AN EVALUATION OF THE GROUND WATER POTENTIAL OF THE SANA'A BASIN, YEMEN ARAB REPUBLIC

by

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STATEMENT BY AUTHOR

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ABSTRACT

A finite element model was used to estimate the potential of the ground water resource of the Sana'a basin in central Yemen. Input parameter values were obtained primarily from previous reports.

Analysis of the model output indicated that the potential ground water supply in both the Eastern and Western portions of the basin is 0.15×10^6 m^3/day. This amount is adequate to satisfy the needs of the city of Sana'a and its vicinity up to the year 2000, provided that the use of the resource is accompanied by a proper ground water management policy. A maximum of 30 meters drawdown was projected up to the year 2000, considering possible increases in use with time. This amount of drawdown should not endanger ground-water storage. However, any additional increase in ground water use greater than an estimated amount of 0.13×10^6 m^3/day would result in excessive drawdown. This would greatly increase investment and operational costs.

INTRODUCTION

One of the earliest hydraulic civilizations was established in the Kingdom of Saba in what is now the country of Yemen (see Figure 1). The civilization was made possible by the construction of the Mareb dam and associated irrigation works at about 500 B.C., and it reached a peak during the reign of the Queen of Saba. This era was known as "The Yemenite hydraulic civilization" (Caponera, 1973). Additional water-harvesting works were constructed in the region around 100 A.D. to augment the system. However, the Mareb dam was breached in 575 A.D., and the civilization rapidly declined. It is thought that the works were never rebuilt due to climatic change and the associated reduction in surface water flow. Today, the development of surface water is considered economically impractical.

In the last decade, the pressing need to increase agricultural output and satisfy the growing population has greatly accelerated the use of ground water. This situation, along with the introduction of power-driven pumps and the practice of drilling rather than digging wells, has undoubtedly depleted the aquifer. This depletion has been reported in several studies by consulting firms. The reports indicate an extensive over-development of Yemen's ground water supply, particularly in the Sana'a basin. The present study was made to investigate the status of ground water and to improve its development

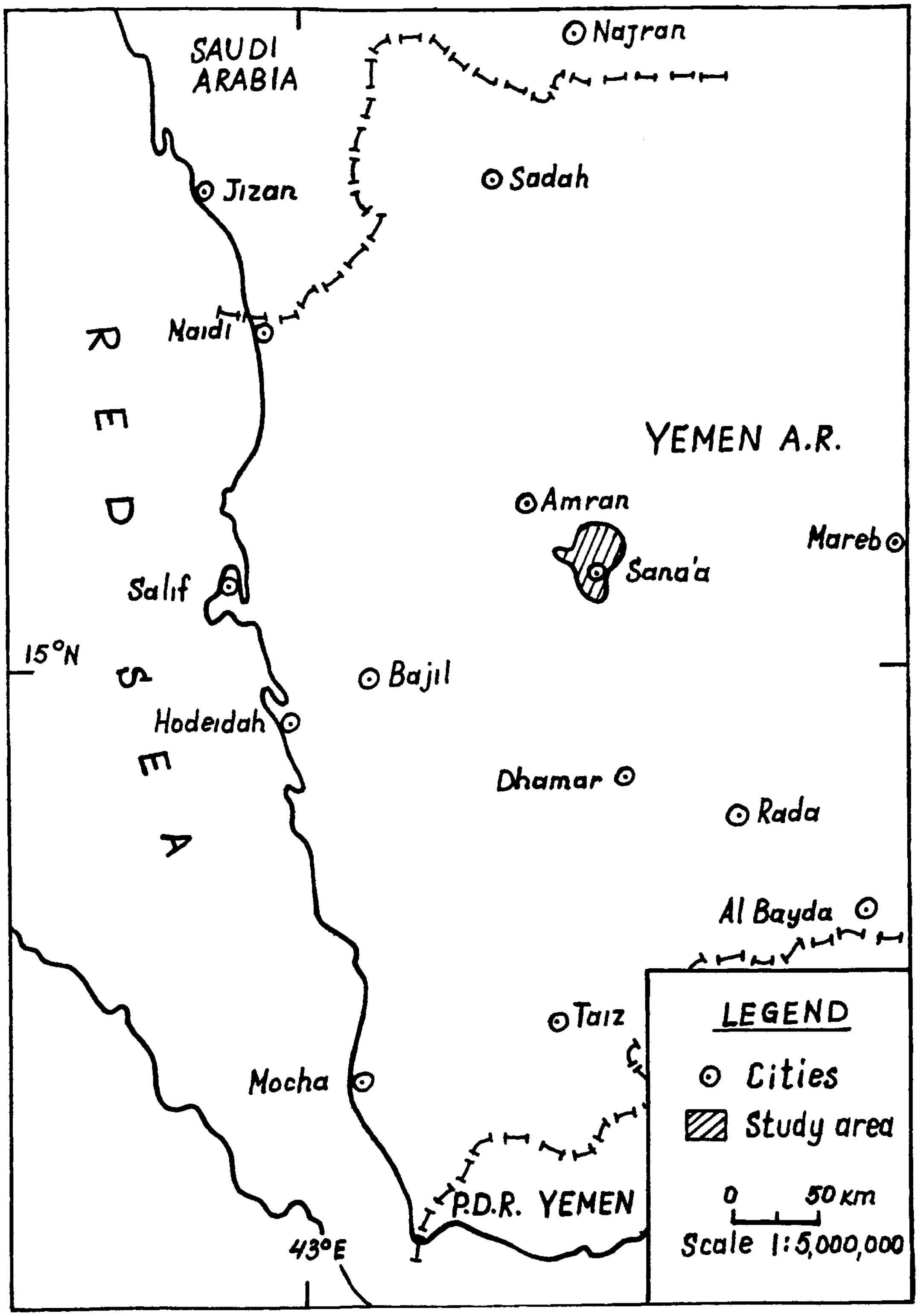

Figure 1. Physiographic Map of the Yemen Arab Republic (after Wagner, 1978).

in the Sana'a basin where the capital city, Sana'a, is located and where ground water withdrawal is rapidly becoming a serious problem.

OBJECTIVES

The primary objectives of this study were:

1. To explore the feasibility of conjunctive use of the Eastern and Western wellfields in the Sana'a basin to determine the effects of ground water use on future water supplies up to the year 2000.
2. To determine how drawdown can be more equitably distributed within the basin.
3. To locate areas of high productivity for future ground water development.

The aim of the study was to develop a preliminary ground water model for the Sana'a basin from the limited data available. Improvements in the output of the model are anticipated as more information becomes available.

SCOPE

The Sana'a basin depends entirely upon ground water. Preliminary hydrogeological studies were begun in the basin in 1965. In 1979, the basin was divided into sub-basins: the Western well field and the Eastern well field. However, only the Western well field was studied. Furthermore, the boundaries between the sub-basins were not precisely defined. In this study, the Western well field covers the entire western portion of the basin including the city of Sana'a. The Eastern well field covers the entire eastern portion of the basin including the town of Rawda (Figure 2). Almost all of the well data used in this study were obtained from the Western well field, and by inference has been extrapolated to the geologic conditions found in the Eastern well field. Much of the data used in the study were obtained by Italconsult (1973), Dar Al Handasah (1980) and Howard Humphreys and Sons (1980).

The Eastern well field was selected for detailed study based on the recommendation of Howard Humphreys and Sons (1980). They concluded that future development of the Western well field would not be worthwhile, firstly because the main aquifer becomes thinner toward the north-northwest and thus less productive, and secondly because the conveyance of water from such a distant source would be uneconomical.

