POTENTIAL FOR UPDIP MOVEMENT OF SALINEWATER IN THE EDWARDS AQUIFER, SAN ANTONIO, TEXAS

By Roberto Perez

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CONVERSION FACTORS

For use of readers who prefer to use metric units, conversions factors for terms used in this report are listed below:

From	Multiply by	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per year (ft/yr)	0.3048	meter per year
foot squared per day (ft^2/day)	0.09290	meter squared per day
acre-foot (acre-ft)	1,233	cubic meter
gallon per minute (gal/min)	0.06308	liter per second
mile (mi)	1.609	kilometer
ton	0.9072	megagram

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ABSTRACT

The salinity front, locally known as the "bad-water" line, in the Edwards aquifer separates the freshwater from the salinewater and occurs where the aquifer is confined. The concentration of dissolved solids of the salinewater at the salinity front is 1,000 milligrams per liter. The concentration of dissolved solids in water within the freshwater zone of the aquifer usually ranges from 250 to 350 milligrams per liter. A digital model was used to investigate the potential movement of the salinity front by simulating the transport of salinewater into the freshwater zone as a result of pumping from the freshwater zone.

The model simulations indicate that a large range in the quantity of solute transported from the salinewater zone into the freshwater zone is possible. This uncertainty is caused by the range of estimates of transmissivity, the magnitude of water-level decline, and porosity. Simulated transmissivity values for the Edwards aquifer within the salinewater zone ranged from 134 to 3,340 feet squared per day and resulted in potential lateral shifts of the salinity front from 16 to 425 feet updip into the fresh-water zone at the end of a 10-year simulation. A simulated decline in water levels from an altitude of 660 to 582 feet above sea level resulted in a potential lateral shift in the salinity front of 133 feet updip into the freshwater zone at the end of the 10-year simulation. Simulated porosity values from 1 to 20 percent resulted in lateral shifts of the salinity front from 42 to 854 feet updip into the freshwater zone at the end of the 10-year simulation. An evaluation of the results of the model simulations indicates that contamination created by the movement of saline-water into the freshwater zone of the Edwards aquifer will be limited to an area within 0.2 mile of the present salinity front under the tested conditions.

INTRODUCTION

The abundant supply of freshwater from the Edwards aquifer has provided one of the necessary resources for the development of communities, a substantial irrigation-based farming industry, and attractive tourist and recreational facilities in the San Antonio area of Texas. With the relative ease of groundwater development and a rapid increase in population, ground-water withdrawals are increasing at a substantial rate. Future withdrawals from the Edwards aquifer may exceed recharge for prolonged periods. Under these conditions, it is possible for salinewater occurring in the downdip part of the Edwards aquifer to move updip into the freshwater zone of the aquifer. Because these water-level declines would be more severe and of longer duration than previously experienced, estimates of the potential intrusion of salinewater are needed for managing the present resources and planning for future ground-water supplies.

Purpose and Scope

The purpose of this study was to gain a better understanding of the potential for intrusion of salinewater into the freshwater zone of the Edwards aquifer. This was accomplished by the application of numerical-simulation techniques using regional values for transmissivity, storage coefficient, porosity, and water level. The estimates are intended to indicate the magnitude of the potential salinewater intrusion and the characteristics of the intrusion. The study is not intended to be a detailed analysis that would simulate the intrusion of the salinewater at any particular location.

General Description of Study Area

The Edwards aquifer in the San Antonio area (fig. 1) consists of the Cretaceous Edwards Limestone and associated limestones. The boundaries of the freshwater zone of the Edwards aquifer are the outcrop of the Edwards and associated limestone to the north, the ground-water divides to the west in Kinney County and to the east in Hays County, and an area of considerably less-permeable limestone, which contains salinewater, to the south, overlain by the Gulf Coastal Plain. The freshwater-salinewater interface, which is referred to as the salinity front in this report and which is locally known as the "bad-water" line, is defined as the location in the aquifer where the concentration of dissolved solids in the water is 1,000 mg/L (milligrams per liter).

HYDROGEOLOGY

The freshwater zone of the Edwards aquifer contains highly permeable and porous rocks (Maclay and Small, 1984). Because of these geologic characteristics, the aquifer is capable of storing and transmitting a large quantity of water. Adjacent to the freshwater zone, on the downdip side, the Edwards and associated limestones are much less permeable. Ground-water movement in this less permeable area is very slow in comparison to movement in the freshwater zone.

The Edwards and associated limestones occur throughout the subsurface east and south of the Balcones fault zone in south Texas. The rock units comprising the aquifer within the freshwater and the salinewater zones are geologically and hydraulically continuous except in local areas where major faults occur. In the vicinity of the salinity front, there is a zone of salinity transition from freshwater to salinewater.

The width of the outcrop of the Edwards aquifer varies from 5 to 40 mi and the thickness of the aquifer is about 500 ft. Downdip, at the salinity front, the top of the aquifer varies from 400 to 1,500 ft below the land surface (Maclay and Small, 1984). Recharge to the Edwards aquifer occurs along the outcrop of the Edwards and associated limestones. Surface water from streams crossing the outcrop area infiltrates the permeable limestone and recharges the aquifer. The regional direction of ground-water movement is from

