COMPUTER SIMULATION OF SALTWATER INTRUSION

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INTRODUCTION

Careful management and planning of groundwater aquifers is essential to assure users of an adequate and sustained yield of water. This process helps to avoid the "mining" of water and excessive drawdown of the water table and the dangers inherent therein. When the aquifer has a coastal boundary, an additional danger is the intrusion of the seawater into the aquifer. Excessive pumping could cause an increase in the salinity concentration of water, rendering it unfit for drinking and other purposes. Management of the aquifer includes knowing the location of the salt water interface under present and future pumping conditions. A numerical model is one method by which the location of the salt water interface can be estimated for a given set of hydrologic conditions.

Two types of models can be used to study saltwater intrusion into aquifers. The first type of model is one in which a sharp interface separates the fresh water and salt water (Bear and Dagan, 1964; Fetter, 1972; Glover, 1959; Kashef, 1975; Pinder and Page, 1976; Rumer and Harleman, 1963; Shamir and Dagan, 1971; Van der Veer, 1976). The second type assumes that the salt water has gradually mixed (diffused) with the fresh water resulting in salt concentration from zero to the concentration that exists in the sea (Bear and Dagan, 1963; Desai and Contractor, 1977; Gelhar et al., 1972; Henry, 1964; Segol et al., 1975). In general, there is always some degree of salt water diffusion in coastal aquifers. However, when the diffusion is confined to a narrow band in the aquifer, it may still be appropriate to use a sharp interface model. This report describes the development and use of a sharp interface model.

Several numerical methods have been used in sharp interface models, including the method of characteristics, finite difference and finite element methods. The concepts and techniques described by Sa da Costa and Wilson (1979) have some unique features and are used extensively in this study (Contractor, 1981a). The model utilizes linear triangular elements and the Galerkin weighted residual method for deriving the element equations. The model has been applied to a variety of flow situations for which analytic solutions are available and the numerical accuracy of the model confirmed. The model was also used to study the behavior of the aquifer in Guam; an aquifer which had a complex boundary geometry, basement topography and boundary conditions (Contractor et al., 1982). The model also has the capability of studying aquifers that are partially confined and partially unconfined. Even though aquifers of this type are rare, they are known to exist in Hawaii. An application of this kind is presented in this paper.

CAPABILITIES OF COMPUTER PROGRAM

The computer program can handle steady or unsteady flows, and can analyze both confined and unconfined aquifers. If the aquifer is confined, the program can consider leaky and nonleaky conditions. Additionally, any number of pumps can be accommodated at the nodes of the network. Recharge is constant in an element but can be varied from element to element. Specified head or flow conditions can be applied at the boundaries. At a coastal boundary, a mixed or third-type boundary condition can be specified. For steady flow conditions, the saltwater head can be specified to be zero along the boundary or at every node in the network. This procedure assures that the Ghyben-Herzberg condition is satisfied. The program can also be run in the unsteady mode with the Ghyben-Herzberg condition. If the saltwater head at every node in the network is specified to be much less than the anticipated freshwater head, the results of the computer program will show that the thickness of the saltwater layer is equal to an arbitrarily small value (BTOE). Under these conditions, the program can simulate flow in a freshwater aquifer. Since the heads are assumed to vary linearly across the triangular element, the velocity in each element will be constant and the program can print out the components in the x and y directions in each element in both the fresh water and salt water layers. These velocities can then be used to calculate the flow rates across any line or boundary. The program can also determine where in the network a freshwater or saltwater toe occurs. A saltwater toe occurs where the interface intersects the lower impervious boundary. The output provides the element number, the node numbers, and the fractional distance between the two nodes where the saltwater toe occurs. The same kind of information is also provided about the freshwater toe. A freshwater toe occurs where the phreatic surface intersects the lower impervious boundary or where the interface intersects the upper impervious boundary in confined aquifers.

