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GROUNDWATER FLOW AND SOLUTE TRANSPORT IN THE INDUSTRIAL WELL FIELDS OF THE TEXCOCO SALINE AQUIFER SYSTEM NEAR MEXICO CITY

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RESUMEN

En este trabajo se investiga el comportamiento hidráulico del sistema acuífero salino de Texcoco, cerca de la ciudad de México, mediante la evaluación de los datos históricos, estudios de campo y análisis numérico del flujo subterráneo y el transporte de solutos dentro de un gran campo de pozos de donde se extraen las aguas salobres para fines industriales. Los dos acuíferos de poco espesor que se explotan en esta área están limitados por acuitardos de alta compresibilidad, los cuales proporcionan enormes volúmenes de agua a los acuíferos, por filtración. Para el modelado del flujo se utiliza un sistema de ecuaciones integrodiferenciales quasi-tridimensional que se resuelve numéricamente mediante un sistema triangular de elementos finitos. El modelo del transporte masivo de solutos está basado en el método de características combinado con un rastreo de partículas. Ambos modelos están calibrados con precisión, de acuerdo con las mediciones piezométricas de campo y los datos de distribución de concentraciones provenientes de los pozos explotados. Los nidos piezométricos instalados en el acuitardo arcilloso superficial indican que en las áreas intensamente bombeadas, la infiltración pluvial está diluyendo las concentraciones de agua de las porosidades del acuitardo, lo que podría explicar las concentraciones decrecientes que han sido observadas recientemente en los pozos explotados. El análisis de los datos de campo indica también que el acuitardo superficial está fracturado y es probable que la red de fracturas juegue un papel importante en el movimiento de solutos en el acuitardo. Los modelos aquí descritos se están utilizando en la actualidad para investigar las posibles estrategias alternativas para su manejo, con el fin de optimizar la producción del campo de bombeo industrial.

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ABSTRACT

The hydraulic behavior of the Texcoco saline aquifer system near Mexico City is investigated through the evaluation of historical data, field studies, and numerical analysis of groundwater flow and solute transport within a large well field which is extracting the saline water for industrial purposes. The two thin aquifers under production in this area are bounded by highly compressible aquitards which supply tremendous volumes of water to the aquifers through leakage. A quasi three-dimensional integrodifferential equation scheme is used for the flow modelling and is solved numerically with a triangular finite element scheme. The solute mass transport model is based on the method of characteristics combined with a particle tracking scheme. The models are accurately calibrated to piezometric field measurements and concentration distribution data from the production wells. Piezometric nests installed in the surficial clay aquitard indicate that in the heavily pumped areas, infiltrating rainfall is diluting the pore water concentrations in the aquitard which may account for declining concentrations in the production wells which have been recently observed. Analysis of the field data also indicates that the surficial aquitard is fractured and that the fracture network may play an important role in the movement of solutes in the aquitard. The models are currently being used to investigate alternative management strategies to optimize production from the industrial well field.

INTRODUCTION

The occurrence and extraction of the groundwater resources within the Valley of Mexico has been one of the key elements supporting the enormous industrial and residential growth of Mexico City. The complex series of aquifer systems within the unconsolidated sediments of the Valley of Mexico not only provides the main potable water supply for the nearly 20 million inhabitants, but also represents a very important source of industrial minerals. In an area northeast of the Mexico City limits, the groundwater found in the lacustrine clay sediments is a very concentrated sodium chloride (NaCl) - sodium carbonate (Na_2CO_3) brine. A large well field consisting of some 300 production wells completed in thin, permeable strata interlayered in the thick clay deposits, extracts the brine which is used as raw material for chemicals serving the glass, paper, and detergent industries. This industrial well field produces over 70% of the 300 000 tons of sodium bicarbonate consumed annually in the entire country of Mexico and is by far the largest field of its kind in Latin America (Zacaula, 1977).

The Valley of Mexico is situated on a very active tectonic zone referred to as the Transmexican Volcanic Belt (Mooser, 1975). The valley was formed as a series of grabens which developed in the uplifted central region of Mexico. Intensive volcanic activity in the valley and its flanks produced huge volumes of clastic materials which intermixed with alluvial material to form the valley fill sediments. An extensive drainage system developed on the valley floor and reworked the sediments which now form part of the main production aquifer currently in use below Mexico City.

Near the end of the Quaternary, a volcanic event in the southern part of the valley effectively blocked the drainage system resulting in the formation of a large lake which covered a considerable portion of the valley floor (Mooser, 1978). Over a period of several hundred thousand years, a thick section of lacustrine sediments were deposited in the valley overlaying the alluvial-fluvial sediments. The high compressibility of these materials have been the cause of severe geotechnical problems related with land subsidence due to the extraction of groundwater. The extent of these lacustrine sediments and the general configuration of the basin which contains the Valley of Mexico are illustrated in Figure 1.

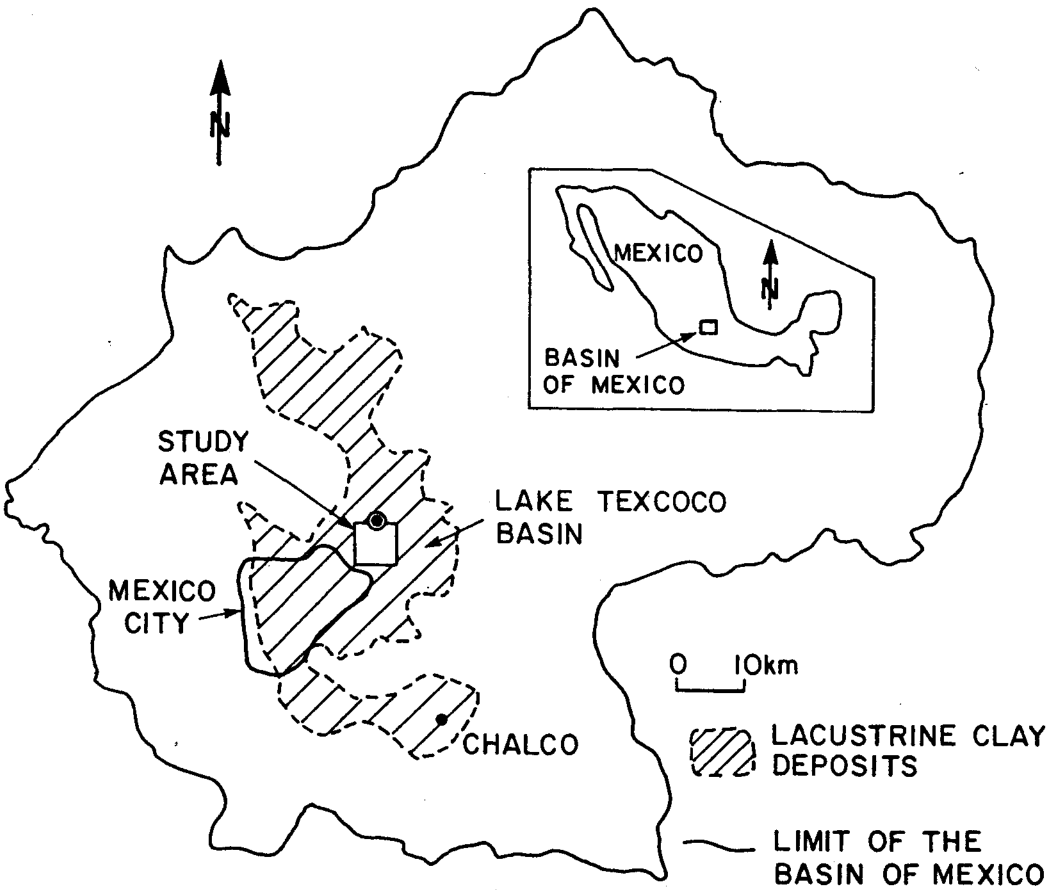

Fig. 1. General location map.

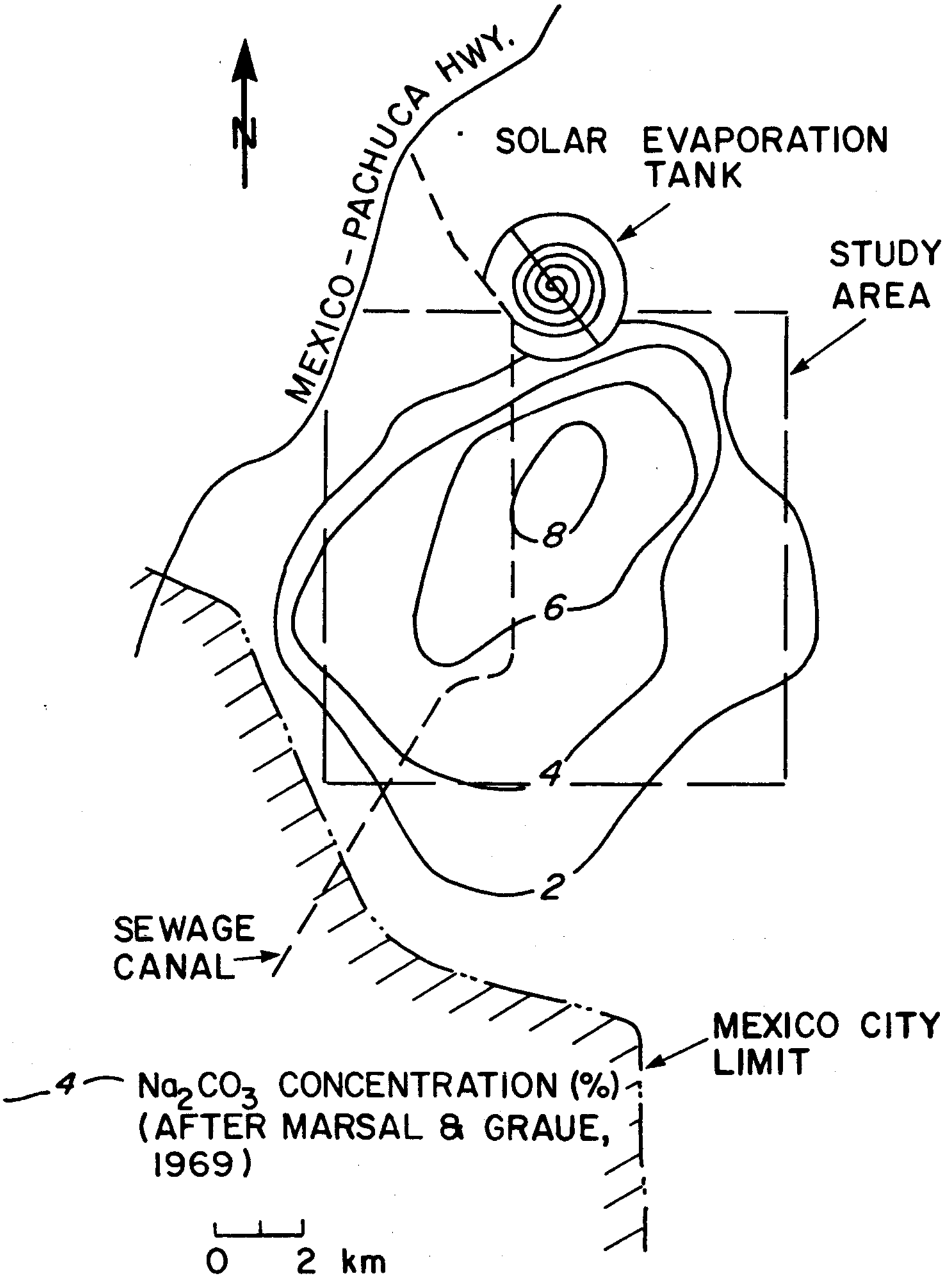

Fig. 2. Distribution of saline groundwater in Lake Texcoco Basin.

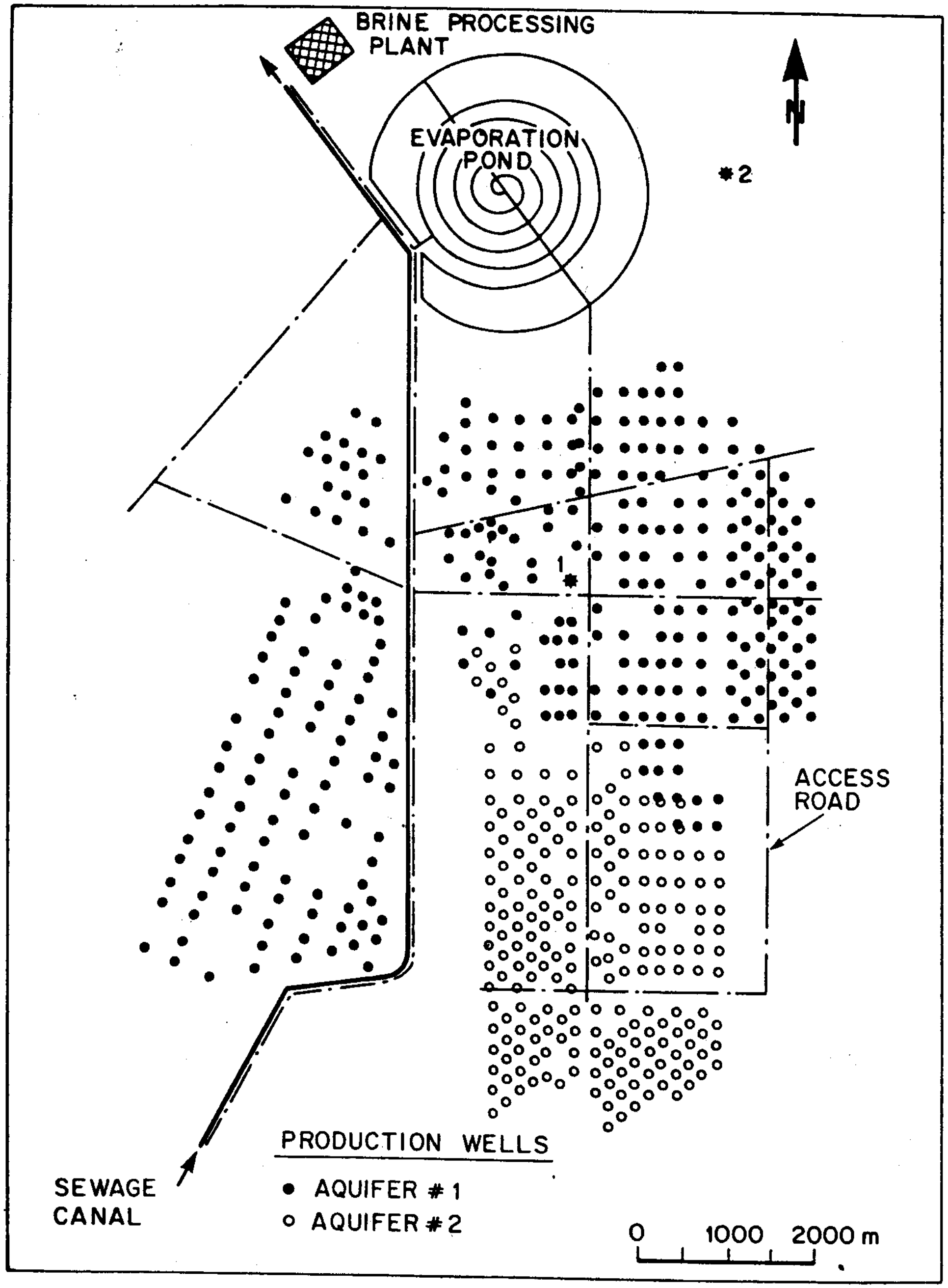

Fig. 3. Sosa Texcoco well fields.