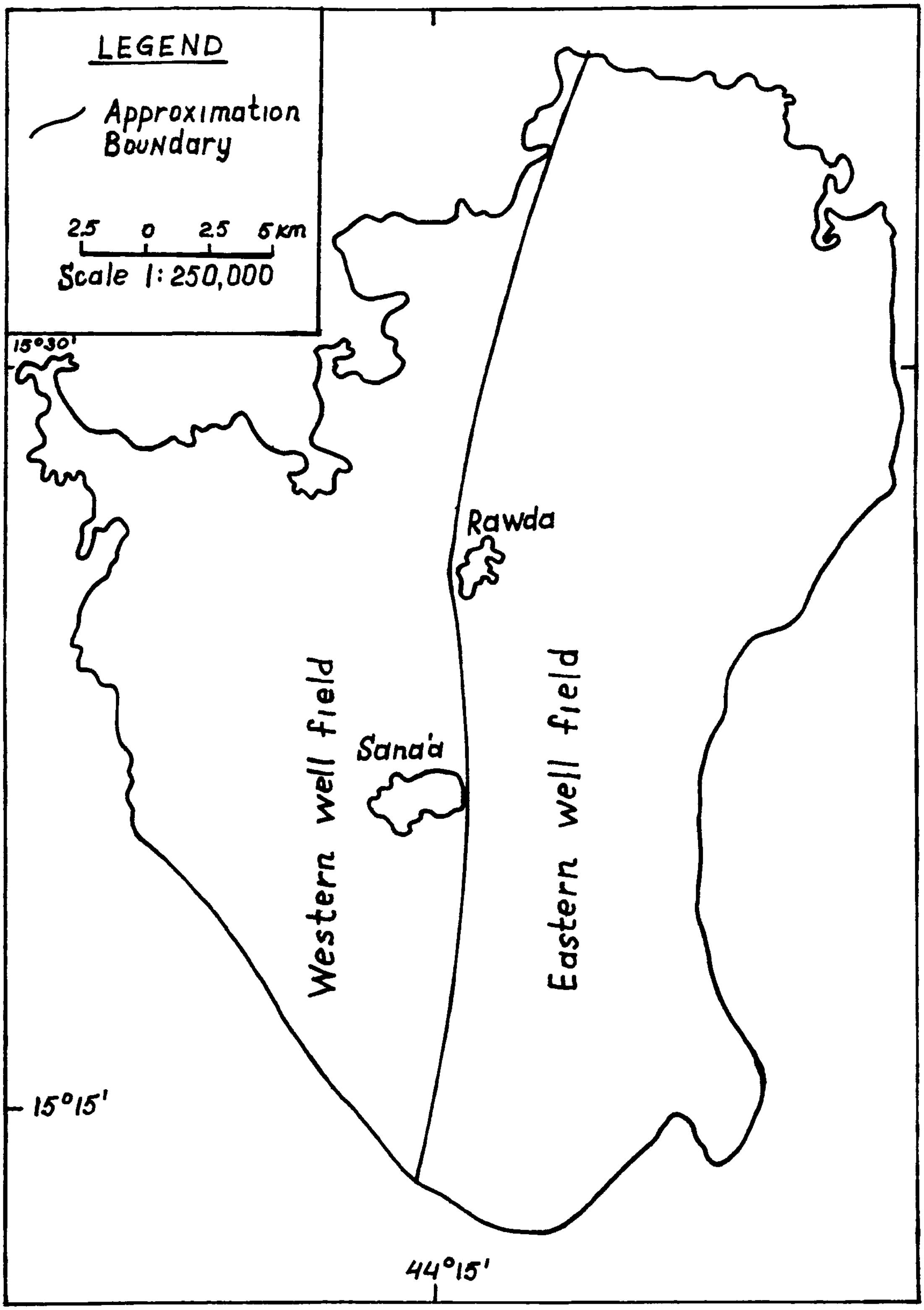

Figure 2. Location of the Eastern and Western Well Fields.

PREVIOUS INVESTIGATIONS

Several ground water investigations have been made in the Sana'a basin by foreign consulting firms, but only to a limited extent. In the late 1960's, American, Chinese, German and Czechoslovakian teams made preliminary surveys, but much of the information now available is incomplete or missing. More extensive studies were made by an Italian firm, the Italconsult, in 1972-73. This study included a geological and geophysical map of the basin. In addition, ten wells were drilled in the basin to depth of 88 to 350 meters, and a hydrogeological map of the basin was made based on the data from the wells.

Between 1970 and 1972, the Iraqi government drilled one well and the West Germans drilled two wells in the basin to depths of 65 to 250 meters. Between 1978 and 1979, Howard Humphreys Consulting Engineers, a British firm, supervised the drilling procedure of 25 wells ranging in depth from 153 to 220 meters. Finally, seven wells were drilled to depths of 200 meters in 1979. The drilling procedures were supervised by Dar Al Handasah Consultants, a Lebanese firm. Out of the total 45 wells drilled in the basin (Table 1), 38 wells were drilled in the Western well field and the rest were drilled in the Eastern well field. The hydrogeological parameters of these 45 wells are presented in Appendix A.

Data used in this study were obtained from geological, geophysical and hydrogeological studies made by the consulting firms.

Table 1. Wells Drilled by Various Agencies and Their Locations.

Location	Borehole Number	Year Drilled	Supervising Body
Western Well Field	GW1 GW2	1970/72	West German firm
	ST1 ST4 ST5 ST6 ST7	1972	Italconsult
	ST8 ST9 ST10 ST10A ST11 ST12 ST13	1979	Dar Al Handasah
	P1 P6 P7 P8 P9 P10 P13 P14 P15 P16 P17 P18 P19 P20 P21	1973/79	Howard Humphreys and Partners
	SE1 SE2 SE6 SE7 SE9	1972	Italconsult

Table 1. -- Continued

Location	Borehole Number	Year Drilled	Supervising Body
	02	1978/79	Howard Humphreys
	03		
	04		
	05		
	011		
	012		
Easter Well Field	I.W.	1970-72	Iraqi firm
	ST2	1972	Italconsult
	ST3		
	EX1	1979	Howard Humphreys
	EX2		
	EX3		
	EX4		

DESCRIPTION OF STUDY AREA

Location and Description

Sana'a basin is a plateau surrounded by a chain of mountains to form the Sana'a plain with an area about 1500 km^2. The elevation of the central plain ranges from 2,200 to 2,350 meters above mean sea level (m.a.m.s.l.), while the highest portions have an elevation of 3,000 meters. Numerous agricultural terraces have been constructed in the area and have important effects in regulating and distributing the recharge effect of floods. The basin is divided into southern, central, western, and northern portions based on the main watershed catchment areas (Figure 3).

Climate

The basin has hot to moderate summers and cold winters. Ital-consult (1973) reported that the average summer temperature is 28.5^{o}C and the average winter temperature is 18^{o}C. Snowfall is very rare. Evaporation rates overall are about 6 mm/day. Mean daily wind speed is about 175 km/day in winter and 225 km/day in summer.

The rainfall pattern is bi-seasonal, consisting of a spring season of April and May, and a summer season of July and August. More than three-fourths of the 300 to 325 mm total annual rainfall occurs in these seasons. For the rest of the year, precipitation is very low with only a few light showers and occasional moderate storms.

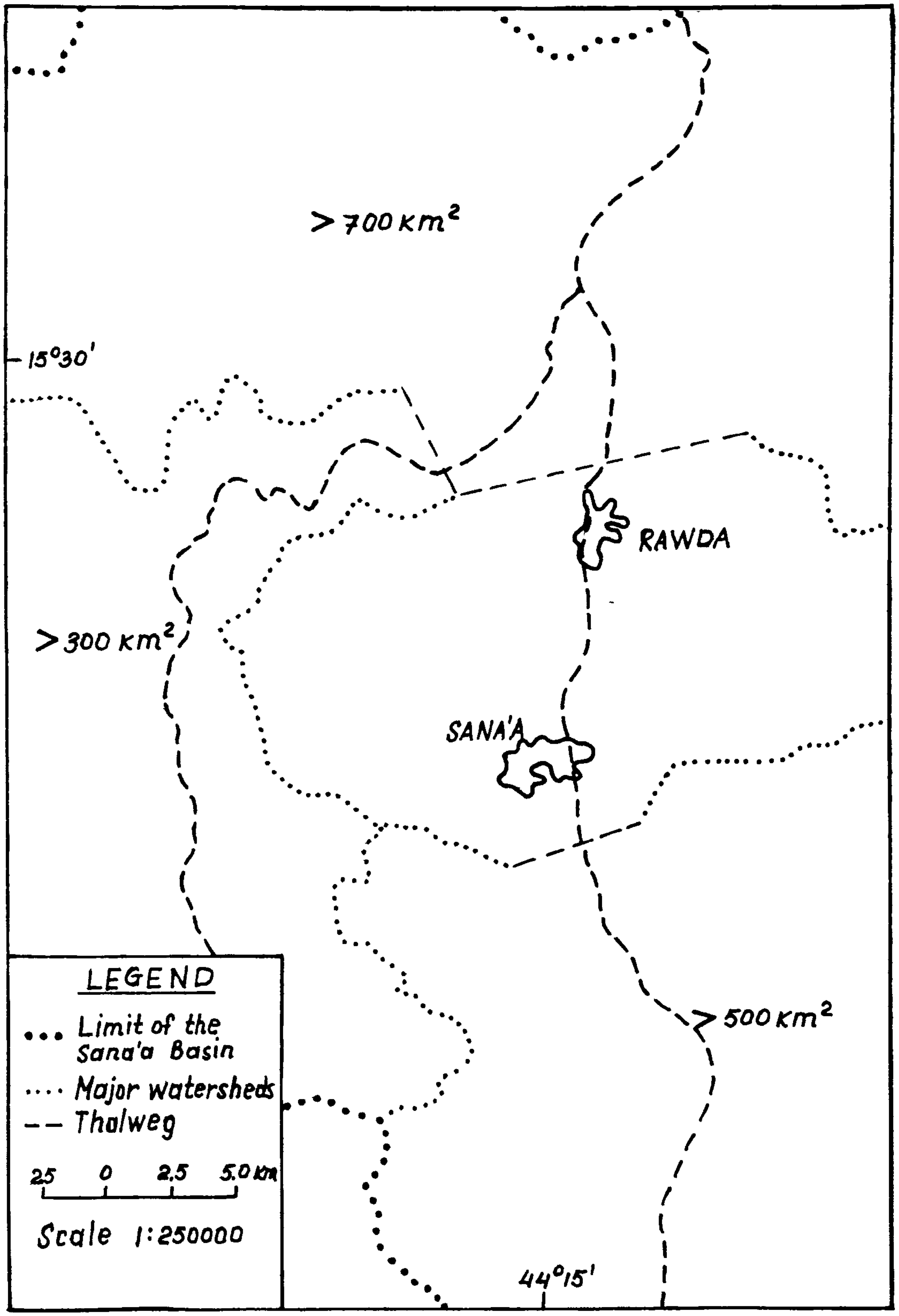

Figure 3. Catchment Areas in the Sana'a Basin (after Italconsult, 1973).

The runoff in the study area is low, particularly from the terraced areas. Runoff generated on unprotected slopes quickly reaches stream channels and is usually diverted to wadi side terraces. Major floods may be capable of saturating the available soil storage and proceed as a sheet flow before draining back into the lower channels where some recharge may occur. Therefore, surface runoff is not an exploitable resource and at best makes some contributions to the alluvial aquifers. However, along the wadis these aquifers are already being efficiently exploited by local farmers.

Geology

Stratigraphy

The stratigraphy of the basin ranges from Jurassic to Quaternary (Figure 4). The main geological sequences are described below (Geukens, 1966; Italconsult, 1973).