VERIFICATION WITH ANALYTIC SOLUTIONS

To promote confidence in the program, it was advisable to check the output of the program against results that are analytically known. The program was checked out against three different groundwater problems. The first problem dealt with the steady state, one-dimensional saltwater intrusion into confined and unconfined aquifers. The second case was the unsteady drawdown of head due to pumping of a well (Theis solution) in a confined aquifer. Finally, the program was checked against the analytic solution of the one-dimensional gravitational segregation problem (Gelhar et al., 1972). The results of all three simulations (Contractor, 1981(a)) indicated good agreement with the analytic solutions. Many more analytic solutions are available in the literature to check the numerical output of the program. However, the satisfactory agreement obtained in these three flow cases indicated that the basic numerical technique and procedures are sound.

APPLICATION OF MODEL TO THE NORTHERN GUAM AQUIFER

Guam is located within Micronesia at 13°28' North latitude and 144°45' East longitude. It is the largest and southernmost of the Mariana Islands. It is approximately 30 miles long, ranges from 4 to 11-1/2 miles wide and has a land area of 212 square miles excluding reefs. The island is divided into two nearly equal areas of different geology (WERI Staff, 1980). The northern half is a broad limestone plateau bounded by cliffs and the southern half is a dissected volcanic upland fringed with limestone along the east coast. The limestone plateau of Northern Guam slopes gently to the southwest from an altitude of about 600 feet in the north to less than 100 feet at the narrow midsection of the island. The various limestone units rest on a basement complex of older volcanic rocks. Because of their low permeability, the volcanic rocks act generally as a barrier to groundwater movement and in Southern Guam do not readily yield water to wells. The Mariana and the older Barrigada limestone constitute the main aquifer of Northern Guam. Taken together, the two limestone formations may be described as a permeable, massive, clean limestone that is relatively free of clay and volcanic detritus. The most important characteristics of the limestones in relation to groundwater movement are their high hydraulic conductivity and porosity.

Almost all residences on Guam are served by the public water supply system. The approximate amount of water produced from all sources is 28.5 million gallons per day (mgd). Most of this water (56%) is withdrawn from the aquifer underlying the northern half of the island by means of approximately 75 wells. The remainder of the water is obtained from surface water sources in Southern Guam (28%) and springs (16%). The economic growth and development of Guam is inextricably intertwined with the water resources available on the island. Increased quantity of water made available to the public is essential to future growth in population, industry and agriculture (Marsh and Winter, 1975; PUAG, 1971). Pumping water from the Northern Guam lens is a very cost-effective method of increasing the water supply. Increased pumping, however, should guarantee that the quality of the water is not compromised at the higher level of pumping. Sea water intrusion depends on the recharge to the aquifer and the distribution and rate of pumping from the aquifer. If the rate of pumping exceeds the natural rate, then mining of water from the aquifer will take place, and it will be only a matter of time before the lens is depleted and the aquifer is contaminated with salt water. Recovery of the aquifer from such a condition would be a very slow process.

The aquifer in Northern Guam is bounded by the sea coast on the east, north and west and by a volcanic outcrop on the south. The aquifer also has a complex basement of impervious volcanic rock. The elevations of the basement were the subject of a separate study (Biehler and Walen, 1981). Fifty-six reversed seismic refraction profiles were established throughout Northern Guam in order to define the basement.
Seismic refraction was successful because the volcanic rocks have a consistently higher seismic velocity (7,000-9,000 ft/sec) than the limestones (2,500-3,000 ft/sec) throughout most of the aquifer. On the basis of these data, a contour map of the basement surface was assembled. The basement elevations at the nodes of the element network were interpolated from this contour map.