Geologic evidence indicates that the lake which originally covered the valley floor, was in fact a series of isolated lakes linked to form one water body only during wet climatic conditions. Of the five lakes that formed this system, Lake Texcoco, portions of which still exist today, was located at the lowest part of the valley and received drainage from all other lakes (del Castillo, 1978, Durazo and Farvolden, 1989). Because Lake Texcoco (Figure 1) had no natural outflow, saline waters, which resulted from extensive evaporation, concentrated in this part of the valley and this is considered to be a plausible explanation for the origin of the saline groundwaters now being exploited industrially. Figure 2 shows the areal distribution of the saline groundwater within the Lake Texcoco basin (Marsal, 1975).

In 1944, a company known as Sosa Texcoco, S. A., was granted mineral rights to the saline deposits in the Lake Texcoco area and construction began on a processing plant and well field. A large solar evaporation pond, constructed in the late thirties as a method of concentrating brine washed from the local surficial sediments, was incorporated into the Sosa Texcoco, S. A. extraction system (Figure 2). Production began in 1955 with approximately thirty extraction wells in operation. Over the following two decades the well fields continually grew until presently approximately 300 wells are producing from two main aquifers. The annual production of brine is, on average, nine million cubic meters but the average pumping rate for an individual well is relatively low, in the order of 0.5 - 1.0l/sec.

The brine produced at the well head is transported by gravity to a network of collector pipes which lead to pumping centres in the well field. From these centres, the brine is pumped to the evaporation pond where it enters near the outside limit of the pond and slowly circulates in a spiral motion towards the centre. The residence time in the pond is around four to six months during which the brine is further concentrated through evaporation. From the centre of the pond, the concentrated brine is pumped to the processing plant and the minerals are extracted. Figure 3 shows the main components of this production process and Table 1 summarizes the general chemistry of the brine.

The lacustrine sediments in this part of the Valley of Mexico consist of a 60 m to 70 m thick section of clay interlayered by 5 m to 10 m thick units of cemented clastic material which are known elsewhere in the valley as the *capas duras* or hard layers. These units form the aquifers from which the brine is extracted. The lacustrine sediments overlay thick deposits of sands and gravels that are thought to be a

Table 1

General chemistry of saline groundwater

Ionic Species	Concentration (mg/1)
Cl	47,730
SO_4	30.0
Na	51,840
K	5,952
.	- - -
Mg	1.33
Total Alkalinity	80,570

continuation of the sediments that form the main aquifer of Mexico City. In this area however, the water in these deeper sediments is somewhat brackish (>2000mg/1 TDS) and is not used for human consumption. A cross section of the general stratigraphy is shown in Figure 4.

The clay deposits have been the object of many detailed investigations in the immediate vicinity of the Lake Texcoco area and have been shown to possess very remarkable geotechnical properties. Of particular interest are the exceedingly high moisture contents (300%) and void ratios (7 - 8) (Marsal, 1975). These relate to porosity values of 0.8 to 0.9. In addition, standard consolidation tests have shown the clay to be extremely compressible (Marsal and Mazari, 1959), accounting for the high degree of land subsidence observed in many areas of the clay plain related to the extraction of groundwater.

Within the brine well field, the thin production aquifers are confined above and below by the lacustrine clay. Due to its highly porous and compressible nature, the clay strata adjacent the aquifers act as semi-confining aquitards which can supply water to the aquifers in the form of leakage flux during pumping. This leakage flux is derived mainly from a depletion of storage in the clay sediments.

Recently, the operators of this industrial operation (Sosa Texcoco, S. A.) have expressed concerns about excessive drawdowns observed in pumping wells, especially in the centre of the well field, and slight declines in the brine concentrations overall.

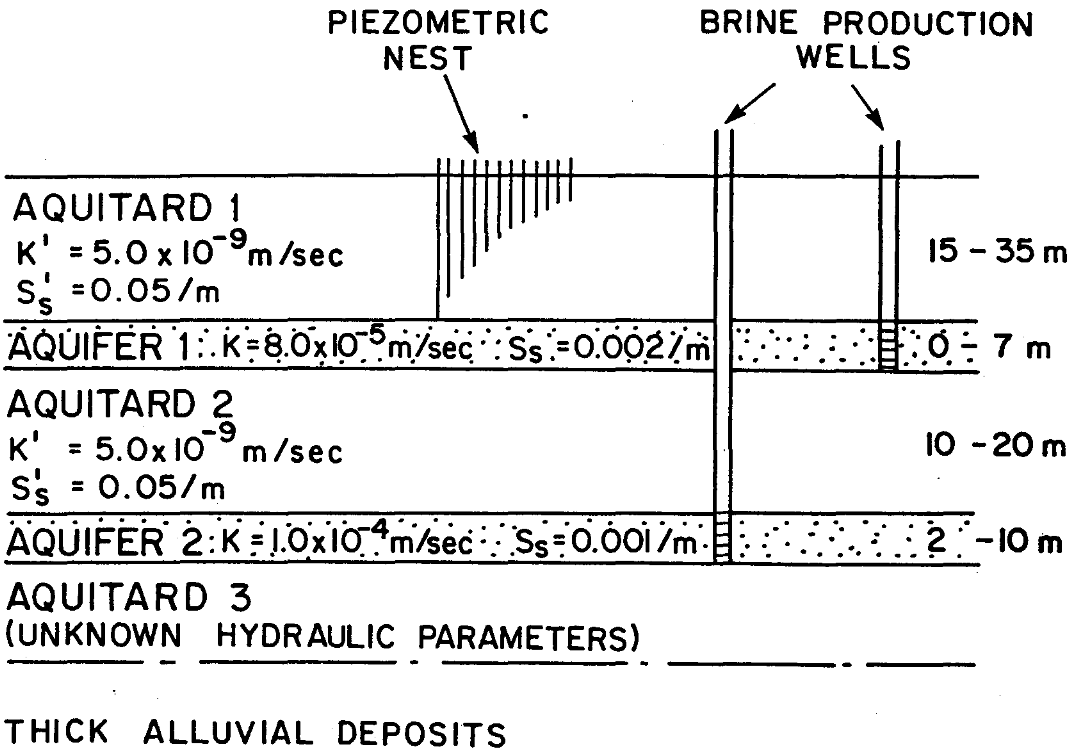

Fig. 4. Generalized stratigraphic cross-section of Texcoco aquifer system.

A need has been identified for a well field management strategy that would allow for the most efficient exploitation of the groundwater mineral resource in both the short and long term. For this purpose, the Institute of Geophysics (IGF) at the National Autonomous University of Mexico (UNAM) has carried out a hydrogeological investigation of the industrial well field. The ultimate objective of the study was to prepare a computer model of the aquifer system which could be both used to investigate the nature of flow and solute transport in both the aquifers and the aquitards and to evaluate various alternative production scenarios to help establish a long-term development plan for managing the well fields.

An extensive data base including detailed extraction records, well drilling logs, brine concentrations in both the aquifers and aquitards, and piezometric information has been carefully amassed by Sosa Texcoco personnel since the first production wells were installed. The Texcoco aquifer system provides a unique opportunity to study the response of highly compressible aquitards to extensive groundwater extraction. This aquifer system is similar, in many respects, to the system supplying Mexico City with the majority of its municiple water, albeit on a much smaller scale. Investigations at this site, therefore, may provide insight into the hydraulic behaviour of the Mexico City aquifer system which could prove useful in the further understanding of this critical water resource.

Based on the results of the hydrogeologic investigation and numerical simulations carried out by scientists at IGF-UNAM, a follow-up field study was conducted by the Waterloo Centre for Groundwater Research (WCGR) at the University of Waterloo in Canada, in collaboration with IGF-UNAM and Sosa Texcoco, S. A. The field investigations were directed towards studying the hydraulic and hydrochemical behaviour of the surficial clay aquitard by observing the distribution of hydraulic head, major ion concentrations and environmental isotope composition in the clay pore water between ground surface and the first aquifer-aquitard interface. Piezometer nests were installed both near the centre of the drawdown cone and outside the cone of influence to evaluate the effects of groundwater extraction from the underlying aquifer on the distribution of pore pressures and the infiltration rates. By calibrating various one-dimensional analytical models to the field data, the groundwater flow and solute transport characteristics of the clay aquitard were investigated.

This article discusses the numerical modelling techniques selected to simulate this system, and the model construction and calibration procedures. In addition, the modelling results are presented in light of the observations made during the field investigations. Conclusions with respect to the future management and long-term prospective of the well fields are presented along with a discussion of the overall significance of the lacustrine clay aquitards in the Texcoco aquifer system.

GENERAL HYDROGEOLOGY

The Texcoco aquifer system is comprised of three relatively continuous independent aquifers, the two shallowest of which are exploited by Sosa Texcoco, S. A., for the extraction of industrial minerals and a deeper aquifer which contains nearly potable water and is thought to be an extension of main aquifer used by Mexico City. For

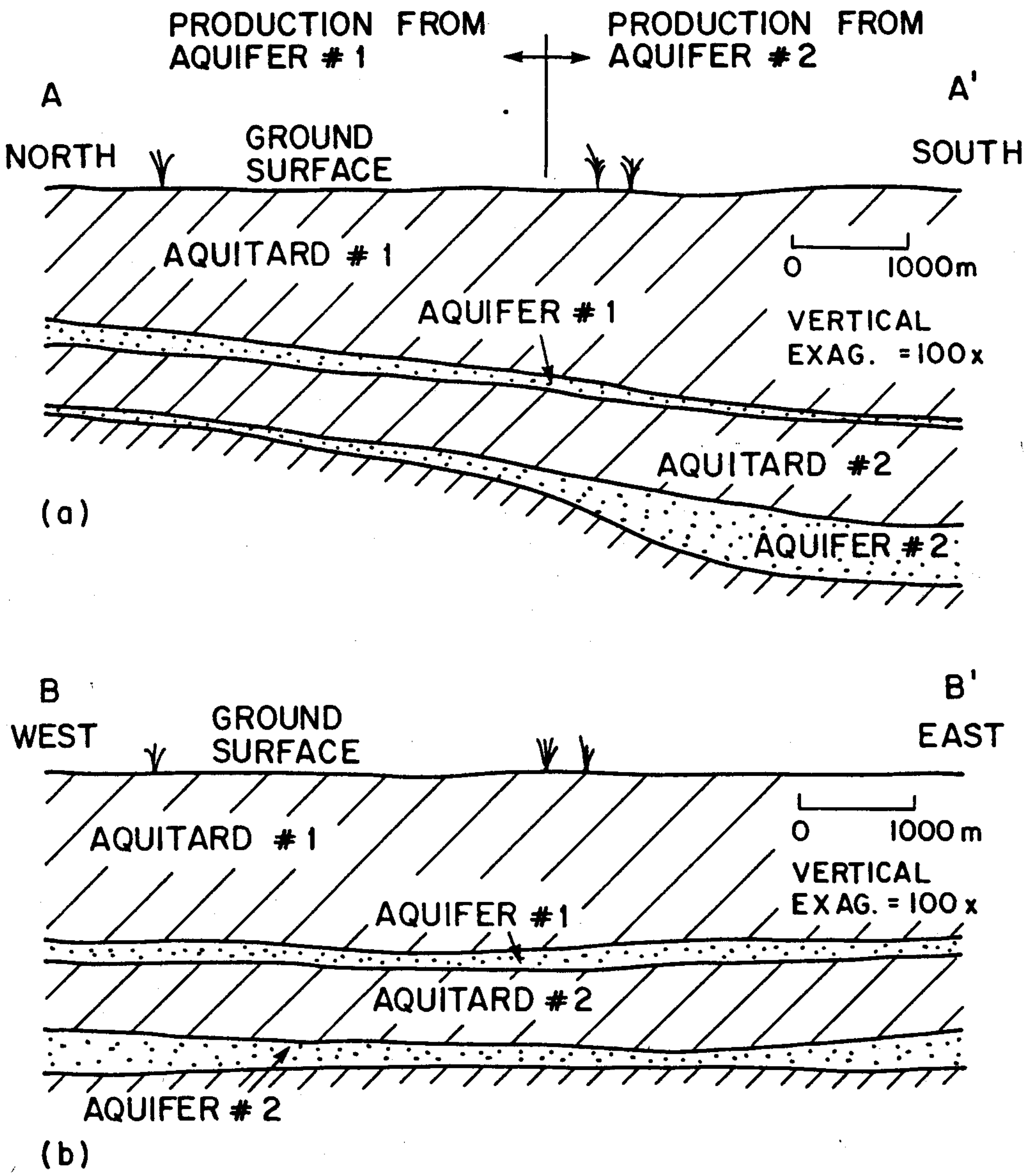

Fig. 5. a) North-south cross-section, b) West-east cross-section.

