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CNWRA92-001

REGIONAL GROUNDWATER MODELING OF THE SATURATED ZONE IN THE VICINITY OF YUCCA MOUNTAIN, NEVADA

ITERATIVE PERFORMANCE ASSESSMENT - PHASE II

Prepared for

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EXECUTIVE SUMMARY

Simulation of flow in the saturated zone in the region containing Yucca Mountain in Nevada was undertaken as an auxiliary analysis for the Iterative Performance Assessment (IPA) Phase 2. The primary purpose of the study is to gain experience in modeling large-scale saturated flow and to draw very preliminary inferences regarding the effects of certain selected scenarios on the position of the water table.

A two-dimensional planar finite-difference grid (13161 computational cells) is imposed on a region approximately 200 by 200 kilometers. At this scale, the Yucca Mountain repository area is represented by approximately two grid nodes. The hydrological data for the simulation are obtained from previously published studies which themselves depended on numerical model calibration for their parameter values.

Recharge was assumed to occur on outcrops at higher elevations. Recharge areas included the Spring Mountains, Sheep Range, Pahranagat Range, Kawich Range, and Pahute Mesa (see Figure 5.1). Recharge in these areas averaged from 25 to 50 mm/yr. Discharge areas included Alkali Flats and the Furnace Creek Ranch which were modeled as fixed head boundaries. The entire modeled region was divided into eight zones in which the hydraulic conductivity varied from $5x10^{-8}$ to $3.5x10^{-3}$ m/sec. A low permeability zone is assumed to exist northwest of Yucca Mountain which causes the present-day high hydraulic gradient. The actual cause of the steep gradient is not yet fully known.

Considering the present-day conditions, a steady-state solution to the flow system was obtained. This steady-state solution was then used as the starting point for simulating other scenarios. The scenarios simulated include: (1) Climatic change in the future increasing the recharge at higher elevation by a factor of 10; (2) Climatic change increasing recharge by a factor of 20; (3) Increase of recharge in the Forty Mile Wash by a factor of 10; (4) Rise in water level at Alkali Flats discharge area by 10 meters; (5) Geologic activity (volcanic or tectonic) to the south of Yucca Mountain creating a flow barrier twenty kilometers long; and (6) Geologic activity to the north of Yucca Mountain breaking the existing flow barrier. Most of the scenarios were simulated in a transient mode so that the time variation of water table could be studied.

The rise in the water table under Yucca Mountain due to various scenarios ranged from only a few meters to 275 meters. When the recharge at higher elevations was increased by a factor of 20, the water table under Yucca Mountain rose by 43 meters in about 700 years. Increase in recharge in the Forty Mile Wash by a factor of 10 raised the water table by about 100 meters. Backing up of groundwater due to creation of a flow barrier south of Yucca Mountain resulted in a water table rise under Yucca Mountain of about 200 meters. The largest water table rise of 275 meters was calculated when the flow barrier to the north of Yucca Mountain is removed.

A number of assumptions were made in this study with regard to the numerical model as well as the data. These assumptions, which are discussed in the body of the report, should be kept in mind in interpreting the preliminary results given above. Specifically, with regard to the high water table rises predicted, formation of new discharge areas was completely neglected.

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1 INTRODUCTION

To fulfill its mandate of licensing a High-Level Nuclear Waste Repository under the Nuclear Waste Policy Act, as amended (1982 and 1987), the U. S. Nuclear Regulatory Commission (NRC) is developing methods and procedures for an efficient and effective review of Department of Energy's license application. The Center for Nuclear Waste Regulatory Analyses (Center) at the Southwest Research Institute is a Federally Funded Research and Development Center created to assist the NRC in this endeavor.

Iterative Performance Assessment (IPA) is one of the approaches adopted by the NRC/Center to develop its review methods and capabilities. The work reported in this document was performed as a part of Phase 2 of the IPA Project.

IPA Phase 2 includes performance assessment of the total waste isolation system and detailed auxiliary analyses of certain important features of subsystems. The main objective of the auxiliary analyses is to provide support to simplifications made in the performance assessment of the total system by obtaining better understanding of a subsystem through detailed analysis. As one of the auxiliary analyses in IPA Phase 2, it was decided to simulate the flow field in the saturated unconfined region that contains Yucca Mountain. The specific objective of this analysis is to study the fluctuations in the water table in response to postulated changes in recharge rates and other modifications in geohydrologic structures. Such simulations may also provide boundary conditions for simulations of the saturated zone at a smaller scale, e.g., scale of Yucca Mountain. An auxiliary analysis on estimation of flow fields in the unsaturated zone at the scale of Yucca Mountain was also performed in IPA Phase 2. Results of the unsaturated analysis will be documented in another report.

The limited objective of the analysis presented in this report should perhaps be reemphasized. Specifically, no effort is made to make the analysis comprehensive; only data that are readily available are used. Some parameter values are taken from other published reports without verifying their accuracy. The analysis is performed primarily to gain experience in large-scale modeling of the saturated zone around Yucca Mountain. Therefore, the analysis results should be considered as very preliminary that are likely to change when actual field data are used in simulations.

The simulation results pertain to a two-dimensional regional (about 200 km by 200 km area) saturated groundwater flow analysis beneath Yucca Mountain and the surrounding area. For this application, PORFLO-3 (Runchal and Sagar, 1989, Sagar and Runchal, 1990), an integrated finite difference code, was modified to incorporate the free surface (water table) in a groundwater flow model. The model was set up in the x-y (horizontal) plane, and allowed for specification of recharge and discharge areas. An approximate model of the regional groundwater flow system around Yucca Mountain was first developed for the PORFLO code. Once this was completed, various scenarios were postulated, such as increasing the recharge to simulate future climatic changes that might take place in the geohydrologic basin containing Yucca Mountain.

This report is organized as follows. The concepts and assumptions used in modeling the free surface are outlined first. Next, a brief review of existing regional saturated zone modeling studies is provided. The data used in the simulations for this work are then reported. Finally, the simulation results are discussed.

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2 NUMERICAL MODEL OF FREE SURFACE

2.1 GENERAL CONSIDERATIONS

Conceptually, the water table separates the groundwater flow regime into two distinct zones - the fully saturated zone on one side and the partially saturated zone on the other. Obviously, flow in the fully saturated zone can be treated as a special (or limiting) case of the partially saturated flow zone, i.e., where relative saturation becomes unity. If the movement of the gas phase in the unsaturated system is neglected then it is possible to represent the variably saturated flow, which includes the case of fully saturated flow, by a single governing equation. Thus, in a general sense, simulations incorporating the region from the ground surface down to the depth of interest and incorporating both the unsaturated and the saturated zones can be set up. Such simulations will provide the location of the water table as an output as that surface at which the relative saturation is unity. Such formulations are general as these can admit formation of localized saturated zones (e.g., perched water tables) and unrestricted free surface geometries. However, there is a large penalty to be paid for such generality. The penalty is in terms of large computation time for solving the non-linear unsaturated flow equation.

It is therefore of considerable interest to model the unsaturated and saturated zones separately and independently. In such modeling, of course, the determination of free surface is not automatic and special care must be taken to determine its location. In modeling unsaturated zones, it is not uncommon to specify the water table as a fixed (invariant in time) boundary with zero gage pressure (i.e., equal to atmospheric pressure). In the saturated case, the water table is designated an upper boundary which must satisfy two conditions simultaneously: 1) the gage pressure at this boundary is zero at all times, and 2) it is a stream line, i.e., there is zero flux crossing the boundary. These two conditions are stricktly true at stead state, however, even in the transient case, by representing the recharge as a source term, we try to satisfy both these conditions at the water table. Since the location of the boundary is not known a priori, it must be determined iteratively to satisfy the above two conditions. The free surface boundary condition and approximations (e.g., Dupuit) are described in Bear (1972, Chap. 8). This will not be repeated here, instead, the specific modifications made to PORFLO-3 to accommodate the free surface boundary condition are discussed.

2.2 MODIFICATIONS TO PORFLO-3[1]

PORFLO-3 is a computer code designed for analysis of three-dimensional variably saturated flow fields, heat transfer and mass transport. The PORFLO-3, Version 1.0 governing

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[1] The Analytic and Computational Research Incorporated (ACRI), Los Angeles hold copy right privileges on the PORFLO-3 software. The United States Government, however, has retained rights for its unlimited use in its work. Commercial users of PORFLO-3 should contact ACRI before using this software.

saturated flow problem, in which case the water table will be determined as part of the solution, or it can be used to solve a fully saturated flow problem in a confined (i.e., in the absence of free surface) aquifer. The first option of using the saturated-unsaturated regimes was considered to be too expensive (in terms of computation time) for this application. Therefore, it was decided to modify the code to incorporate the time-varying free surface boundary condition in a fully saturated flow regime.

The PORFLO-3 code uses a fixed (in contrast to deforming or adaptive) three-dimensional, finite-difference mesh to solve its governing equations. In order to model a moving water table in a fixed mesh, the following assumptions were made.

1. The geometry of the water table surface can be approximated by pieces of straight surfaces aligned with the coordinate directions. This is shown in Figure 2-1 in two-dimensions where the grid scheme used in PORFLO-3 is also shown. The water table is thus represented by a stair-step boundary. Obviously, this assumption can produce large errors in the regions where the water table has steep slopes unless fine meshes are used in those regions. Because the location of steep gradients cannot be predicted a priori, use of fine meshes cannot always be pre-planned. The advantage of this assumption is that the calculation of geometric elements (cell areas, cell volumes where cell is a computational element as shown in Figure 2-1) required for numerical calculations becomes very easy.

2. The second assumption is that water flow is restricted to saturated regions only. Although in actuality, some water will flow into dry cells adjacent to wet cells as shown in Figure 2-2, this is not allowed in the modified PORFLO-3. If this realistic flow situation was modeled correctly, a water table configuration shown in Figure 2-3 may exist. However, such a correct modeling will require either modeling of the unsaturated flow or development of rules that can determine the rate at which water will exchange between dry and wet cells. No such rules are currently embedded in the modified PORFLO-3 code.

   This assumption does not cause much error if the aquifer is homogeneous. However, for heavily stratified aquifers, extreme errors can occur. If a general water table configuration such as shown in Figure 2-3 is to be modeled, then PORFLO-3 should be used in the unsaturated mode which may be computationally feasible on a scale smaller than the regional scale used in this application.

The second assumption is needed because the water movement calculations which are based on pressure gradients are restricted to fully saturated flow only. Since water pressures are defined only in those cells that contain water, water pressures have no defined value in cells that are devoid of water. Therefore, the rule for flow exchange between dry and wet cells cannot be based on pressure gradients.

