head between simulations with and without recharge to zones 1 and 2-----	19
9. Thickness of interval between bottom of potential repository and modern-day water table-----	22

CONTENTS

	Page
Figure 10. Graphs showing sensitivity of simulated hydraulic head to changes in flux: A, In zone 1; B, in zone 2; C, at northern boundary; D, at Fortymile Wash; and E, at all four flux locations-----	23
11-16. Maps showing:	
11. Simulated hydraulic head for simulation involving a 100-percent increase in precipitation-----	24
12. Location of head-dependent sinks for simulation involving a 100-percent increase in precipitation--	25
13. Differences in simulated hydraulic head between baseline simulation and the simulation involving a 100-percent increase in precipitation-----	26
14. Baseline, vertically integrated ground-water flux vectors at and in vicinity of primary repository area-----	29
15. Increased-recharge, vertically integrated ground-water flux vectors at and in vicinity of primary repository area-----	30
16. Geographic distribution of the ratio of vertically integrated flux-----	31

TABLES

	Page
Table 1. Model variable values-----	6
2. Modern-day estimated average annual precipitation and resultant recharge at Jackass Flats, Crater Flat, Buckboard Mesa, and Gold Flat-----	16
3. Estimated maximum precipitation (100 percent greater than modern-day conditions) and resultant recharge at Jackass Flats, Buckboard Mesa, and Gold Flat-----	17

CONVERSION FACTORS

<i>Multiply SI units</i>	<i>By</i>	<i>To obtain inch-pound units</i>
millimeter (mm)	0.03937	inch
cubic meter per annum (m ³ /a)	0.0004184	gallon per day
cubic meter per day (m ³ /d)	0.1527	gallon per day
cubic meter per second (m ³ /s)	35.315	cubic foot per second
cubic meter per second (m ³ /s)	1.32 x 10 ⁴	gallon per minute
kilometer (km)	0.6214	mile
meter (m)	3.281	foot
meter per day (m/d)	3.281	foot per day
meter per second (m/s)	3.281	foot per second
meter per annum (m/a)	3.281	foot per year
millimeter per annum (mm/a)	0.03937	inch per year
meter squared per day (m ² /d)	10.764	foot squared per day
meter squared per second (m ² /s)	10.764	foot squared per second
<i>Multiply inch-pound units</i>	<i>By</i>	<i>To obtain SI units</i>
inch per year (in./yr)	25.4	millimeter per annum
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
acre	0.4047	hectare
acre-foot (acre-ft)	1233.4818	cubic meter

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FLOW SYSTEM OF YUCCA MOUNTAIN AND VICINITY, NEVADA-CALIFORNIA

By John B. Czarnecki

ABSTRACT

A study was performed to assess the potential effects of changes in future climatic conditions on the ground-water system in the vicinity of Yucca Mountain, the site of a potential mined geologic repository for high-level nuclear wastes being evaluated by the U.S. Department of Energy. These changes probably would result in greater rates of precipitation and, consequently, greater rates of recharge. The study was performed by simulating the ground-water system using a two-dimensional, finite-element ground-water flow model. The simulated position of the water table rose as much as 130 meters near the primary repository area at Yucca Mountain for a simulation involving a 100-percent increase in precipitation compared to modern-day conditions. Despite the water-table rise, no flooding of the potential repository would occur at its current proposed location. According to the simulation, springs would discharge south and west of Timber Mountain; along Fortymile Canyon; in the Amargosa Desert near Lathrop Wells and Franklin Lake playa; and near Furnace Creek Ranch in Death Valley, where they presently discharge. Simulated directions of ground-water flow paths near the potential repository area generally would be the same for the baseline (modern-day climate) and the increased-recharge simulations, but the magnitude of flow would increase by 2 to 4 times that of the baseline-simulation flux.

INTRODUCTION

Yucca Mountain, located on the western boundary of the Nevada Test Site, is being studied by the U.S. Department of Energy as a potential site for construction of a mined geologic repository for high-level nuclear waste (fig. 1). Various ongoing studies are focusing on the potential of ground water in transporting radionuclides to the accessible environment. Because a repository is designed to protect the environment far into the future (10,000 years or longer), one aspect to consider is potential future changes in the ground-water-flow system, caused by possible climatic changes in the vicinity of the repository.

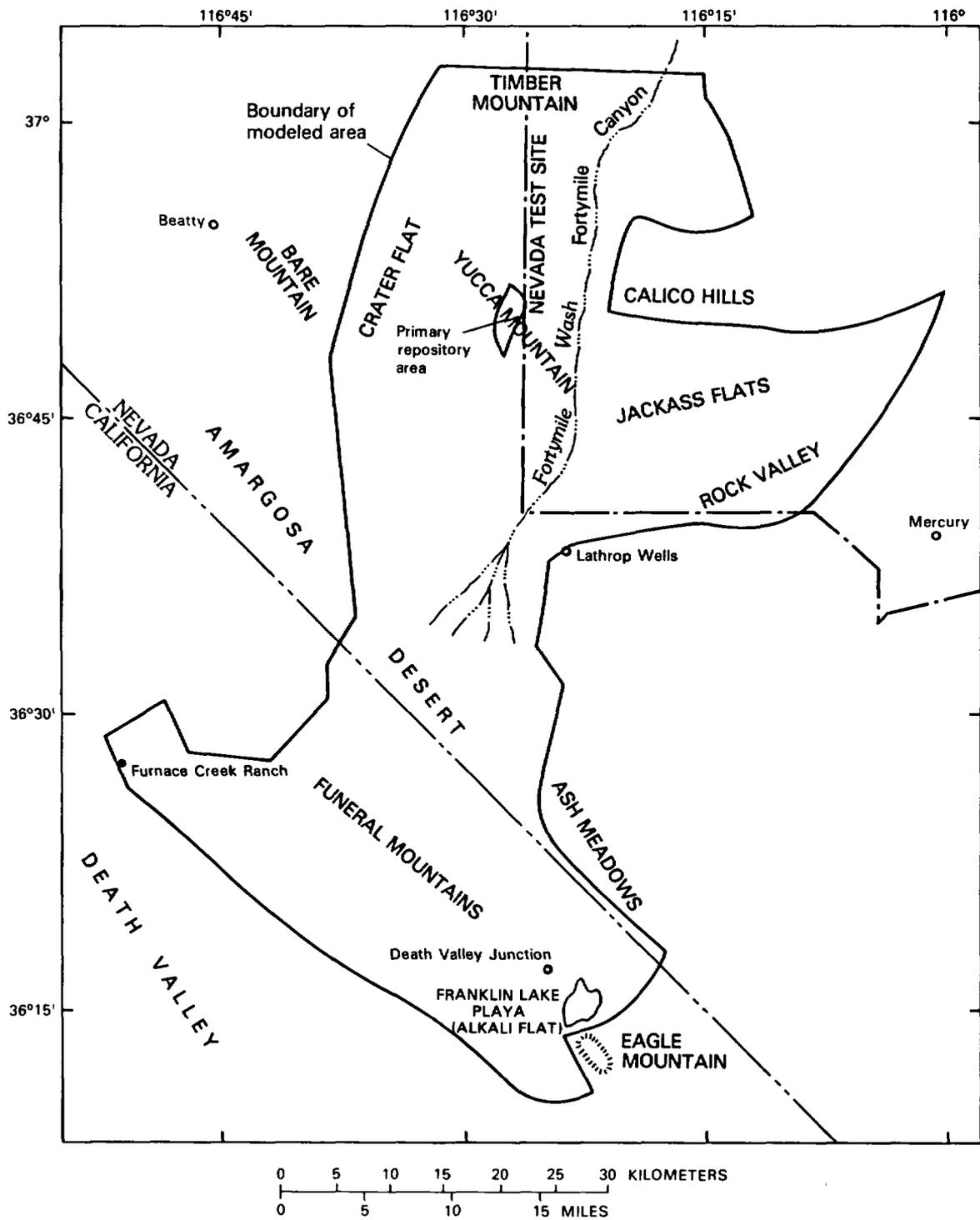


Figure 1.--Location of modeled area.

Purpose and Scope

The purpose of this report is to evaluate the effects of increased ground-water recharge on the ground-water system in the vicinity of Yucca Mountain. The specific questions addressed are: (1) Would increased recharge cause a rise in the water table sufficient to flood a repository at its current primary location; and (2) would changes in the position of the water table significantly alter the direction and rate of ground-water flow near the primary repository location?

Acknowledgments

The author is indebted to R. K. Waddell, W. E. Wilson, F. E. Rush, and Joe S. Downey, of the U.S. Geological Survey, for their assistance with the conceptualization of potential, future recharge mechanisms. L. J. Torak and R. L. Cooley, of the U.S. Geological Survey, provided the computer code used to perform the simulations, as well as valuable suggestions related to its use. The investigation was conducted for the U.S. Department of Energy under Interagency Agreement DE-AI08-78ET44802 as part of the Nevada Nuclear Waste Storage Investigations.

Previous Work

The hydrology of the Nevada Test Site and surrounding areas was discussed in reports by Winograd and Thordarson (1975) and Waddell (1982). Waddell developed a two-dimensional, finite-element, ground-water flow model of the Nevada Test Site and vicinity and provided background information for subsequent modeling of this flow system. Czarnecki and Waddell (1984) analyzed the flow system in the vicinity of Yucca Mountain using a two-dimensional, finite-element, parameter-estimation model; the parameters and baseline conditions for the model presented in this report are derived from their work.

Paleoclimatological analyses of the region were made by Spaulding (1983), and Spaulding and others (1984); these authors presented a reconstructed history of climatic conditions within and near the Nevada Test Site, based on analyses of vegetation remains found in fossil pack-rat middens. These analyses provided preliminary estimates of maximum-expected average annual and seasonal precipitation within the modeled area. Walker and Eakin (1963) reported on the hydrology of the Amargosa Desert and established empirical regional relationships between annual precipitation and annual recharge to the ground-water system. Rush (1970) estimated modern-day ground-water recharge rates in the modeled area, based on an adaptation of the empirical procedure of Eakin and others (1951).

GENERAL HYDROGEOLOGY OF THE MODELED AREA

The hydrogeology of the modeled area is complex and involves ground-water flow through a variety of lithologies. In general, ground water in the northern part of the modeled area (fig. 1) flows through volcanic rocks; whereas in the southern part (Amargosa Desert) ground water flows through alluvium and probably underlying carbonate rocks. Flow through carbonate rocks occurs in the easternmost area (Rock Valley) and beneath the Funeral Mountains. The area represented by the finite-element model is shown in figure 1 and is identical to the area modeled in Czarnecki and Waddell (1984). More complete descriptions of the hydrogeology of the modeled area are contained in Winograd and Thordarson (1975), Waddell (1982), Czarnecki and Waddell (1984), and Waddell and others (1984).

MODELING OF THE GROUND-WATER FLOW SYSTEM

Description of Computer Program

The finite-element computer program used in the simulations of this study is **FEMOD** developed by R. L. Cooley and L. J. Torak of the U.S. Geological Survey (written commun., 1984). The program uses triangular elements with linear-basis functions and the extended-Galerkin method of weighted residuals. The program is modular in design, so that a series of subroutines may be linked together by the main program to provide many different options for solving ground-water flow problems, including nonlinear water-table problems. Boundary conditions may be specified as point, line, or areally distributed sources or sinks, depending on the nature of the field problem to be solved. Fluxes from these boundaries may be specified, or, may be computed as a function of aquifer hydraulic head during the simulation. Examples of these head-dependent fluxes are flows derived from specified-head boundaries and evapotranspiration. Flow parameters, such as transmissivity or hydraulic conductivity, storage coefficient, hydraulic conductivity of confining layers, and rates of areally distributed recharge, may be specified for individual finite elements or for sets of finite elements (zones).

The solution algorithm incorporated in the program uses a modified incomplete-Cholesky, conjugate-gradient method to solve equations of flow for hydraulic head at each node in the model. This algorithm is coupled with an iterative process that automatically damps computed hydraulic-head changes to permit solution of steady-state, water-table, ground-water flow problems. Specific storage for these steady-state problems was set equal to zero, because the solution is not time dependent.

Model Variables

Boundary Fluxes

Boundaries of the modeled area generally coincide with boundaries of the ground-water basin, where either ground-water divides or streamlines are believed to occur. Along most of these boundaries, no flux into or out of the model is allowed; however, in several places a ground-water flux, Q , was specified across the model boundary. These fluxes are either positive (water is entering the flow system); or negative (water is leaving the flow system). The fluxes specified in the model for the present-day flow regime are summarized in table 1 and shown schematically in figure 2. Flux values given in table 1 are the same as those in Czarnecki and Waddell (1984).