There are about a dozen rain gages scattered over the island. The rainfall in Northern Guam undergoes a loss due to evapotranspiration and the rest of the rainfall recharges the aquifer. There is no surface runoff (streamflow) in Northern Guam. On the other hand, the rainfall in Southern Guam undergoes a loss due to evapotranspiration and the rest of the rainfall becomes direct runoff and streamflow. Very little infiltration occurs because of the impermeable volcanic rocks that outcrop in the south. This contrasting hydrologic feature is made use of by Mink (1976) to calculate the recharge to the aquifer in the north. The same technique is used in this paper. The USGS publishes streamflow records for many streams in the south of Guam (U.S. Geological Survey, 1978). The annual flow in these streams can be converted to inches of runoff. The evapotranspiration in the south is calculated as the difference between the average rainfall in the south and this runoff. The evapotranspiration in the north can be taken to be equal to that in the south. The recharge to the aquifer is then equal to the average rainfall in the north minus the evapotranspiration.

The Northern Guam aquifer was discretized into 222 triangular elements and 149 nodes (fig. 1). Pumps are located at 70 of these nodes. Thirty-three elements have one side along the coastline and 35 nodes on the coastline have saltwater heads specified as a function of time. Region I of the aquifer consists of the Mariana limestone and Region II the Barrigada limestone. The porosity of both regions was estimated to be 0.25. However, the conductivity of each region had to be determined by calibration of the model. This was done by using the historical hydrologic data of 1978, 79 and 80. The input data consisted of the recharge, pumping rates and elevations of the sea on a monthly basis. The output of the model was compared with the measured elevations of the water in six observation wells. The permeability in each region was varied till satisfactory agreement was obtained between the computed and and measured elevations. The result of the calibration run at one of the observation wells is presented in fig. 2. It was determined that the best estimate of conductivity for region I was 1000 ft per day (fpd) and for region II was 5000 fpd.

MANAGEMENT RUNS

The model was used to determine the effect of increasing the current pumping rate of 18.5 million gallons per day (mgd) to 60 mgd. An analysis of the monthly rainfall and evapotranspiration over the aquifer showed that substantial recharge occurs only during the months of July to November, the remaining months of the year having zero recharge. This management scenario was modeled on the computer. The initial conditions were taken to be the same as those used for the calibration runs. The simulation was run for a year and the results at the end of the year were used as the initial conditions for simulation of a second year of the hydrologic conditions. This process was repeated for five years, at which time it was felt that steady cyclic conditions would prevail. Fig. 3 shows the water surface elevation at one of the nodes for the five year simulation. It can be seen that steady cyclic conditions were not achieved and that the simulation would need to be continued for several more years. Fig. 4 shows the variation of the saltwater head at the same node. It can be seen that the saltwater has to encroach into the aquifer much more before steady cyclic conditions prevail in the aquifer. Fig. 4 also shows that the interface has risen 35 feet in five years and would rise even more for steady cyclic conditions. The interface moves slowly to its new steady cyclic position because it has to force a large amount of seawater through the porous media.

APPLICATION TO AN AQUIFER THAT IS PARTLY CONFINED AND PARTLY UNCONFINED

Some aquifers have the unusual characteristic that a portion of it is confined and the rest of it unconfined. Aquifers of this kind are known to occur in Hawaii and their analysis has been difficult. The aquifer in Southern Oahu is composed of basalt. However, the basalt has a cap of limestone of lower conductivity than the basalt near the coastline. Fig. 5 shows the details of such an aquifer. The limestone acts as a leaky aquitard above the basalt aquifer. The location of the saltwater interface depends on the flow of fresh water and the hydraulic conductivity of the aquitard. A finite element grid was used to simulate the aquifer in fig. 5 using parameter values close to those of Southern Oahu. Figure 5 shows the location of the interface for different values of the flow rate and the hydraulic conductivity of the limestone cap (aquitard). It can be seen that the interface moves out toward the ocean for increasing values of flow rate and for decreasing values of the aquitard conductivity. The program can handle additional complexities such as pumps, local non-homogeneities, recharge, etc. Thus, this program is very well suited to manage aquifers of this type.