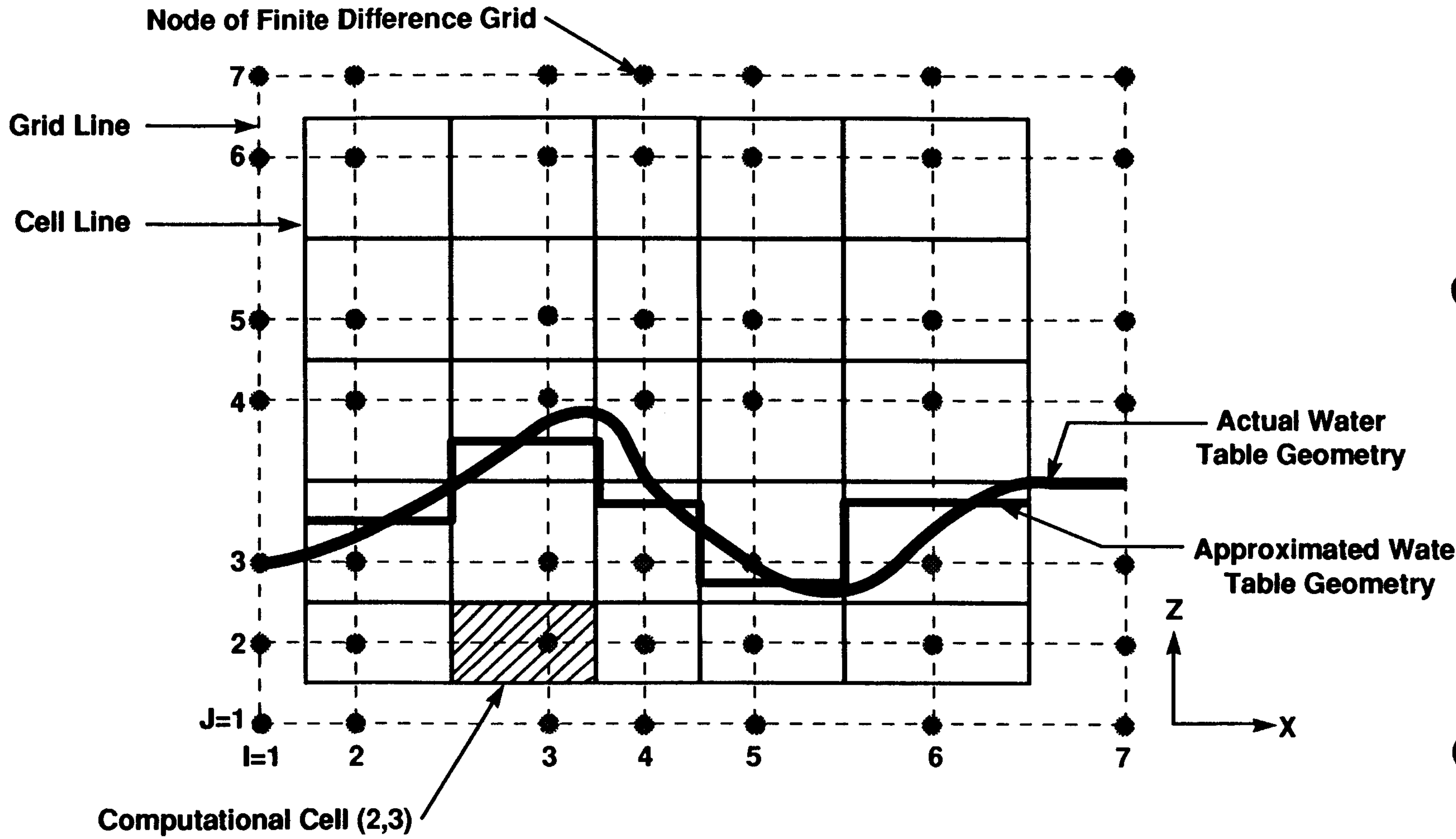


Figure 2-1. Computational grid and approximated water table geometry

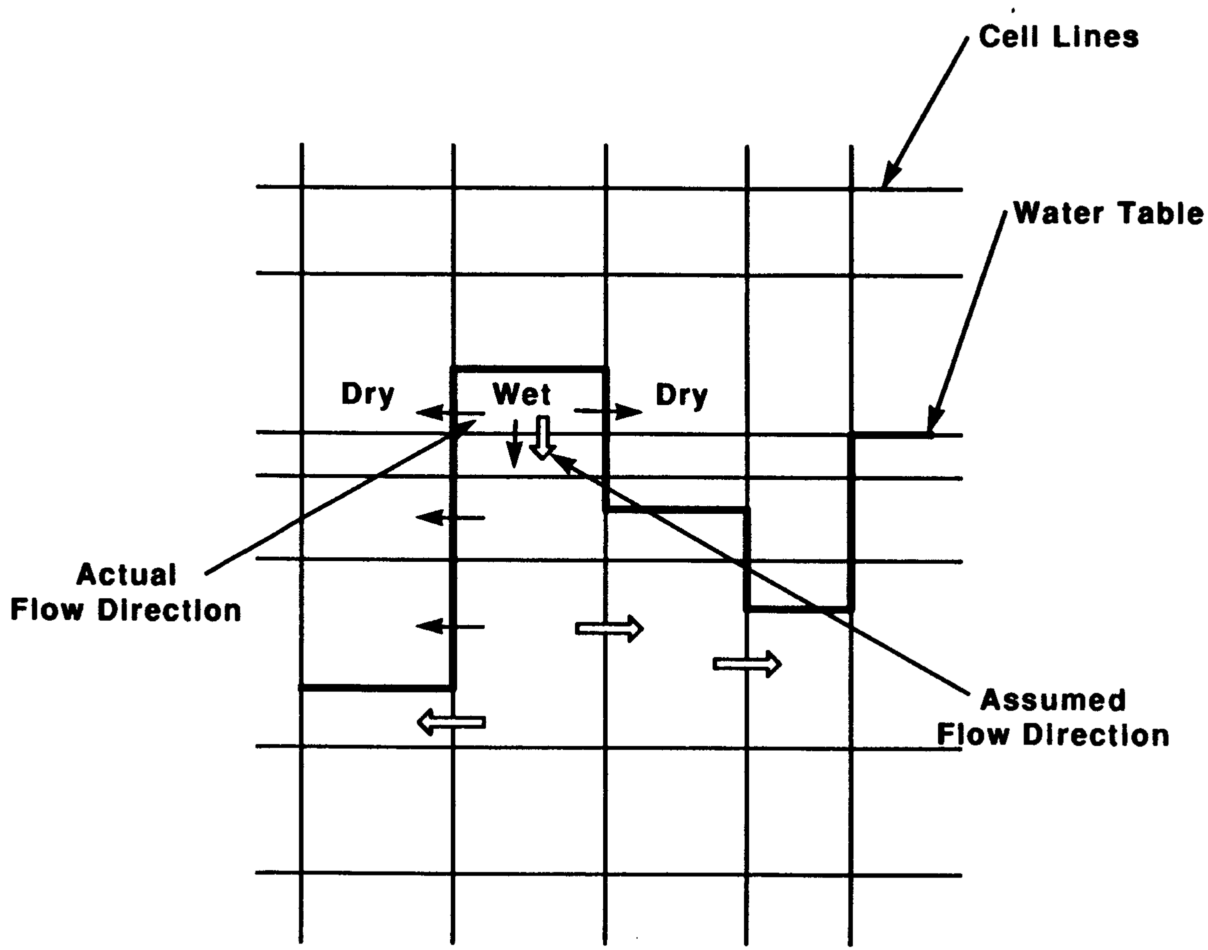


Figure 2-2. Actual and assumed flow directions at the water table (flow only in the saturated region)

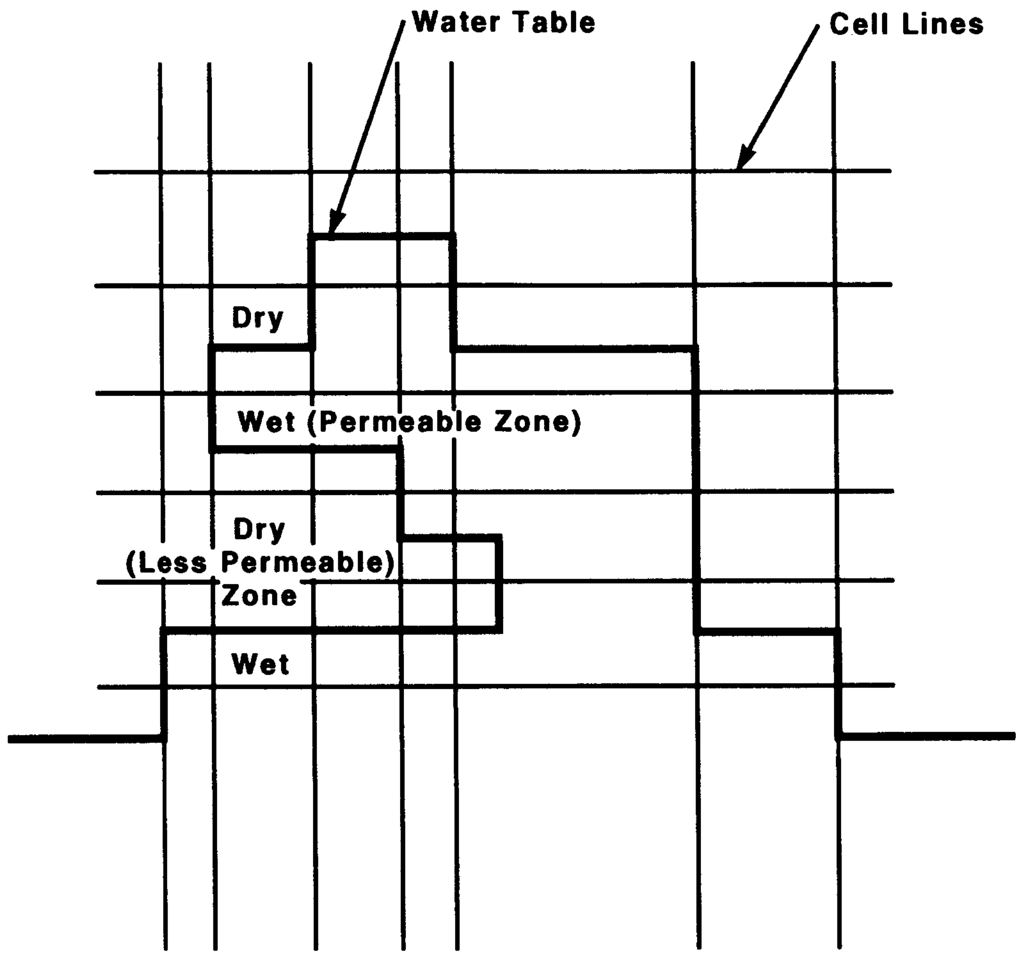


Figure 2-3. Water table configuration in stratified aquifers which is difficult to model in "saturated flow only" codes

Although the code has been modified in a manner that either three- or two-dimensional problems can be solved, only a two-dimensional application is discussed in this report. In the two-dimensional case, calculations can be done in either a horizontal plane or the vertical plane. Even in two-dimensional cases, hydraulic conductivity rather than transmissivity is used as input. Thus in a two-dimensional simulation in the horizontal plane, hydraulic conductivity averaged over the vertical direction needs to be specified.

2.3 COMPUTATIONAL STEPS

The following steps are followed in calculating two-dimensional flow in a fully saturated regime with a time-varying free surface boundary condition:

1. The initial water table position is approximated with the stair-step curve of Figure 2-1.

2. The pressure head at nodes is calculated assuming that the pressure at the free surface is zero.

3. A condition of zero flux is imposed all along the water table as indicated in Figure 2-4. Note that part of the vertical cell surfaces are open to flow in those cells that contain the water table. This fact is considered in discretization of the governing equation and during assemblage of the coefficient matrix.

4. The flow equation is solved under the imposed boundary condition at the water table. The solution is in terms of hydraulic heads at all nodes below the water table. In general, the new solution will indicate that the pressure at the water table is no longer zero.

5. The location of the water table is adjusted to meet the condition of zero pressure at the water table. This simply requires moving the water table up or down in each cell by an amount such that the head at the former water table is equal to the one calculated in step 4 and the new water table is designated where the pressure is zero.

6. Steps 3 to 5 are repeated until the change in calculated heads is acceptably small.

Note that the above algorithm satisfies the dual boundary condition of zero pressure and zero flux at the water table boundary. Any natural recharge (or evaporation) is treated as a source term on nodes immediately below the current water table location. Pumping (or artificial recharge), if any, can be specified at any node.

While using the modified code for modeling unconfined regions, the specific storage term should be replaced with the specific yield. Note that specific yield is the amount of fluid released or taken into storage per unit area of the aquifer due to drainage or filling up of pores. In contrast, the specific storage of confined aquifers is due to the compressibility of the medium

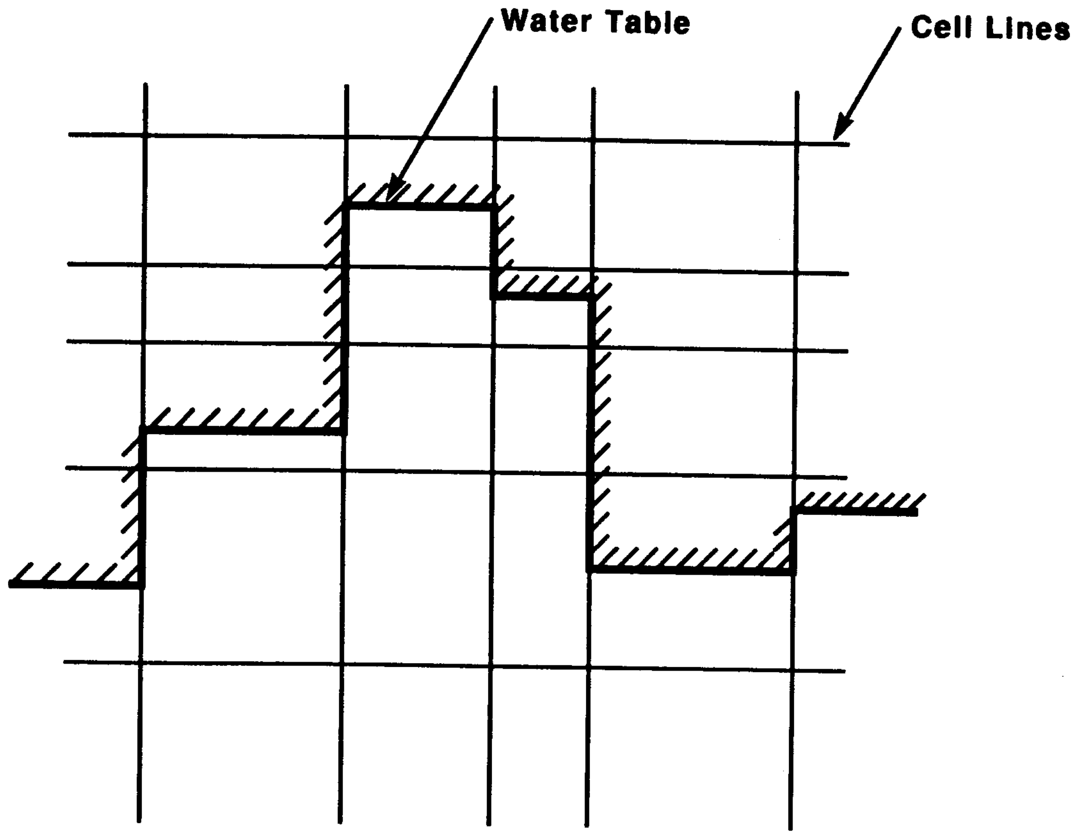


Figure 2-4. Zero flux boundary condition on water table during iterations

those grid elements containing the water table. The code modifications include automatic replacement of specific storage by drainable porosity in grid elements that contain the changing position of the water table. However, if some part of the modeled region is confined, then those grid elements will correctly retain the specific storage terms. Additionally for an unconfined but saturated region, specific storage should be specified. In summary, only those grid elements that actually contain the free surface boundary will be assigned specific yield values; all other grid elements will have specific storage values.

3 BRIEF SITE DESCRIPTION

Yucca Mountain is located within the Basin and Range Province of southern Nevada. This area is characterized by alternating basins (valleys) and mountain ranges with unconsolidated alluvial sediments filling in the basins and with consolidated rock outcroppings in the mountainous areas as well as underlying the alluvial deposits in the basins. Hydrogeologically, the area consists of three groundwater subbasins: 1) Oasis Valley, 2) Ash Meadows, and the 3) Alkali Flat-Furnace Creek Ranch. These subbasins are bounded by Death Valley to the west and southwest, as well as the mountainous region of the Cactus and Kawich Ranges to the north, the Pahrangat and Sheep Ranges to the east, and the Spring Mountains to the southeast (Figure 4-2). Yucca Mountain itself is located within the Alkali Flat-Furnace Creek Ranch groundwater subbasin, which is a tributary to groundwater flow into Death Valley. This subbasin has two major groundwater discharge areas: 1) Alkali Flats (Franklin Lake Playa), where discharge occurs primarily by evaporation; and 2) Furnace Creek Ranch area in Death Valley, where discharge results from numerous small springs (Waddell et al., 1984). The proposed site for a geologic repository at the Yucca Mountain would lie in the unsaturated zone approximately 300 m above the present water table. Current climatic conditions are arid, with no perennial streams present in the region except those fed by springs, or by snow melt in the higher mountain ranges.

Precipitation within the region ranges from approximately 43 mm/year in Death Valley to 760 mm/year in the Spring Mountains (Winograd and Thordarson, 1975). At Yucca Mountain, the average annual precipitation is estimated to be 100 to 150 mm/year. The majority of the groundwater recharge to the area occurs at Pahute Mesa as well as mountain ranges to the north and east. Direct recharge at Yucca Mountain is generally considered to be less than 5 millimeters per year (DOE, 1988). The groundwater flow beneath the Yucca Mountain site is believed to occur primarily through fractures within the volcanic tuffs. A more detailed discussion of geology and hydrology of the region can be found in the Site Characterization Plan (DOE, 1988).