Areally Distributed Fluxes

In addition to boundary fluxes, which may be considered as a linear distribution of flow into or out of the model, areally distributed fluxes also were specified. A recharge rate of 0.41 m/a was applied along Fortymile Wash (Q_{fm} , fig. 2). This value was obtained through trial and error during the parameter-estimation modeling (Czarnecki and Waddell, 1984); the value is assumed to be the average annual recharge occurring through the stream channel. During that modeling effort, other areally distributed fluxes (recharge into Timber Mountain, Jackass Flats, Crater Flat, and the Funeral Mountains) were considered to be insignificant. Simulations involving increases in recharge required that additional areally distributed fluxes be specified. A discussion of these additional areally distributed fluxes is presented in subsequent sections.

Land-Surface Altitudes

Accurate land-surface altitudes were required to simulate conditions where the water table might rise to the level of land surface. Land-surface altitudes for the modeled area were obtained in digital format from the National Cartographic Information Center (NCIC) of the U.S. Geological Survey and from published topographic maps of the area. Altitudes were obtained for each nodal point in the finite-element mesh by searching through the NCIC computerized data files for a data point located within a radius of 500 m from the nodal point. Altitudes were verified by comparing contour maps of nodal altitudes with U.S. Geological Survey 1:250,000-scale topographic maps of the area. The agreement in contoured altitudes generally was very good (within 10 m), particularly where land-surface-altitude changes were gradual (the greater part of the modeled area); exceptions were in mountainous areas where small inaccuracies in locating the closest altitude-data point might result in altitude discrepancies of as much as 200 m.

Table 1.--Model variable values

[Q, flux, in cubic meters per second (cubic meters per day); K, hydraulic conductivity, in meters per second (meters per day); number following letter is zone number; rv, Rock Valley; jf, Jackass Flats; wad, Western Amargosa Desert; fm, Fortymile Canyon; am, Ash Meadows; tm, Timber Mountain]

Model variable	Value	Dominant lithology
Q _{rv} -----	0.1249E-01 (1,079)	-----
Q _{jf} -----	.1835E-02 (158.5)	-----
Q _{wad} -----	.2244E-03 (19.39)	-----
Q _{fm} -----	.2563 (22,140)	-----
Q _{am} -----	.8990E-03 (77.67)	-----
Q _{tm} -----	.2959 (25,570)	-----
K1,K2-----	.1691E-04 (1.461)	Alluvium
K3-----	.1484E-05 (.1282)	Volcanic rocks
K4-----	.1000E-05 (.864)	Carbonate rocks
K5-----	.1480E-03 (12.790)	Do.
K6,K7,K8-----	.4229E-04 (3.654)	Tuffaceous rocks
K9-----	.1105E-05 (.0954)	Do.
K10-----	.9100E-06 (.0786)	Do.
K11-----	.4500E-07 (.0038)	Do.
K12-----	.1000E-08 (.00086)	Lakebeds, alluvium

Evapotranspiration

An increase in the rates of recharge would cause a rise in the position of the water table and conceivably could cause new areas of ground-water discharge to form. Water leaving the ground-water system either would evaporate or run off. Extensive lakes or ponds probably would not form in the modeled area, because no closed basins are present. Removal of water from the ground-water system is simulated in the model through the use of an evapotranspiration coefficient. The coefficient in this case is 1×10^{-5} m/s (8.64×10^{-1} m/d) per unit area at land surface; the value decreases linearly to zero at an extinction depth of 5 m below land surface. A large evapotranspiration coefficient was set to prevent any rise in water table above land surface. The procedure serves to remove water from the modeled area that might have left by surface-water runoff or evapotranspiration. The evapotranspiration function was not expected to be activated throughout the entire modeled area. The function was used as a head-dependent discharge mechanism to quantify the existing ground-water discharge and to locate and quantify additional discharges in relation to increased recharge. The 5-m extinction depth is considered to be the maximum depth to which bare-soil evaporation could occur.

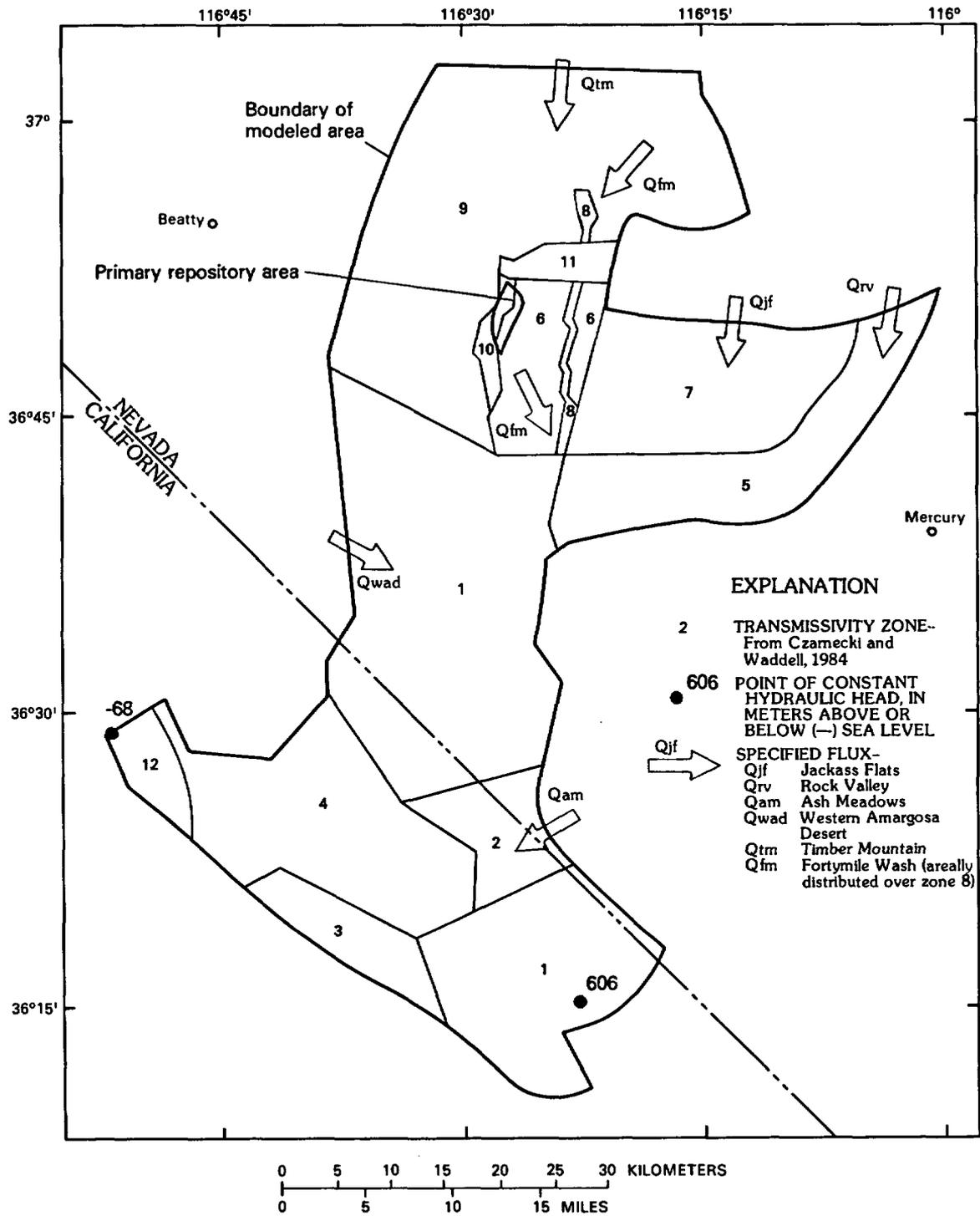


Figure 2.--Model boundary fluxes, constant-head nodes, and transmissivity zones.

Constant-Head Nodes

Two constant-head (or specified-head) nodes are specified at discharge areas in Franklin Lake playa (altitude, 606 m) at the southern end of the modeled area, and at Furnace Creek Ranch in Death Valley (altitude, -68 m), in the southwestern part of the modeled area (fig. 2). Hydraulic-head values at these nodes were estimated from values of land-surface altitude.

Hydraulic Conductivities

The ground-water flow system in the modeled area is considered to be unconfined. Hydraulic conductivities (table 1) were determined by dividing transmissivity values from parameter-estimation runs by an assumed uniform saturated thickness of 1,000 m throughout the modeled area. Location of transmissivity zones were based on the zonation used in Czarnecki and Waddell (1984) and are illustrated in figure 2. Saturated thicknesses are not well known for the model area. The assigned value (1,000 m) was estimated from drillhole information [Yucca Mountain (Benson and others, 1983) and the Amargosa Desert (Walker and Eakin, 1963)] and resistivity surveys in the Amargosa Desert (Greenhaus and Zablocki, 1982).

Transmissivity zones are from an improved version of the model reported in Czarnecki and Waddell (1984). The improvement consists of subdividing the transmissivity zone assigned to the Amargosa Desert into three distinct areas, shown in figure 2: Zone 1 (consisting of a northern and southern section, both assigned the same transmissivity); and zone 2 (assigned a smaller value of transmissivity corresponding to a steeper hydraulic gradient). Model results showed a decrease in the range of residuals (-18.9 to +21.0 m) and a decreased estimated sum-of-squared errors for measured-versus-calculated hydraulic heads ($4,101.4 \text{ m}^2$), compared to those values reported in Czarnecki and Waddell (1984).

Modeling Results

Baseline Simulation

Several cases involving changes in recharge conditions were simulated using the finite-element, ground-water flow model, FEMOD. This model is different from the parameter-estimation model used by Czarnecki and Waddell (1984) and revised during their investigation. Prior to modifying model variables used in FEMOD, a baseline simulation of the ground-water flow system was made, using the same values for most of the variables that were used in the original (Czarnecki and Waddell, 1984) and revised parameter-estimation model simulations. Variables that were changed included the constant-head boundary conditions, which were changed for the baseline simulation from the upstream, northernmost edge of the modeled area near Timber Mountain (used in the parameter-estimation model) to the two previously mentioned constant-head nodes.

Also, incoming fluxes were specified across the northern boundary of the model for the baseline simulation (Q_{tm} , fig. 2), based on flux estimates from the parameter-estimation modeling results. These flux specifications were made to allow for the subsequent specification of different flux rates across the northern boundary that would correspond to various increased recharge rates. By specifying constant-head boundary conditions at Franklin Lake playa and Furnace Creek Ranch (two modern-day discharge areas), a more appropriate boundary condition was imposed. This condition allowed for variable discharge rates at these nodes as incoming flux was increased in subsequent simulations, corresponding to increased recharge.

Because the water table is very near or at land surface in Death Valley, an altitude 5 m below land surface was selected as the specified value of head at the Furnace Creek constant-head node (-68 m). The water table also is very near the surface at Franklin Lake playa; a value of 606 m was selected for this constant-head node. These specifications of hydraulic head were made to correspond to a depth of 5 m below land surface to be consistent with the extinction depth of 5 m assigned for use with the head-dependent sink function (evapotranspiration nodes). Specification of extinction depths less than 5 m led to numerical instabilities in the model, causing mass-balance errors.

Contours of the simulated values of hydraulic head for the modern-day, baseline ground-water flow system are shown in figure 3. As a comparison, contours based on measured hydraulic-head values and the approximate location of these measurement sites are shown in figure 4.

Because the arrangement of constant-head nodes in these simulations is significantly different from that used for the parameter-estimation model simulations, special consideration was given to the hydraulic gradients and transmissivities in the vicinity of these nodes. The simulated hydraulic gradient is affected by local ground-water flux near the node and by the transmissivity of the zone containing the specified-head node. While specifying a value for a constant-head node insures that the hydraulic head will remain constant at that node throughout the simulation, the constant-head node alone cannot generate the proper hydraulic-head distribution in its vicinity to give the correct, or expected, hydraulic gradients. By adjusting values of transmissivity upgradient from the constant-head nodes, an attempt was made to match simulated hydraulic heads obtained from the baseline simulations to those obtained from the parameter-estimation simulations in the area immediately upgradient from the constant-head node at Furnace Creek Ranch. Generally, simulated hydraulic-head values obtained from the baseline simulation, when compared to simulated hydraulic-head values obtained from the parameter-estimation model, differed by 10 m or less in the Amargosa Desert and by about 1 m or less near Yucca Mountain (fig. 5). The greatest deviation occurred in the Furnace Creek discharge area, resulting from the change in boundary conditions and transmissivities assigned in this area. This area also contained the fewest number of measurement sites and a steep hydraulic-head gradient, making it difficult to compare against modeled results.