CONCLUSIONS

1. A two-dimensional finite element model has been developed to solve problems of saltwater intrusion into aquifers.

2. The finite element program has been checked for accuracy against analytic solutions of three different groundwater flow cases.

3. The model has been applied to the Northern Guam aquifer. The conductivity of the aquifer was calibrated using hydrologic data of 1978-80.

4. A Management run was made to determine the response of the aquifer to increased pumping. Simulation for a five-year period did not result in steady cyclic conditions. The reason for this appears to be the sluggish movement of the interface.

5. Some aquifers in Southern Oahu, Hawaii have the characteristic of being partly confined and partly unconfined. Such aquifers have been difficult to analyze. This program, however, can be used to locate the interface. An application of the program to such an aquifer is provided.

ACKNOWLEDGMENTS

The study reported in this paper was part of the Mathematical Modeling Sector of a research contract awarded the Water and Energy Research Institute of the Western Pacific, University of Guam. This sector was part of a larger study entitled, "The Northern Guam Lens Study", sponsored by the Guam Environmental Protection Agency.

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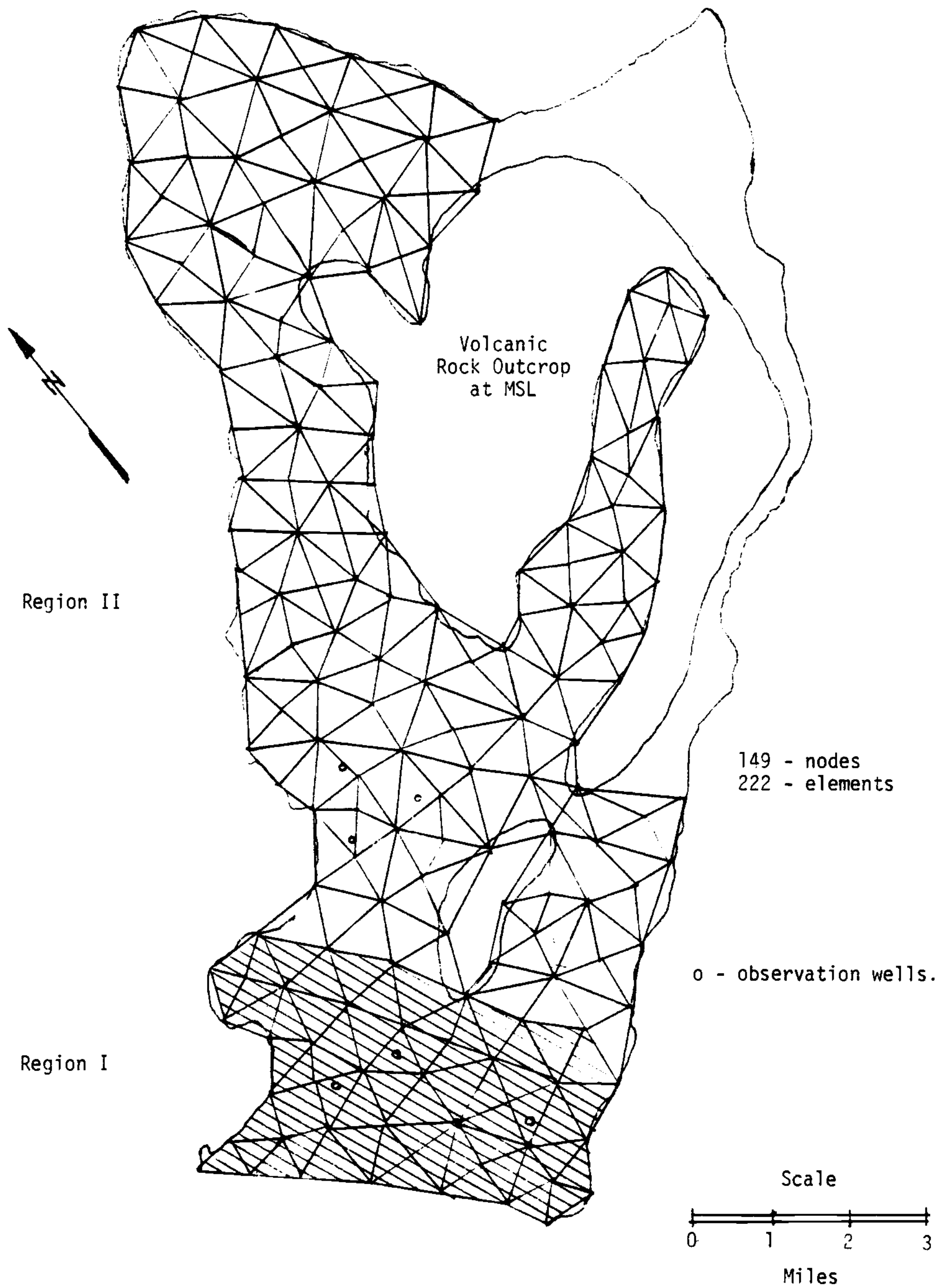