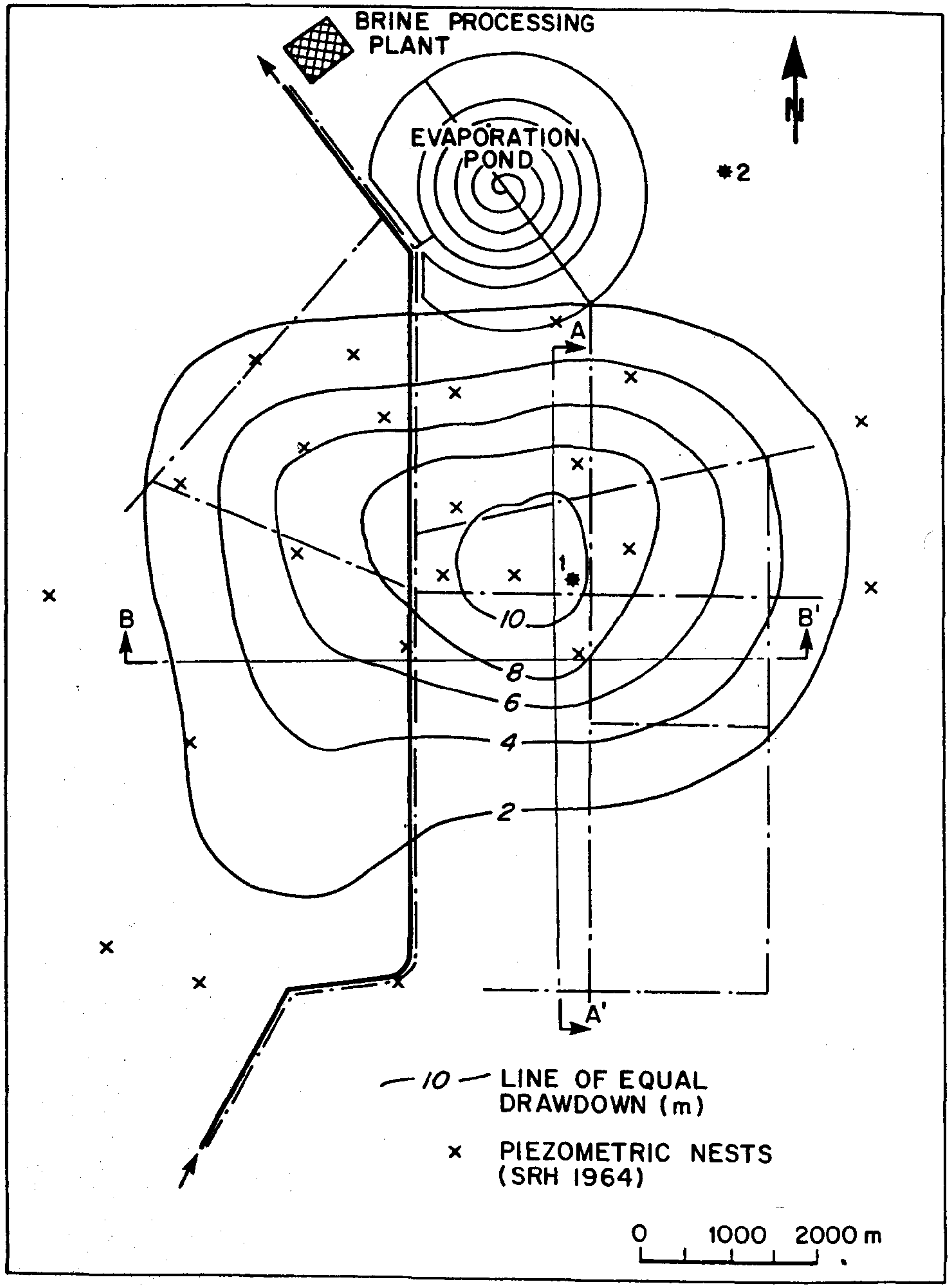

Fig. 6. Observed drawdown cone in 1977.

the sake of this discussion, the behaviour and response of this lower aquifer will be considered to have insignificant influence on the shallow aquifers. The general stratigraphy and associated hydraulic parameters of each unit are shown in Figure 4. Detailed drilling records from each of the ±300 production wells and exploratory test holes provide a relatively clear picture of the distribution of the two shallow brine production aquifers and intervening aquitards within the well fields. The stratigraphy below the base of the second aquifer, however, is not well understood. Two perpendicular cross-sections through the well field are shown in Figure 5. The locations of these sections are indicated in Figure 6.

Values of hydraulic conductivity (K) and specific storage (S_s), in the aquifers were determined from a series of pumping tests conducted by Zacaula (1977) and average values are listed in Figure 4. The aquitard parameters (K′ and S'_s) were determined through a series of geotechnical investigations conducted by Marsal and Mazari (1969) and Marsal and Graue (1969). Additional information regarding the physical nature of the clays was obtained during the investigations for the construction of artificial Lake Nabor Carrillo and is reported in SHCP (1969) and Herrera *et al.* (1974). In a normally consolidated state, average values of K′ and S'_s of the clay are in the order of 5.0×10^{-9} m/s and 0.04/m respectively. The extremely high values of S'_s reflect the compressible nature of these clay aquitards and suggests that the aquifer system will respond to pumping as a classical *leaky* multiaquifer system with leakage flux entering the pumped aquifers from adjacent aquitards. This type of aquifer response is discussed in detail by Neuman and Witherspoon (1969, a, b) and Herrera y Figueroa (1969; Herrera 1970).

In the case of the Texcoco aquifer system, the thin, interlayered aquifers are thought to act as permeable underdrains conducting brine leaking out of the adjacent clay aquitards towards the production wells. The percentage of the extracted brine originating from storage in the aquitards, however, is not well understood and is one of the objectives of this study.

The nature of the groundwater flow system in the brine aquifers prior to the commencement of pumping is not well documented. The earliest piezometric measurements reported by well drillers and obtained from piezometric nests installed by SRH (1964), however, indicate that the vertical gradients were extremely small and that discharging conditions may have prevailed throughout the Lake Texcoco basin (Durazo and Farvolden, 1989).

A series of 25 piezometer nests, shown in Figure 6, were installed by the Secretary of Water Resources (SRH) in the early to mid 1960's and monthly water level data has been recorded continuously from most of the piezometers. Each nest consists of 4 to 10 discrete monitoring points installed at different depths from near ground surface to total depths of between 30 m and 100 m. Throughout the expansion of the well field, vertical gradients evolved in the aquitards to being strongly downward in response to the extraction of the saline groundwater from the thin aquifers. The result is that within the cone of influence of the well field (Figure 6) recharging conditions now exist.

The distribution of porewater mineralization in the lacustrine sediments of the Lake Texcoco basin dictated the well placement and extraction strategy for the Sosa Texcoco, S. A. operation. During the drilling of the production wells and exploratory test holes, soil samples were taken at regular intervals throughout the clay aquitards. Chemical analysis of mineralized water leached from the samples provided a detailed distribution, both laterally and vertically, of the mineralization in the porewater. These data indicate that although the porewater concentrations vary laterally in a nearly concentric fashion as seen in Figure 2, the concentrations in the vertical profile were initially nearly uniform. Since the initiation of recharging conditions within the drawdown cone, however, rainfall has begun to infiltrate and this fresh water may be diluting the porewater concentrations from ground surface. The distribution of this dilution profile was studied as part of the field investigations because of its potential bearing on the production life of the well field.

Several investigators have reported the occurrence of fractures in the surficial clay aquitard. Marsal and Mazari (1969), Murillo and García (1978), Juárez-Badillo (1982) and others have reported the existence of extensive fracture networks in the Lake Texcoco region and in other parts of the Valley of Mexico. The importance of these fractures in the groundwater flow and solute transport behaviour of the clay will be dealt with elsewhere.

NUMERICAL SIMULATIONS

The production of brine and subsequent commercial viability of the Sosa Texcoco, S. A. operation depends directly on the long-term behaviour of the hydrogeological system. Due to the high density of the production wells (Figure 3), interference effects between neighboring wells results in exaggerated drawdowns. In some areas of the well field, particularly near the centre of the drawdown cone (Figure 6), Sosa Texcoco, S. A. personnel report excessively high drawdowns which are beginning to jeopardize the production capacity of the wells.

Continuous records of brine concentration from the production wells indicate that in recent years, concentrations are beginning to decrease. The reason of this gradual decrease is not clear but inflow of fresh water from the lateral boundaries of the well field is one possible explanation. Maintaining high concentrations in the extracted brine is critical to the economic feasibility of the entire industrial operation.

Officials at Sosa Texcoco, S. A., concerned about both the excessive drawdowns being observed in the well field and the decreasing brine concentrations, recognized the need for a more thorough understanding of the behaviour of the aquifer system as well as a strategy for both the short and long-term operation of the well field. To this end, researchers at IGF-UNAM recommended the construction of a computer model of groundwater flow and solute transport in the Texcoco aquifer system which could be used to evaluate complex well interference effects, lateral boundary inflow, and detailed response of the confining aquitards. The model could be used to investigate both the short and long-term response of the well field to various alternative production scenarios as well as providing insight into the behaviour and relative significance of the main components of the hydrogeological system.

In selecting an appropriate numerical model to simulate flow and transport in this aquifer system, several physical characteristics of the system had to be considered. Because it was anticipated that the response of the clay aquitards is extremely important in the overall behaviour of the aquifer system, accurate simulation of transient aquitard response was required throughout the complex extraction history. Also, considering the large contrast in hydraulic conductivity between the aquifers and aquitards of the system (nearly four orders-of-magnitude), the assumption can be made that flow is essentially horizontal in the aquifers and vertical in the aquitards (Neuman and Witherspoon, 1969 a, b). The physical consequence of this is that flow and transport can be adequately simulated in one dimension in the aquitards, and in the two-dimensional areal plane in the aquifers which simplifies the numerical formulation significantly. This assumption has been incorporated into many groundwater flow models (Herrera and Figueroa, 1969; Herrera, 1970; Bredehoeft and Pinder, 1970; Herrera and Yates, 1977). Models based on this assumption are referred as quasi three-dimensional. It has been adopted and applied by many researchers. Its range of applicability was thoroughly analyzed by Neuman and Witherspoon (1969b).

The numerical model selected to simulate groundwater flow is based on a set of integrodifferential equations formulated to define flow in leaky aquifer systems by Herrera and Rodarte (1973). In this system, flow in the aquitards is represented in a highly accurate manner by expressing the exact analytical solution to flow in the aquitard by a convolution of two convenient functions (*memory* function and *influence* function) which depend only on the potential distribution in the aquifers. These functions are subsequently incorporated into the equations governing flow in the aquifers and solved numerically to determine the hydraulic head distribution in the individual aquifers (Herrera and Yates, 1977).

The integrodifferential equation formulation has several distinct features which make it attractive for simulating flow in the Texcoco system. In the first instance, it is a quasi three-dimensional numerical treatment which, as outlined above, takes advantage of the hydraulic conductivity contrast to reduce the dimensionality of the problem and the corresponding computational effort. The accurate simulation of aquitard response and resulting leakage flux is inherent in this scheme yet there is no need to determine the hydraulic head distribution within the aquitard. As such, no discretization is required in the aquitards again simplifying the numerical analysis. The formulation is applicable to a system involving any number of independent aquifers. By the nature of the functions representing the aquitard response, however, the aquifer equations are effectively uncoupled for a considerable period of time as the pressure pulse from the neighboring aquifer is time lagged in relation to the square of the aquitard thickness and its hydraulic diffusivity (Herrera, 1970; Herrera y Yates, 1977; Frind, 1979). This also simplifies the numerical analysis.

For simulation of solute mass transport in the aquifer system, a method involving the advection of mass in the aquifers, coupled with mass entering the system through leakage from the aquitards and leaving through the extraction wells, is developed. The mass transport model uses the nodal velocity and leakage flux values calculated by the flow model along with the total volumes of extraction from wells, to simulate the transport of brine in the discretized domain during each time step. The mathematical formulation of both the groundwater flow model and the mass transport model are presented below along with a discussion of assumptions and numerical approximations.

MATHEMATICAL FORMULATION

Flow model

In the mathematical formulation of the groundwater flow model, several assumptions are adopted in the specification of the governing differential equations. Due to the high permeability contrast between the aquifers and the aquitards (>2 orders-of-magnitude), flow in the aquitards will be assumed to be strictly vertical and flow in the aquifers strictly horizontal (quasi three-dimensional). The differential equation describing flow in the aquitard, therefore, need only be expressed in one dimension and in the aquifers in two dimensions. This assumption conveniently reduces the complexity of the problem from a fully three-dimensional one to a series of one and two-dimensional problems. This reduction in dimensionality simplifies the numerical treatment of the problem and substantially improves the computational efficiency of the numerical analysis compared to a fully three-dimensional formulation. All hydrostratigraphic units are assumed to be continuous throughout the flow domain and the aquitards homogeneous with respect to K' and S'_s. The hydraulic parameters in all aquifers and aquitards are assumed to remain constant in time.

In the Texcoco aquifer system, the groundwater is highly saline and variations in fluid density exist throughout the entire system. For the sake of this regional modelling project the effects of variable fluid density will be considered insignificant. Variations in dynamic fluid viscosity will also be assumed to have little effect on the nature of the groundwater flow and solute transport processes.

Consider the simple multiaquifer system shown in Figure 7. According to Hantush (1960), the governing equation for two-dimensional groundwater flow in the aquifers can be stated in terms of drawdown as

$$\frac{\partial}{\partial x}\left[T(x,y)\frac{\partial s}{\partial x}\right]+\frac{\partial}{\partial y}\left[T(x,y)\frac{\partial s}{\partial y}\right]+q_p+q_l = S\frac{\partial s}{\partial t} \tag{1}$$

where $T(x, y) = K(x, y)b$ is the aquifer transmissivity (L^2/T) and $S = S_s(x, y)b$ is the aquifer storativity with b being the aquifer thickness (L) and K and S_s the hydraulic conductivity (L/T) and specific storage (L^{-1}) respectively. The q_p term represents the loss or gain of water to the aquifer through pumping or injection and can be defined as $q_p = \pm Q_p\delta(x-x_p)\delta(y-y_p)$ where Q_p is the strength of the source or sink (L^3/T) and δ is the Dirac delta function locating Q_p at coordinates

(x_p, y_p). The leakage flux entering or leaving the aquifer through adjacent aquitards is represented by the q_1 term(L/T).

One-dimensional flow in the aquitards is governed by (Hantush, 1960)

$$\frac{\partial}{\partial z}\left(K' \frac{\partial s'}{\partial z}\right) = S' \frac{\partial s'}{\partial t} \tag{2}$$

where s' is the drawdown in the aquitard (L).

For each aquifer, (1) is specified according to the following initial and boundary conditions,

$$s(x, y, 0) = 0 \tag{3}$$

$$s(x, y, t) = s_0 \qquad \text{on } \Gamma_1 \text{ (Dirichlet)} \tag{4}$$

$$\frac{\partial s(x, y, t)}{\partial n} = \frac{-q_0}{K} \qquad \text{on } \Gamma_2 \text{ (Neumann)} \tag{5}$$

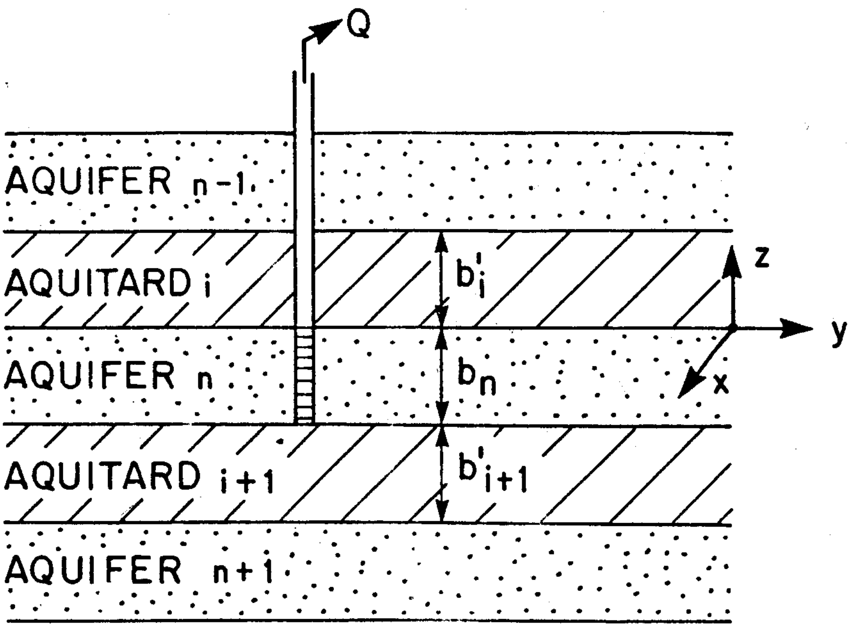

Fig. 7. Hypothetical multiaquifer system.

where $\Gamma = \Gamma_1 + \Gamma_2$ is the aquifer domain boundary, s_0 is a specified drawdown (L), q_0 is a specified normal boundary flux (L/T) and $\partial s(x, y, t)/\partial n$ is the gradient normal to the boundary. With (3) the assumption is made that the aquifers are in hydrostatic equilibrium, however, unique values of both (4) and (5) must be specified for each individual aquifer.