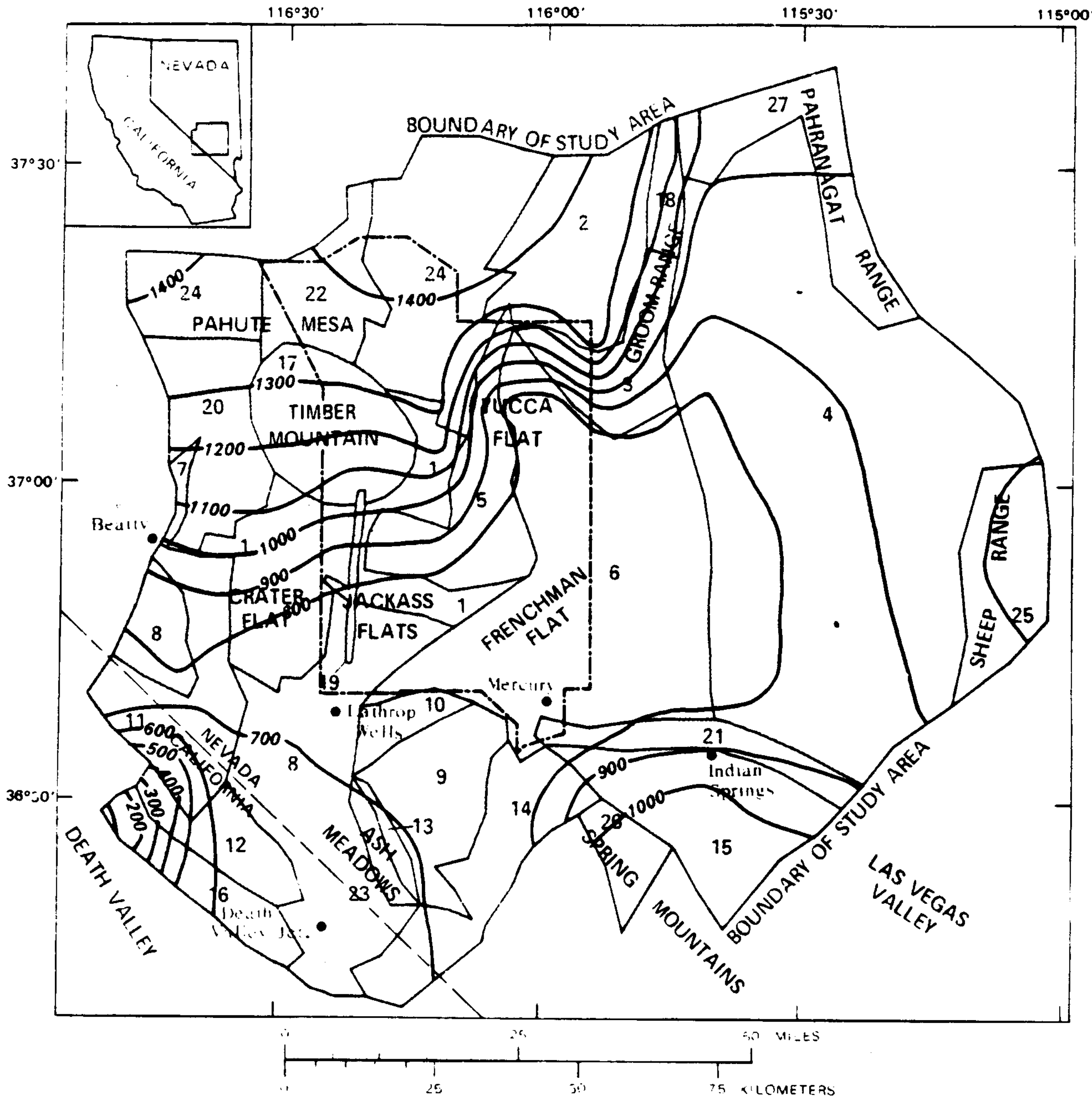
4 PREVIOUS WORK

A brief review of previous studies on the saturated zone hydrology in the vicinity of Yucca Mountain follows. For this study, a comprehensive literature review of all hydrologic studies on the area was not conducted. A fairly detailed discussion of previous studies of the saturated zone hydrology can be found in the Site Characterization Plan (DOE, 1988). The purpose of this review was mainly to determine what other modeling studies were conducted to simulate the regional saturated hydrology, and to utilize the results and data (i.e. hydraulic conductivities, boundary conditions, etc.) from such studies for the PORFLO-3 analysis. These previous studies were more comprehensive in that their models were calibrated on measured heads. For this study, no model calibration was done; rather, parameter values from previous studies were adopted.

Flow modeling on a regional basis was performed for the regional flow system of the Nevada Test Site and vicinity by Waddell (1982). The main goals of his investigation were: (1) to estimate fluxes for use in predictions of transport of radionuclides, and (2) to study the effects of uncertainty in model parameters on these estimates. Waddell used a horizontal two-dimensional finite element model consisting of 685 nodes. The model encompassed an area approximately 175 by 175 kilometers, the boundaries of which were taken mainly along topographic highs to the north and east, and topographic lows to the southwest. For model calibration, a numerical parameter-estimation technique was used in which parameters such as transmissivities, groundwater sources, and sinks were derived throughout the modeled area such that the weighted sum of the squared residuals (observed head minus simulated head) was minimized. An iteration scheme was used to minimize the weighted sum of squared residuals by successive approximation to model parameters. It was generally found that absolute values of residuals were less than 30 meters. The model took into account recharge originating in the Spring Mountains, Pahranagat, Timpahute, and Sheep Ranges, and in Pahute Mesa. Known discharge areas (Ash Meadows, Oasis Valley, Alkali Flat, and Furnace Creek Ranch) were modeled by specifying a constant head at a node, or specifying discharge at a node.

Figure 4-1 shows the simulated hydraulic heads calculated by Waddell (1982). High hydraulic gradients can be observed to occur immediately upgradient from Yucca Flat. Inflections in potentiometric contours in this area induce greatly differing hydraulic gradients. Groundwater barriers within the study area were found to have a great effect on measured, and, therefore simulated heads. It was also found that recharge on Pahute Mesa and underflow from regions north of the mesa had a significant impact on the model.

Czarnecki and Waddell (1984) developed a smaller subregional horizontal finite-element model of the groundwater flow system in the vicinity of Yucca Mountain at the Nevada Test Site using parameter estimation techniques. This model was formulated as a portion of the regional model conducted by Waddell (1982) as shown in Figure 4-2, and included the area directly within the vicinity of Yucca Mountain. Some of the boundaries for this subregional model were taken along groundwater barriers from the larger regional model. The remaining boundaries had either specified pressure heads or fluxes, which were calculated from the regional model. This



EXPLANATION

900 — **SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude of simulated potentiometric surface. Contour interval 100 meters. Datum is sea level.**

26 — **ZONE NUMBER AND BOUNDARY**

—·—·— **BOUNDARY OF NEVADA TEST SITE**

Figure 4-1. Simulated hydraulic heads for the regional study area containing Yucca Mountain obtained by Waddell, 1982

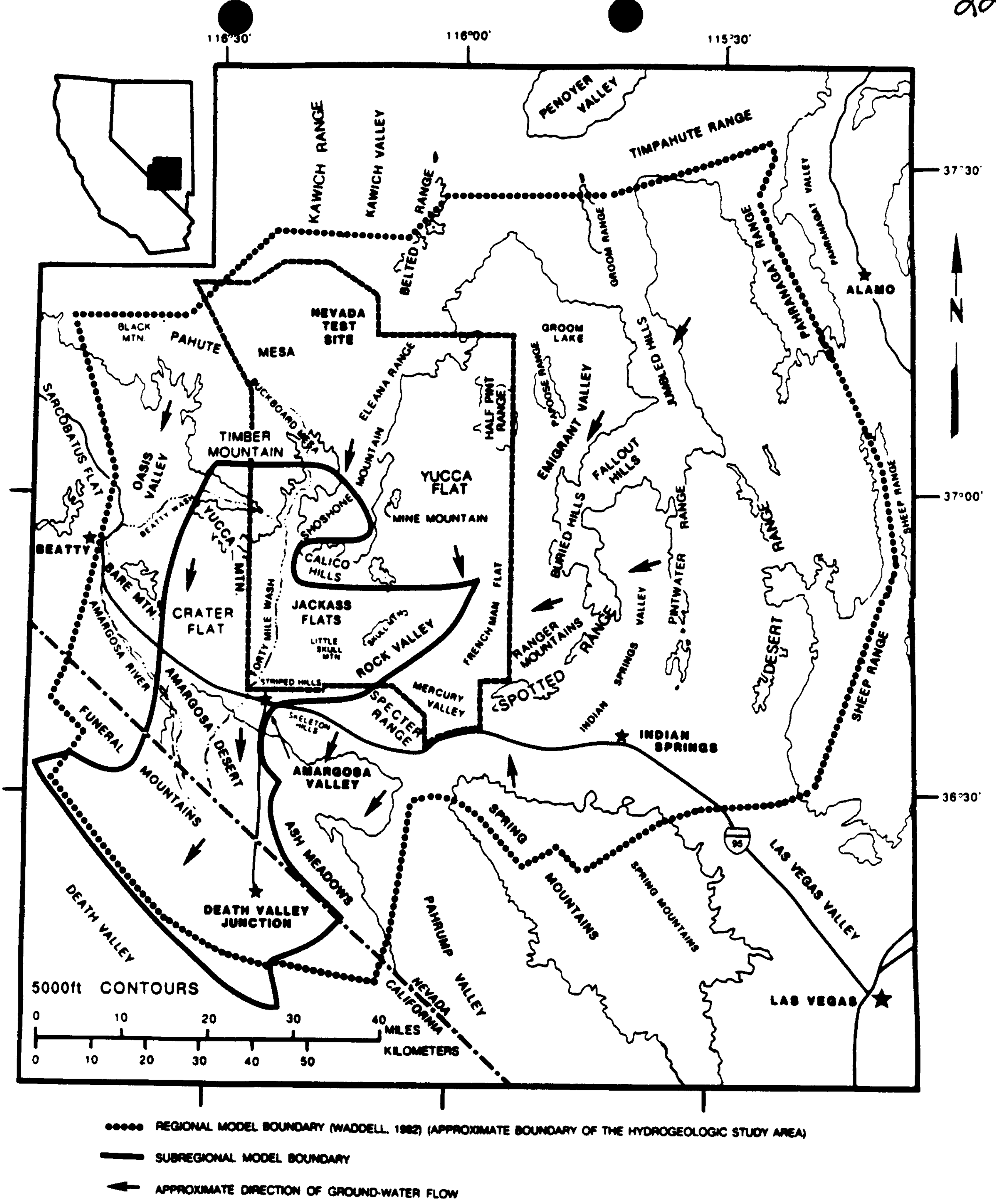


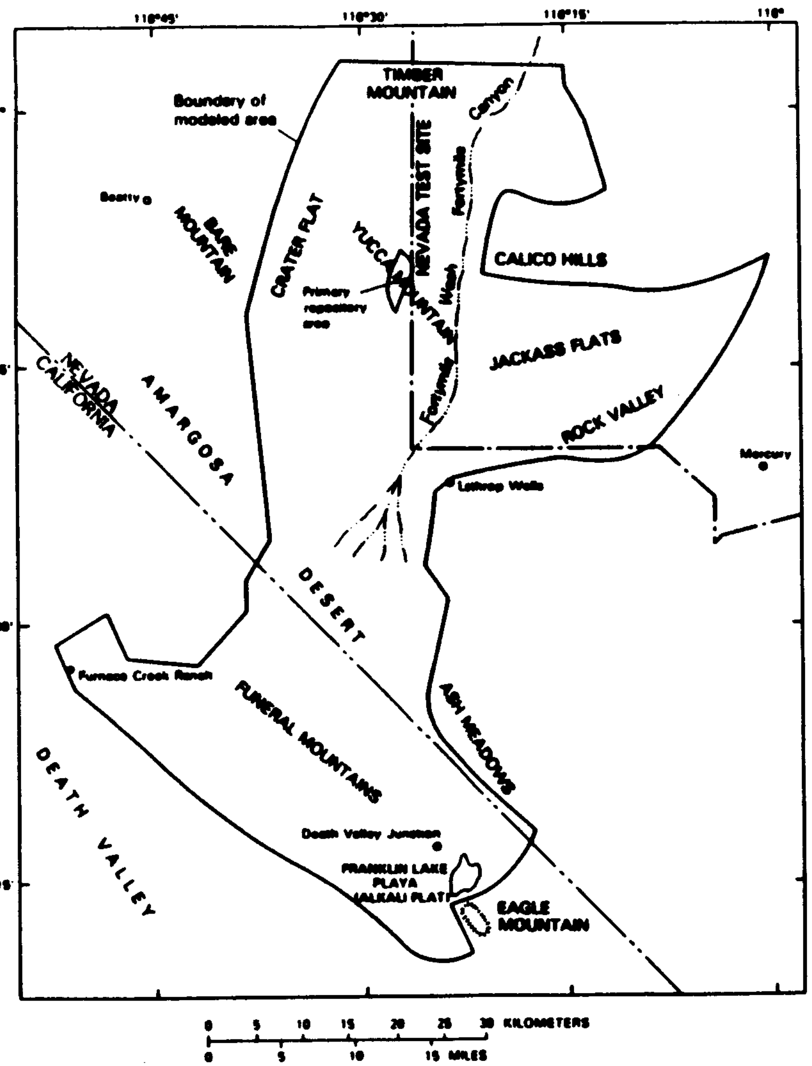
Figure 4-2. Location of regional and subregional modeled area, with generalized groundwater flow directions (from U. S. Department of Energy Site Characterization Plan, 1988)

model simulated steady-state groundwater flow occurring mainly in tuffaceous, volcanic, and carbonate rocks, and alluvial aquifers. The purpose of this subregional model study was to gain a better understanding of the groundwater 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. The flow vectors of the groundwater movement presented in this report provide a preliminary basis for estimating the direction and time of travel of groundwater. The model was also designed to provide future simulations of potential groundwater transport of radionuclides.