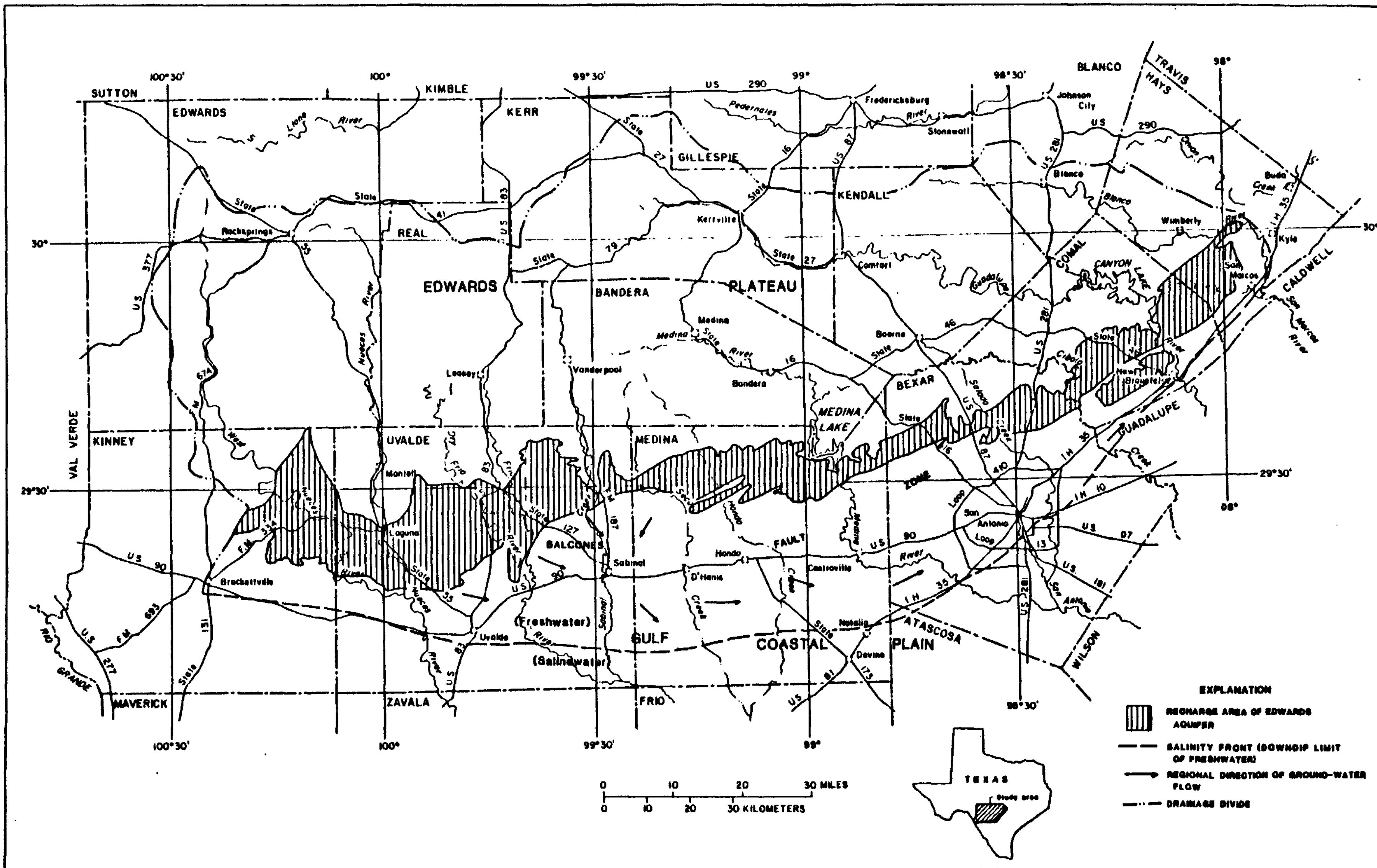

Figure 1.—Location and hydrogeologic features of study area.

west to east, approximately parallel to the plan view of the salinity front (fig. 1). Ground-water discharge from the aquifer is through spring flow and by pumping from wells.

The Edwards aquifer is heterogeneous and anisotropic (Maclay and Small, 1984). The heterogeneity of the aquifer can be classified as layered, discontinuous, and trending. The anisotropy of the aquifer varies areally and the major axis trend usually coincides with the local direction of faulting. Although the regional direction of ground-water flow within the Edwards aquifer is from west to east, the heterogeneity and anisotropy of the aquifer exert a major control on the local direction of ground-water flow. Sufficient data are not available to adequately define these properties on a local scale.

When recharge to the aquifer is substantially decreased for a long time, such as during the drought that occurred in 1957, the hydraulic gradient declines to the point where the rate of ground-water flow in the freshwater zone is relatively slow and thus, for the purpose of this study, the flow is considered to be negligible. Because the salinewater zone is less permeable, the rate of water-level decline in the salinewater zone lags behind the decline that occurs in the freshwater zone. Because of the decreased gradient within the freshwater zone, salinewater could move into the freshwater zone in greater quantities than would normally occur, and this salinewater would be subject to less dilution and would intrude into a larger area of the freshwater zone.

MODEL DESIGN

The first attempt to simulate the movement of salinewater into the freshwater part of the Edwards aquifer was in a local test area of 11.8 by 7.9 miles. In two dimensions, the model was designed to simulate the regional sweep of water along the salinity front as well as updip movement. Because of the difficulty in estimating and simulating the rate of water movement parallel to the transition zone and the distribution of aquifer properties and effects of boundaries, numerical difficulties caused the results to be unreliable. In the freshwater section of the aquifer, the estimated transmissivities were so large that the saline water zone approximated an impermeable boundary. If simulation in two dimensions is to be adequately addressed, more data will be needed than are currently available, and a larger area will need to be simulated.

An alternative approach in conducting the study was to use a one-dimensional model. Consequently, the assumption is required that ground-water flow is one dimensional and normal to the salinity front. The direction of the salinewater movement in the vicinity of the salinity front is unknown but is believed to be nearly normal to this front (R. W. Maclay, U.S. Geological Survey, written commun., 1981). The direction of the freshwater movement is known to parallel the salinity front during normal water-level conditions. However, during very low water-levels (drought conditions) the movement along the salinity front is believed to be very slow or nearly stagnant. Also, the extremely large transmissivity values which occur throughout a large part of the freshwater zone of the aquifer causes the drawdowns to be spread almost uniformly along most of the salinity front. The one-dimensional assumption is believed to be acceptable for low water-level conditions. The results of the one-dimensional model study are expected to be similar to the results from an approach using analytical equations.

DESCRIPTION OF MODEL

The numerical model used in this study to simulate solute transport and dispersion in ground water is documented by Konikow and Bredehoeft (1978). The model uses a finite-difference technique to solve the ground-water flow equation and the method of characteristics to solve the solute-transport equation. The model requires that water levels, concentrations of a selected water-quality constituent, hydraulic properties, boundaries, withdrawals, and recharge be defined.

In designing the model to represent the aquifer system, the following assumptions were made:

1. The aquifer is under drought conditions.
2. Ground-water flow is one dimensional and normal to the salinity front.
3. The aquifer is a single-layer which is confined, homogeneous, and isotropic.
4. The aquifer is extensive enough, and the simulation short enough, that the aquifer can be treated as if an unlimited supply of water of a given salinity is available at a given distance downdip from the salinity front.
5. The ground-water withdrawals can be represented by continuous pumping at a constant rate.
6. The pressure variations due to density are negligible.

The assumptions used to define the boundaries and initial conditions simplify a complex system. Considering the preliminary nature of the investigation and the limited hydrogeologic data available, the assumptions used to simplify the flow system will still allow the development of a better understanding of the potential and the magnitude of salinewater intrusion into the freshwater zone.

The test model was designed using a rectangular, block-centered, finite-difference grid that was 1 cell wide and 200 cells long. As shown in figure 2, each cell measured 1 ft wide, 150 ft long, and 500 ft thick (the thickness of the Edwards aquifer). Thus, the model area is 1 by 30,000 ft and 500 ft thick. To establish the desired flow pattern and stress, a withdrawal node (discharge well) was located in the freshwater zone and a constanthead node was located in the salinewater zone. The withdrawal and constant-head nodes are located at opposite ends of the model (fig. 2). Ideally, model boundaries need to be designed so that they represent the actual hydraulic boundaries and limits of the system. In this study, the model simulates drawdown in a stream tube of an aquifer confined by overlying and underlying impermeable beds. However, it is believed that at some distance downdip in the salinewater zone, hydraulic head does not change significantly in response to stresses in the freshwater zone. The hydraulic head at this location, represented by the constant-head node, probably is controlled by leakage from either overlying or underlying geologic formations, or from both.