Jurassic Amran Formation. This formation outcrops in the northern outer boundary of the study area, and consists of limestone, argillaceous limestone and some calcareous shale with interbedding of marine material. The formation is about 350 meters thick and it has poor water-bearing properties (Wagner, 1978; Tibbits, 1980). The formation is underlain by the Jurassic Kohlan sandstone formation with a good ground water potential and can be reached at depths between 300 to 700 meters.

Cretaceous Tawilah Formation. This formation consists of fine- to coarse-grained sandstone cross-bedded with layers of claystone and ironstone. The thickness of the formation is about 370 meters and

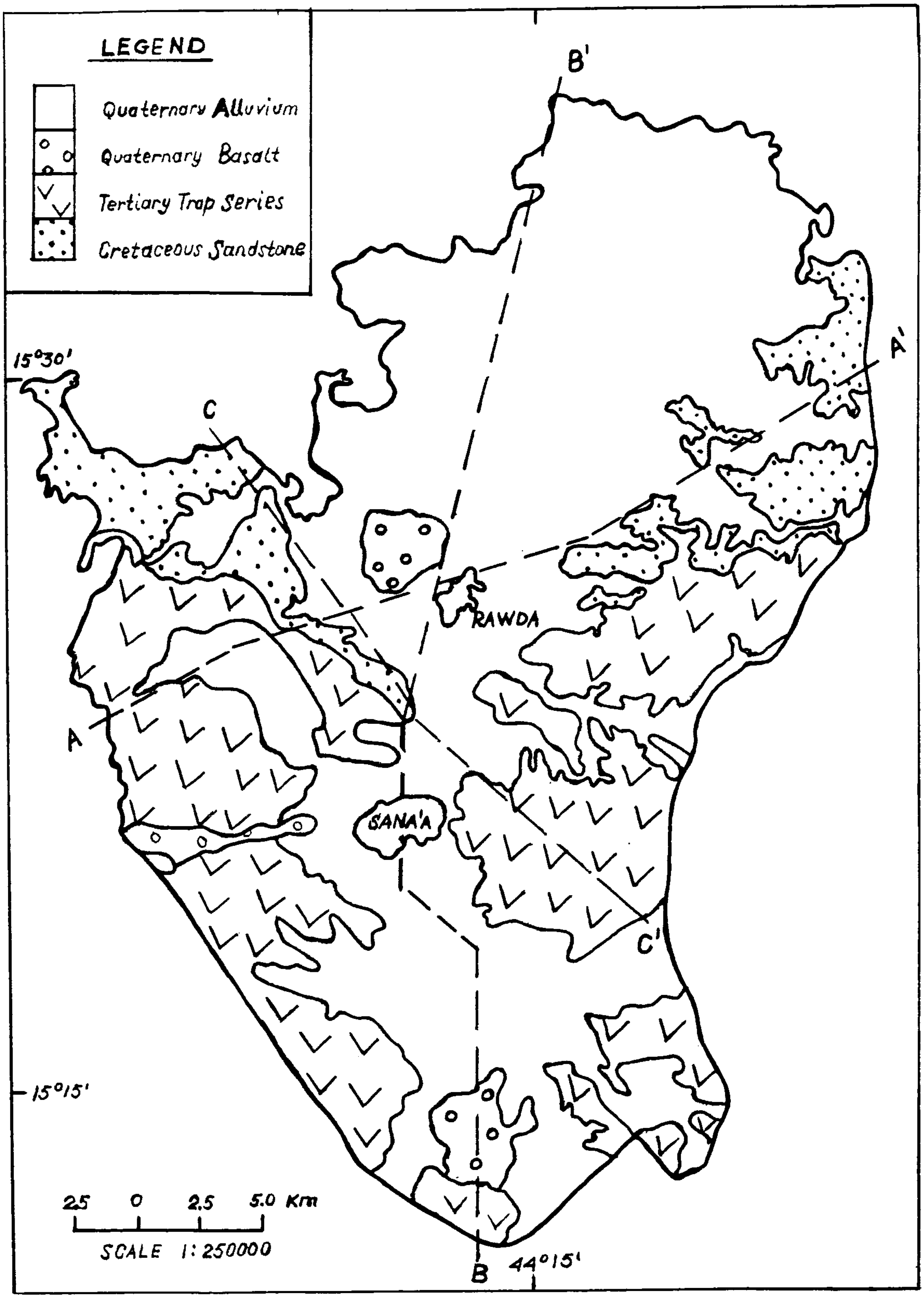

Figure 4. Simplified Geological Map of the Sana'a Basin (after Italconsult, 1973).

outcrops along the northwestern and northeastern part of the study area. Fracturing is a peculiarity of this formation. Some major fractures are occupied by basalt dikes. The Tawilah formation is the most important ground water reservoir in the basin.

Quaternary Formation. The quaternary alluvial formation, which is widely spread in the Sana'a basin, consists of silty, sandy gravel with occasional boulders. The thickness of this formation varies from less than ten meters in the southern part to over 300 meters in the north. The water-bearing property of this formaton is low, particularly in areas of high clay content.

Quaternary Basalts. The quaternary basalts, which are composed of basalt, augite basalt, nepheline basalt and basalt tuffs are widely spread in the western and northwestern outer boundary of the study area. The thickness of these basalts has been estimated at several hundred meters. Even though little is known about the water-bearing properties of the quaternary basalts, it is believed that their good water-bearing properties are limited to the fractured zones.

Structural Geology

Fracturing in the formation is the most important structural phenomenon, especially from a hydrogeological aspect. Italconsult (1973) demonstrated that fractures are distributed in a nonuniform manner and their high density indicates zones of greater weakness and tension. The zones most fractured are those where the cretaceous sandstones outcrop in the northwest to Dahban to Wadi Dahr and also farther north.

Geophysics

Italconsult (1973) conducted 228 electrical soundings (ES) by the four-electrode Schlumberger method in the southern half of the basin and in portions of the northern area. From the calibration ES's run-on outcrops and from boreholes with known logs, it was possible to establish scales of resistivities (Table 2). This study showed that the thickness of the alluvial deposits ranges between 100 and 150 meters in the south, 160 and 200 meters beneath Sana'a and 350 and 400 meters north of Sana'a. The low resistivity of this layer, particularly toward the north, probably indicates low permeability in this direction. Very resistive Quaternary Basalt flows having a thickness of not more than 100 meters locally overlie the conductive alluvium.

The sides of the valley were formed in the north by resistive cretacous sandstones whose thickness, on the basis of the electrical soundings, varied from about 100 to about 350 meters. These sandstones appear to plunge rapidly to depths greater than 300 meters starting from the north of Sana'a. In the southern area, medium-resistivity tuffs of the Trap series generally prevail down to 300-500 meters. For more detailed geophysical study, see "Water supply for Sana'a and Hodeida," Italconsult (1973).

Hydrogeology

Previous studies made in the basin indicates that from a regional aspect, the various aquifers in the basin down to Cretaceous sandstones do not constitute hydraulic barriers, due to the fractured

Table 2. Scale of Resistivities of Various Formations (adapted from Italconsult, 1973).

Electrical Medium	Resistivity of Medium (ohm m)	Probable Geological Formation
Cover		
Highly resistive layer	200–2,000	Quaternary basalts
Resistive layer	30–150	Dry sandy alluvium
Conductive layer	5–12	Moist or saturated clayey "alluvium"
Bedrock		
Upper medium resistivity complex	30–50	Trap series (mainly tuffs) of locally clays overlying the sandstones
Resistive complex	100–500	Sandstones of layers of lava belonging to the Trap series
Lower medium resistivity layer	30–80	Limestones

nature of the bedrock formations. These fractures traverse the stratigraphic boundaries, making them permeable. Perched groundwater bodies, generally of limited extent, are found. However, Italconsult (1973) mentioned that these water bodies rest on aquitards rather than on real aquicludes.

On the basis of the hydrogeological mapping and drilling operations, the following geohydrological units have been identified:

1. Cretaceous Sandstone
2. Trap Basal Basalt
3. Quaternary Valley-fill
4. Quaternary Basalt

The hydrogeological cross-sections of these units are shown in Figures 5, 6, 7 and 8.

Cretaceous Sandstone

This geohydrological unit includes the Tawilah and Mejd-zir formations, which are hydraulically inseparable. The outcropping of the sandstone aquifer mainly refers to unconfined conditions, while leaky artesian conditions occur where the sandstone is covered by other formations, particularly the Trap series. The sandstone aquifer is the most productive aquifer in the study area, and about 90 percent of the wells are drilled in this aquifer. This aquifer is characterized by both primary and secondary permeability. The depth to water in this aquifer is a function of altitude and hydraulic gradients. It varies from a minimum of 35 meters in the lower-lying areas to more than 110 meters on the highlands of the plateau surrounding the Sana'a basin.