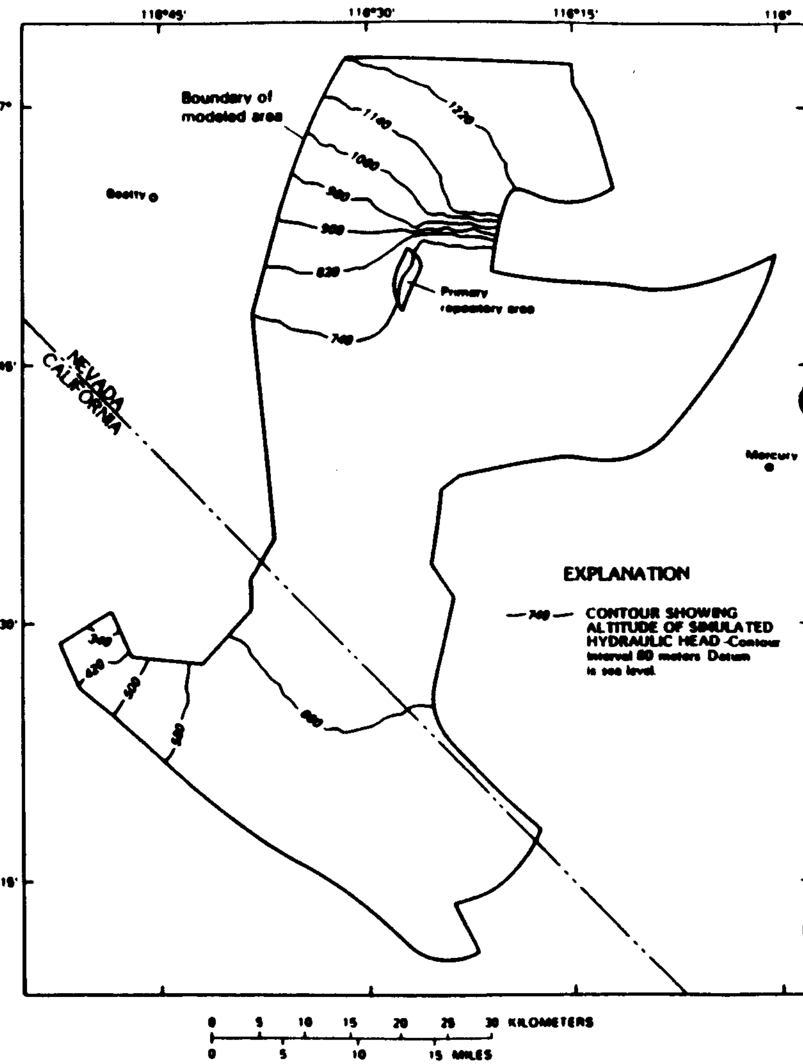
Figure 4-3a shows a more detailed illustration of the modeled area which encompasses about 6,000 square kilometers and extends from Timber Mountain in the north to discharge areas at Alkali Flat in the south and Furnace Creek Ranch in the southwest. Results of the simulated hydraulic heads (Figure 4-3b) show a water table elevation of approximately 740 meters above sea level throughout the potential repository site, with a relative steep hydraulic gradient of approximately 0.19 in the east-west oriented barrier slightly northeast of the potential repository site. Czarnecki (1989) attributed this large hydraulic gradient to one or more of the following possibilities: (1) faults that contain nontransmissive fault gouge or that juxtapose transmissive tuff against nontransmissive tuff; (2) the presence of a different type of lithology that is less subject to fracturing, such as rhyolite or argillite, or the presence of an intrusive body, such as a volcanic dike; or (3) a change in direction of the regional stress field and a resultant change in the frequency, interconnection, and orientation of open fractures on either side of the large hydraulic gradient.

The simulated hydraulic heads in Figure 4-3b were shown to compare well with available measured hydraulic heads, with the exception of areas where vertical-flow components are present, such as the discharge areas, and in areas where steep hydraulic gradients occur, such as directly north of Yucca Mountain. This is because the model assumes strictly horizontal flow. The simulations showed groundwater flow trending generally north to south. However, through the potential repository site, the flow trended slightly to the southeast. Travel time-estimations for a particular length of a flow line were shown to depend greatly on the estimates of the both the saturated thickness and porosity.

Czarnecki (1985) used the same two-dimensional finite-element subregional model discussed above to assess the potential effects of changes in future climatic conditions on the groundwater system in the vicinity of Yucca Mountain. He found that 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. The average increase in recharge for the case of this 100-percent increase in annual precipitation was set at 15 times the modern-day recharge rate in all areas of his model. The primary factor in this water table rise was due to the increase in recharge applied to Forty-Mile Wash to the east of Yucca Mountain by a factor of 15 times the baseline rate of 0.41 m/yr. For a factor of 10 increase in the flux into the model, Czarnecki shows an increase in hydraulic head near Yucca Mountain of approximately 100 m. Flooding of the primary repository area would require a water-table rise of at least 300 meters. Upon comparing the simulated water table rise



(a)



(b)

Figure 4-3a. Location of subregional modeled area containing Yucca Mountain and nearby geologic features

Figure 4-3b. Simulated hydraulic heads (obtained from Czarnecki and Waddell, 1984)

with the existing land surface elevations under these conditions of increased recharge, it was found that springs would develop south of Timber Mountain, in Forty Mile Canyon, in the Amargosa Desert southwest of Lathrop Wells, and west of the Ash Meadows area. It was also found that changes in the direction of groundwater flow at and near the primary repository area would be small, but the magnitude of flow would increase by 2 to 4 times that of the baseline-simulation flux.

Rice (1984) also developed a two-dimensional regional hydrologic model for the saturated flow system surrounding Yucca Mountain. A finite-difference grid consisting of 5,600 nodes in the x-y plane was used for the simulations. The flow system was modeled under confined conditions, and only horizontal flow was allowed. Boundaries of the model were taken along topographic highs to the north, east, and south of the modeled area, while the topographic low along Death Valley was taken as the western boundary. Boundary conditions were designated as either no-flow or constant head along these topographic highs and lows. Model calibration was accomplished by adjusting the transmissivities within reasonable limits in order to minimize the difference between the hydraulic heads simulated by the model and hydraulic heads measured at well locations. Results of simulated hydraulic heads compared well with USGS-interpreted head distribution based on well observations.

5 DESCRIPTION OF NUMERICAL GRID AND DATA

A horizontal two-dimensional finite difference grid was set up for simulations with the PORFLO-3 computer code. In modeling two-dimensional problems, PORFLO-3 requires 3 grid nodes in the out of plane direction, resulting in a pseudo-three-dimensional problem. Both transient and steady-state problems were solved.

The regional model for the groundwater study encompassed an area roughly 200 by 200 kilometers. A rectangular finite difference grid was used for the analysis, and consisted of 109 by 125 node points in the x and y directions respectively. Each grid cell was 2.5 kilometers on a side, encompassing an area of 6.25 square kilometers. PORFLO-3 calculates the hydraulic heads at the grid nodes, while the fluxes are calculated at the grid cell boundaries between the nodes (see Figure 2-1). The region modeled was actually within the rectangular finite difference grid and bounded by the irregular region as shown in Figure 5-1. Boundary conditions along the irregular region shown in Figure 5-1 consisted of either constant head or no-flow boundaries as done in a similar study by Rice (1984). Since boundary conditions for the code could only be specified along the edges of the rectangular grid, at boundaries within the interior region constant head boundaries were maintained by fixing the pressures at those node points while no flow boundaries were simulated by setting the permeabilities in the x or y direction to a very small number.

The entire groundwater flow system in the modeled area is considered to be unconfined. Estimated hydraulic conductivities for the model were determined by dividing the transmissivity values obtained by Rice (1984) by an assumed uniform saturated thickness of 1,000 meters throughout the modeled area. This is a fairly rough approximation, and future studies should take into account the variable groundwater surface in calculating hydraulic conductivities for input into PORFLO-3, based on the transmissivity data obtained from previous regional groundwater studies. The hydraulic conductivities used for the various zones indicated in Figure 5-1 are given in Table 5-1. Rice (1984) gave a range of transmissivities for each of the eight regions. For this analysis, the average value for each of the eight transmissivity regions was used in calculating hydraulic conductivities listed in Table 5-1. The model shown in Figure 5-1 does not include many of the smaller transmissivity regions used by Rice (1984), since they were felt to not greatly affect the groundwater flow on the regional scale, and made the model somewhat simpler. As shown in Figure 5-1, several regions consisting of low permeability areas or aquitards are present, namely in the Death Valley, north of Yucca Mountain, east and north of Yucca Flat, and south of Frenchman Flat. These barriers have a significant impact on the groundwater flow through the area.

Discharge areas where the water table intersects the land surface altitude were simulated by fixing the head at that elevation. For this model, a constant head node was specified at Alkali Flats (altitude, 606 m) where the water table is within several meters of the ground surface. At this location, discharge is primarily by evapo-transpiration. Discharge also occurs to the west of Alkali Flats in the Furnace Creek Ranch area in Death Valley. Recharge areas for the model were specified at the higher elevations such as the Spring Mountains, Sheep Range, Pahranagat

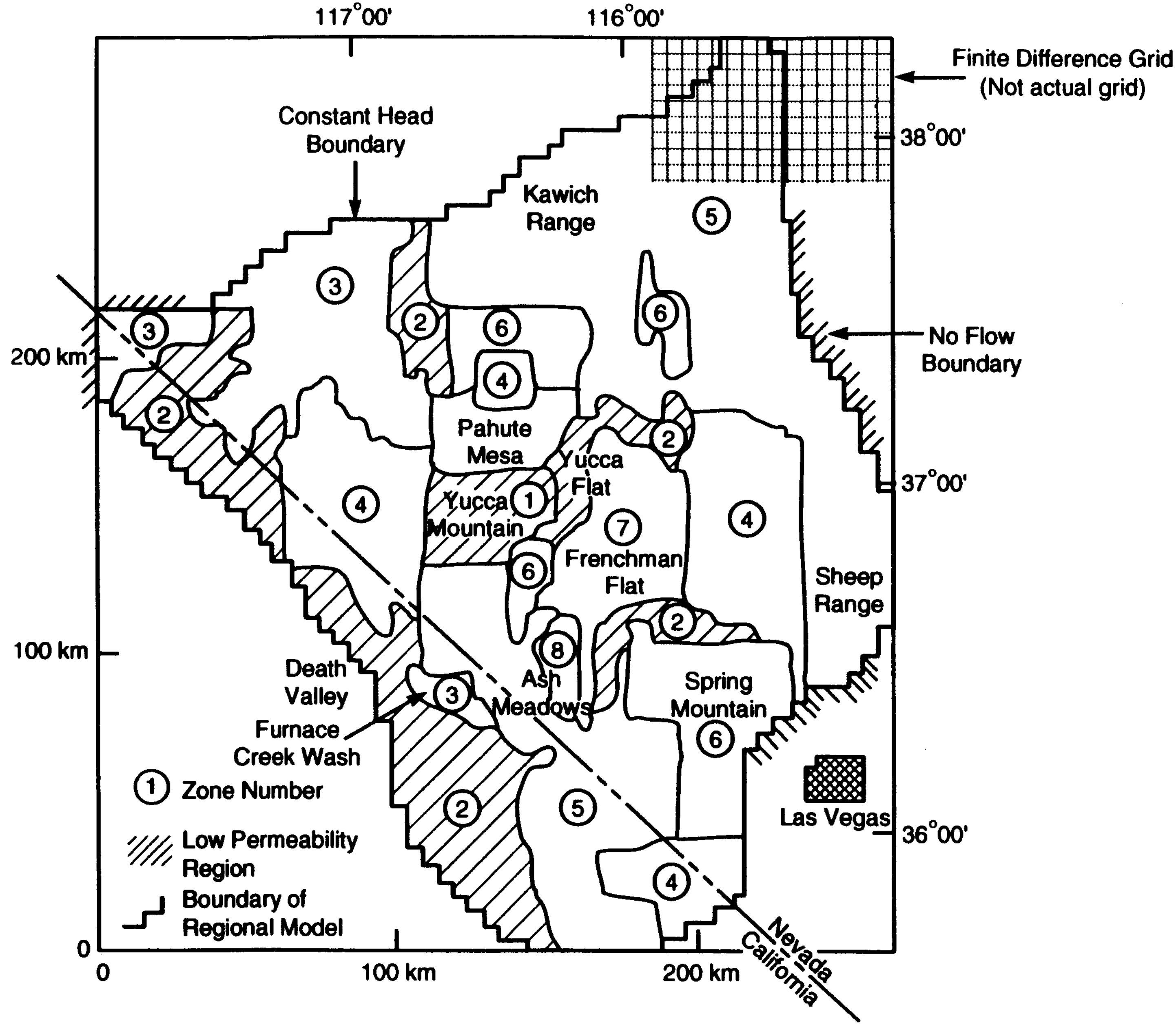


Figure 5-1. Regional model for PORFLO-3 depicting boundary conditions and various hydraulic conductivity zones (modified from Rice, 1984)

Table 5.1 **HYDRAULIC CONDUCTIVITIES FOR THE MODEL**

Zone Number	Hydraulic Conductivity (m/sec)
1	5.80×10^{-8}
2	6.34×10^{-7}
3	3.49×10^{-6}
4	8.69×10^{-6}
5	3.47×10^{-5}
6	1.00×10^{-4}
7	6.00×10^{-4}
8	3.50×10^{-3}

Range, Kawich Range, and Pahute Mesa. Recharge in these areas averaged 25 to 50 mm/year. Figure 5-2 shows the locations of the recharge and discharge areas for the regional model.

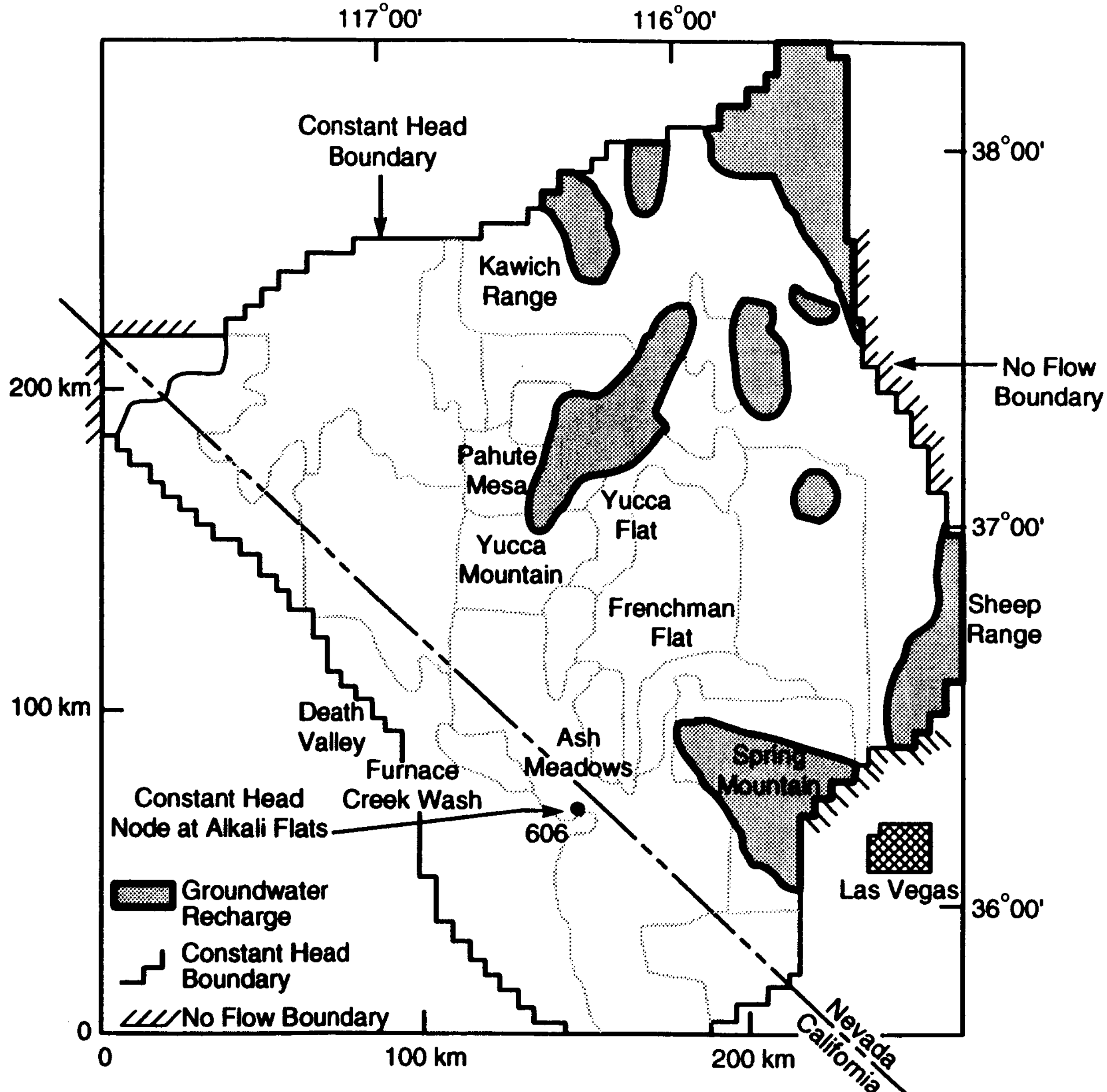


Figure 5-2. Location of recharge and discharge areas for the regional model (modified from Rice, 1984)

6 SIMULATION RESULTS

Figure 6-1 shows the simulated regional water table under assumed modern day recharge. It should again be stressed that this regional model has not been calibrated. The results are based on the use of data interpolated from previous calibrated groundwater models. The intent was to utilize as much information as possible from previous reports in order to best simulate the present day saturated flow conditions throughout the region containing Yucca Mountain. Once this was established, various postulated scenarios could be modeled.