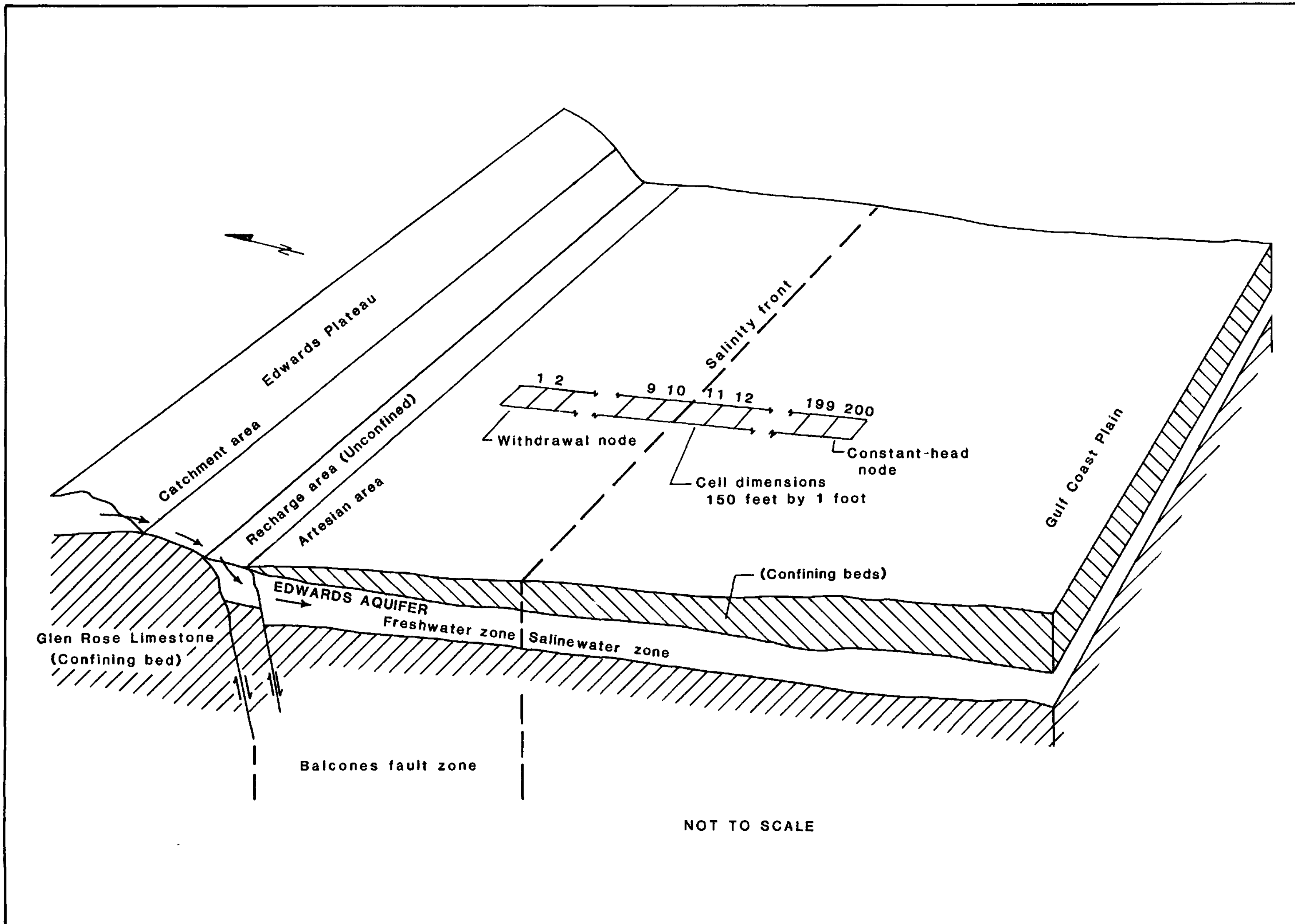

Figure 2.--Model grid used to represent the Edwards aquifer

A linear interface was used between the salinewater and freshwater zones to illustrate the effect of dispersion and movement of the salinity front. The interface differentiates the lower transmissivity of the salinewater zone and the greater transmissivity of the freshwater zone, separating the aquifer initially into two discrete zones of dissolved-solids concentration.

SIMULATED UPDIP MOVEMENT OF SALINEWATER

For all simulations, which were for 10 years, initial estimates of dissolved-solids concentrations, pumpage, storage coefficient, and transmissivity in the freshwater zone were unchanged. Except for pumpage, these initial estimates were obtained from a regional study of the Edwards aquifer by Maclay and Small (1984). These estimates were used because sufficient data were not available to define the distribution of dissolved-solids concentrations or hydraulic properties along any cross section. A dissolved-solids concentration of 5,000 mg/L was assigned to each node in the salinewater zone, and a dissolved-solids concentration of 300 mg/L was assigned to each node in the freshwater zone; a hydraulic head of 660 ft was assigned to each node in the grid array; a storage coefficient of 0.0001 was assigned to each node in the grid array; and a transmissivity of 134,000 ft^2/d was assigned to each node in the freshwater zone.

Initial estimates that were varied in some of the simulations were: transmissivity in the salinewater zone, 668 ft^2/d, which was assigned to each node in the salinewater zone; porosity, 10 percent, which was assigned to each node in the grid array; and dispersivity coefficient, 1.0 ft, which was assigned to each node in the grid array. The estimates of transmissivity and porosity were obtained from the regional study by Maclay and Small (1984). No data are available for estimating the dispersivity coefficient. From Mercer and others (1982), dispersivity coefficients used by other investigators for limestone aquifers were in the 20- to 200-foot range. However, the coefficient is dependent upon the dimension of the model grid. A value of 1.0 ft was selected because of the uncertain solution-riddled nature of the porous media and the small cell dimension of the selected model.

The pumping rate was estimated by using Darcy's law for equilibrium flow and then adjusted by trial and error to produce a drawdown of 50 ft at the discharge node. The drawdown of 50 ft is approximately equal to the declines in the San Antonio area that occurred during the 1950's drought. The initial pumping rate to achieve the 50-ft drawdown was 13.6×10^{-6} ft^3/s (0.006 gal/min). This pumping rate is small compared to the pumping rate of large production wells in the area because the section modeled actually is a 1-ft-wide stream tube, and the only source of water is storage in the model and the constant head in the salinewater part. The pumping rate also was varied in some of the simulations to either duplicate the drawdown of 50 ft or to achieve different desired drawdowns. The various pumping rates used in the simulations remained constant during the entire simulation of 10 years. For the analyses of the movement of the salinity front, the drawdown in the freshwater zone is the important parameter, not the pumping rate.