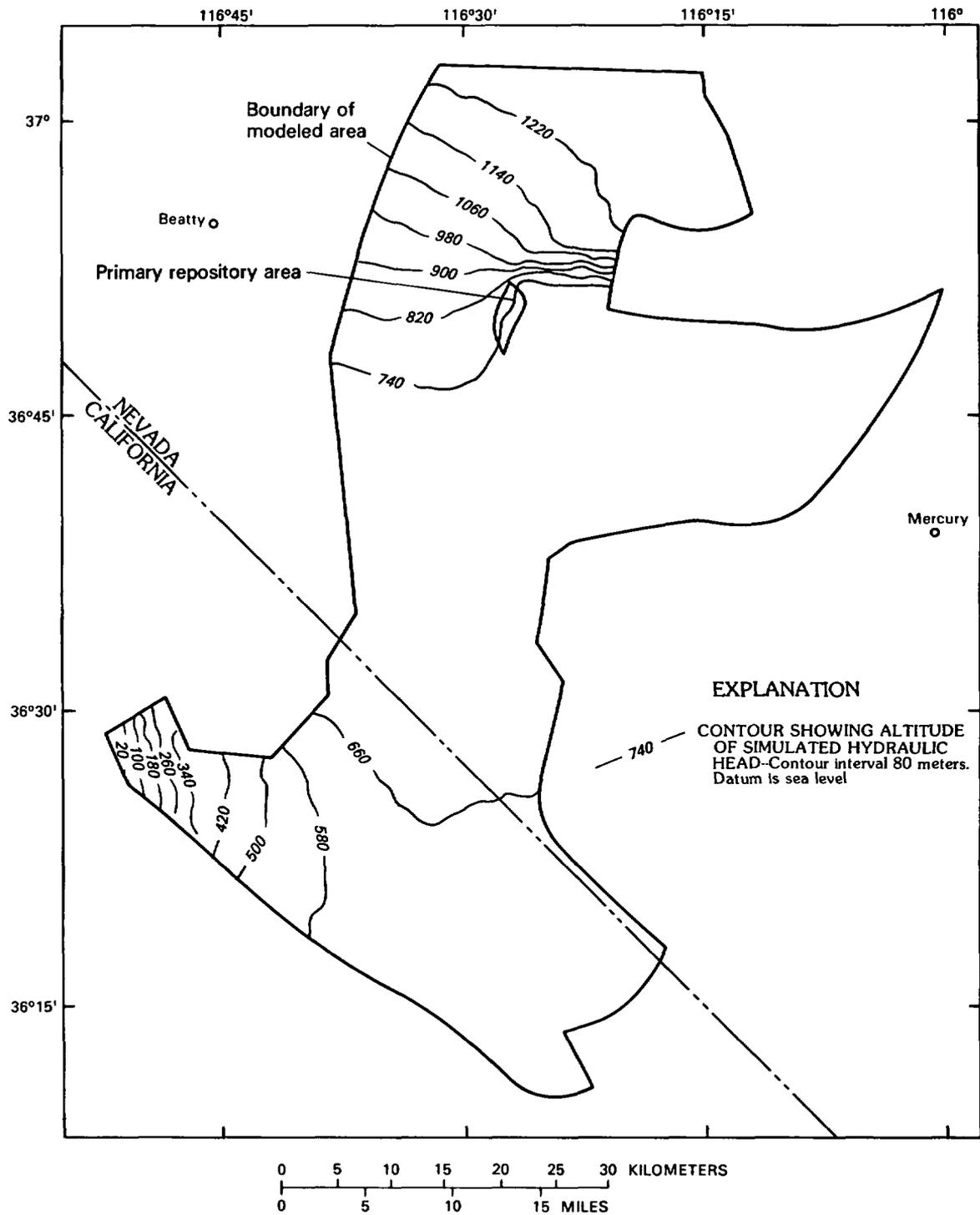


Figure 3.--Simulated hydraulic head for the baseline-condition simulation.

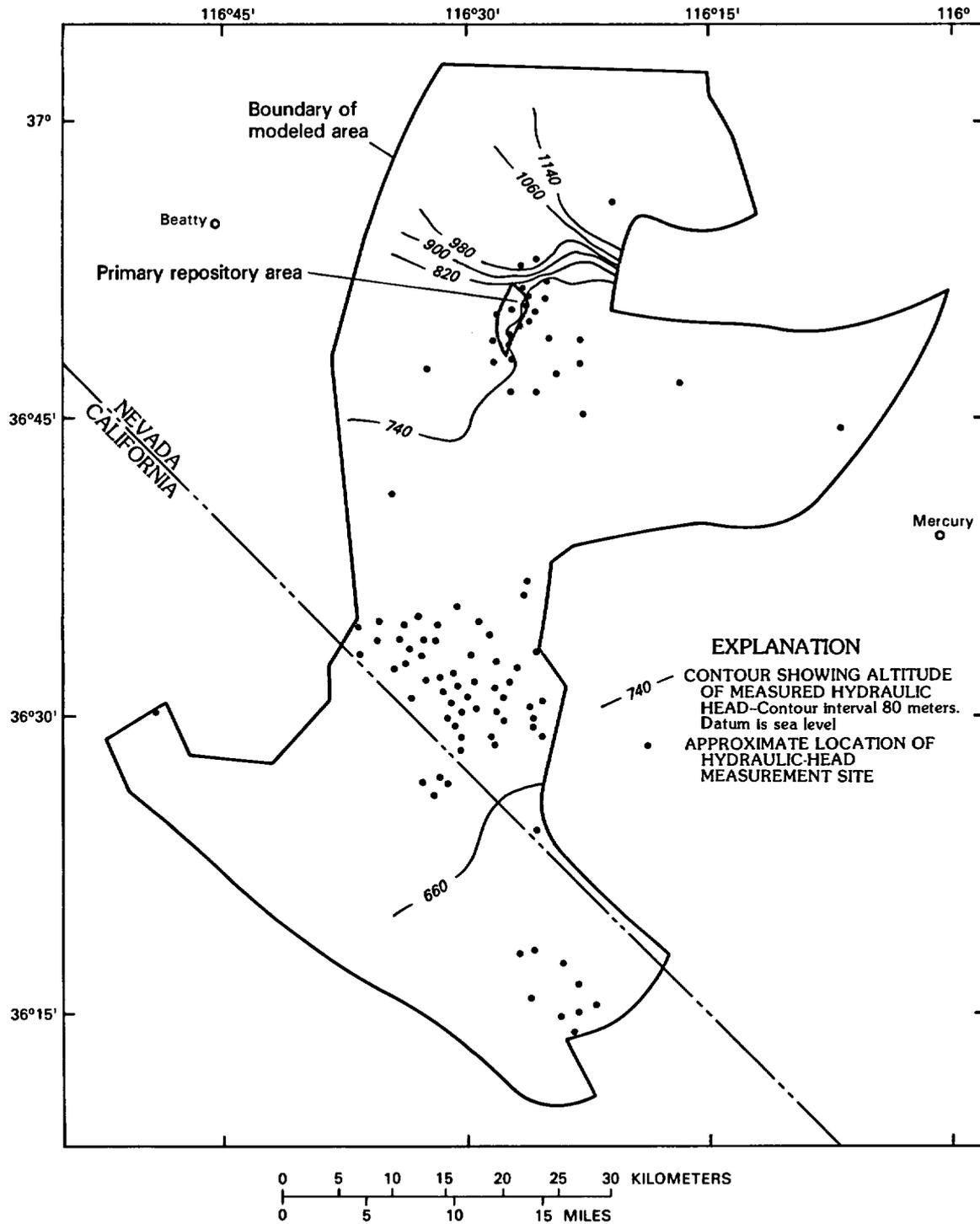


Figure 4.--Measured hydraulic head and location of measurement sites.

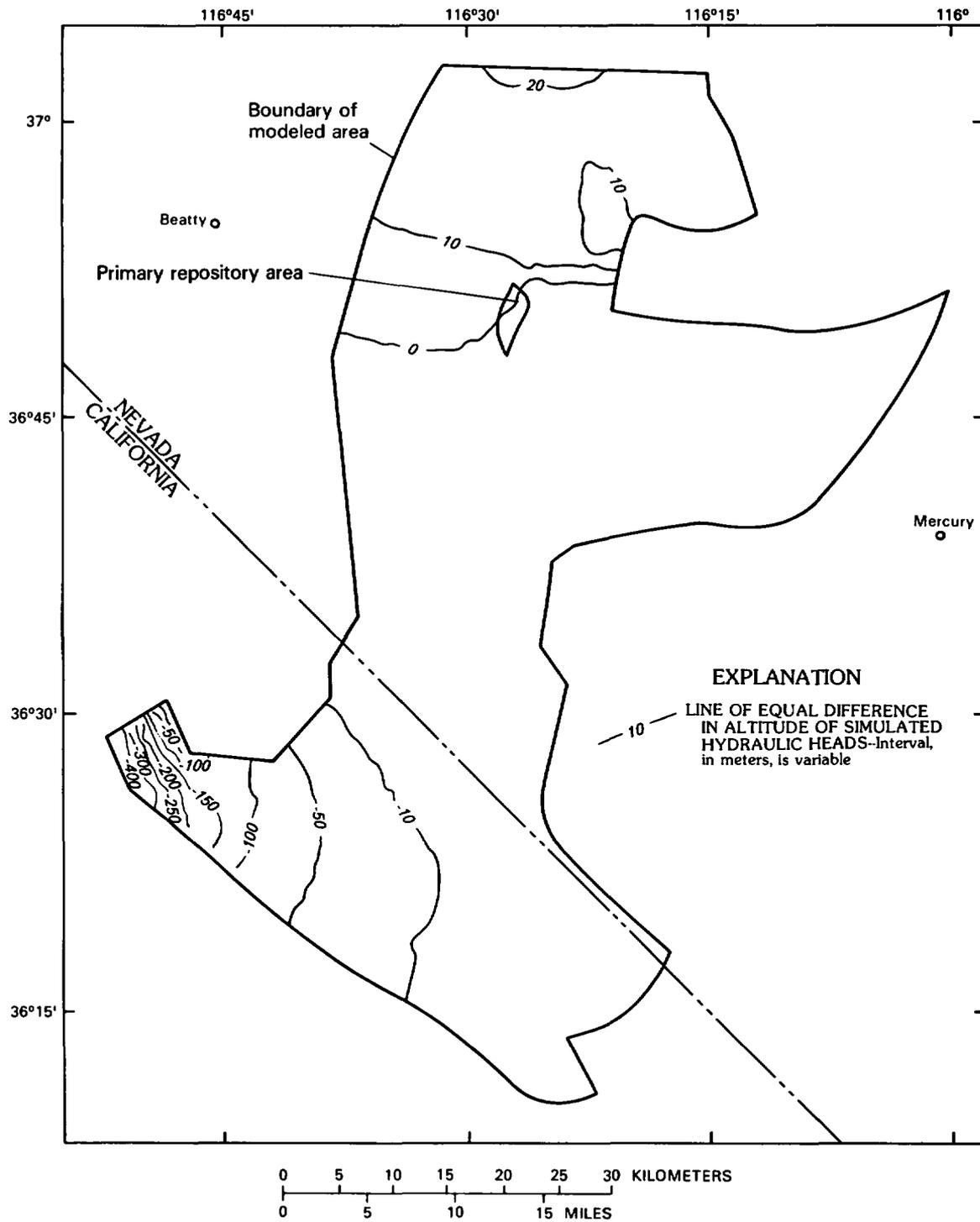


Figure 5.--Difference in simulated hydraulic head between baseline-simulation results and parameter-estimation-simulation results.

The location of areally distributed head-dependent sinks (evapotranspiration nodes) and contours of discharge rates associated with the baseline simulation are shown in figure 6. These sinks are located where the water table has risen to within 5 m of land surface.

Simulation of Increased Ground-Water Recharge

Recharge estimation

Based on the work of Spaulding (1983) and Spaulding and others (1984), in which the authors evaluated changes in vegetation and climate of the last 45,000 years in the vicinity of the Nevada Test Site, a maximum increase in precipitation of 100 percent compared to modern-day, average annual precipitation was assumed for Yucca Mountain and vicinity. To simulate the effect of increased precipitation on the position of the water table, estimates of both modern-day and future increased recharge rates were required.

