Regional Groundwater Modeling of the Saturated Zone in the Vicinity of Yucca Mountain, Nevada

Iterative Performance Assessment – Phase 2

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Prepared by
M. Ahola, B. Sagar

Center for Nuclear Waste Regulatory Analyses
Southwest Research Institute
6220 Culebra Road
San Antonio, TX 78228

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ABSTRACT

Results of groundwater modeling of the saturated zone in the vicinity of Yucca Mountain are presented. Both a regional (200 x 200 km) and subregional (50 x 50 km) model were used in the analyses. Simulations were conducted to determine the impact of various disruptive conditions that might take place over the life span of a proposed Yucca Mountain geologic repository on the groundwater flow field, as well as changes in the water-table elevations. These conditions included increases in precipitation and groundwater recharge within the regional model, changes in permeability of existing hydrogeologic barriers, and the vertical intrusion of volcanic dikes at various orientations through the saturated zone. Based on the regional analysis, the rise in the water-table under Yucca Mountain due to various postulated conditions ranged from only a few meters to 275 meters. Results of the subregional model analysis, which was used to simulate intrusive dikes approximately 4 kilometers in length in the vicinity of Yucca Mountain, showed water-table rises ranging from a few meters to as much as 103 meters. Dikes oriented approximately north-south beneath Yucca Mountain produced the highest water-table rises. The conclusions drawn from this analysis are likely to change as more site-specific data become available and as the assumptions in the model are improved.

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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 was to gain experience in modeling large-scale saturated flow and to draw very preliminary inferences regarding the effects of certain selected conditions on the position of the water-table.

A two-dimensional planar finite-difference grid (13161 computational cells) was imposed on a region approximately 200 by 200 kilometers. At this regional scale, the Yucca Mountain repository area was represented approximately by two grid nodes. In addition, to conduct more detailed saturated flow modeling in the vicinity of Yucca Mountain, a subregional model consisting of a finite difference grid (18225 computational cells) was imposed on a region 50 x 50 kilometers around the proposed repository site. Boundary conditions for this subregional model consisted of fixed pressures obtained from the larger regional model. The hydrological data for the simulations were 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, Pahrangat 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 5×10^{-8} to 3.5×10^{-3} m/sec. The model contains a low permeability zone northwest of Yucca Mountain for simulating the present-day high hydraulic gradient at that location. The actual cause of the steep gradient is not yet fully known.

Considering the current conditions, a steady-state solution to the flow system was obtained. This steady-state solution was then used as the starting point or initial state for simulating other conditions. The conditions simulated in the regional model include: (i) climatic change in the future increasing the recharge at higher elevations by factors of 10, 20, and 30; (ii) increase of recharge in the Forty Mile Wash by a factor of 10; (iii) rise in water level at Alkali Flats discharge area by 10 meters; (iv) geologic activity (volcanic or tectonic) to the south of Yucca Mountain creating a flow barrier 20 kilometers long; and (v) geologic activity to the north of Yucca Mountain breaking the existing flow barrier. Most of the above conditions were simulated in a transient mode so that the time variation of the water table could be studied.

Using the steady-state solution obtained from the regional model for the current conditions, a total of ten additional simulations of volcanic dike intrusions in the vicinity of Yucca Mountain were conducted using the subregional model. These volcanic dikes were situated at various orientations directly below the repository site as well as approximately 5 kilometers southeast of the site to determine their impact on the groundwater flow.

Based on the regional analysis, the rise in the water table under Yucca Mountain due to various postulated conditions 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 87 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 was removed.

Results of the subregional model analysis of the intrusive volcanic dikes in the vicinity of Yucca Mountain showed groundwater table rises ranging from only a few meters to as much as 103 meters. For certain dike locations and orientations, the water table actually dropped several meters in the vicinity of the site.

A number of assumptions were made in this study with regard to the numerical model and to the data. These assumptions, 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 that such a rise may cause was completely neglected.

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The original document prepared in January 1992 has been revised to (i) incorporate technical comments from NRC staff, and (ii) includes the additional analyses performed after completion of the original report. The authors express their appreciation to Dr. Norman Eisenberg (NRC) for his critique as well as suggestions for the additional analyses. The size, location, and orientation of the volcanic dikes utilized in the analyses were suggested by Dr. John Trapp (NRC).

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. The simulations were conducted both on a regional scale as well as a smaller scale, i.e., the scale of Yucca Mountain. The regional scale analysis provided the boundary conditions for the simulations of the saturated zone in the subregional model. 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 are documented in another report (Bagtzoglou et al., 1992).

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 and as likely to change when actual field data are used in simulations.

