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Thomas F. Corbet and Michael G. Wallace

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POST-PLEISTOCENE PATTERNS OF SHALLOW GROUNDWATER FLOW IN THE DELAWARE BASIN, SOUTHEASTERN NEW MEXICO AND WEST TEXAS

THOMAS F. CORBET[1] and MICHAEL G. WALLACE[2]
[1]Dept. 6119, Sandia National Laboratories, P.O. Box 5800, Albuquerque, New Mexico 87185;
[2]RE/SPEC Inc., 4775 Indian School Rd. NE, Suite 300, Albuquerque, New Mexico 87110

Abstract — We used a numerical model to evaluate factors potentially affecting ground water flow in the Rustler and Dewey Lake Formations within a northern portion of the Delaware Basin. The model, which is based on the concept of the ground water basin, suggests that flow patterns respond significantly to changes in climate. We include the effects of climate change in the model by varying the amount of moisture that infiltrates to the saturated zone. Calculated hydraulic heads in confined units, such as the Culebra Dolomite Member of the Rustler Formation, change by as much as tens of meters in response to long-term changes in the infiltration rate. Results support the concept that patterns of ground water flow in confined units are strongly influenced by the relief of the overlying water table. A substantial portion of the water flowing in the confined units is derived from slow vertical leakage through underlying and overlying aquitards. Flow rates and directions at depth can apparently be affected by changes of only a few tenths of a millimeter per year in the rate of infiltration to the saturated zone. During the simulated period of time, reversals in the direction of vertical flow through the aquitards occur over extensive areas of the model domain. There is great uncertainty in many of the parameters used in our calculations. We do not, therefore, claim that these results are quantitatively correct. Instead, these results improve our intuitive understanding of regional ground water flow in the shallow portion of the Delaware Basin.

INTRODUCTION

Regional ground water flow in the Delaware Basin in southeastern New Mexico and western Texas is a dynamic and integral part of the geologic environment. Moving ground waters interact chemically with the rocks and transport dissolved mass and heat. Ground water flow, therefore, plays an important role in diagenetic processes. In addition, regional ground waterflow has the potential to transport contaminants introduced by human activities.

Our motivation for studying ground water flow in the Delaware Basin is to provide information to assist in predicting the performance of the Waste Isolation Pilot Plant (WIPP). The WIPP is a potential repository for defense-generated transuranic waste in bedded evaporites of the Permian Salado Formation. Our focus is on simulating directions and rates of ground water flow near the proposed repository. These simulations provide a better understanding of the processes that generate the gradients of hydraulic head that drive ground water flow in the vicinity of the WIPP. We believe that only through this approach can factors such as the importance of vertical flow through confining layers and the effect of climate change on flow patterns be properly evaluated.

The WIPP disposal horizon is located in the lower Salado Formation. One scenario that is considered in evaluating the performance of the repository is that a future society might drill one or more exploration holes that would inadvertently penetrate the repository. Given certain circumstances, these holes could provide a path for contaminated brine to move upward in the drill hole, bypassing the Salado halite barrier and then laterally along more permeable strata above the repository. An objective of our work is to aid in evaluating the latter portion of this scenario. Therefore, we focus on the strata that lie between the top of the Salado Formation and the land surface in this study.

Natural hydrogeologic processes, as they occur over geologically significant periods of time, can be difficult to understand and visualize. Our approach is to construct computer models that allow us to simulate and test our conceptual models of how these processes work. We used the computer models to calculate patterns of ground water flow in three dimensions over tens of thousands of years. When interpreting the model results, we realize that it is not possible to show that a particular conceptual model or set of simulation parameters is "correct." Instead we believe that mathematical models can improve our intuition and demonstrate that certain conceptual models are plausible.

The results presented here are our first for this model region. We intend to continue to refine our models to include more complexity.

However, the results of these relatively simple models have important implications. These models suggest, for example, that ground water flow at depth responds noticeably to very small changes in the amount of water that infiltrates to the water table. In our simulations, vertical leakage through strata with extremely low permeability is a critical part of the regional flow system.