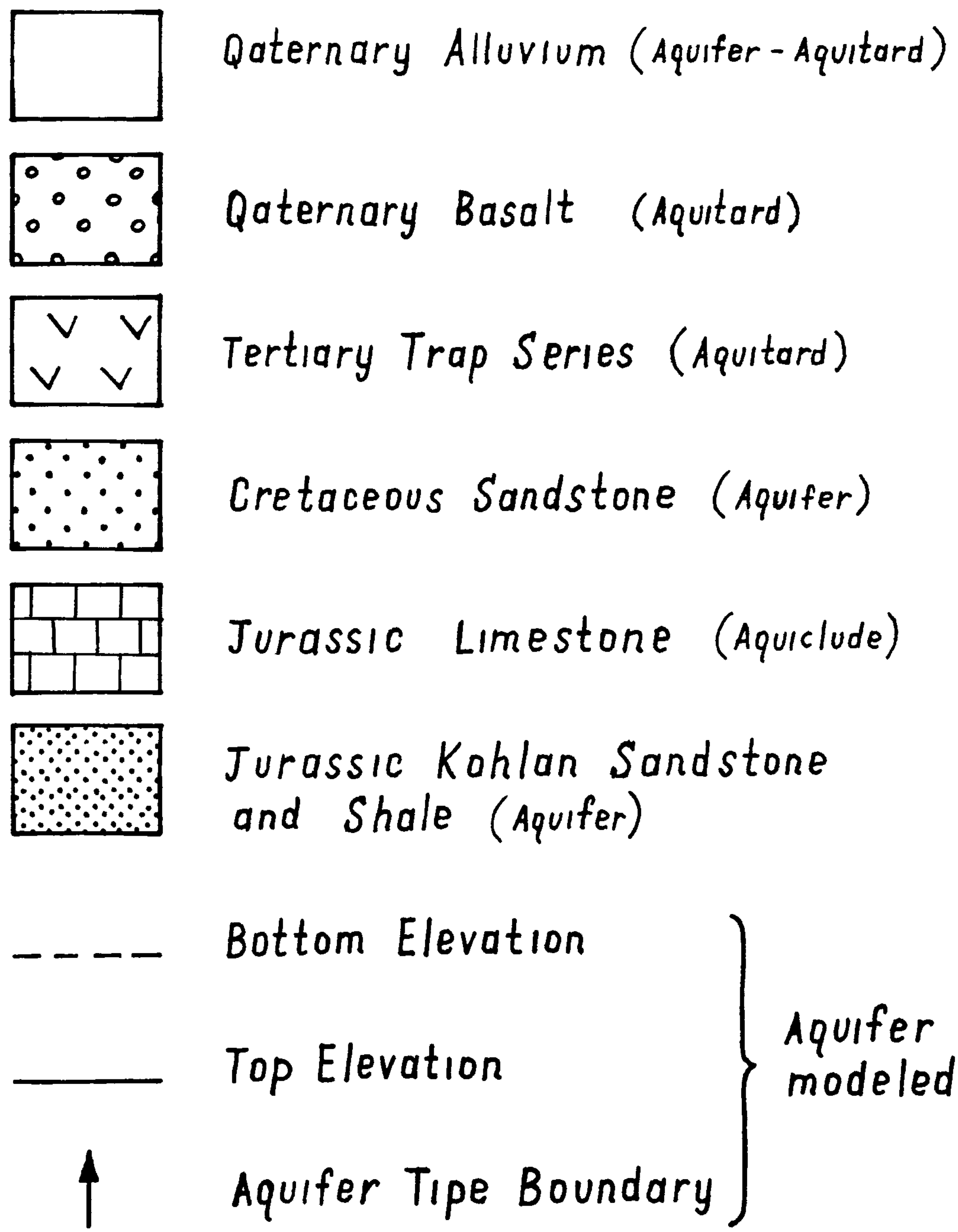

Figure 5. Legend for Hydrogeological Cross-Sections.

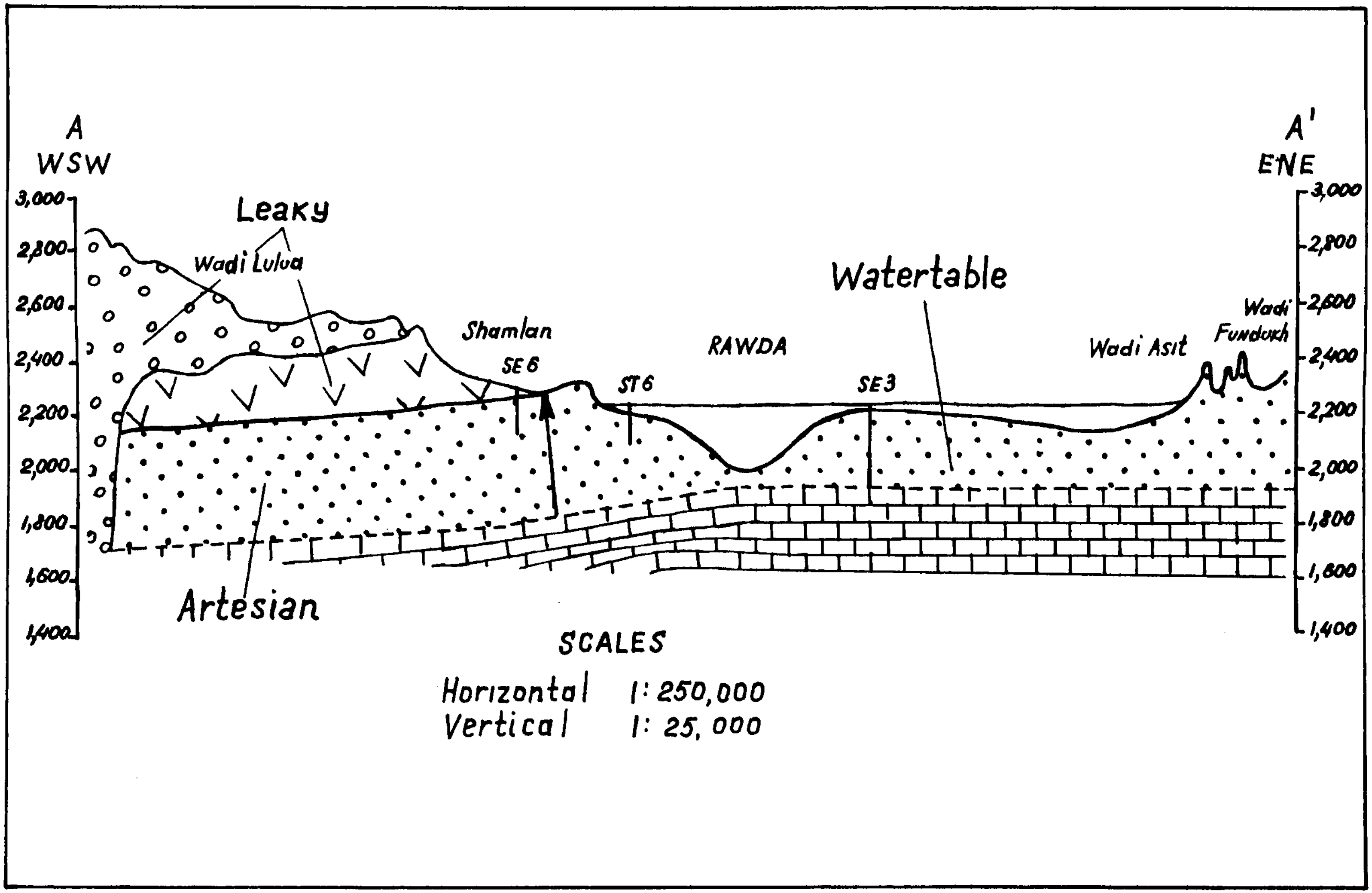

Figure 6. Hydrogeological Cross-Section Across the Sana'a Basin, Along Line A-A' (after Italconsult, 1973).

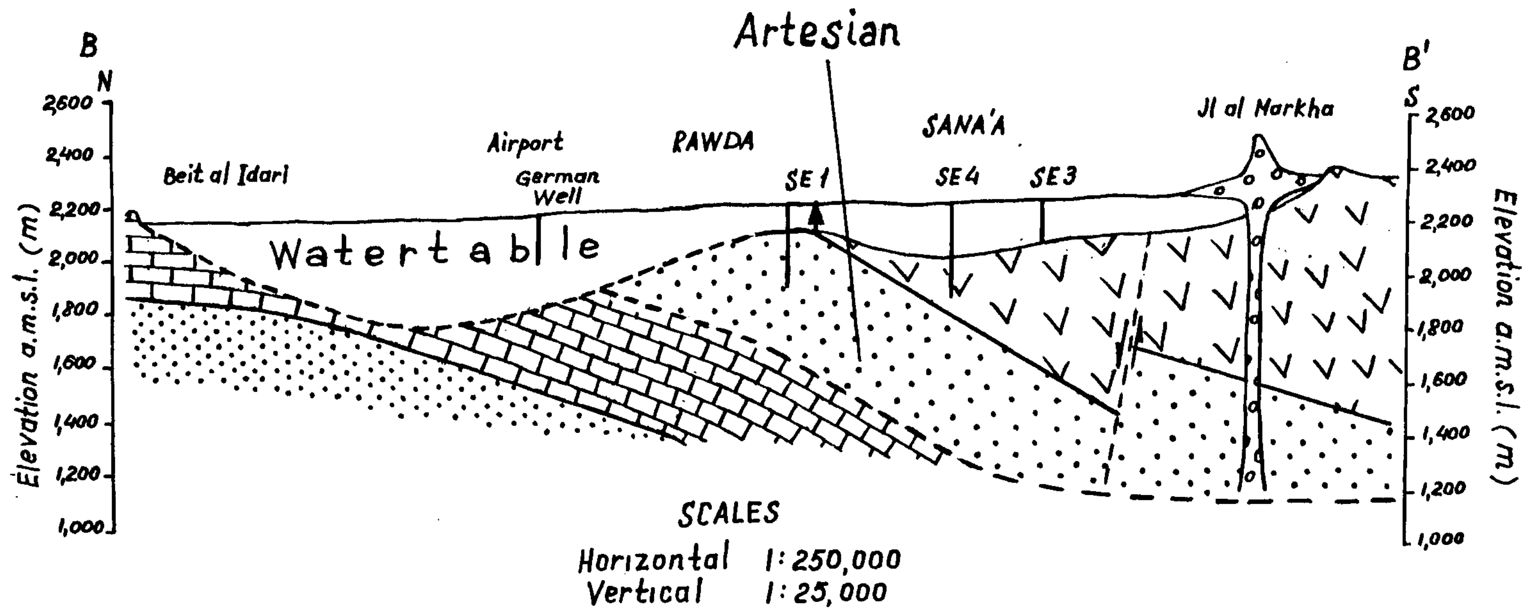

Figure 7. Hydrogeological Cross-Section Across the Sana'a Basin, Along Line B-B'
(after Italconsult, 1973).