The simulation results pertain to a two-dimensional regional (about 200 by 200 km) and subregional (50 by 50 km) area, saturated groundwater flow analysis beneath Yucca Mountain and the surrounding area. For this application, PORFLOW (Runchal and Sagar, 1989; Sagar and Runchal, 1990), an integrated finite difference code, was modified (Version 1.11) 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 PORFLOW code. Once this was completed, various conditions 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.

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 provide the location of the water table, as an output as that surface at which the relative saturation is unity. Such formulations are general because they 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 nonlinear 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 gauge 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: (i) the gauge pressure at this boundary is zero at all times, and (ii) it is a stream line (i.e., there is zero flux crossing the boundary). These two conditions are strictly true at steady state; however, even in the transient case, by representing the recharge as a source term, both these conditions are approximately satisfied 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 PORFLOW (Version 1.11) to accommodate the free surface boundary condition are discussed.

2.2 MODIFICATIONS TO PORFLOW¹

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

¹ The Analytic and Computational Research Incorporated (ACRI), Los Angeles, holds copyright privileges on the PORFLOW software. The United States Government, however, has retained rights for its unlimited use in its work. Commercial users of PORFLOW should contact ACRI before using this software. The name PORFLO-3 has also been used for this code.

governing equations and their numerical treatment, have been documented (Runchal and Sagar, 1989; Sagar and Runchal, 1990). Version 1.0 of this code can be used to solve an unsaturated-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 PORFLOW 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 PORFLOW 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, or cell volumes, where cell is a computational element as shown in Figure 2-1) required for numerical calculations becomes very easy.
- (2) *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 PORFLOW. If this realistic flow situation were 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 PORFLOW (Version 1.11) 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 PORFLOW 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

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

that are devoid of water. Therefore, the rule for flow exchange between dry and wet cells cannot be based on pressure gradients.

Although the code has been modified so 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 a horizontal or vertical plane. Even in two-dimensional cases in PORFLOW, 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 here.

- (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 that 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 conditions 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.

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

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 and fluid. In the application presented here, specific yield is equated to drainable porosity in 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 outcropping in the mountainous areas and underlying the alluvial deposits in the basins. Hydrogeologically, the area consists of three groundwater subbasins: (i) Oasis Valley, (ii) Ash Meadows, and (iii) Alkali Flat-Furnace Creek Ranch. These subbasins are bounded by Death Valley to the west and southwest, 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: (i) Alkali Flats (Franklin Lake Playa), where discharge occurs primarily by evaporation, and (ii) 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 and at 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 and boundary conditions) from such studies for the PORFLOW 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: (i) to estimate fluxes for use in predictions of transport of radionuclides and (ii) 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 km, 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, Pahranaagat, 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

- 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 (from 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 reasons for this subregional model study were to gain a better understanding of the groundwater flow system beneath the Yucca Mountain area and to use it later 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 relatively 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: (i) faults that contain nontransmissive fault gouge or that juxtapose transmissive tuff against nontransmissive tuff; (ii) 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 (iii) 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 current 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 with the

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)

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

Horizontal, two-dimensional finite-difference grids were set up for simulations with the PORFLOW computer code. In modeling two-dimensional problems, PORFLOW requires three 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 km. A rectangular finite-difference grid used for the analysis consisted of 109 by 125 node points in the x and y directions, respectively. Each grid cell was 2.5 km on a side, encompassing an area of 6.25 km². PORFLOW 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 conditions 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 PORFLOW, 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 it 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

Figure 5-1. Regional model for PORFLOW 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}

were specified at the higher elevations such as the Spring Mountains, Sheep Range, Pahrnagat 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.

The subregional groundwater study area in the vicinity of Yucca Mountain, indicated by the dashed rectangular area in Figure 5-2, encompassed an area 50 x 50 km. The finite-difference grid for this analysis consisted of 137 x 137 node points in the x and y directions. The potential repository site was centered within the grid. The finite-difference grid was graded finer towards the middle, where the grid cells were 100 x 100 m on a side. Boundary conditions for this model consisted of fixed pressures along all four sides of the rectangular grid. These pressures were obtained directly from the larger regional model simulations.

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

6 SIMULATION RESULTS

6.1 REGIONAL MODEL ANALYSIS

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 disruptive conditions could be modeled.

Yucca Mountain, indicated in Figure 6-1 by the small rectangular box, is represented approximately by two grid nodes in the regional model. Thus on the Yucca Mountain scale, the regional 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. The intent of the analysis was to focus more on relative changes in the regional water table rather than on the absolute water table elevation itself. Nevertheless, the uncalibrated results were deemed acceptable for use as a base case for analyzing the effects of various postulated disruptive conditions.