CONCEPTUAL MODEL

We used the concept of the ground water basin as the basis of our modeling. Freeze and Witherspoon (1966) summarized the basic principles and assumptions of the basin model. This conceptual model has a strong theoretical basis (Hubbert, 1940; Toth, 1963) and is widely accepted and applied by hydrogeologists. A ground water basin is a three-dimensional closed hydrologic unit bounded on the bottom by an "impermeable" rock unit (actually a stratigraphic layer with much smaller permeability than the layers above), on the top by the ground surface and on the sides by ground water divides. In mathematical models, ground water divides are represented by vertical boundaries across which horizontal flow cannot occur. The upper boundary of the flow domain is the water table which may or may not coincide with the land surface. All rocks in the basin have finite permeability, i.e., hydraulic continuity exists throughout the basin. Implicit in this description of the ground water basin is that the entire length of each flow path is contained within the basin. All recharge to the basin (if it occurs) is by infiltration of precipitation to the water table and all discharge from the basin (if it occurs) is by flow across the water table to the land surface.

Differences in elevation of the water table across the basin are assumed to be the driving force for ground water flow. Water flows along gradients of hydraulic head from regions of high head to regions of low head. The highest and lowest heads in the basin occur at the water table at its highest and lowest points respectively. Therefore ground water generally flows from the elevated regions of the water table, downward across aquitards (layers with relatively low permeability), then laterally along layers with relatively high permeability and then finally upward to exit the basin in regions where the water table (and by association, the land surface) is at low elevations. Infiltration is necessary to maintain relief on the water table. If infiltration were to stop for a sufficient period of time, flow from regions of high to low head would "level" the water table and ground water would become stagnant. However, a lack of infiltration rarely, if ever, actually results in stagnant conditions because long periods of time are required for ground water to "drain" from the regions of high head. The time required for the system to drain is controlled by the thickness, permeability and compressibility of aquitards in the basin, as well as the initial relief of the water table. The adjustment time could be tens of thousands of years or longer.

The pattern of ground water flow depends on the lateral extent and depth of the basin, the shape of the water table and the heterogeneity of the permeability of the rocks in the basin. Field observations and numerical studies have demonstrated that flow in strata with relatively large permeability is mainly horizontal and flow in strata with low permeability is vertical. Even extremely slow vertical flow is significant, on a regional scale, because it is summed over the very large areas of the upper and lower surfaces of rock layers. The importance of vertical flow through aquitards is often indicated in observations and numerical experiments by the tendency of the potentiometric surfaces of more permeable strata at depth to resemble the shape of the water table. An excellent way to get a conceptual feel for the effects of low permeability strata on flow patterns is to review results of numerical experiments performed by Freeze and Witherspoon (1967).

MATHEMATICAL MODEL

The following partial differential equation describes flow of water in porous media.

$$\frac{\delta}{\delta x}(K_x \frac{\delta \boldsymbol{h}}{\delta x}) + \frac{\delta}{\delta y}(K_y \frac{\delta \boldsymbol{h}}{\delta y}) + \frac{\delta}{\delta z}(K_z \frac{\delta \boldsymbol{h}}{\delta z}) - I = S_s \frac{\delta \boldsymbol{h}}{\delta t}$$

Here $\mathbf{K_x}$, $\mathbf{K_y}$ and $\mathbf{K_z}$ are values of hydraulic conductivity [LC] in the x, y and z directions; **h** is hydraulic head [L]; **I** is the volumetric infiltration rate per unit volume WI; and $\mathbf{S_s}$ is specific storage [L^{-1}].

We used a finite difference code (MODFLOW; McDonald and Harbaugh, 1988) to solve equation (1) for the simulations presented here. We used a version of the code (McDonald et al., 1991) that allows each nodal block to saturate and desaturate as the hydraulic head rises and falls across the bottom face of the block. We also added an adaptive boundary condition that allows seepage faces to develop along the land surface when the sum of potential infiltration and net ground water flow into a nodal block is sufficient to maintain a water table at the surface. The resaturation capability and the seepage face boundary condition make the governing equation nonlinear and therefore more difficult to solve.