Considering Aquitard i in Figure 7, the initial and boundary conditions on (2) for that aquitard will be

$$s_i'(x, y, z, 0) = 0 \tag{6}$$

$$s_i'(x, y, 0, t) = s_n(x, y, t) \tag{7}$$

$$s_i'(x, y, b', t) = s_{n-1}(x, y, t) \tag{8}$$

where $z = 0$ and $z = b'$ indicate the lower and upper surfaces of Aquitard i. Again (6) implies that the aquitards are also in hydrostatic equilibrium initially.

In (1), q_l, the aquitard leakage flux, is given by Darcy's law for Aquifer n in terms of drawdown in the aquitard as

$$q_l = K_i' \frac{\partial s_i'}{\partial z} \Big|_{z=0} - K_{i+1}' \frac{\partial s_{i+1}'}{\partial z} \Big|_{z=-b_n} \tag{9}$$

where b_n is the thickness of Aquifer n.

The aquifers in the system (Figure 7) are coupled through the leakage term and as indicated by (2), (7) and (8), the response of each aquitard depends on the hydraulic conditions in the aquifers which bound it above and below. The solution to (2) for the drawdown in Aquitard i (Figure 7) can be written in the form of a convolution integral, after Herrera and Rodarte (1973), as

$$\begin{aligned} s_i'(x, y, z, t) = & \int_0^t \frac{\partial s_n}{\partial t}(x, y, t-\tau)u(z, \tau)d\tau \\ & + \int_0^t \frac{\partial s_{n-1}}{\partial t}(x, y, t-\tau)v(z, \tau)d\tau \end{aligned} \tag{10}$$

where u(x, t) and v(z, t) are auxiliary functions describing the diffusion, through the aquitard, of a unit pressure pulse originating in the underlaying and overlaying aquifers respectively. The auxiliary functions are (Courant and Hilbert, 1962)

$$u(z, t) = 1 - \frac{z}{b'} - 2 \sum_{n=1}^{\infty} \frac{e^{\frac{-n^2\pi^2 K' t}{S_s' b'^2}}}{n\pi} \sin \frac{n\pi z}{b'} \tag{11}$$

$$v(z, t) = \frac{z}{b'} + 2 \sum_{n=1}^{\infty} (-1)^n \frac{e^{\frac{-n^2\pi^2 K' t}{S_s' b'^2}}}{n\pi} \sin \frac{n\pi z}{b'} \tag{12}$$

An expression similar to (10) can be written for each aquitard. By taking the derivative of (10) with respect to z at each aquitard-aquifer interface, one arrives at an expression for the vertical gradient of the aquitard drawdown $s'(x, y, z, t)$ in terms of the drawdowns in the adjacent aquifers s_n and s_{n-1}. We will define two additional auxiliary functions resulting from the differentiation as (Herrera and Rodarte, 1973),

$$f(t) = 1 + 2 \sum_{n=1}^{\infty} e^{\frac{-n^2\pi^2 K' t}{S_s' b'^2}} \tag{13}$$

$$h(t) = 1 + 2 \sum_{n=1}^{\infty} (-1)^n e^{\frac{-n^2\pi^2 K' t}{S_s' b'^2}} \tag{14}$$

The expression (13) is classically referred to as the *memory* function and represents the rate of flow into the aquifer from the adjacent aquitard and reflects the drawdown history in that aquifer. On the other hand, (14) represents the rate of flow into the aquitard from the adjacent aquifer incorporating the drawdown history in that aquifer. This function is referred to as the *influence* function.

Referring again to the expression for the aquitard leakage flux for Aquifer n, (9), the component of leakage from the overlaying aquitard can be written using (10), (13), and (14) as

$$q_{li}(0,t) = -\Big(\frac{K_i'}{b_i'}\int_0^t \frac{\partial s_n}{\partial t}(x,y,t-\tau)f\Big(\frac{K_i'}{S_{s_i}'b_i'^2}(\tau)\Big)\,d\tau$$

$$-\frac{K_i'}{b_i'}\int_0^t \frac{\partial s_{n-1}}{\partial t}(x,y,t-\tau)h\Big(\frac{K_i'}{S_{s_i}'b_i'^2}(\tau)\Big)\,d\tau\Big) \tag{15}$$

An expression similar to (15) can be written for every aquitard in the flow system. The equation governing flow in Aquitard n can be stated using (1) and (15) as

$$\frac{\partial}{\partial x}\Big[T_n(x,y)\frac{\partial s_n}{\partial x}\Big] + \frac{\partial}{\partial y}\Big[T_n(x,y)\frac{\partial s_n}{\partial y}\Big] + Q_p\delta(x-x_p)\delta(y-y_p)$$

$$-\frac{K_i'}{b_i'}\int_0^t \frac{\partial s_n}{\partial t}(x,y,t-\tau)f\Big(\frac{K_i'}{S_{s_i}'b_i'^2}(\tau)\Big)\,d\tau$$

$$+\frac{K_i'}{b_i'}\int_0^t \frac{\partial s_{n-1}}{\partial t}(x,y,t-\tau)h\Big(\frac{K_i'}{S_{s_i}'b_i'^2}(\tau)\Big)\,d\tau$$

$$-\frac{K_{i+1}'}{b_{i+1}'}\int_0^t \frac{\partial s_n}{\partial t}(x,y,t-\tau)f\Big(\frac{K_{i+1}'}{S_{s_{i+1}}'b_{i+1}'^2}(\tau)\Big)\,d\tau$$

$$+\frac{K_{i+1}'}{b_{i+1}'}\int_0^t \frac{\partial s_{n+1}}{\partial t}(x,y,t-\tau)h\Big(\frac{K_{i+1}'}{S_{s_{i+1}}'b_{i+1}'^2}(\tau)\Big)\,d\tau$$

$$= S_n\frac{\partial s_n}{\partial t} \tag{16}$$

Equation (16), written for all aquifers in the flow system, constitutes a set of integrodifferential equations which can be solved numerically. As can be seen in (16), the drawdown in the aquitards s' does not occur in the equations and need not be calculated. If s' is required, however, it can be determined from (10).

The numerical technique adopted for the solution of eqns. (16) involves the Galerkin method of weighted residuals in the spatial coordinates with triangular finite elements, and a Crank-Nicolson approximation in time. These standard techniques are presented in detail in Pinder and Gray (1977) and need not be described here. The *memory* and *influence* functions in the aquitard leakage flux term are approximated by convenient truncations of the exponential series expansions for these functions. The truncation is done in such a way as to minimize computational effort while ensuring the values of the integrals are preserved. A detailed discussion of the numerical procedure is given in Herrera and Yates (1977).

Solute mass transport model

In simulating the transport of dissolved species in the Texcoco aquifer system, the governing equations must account for mass entering or leaving the aquifers as leakage flux through the semi-confining aquitards, as inflow along lateral boundaries of the flow domain and as discharge through the production wells. The dissolved solutes are assumed to be nonreactive for these simulations. Under these conditions, the mass transport of dissolved species in the aquifers can be described in the two-dimensional horizontal plane by

$$\frac{\partial}{\partial x}\left(D_x \frac{\partial \phi c}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y \frac{\partial \phi c}{\partial y}\right) - \frac{\partial}{\partial x}(\bar{v}_x \phi c) - \frac{\partial}{\partial y}(\bar{v}_y \phi c)$$

$$- q_l(c - c') - Q_p(c - c^*) = \frac{\partial \phi c}{\partial t} \qquad (17)$$

where D_x and D_y are the dispersion coefficients (L^2/T), $\bar{v}_x$ and $\bar{v}_y$ are the average linear groundwater velocities (L/T), ϕ is the porosity of the porous medium, c is the solute concentration in the aquifer (M/L^3), c' and c^* are the solute concentrations in the aquitard and the extraction fluid, and q_l and Q_p are the aquitard leakage flux and well discharge rates respectively.

The average linear velocity field and the distributed aquitard leakage flux is taken directly from the flow simulations. Eqn. (17) can be solved numerically with a time-stepping scheme incorporating the transient behavior of the flow field. In the Texcoco aquifer system, relatively high groundwater flow velocities occur within the well fields and the assumption can be made that solute transport is dominated by convection. The contribution to the mass transport process by the dispersion terms will be assumed to be significant.

Based on the above assumption, the method of characteristics combined with a particle tracking technique as outlined in Huyakorn and Pinder (1983) was selected for the numerical approximation of (17). In this method, a set of particles is initially distributed evenly throughout the flow domain in the elements of the triangular finite element grid used in the flow simulations. The particles are assigned initial concentrations equal to an average of the groundwater solute concentrations at the nodes of the element confining that group of particles. During each time step of the transient simulation, the particles are moved throughout the flow domain in proportion to an interpolated average of the nodal velocities determined by the flow model.

The new positions of all particles are determined at the end of each time step and the concentrations of the particles are updated to account for any addition or depletion of mass resulting from the aquitard leakage flux in that area of the flow domain. In the case of purely convective transport, the numerical expression for the updating of the particle concentrations, employing a Crank-Nicolson approximation in time, is

$$c(x + \bar{v}\Delta t, t + \Delta t) = \frac{1}{(1 + \frac{q_l \Delta t}{2\phi})} [c(x, t)(1 - \frac{q_l \Delta t}{2\phi}) + c'(x + \frac{\bar{v}\Delta t}{2}, t + \frac{\Delta t}{2})\frac{q_l \Delta t}{\phi}] \tag{18}$$

where Δt is the length of the simulation time step. The wells in this case are taken to be extraction wells and as such the term in (17) involving Q_p vanishes because the concentration of the discharge fluid c^* and the concentration in the aquifer c are the same.

Along the lateral boundaries, particles are allowed to enter or leave the flow domain in response to the mass flux calculated at each boundary segment. Particles will also leave the domain through the pumping wells. At the end of each time step, the new location and concentration of each particle is determined and the concentration at each node is updated based on the distribution of particles in all elements connected to that node. In this way, the solute transport model is solved essentially simultaneously with the flow model to provide a transient simulation of the movement of dissolved species in the aquifers.

Flow field simulations

The main objectives of the flow field simulations were to provide both a velocity field in the aquifer and distributed leakage flux from the aquitard which were representative of the actual field conditions, for use in the solute mass transport simulations. The flow modelling also allowed for an evaluation of the significance of regional inflow recharging the aquifer along lateral domain boundaries in comparison to the aquitard leakage flux. The calibration procedure and analysis of the flow and transport modelling in the uppermost aquifer (Aquifer 1, Figures 4 and 5), will be presented here for discussion purposes. Calibration on the deeper aquifer is currently being done by Sosa Texcoco, S. A. personnel.

In the preparation of the flow model, stratigraphic records from the production wells and test holes were compiled and used to construct isopach maps of the aquifer and aquitard units. Ground surface elevations were obtained from regional topographic maps. The pumping history of each well, including average extraction rates and times of operation, were obtained from Sosa Texcoco records. Water level data from the SRH piezometer nests located throughout the well field (Figure 6), were used to calibrate the flow model. Due to clogging of several of the piezometers, the most recent complete set of piezometric measurements were made in 1977. The transient flow simulations were calibrated to the 1977 data and subsequently carried out to 1986 without further calibration, to represent the flow system at the time of this study.

Discretization

The domain boundaries for the numerical simulations were selected on the basis of several criteria. A rectangular area was selected to symmetrically confine the well fields producing from both aquifers and the corresponding regional drawdown cones. The drawdown cones were drawn on the basis of data from the SRH piezometers. The lateral boundaries were located far enough away from the edge of the well field to minimize the influence of the specified boundary conditions on the flow and transport solutions. The domain has dimensions of 11.4 km by 10.2 km for a total surface area of ±120 km². The area of simulation was uniformly discretized with

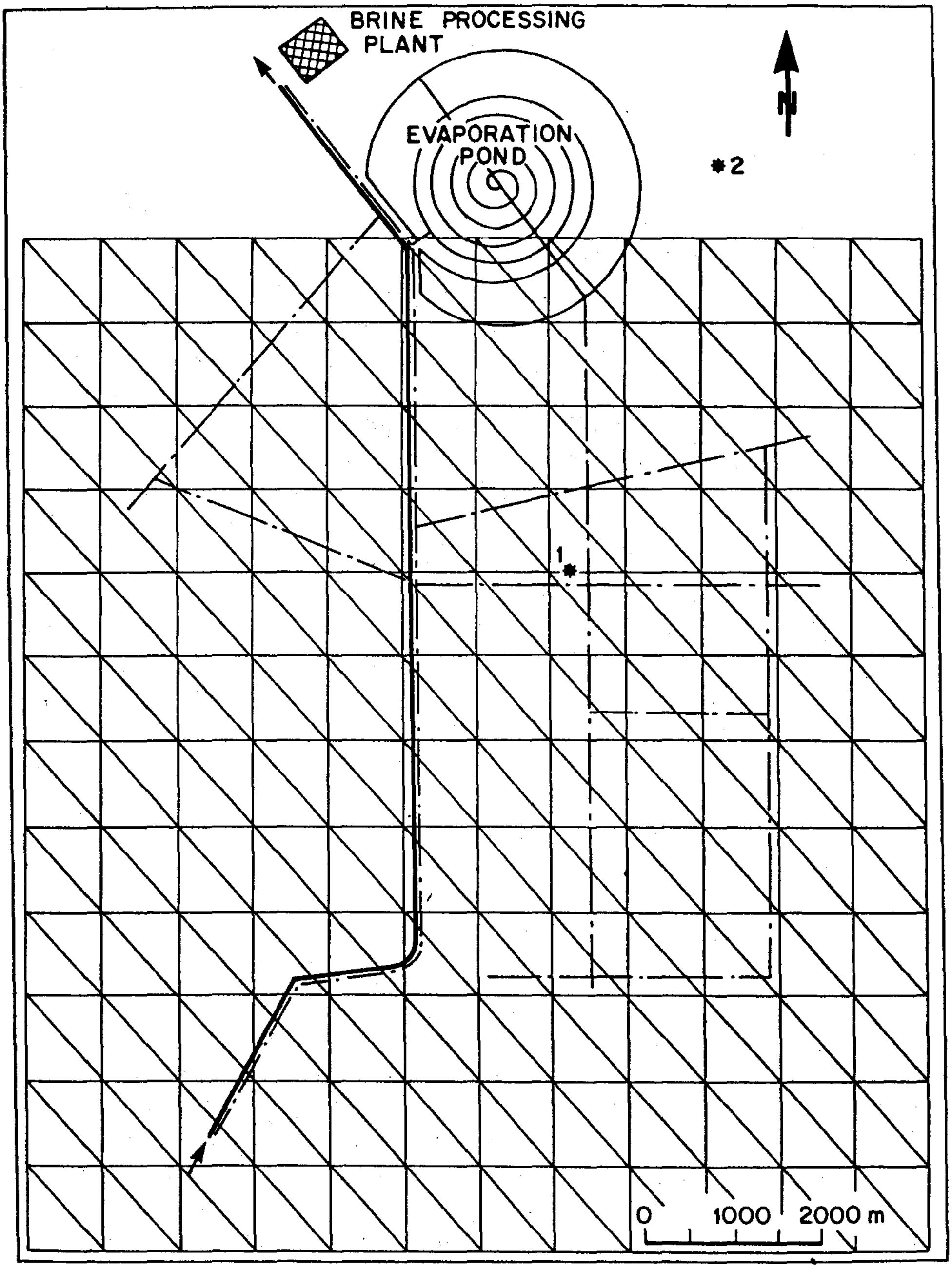

Fig. 8. a) Finite element grid.