Yucca Mountain, indicated in Figure 6-1 by the small rectangular box, is represented by approximately two grid nodes in the regional model. Thus on the Yucca Mountain scale, the model is quite coarse. Based on the simulation, one can see the steep hydraulic gradients to the north and northeast of Yucca Mountain, as well as to the southwest into Death Valley. The hydraulic head distribution around these low permeability regions or groundwater barriers is comparable to those potentiometric surfaces developed from previous studies and is consistent with well bore data. However, this model took into account only the major discharge and recharge areas, and thus some calibration or fine tuning would have been necessary in order to obtain the best match with existing water well data throughout the modeled region. Nevertheless, the uncalibrated results were deemed acceptable for use as a base case for analyzing the effects of various postulated scenarios.

Flux into the regional model occurs through the Kawich, Pahrangat, and Sheep Ranges. Figure 6-2a shows a partial view of the area in the immediate vicinity of Yucca Mountain under the simulated modern day conditions. The simulated hydraulic heads in the vicinity of Yucca Mountain range from approximately 850 to 950 m above sea level. The hydraulic gradient to the north of the site is approximately 0.027 and becomes much less to the south. Figure 6-3 shows the velocity field in the vicinity of Yucca Mountain for this simulation. The groundwater can be seen to travel around the low permeability region to the north of Yucca Mountain. The largest velocities can be seen to the east of Yucca Mountain in the areas representing Forty Mile Wash and Frenchman Flats. The maximum velocities in this area are approximately 10.0 m/year.

The flow regime illustrated in Figure 6-2a was obtained using the steady-state solution algorithm in PORFLO-3. This steady-state solution was then used as input to subsequent transient analyses to simulate various postulated scenarios of increased recharge as well as alteration of existing hydrologic barriers. The transient analyses took approximately 45 minutes to an hour to execute on the Cray X-MP computer at the Idaho National Engineering Laboratory (INEL). Figure 6-2b shows the same partial view of the area surrounding Yucca Mountain as a result of increasing the present recharge by a factor of 10 over those recharge areas indicated in Figure 5-2. For this model, there is no significant change in the flow regime in the vicinity of Yucca Mountain caused by increasing recharge by a factor of 10. A rise of approximately 30-40 meters occurs north of the potential repository in the vicinity of the recharge area at Pahute Mesa. A smaller rise on the order of 15 meters occurred at nodes in the vicinity of Yucca Mountain. A comparison of Figures 6-2a and 6-2b illustrates the significance of the effect of this increase in

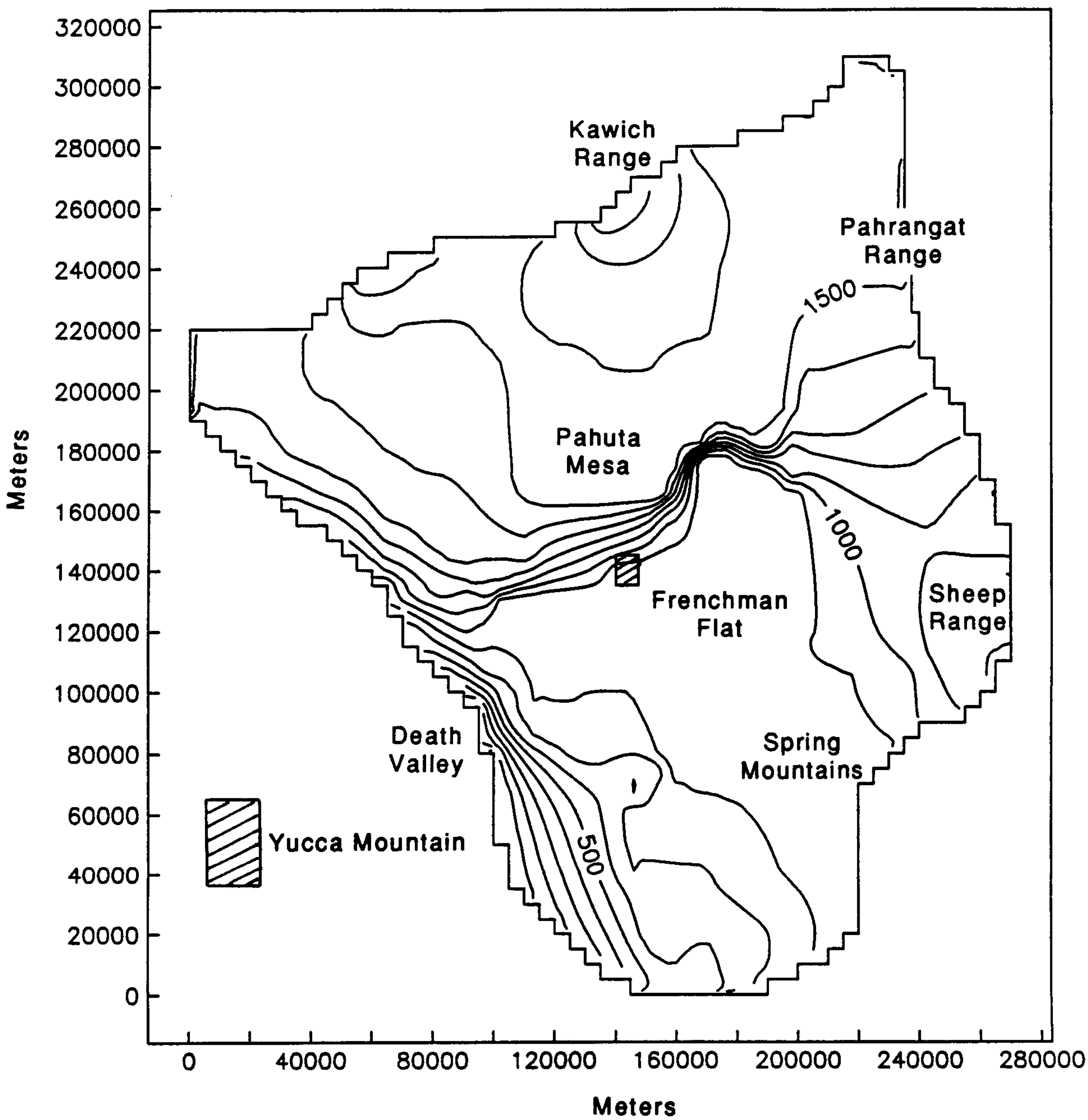
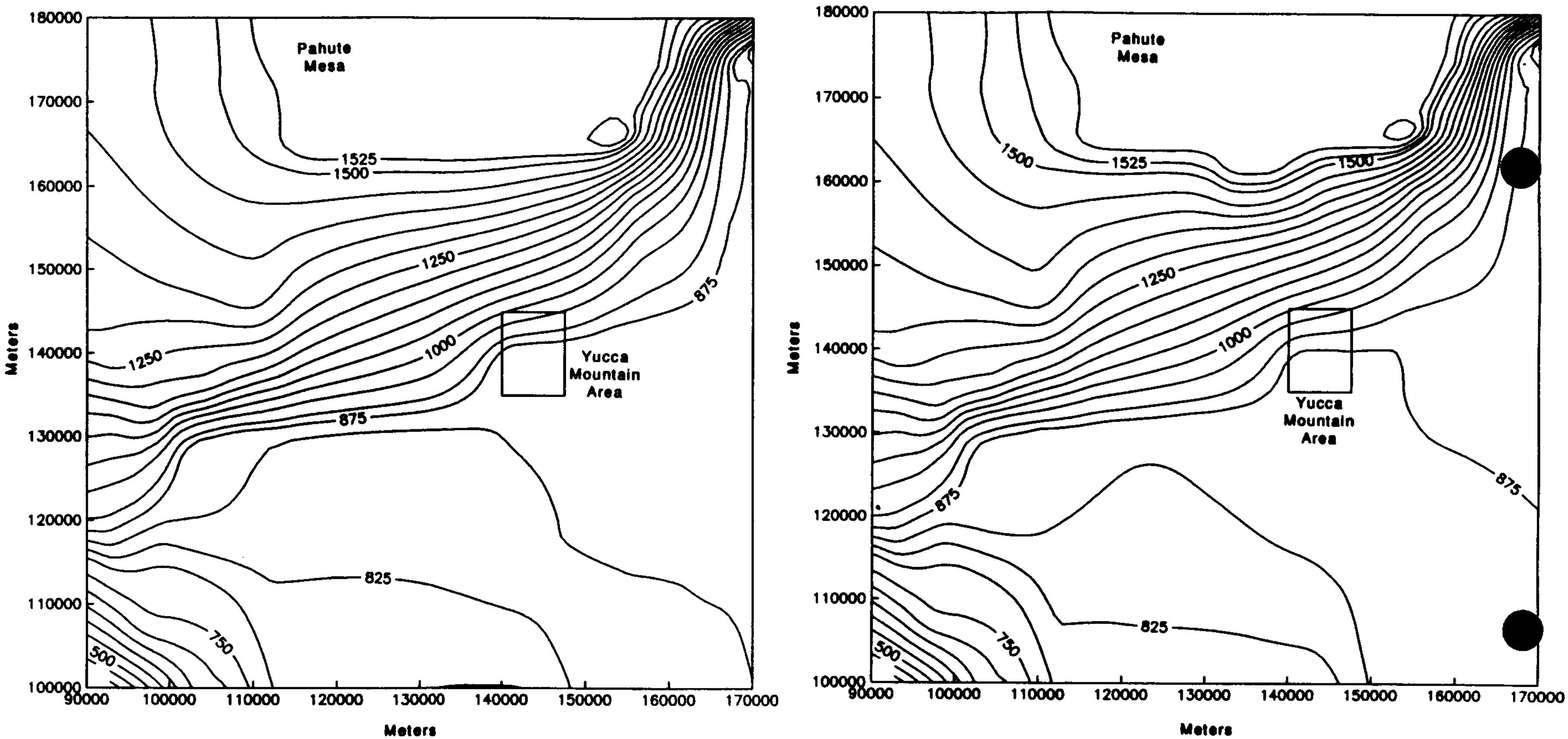


Figure 6-1. Simulated hydraulic head distribution obtained from PORFLO-3 under present day conditions



(a) (b)

Figure 6-2. Simulated hydraulic head distribution in the vicinity of Yucca Mountain under (a) assumed present day conditions and (b) postulated increase in recharge by a factor of 10

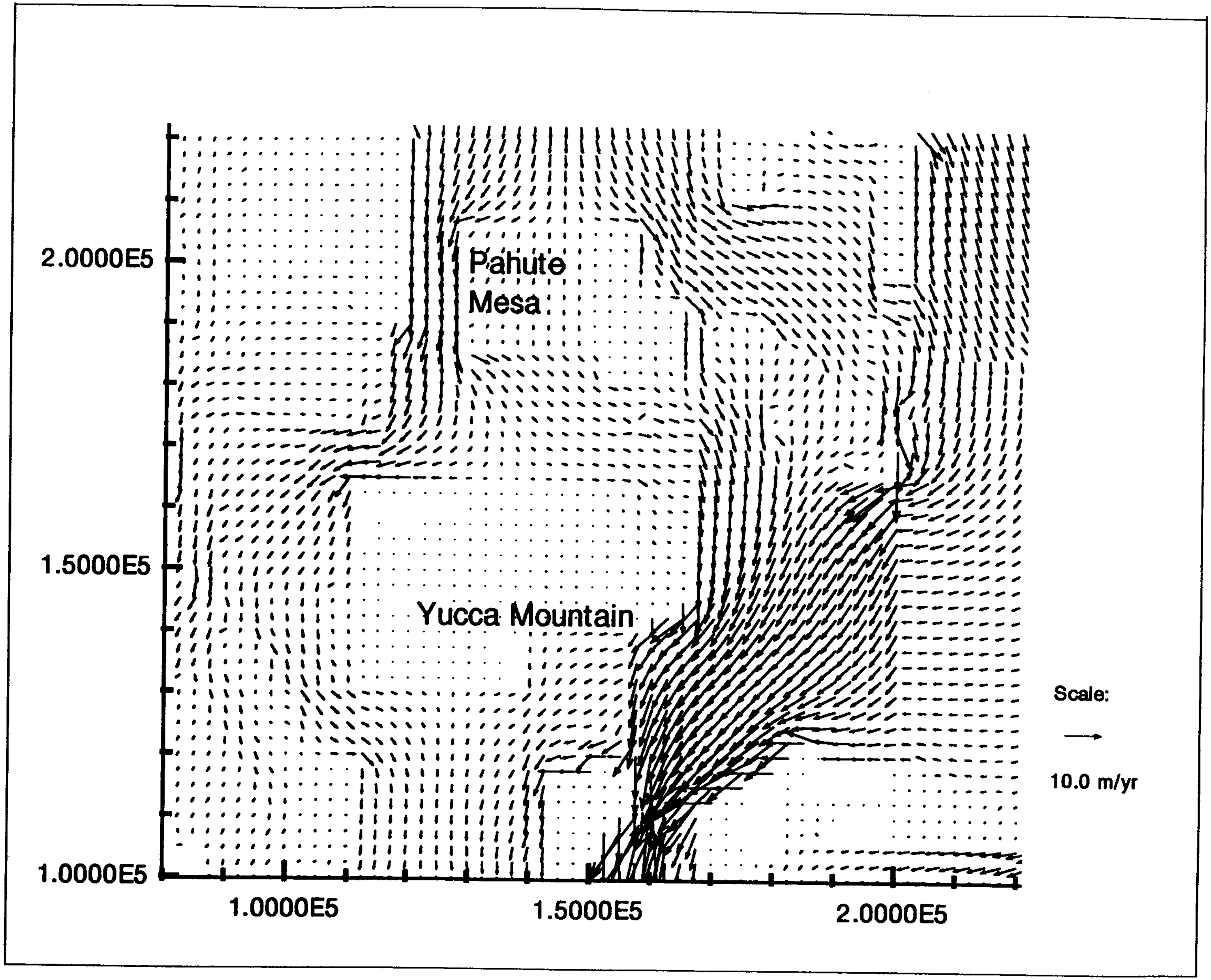


Figure 6-3. Simulated velocity vectors in the vicinity of Yucca Mountain under present day conditions

recharge compared to the base case. Figures 6-4a and 6-4b show time history plots of two points, one in the vicinity of Yucca Mountain, and the other near the recharge area at Pahute Mesa. The time was initialized to zero at the start of this increase in recharge, and a transient analysis was performed to determine the time required for the groundwater table to reach a new equilibrium state. Results show that approximately 400 years after recharge is increased, a new steady-state is reached throughout the regional model. As shown in Figures 6-4a and 6-4b, the hydraulic head begins increasing immediately for the node near Pahute Mesa where the recharge is occurring, while in the area of Yucca Mountain a period of approximately 50 years elapses before the effect of the recharge can be observed. Figures 6-5a and 6-5b show time histories at the same two points due to increasing the recharge by a factor of 20. For the nodal point near Yucca Mountain the hydraulic head increases 43 m, while the nodal point near Pahute Mesa experiences an increase in head of 85 m. For this case, equilibrium is not reached until approximately 700 years.