We considered the behavior of a regional hydrologic system that includes all of the rocks above the Salado Formation and extends outward to its natural hydraulic boundaries (Fig. 1). The lateral boundary of the numerical model follows ground water divides that we believe are valid for the entire period of time simulated. The elevation of the land surface ranges from 850 m to over 1200 m above mean sea level. The boundary follows major topographic depressions such as Nash Draw and the Pecos River valley along the west and south portion of the boundary and the San Simon Swale to the east (Fig. 2). The boundary continues up drainages and dissects topographic highs in the northern part of the model region. No-flow boundaries represent ground water divides in numerical models because divides are planes of symmetry in the regional flow field.

The lower surface of our model domain is the top of the Salado Formation and the upper surface coincides with the land surface. Ten hydrostratigraphic units are represented by 15 model layers (Table 1; Fig. 3). The horizontal faces of every nodal block are dimensioned 2000 by 2000 m and the vertical dimensions of the blocks range from 0.5 to 100 m. In each layer there are 56 blocks in the north-south direction and 39 blocks in the east-direction, for a total of 32,760 blocks and an area of over 8700 km'. Many of the blocks are not active as a consequence of using a finite difference code to simulate an irregularly bounded domain. All map figures in this paper depict the active model area for the Culebra layer horizon, which covers a region of slightly under 6000 km². The total vertical thickness of the model within the active region ranges from 40 m to 655 m. Each stratigraphic layer is assigned a hydraulic conductivity that is representative of the dominant

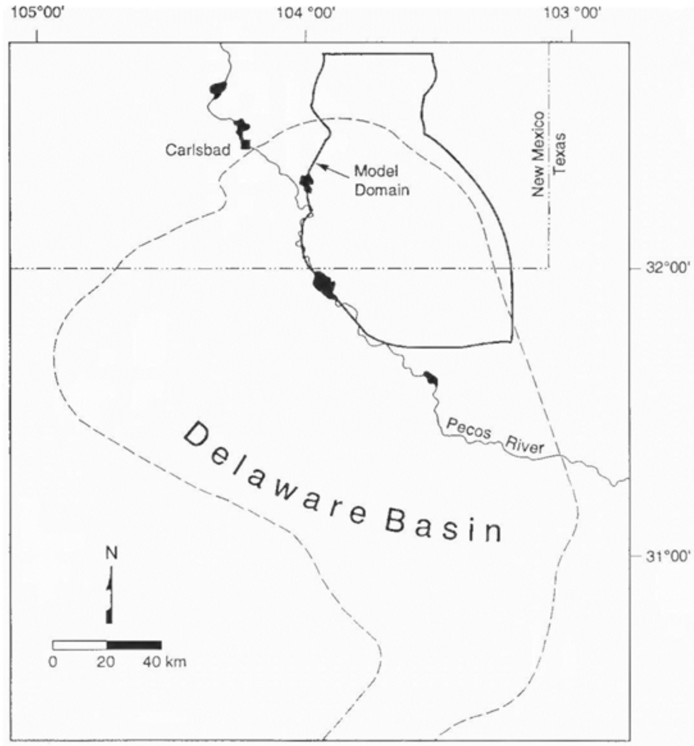

FIGURE 1. Outline of the domain used to model ground water flow in the northern Delaware Basin.