FIG. 1. DISCRETIZATION OF GUAM AQUIFER.

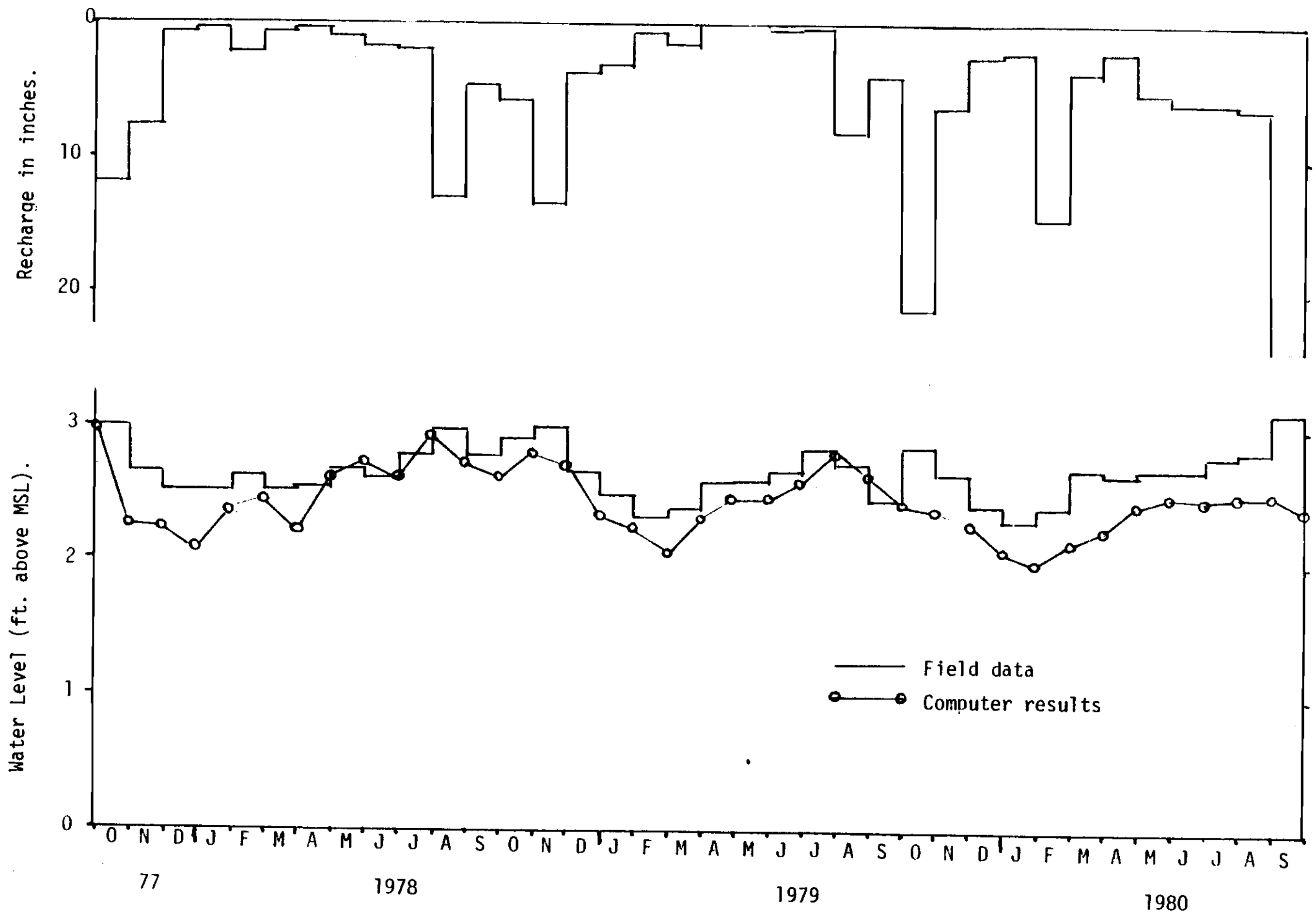

FIG. 2. CALIBRATION RESULTS AT AN OBSERVATION WELL.