The distribution of average annual precipitation in the modeled area and vicinity is illustrated in figure 7. Based on this distribution, three ranges or zones of precipitation were delineated within the modeled area. Zone 1 (fig. 7) corresponds to a range of precipitation of about 6 to 10 in./yr (152 to 254 mm/a); zone 2 (which is actually two distinct areas) corresponds to a range of precipitation of about 3 to 6 in./yr (76 to 152 mm/a). In Zone 3, in the Amargosa Desert and near Death Valley, precipitation is less than 3 in./yr (76 mm/a).

Rush (1970) estimated average annual ground-water recharge to areas in and around the modeled area using a technique developed by Eakin and others (1951). (This technique uses inch-pound units of measure, which are used in tables 2 and 3 of this report.) These estimated recharge rates were based on measuring areas of a ground-water basin that were within a specified altitude range, then assigning a corresponding estimate of precipitation and associated percentage of precipitation infiltrating as recharge. Larger precipitation ranges were assigned larger percentages of estimated recharge. By measuring the areas corresponding to altitude ranges in a specific ground-water basin, Rush (1970) estimated precipitation and corresponding recharge volumes.

Rush's (1970) results were applied to the precipitation zones delineated in this investigation. Recharge for zone 1 occurs principally within Gold Flat and Buckboard Mesa, north of zone 1; zone 2 is within Jackass Flats and Crater Flat; and zone 3 is within the Amargosa Desert. From Rush's (1970) report (see table 2), recharge in zone 1 was calculated to be 2.6 mm/a in the Gold Flat part and 2.8 mm/a in the Buckboard Mesa part. Recharge in zone 2 was calculated to be 0.7 mm/a. In the analysis of zone 2, precipitation zones above 6,000 ft (1,829 m) in altitude were omitted, because they do not occur in the area defined by zone 2. Because of the minimal precipitation in zone 3, it was assumed that minor recharge occurs in this zone.

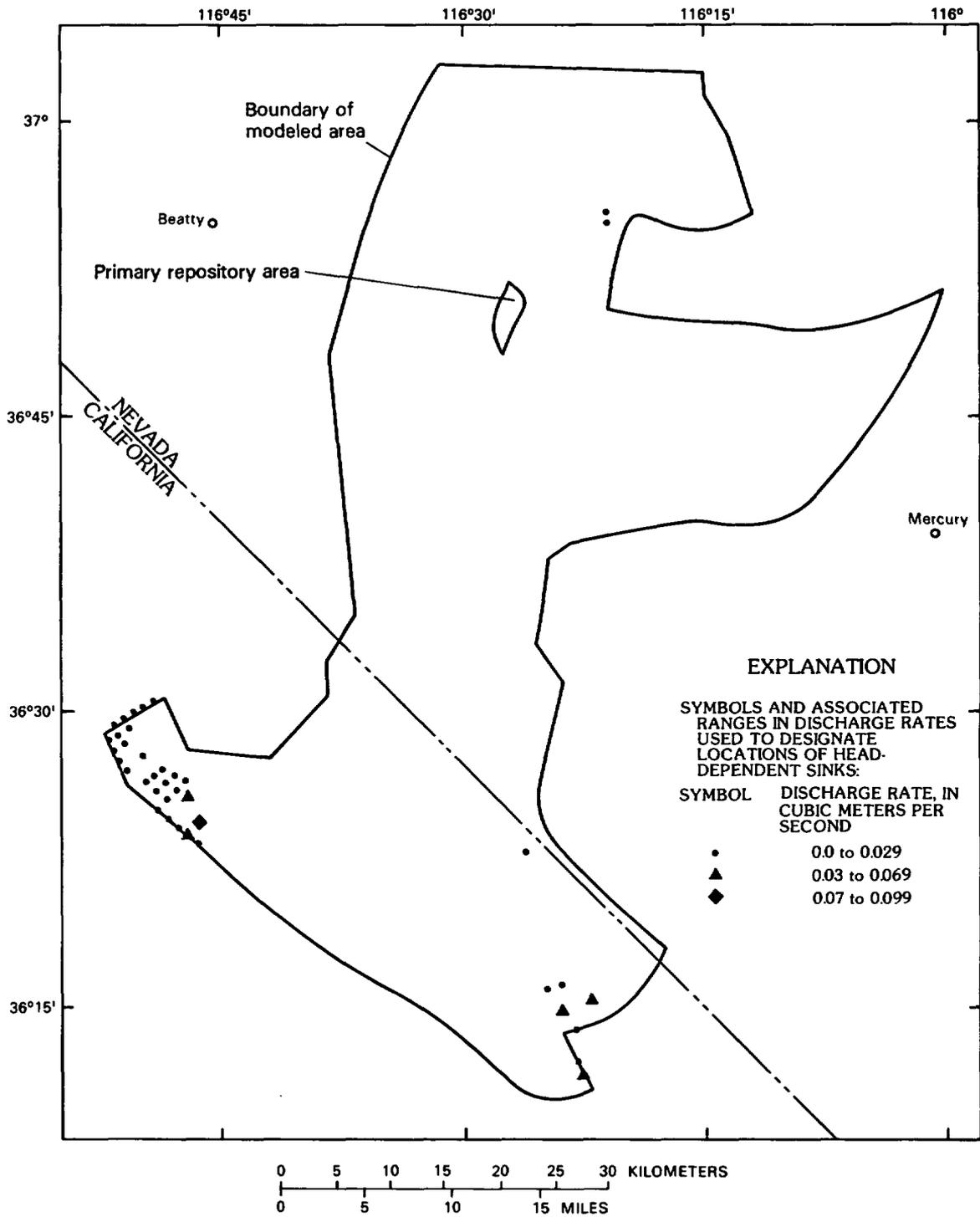


Figure 6.--Location of head-dependent sinks for baseline simulation.

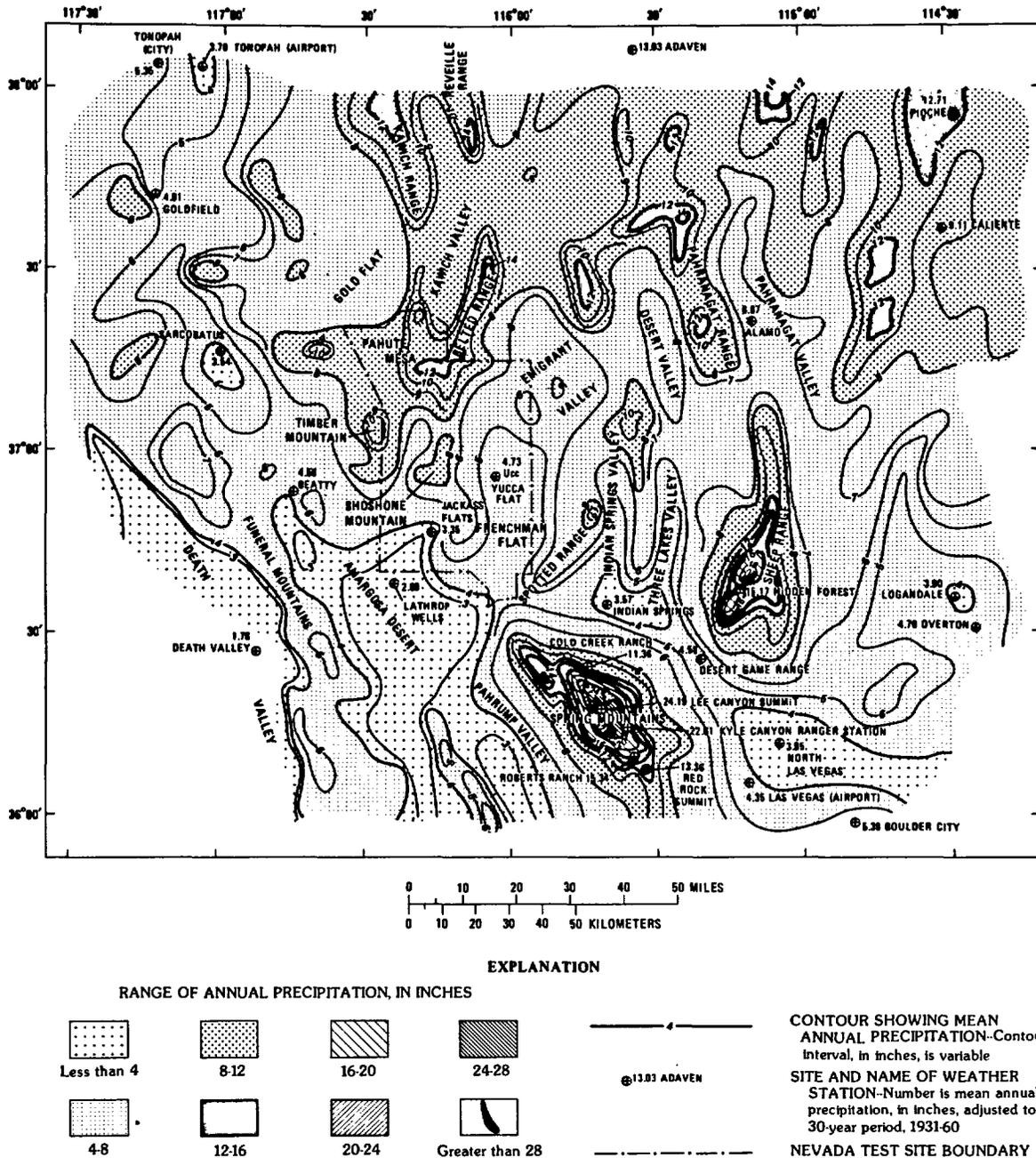


Figure 7.--Mean annual precipitation and model zonation for recharge.

Table 2.--Modern-day estimated average annual precipitation and resultant recharge at Jackass Flats, Crater Flat, Buckboard Mesa, and Gold Flat

[Modified from Rush, 1970, table 3]

Altitude zone (thousands of feet)	Area (acres)	Estimated precipitation			Estimated recharge	
		Range (inches)	Average (feet)	Average (acre-feet)	Percent of Precipitation	Acre-feet
Jackass Flats						
<u>(western two-thirds)</u>						
>7	Minor	>15	1.5	-----	15	-----
6-7	3,280	12-15	1.1	3,600	7	250
5-6	14,300	8-12	.8	11,000	3	330
<5	<u>101,000</u>	<8	<u>.5</u>	<u>50,000</u>	<u>Minor</u>	<u>-----</u>
Subtotal (rounded)	119,000		0.5	65,000	0.9	580
Crater Flat						
>6	220	>12	1.1	240	7	20
5-6	8,080	8-12	.8	6,500	3	200
<5	<u>108,000</u>	<8	<u>.5</u>	<u>54,000</u>	<u>Minor</u>	<u>-----</u>
Subtotal (rounded)	116,000		0.5	61,000	0.4	220
Buckboard Mesa						
>7	6,400	>12	1.1	7,000	7	490
6-7	39,400	8-12	.8	32,000	3	960
<6	<u>105,000</u>	<8	<u>.5</u>	<u>52,000</u>	<u>Minor</u>	<u>-----</u>
Subtotal (rounded)	151,000		0.6	91,000	2	1,400
Gold Flat						
>8	1,260	>15	1.5	1,900	15	280
7-8	17,400	12-15	1.1	19,000	7	1,300
6-7	91,000	8-12	.8	73,000	3	2,200
<6	<u>325,000</u>	<8	<u>.5</u>	<u>160,000</u>	<u>Minor</u>	<u>-----</u>
Subtotal (rounded)	435,000		0.6	250,000	2	3,800

Table 3.--Estimated maximum precipitation (100 percent greater than modern-day conditions) and resultant recharge at Jackass Flats, Buckboard Mesa, and Gold Flat

[Modified from Rush, 1970, table 3]

Altitude zone (thousands of feet)	Area (acres)	Estimated precipitation			Estimated recharge	
		Range (inches)	Average (feet)	Average (acre-feet)	Percent of Precipitation	Acre-feet
<u>Jackass Flats</u> (western two-thirds)						
>7	Minor	>30	2.5	-----	--	-----
6-7	3,280	24-30	2.25	7,400	25	1,900
5-6	14,300	16-24	1.67	24,000	15	3,600
4-5	25,000	10-16	1.1	28,000	7	2,000
4	¹ 25,000	<10	0.8	20,000	3	1,600
Subtotal (rounded):						8,000
Modern-day subtotal (from table 2) (rounded):						580
Ratio (increased/modern) (rounded):						14
<u>Buckboard Mesa</u>						
>7	6,400	>24	2.0	13,000	25	3,200
6-7	39,400	16-24	1.67	66,000	15	9,900
<6	105,000	10-16	1.1	116,000	7	8,100
Subtotal (rounded):						21,000
Modern-day subtotal (from table 2) (rounded):						1,400
Ratio (increased/modern) (rounded):						15
<u>Gold Flat</u>						
>8	1,260	>30	2.5	3,200	25	800
7-8	17,400	24-30	2.25	39,000	25	10,000
6-7	91,000	16-24	1.67	152,000	15	23,000
5-6	² 100,000	10-16	1.1	110,000	7	7,700
4-5	² 225,000	10	.8	180,000	3	5,400
Subtotal (rounded):						47,000
Modern-day subtotal (from table 2) (rounded):						3,800
Ratio (increased/modern) (rounded):						12

¹Estimated area receiving more than 8 inches of precipitation in altitude zone.