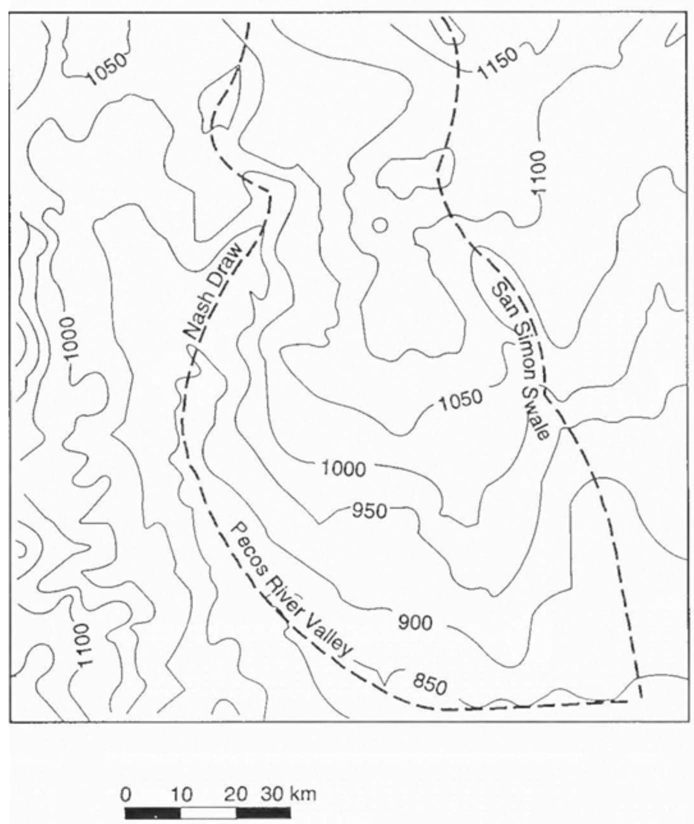

FIGURE 2. Outline of the domain (dashed line) used to model ground water flow on a topographic map. The contour interval for the elevation above mean sea level of the land surface is 50 m. The model boundary follows major hydrologic divides.

TABLE 1. Hydraulic properties used for the basin model.

Hydrostratigraphic Unit	Thickness (m)	log Hydraulic Conductivity (m/s)	Model Layers
Dewey Lake Fm.	0 - 600	-7	6
Anhydrite 5	9.5	-12	1
Mudstone/Halite 4	2 -60	-9	1
Anhydrite 4	5	-12	1
Magenta Dolomite	6	-7	1
Anhydrite 3	16	-12	1
Mudstone/Halite 3	2 - 35	-9	1
Anhydrite 2	7.5	-12	1
Culebra Dolomite	7	-7	1
Unnamed Member	10 - 75	-9	1

Specific Storage 10^{-5} m^{-1}
Specific Yield 0.1

rock type in that layer (Table 1). Each layer is homogeneous; the heterogeneity known to exist within each layer is not represented in this simulation.

The simulation represents changes in the ground water flow field that occur over a hypothetical period of 41,000 years. Initially, a steady-state flow field in which the water table is fixed at the land surface is assumed to exist. This condition implies sufficient infiltration of moisture to maintain the water table near the surface and a steady-state flow of water across the upper surface of the model domain. Water moves downward across the upper boundary (infiltrates) in regions of high topography and moves upward across the upper boundary (evapotranspiration or stream base-flow) in regions of low topography. This is the normal condition in regions with humid climates and could be thought to represent the wetter climate that prevailed in this region at the end of the Pleistocene (Swift, 1993). The first 21,000 years of the simulation represent a dry period (zero infiltration) and the final 20,000 years represent a somewhat wetter period (maximum potential infiltration of 0.5 mm/yr). This infiltration rate represents, for example, less than 0.2% of the modern average annual rainfall in the model area. Such a low rate reflects the fact that most rainfall is lost to surface runoff or evapotranspiration before it can infiltrate to the saturated zone.