Simulation 1 used the initial estimates of dissolved-solids concentrations (5,000 mg/L in the salinewater zone and 300 mg/L in the freshwater zone), hydraulic head (660 ft), storage coefficient (0.0001), transmissivity (134,000

ft^2/d in the freshwater zone and 668 ft^2/d in the salinewater zone), porosity (10 percent), pumping rate (13.6×10^{-6} ft^3/s or 0.006 gal/min), and dispersivity coefficient (1.0 ft). The desired drawdown of 50 ft at the discharge node was simulated at the end of 10 years of pumping. After completion of simulation 1, the sensitivity of the model to various input data was tested by varying values of input data one at a time to determine the effect of these variations on the potential movement of the salinity front updip into the freshwater part of the aquifer. The purpose of these sensitivity simulations was to show the effects of possibly poor estimates in simulation 1. In these sensitivity tests, different values of the following were used: Distance to the constant-head boundary (simulations 2 and 3); transmissivity in the salinewater zone (simulations 4 and 5); porosity (simualtions 6 and 7); drawdown (simulations 8 and 9); and dispersivity coefficient (simulation 10). The input data, except that which remained constant for all simulations, used for the 10 simulations are summarized in table 1.

Results Using Initial Estimates of Hydrogeologic Variables

The model simulates one-dimensional transient flow within a rectangular section 5.7 mi long. The concentration of dissolved solids computed as an average in each cell by the method of characteristics at the end of the 10 years of simulation is shown in figure 3. From the changes in concentration computed at the end of each time step in the simulation, abrupt increases in concentrations were apparent. The reason for these irregularities may be the averaging of concentrations within the entire cell and the large concentrations associated with a particle in the method of characteristics. To resolve these conditions, a more detailed grid would be required. However, the irregularities may not affect usefulness of the results computed at the end of 10 years. Because of a small dispersion coefficient, solute transport in the simulation is dominated by convective transport. As a result, the quantity of solute transported and the location of the salinity front can be computed more precisely using an average velocity obtained from velocities derived in the flow part of the simulation than by using the cell concentrations derived by the method of characteristics. The location of the salinity front assuming average velocity is compared to the location of the front computed using the method of characteristics in figure 3.

During simulation 1, the water levels in the freshwater zone of the aquifer were lowered from an altitude of 660 to 610 ft. The drawdown was computed using nine time-steps. The water-level profiles at the end of four of the nine time-steps during the simulation are shown in figure 4. A summary of the simulation, which includes average velocity, the distance traveled by the salinity front, and drawdown during the initial simulation, and quantity of solute transported across the initial position of the salinity front, is shown in figure 5. The plots show that the model approached steady-state conditions at the end of 1 year. At the end of the 10-year simulation, the solute flux across the initial position of the salinity front had introduced 0.67 ton of dissolved solids into the freshwater zone, the salinity front (1,000 mg/L concentration) moved updip about 120 ft, and the leading edge of the front (a detectable increase in salinity) moved 300 to 450 ft (table 2).

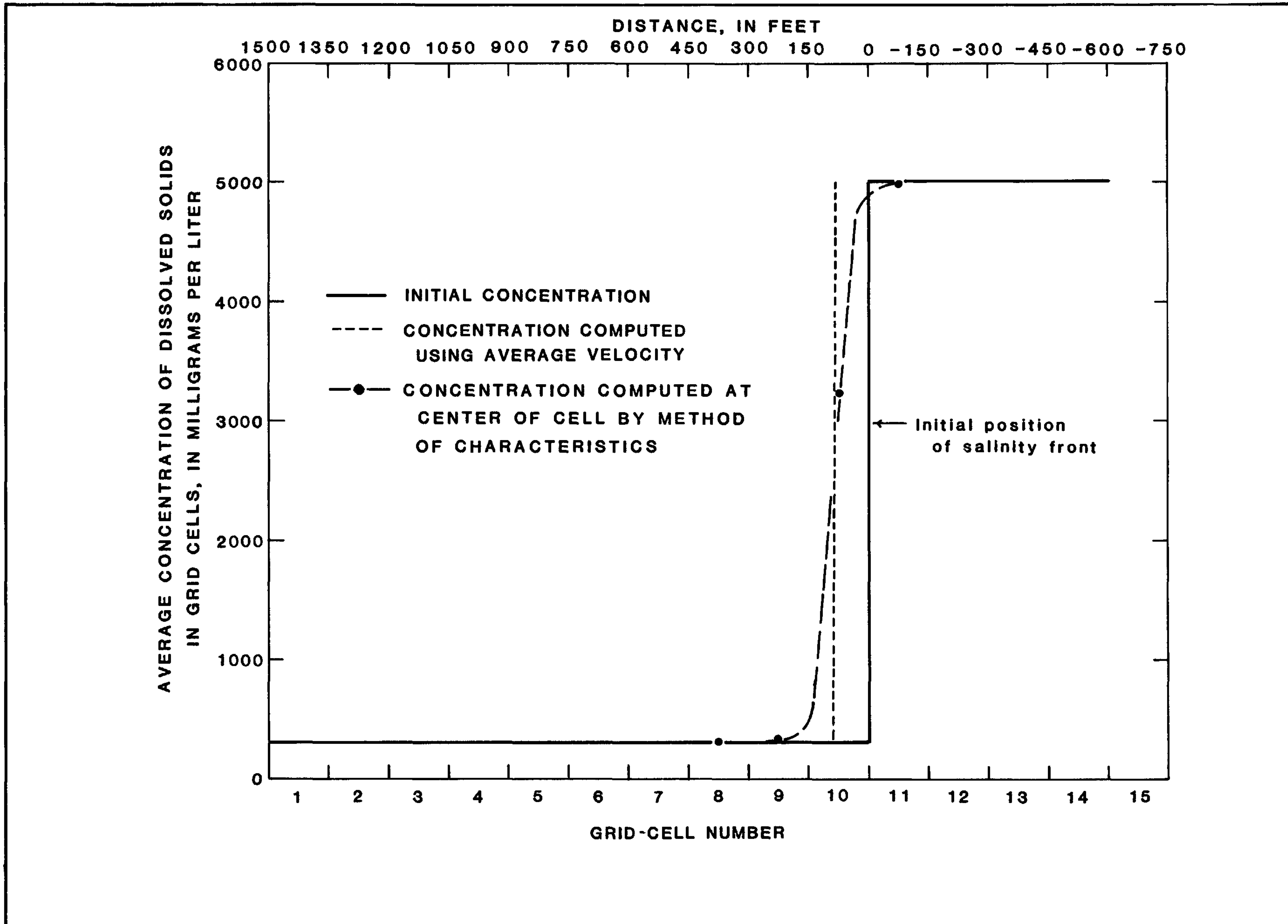

Figure 3.--Average dissolved-solids concentrations in grid cells and position of salinity front at the end of a 10-year simulation period.