Increased precipitation in the higher elevations would also conceivably cause greater runoff into a wash such as Forty Mile Wash just east of Yucca Mountain. One would thus expect increased recharge to the water table below such washes as a result of increased precipitation, which under present day conditions is expected to be very small. The present analyses did not include recharge into Forty Mile Wash. As mentioned earlier, Czarnecki (1985) found that increasing the recharge into Forty Mile Wash above an annual baseline recharge of 0.41 m/year had a significant effect on the water table rise near Yucca Mountain. In order to incorporate such recharge into the present regional model, additional detail had to be added into the model to better depict Forty Mile Wash. Due to the large scale of the model, the recharge into Forty Mile Wash was applied along a line of nodes running roughly north-south and just to the east of Yucca Mountain.

Figure 6-6a shows the effect of increasing recharge by a factor of 10 both over the recharge areas indicated in Figure 5-2 as well as beneath Forty Mile Wash using the Forty Mile Wash baseline value of 0.41 m/year given by Czarnecki (1985). Through the area representing Yucca Mountain, hydraulic heads in the simulation range from approximately 950 to 1100 m above sea level. In Figure 6-6a, Forty Mile Wash is located just to the east (approximately 5 km) of the area representing Yucca Mountain. Comparing these simulated hydraulic heads to the base case simulation in Figure 6-2a, shows a water table rise through the area of between 75 and 100 m. This is consistent with the results obtained by Czarnecki (1985) for the case where he used a recharge flux multiplier of 10. Comparing Figure 6-6a with 6-2b one can see that increasing recharge into Forty Mile Wash has a greater effect on the water table near Yucca Mountain, mainly due to its close proximity than other parts of the modeled region. A larger permeability through the site would result in an even a higher water table in the Yucca Mountain area.

Figure 6-6b shows the effect of raising the level of the primary discharge area at Alkali Flats by 10 meters. The potentiometric surface shows the water table backing up slightly southeast of the Yucca Mountain area as compared to the base case shown in Figure 6-2a. Near Yucca Mountain, a water table rise of only 3 meters is experienced.

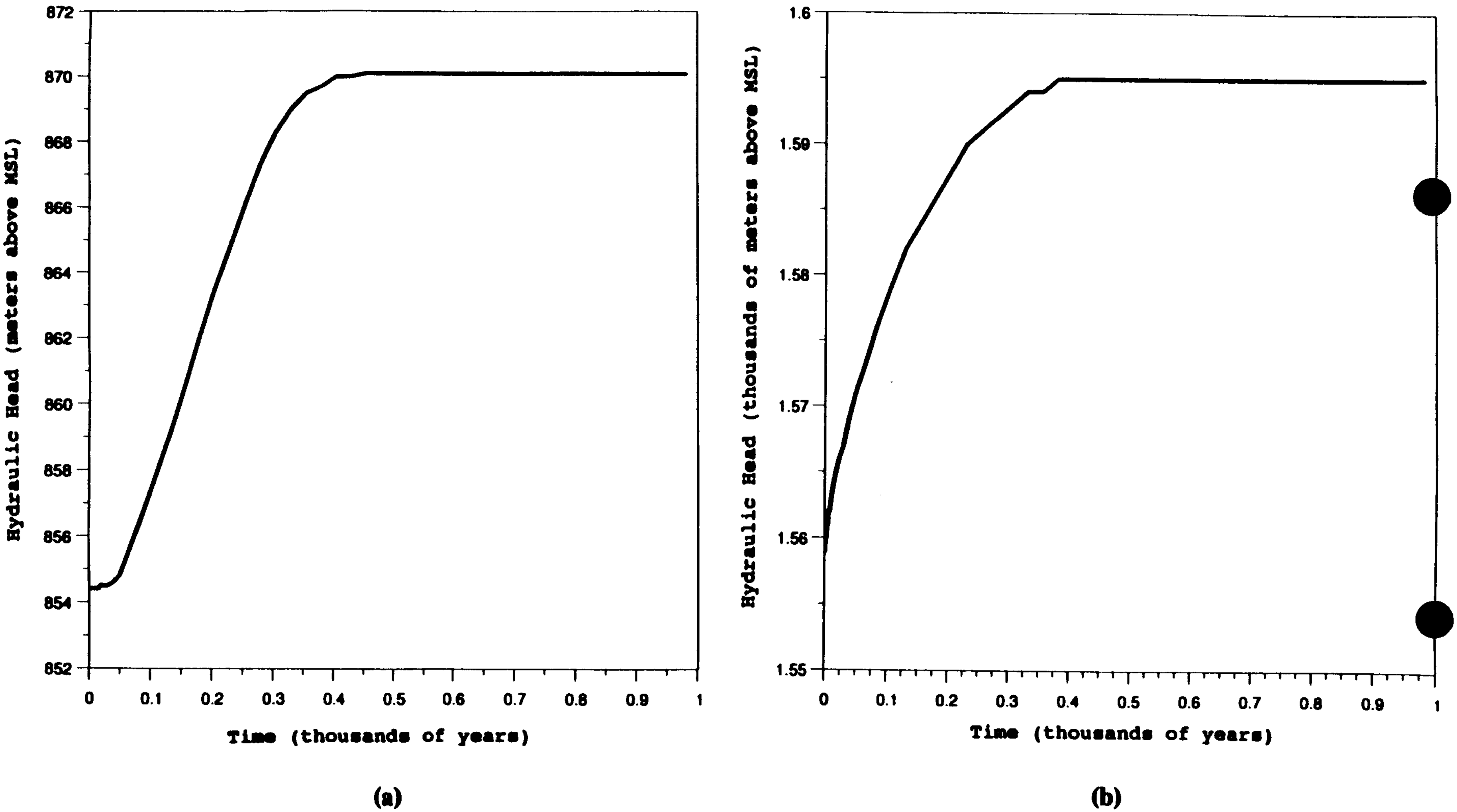
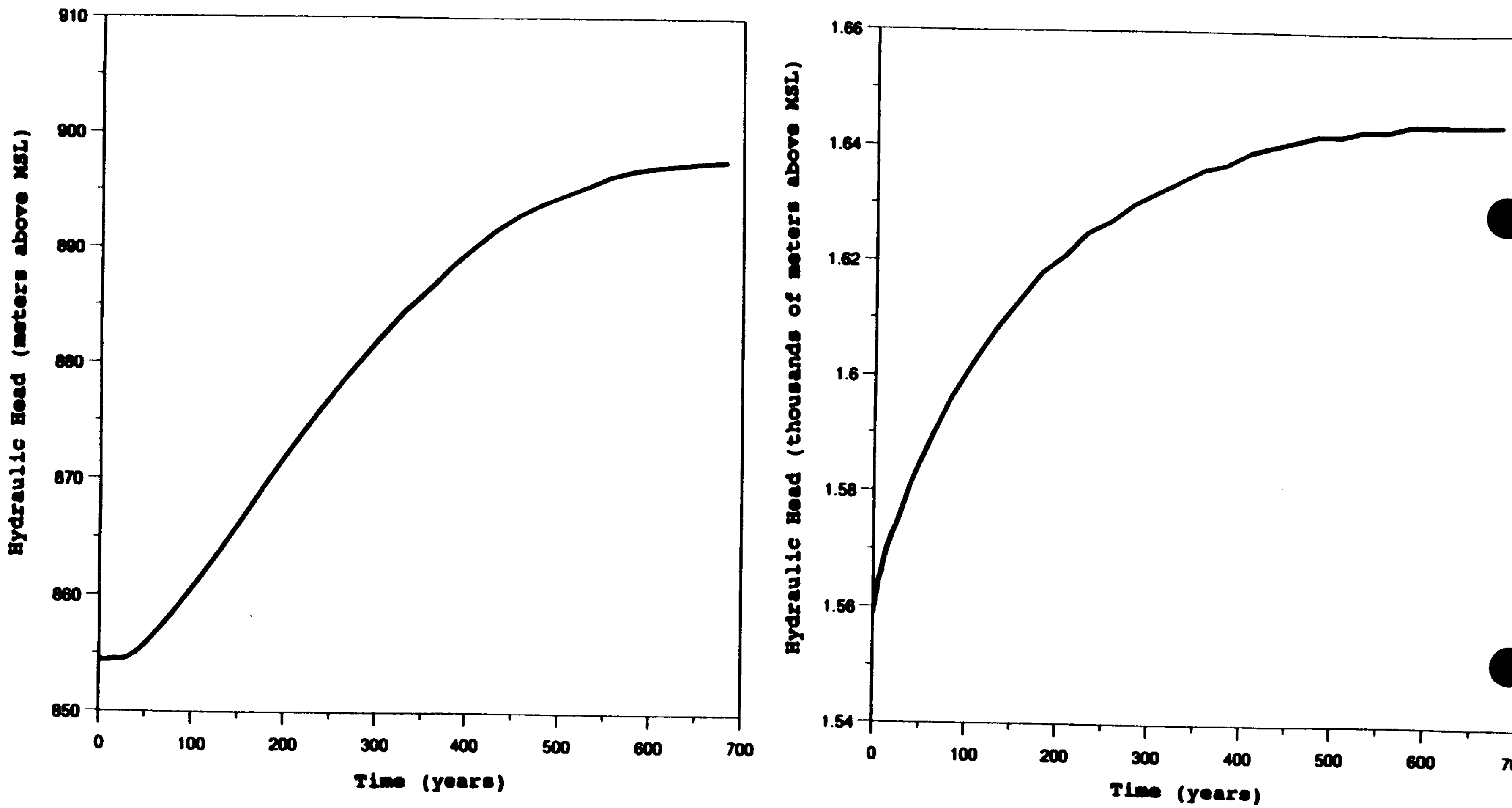


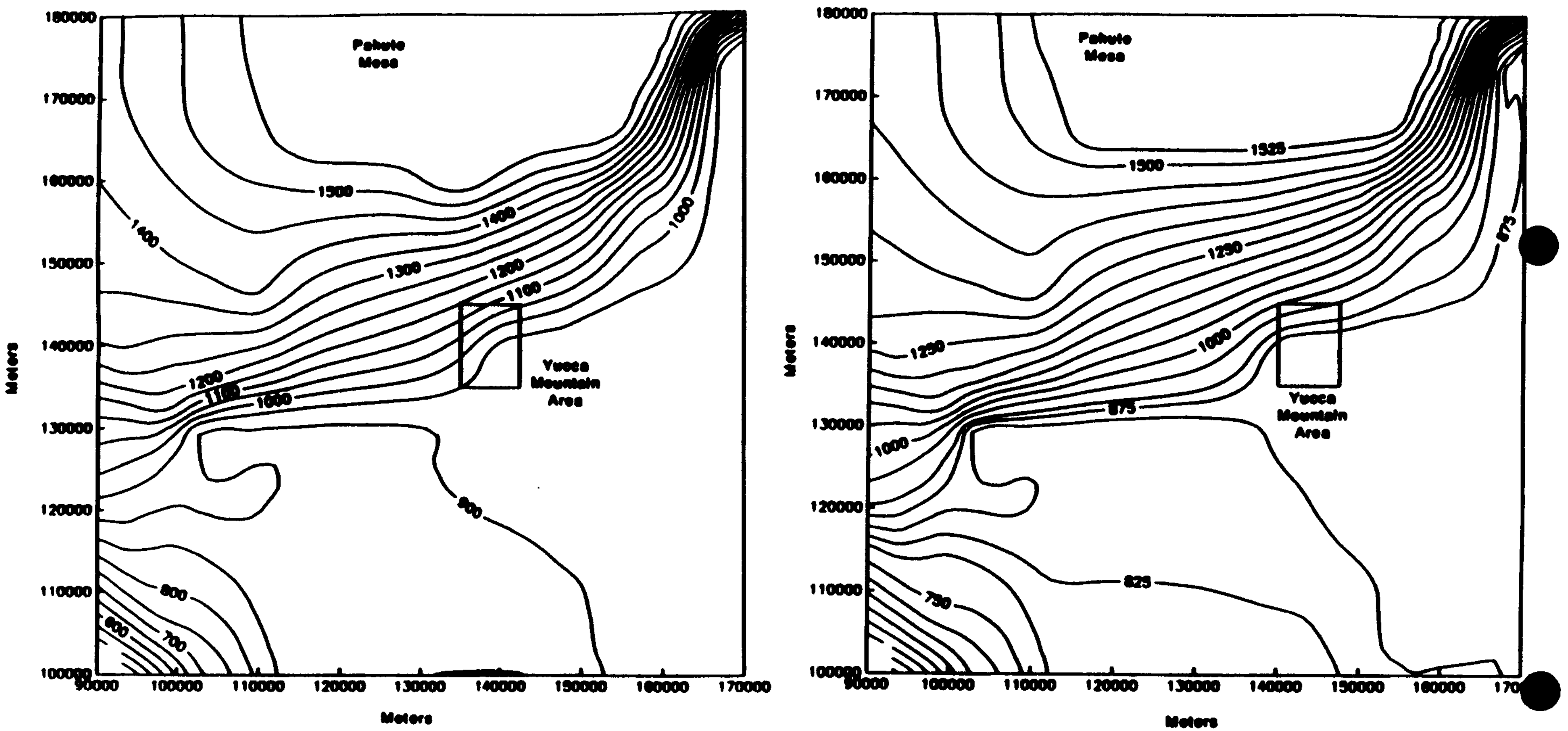
Figure 6-4. Time history plots as a result of increasing the recharge 10 times at nodal points (a) near Yucca Mountain and (b) near the recharge area at Pahute Mesa



(a)

(b)

Figure 6-5. Time history plots as a result of increasing the recharge 20 times at a nodal points (a) near Yucca Mountain and (b) near the recharge area at Pahute Mesa



(a) (b)

Figure 6-6. Simulated hydraulic head distribution in the vicinity of Yucca Mountain as a result of (a) increasing the recharge by a factor of 10 over those areas shown in Figure 5-2, as well as in Forty Mile Wash, and (b) increasing the elevation of the Alkali Flats discharge area 10 m

Other types of scenarios could be envisioned in which tectonic or volcanic activity could alter geohydrologic structures and consequently effect the groundwater flow or water table elevation near the potential repository site. For instance, future volcanic activity to the south of Yucca Mountain resulting in the formation of a low permeability intrusive dike or sill, might cause the groundwater table to rise at Yucca Mountain. Such an intrusive dike or sill could be many kilometers long and only a few meters thick. Figure 6-7 shows the effect of simulating such an intrusion just to the south of Frenchman Flats or southeast of Yucca Mountain. The intrusion was taken to be approximately 20 km in length and situated in the east west direction. As indicated in Figure 5-1, the area to the south of this postulated intrusion is a region of high permeability (zone 8) through which channeled much of the groundwater flow southward towards the Ash Meadows discharge area. As seen in Figure 6-8, water-table elevations through the site range from 1050 to 1150 meters above sea level. Compared with Figure 6-2a, this would indicate a rise in the water table of approximately 175 to 200 m. Figure 6-9 shows that this water table rise is a result of groundwater flow being diverted westward towards Forty Mile Wash and the potential repository site. The flow field without the presence of this barrier was presented in Figure 6-3, and shows that the majority of this groundwater flow was previously towards the south. In reality, an intrusion of such nature would be subjected to fracturing over time, and thus may allow some groundwater flow through.