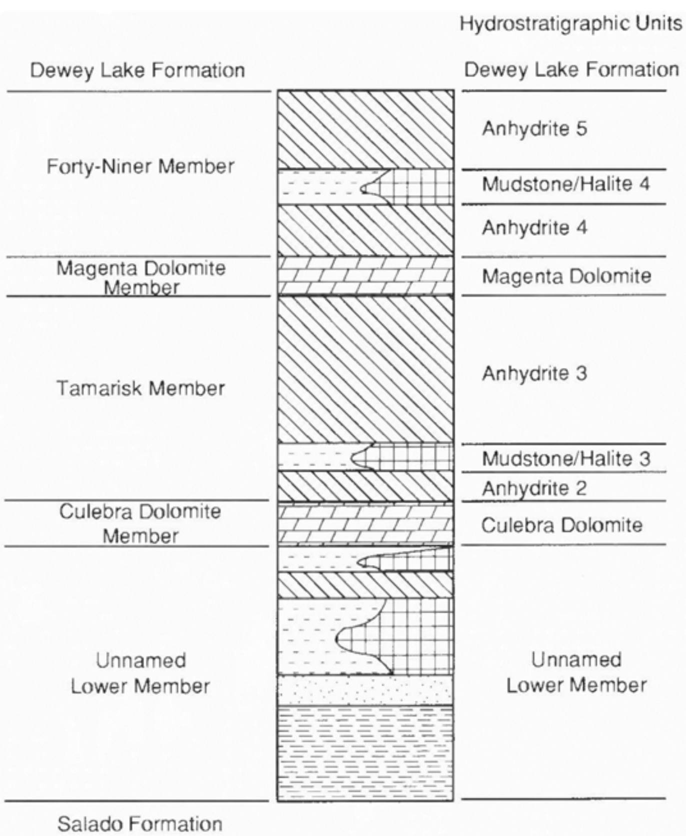

FIGURE 3. Hydrostratigraphic units used to represent the Rustler Formation in the numerical model. Modified from Powers and Holt (1990); original stratigraphy from Vine (1963).

SIMULATION RESULTS

We calculated the flow field for the entire stratigraphic sequence above the Salado Formation. However, here we present results for just one unit, the Culebra Dolomite Member of the Rustler Formation. The Culebra is the unit with relatively high permeability that is lowest in stratigraphic position above the Salado.

The initial calculated head distribution (at time = 0 years) in the Culebra dolomite (Fig. 4) is a subdued replica of the land-surface topography (Fig. 2). This influence of the topography is apparent even though there are four model layers between the Culebra and the land surface that have a hydraulic conductivity five orders of magnitude smaller than that of the Culebra.

At the start of the transient portion of the simulation, we assumed that infiltration instantly decreases to zero. The entire flow system begins to drain, because water can still move upward and discharge across the land surface (the upper boundary of the model) at local and regional topographic lows. If this draining process were to continue for a sufficiently long period of time, the water table would eventually achieve a flat surface at the lowest elevation along the upper model boundary and all flow would stop. This portion of the simulation rep-

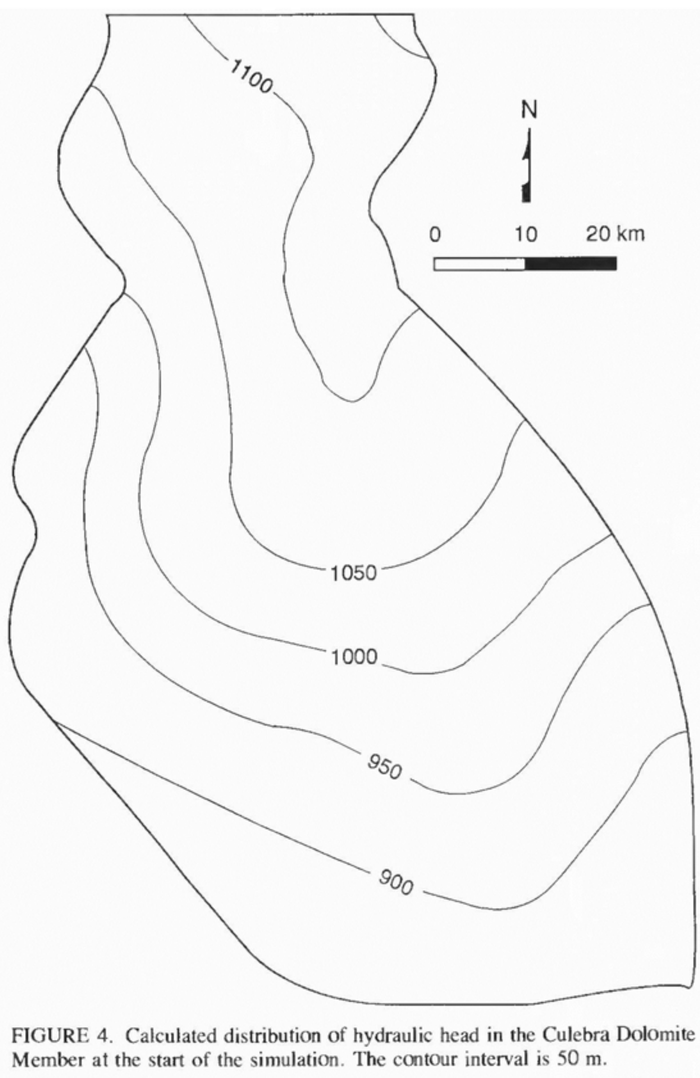

FIGURE 4. Calculated distribution of hydraulic head in the Culebra Dolomite Member at the start of the simulation. The contour interval is 50 m.

resents a drying of the climate. The simulated "drain time" is 21,000 years.