288 triangular elements and 169 nodes for the regional modelling. The resulting finite element grid is shown in Figure 8a.

Simulation of pre-pumping conditions

The regional flow system, prior to the commencement of pumping, was simulated first in order to provide a reference elevation for the piezometric surface throughout the flow domain. The transient solution was then superimposed on this initial condition in order to calibrate the simulations with the piezometric data. Unfortunately, very little historical information exists regarding the nature of these initial flow conditions. Piezometers located some distance from the well field, indicate that the piezometric surface is very near ground surface outside of the cone of influence. The assumption will be made that these piezometers reflect the conditions which most likely existed throughout the region prior to pumping. As such, the boundary conditions selected for the simulation of the initial flow conditions will be specified hydraulic head values equal to the ground surface elevation. Fixed hydraulic head values along the boundaries are referred to as *first-type* or *Dirichlet* boundary conditions. In addition, the aquitards will be assumed to have been in hydraulic equilibrium with the aquifer and as such no vertical pressure gradients will exist within the system initially.

The initial flow system was simulated under steady-state conditions and the resulting simulated piezometric surface is shown in Figure 8b. The hydraulic head contours show groundwater flow from east to west under a very gentle gradient of $\pm 5.0 \times 10^{-4}$.

Transient simulations

Brine production began in 1956 when ±30 wells were put into operation. The transient simulations were, therefore, initiated in 1956 and were progressively marched through time until 1977 which was the calibration reference point. The mathematical formulation of the model requires that the initial conditions throughout the entire domain be uniform. Because the model solves for drawdown, initial zero drawdown conditions were specified at all nodes in the interior of the grid. The assumption is made that no drawdown occurs along the boundaries throughout the simulation period and consequently, zero drawdown values were specified as *first-type* boundary conditions along all domain boundaries.

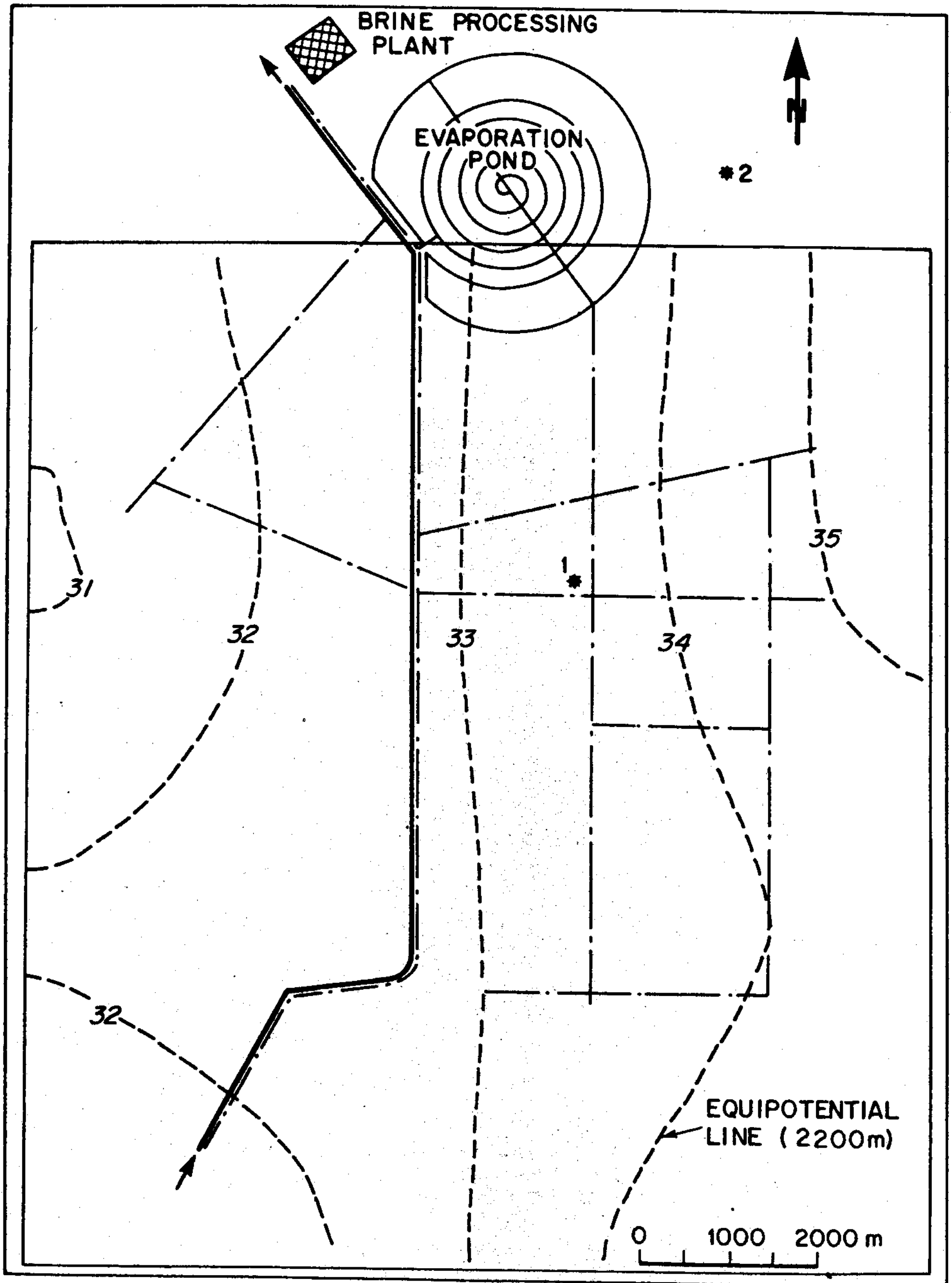

Fig. 8. b) Simulation of initial regional flow system.

The production wells completed in Aquifer 1 are shown in Figure 3. The year in which pumping commenced and ceased in each well along with average extraction rates, were available from Sosa Texcoco records. These data permitted the detailed reconstruction of the brine production history of the well field for simulation purposes. Because it was not feasible to have nodes of the finite element grid positioned at each of the wells, the brine production from each well was proportioned through linear interpolation to the three nodes of the element confining it. In this way the nodal points of the grid became local pumping centres with the corresponding extraction rates dependent on the pumping history of the individual neighboring wells.

The hydraulic parameters of the aquitards (K' and S'_S) and of the aquifer (K and S_S) were the physical variables available for modification during the calibration procedure. The flow solution was calibrated to the piezometric levels measured in 1977 in the SRH piezometers. The drawdown cone constructed from these data is shown in Figure 6 and the final calibrated simulation is shown in Figure 9. The overall lateral extent, general shape and maximum drawdown of the simulated piezometric surface agree extremely well with the field data. The physical parameters used in the calibrated solution are compared to the field measured values in Table 2. Both sets of parameters are very similar.

Table 2

Measured and calibrated hydraulic parameters

Parameter	Measured	Calibrated
S'	1.3	0.95
S	0.009	0.0053
K'	6.0×10^{-9} m/s	4.0×10^{-9} m/s
K	9.6×10^{-5} m/s	7.7×10^{-5} m/s

The solution was marched forward in time to 1986 and the resulting piezometric surface is shown in Figure 10a. A slight increase in both the maximum drawdown and the lateral extent of the cone is observed during the additional nine years of pumping although, the general shape remains relatively constant.

In comparing the main components of recharge entering the aquifer, the 1977

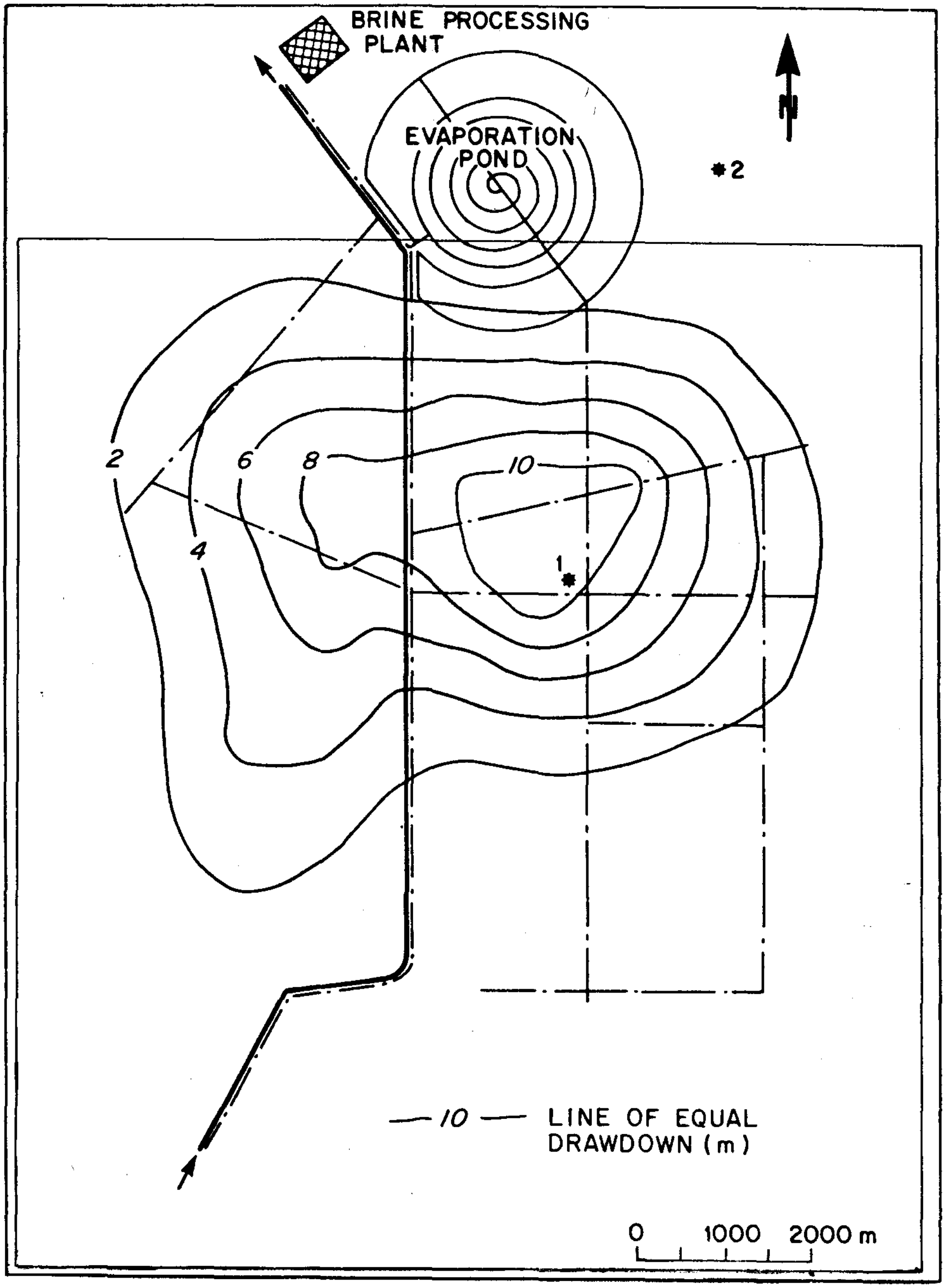

Fig. 9. Transient flow simulation for 1977.

simulation indicates that only 6% of the total volume extracted by the wells comes from inflow across the lateral boundaries of the domain, whereas the aquitards contribute 94%. In 1986 the boundary inflow increases slightly to 7%.

The results of the flow simulations indicate that indeed the majority of brine being extracted by the production wells originates on leakage from the aquitards. The boundary inflow is almost insignificant. The very small change in boundary flux between the 1977 and 1986 simulations as well as the excellent agreement between the simulated and actual potentiometric surfaces, suggest that the choice of *first-type* boundary conditions was appropriate and that the boundary conditions have a very minor influence on the overall flow solution within the domain. The transient characteristics of the drawdown cone indicate that the aquifer system has not yet reached steady state.

By relating the depth of the upper aquifer-aquitard interface with the simulated drawdown cone, the remaining available drawdown throughout the field can be estimated as shown in Figure 10b. This represents the theoretical drawdown available with 100% efficient production wells. Measurements of water levels in many wells under pumping conditions show drawdowns considerably deeper than either the nearby piezometers or the simulation results would suggest. This excess drawdown is most likely due to well losses which lower well efficiency. An evaluation of several pump test results shows that well efficiencies as low as 35% may be common throughout the well field (Herrera *et al.*, 1987). Encrustation from the highly mineralized groundwater may be one of the causes of well loses. Sosa Texcoco, S. A. personnel have begun further tests on several wells and have developed several strategies for improving well efficiency.