²Estimated for precipitation zone based on the division of the less than 6,000-foot zone of Rush (1970, table 3).

The technique of Eakin and others (1951) used by Rush (1970) to estimate recharge was compared by Crosthwaite (1969) and Watson and others (1976) to other methods of estimating recharge. They concluded that the method was suitable for obtaining only a very approximate estimate of recharge. No method was considered to be fully reliable in predicting recharge, although the method of Eakin and others (1951) has been used extensively in basin studies in Nevada. This method ignores topographic slope and aspect and only indirectly includes rock lithology and vegetation type and density. With this technique, drainage channels are treated the same as other areas, because recharge, although assigned to defined areas, may not occur in these areas resulting from infiltration of runoff elsewhere. Recharge beneath channels probably is greater, because surface runoff is concentrated in them. Conversely, the method does not account for runoff during intense storms and consequent loss of water by runoff from the basin. Additionally, recharge is related to numerous factors besides average annual precipitation. These factors include rainfall distribution and intensity, snowmelt, temperature, and vegetative cover.

In the Yucca Mountain area, runoff occurs periodically in Fortymile Wash, carrying potential recharge water away from zone 1. Because of this factor, and because of the considerable uncertainty associated with applying the method of Eakin and others (1951) to zones within the modeled area, the recharge rates were set as follows for purposes of modeling baseline conditions: zone 1, 2.0 mm/a; zone 2, 0.5 mm/a; and zone 3, minor recharge.

The parameter-estimation simulation presented in Czarnecki and Waddell (1984) did not include recharge to zones 1 and 2 because the estimated modern-day recharge rates in these zones (2 mm/a and 0.5 mm/a) were considered to be insignificant. Contours of hydraulic-head differences between the baseline simulation, with and without these recharge rates included, are shown in figure 8. The maximum difference in these hydraulic heads is about 9 m, which is small, considering the overall range in hydraulic-head values throughout the modeled area (about 1,300 m).

The empirical approach of Eakin and others (1951) also was used in this investigation to obtain estimates of potential increased recharge rates, based on paleoclimates described by Spaulding and others (1984). Annual precipitation 12,000 to 9,000 years before present in the modeled area may have been 100 percent greater than modern-day annual precipitation (Spaulding and others, 1984).

A 100-percent increase in modern-day precipitation is assumed in this study to be the probable maximum increase in the next 10,000 years. To obtain recharge volumes, precipitation values from Rush (1970) were increased 100 percent (multiplied by 2), and then multiplied by the percentage of precipitation occurring as recharge that is associated with similar precipitation values from Rush (1970). Increased flux across the northern boundary of the modeled area was assumed to occur, because of increased precipitation in recharge areas north of this boundary (Buckboard Mesa, Gold Flat, fig. 7). Increased vertical infiltration into Fortymile Wash also was assumed to occur, because of increased precipitation throughout the regional drainage basin for Fortymile Wash, resulting in surface-water runoff into Fortymile Wash.

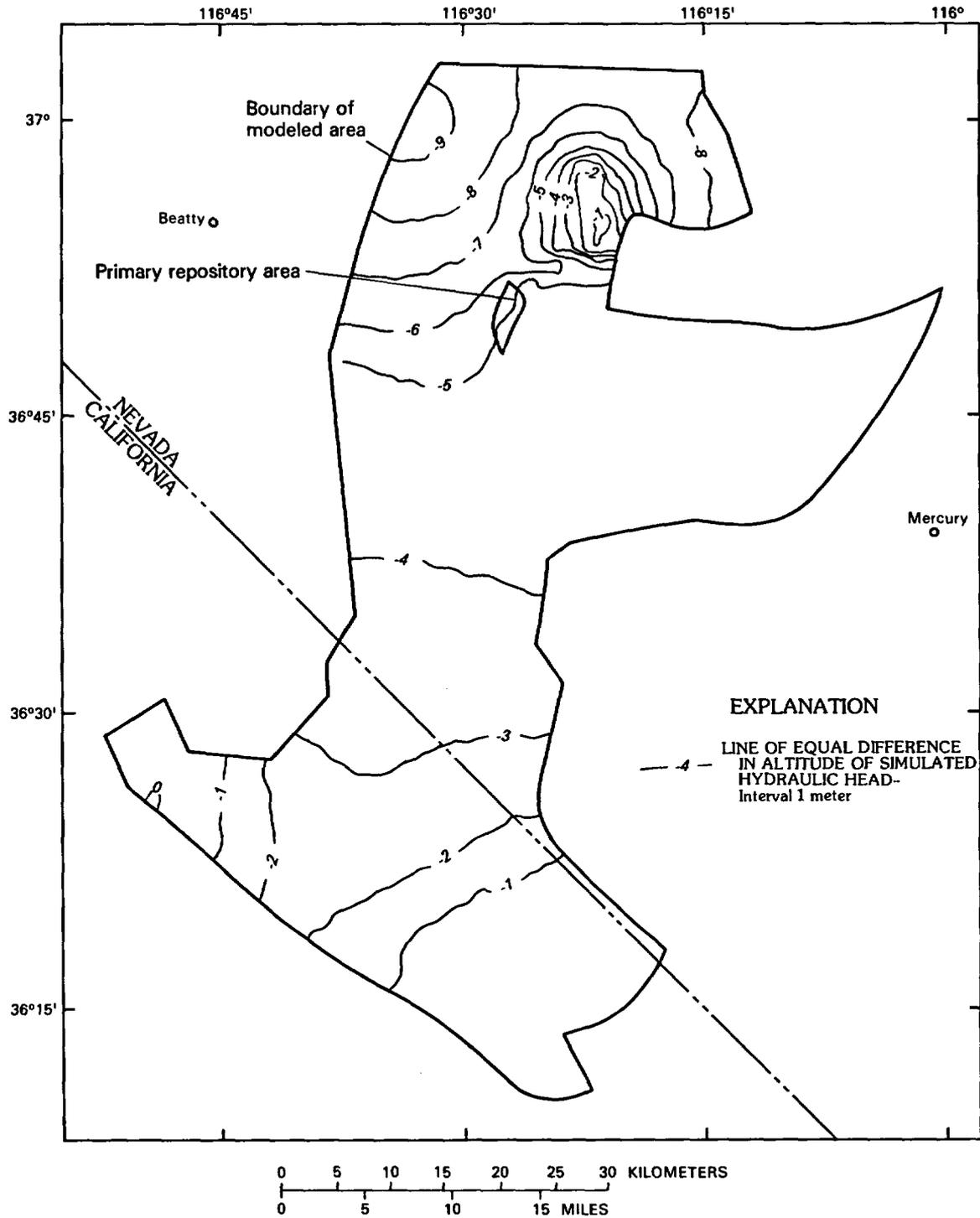


Figure 8.--Difference in simulated hydraulic head between simulations with and without recharge to zones 1 and 2.

Values of increased precipitation and corresponding recharge for areas associated with the study area are shown in table 3. The ratio of the total increased recharge to modern-day recharge is listed in table 3 for Jackass Flats, Buckboard Mesa, and Gold Flat (fig. 7). Buckboard Mesa and Gold Flat, while not in the modeled area, are considered in this report to be recharge areas, supplying ground water that ultimately flows across the northern boundary into the modeled area. Average increased recharge from a 100-percent increase in annual precipitation throughout these three areas is 13.7 times greater than estimates of modern-day recharge. For the purposes of this study, the average increase in recharge for the case of a 100-percent increase in annual precipitation was set at 15 times the modern-day recharge rate in all areas.

A comparison was made by F. E. Rush (U.S. Geological Survey, written commun., 1984) between: (1) The ground-water flow system beneath Yucca Mountain and vicinity, for conditions 100 percent wetter than modern; and (2) a modern analog area. The purpose of the comparison was to determine if the computed increased ground-water recharge for the study area was realistic, or whether some of the potential recharge would be runoff because infiltration limits would be exceeded; thus, some water would flow from the model area as runoff. Huntington Valley in northern Nevada (Rush and Everett, 1966) was selected for the comparison. This valley has the following similarities to the Yucca Mountain area for conditions 100 percent wetter than modern:

Factor	Value	
	Huntington Valley (three subareas)	Yucca Mountain area (precipitation increased by 100 percent in each of three subareas)
Maximum average annual precipitation in the area (based on maximum altitudes).	As much as 762 millimeters	762 millimeters or more
Average annual precipitation for the area.	335 millimeters	335 millimeters
Computed recharge as a percent of precipitation.	10 percent	10 percent

In Huntington Valley, much of the computed potential recharge occurs as runoff that flows from the valley to other downstream areas. Using the Eakin method of computation, the average annual recharge would be about 86,000 acre-ft/yr. However, the actual recharge to the ground-water system is 30,000 acre-ft/yr (Rush and Everett, 1966, p. 27), indicating that about two-thirds of the potential recharge is runoff. Thus, at Yucca Mountain, under a 100-percent increase in precipitation, large quantities of runoff may flow from the area down Fortymile Wash and other drainages. The effect would be to decrease the effective ground-water recharge to much less than the computed volumes used in the analyses of this report. On the basis of this comparison, the analyses presented in this report may show a greater water-table rise in the modeled area than if runoff were considered.

Hydraulic-head sensitivity analysis

Sensitivity of simulated hydraulic head was computed at five points in and around the primary repository area (fig. 9) for changes in recharge rates in zones 1 and 2, across the northern boundary of the modeled area, and in Fortymile Wash (zone 8, fig. 2). The sensitivity of simulated hydraulic heads to changes in specified recharge rates is shown in figures 10A through 10E. The purpose of these recharge-flux sensitivity analyses is, in part, to provide a range in results corresponding to the uncertainty in the value of applied maximum probable-recharge flux. The range was selected such that the actual value of recharge flux probably is included. One or all of the baseline-condition fluxes for zones 1 and 2 (2.0 and 0.5 mm/a), for the northern boundary of the modeled area (equal to those values obtained from the parameter-estimation results of Czarnecki and Waddell, 1984), and for Fortymile Wash (410 mm/a) were multiplied by different factors in later simulations to analyze the sensitivity of computed hydraulic heads to changes in these fluxes. The flux-multiplier ordinates in figures 10A through 10E represent the factors by which the baseline fluxes were multiplied. Fluxes were multiplied by 1 to 30 times their original baseline values. The multiplier of 15 times represents the maximum probable increase.

Of the four flux zones examined, changes made to fluxes from the northern boundary and Fortymile Wash had the greatest effect on the water-table position in the vicinity of the primary repository area. This effect resulted because the largest baseline fluxes were assigned at the northern boundary ($0.3 \text{ m}^3/\text{s}$) and at Fortymile Wash ($0.26 \text{ m}^3/\text{s}$). The sum of areally distributed baseline fluxes in zones 1 and 2 is only $0.05 \text{ m}^3/\text{s}$. This value was obtained by multiplying 2.0 mm/a times the area of zone 1 and adding it to the product of 0.5 mm/a times the area of zone 2. The change in water-table position resulting from applying the same multiplier simultaneously to all of the above fluxes is shown in figure 10E. The change in water-table position for a multiplier of 15 times the baseline fluxes (corresponding to a 100-percent increase in precipitation) is between +119 m and +129 m and results primarily from flux increases applied at Fortymile Wash (fig. 10E).

Changes in water-table position

Contours of simulated hydraulic head for the simulation involving a 100-percent increase in precipitation are shown in figure 11. In this simulation, additional spring discharge occurs as a result of the increased flux to the ground-water system; discharge location and rates are shown in figure 12.

The change in water-table position resulting from a 100-percent increase in precipitation compared to modern-day estimated precipitation is shown in figure 13. The maximum water-table rise near the primary repository area is about 130 m, less than the minimum distance between the potential base of the repository and the modern-day, water-table position (200 m) shown in figure 9. Therefore, for the case involving increased recharge resulting from the maximum probable increase in precipitation, the position of the primary repository area would be above the simulated water-table position.