Comparison of Figs. 4 and 5 shows that during the drain period heads decrease over all regions of the Culebra, but decrease most rapidly in the regions of relatively high head. For example, heads decrease by more than 60 m in the region of head greater than 1100 m in Fig. 4. In contrast, the average decrease in head in the region of 900 m of head is less than 10 m.

The maximum possible infiltration is increased from zero to 0.5 mm per year at time = 21,000 years and remains at that value for the duration of the simulation. Even this very small rate of infiltration is sufficient to increase heads in the Culebra to levels that approach the initial levels (Fig. 6). This portion of the calculation illustrates that a future wetter climate could affect the Culebra flow field.

Potentiometric-surface maps, such as Figs. 4, 5 and 6, indicate directions of lateral flow. These maps, however, do not provide information about the quantity of ground water that is lost or gained by vertical flow across confining strata. Fig. 7 shows regions of upward and downward flux across the upper surface of the Culebra at time =0 years. Downward flux occurs in the stippled region and upward flux occurs over the remainder of the model domain. The flux map shows a greater correspondence to the relief of the land surface (Fig. 2) than do the modeled potentiometric surfaces (Figs. 4-6). Flow, for example, is upward and out of the Culebra in areas of low topography along Nash Draw, the Pecos River valley and the San Simon Swale.

The pattern of vertical leakage can change as the amount of moisture infiltration to the water table changes. The dashed line in Fig. 7 is the calculated boundary between upward and downward flow at the end of the 21,000-year drain period. The overall pattern is similar to the pattern at time = 0 years, but the degree to which the distribution of vertical flow reflects the details of the land surface has decreased. Furthermore, in some areas the directions of vertical flow have reversed over the 21,000-year time period. Some areas that initially experienced downward flux later exhibited upward flow. Other areas that initially experienced upward flux later exhibited downward flow. These regions of flow reversal cover hundreds of square kilometers of the model domain.

The relative magnitudes of vertical and horizontal flow was an important factor for our consideration. Using the model results at time = 21,000 years, we summed the simulated fluxes across the upper and lower faces of the Culebra over the region outlined by the rectangle in Fig. 7. We also summed the lateral fluxes into and out of the Culebra over that region. About 57% of the total flux entering this region is by vertical flow across the upper and lower surfaces of the Culebra. About 32% of the outflow is by vertical flow. Calculated values of vertical specific discharge range from zero to 0.05 mm per year.

DISCUSSION

We have presented results for a single set of model parameters: one permeability distribution, one infiltration function and one set of initial conditions. There is great uncertainty in all these parameters and many other choices for these parameter values might be equally representative of real conditions. Also, our model contains significant simplifications of the real world. We do not, therefore, claim that these results are quantitatively correct. Instead, they improve our intuitive understanding