Solute transport simulations

As was the case with the flow model, simulation of solute transport in the aquifer system requires the specification of both the initial conditions and realistic boundary conditions. The flow simulations illustrated the significance of the confining aquitards in supplying water to the production wells and consequently the brine concentrations in the aquitards were very important input parameters. During construction of the production wells the drillers collected core samples of the clay sediments at ±2 m intervals through most of the aquitard. The brine concentrations in these samples were determined through a leaching process in the chemical laboratories of Sosa

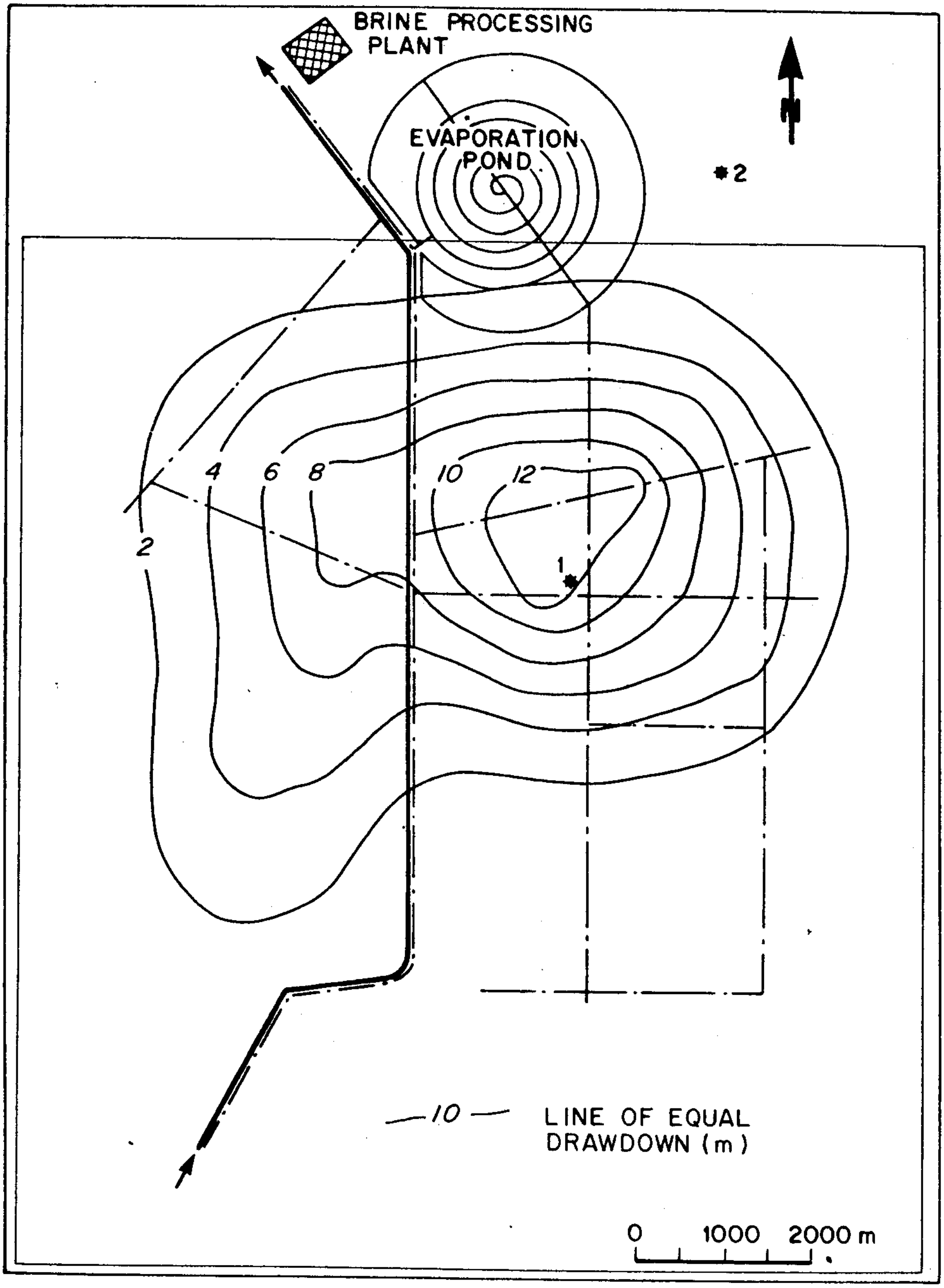

Fig. 10. a) Transient flow simulation for 1986.

Texcoco, S. A. and as a result, a fairly comprehensive record of the distribution of mineralization in the aquitards when the wells were first drilled was available. An extensive review of these data shows that vertical concentrations were nearly uniform. Laterally, however, concentrations vary considerably, decreasing concentrically from a point near the centre of the well field. Because of its importance to Sosa Texcoco, S. A., the distribution of total alkalinity of the groundwater was selected for simulation. It is assumed that the total alkalinity is a nonreactive quantity. The brine concentration in the aquitard, in terms of total alkalinity is shown in Figure 11a. Although no geochemical data were available from the underlying aquitard beneath the Aquifer 1 well field, the assumption was made that the brine concentration distribution in the lower aquitard was the same as that in the overlaying aquitard. Wells drilled through both aquitards in the region of the Aquifer 2 well field indicate a continued uniformity of pore water concentration with depth below Aquifer 1. Concentrations in the aquitards were assumed to remain constant throughout the entire simulation period.

The regional flow system which existed prior to the construction of the well field was controlled by very gentle hydraulic gradients as discussed earlier. The groundwater flux and flow velocity through the Texcoco aquifer system was most likely very low. Considering that the aquifers are relatively thin and that the regional flow rate was very slow, the assumption was made that the groundwater in the aquifer was initially in chemical equilibrium with the confining aquitards and that the initial concentration distribution in the aquifer was the same as in the aquitards. This was used as the initial condition in the aquifer for the transport simulations.

Because brine concentration data were only available from the wells themselves, concentration contours had to be extrapolated to the boundaries of the finite element grid. The interceptions of these contour lines with the domain boundaries were used as the *first-type* or specified concentration boundary conditions for the simulations.

Water samples have been collected from the extraction wells and chemically analysed on a regular basis by Sosa Texcoco personnel since production began. These data have been used to construct contour maps of the concentration distribution of NaCl and the total alkalinity. Throughout the pumping history of the Sosa Texcoco operation, the concentrations in the well field have remained relatively constant, although in recent years, slight declines in brine concentrations have been observed

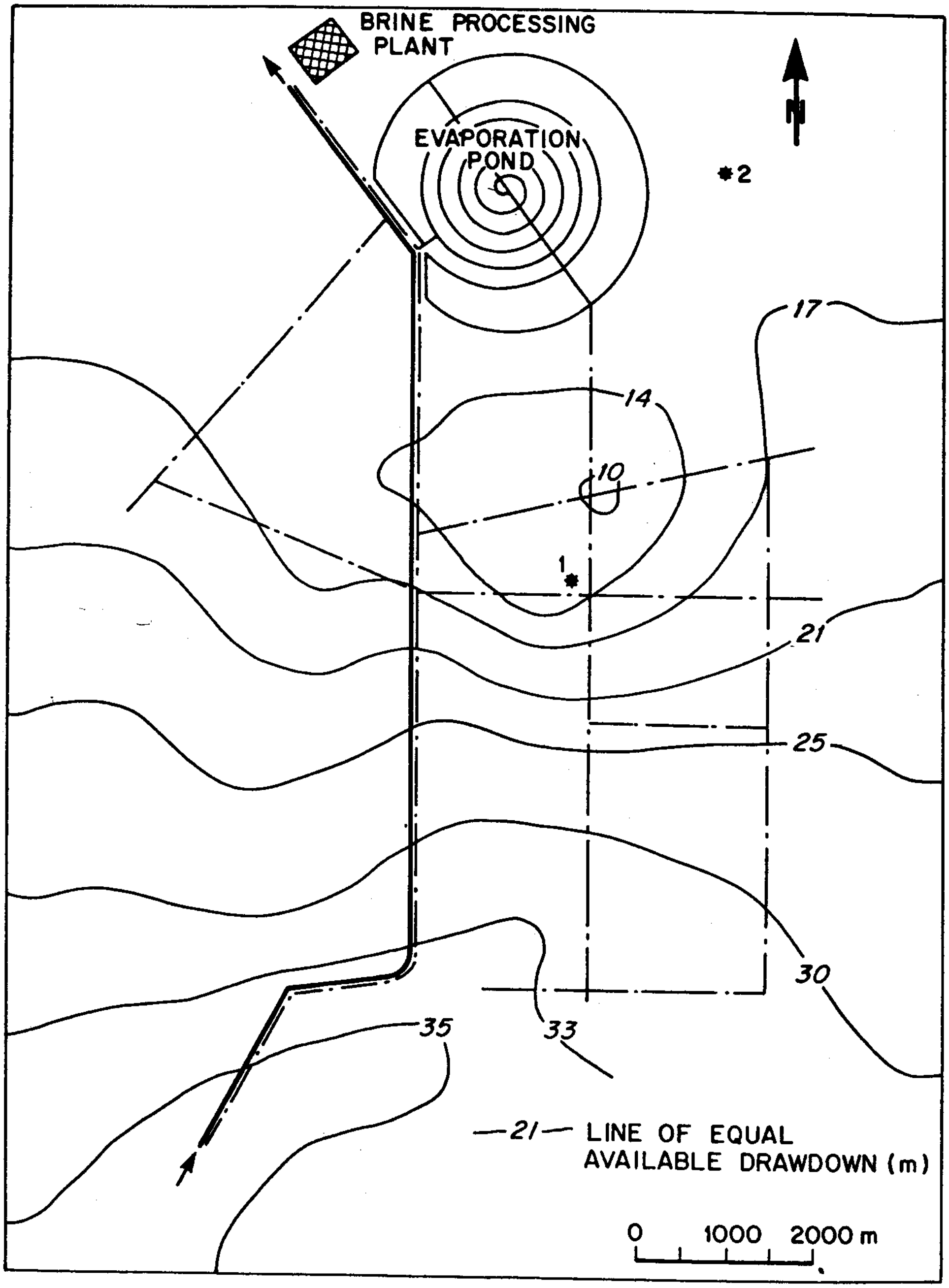

Fig. 10. b) Remaining available drawdown in Aquifer 1.

in some areas. In order to calibrate the transport model, the distribution of total alkalinity in the aquifer in 1977 was selected to be consistent with the target year used in the flow model calibrations. A contour plot of the total alkalinity in 1977 is shown in Figure 11b.

The main parameters controlling solute transport in the aquifer are the velocity field, volume and concentration of the aquitard leakage flux, and the specified boundary conditions. Because the flow field parameters are taken directly from the flow model calculations and the concentrations in the aquitards are based on detailed field measurements, the boundary conditions are the only variables to be determined during calibration.

With very slight local refinements to the boundary concentrations, a very accurate simulation of the 1977 total alkalinity distribution was achieved with the transport model. The results of this simulation are shown in Figure 12a. The transport simulation was also carried out to 1980 but because the 1986 chemical data was not available at the time of the simulations, no further calibration was possible. The 1986 simulation is shown in Figure 12b.

Several observations can be made with respect to the results of the transport modelling. The concentrations in the aquifer remain nearly identical to the concentrations in the aquitards (Figure 11a) after 30 years of pumping even along the lateral boundaries of the flow field. This indicates that the brine extracted by the production wells is most likely derived mainly from the aquitards and that there is very little influence of the inflow of dilute groundwater along the lateral boundaries of the flow domain. This is consistent with the analysis of the flow modelling results. The excellent agreement between the simulated total alkalinity distribution and the field measured values provides further evidence that the behavior of the aquifer system has been adequately represented by the flow and transport models.

As mentioned earlier, brine concentrations in the production wells have begun to drop slightly and this has been particularly evident near the centre of the well field where the extraction has been the highest. The flow and transport modelling has indicated that this decline in concentration can not reasonably be accounted for by dilution from inflow along the lateral boundaries. Even in the 1986 simulation (Figure 12 b) there is no evidence of decreasing brine concentrations anywhere in the well field. Alternatively, pore water concentrations in the surficial aquitard may

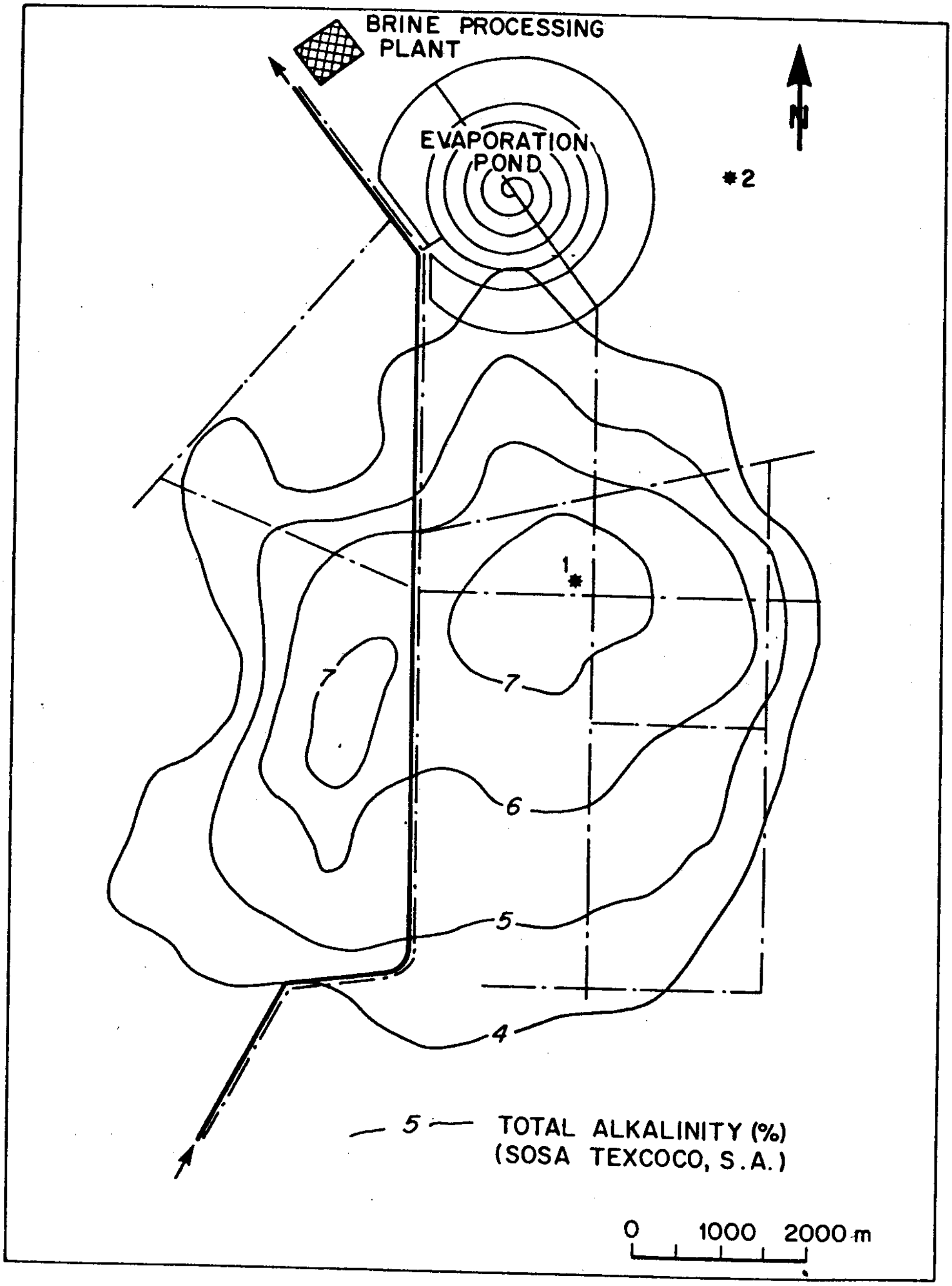

Fig. 11. a) Distribution of total alkalinity in surficial aquitard.