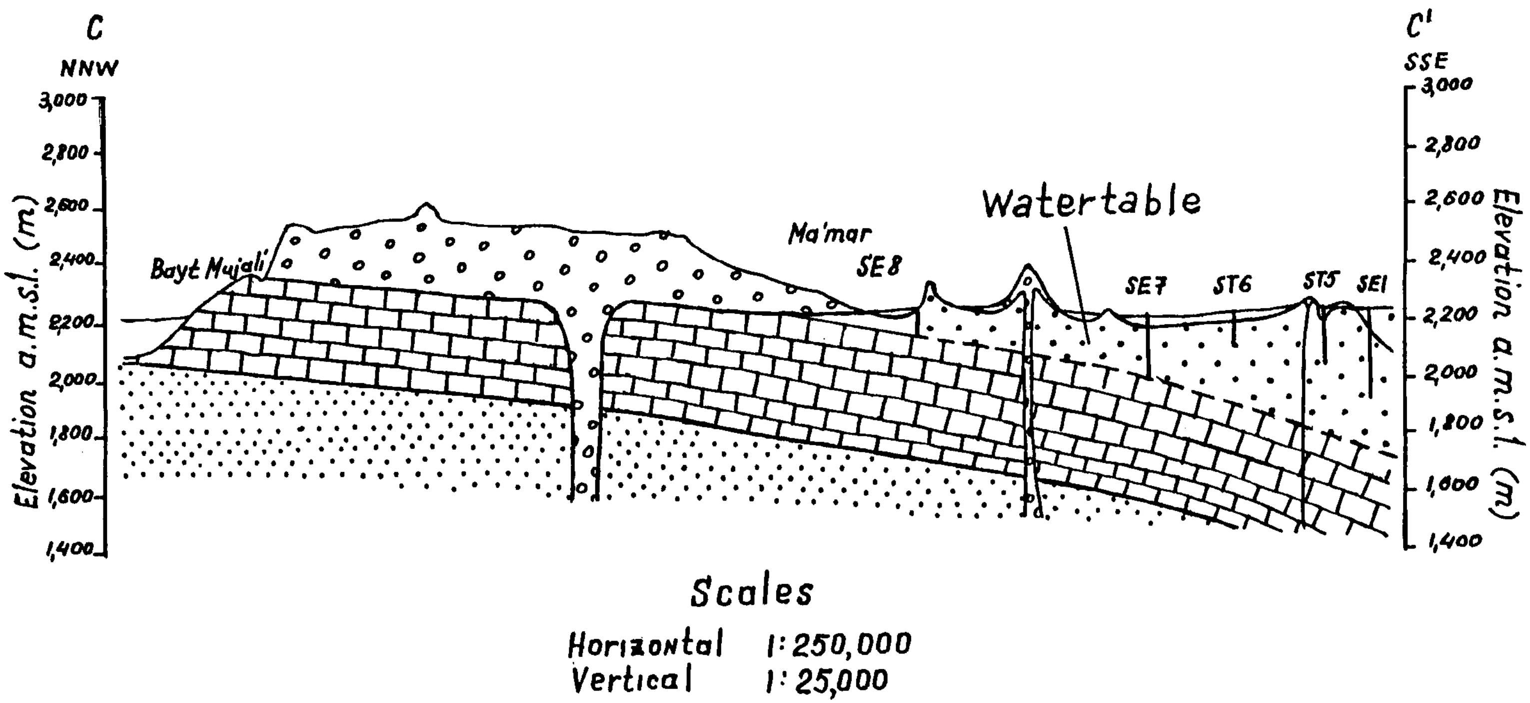

Figure 8. Hydrogeological Cross-Section Across the Sana'a Basin, Along Line C-C'
(after Italconsult, 1973).

Trap Basal Basalt

This geohydrological unit consists of the basal basalt of the Trap series. The thickness of saturated aquifer ranges between a few meters to over 300 meters (Italconsult, 1973). Water table conditions are found in the outcrop areas. Under the cover of Quaternary sediments, leaky artesian conditions are generally assumed. The water-bearing characteristics of this aquifer is governed by fractures, but due to the small openings of the fractures the hydraulic conductivity is low.

Quaternary Alluvium

This geohydrological unit is located in the central part of the basin where water table conditions are dominant. Thickness of the alluvium varies from a few meters in the south to over 300 meters in the north.

Italconsult (1973) and Howard Humphreys (1980) mentioned that this aquifer does not represent a geohydrological unit by itself; instead, it receives ground water from the underlying bedrock aquifer or gives water to other aquifers depending on the vertical gradient. The depth to water increases northward. The depth is less than 15 meters in the south, while in the central and northern parts it varies between 40 and 52 meters. Due to the shallow water table, this aquifer is tapped by a large number of hand-dug wells. The hydraulic conductivity of the aquifer is low.

Quaternary Basalts

This basalt consists of superposed lava flows which may total several hundred meters in thickness. In the northwestern part of the study area, the basalts lie over Amran limestone while in the southeastern part they lie on the Cretaceous sandstones and Trap Basal Basalt, depending on the trend of the original ground surface onto which the lavas were extruded. Little is known about the permeability of the aquifer.

Ground-Water Recharge

Little is known of the rainfall patterns within the ground water catchment basement, and in view of the subsurface interconnection between the various aquifers, the effect of the amount and intensity of rainfall in potential recharge areas is not exactly known.

Italconsult (1973) mentioned that the recharge of the aquifer system is considerable, and that the main direction of flow can be inferred. However, they did not attempt to separate vertical from lateral inflow. Howard Humphreys and Sons (1980) indicated that the bulk of ground-water replenishment into the basin is derived from lateral movement of ground water from a recharge area lying west and southwest of the basin, primarily in the areas of Madbah, Shamlan, Dahr and beyond.

At present, it is not possible to quantify recharge by conventional rainfall/infiltration techniques owing to uncertainties regarding the exact extent of the recharge area, the proportion of rainfall percolating into the aquifer, and general lack of long-term meteorological and water-level data. Therefore, further studies are required before recharge can be meaningfully assessed by conventional techniques. Generally, it is considered that most of the vertical inflow takes place in the Wadi systems, especially where the alluvial cover is thin and where the volcanic cover is fractured.

By comparing the ground water flow values with the available long-term data on rainfall, Italconsult (1973) concluded that about three percent of the 300 mm average annual rainfall infiltrates into the aquifer. Therefore, the vertical inflow would be 2.5×10^{-5} m/day. This value was used in of this study.

METHODS

Previous hydrogeological investigations were concerned mainly with the Western well field. However, this study was aimed at evaluating the ground water potential of both the Western and Eastern well fields as a whole to determine the reliability of ground water supplies for future use by the capital city, Sana'a and its vicinity.

A two-dimensional finite element model was used in the study. The input data included X and Y nodal coordinates, aquifer thickness, hydraulic conductivity, porosity, well field design, pumping rate distribution, and initial and boundary conditions. The general characteristics of the model and methods of obtaining input data for the model are discussed below.

Finite Element Model

General Characteristics

A number of numerical models have been developed to predict different hydrological characteristics of ground water flow. These models can simulate steady or unsteady conditions in confined (with or without leakage) or unconfined aquifers. The Basin model used in this study was developed by Contractor (1981). Contractor originally developed this model to simulate saltwater intrusion into coastal and insular aquifers. The model has a number of advantages.

1. Several types of boundary conditions can be accommodated.

2. Fresh water and salt water heads can be specified as functions of time at any number of nodes.
3. Fresh water and salt water flows can be specified between any pair of boundary nodes.
4. Any number of pumps can be accommodated in the network. Recharge is constant in an element but can be varied from element to element. Specified head or flow conditions can be applied at the boundaries.
5. The model uses linear triangular elements and the Galerkin Weighted Residual Method for deriving the element equation.

Contractor (1981) demonstrated the accuracy of the model by applying it to different flow situations for which analytical solutions were available. Furthermore, the model has been applied to several natural aquifers with complex geometry, basement topography and boundary conditions. It was used in this study to evaluate the development of ground water in the Sana'a basin using the limited data available from the area. The model was adapted to simulate fresh water aquifers by specifying the salt water head at all nodes to be much lower than the expected fresh water head.

The element equation for fresh water flow is given by:

$$\partial/\partial x(k_x^f b^f(\partial\phi^f/\partial x))+\partial/\partial y(K_y^f b^f(\partial\phi^f/\partial y))+N-q_p^f+K_o/B_o(\phi^f-\phi_o) =$$

$$-1/3\{1/2(b_t^f+b_{t+\Delta t}^f)\}[K_{ij}^f](1-\theta)\{\phi_t^f\}-NA/3\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix} - Q_P/n_e\begin{bmatrix}1&0&0\\0&0&0\\0&0&0\end{bmatrix}$$

$$-n\gamma^{f}/\Delta\gamma(A/\Delta t)(1/12)\begin{bmatrix}2&1&1\\1&2&1\\1&1&2\end{bmatrix}\{\phi_t^f\}^e+n\gamma^{s}/\Delta\gamma(A/\Delta t(1/12)\begin{bmatrix}2&1&1\\1&2&1\\1&1&2\end{bmatrix}\{\phi_t^s\}^e$$

$$+K_o\phi_o\ A/3\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}-(1-\theta)K_o\ A/12\begin{bmatrix}2&1&1\\1&2&1\\1&1&2\end{bmatrix}\{\phi_t^f\}^e \quad (1)$$