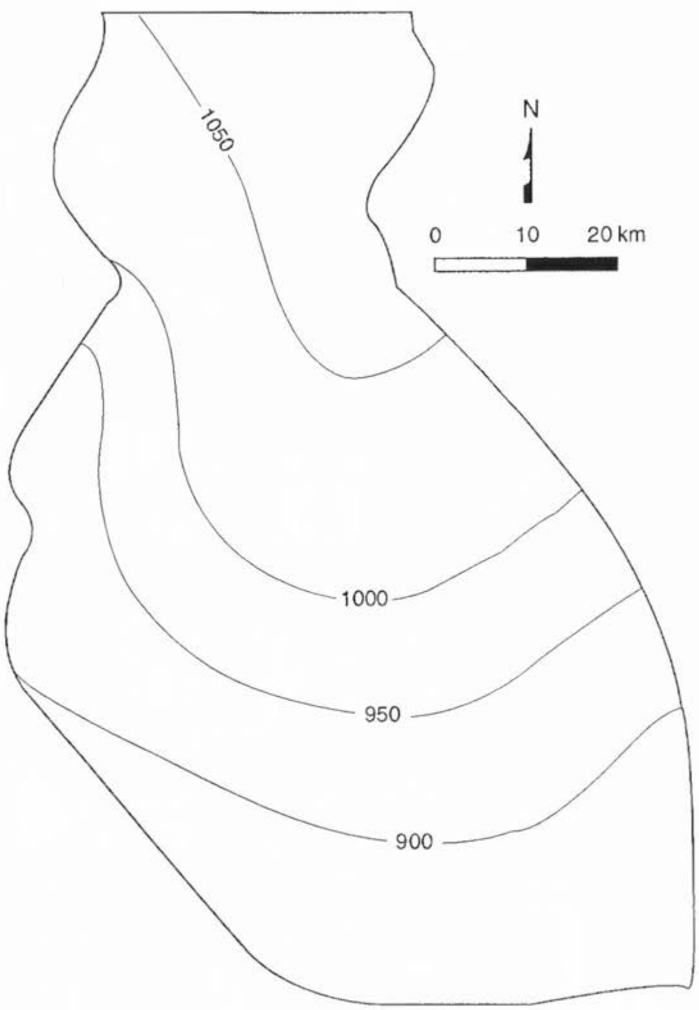

FIGURE 5. Calculated distribution of hydraulic head in the Culebra Dolomite Member at 21,000 years into the simulation. The contour interval is 50 m.

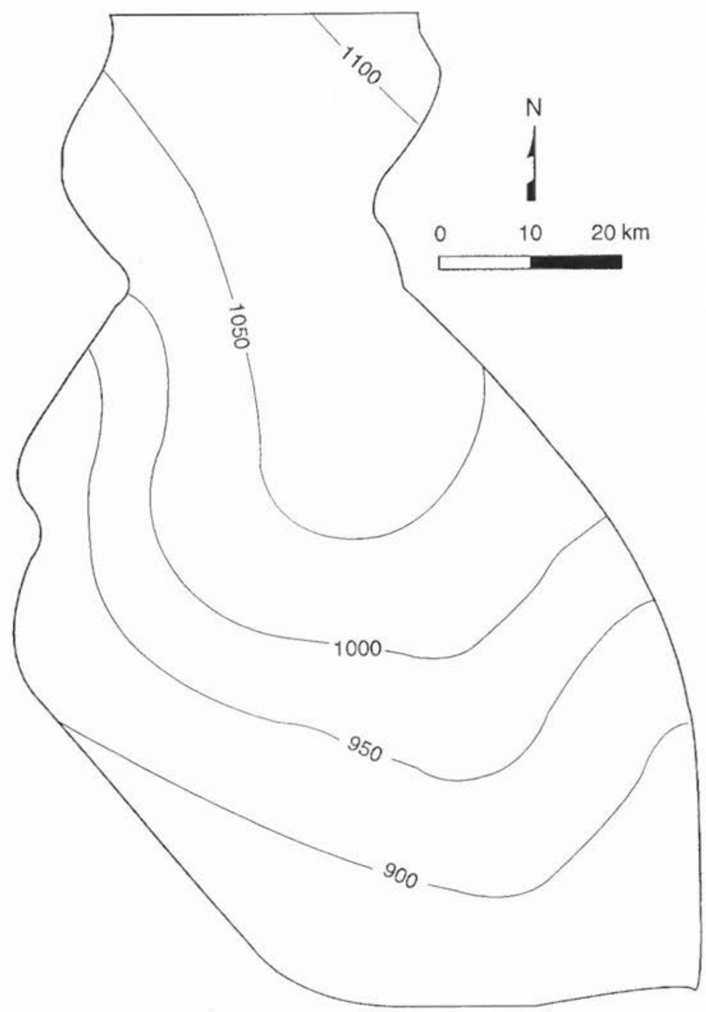

FIGURE 6. Calculated distribution of hydraulic head in the Culebra Dolomite Member at 41,000 years into the simulation. The contour interval is 50 m.