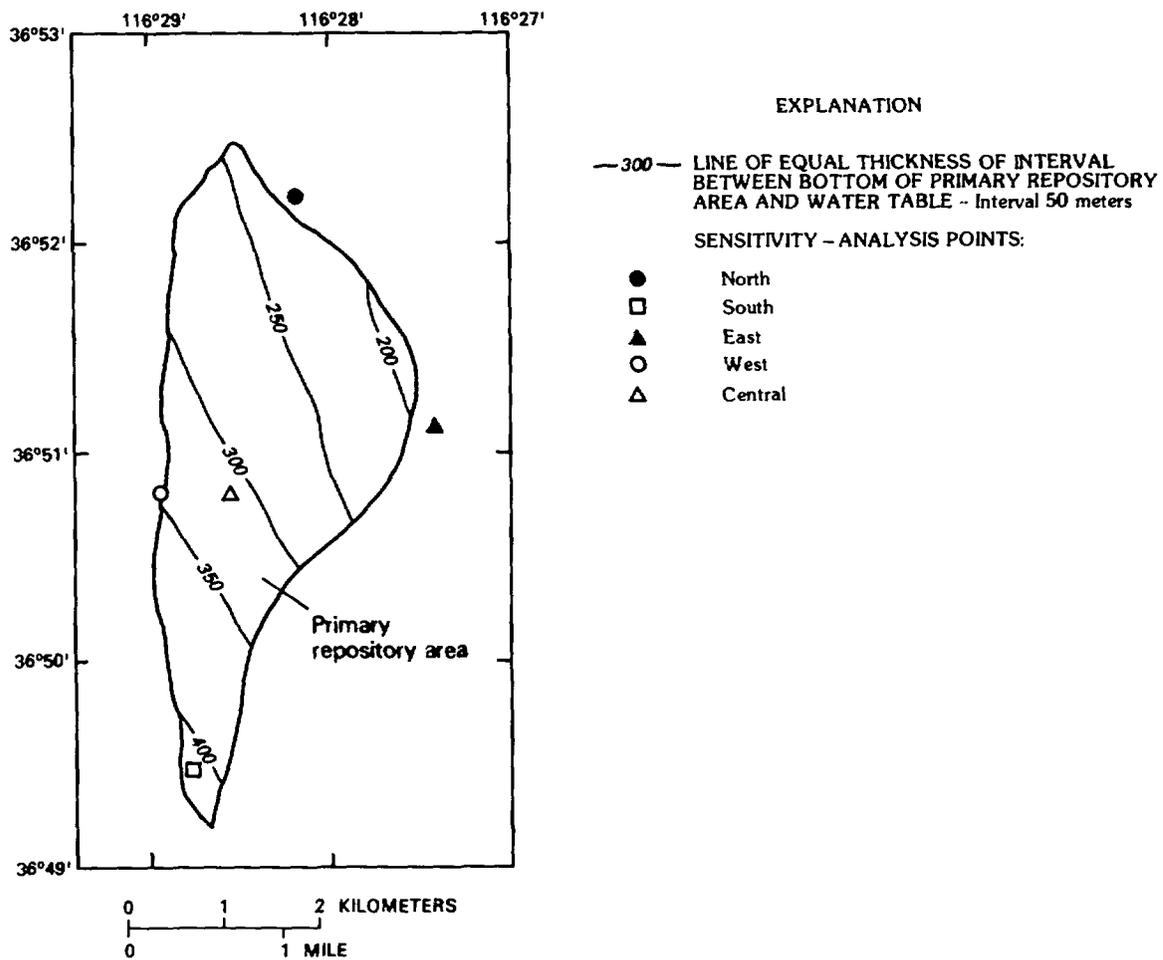


Figure 9.--Thickness of interval between bottom of potential repository and modern-day water table (J. H. Robison, U.S. Geological Survey, written commun., 1984).

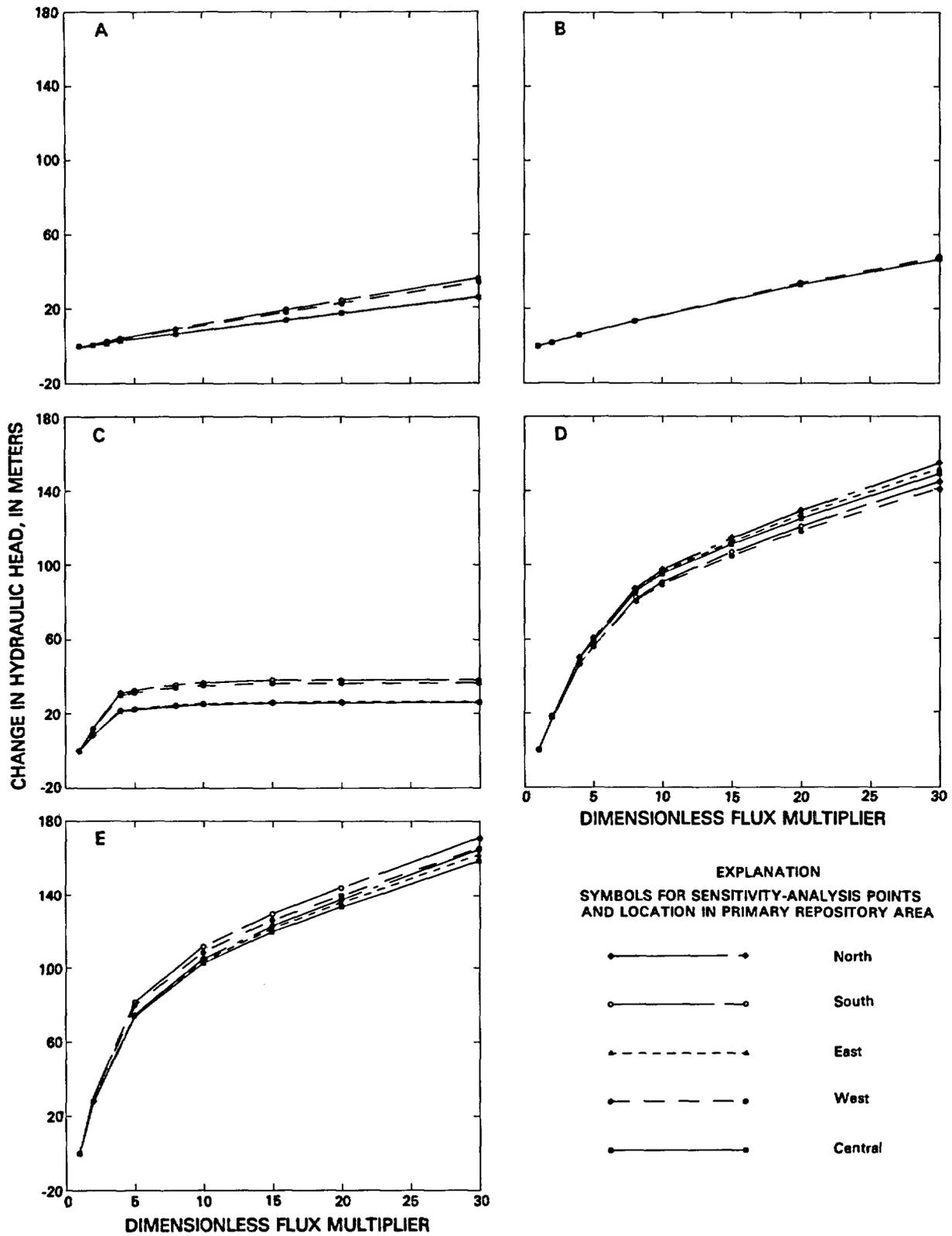


Figure 10.--Sensitivity of simulated hydraulic head to changes in flux: A, In zone 1; B, in zone 2; C, at northern boundary; D, at Fortymile Wash; and E, at all four flux locations.

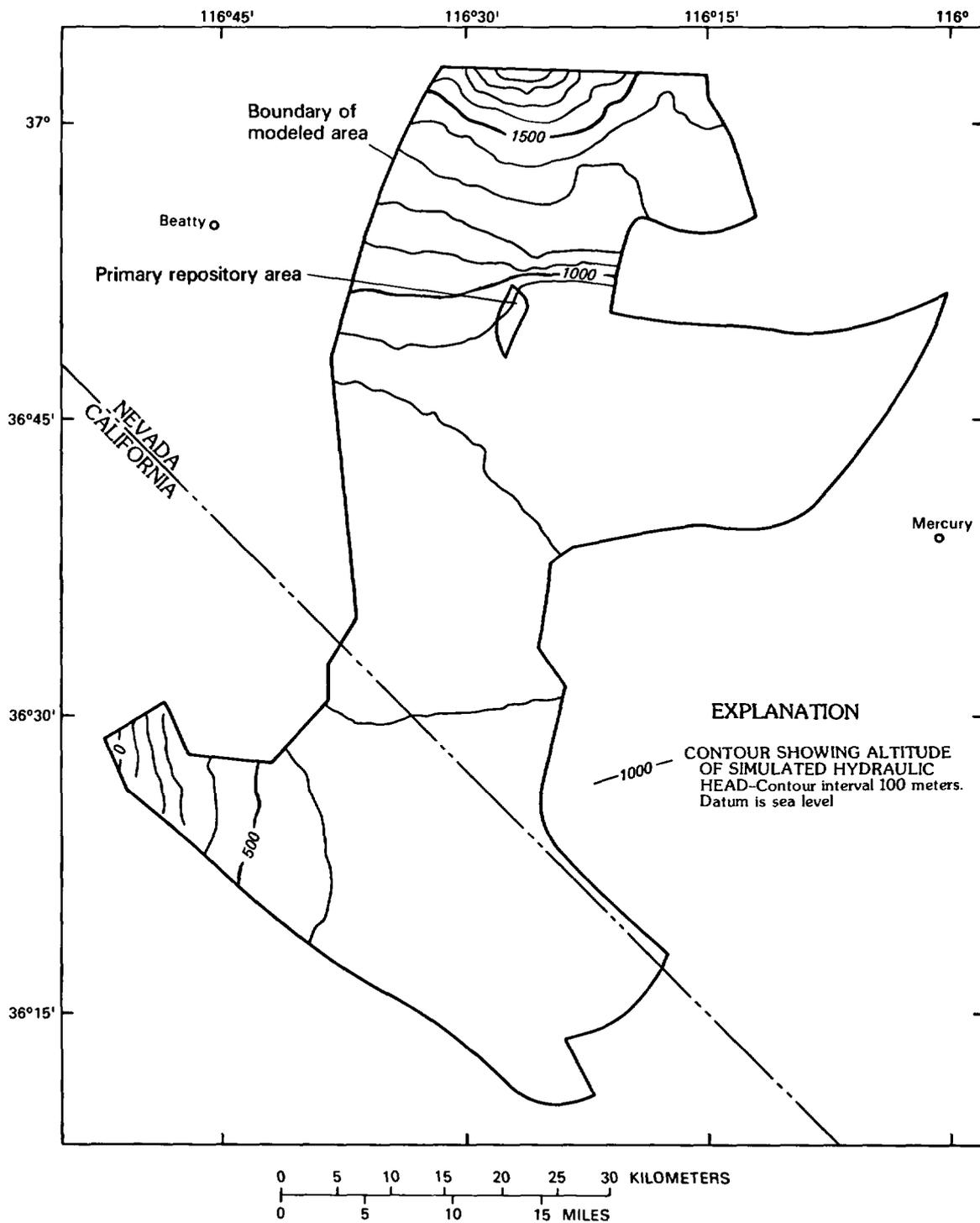


Figure 11.--Simulated hydraulic head for simulation involving a 100-percent increase in precipitation.