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 PORFLOW. This steady-state solution was then used as input to subsequent transient analyses to simulate various postulated conditions 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

Figure 6-1. Simulated hydraulic head distribution obtained from PORFLOW under current conditions

Figure 6-2. Simulated hydraulic head distribution in the vicinity of Yucca Mountain under (a) assumed current 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 current conditions

of Yucca Mountain caused by increasing recharge by a factor of 10. A water-table rise ranging from 40 to 50 occurs throughout the area representing Yucca Mountain. A comparison of Figures 6-2a and 6-2b illustrates the significance of the effect of this increase in 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 87 m, while the nodal point near Pahute Mesa experiences an increase in head of 100 m. For this case, equilibrium is not reached until approximately 700 years.

The parametric relationship between increased recharge and water-table rise is depicted in Figure 6-6 at nodal points in the vicinity of Yucca Mountain and Forty Mile Wash. The numbers representing increase in recharge as shown on the x-axis are multipliers of the baseline (present-day) flux. Again, the recharge is applied over those shaded regions indicated in Figure 5-2. The results show a more or less linear relationship between the two parameters. Czarnecki (1985) states that a 100-percent increase in annual precipitation over the region would correspond to an increase in groundwater recharge of approximately 15 times the present-day recharge rate.

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 current 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 6-7a 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 6-7a, Forty Mile Wash is located just to the east (approximately 5 km) of the area representing Yucca Mountain. Comparing these simulated hydraulic heads

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

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

Figure 6-6. Water table rise at Yucca Mountain and Forty Mile Wash as a function of recharge rate

(a)

(b)

Figure 6-7. 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

to the base case simulation in Figure 6-2a, shows a water-table rise throughout 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 6-7a 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 closer proximity than to other parts of the modeled region.

Figure 6-7b 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.

Other types of disruptive cases 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 6-8 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 (see Section 6.2 for more realistic cases) 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 much of the groundwater flow is channeled southward towards the Ash Meadows discharge area. As seen in Figure 6-9, 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 6-10 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 (presented in Figure 6-3) 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.

For another simulation, we 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 condition was simulated in a regional model by increasing the permeabilities approximately three orders of magnitude in the previously low permeability regions north (zone 1) and northeast (zone 2) of Yucca Mountain, as shown in Figure 5-1, to values comparable to those in surrounding areas.

Figure 6-11 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

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

Figure 6-9. Simulated hydraulic head distribution in the vicinity of Yucca Mountain as a result of a volcanic intrusion to the southeast

Figure 6-10. Velocity vectors in the vicinity of Yucca Mountain as a result of a volcanic intrusion to the southeast

Figure 6-11. Simulated hydraulic head distribution as a result of increasing the permeability through barriers north and northeast of Yucca Mountain

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 6-12 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 6-13a and 6-13b 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 m. In contrast, the nodal point in the area of Yucca Mountain, 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 6-13a 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 three 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, does not lead to such a surge in the pressure head. This is shown by the dashed curves in Figure 6-13.

The parametric relationship between the increase in permeability through this barrier on the water-table rise at nodal points near Yucca Mountain and Forty Mile Wash is shown in Figure 6-14. The numbers along the x-axis represent multipliers of the assumed present-day permeabilities in the barriers directly north and northeast of the Yucca Mountain repository site. The results presented in the previous discussion (i.e., Figure 6-11 through 6-13) assumed the barrier permeability increased several orders of magnitude above that shown in Figure 6-14, and was meant to represent the most extreme condition.

6.2 SUBREGIONAL MODEL ANALYSIS

In addition to the regional groundwater table analysis, a total of ten additional simulations were completed using a subregional model to study in more detail the effect of volcanic activity in the direct vicinity of Yucca Mountain on the potential water-table rise as well as change in flow directions. The additional runs were meant to simulate the intrusion of volcanic dikes having a length of 4 km at various orientations both directly beneath the repository site and at 5 km southeast of the site. The regional model was too coarse to perform these simulations.

The location of the subregional model is depicted by the dashed rectangular region in Figure 6-2. The finite-difference grid encompassed an area of 50 x 50 km. The grid cells were 100 on a side near the center of the mesh where the volcanic dikes were assumed to be located.

Figure 6-12. 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 6-13. Time history plots as a result of increasing the permeability through barriers north and northeast of Yucca Mountain at nodal points (a) near Yucca Mountain and (b) near the recharge area at Pahute Mesa

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Figure 6-14. Water-table rise at Yucca Mountain and Forty Mile Wash as a result of increasing the permeability through the barriers north and east of the site

At the outer boundaries of the model, the largest grid cells were 2.5 km on a side, which corresponded to the size of the grid cells for the regional model. The boundary conditions along all four sides of the subregional model consisted of fixed pressures obtained from corresponding nodes in the regional model. Since additional boundary nodes were incorporated into the subregional model due to the finer mesh, linear interpolation was done to fix their pressures. It should be noted that the fixed boundary pressures corresponded to the baseline (or current) water-table configuration from the regional model.