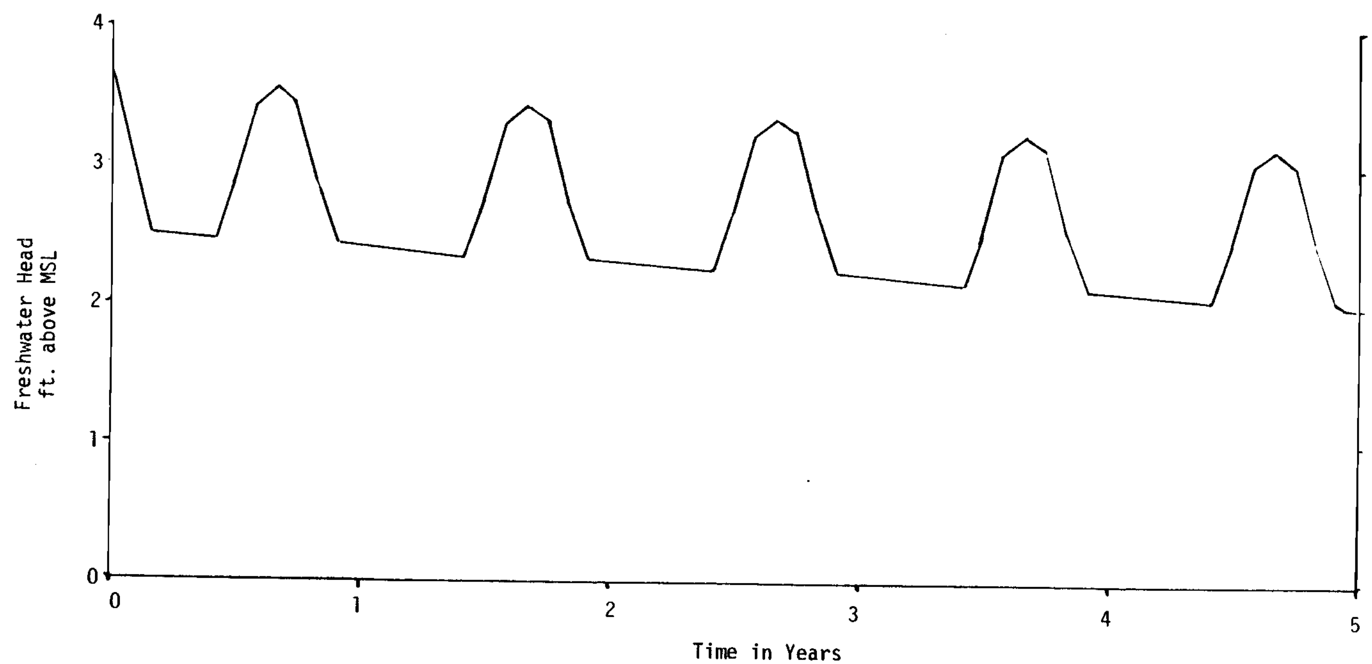

FIG. 3. VARIATION OF FRESHWATER HEAD AT A NODE FOR MANAGEMENT RUN.