Similarly, the element equation for salt water flow becomes:

$$\partial/\partial x(K_x^s b^s(\partial\phi^s/\partial x)) + \partial/\partial y(K_y^s b^s(\partial\phi^s\partial y)) =$$

$$-1/3\{1/2(b_t{}^s+b_{t+\Delta t}^s)\}[K_{ij}^s](1-\theta)\{\phi_t^s\}-n\gamma^s/\Delta\gamma(A/\Delta t)(1/12)$$

$$\begin{bmatrix}2&1&1\\1&2&1\\1&1&2\end{bmatrix}\{\phi_t^s\}+n\gamma^f/\Delta\gamma(A/\Delta t)(1/12)\begin{bmatrix}2&1&1\\1&2&1\\1&1&2\end{bmatrix}\{\phi_t^f\}^e \quad (2)$$

$$\zeta = \gamma^2/\Delta\gamma\phi^2 - \gamma^f/\Delta\gamma\phi^f \quad (3)$$

$$\{\phi^f\}^e = (1-\theta)\{\phi_t^f\ {}^e+\theta\{\phi_{t+\Delta t}^f\}^e \quad (4)$$

where

ζ = depth of interface below datum (L)

b = thickness of saturated layer (L)

A = area of element (L^2)

K_o = hydraulic conductivity of aquitard overlying aquifer (L/T)

ϕ_o = constant piezometric head of aquitard (L)

K_{ij} = matrix (L)

ϕ = piezometric head (L)

Q_p = pumping rate (L^3/T)

n = porosity (as a fraction)

t = time (T)

t = time increment (T)

γ = specific weight of fluid (M/L^2T^2)

$\Delta\gamma$ = difference in specific weight of salt and fresh water (M/L^2T^2)

θ = weighting factor

N = recharge (L/T)

Superscripts

f = fresh water quantity

s = salt water quantity

e = referring to element

Computer Program

The general computer program of the model was published by Contractor (1981). The principal modifications made in the program for the study were to reduce the salt water head to insignificant value and to eliminate the boundary conditions for salt water flow.

The velocity in each element is assumed constant but the head varies linearly across the element. By specifying NVEL = 1, the program prints the velocities in the X and Y directions in each element. The velocities can then be used to calculate the flow rates across any line or boundary. By specifying NTOE = 1, the program determines where in the network a salt water or fresh water toe occurs.

Since the occurrence of salt water is omitted, the program assumes that the fresh water head is an independent variable. After solving for the head, Equation (3) is used in the program to determine the thickness of the fresh water while reducing the salt water thickness to an arbitrarily small value, BTOE.

Equation (4) introduced a weighting factor, θ, which varies between zero and one. This factor is useful in regulating the stability and accuracy of the solution. When $\theta = 0$, the problem formulation is referred to as explicit. In the explicit formulation, the spatial derivatives are evaluated at the known time, t. The time step, Δt, necessary for stable results, is very small. This value of t results in very long execution time for the program. When $\theta = 0.5$, the problem formulation is referred to as Crank-Nicolson approximation. This approach provides high accuracy with large values of Δt, even though the results may show some numerical instability. When $\theta = 1.0$, the formulation is known as implicit. The implicit formulation provides the maximum stability at a sacrifice of some accuracy. Values of θ between 0.5 and 1.0 have been used to provide the proper balance between accuracy and stability. When steady state results are desired, the program should be run with $\theta = 1.0$ and Δt should equal a very large number. Since Δt is large, the time derivative terms in the element Equation (1) become very small. By making $\theta = 1.0$, initial values of the thickness of the fresh water and salt water layers are not used in the solution of the problem. In this study the program ran with $\theta = 1$. The program should be run for several time steps until the error is less than the specified tolerance in one or two iterations.

The time step Δt necessary for accurate results had to be determined. Therefore, the program was run using time steps equal to a half year, one year, one and one-half years, and two years, to obtain the correct time step with small error. Change in head versus time for selected wells, with different time steps, is shown in Figure 9. The time steps selected were not sufficient to obtain extremely high accuracy. It appears that the program should be run with Δt less than half a year. However, for practical purposes Δt was taken at one year for subsequent analyses because the change in head for the different test was found to be small, and the error believed to be of little consequence.

The maximum value of the time counter J for execution of the program (J_{max}) was 29 years.

Element Network

The Western and Eastern well fields are related hydrogeologically and cover an area of 813 km^2 (see Hydrogeology section). Therefore, it is reasonable to study both well fields as a whole. These well fields were represented by an element network (Figure 10). The network consisted of 92 nodes and 135 triangular elements. Out of the 92 nodes, 45 are located in unconfined aquifers and the rest located in leaky confined aquifers. The 135 elements consisted of 88 in unconfined aquifers and 47 in leaky confined aquifers. The convenience of this triangular element network is that it allows construction of a reasonably accurate finite element network over the irregularly shaped basin. The network was designed using nodal spacings of 2 to 2.5 kilometers in areas where the sandstone aquifer outcropped and 3 to 4 kilometer spacings in the remainder of the area. In certain areas,

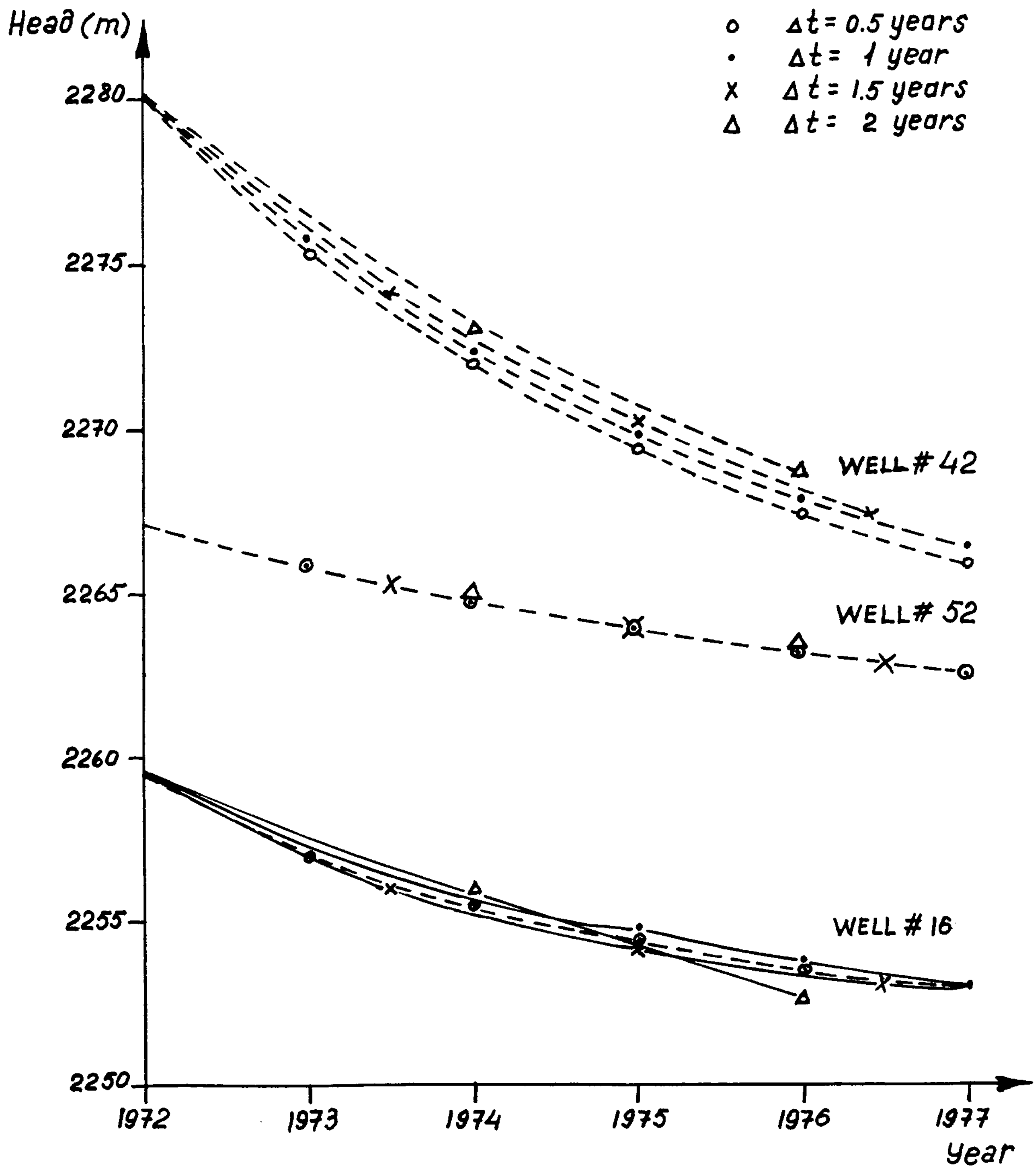

Figure 9. Change of Head with Time at Time Step (Δt) Equal to 0.5, 1.0, 1.5 and 2 Years.