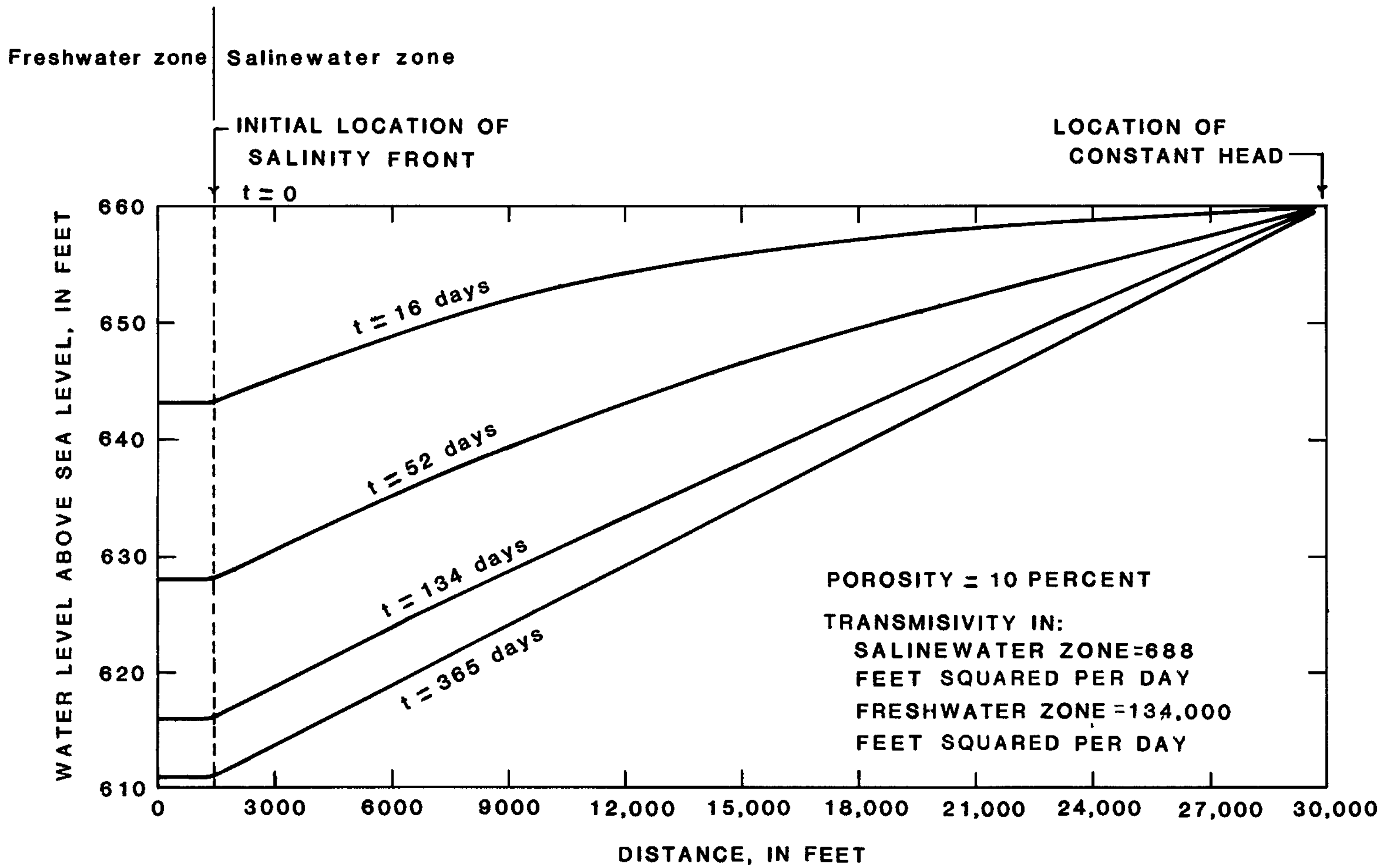

Figure 4.--Water-level profiles for four time steps during initial simulation.

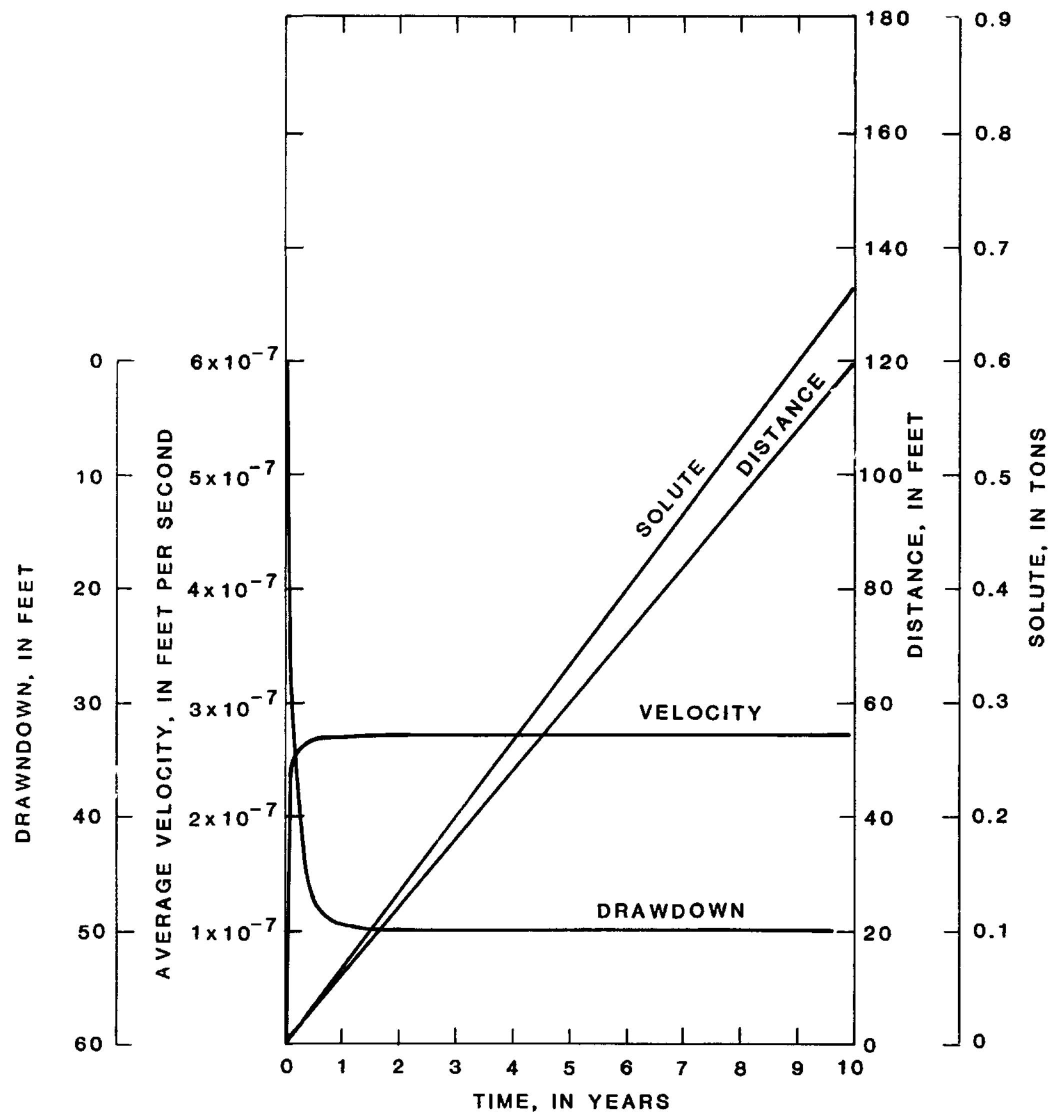

Figure 5.--Drawdown, average velocity, distance traveled by the salinity front during initial simulation, and solute transported across initial position of salinity front.