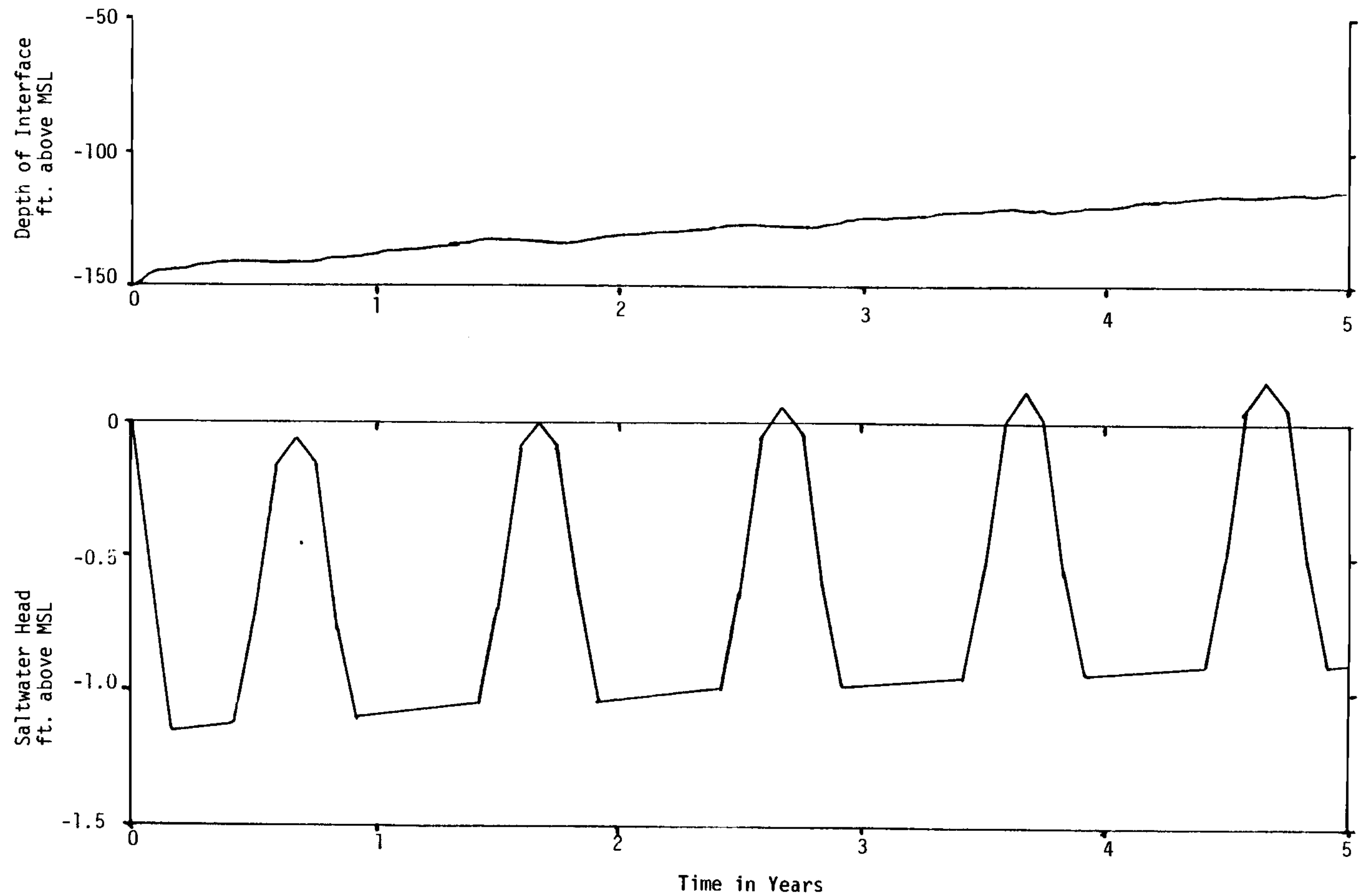

FIG. 4. VARIATION OF SALTWATER HEAD AND DEPTH OF INTERFACE AT A NODE FOR MANAGEMENT RUN.