As a final scenario, it could be postulated that future tectonic activity throughout the Basin and Range region could result in slip or opening of fractures through the low permeability regions north and northeast of Yucca Mountain. This could result in an increase in groundwater flow through such areas, especially if the faults and joints strike in the north-south direction as is presently the case near Yucca Mountain. This scenario was simulated in a regional model by increasing the permeabilities in the previously low permeability regions north and northeast of Yucca Mountain, as shown in Figure 5-1, to values comparable to those in surrounding areas. Figure 6-10 shows the potentiometric surface for the regional model as a result of increasing the permeability through those areas to values representative of hydraulic conductivity zone number 7 (Table 5-1). The steep hydraulic gradient is still present into Death Valley, mainly due to the low permeability along this portion of the regional model. However, north and northeast of Yucca Mountain, a steep gradient no longer exists. As a result of increasing the permeability through these barriers, a water table rise in the area of Yucca Mountain of approximately 275 meters is calculated. In the area of Pahute Mesa, the water table drops approximately 300 meters. Additional simulations could be made to determine whether or not changing the boundary condition in Death Valley from a constant head to a constant flux boundary would lead to a similar rise in the groundwater elevation at Yucca Mountain. Figure 6-11 shows the velocity vectors as a result of increasing the permeability through this area. Compared with Figure 6-3, it can be observed that more flow now takes place through area representing Yucca Mountain, and that the velocity vectors in this area have a southeast trend into Forty Mile Wash. In addition, maximum velocity vectors occur to the northeast of Yucca Mountain with magnitudes of approximately 40 m/year. Figures 6-12a and 6-12b show time history plots for the two nodes in the vicinity of Yucca Mountain and Pahute Mesa. The nodal point within the area of Pahute Mesa had a water table elevation initially at 1554 m and over a period of approximately 100 years, the water table elevation dropped to a new equilibrium value of 1267

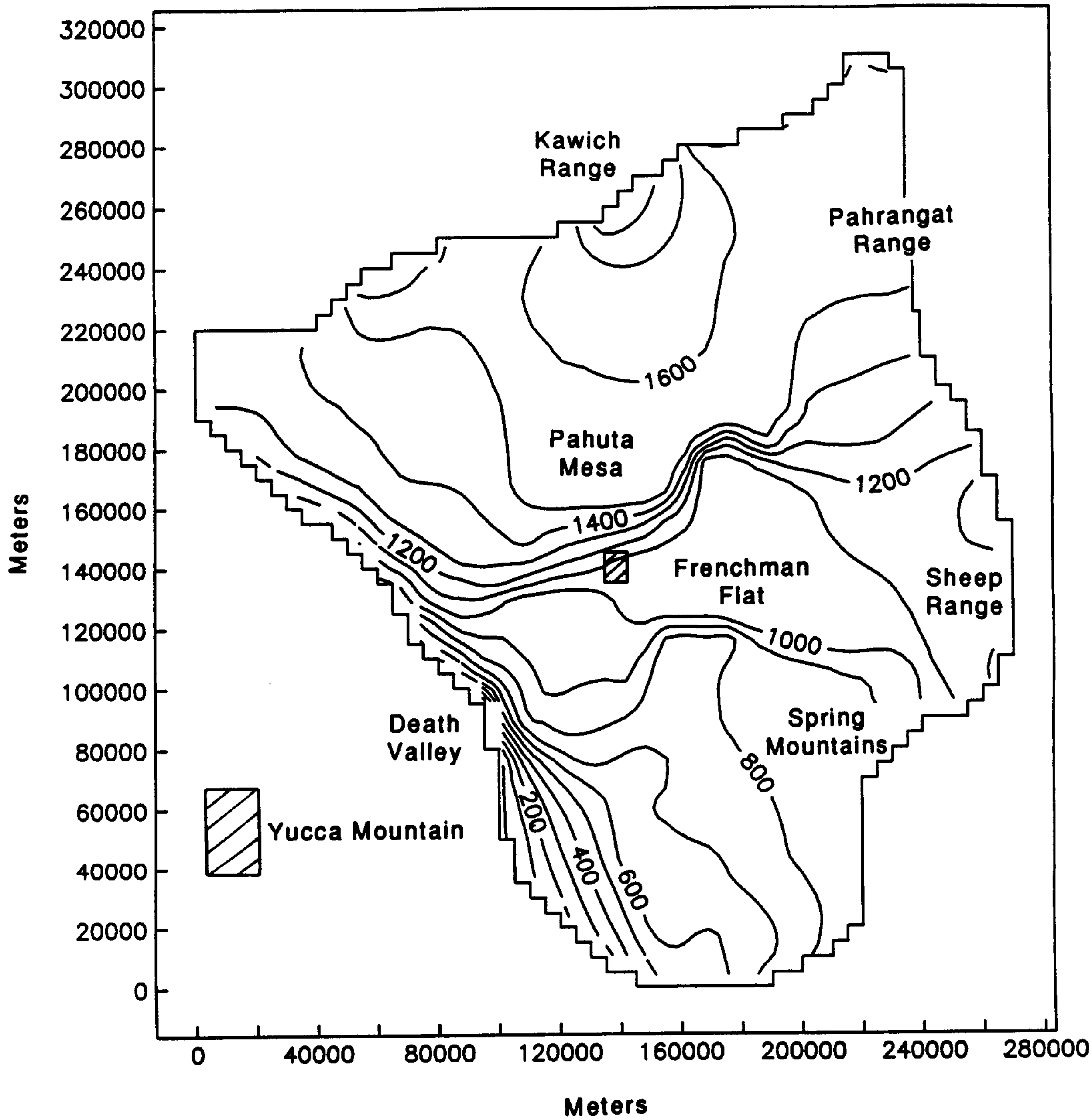


Figure 6-7. Simulated hydraulic head distribution as a result of a volcanic intrusion southeast of Yucca Mountain

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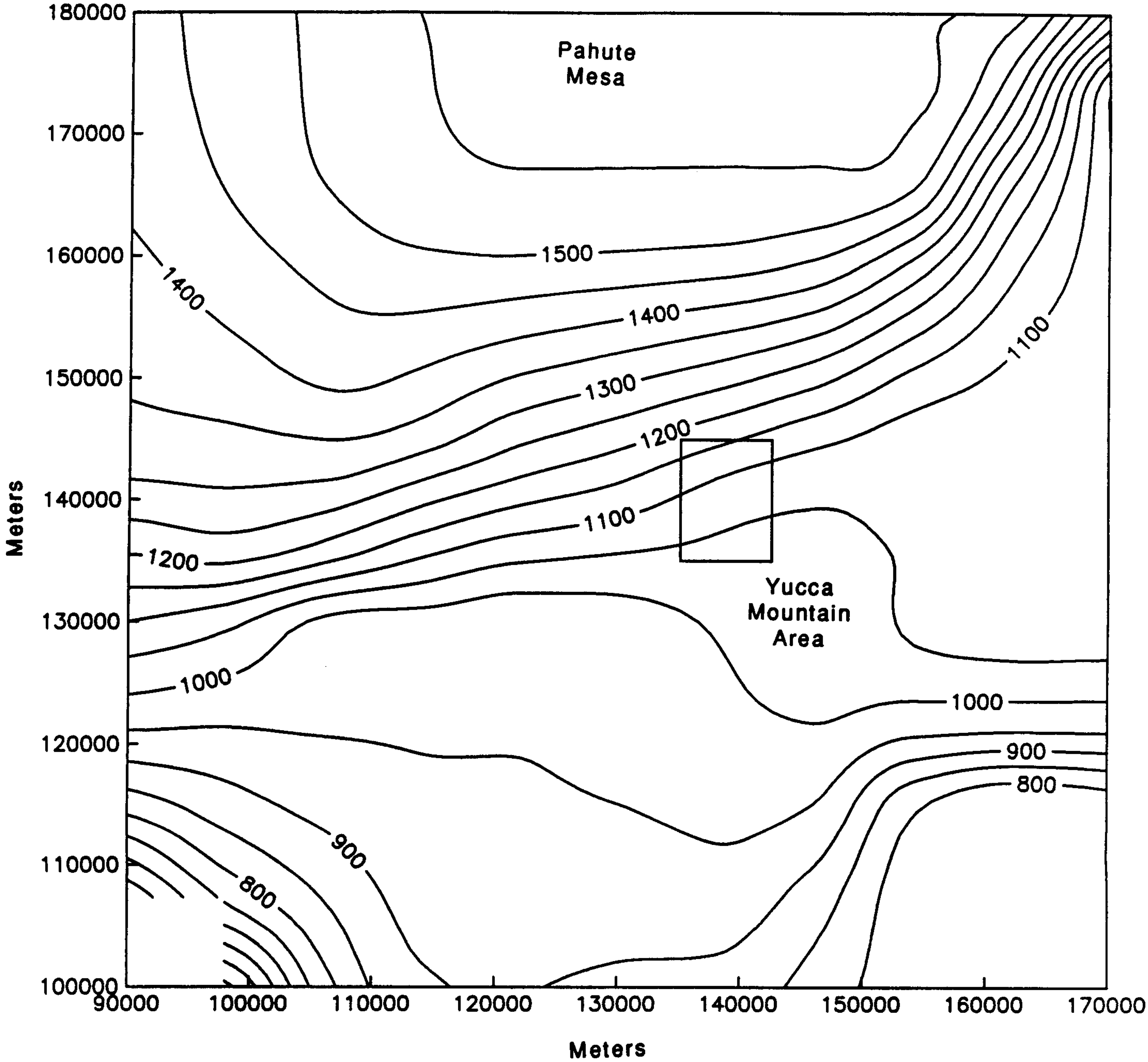


Figure 6-8. Simulated hydraulic head distribution in the vicinity of Yucca Mountain as a result of a volcanic intrusion to the southeast

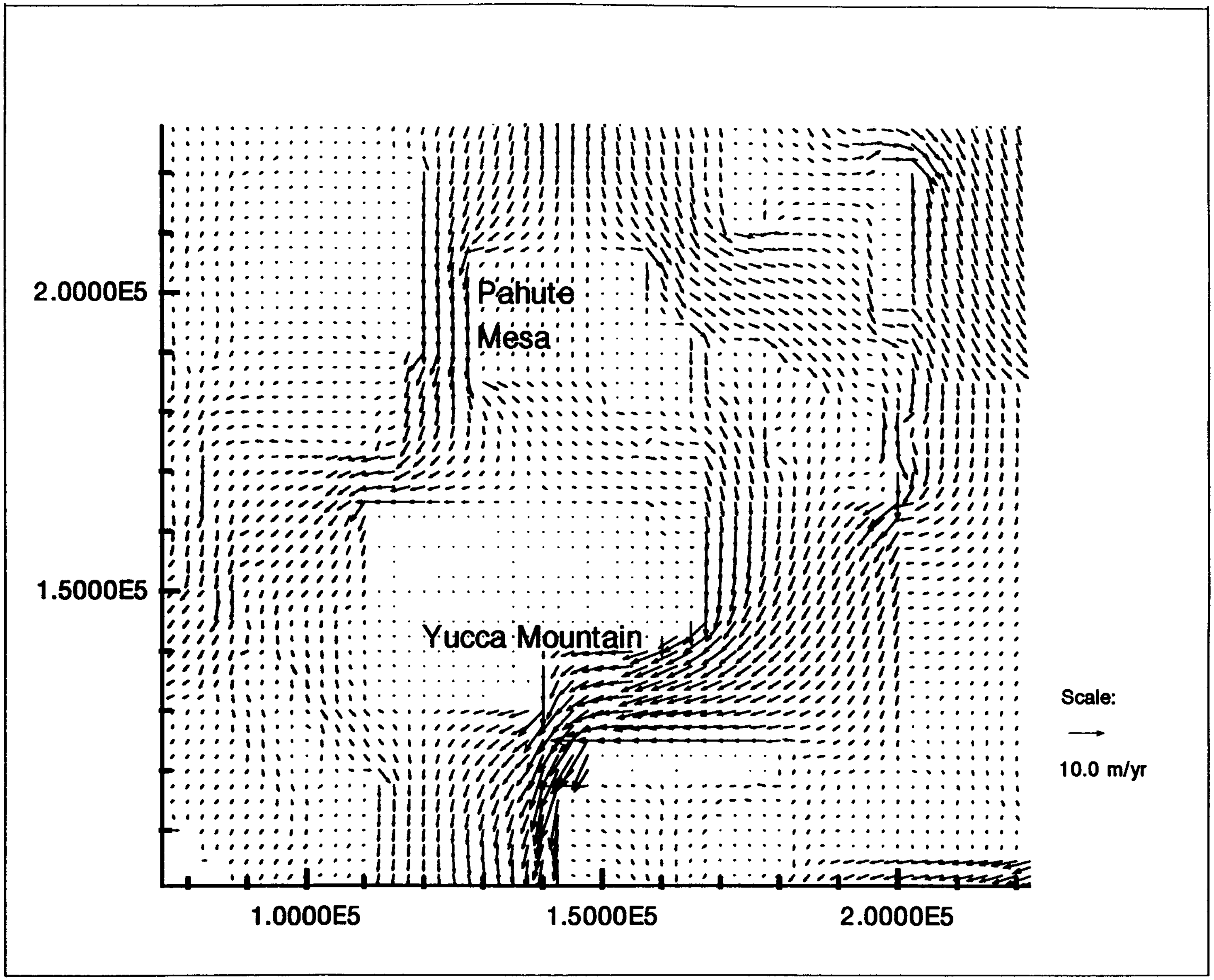


Figure 6-9. Velocity vectors in the vicinity of Yucca Mountain as a result of a volcanic intrusion to the southeast