Table 1.--Selected input data used in simulation 1 and variations in that data used in sensitivity simulations 2 through 10

[T(SW), transmissivity in salinewater zone; ft^2/d, feet squared per day; ft, feet; ft^3/s, cubic feet per second; gal/min, gallons per minute]

Simulation	Input data						
	T(SW) (ft^2/d)	Porosity (percent)	Drawdown in grid-cell no. 1, after 10 years of pumping (ft)	Pumping rate required to produce drawdown (ft^3/s)	Pumping rate required to produce drawdown (gal/min)	Grid-cell length (ft)	Dispersivity coefficient (ft)
1	668	10	50	13.6×10^{-6}	0.006	150	1
2	668	10	50	40.8×10^{-6}	.020	50	1
3	688	10	49	4.08×10^{-6}	.002	500	1
4	134	10	50	2.72×10^{-6}	.001	150	1
5	3,340	10	50	68.0×10^{-6}	.030	150	1
6	668	1	50	13.6×10^{-6}	.006	150	1
7	668	20	50	13.6×10^{-6}	.006	150	1
8	668	10	20	5.43×10^{-6}	.002	150	1
9	668	10	78	21.2×10^{-6}	.009	150	1
10	668	10	50	13.6×10^{-6}	.006	150	75

Table 2.--Total solute flux across the initial position of the salinity front and corresponding movement of the salinewater for different sets of input data

[ft, feet; mg/L, milligrams per liter; >, more than; MOC, method of characteristic]

Simulation	Solute flux (tons)	Salinity front (1,000 mg/L) Average velocity 1/ (ft)	Salinity front (1,000 mg/L) MOC 2/ (ft)	Leading edge 3/ (>300 mg/L) MOC 2/ (ft)	Head in grid cell no. 1 (ft)	Remarks
1	0.67	85	120	300-450	610	Initial simulation.
2	2.00	257	255	350-400	610	Decreased grid-cell length by a factor of 3.
3	.20	25	0	0	611	Increased grid-cell length by a factor of 3.33.
4	.13	16	38	0-150	610	Decreased transmissivity in the salinewater zone by a factor of 5.
5	3.31	425	480	600-750	610	Increased transmissivity in the salinewater zone by a factor of 5.
6	.67	854	922	1,050-1,200	610	Decreased porosity by a factor of 10.
7	.67	42	85	0-150	610	Increased porosity by a factor of 2.
8	.27	34	85	150-300	640	Decreased drawdown.
9	1.04	133	180	300-450	582	Increased drawdown.
10	.67	85	210	600-750	610	Increased dispersivity coefficient by a factor of 75.

1/ Computed from average ground-water velocity from simulation.
2/ Determine from graph of salinity versus distance derived by the method of characteristic (MOC).
3/ Detectable increase in salinity.

As described earlier, freshwater flow parallel to the salinity front was not simulated. If there is flow along the salinity front, the salinewater from a given cross section would be swept downgradient, but salinewater intruding from locations upgradient would appear at the given location. However, the flux across the original front is independent of the flow along the front. The model simulated a condition believed to be the worst case because solute moving across the initial position of the salinity front encounters less dilution.

Results of Using Different Values of Hydrogeologic Variables

Effect of Varying Distance to the Constant-Head Boundary

In the model, a constant-head boundary is used to simulate an unlimited source of salinewater to the flow system. In reality, the source represented by the constant head is limited only by the areal extent of the Edwards aquifer. As shown in figure 4, the cone of depression reaches the constant head node within the first time step, only 16 days after the pumping starts. To determine the sensitivity of the model to the distance between the constant-head node and the salinity front, two additional simulations were made. In the initial simulation, the constant-head node was located 28,500 ft from the salinity front. In simulation 2, the distance between the constant-head node and salinity front was changed to 9,500 ft by decreasing the grid-cell length from 150 ft to 50 ft. In simulation 3, the distance was increased to 95,000 ft by changing the grid-cell length from 150 to 500 ft. The results at the end of simulations 2 and 3 are shown in table 2.

The solute flux across the initial position of the salinity front was found to be virtually inversely proportional to the distance between the constant-head node and the salinity front because near steady-state conditions occurred during the last 9 years of the simulation. One would expect the inversely proportional relationship for steady-state conditions. In general, if the distance is increased by a factor of 10, the solute flux across the initial position of the salinity front and the distance traveled by the front is decreased by a factor of 10. Consequently, the location of the constant-head node in the model has a significant effect on the total solute flux moving across the initial position of the salinity front.

Effect of Varying Transmissivity

The original estimates of transmissivity within the Edwards aquifer in the San Antonio area ranged from 6,680 to 1,340,000 ft^2/d in the freshwater zone and 134 to 3,340 ft^2/d in the salinewater zone (Maclay and Small, 1984). For the model, values of 134,000 ft^2/d in the freshwater zone and 668 ft^2/d in the salinewater zone were used as the initial estimates of transmissivity. In order to determine the sensitivity of the model to different transmissivities, two additional simulations were made in which the transmissivity values in the salinewater zone were varied. No sensitivity tests were made for transmissivity variation in the freshwater zone because the interest is in the immediate vicinity of the salinity front, and the flux into the freshwater zone is dependent on the hydraulics of the salinewater zone.

In simulation 4, the initial estimate of transmissivity within the salinewater zone was decreased from 668 to 134 ft^2/d. In simulation 5, the transmissivity was increased from 668 to 3,340 ft^2/d. In simulations 4 and 5, transmissivity within the freshwater zone remained unchanged. Results of the transmissivity sensitivity tests at the end of the two simulations can be compared in table 2.

The results show that the change in flux across the initial position of the salinity front virtually is directly proportional to the ratio of change in magnitude of the transmissivity within the salinewater zone if the transmissivity within the freshwater zone remains unchanged. If the estimated transmissivity in the salinewater zone is increased by a factor of 5, that is from 668 to 3,340 ft^2/d, the solute flux across the initial position of the salinity front also is increased by a factor of 5. As a result, the distance traveled by the salinity front increased by the same factor.