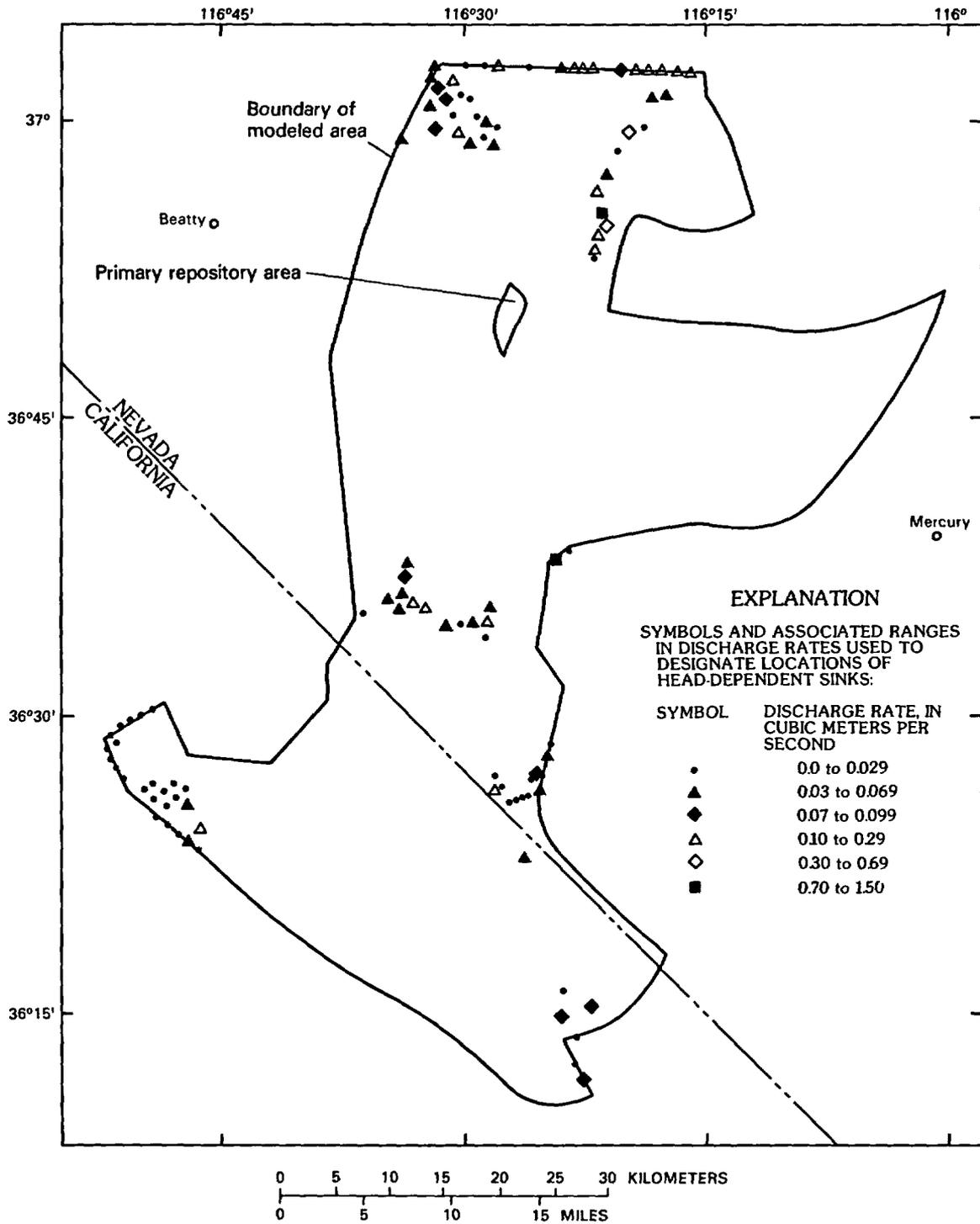


Figure 12.--Location of head-dependent sinks for simulation involving a 100-percent increase in precipitation.

From USGS WRI Report 84-4344 (J. Czarnecki, 1985)

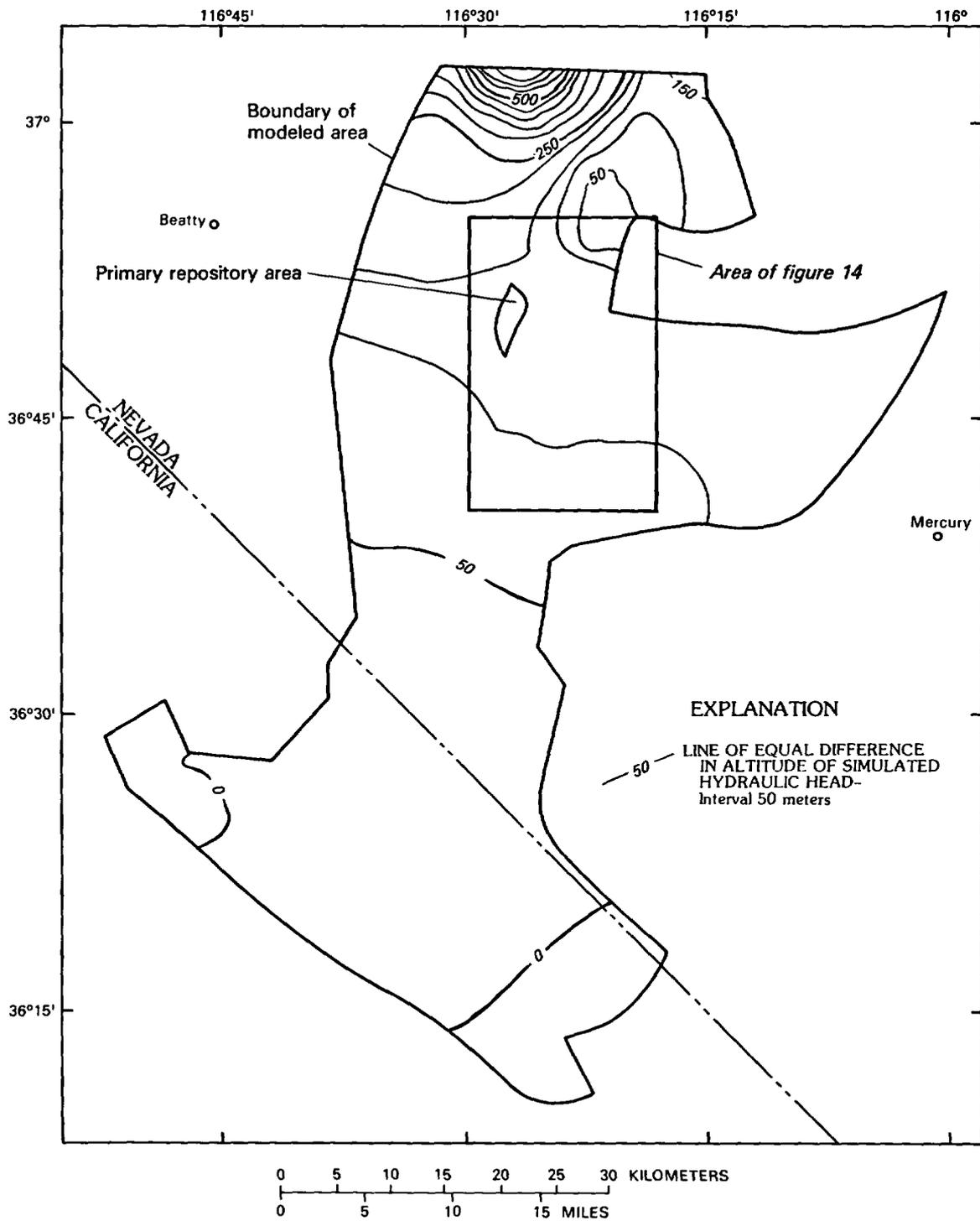


Figure 13.--Differences in simulated hydraulic head between baseline simulation and the simulation involving a 100-percent increase in precipitation.

Because these simulations assume uniform vertically averaged hydraulic conductivities, no allowance is made for water rising into hydrologic units that have hydraulic conductivities different from the average. Increasing the zone of saturation into less transmissive hydrologic units (such as the tuffaceous beds of Calico Hills), would decrease the overall, vertically averaged hydraulic conductivity. This decrease would result in a steeper gradient and higher water-table position. The opposite effect would occur if the water table rose into a more transmissive unit, such as the Topopah Spring Member of the Paintbrush Tuff of Miocene age. This unit might be a primary conduit for ground-water flow, limiting the altitude to which the water table would rise. However, under the conditions simulated, this effect would not occur, because the simulated water-table rise of 130 m is about the minimum distance between the base of the Topopah Spring Member and the modern-day water table beneath the primary repository area (J. H. Robison, U.S. Geological Survey, oral commun., 1984). The effect of increased transmissivity would be more pronounced east of the primary repository area, where the Topopah Spring Member is in the saturated zone.

Location of Pleistocene lakes may place additional constraints on the quantity of precipitation recharged to the modeled area and on the altitude to which the water table might rise. Pleistocene lakes existed at Gold Flat (fig. 7; altitude, 1,539 m); Kawich Valley (fig. 7; altitude, 1,619 m); and Sarcobatus Flat (fig. 7; altitude, 1,200 m) (location and altitude data from Stewart, 1980, and Williams and Bedinger, 1983). A ground-water divide may have existed near Pahute Mesa (fig. 7) during the period of these Pleistocene lakes, causing part of the local recharge at Pahute Mesa (altitude, 2,100 m) to flow northward into Gold Flat and Kawich Valley, and part to flow southward toward Timber Mountain and the northern boundary of the modeled area. However, the altitude of land surface between Pahute Mesa and Timber Mountain decreases to about 1,750 m, which is the maximum altitude to which the water table would rise in the modeled area, as a result of recharge at Pahute Mesa.

The simulated water-table rise in the northernmost part of the modeled area (fig. 11) and the resultant activation of head-dependent discharge nodes located there (fig. 12) resulted from the increase only in Q_{tm} (fig. 2); other recharge fluxes had minimal effect on hydraulic head in this northernmost area. However, hydraulic-head increases away from the northernmost part of the modeled area resulting from the increase in Q_{tm} were minor (15 m or less, fig. 10C). The sum of discharge rates for the northernmost head-dependent sinks (fig. 12), excluding discharge along Fortymile Wash, nearly equaled the increase in recharge from Q_{tm} (+4.2 m³/a); that is, water from Q_{tm} discharged before it reached the primary repository area. The boundary condition imposed by increasing Q_{tm} probably causes a greater water-table rise than if the modeled area were extended to include recharge and discharge areas to the north (Gold Flat, Kawich Valley, and Pahute Mesa).

Development of discharge areas southeast of Lathrop Wells (fig. 12) helped to limit the water-table rise beneath the primary repository area. However, if this discharge were decreased because of the possible existence of marsh deposits or eolian silts, or because of a greatly decreased vertical hydraulic conductivity versus horizontal hydraulic conductivity (greatly anisotropic conditions), then the water-table rise might be greater.

The area throughout which recharge into Fortymile Wash was applied (zone 8, fig. 2) was limited to the main stream channel near Yucca Mountain. Fortymile Wash and its distributaries extend beyond Lathrop Wells (fig. 1). By applying recharge throughout the entire length of Fortymile Wash, a greater water-table rise would be produced.

The model presented in Czarnecki and Waddell (1984) was based in part on the assumption that the ground-water system was under steady-state conditions. If, however, the ground-water system were still equilibrating to recharge that may have occurred 10,000 to 20,000 years before present, then the transmissivities obtained from that model may be too large (M.S. Bedinger, U.S. Geological Survey, oral commun., 1984). Large transmissivities used in increased recharge simulations would produce less water-table rise than if smaller transmissivities were used.

Changes in direction and magnitude of ground-water flux

Vectors of vertically integrated ground-water flux in the vicinity of the primary repository area that corresponds to the baseline simulation are shown in figure 14. The flux vectors for simulations using the 100-percent increase in precipitation are shown in figure 15. A comparison of figures 14 and 15 shows that flow-path directions through the primary repository area generally were the same for both cases; whereas, vector magnitudes are substantially greater for the increased-recharge simulation. Vectors along the southeastern part of the primary repository area and immediately downgradient do have a more southerly component for the case of increased precipitation. Some of the larger vectors occurring along Fortymile Wash were not included in figure 15 for reasons of illustration clarity. Large increases in recharge cause vectors to diverge away from Fortymile Wash, located east of the primary repository area.

Ratios of vertically integrated fluxes obtained from the simulation using the 100-percent increase in precipitation versus those obtained for the baseline simulation are mapped in figure 16. The largest ratios occur where ground water flows around zones of contrasting hydraulic conductivity, and where hydraulic gradients increased substantially (such as along Fortymile Wash). The largest ratio (27:1) occurs along Fortymile Wash; the range in ratios near the primary repository area is from 2:1 to 4:1; that is, the vertically integrated flux for the simulation using the 100-percent increase in precipitation was 2 to 4 times larger than for the baseline simulation.