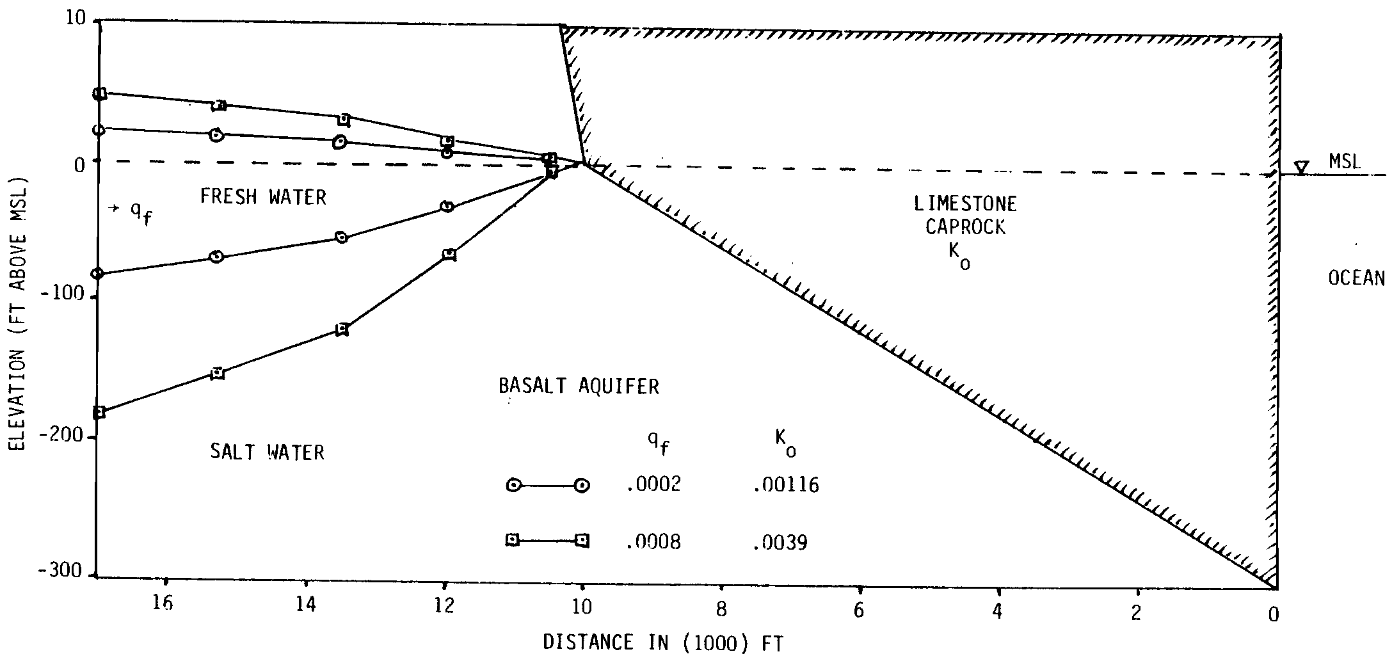

FIG. 5. FLOW INTO AN AQUIFÉR THAT IS PARTLY CONFINED AND PARTLY UNCONFINED.