The narrow dikes were assumed to extend through the water table and well above any potential water-table rise. They essentially acted as dams within the flow field, and were created by specifying a very low permeability along lines one gridpoint in thickness and 4 km in length. Based on discussions with project geologists, the preferred orientation of a potential future volcanic dike intrusion was judged to trend approximately N 15° E, based on existing faulting throughout the region. Figure 6-15 shows the results of this case, assuming that the 4 km dike extends directly through the potential repository site. To the left of the dike, the flow field can be seen to be directed towards the south; and around the lower tip of the dike, some of the flow is directed back to the north. The dark streamlines better illustrate this. Without the presence of the dike, the flow through this area is primarily to the east and southeast. The small velocity vectors to the north of the dike represent the low permeability barrier, whereas the higher velocity vectors to the east represent the area where Forty Mile Wash is located. The small dark circle on Figure 6-15 represents the location where the maximum water-table rise occurred, which for this case was 79.3 and would be located at the northern portion of the potential repository site. Thus, even though the radionuclide travel time through the unsaturated zone would be somewhat decreased, the travel time in the saturated zone could be substantially increased, especially for the portion of the radionuclide inventory that entered the saturated zone on the left side of the dike.

Figure 6-16 shows the intrusion of a second dike, which is perpendicular to the one shown in Figure 6-15. This case was simulated because it is believed to be not uncommon for volcanic dikes to occur in pairs at more or less perpendicular orientations. The velocity vectors in Figure 6-16 indicate that some of the flow stagnates between the dikes as shown by several of the darkened streamlines. This would again have the effect of prolonging the escape of a portion of the radionuclide inventory to the accessible environment, provided the dikes do not extend through the repository horizon located 200-300 above the present water table. The maximum water-table rise for this case was 103.4. The location of this maximum water-table rise is indicated by the dark circle in Figure 6-16.

Eight additional single-dike cases were run using the subregional model. The first four cases again consisted of dike intrusions directly beneath the repository horizon at orientations east-west, north-south, and 45° either side of north. The last four cases consisted of dikes centered 5 km southeast of the potential repository site. For the dike oriented east-west beneath the repository, there was essentially no change in the water-table elevations, primarily because the flow field was trending in the same direction. The dike oriented north-south produced a 60.9 rise in the water table along the northern edge of the dike. The dike oriented N 45° E resulted

Figure 6-15. Impact of the intrusion of a single volcanic dike through the repository on the groundwater flow field

Figure 6-16. Impact of the intrusion of multiple volcanic dikes through the repository on the groundwater flow field

in a maximum water-table rise located along the dike of 59.6. Conversely, the dike oriented N 45° W and directly beneath the repository, produced a maximum water-table rise of only 22.3. Figure 6-17 shows graphically the maximum water-table rise at the repository site as a function of the orientation of this 4 km long dike, which extends vertically through the saturated zone. The dike orientation at approximately N15° E shows the maximum rise in the water table below the repository site. This particular dike orientation has been indicated by project geologists to be the most likely to occur based on the present faulting patterns through the Yucca Mountain area. The four simulations in which the dike was located approximately 5 km southwest of the repository site, and at the same four orientations, showed very little change in the water-table elevations. In fact, several of these cases actually showed a slight drop (several meters) in the water table through portions of the region.

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Figure 6-17. Water table-rise at the site of a potential repository at Yucca Mountain as a function of the orientation of a vertical intrusive dike extending through the saturated zone

7 CONCLUSIONS

The results from a simple regional groundwater-flow analysis of the saturated zone surrounding Yucca Mountain using the modified version of the PORFLOW computer code were presented. These results show the effects of various disruptive conditions on the water-table elevations and the resulting groundwater-flow directions throughout the region. The results give an indication of what conditions 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, based on the various disruptive conditions simulated using the regional model. In addition, the subregional model analysis showed a rise in the water table near the repository site ranging from a few meters to up to 100, depending on the location and orientation of the intrusive volcanic dikes. One should keep in mind that on a Yucca Mountain scale, this regional model is still very coarse.

Also, in viewing the results, one needs to consider the assumptions made, both from a mathematical standpoint in the model development and from a conceptual modeling perspective. For instance, it is most likely that under the simulated conditions 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 PORFLOW code, the intent is to incorporate ground elevation so that formation of springs can be explicitly considered in simulations. Also, for some of the simulated conditions which resulted in large water-table rises, the boundaries of the model may still not be located far enough away to avoid effects on the computed results.

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

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