Effect of Varying Porosity

The effective porosity within the Edwards aquifer in the San Antonio area has been estimated to vary from 1 to 20 percent (Maclay and Small, 1984). In the initial simulation, a porosity of 10 percent was used. To determine the sensitivity of the model to different estimates of porosity, simulations 6 and 7 were made using estimated porosities of 1.0 and 20 percent. The results of the porosity sensitivity tests at the end of the simulations can be compared in table 2.

Comparing the total solute flux computed for simulations 1, 6, and 7, it is apparent that the magnitude of solute flux across the initial position of the salinity front is not affected by the different estimates of porosity. Although the total solute flux is not affected, decreasing the porosity estimate resulted in a corresponding decrease in the void or pore spaces conveying water and this enables the front to advance farther into the freshwater zone. In decreasing the estimate of porosity from 10 to 1 percent, the salinity front moves 10 times farther. The distance that the salinity front moves virtually is inversely proportional to the ratio of change in magnitude of the porosity.

Effect of Varying Drawdown

With the relative ease of ground-water development in San Antonio and the surrounding area, water use is increasing at a rapid rate. In the future, water levels within the Edwards aquifer are projected to decrease to lower altitudes than previously experienced. In this study, simulations 8 and 9 were made to analyze the effect of lowering the water level on the movement of salinewater. The declines represent the range in water levels that would be expected to occur under normal drought conditions and under extreme drought conditions. In simulations 1, 8, and 9, water levels within the freshwater zone were lowered to altitudes of 640, 610, and 582 ft above sea level, respectively. In the San Antonio area, a water-level altitude of 640 ft is typical at the end of summer, 610 ft is approximately the lowest on record, and 582 ft is arbitrarily selected to approximate a combined severe drought and current rates of pumpage. Drawdowns were controlled by the withdrawal of freshwater. The relationship between the solute flux crossing the initial position of the salinity front, the distance traveled by the front, and the drawdown in the freshwater zone is shown in table 2.

The solute flux crossing the initial position of the salinity front virtually is directly proportional to the change in magnitude of water levels. If a 20-ft drawdown is simulated within the freshwater zone, 0.27 ton of solute crosses the initial position of the salinity front. If a 50-ft drawdown is simulated, 0.67 ton of solute crosses the initial position of the salinity front. Increasing the drawdown by a factor of 2.5 increases the tonnage crossing the initial position of the salinity front by a factor of 2.5.

Effect of Varying Dispersion

The value of dispersivity affects the salinity gradient near the salinity front (Freeze and Cherry, 1979). To determine the possible effect of dispersion, the value of the characteristic length, which is the measure of the dispersivity factor, was increased from 1 to 75 ft. The average dissolved-solids concentrations in grid cells computed in simulations 1 and 10 by the method of characteristics are shown in figure 6. The increase in the characteristic length results in a shift in the salinity front of about 210 ft, which is slightly over twice the distance computed in simulation 1. It is apparent that the model is sensitive to a change in the dispersivity factor. Because no data are available for the dispersivity factor of the aquifer, data are needed to define this property in order to determine the effect of dispersion on the movement of the salinity front.

Summary

Sensitivity tests were conducted on the model using different values of distance to the constant-head boundary, transmissivity, porosity, drawdown, and dispersion in order to determine the effect of these variables on the solute flux across the present position of the salinity front. The following is a summary of the sensitivity analysis noted from the model simulations:

1. The solute flux across the initial position of the salinity front and the distance traveled by the front are inversely proportional to the distance between the assumed location of the constant-head node and the salinity front.
2. The solute flux across the initial position of the salinity front and the distance traveled by the front are directly proportional to a change in transmissivity within the salinewater zone.
3. The solute flux across the initial position of the salinity front is independent of the porosity, but the distance traveled by the front is inversely proportional to a change in porosity.
4. The solute flux across the initial position of the salinity front and the distance traveled by the front are directly proportional to a change in drawdown within the freshwater zone.
5. The effect of dispersion on the movement of the salinity front is significant. Data are needed to accurately define the dispersivity factor to properly address the effects of this property on the movement of the salinity front.