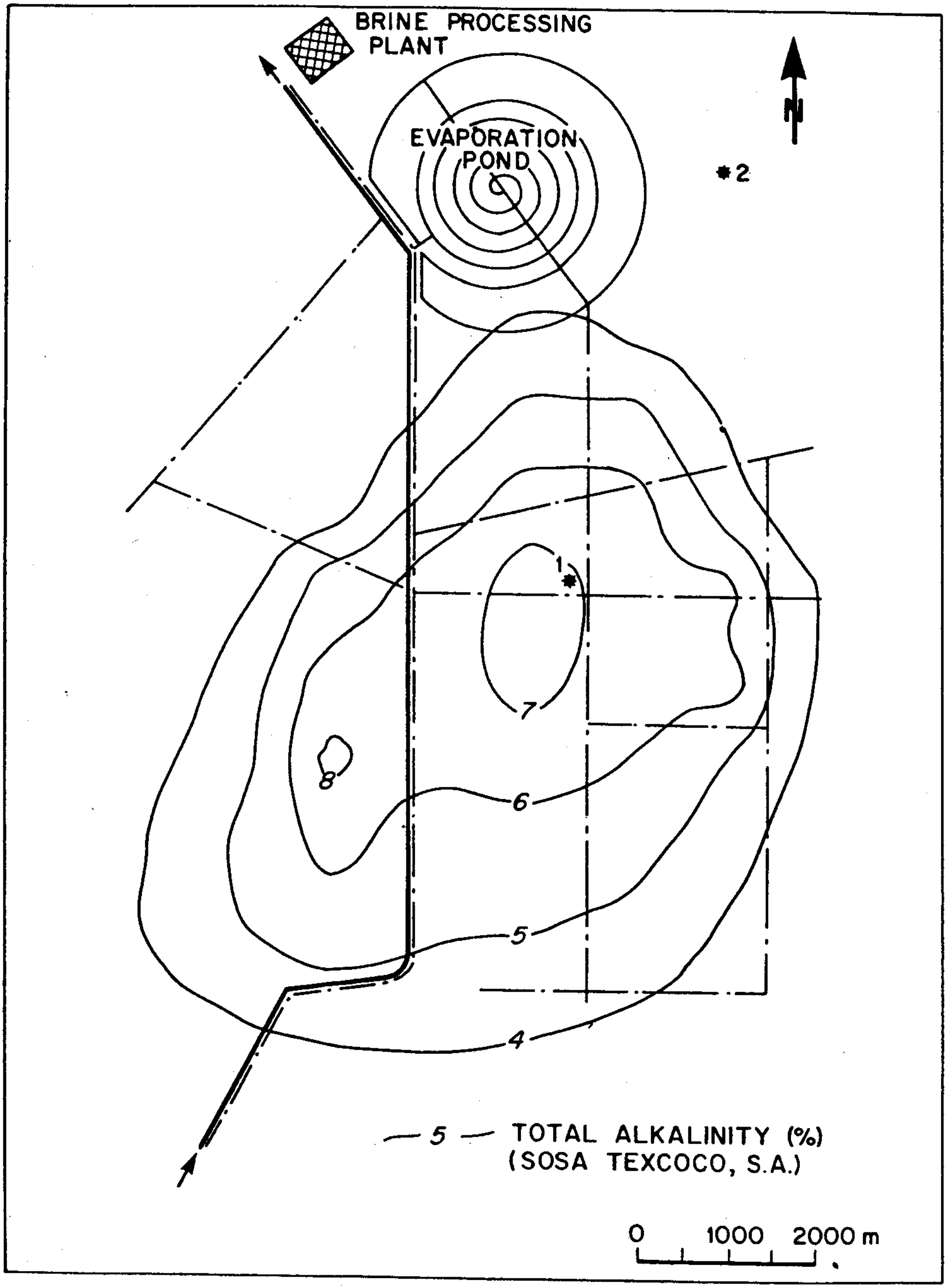

Fig. 11. b) Distribution of total alkalinity in Aquifer 1 in 1977.

be gradually decreasing due to dilution by infiltrating rainfall in which case the assumption of constant concentrations in the aquitard would not be completely valid. In order to investigate the concentration distributions in the aquitard, a series of piezometric nests were installed at several locations throughout the well field. The results of the field investigations are described in the following section.

FIELD INVESTIGATIONS

A field program investigating the hydraulic and hydrochemical characteristics of the lacustrine clays in the area of the Sosa Texcoco well fields was being conducted concurrently with the modelling studies by the University of Waterloo (WCGR). As part of this field study, two nests of piezometers were installed in the surficial clay aquitard to examine the vertical distributions of major ionic species, environmental isotopes, and piezometric levels. These nests consisted of between 10 and 12 individual drive-point piezometers installed at ±2 m intervals from near ground surface to the aquifer-aquitard interface. An example of the piezometer nest configuration is shown in Figure 4. Water samples were collected from each piezometer for chemical and isotopic analyses and once the piezometers had stabilized, water levels were recorded.

The locations of the two nests are shown in relation to the regional drawdown cone in Figure 6 and with respect to the brine concentration in the aquitard in Figure 11a. Site 1 is located in the centre of the drawdown cone in an area of high brine concentration. This section of the well field has been in production continuously since the early 1960's and was assumed representative of an area which has been heavily influenced by pumping. On the other hand, Site 2 is located outside the regional cone of influence in an area of much lower brine concentrations. In this area, there has been very little influence of groundwater extraction and it was anticipated that the vertical ionic profiles would still be representative of the initial conditions which prevailed throughout the Lake Texcoco basin prior to the commencement of pumping.

The piezometric head profiles from both sites are shown in Figure 13. As discussed earlier, very gentle vertical gradients were thought to exist throughout the area initially. At Site 1, strong downward gradients have developed as a result of the extensive pumping in this area and recharging conditions now prevail. At Site 2, however, the vertical gradients are extremely small throughout the entire aquitard indicating very little influence of groundwater extraction.

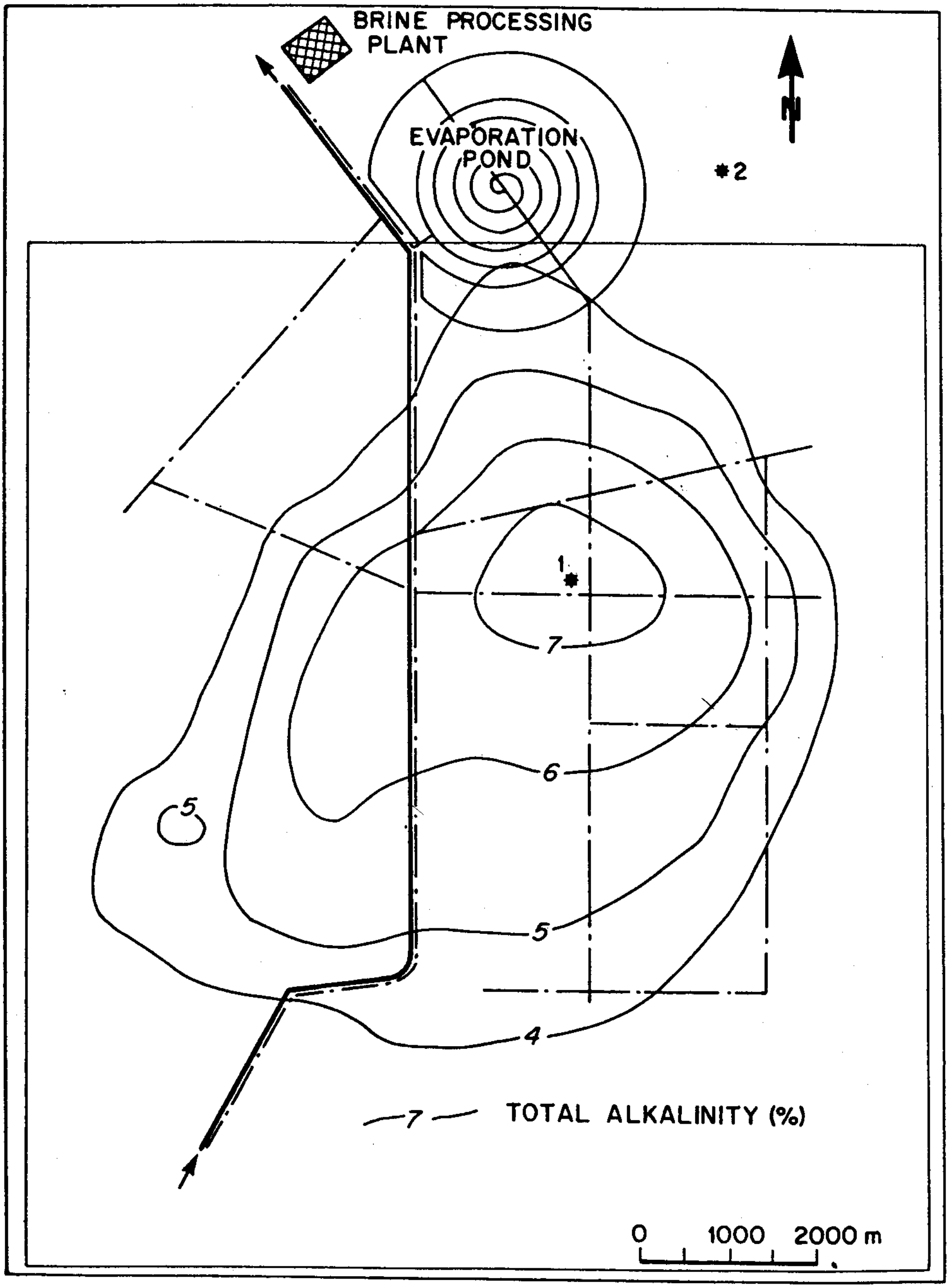

Fig. 12. a) Simulation of total alkalinity in 1977.

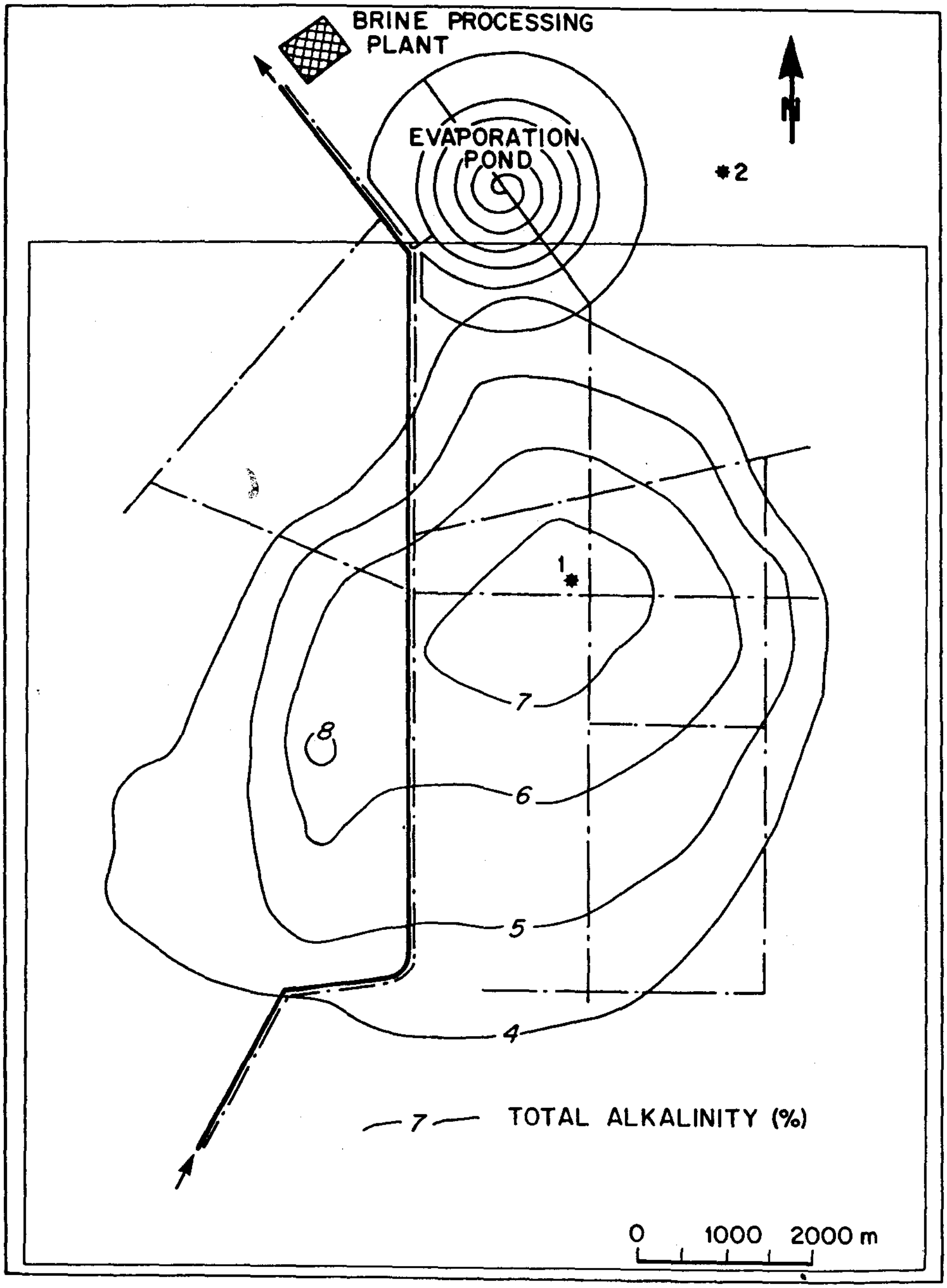

Fig. 12. b) Simulation of total alkalinity in 1986.