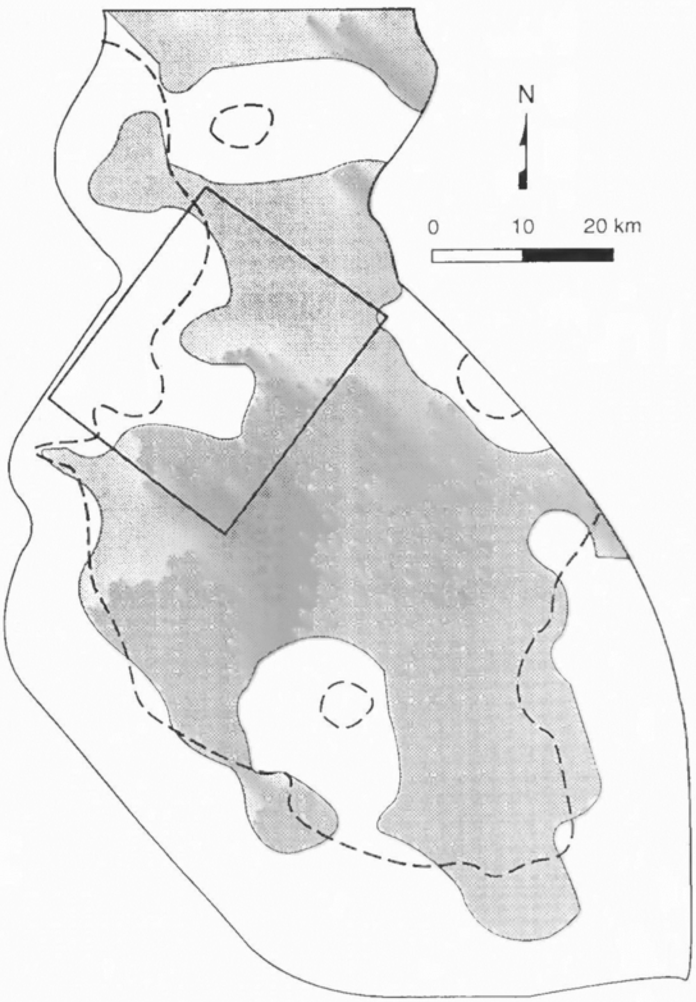

FIGURE 7. Calculated regions of upward (stippled area) and downward flow (white area) across the upper surface of the Culebra Dolomite Member at the start of the simulation. For comparison, the dashed line divides regions of upward and downward flow at 21,000 years into the calculation. The square outlines the region for which total vertical and lateral flow rates were calculated.

of regional ground water flow in the shallow portion of the Delaware Basin.

We have made several notable simplifying assumptions. First, we assume that each layer is homogeneous. This is certainly not correct. Well data indicate that rock properties within units vary significantly across the model domain (Beauheim, 1987). Holt and Powers (1988) suggested that the permeability within each stratigraphic unit is modified by fracturing, dissolution of the Salado Formation, precipitation and dissolution of fracture- and pore-filling minerals and erosional unloading. Certainly, the flow patterns we have calculated would be different if we included this heterogeneity. Also the approximate correspondence of the relief of the water table with the potentiometric surface of the Culebra would be somewhat altered if the heterogeneity within layers were included.

Second, we ignore the unsaturated zone. In regions such as southeastern New Mexico, where the water table is deep, there is a long delay before water that infiltrates at the surface reaches the water table. Our infiltration function should be considered a long-term average of the amount and rate of moisture reaching the water table. Also, we assumed a step function: the amount of infiltration instantly decreases from the pattern implied by the initial conditions at the start of the calculation and increases from zero to 0.5 mm per year 21,000 years into the simulation. We did this to demonstrate the response of the system to an extreme change in climate. Smoother and more realistic changes in infiltration could also be simulated.

The calculation results suggest that flow of ground water in confined units is strongly influenced by the relief of the overlying water table. A substantial portion of the water flowing in relatively permeable layers is derived from slow vertical leakage through confining layers. The results also indicate that flow patterns respond significantly to changes in climate, even to the point of reversing directions. Furthermore, the calculations suggest that tens of thousands of years are required for potentiometric surfaces to completely adjust to the climate changes. Finally, flow in confined units can apparently be affected by changes of only a few tenths of a millimeter per year in the rate of infiltration to the saturated zone.

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Section through upper part of karst dome in Culebra Member of Rustler Formation below east abutment of El Paso Natural Gas pipeline bridge over the Pecos River (Day 1, Stop 5B). Rustler Breaks on eastern skyline.