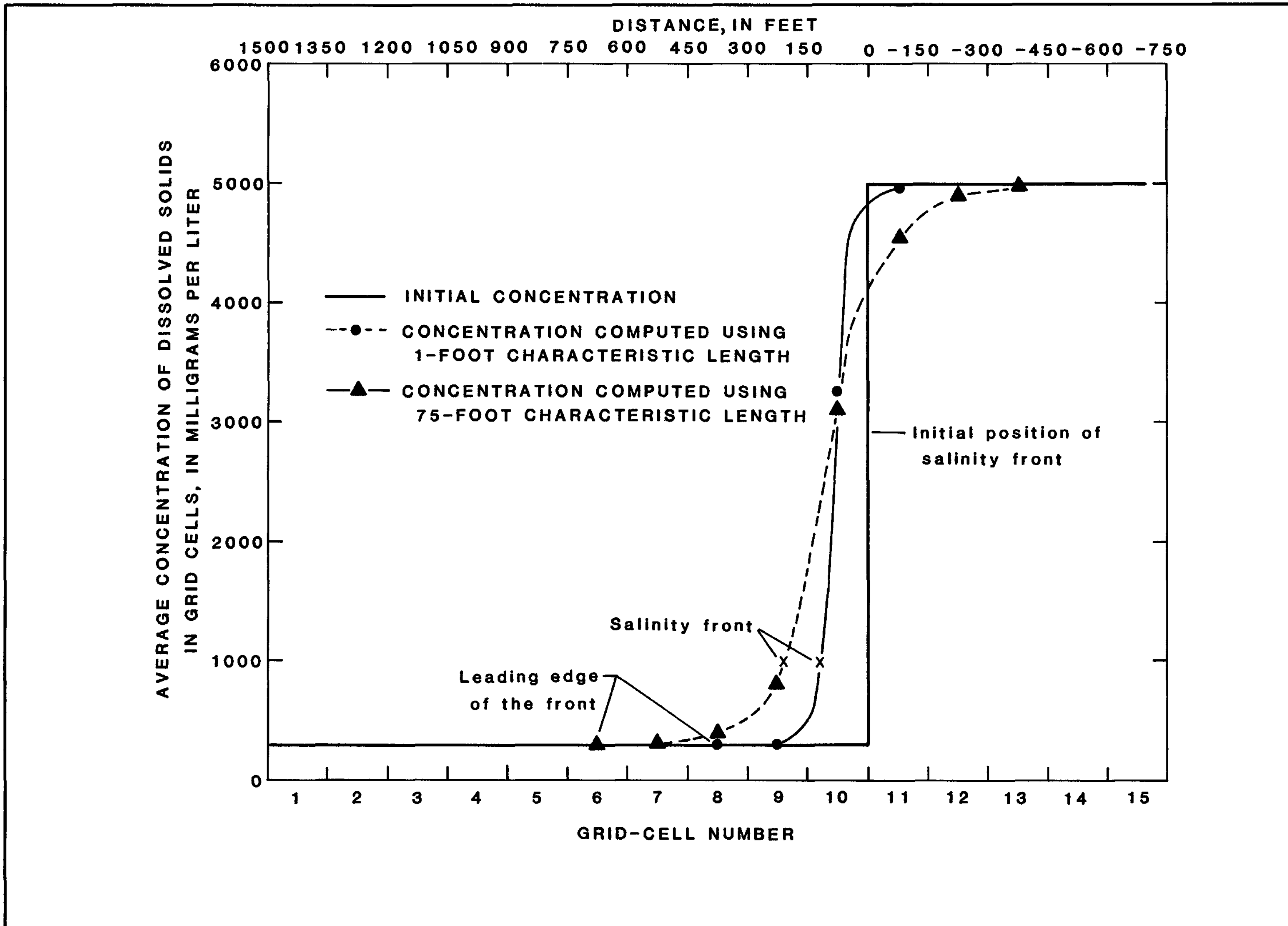

Figure 6.--Average dissolved-solid concentrations in grid cells and position of salinity front computed from different characteristic lengths.

The estimate of transmissivity and drawdown has a significant effect on the transport of solute from the salinewater zone to the freshwater zone. The estimate of porosity has no effect on the transport of solute but had a significant effect on the distance that the salinity front moves into the freshwater zone.

The sensitivity tests conducted on the model indicate that the effect of the change in each variable, except dispersion, on the solute flux across the present position of the salinity front virtually is linear. Although this is not the case during transient conditions, the flow system approaches steady-state conditions fairly rapidly so that the mass transported during the transient stage is a small portion of the total mass transported. Because the effect of a change in each of the variables on the solute flux across the present position of the salinity front virtually is linear, the flux and the distance traveled by the front can be predicted for any combination of aquifer properties analyzed in this study. For example, if the water level within the freshwater zone is lowered from an altitude of 660 to 585 ft in an area where the porosity is estimated at 15 percent and transmissivities within the salinewater and freshwater zones are estimated at 1,000 and 134,000 ft^2/d, respectively, the solute flux and distance could be computed by applying the results derived in simulation 1.

The solute flux crossing the present position of the salinity front and the distance traveled by the front can be computed for steady-state conditions for the given example directly by the following equation:

$$q(\text{solute flux}) = (\text{ratio of change in magnitude of transmissivity})(\text{ratio of change in magnitude of water levels})\ (q1)\ (t)\ (10^{-1})$$

$$D(\text{distance}) = \frac{(\text{ratio of change in magnitude of transmissivity})\ (\text{ratio of change in magnitude of water levels})\ (D1)\ (t)}{(\text{ratio of change in magnitude of porosity})\ (10)}$$

where q1 and D1 are the values of solute flux and distance computed in simulation 1. For the given example, the flux and distance can be computed as follows:

$$q(\text{solute flux}) = (1.5)(1.5)(0.67\text{ ton})(10\text{ years})(10^{-1})$$

$$= 1.5\text{ tons}$$

$$D(\text{distance}) = \frac{(1.5)(1.5)(8.5\text{ ft})\ (10\text{ years})}{(1.5)(10)}$$

$$= 128\text{ ft.}$$

APPLICATION OF RESULTS

Application of the simulated results to the Edwards aquifer requires consideration of how far the salinity front advances into the very transmissive part of the aquifer and the quantity of salinewater and salts that would be drawn into the aquifer.

With regard to the advancement of the salinity front into the highly permeable part of the aquifer, the actual profile of the front after a period of low water-levels will be irregular. The advancement will be less in a stratum with small hydraulic conductivity than in a stratum with a large hydraulic conductivity. The distances computed by the model are average values and may be reasonable and applied directly. The advancement of the front is expected to be uniform over a large part of the aquifer because: (1) The high transmissivity in the freshwater zone causes the water levels to change very uniformly over the region and (2) hydraulic properties of the aquifer in the salinewater zone are expected to be rather uniform except where discontinuties occur along faults. Ground-water circulation in the freshwater zone will change with the water-level conditions and is expected to become slower and, in some localities, the directions will change during low water-level conditions. Regional circulation will still exist. Instead of rapidly sweeping eastward and northeastward along the transition zone as it does in normal- and high-water-level conditions, the circulation would be strongly influenced by large wells near the transition zone. The flow is expected to remain approximately parallel to the transition zone at a distance from the large wells and then it will gradually be diverted toward the pumping wells in the restricted local vicinity. The net effect is that the advancement is slightly less than the computed values at a distance from the pumping wells, but greater in the vicinity of these wells. Only a small percentage of the well water would originate from the saline zone.

With regard to the amount of solute entering the highly transmissive zone of the aquifer, the impact is indicated by computing the amount of salinewater and salts drawn into the aquifer and comparing with historical natural recharge of freshwater and current withdrawals. The amount of intrusion is based on a salinity front 140 miles long and the simulations for the originally estimated hydraulic properties (simulations 1, 8, and 9). Natural recharge and withdrawal data are available from Reeves and Ozuna (1985). For comparison purposes, natural recharge amounts are presented for the minumum, long-term average, and maximum conditions. A uniform dissolved solids concentration of 300 mg/L was assumed for the recharge and withrawals. The comparisons are presented below:

Condition	Recharge (acre-ft/year)	Solute load (tons/year)
	Natural Recharge (1932-82)	
Minimum (1957)	43,700	17,800
Long-term average	608,000	248,000
Maximum (1958)	1,490,000	608,000
	Withdrawals from Wells (1978-82)	
	430,000	176,000

Salinewater Intrusion

Simulation no.	Condition	Salinewater (acre-ft/year)	Solute Load (tons/year)
8	Typical end of summer levels	2,910	20,000
1	Historical drought	7,280	49,500
9	Large withdrawals and drought	11,300	76,900

Inspection of the above information shows that the amount of salinewater intrusion is only a fraction of the amount of natural recharge and ground-water withdrawals. The only similar quantities are the minimum recharge and the historical drought (simulation 1). During this event salinewater was about 15 percent of the natural recharge but contributed three times the salt load. If this drought had coincided with the average 1978-82 withdrawals, salinewater intrusion would have been about 2 percent of the amount of water withdrawn.

CONCLUSIONS

Because of the limited data available on the hydrogeology within the vicinity of the salinity front, certain assumptions were made to simplify the analysis of the flow system. The assumptions have resulted in model predictions that reflect the worst possible conditions. In this context, the results of the study can be used to predict the movement of the salinity front, assuming no flow perpendicular to the section modeled.

The maximum advancement of the salinity front predicted by the model under the conditions tested in the simulation was 854 ft at the end of a 10-year pumping period. A shift of this magnitude indicates that contamination created by salinewater will be limited to the area within 0.20 mi of the present position of the salinity front.

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