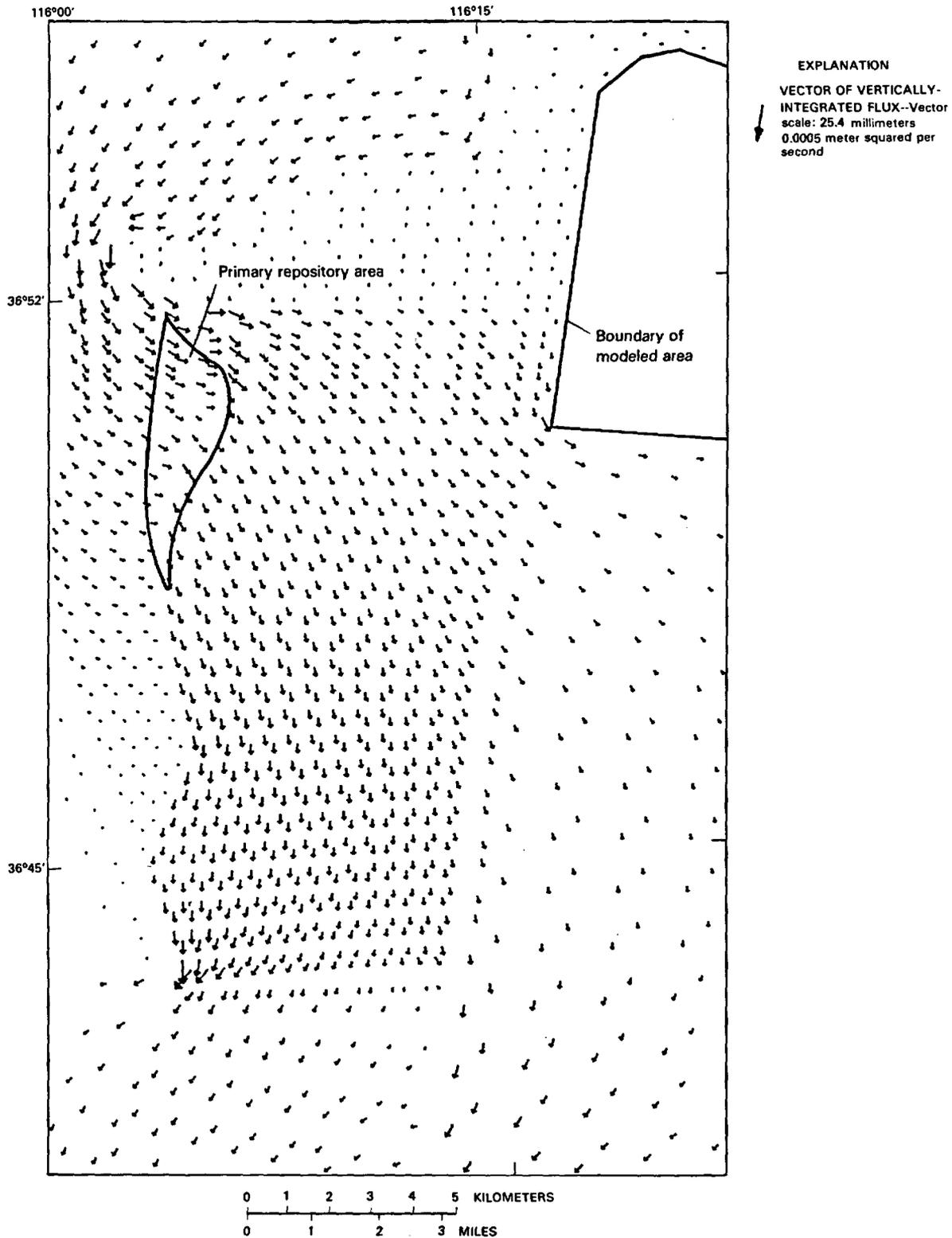


Figure 14.--Baseline, vertically integrated ground-water flux vectors at and in vicinity of primary repository area.

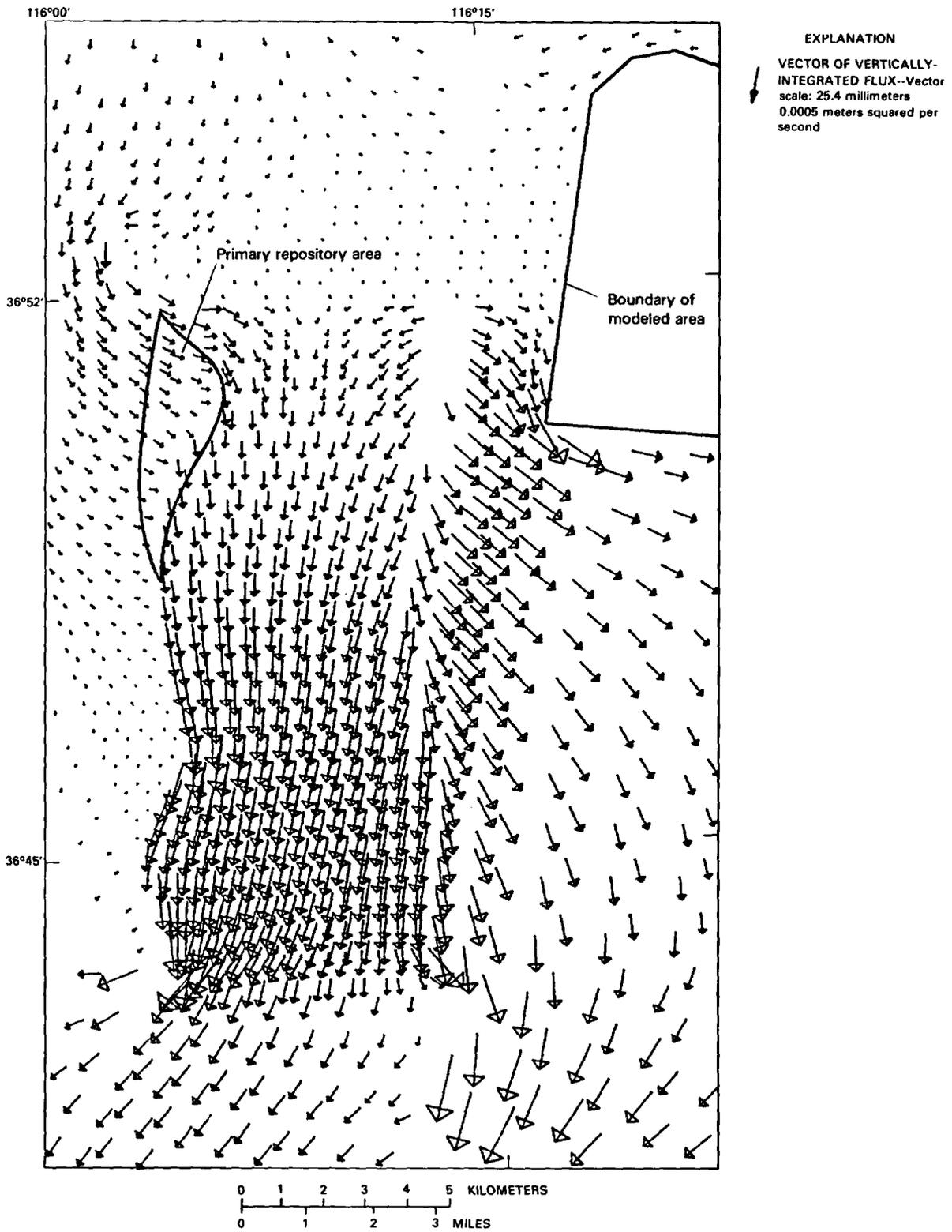


Figure 15.--Increased-recharge, vertically integrated ground-water flux vectors at and in vicinity of primary repository area.

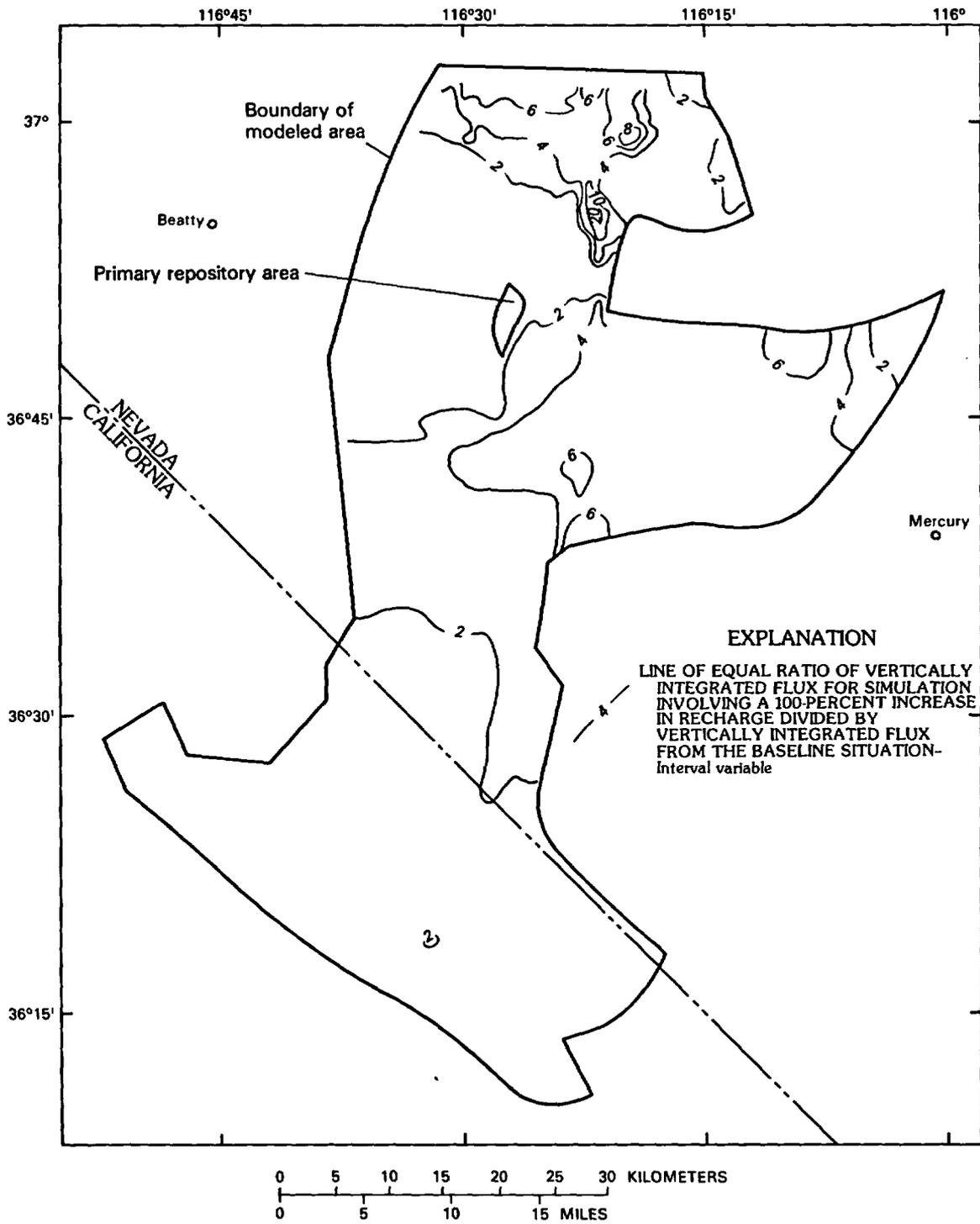


Figure 16.--Geographic distribution of the ratio of vertically integrated flux.

SUMMARY AND CONCLUSIONS

Simulations of water-table rise that might be caused by greater ground-water recharge rates during future pluvial climatic conditions indicate that the maximum hydraulic head increase would be about 130 m near the primary repository area at Yucca Mountain. Flooding of the primary repository area would require a water-table rise of at least 200 m. Under the conditions of increased recharge, springs would develop south of Timber Mountain, in Fortymile Canyon, in the Amargosa Desert southwest of Lathrop Wells, and west of the Ash Meadows area.

Changes in the direction of ground-water flow at and near the primary repository area would be small, but vertically integrated flux vectors would have a more southerly component for the increased-recharge simulation, when compared to the baseline simulation. The change in flux magnitude near the primary repository area would be substantial (2 to 4 times greater). These increases would decrease ground-water traveltimes in the vicinity of the primary repository area. Of the increased recharge rates examined, the increase in flux into Fortymile Wash, Q_{fm} , had the greatest effect on increasing the altitude of the water table in the primary repository area.

Results of this investigation provide a preliminary basis for estimating the potential effects of possible climatic changes on the ground-water system near a potential site for a nuclear-waste repository. However, one of the major assumptions made in this study is that the empirical relationship between increased precipitation and consequent increased recharge is valid. Little basis exists for this assumption; additional work is needed to document recharge mechanisms and rates, and to establish analytical expressions between precipitation rates and associated ground-water recharge rates.

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