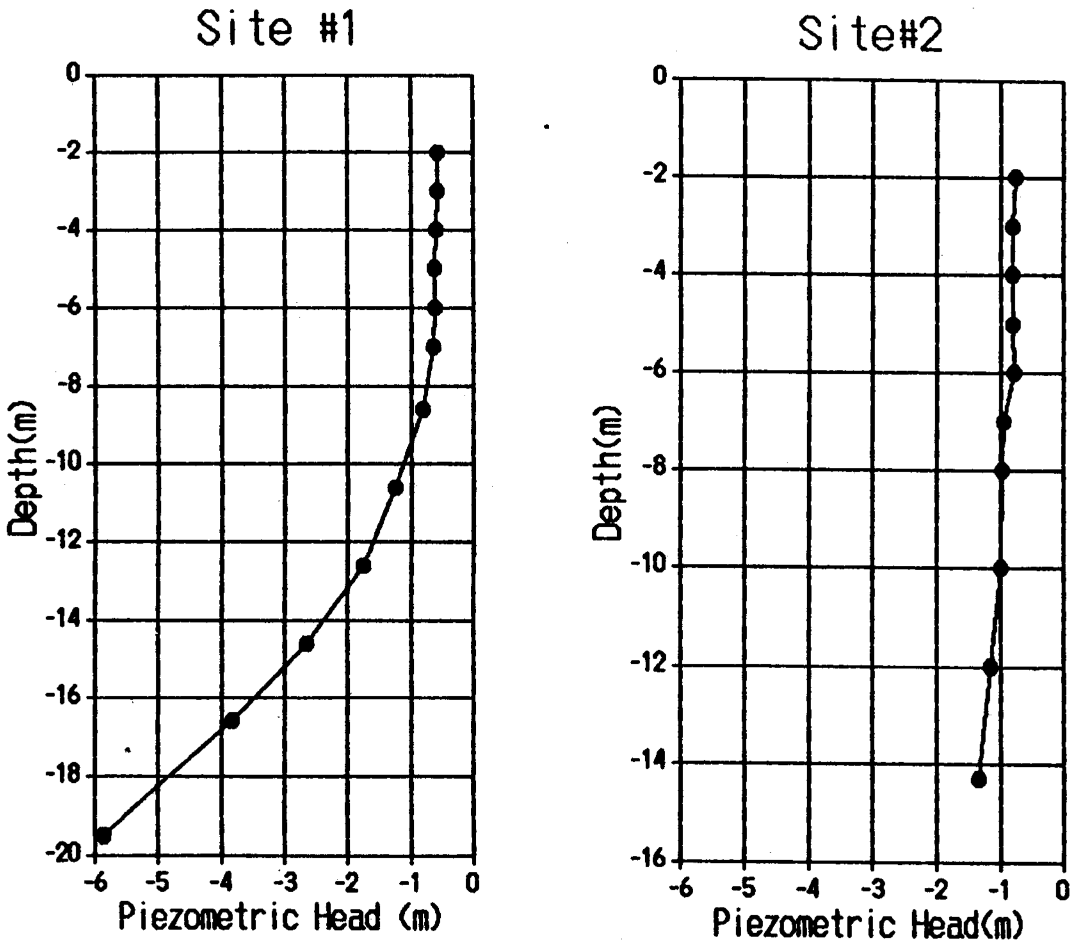

Fig. 13. Piezometric head profiles at Sites 1 and 2.

Figure 14 shows the vertical distributions of Cl^- and oxygen-18 (^{18}O) at Sites 1 and 2. The initial ionic concentration profiles were assumed to have been nearly uniform. The high mineralization in the pore water in this area is thought to be the result of extensive evaporation of surface waters. During evaporation, the heavy isotopes of oxygen (^{18}O) and hydrogen (^{2}H) tend to remain in the water body while the lighter isotopes evaporate away. This results in an enrichment in the heavy isotopes

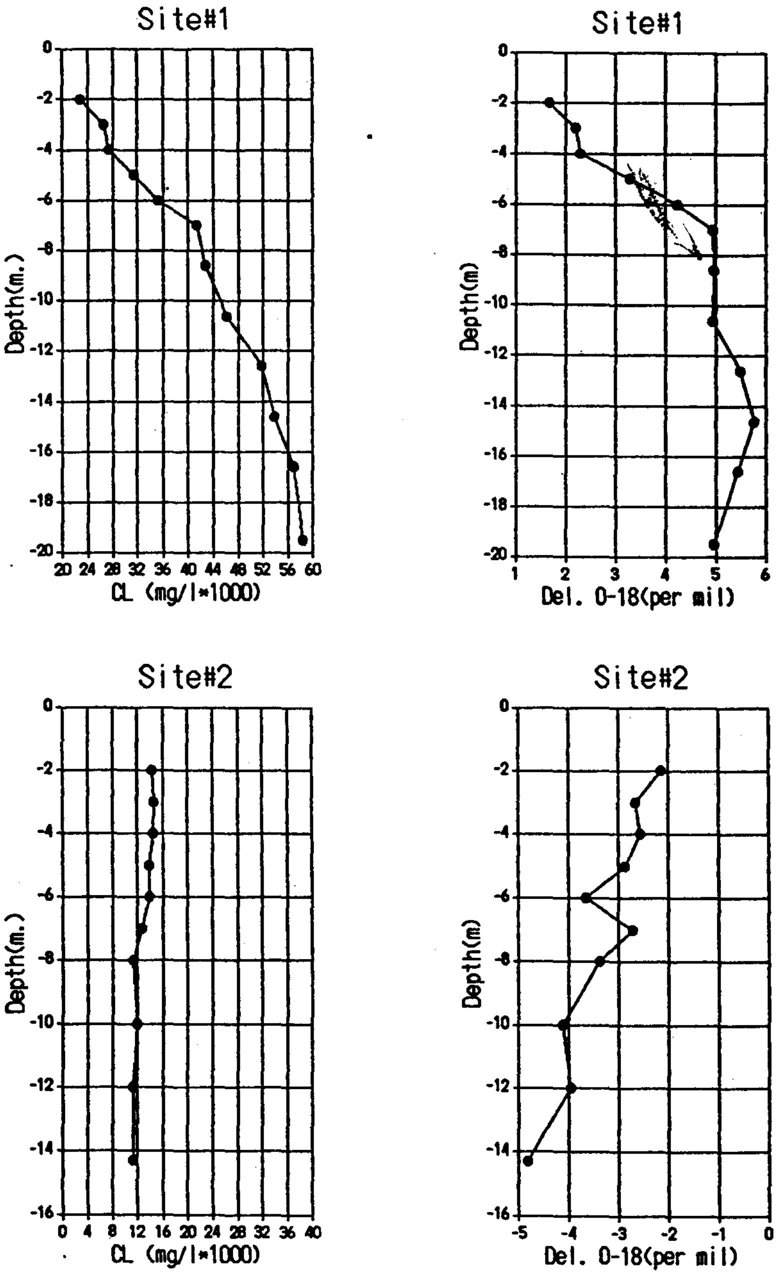

Fig. 14. Vertical profiles of Cl and ^{18}O.

(IAEA, 1983). In general, higher concentrations of ionic species in an evaporating water body are associated with a higher enrichment in heavy isotopes as both are related to the amount of evaporation which has occurred. Meteoric water, however, tends to be depleted in the heavy isotopes. Although no historic isotopic data is available for the aquitard pore water, the assumption can be made that a uniform isotopic composition also existed vertically through the aquitard prior to pumping. These conditions still prevail at Site 2 where infiltration rates are very low. The profiles at Site 1, however, show a distinct decrease in porewater concentration towards ground surface parallelled by a depletion in (^{18}O). This indicates that fresh, isotopically light meteoric waters are infiltrating and diluting the salt concentrations in the surficial aquitard in the area of the Site 1 piezometer nest.

In order to evaluate the infiltration rates and the hydraulic behavior of the clay aquitard, a series of one-dimensional analytical models to the field data at Sites 1 and 2 were applied and calibrated. The clay aquitard was modelled as both a massive, non-fractured porous medium (Ogata, 1970), and as a fractured porous medium (Sudicky and Frind, 1982). Using appropriate hydraulic and mass transport parameters obtained from field measurements and from relevant literature, both models were calibrated to the Site 1 Cl^- profile. The results of the simulations are shown in Figure 15. It is clearly apparent that the massive, non-fractured porous medium model cannot adequately reproduce the observed ionic profile. The fractured porous medium model, however, accurately simulates the field data. The final calibrated simulation shown in Figure 15 is based on a system of parallel fractures spaced a distance of 1.25 m with fracture apertures of 25μ. It can be concluded from these analyses that the fracture network plays an important role in the movement of dissolved species in the surficial aquitard. The flushing of the aquitard by infiltrating meteoric water may account for the gradual decline in brine concentrations in the underlaying aquifer.

CONCLUSIONS AND IMPLICATIONS

Through the evaluation of the historical performance of the well field, local and regional numerical analyses of the groundwater flow system, and field investigations, evidence indicates that the Texcoco aquifer system behaves as a classical *leaky* aquifer system. Due to ±30 years of pumping, a large regional drawdown cone has developed in the uppermost aquifer (Aquifer 1) which reflects the cumulative interference effects of the closely spaced production wells. The results of the groundwater

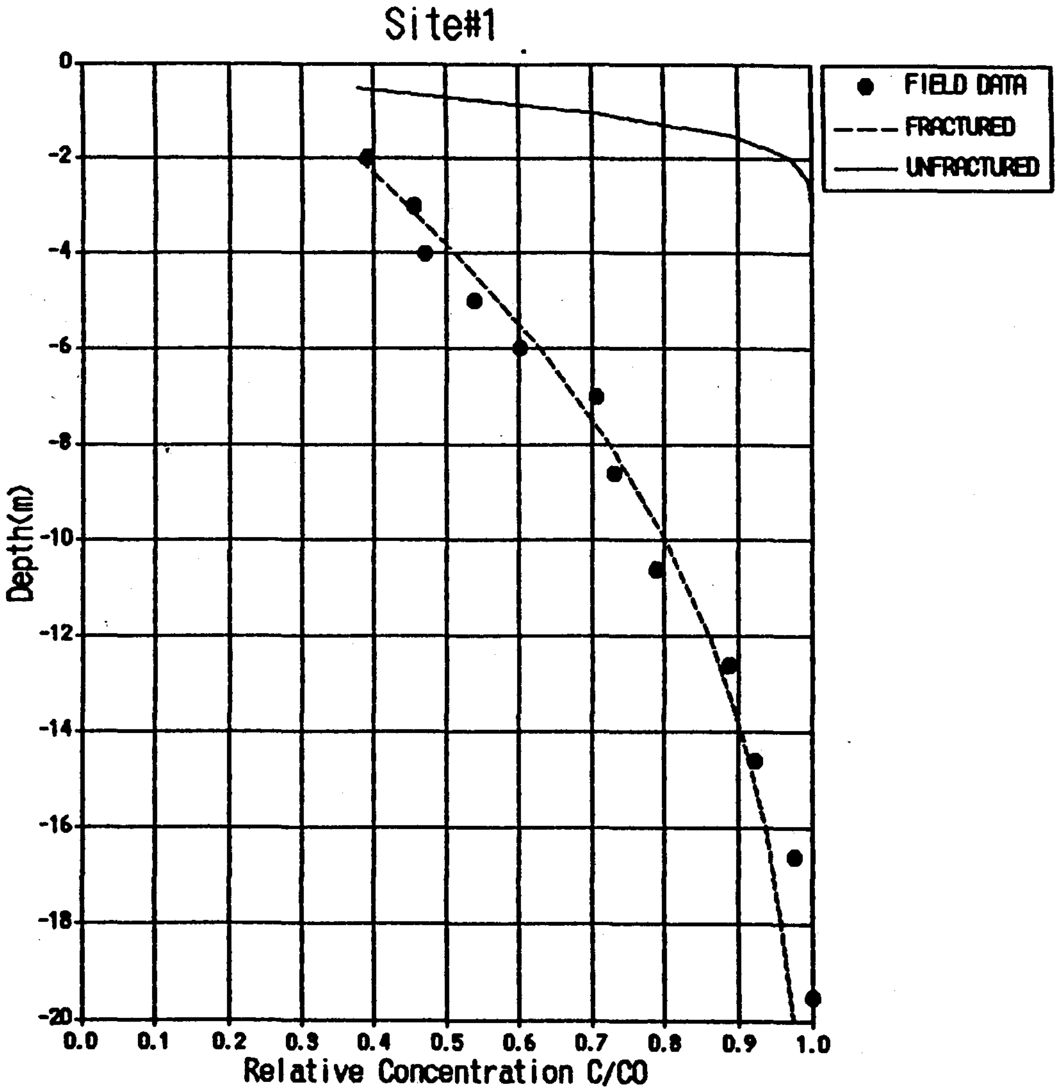

Fig. 15. Simulations of vertical mass transport at Site 1.

flow modelling indicate that this cone of influence has not yet stabilized and that at least part of the aquifer system continues to be in a transient state with respect to flow. The lateral boundaries of the cone, however, are expanding at a very slow rate and numerical analysis indicates that nearly 95% of the water currently being extracted by the production wells, originates as leakage flux from the semi-confining aquitards. Regional inflow accounts for only 5% of the total volume.

The flow and transport models were calibrated to field data and very accurate simulations of both the measured piezometric surface and the distribution of total alkalinity in the well field were achieved. The quasi three-dimensional, integrodifferential equation formulation for the flow simulations and the method of characteristics and particle tracking scheme for the mass transport simulations, proved to be suitable and efficient techniques for the numerical analysis of the Texcoco aquifer system.

The flow modelling results indicate that the excessive drawdowns which have been observed by Sosa Texcoco personnel in several areas of the well field are not due to the hydraulic behavior of the aquifer system but are likely a result of declining well efficiency. This conclusion is also supported by analyses of pump test data. Improvements in well efficiency would improve the production capacity of the affected wells.

The historical records of brine concentrations in the production wells show that throughout most of the life of the well field, concentration levels have remained relatively constant. The solute transport modelling results also substantiate this conclusion. Concentrations in individual wells tend to be very similar to the local concentrations in the adjacent aquitards which suggests that the majority of the extracted fluid is derived from the aquitards. Recent declines in brine concentrations, however, are not justifiable on the basis of dilution by inflow along lateral boundaries. The transport simulations show no evidence of decreasing concentrations anywhere within the flow domain.

The chemical and isotopic analyses of pore water taken from piezometer nests both within and outside of the drawdown cone indicate that in areas where strong downward gradients exist, fresh, meteoric water is infiltrating and diluting the concentrations in the surficial aquitard. In addition, more detailed numerical analysis of the aquitard indicates that the fracture network, reported in the past by many researchers, plays an important role in the transport of dissolved constituents in the clay aquitard. The rate of dilution of the surficial aquitard will depend, therefore, on both the strength of the downward vertical gradients and on the nature of the fracture network locally.

The flow and transport models have been adequately calibrated to the conditions within the Texcoco aquifer system and are now suitable to assist in the evaluation of various extraction scenarios and management strategies to optimize the production of brine from the well fields. Personnel at Sosa Texcoco are currently involved in the planning of both short and long-term goals for the industrial operation and are able to employ the models as investigative tools.

The effects of dilution in the surficial aquitard from the infiltration of rainfall should be studied more extensively as the overall economic life of the well fields are highly dependant on the concentration levels in the aquifer system. Future regional modelling studies should incorporate the effect of the fracture network in the surficial aquitard in order to more realistically represent actual physical conditions in the Texcoco aquifer system.

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