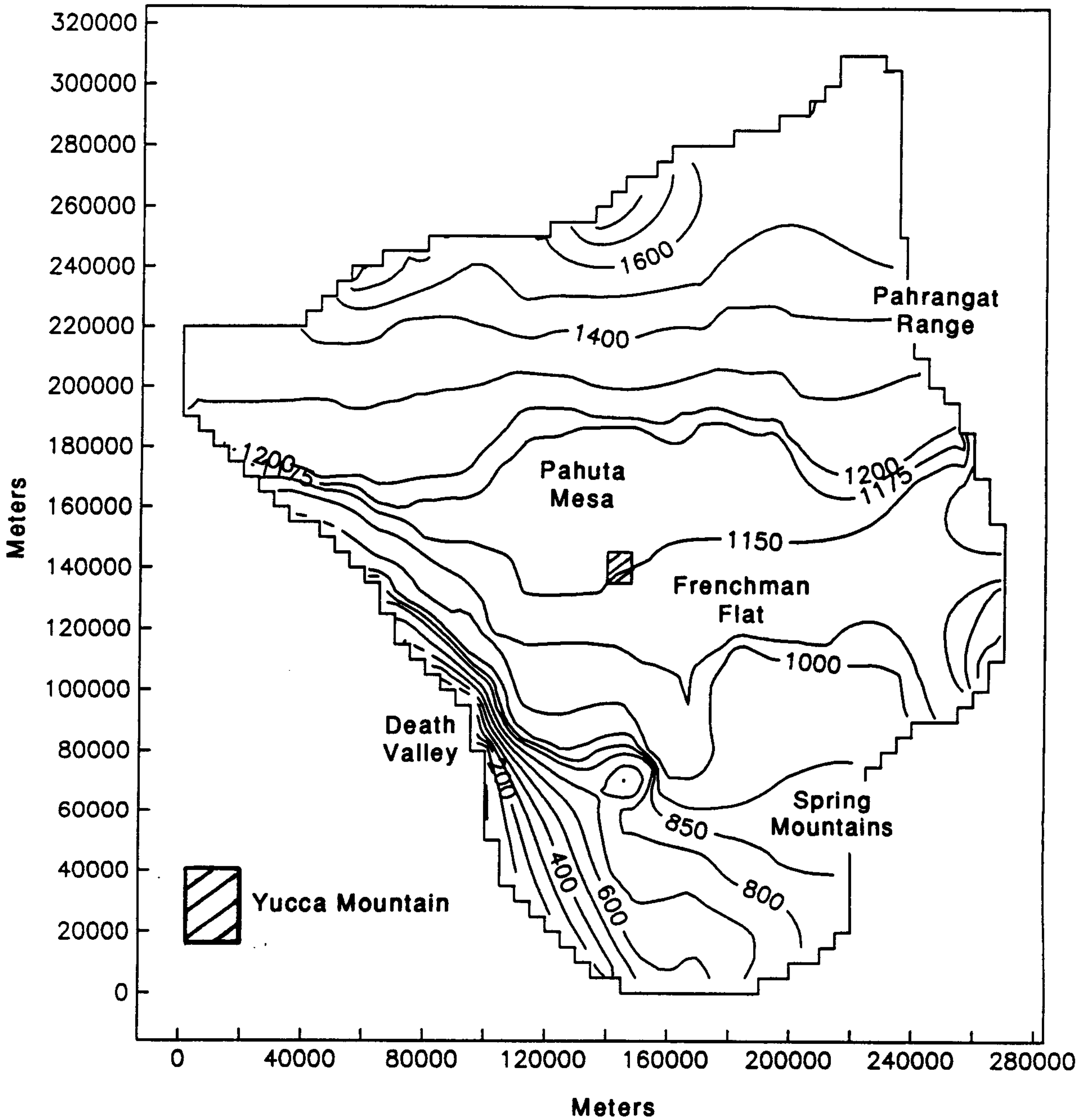


Figure 6-10. Simulated hydraulic head distribution as a result of increasing the permeability through barriers north and northeast of Yucca Mountain

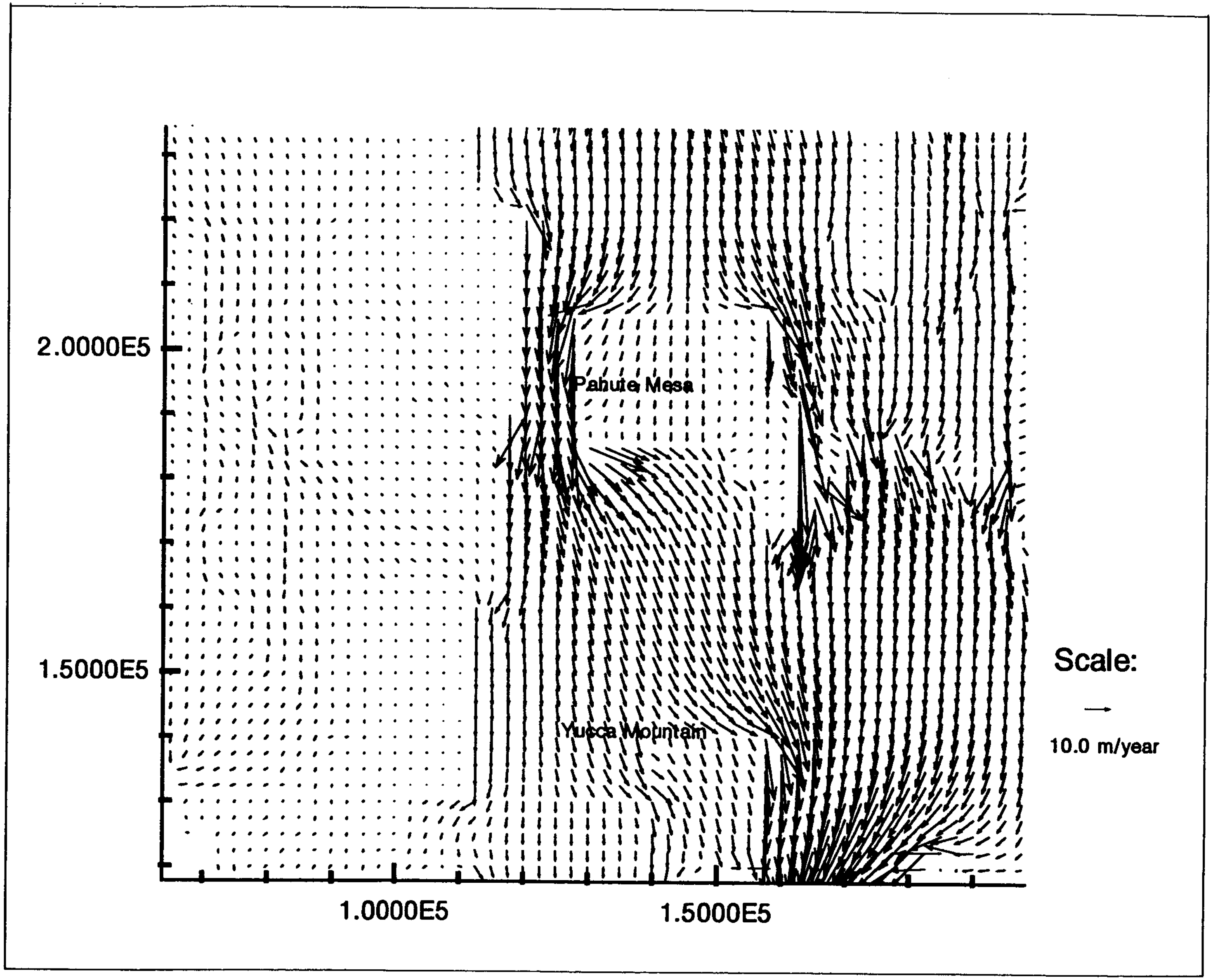
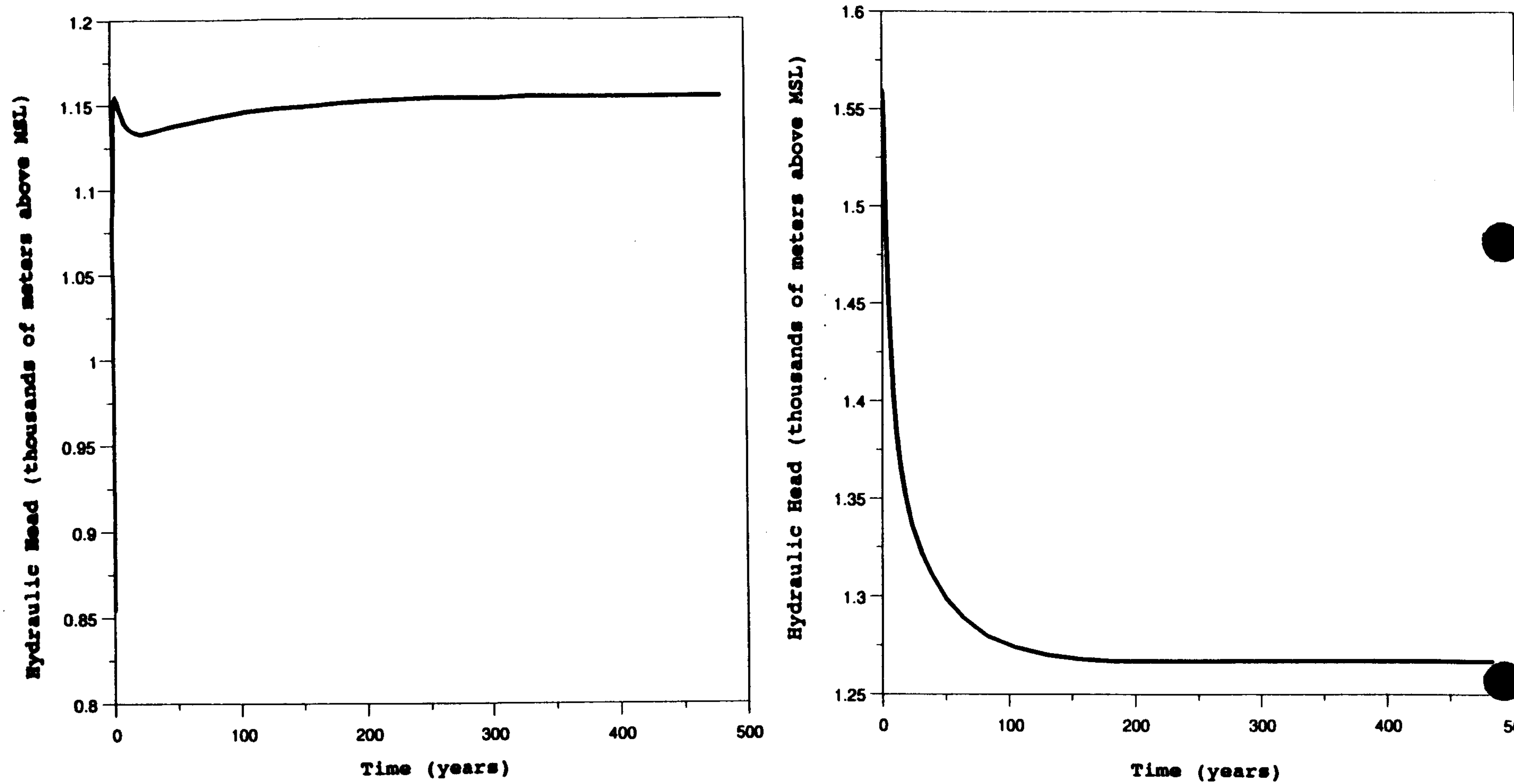


Figure 6-11. Simulated velocity vectors in the vicinity of Yucca Mountain as a result of increasing the permeability through barriers north and northeast of Yucca Mountain



(a) (b)

Figure 6-12. Time history plots as a result of increasing the permeability through barriers north and northeast of Yucca Mountain at nodal points (a) near Yucca Mountains, and (b) near the recharge area at Pahute Mesa

m. In contrast, the nodal point in the area of Yucca Mountain which was initially at a water table elevation of 854 m rose much more rapidly to a new equilibrium value of 1155 m. The surge in the pressure head in Figure 6-12a is not believed to be a result of any numerical instability in the solution process. It is thought to be more a consequence of the modeling approach in which the permeability of the barrier north of the repository site was suddenly increased several orders of magnitude, allowing a rapid influx of water through the area to equalize the pressures. Increasing the permeability of this barrier in more gradual steps, as might be expected to occur in reality, would most likely not lead to such a surge in the pressure head.

7 CONCLUSIONS

The results from a simple regional groundwater flow analysis of the saturated zone surrounding Yucca Mountain using the modified version of the PORFLO-3 computer code are presented. These results show the effects of various scenarios on the water table elevations and the resulting groundwater flow directions throughout the region. The results give an indication on what scenarios would have a minimum impact on the saturated zone hydrology near the site, and those that would have a major impact. A rise in water table near the site ranged from only a few meters to as much as 275 m, depending on the scenario. One should keep in mind that on a Yucca Mountain scale, this regional model is still very coarse. To conduct more detailed analyses of the groundwater flow near the repository site, a smaller model would be necessary.

Also, in viewing the results, one needs to consider the assumptions made, both from a mathematical standpoint in the model development, as well as from a modeling perspective. For instance, it is most likely that under the simulated scenarios causing a rise in the water table, springs would form in areas where the potentiometric surface intersected the land surface elevations, resulting in some surface runoff. In this modeling effort, no attempt was made to compare the simulated potentiometric surfaces with land surface elevations and take into account the effect that any springs might have on the extent of the water table rise. Most likely, incorporating the effect of springs and increased evaporation as the water table approaches the land surface would lower the extent of water table rise in adjacent areas. In the next modification of PORFLO-3 code, we intend to incorporate ground elevation so that formation of springs can be explicitly considered in simulations.

The scenarios presented in this report are meant to show the utility of numerical simulation in studying their effects. In the final performance assessment, the probability of occurrence of such events should also be taken into account, since for some scenarios, the probability of occurrence may be very low. Site characterization studies at Yucca Mountain may provide better information on which scenarios would be more apt to occur in the future.

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