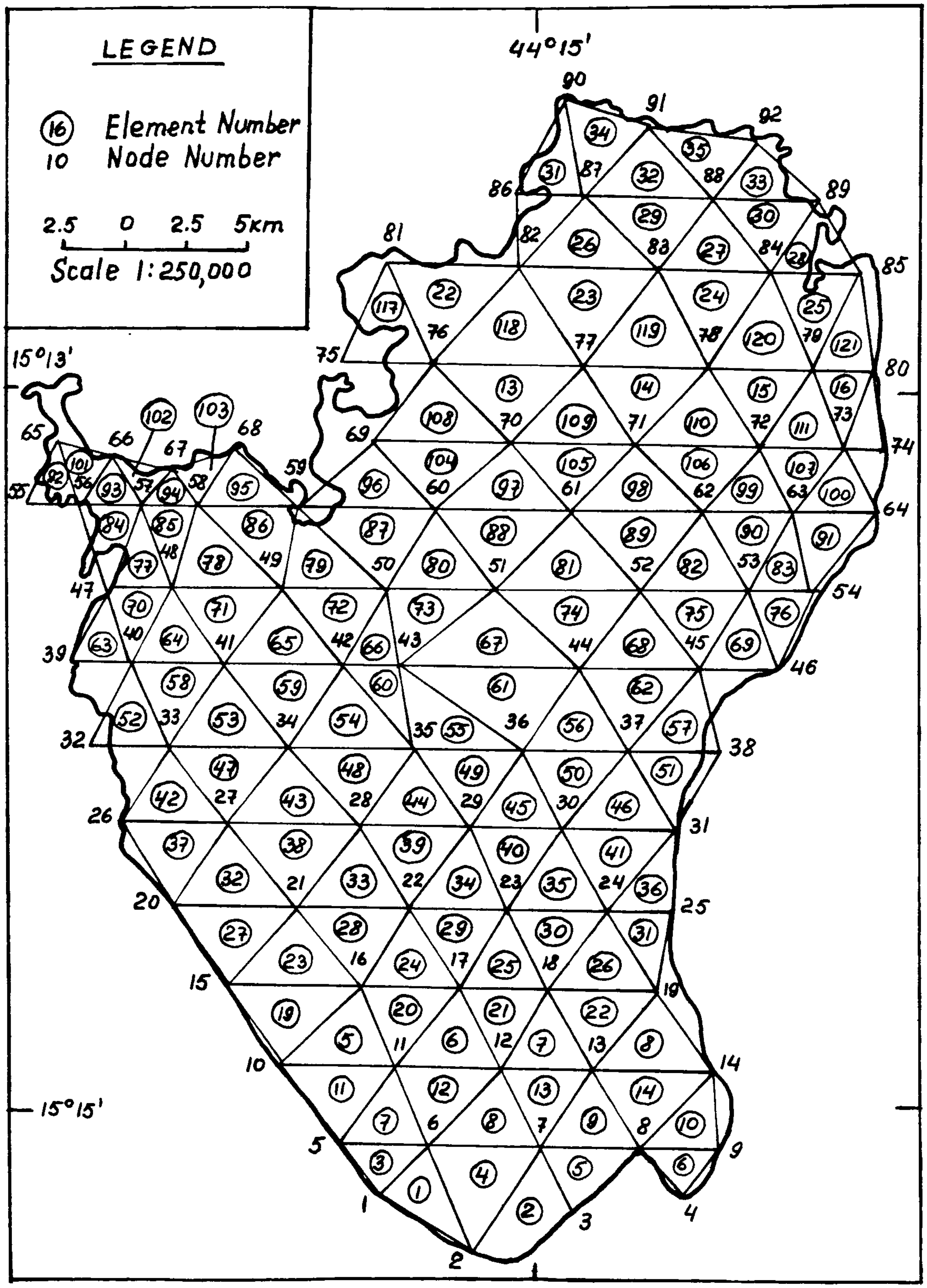

Figure 10. Element Network.

however, where abrupt changes in the properties of the geological materials occurred, modifications were made in element size.

Input Data

X and Y Coordinates

The X and Y coordinates of each node were obtained from a topographic map of the Sana'a basin. Using these coordinates, the program calculated the area of each triangular element. Then, using the average head of each element at given intervals of time, the program calculated the volume of water below each element.

Aquifer Thickness

The bottom and top elevations of the aquifer (saturated thickness of the aquifer) for each element were obtained from the geological map (Figure 4) and hydrogeological cross-sections (Figures 6, 7 and 8). The bottom and top elevation of the confined aquifer was simply taken as the lower and the upper levels of the aquifer. For the unconfined aquifer, the bottom elevation is the lower level of the aquifer. The upper level is unknown because of the variability of head with time and space. Therefore, the value 1000.1 was introduced into the program and the value of top elevation at any given time was calculated. For leaky aquifer, the input parameter is the thickness of the leaky part of the aquifer, which consists of part of the Trap series and the unfractured quaternary basalt. This parameter was also obtained from the geological map and hydrogeological cross-sections.

Hydraulic Conductivity

In this study, the following methods were used to estimate the value of hydraulic conductivity.

Specific Capacity of Wells. The storage property of confined aquifer was given quantitative significance for the first time in 1935 by Theis (Lohman, 1979), who introduced the storage coefficient (S) in his classic equation:

$$s = Q/4\pi T \int_{o}^{u} e^{-u}\, du/u \qquad (5)$$

where

s = drawdown (L)

Q = constant discharge rate from well (L^3/T)

T = transmissivity (L^2/T)

r = distance from discharging well to point of observation of s (L)

S = storage coefficient (dimensionless)

t = time since discharge began (T)

u = variable of integration (dimensionless) = $\frac{r^2S}{4tT}$

Theis' definition in 1938 (Lohman, 1979) of the storage coefficient is "the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head." Therefore, from the definition, the storage coefficient is dimensionless.

The storage coefficient of unconfined aquifers is virtually equal to the specific yield, as most of the water is released from storage gravity drainage and only a very small part comes from compression of the aquifer and expansion of the water.

The storage coefficient of most confined aquifers ranges from about 10^{-5} to 10^{-3}. In contrast, the specific yield of most unconfined aquifers ranges from about 0.1 to about 0.3 and averages about 0.2

Equation (5) cannot be integrated directly, but its value is given by the infinite series in the following equation:

$$s = Q/4\pi T[-0.577216 - \log_e u + u - u^2/2.2! + u^3/3.3! \ . \ . \ .] \qquad (6)$$

where

$$u = \frac{r^2 S}{4Tt} \qquad (7)$$

which is the lower limit of integration in Equation (5). The value of series is commonly expressed as W(u), the well function. Values of W(u) for values of u from 10^{-5} to 9.9 are tabulated in Wenzel (1942) and Todd (1973). For given values of u and W(u), T may be determined from

$$T = Q/4\pi s \ W(u) \qquad (8)$$

and S may be determined by rewriting Equation (7):

$$S = 4Ttu/r^2$$

or

$$S = \frac{4Tu}{r^2/t} \qquad (9)$$

Theis (Wensel, 1942) devised a simple graphical method of superimposition that makes it possible to obtain solutions of Equations (8) and (9). Selected values of W(u) versus u are plotted on logarithmic graph paper to form a type curve.

Equations (8) and (9) may be rearranged to obtain

$$s = [Q/4\pi T]W(u) \tag{10}$$

or

$$\log_{10} s = [\log_{10} Q/4\pi T] + \log_{10} W(u) \tag{11}$$

Cooper and Jacob (1946) showed that for values of $u = r^2S/4Tt \leq 0.01$, all but the first two terms between brackets in Equation (6) may be neglected and Equation (6) may be closely approximated by:

$$s = Q/4\pi T[-0.577216 - \log_e \frac{r^2S}{4Tt}] \tag{12}$$

This may be simplified and rewritten as:

$$T = Q/4\pi s[\log_e 0.562 + \log_e \frac{4Tt}{r^2S}]$$

$$= \frac{2.30Q}{4\pi S} \log_{10} \frac{2.25Tt}{r^2S} \tag{13}$$

Note that in Equation (13) Q, T and S are constant, and that either t or $1/r^2$ may be considered a constant.

Solving Equation (13) for Q/S_w (specific capacity), using S_w as the drawdown in the discharging well, and r_w as the radius of the well, and asuming that the well is 100 percent efficient, the following equation is obtained:

$$Q/S_w = 4\pi T/2.30\log_{10} 2.25Tt/r_w{}^2S \tag{14}$$

and

$$S_w = 2.30Q/4\pi T \log_{10} \frac{2.25Tt}{r_w^2 S}$$

or

$$S_w = 264Q/T \log_{10} 0.3Tt/r_w^2 S \tag{15}$$

where

S_w = drawdown (ft)

Q = discharge (gpm)

t = time after pumping started (hours) convert to day

r_w = radius of well (ft)

T = transmissivity (gpd/ft)

S = storage coefficient estimated usually 0.2 for confined and 0.0001 for unconfined aquifer (Ziezel and others, 1962, and Lohman, 1979)

Substituting the value of the above parameters into Equation (15), a drawdown of the nearby well was obtained. Using this value of drawdown, the value of specific capacity was calculated in this study by the following equation:

$$SP\ cap = Q/S_w \tag{16}$$

Using this calculated value of specific capacity with Figure 11, the value of transmissivity was obtained for confined and unconfined aquifers. The assigned storage coefficient values (S) for confined and unconfined aquifers are 0.0001 and 0.2, respectively. Therefore, the required hydraulic conductivity value (K) is:

$$K = T/b \tag{17}$$

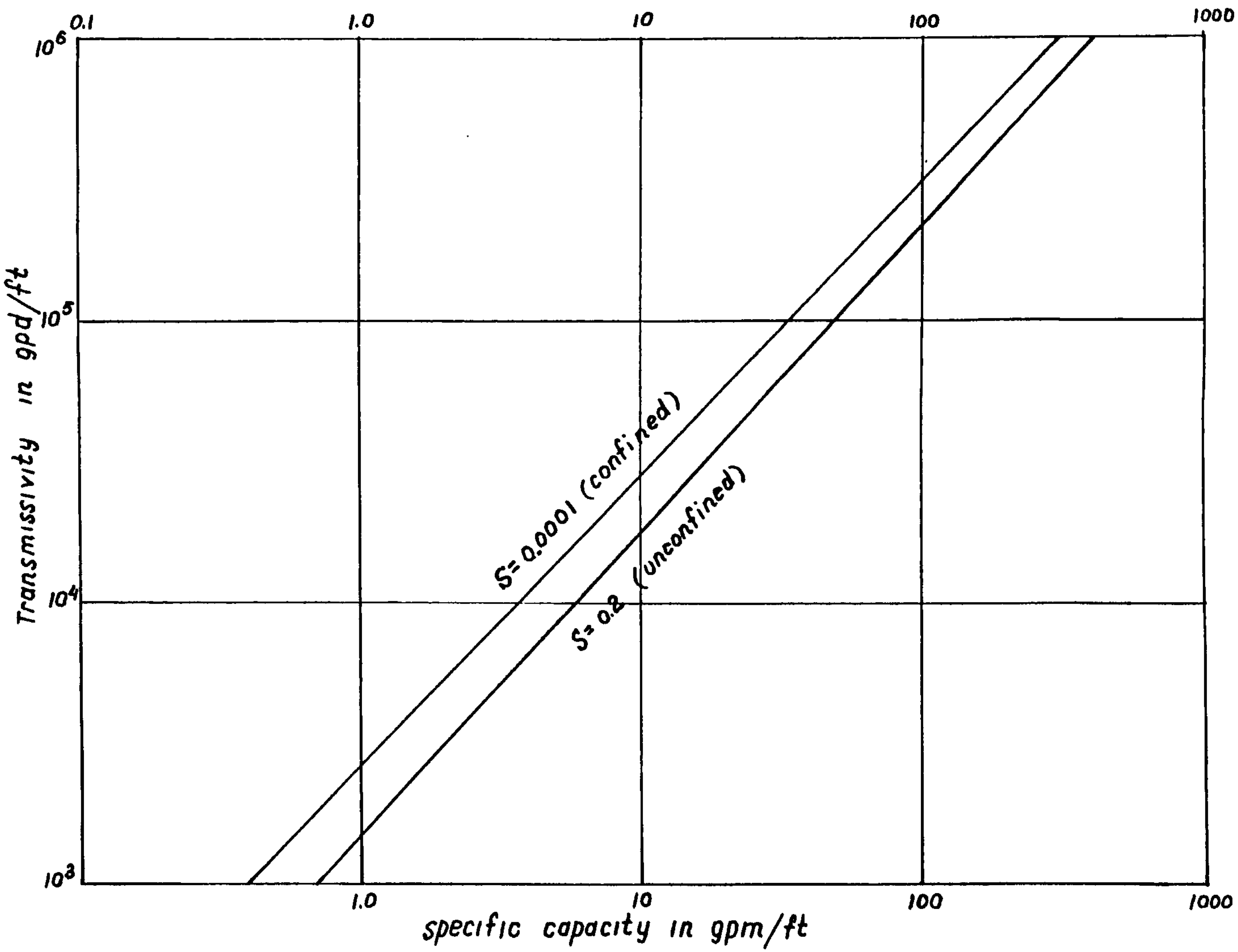

Figure 11. Graph of Specific Capacity Versus Transmissivity (after Lohman, 1979).

where

b = saturated thickness of the aquifer (L)

Subjective Hydrogeological Interpolation. The hydraulic conductivity (K) for the 45 wells in the basin were studied to determine the relationships between the value of K and the aquifer characteristics such as primary or secondary permeability and partial or full penetration of the aquifer. The present investigation included a review of the available geological, geophysical and hydrogeological information. Based on the relationships found between aquifer characteristics and hydraulic conductivity, the values of K was transferred to areas of Eastern well field with the similar characteristics to those of the Western well field. This method was applied only to the sandstone and alluvial aquifers.

There was only one well which penetrated the basalt aquifer. The hydraulic conductivity was determined to be only 0.58 m/day, and this value was assigned to areas where the basalt aquifer was dominant.

Cretaceous Sandstone Aquifers

This aquifer is characterized by both primary and secondary permeabilities. The primary permeability is determined by the pore space in the small interstices between the grains of sand. Therefore, the K value is low. Representative wells which were drilled in this kind of aquifer are:

Wells	K (m/day)
ST4	0.70
03	0.80
05	0.60
P14	1.20
Gw1	0.90

The value of K for the primary permeability ranged from 0.6 to 1.2 m/day, with a geometric mean of 0.80 m/day.

The secondary permeability is determined by fractures of variable density which provide channels of high permeability. These fractures are common, particularly in the northwestern part of the study area and are of two types.

The first type consists of fractures formed due to the contact between the Trap series and the sandstone aquifer (Figure 4). Representative wells for this type of aquifer are:

Wells	K (m/day)	Wells	K (m/day)
P21	0.64	P15	1.18
P8	0.85	P20	1.40
P13	0.86	SE1	2.00
SE7	2.40	ST1	2.60
P7	1.15		

The value of K for these wells ranges between 0.64 to 2.6 m/day, and the geometric mean is 1.31 m/day.

The second type of fracturing is formed by substantial fissuring due to volcanic dykes in the surrounding area. Wells located in this area seem to be the most productive, particularly in areas where this activity has occurred at a depth of more than 800 meters. The following wells are representative of this type of aquifer:

Wells	K (m/day)	Wells	K (m/day)
P17	1.45	P9	3.73
SE7	2.17	P16	6.32
P18	3.22	02	12.33

The K value of this type of aquifer ranges between 1.45 and 6.32, and the geometric mean is 2.1 m/day. It should be noted that the K value of well 02 is not included in the mean because such a high value of K (12.33 m/day) is very uncommon in the study area.

Alluvial Aquifer

Four wells were drilled in the alluvial aquifer to a depth of about 80 percent of the aquifer thickness. The values of K published for these wells are:

Wells	K (m/day)
ST3	0.80
SE5	1.00
WM224	1.23
WM425	1.10

The values of K ranged between 0.8 and 1.23 m/day, depending on the texture of the aquifer. The geometric mean is 1.02 m/day.

The K values of various aquifers are summarized in Table 3. The data indicate that there is no difference in the K values between the primary and secondary (first type) permeability of the sandstone aquifer at the lower range. The reason could be that the formation with secondary (first type) permeability was plugged by sand or gravel materials from natural processes or by poor well construction. The values of K for the sandstone and alluvial aquifer ranged from 0.6 to 6.32 m/day. Hydraulic conductivities within this range, after adjustment for aquifer characteristics, were assigned to the element network designed for this study.

Calibration Technique. For those areas of the Eastern well field where hydrogeological data were lacking, a calibration technique was used to estimate the K values. Calibration consisted of trial and error adjustments of K values until the head simulated by the model matched the measured head distribution.

Adjustment of K Values. In areas of the Eastern well field where hydrogeological conditions were similar to those of the Western well field, the values of K determined for selected wells in the Western well field were applied without modification to the Eastern well field. For those areas of the Eastern well field not completely similar to the Western well field, but having major hydrogeological characteristics in common (such as density of fractures), a mean value of K was applied. In areas where an aquifer was overlain by another aquifer (for example, where an alluvial aquifer was overlain by a sandstone aquifer), the average of the K values for both aquifers was assigned to that area.

Table 3. Summary of K Values for the Various Aquifers.

Aquifer	K (m/day)	
	Range	Mean
Sandstone		
Primary permeability	0.60–1.20	0.80
Secondary permeability, first type	0.64–2.60	1.31
Secondary permeability, second type	1.45–6.32	3.10
Alluvium	0.80–1.23	1.02
Basalt	–	0.58
Leaky	–	0.48

Leakage is common in some areas of the basin, particularly where the sandstone aquifer is covered by semipervious volcanics, because the semipervious formations have lower K values than those of the sandstone aquifer. Based on the hydraulic conductivity value obtained from well SE4 drilled in the volcanics, a K value of 0.48 m/day was assigned to the leaky portion of the aquifer.

For partially penetrating wells, it is usually necessary to modify the K values because the average length of a flow line into a partially penetrating well exceeds that of a flow line into a fully penetrating well. Great resistance to flow and consequently lower conductivity is thus encountered. However, most of the K values for the Western well field were obtained from observation wells that were located a minimum distance of 600 meters from the productive wells (1.5 to 2 times the saturated aquifer thickness). Therefore, the effect of this flow line phenomena was negligible (Todd, 1980). The K values of the Western well field were therefore transferred to the Eastern well field without any modification for partial penetration.

The K values within the range of 0.6 to 6.32 m/day, after adjustment for the various conditions, were assigned to the nodal element network of the model. However, the input to the model requires a single value for each element, which was obtained by averaging the K values for each of the three nodes surrounding the element. The range of K averaged values for input into the model ranged from 0.5 to 2.5 m/day.

Porosity

Porosity values were not available for the Sana'a basin. Therefore, estimates were made from a review of literature from areas with similar aquifers.

In the sandstone reservations, with primary porosities of 15-26% in the oil fields of the West Siberian lowland, fracturing may account for variations in permeability from less than 1 m/day to as high as 1500 m/day (Chow, 1978). The Shuebelinsky gas field (U.S.S.R.) has fractured sandstone with primary porosity ranging from 5 to 27% but very low permeability. Although the fractures made complex porous patterns in the sandstone, they do not contribute much to the primary porosity of the rock (Chow, 1978).

McWhorter (1977) and Todd (1980) gave representative values of porosity for different formations which are summarized in Table 4. The data in the table show that porosity is generally inversely proportional to K. Based on this relationship, values of porosity estimated for the study area were:

Aquifer	K (m/day)	Porosity (%)
Sandstone Primary Permeability	0.6 - 1.5	30
Sandstone Secondary Permeability	0.64 - 6.32	20-25
Alluvium	0.8 - 1.23	35

Assumed Well Field Design

A well field was designed to be operated by the model with consideration for the hydrology of the basin and well field economics,

Table 4. Porosity of Aquifer Materials (adapted from McWhorter, 1977 and Todd, 1980).

Aquifer Materials	Number of Analyses	Range	Arithmetic Mean
Igneous Rocks			
Weathered gabbro	4	0.42-0.45	0.47
Basalt	94	0.03-0.35	0.17
Sedimentary Materials			
Sandstone	65	0.14-0.49	0.34
Siltstone	7	0.21-0.41	0.35
Sand (fine)	243	0.26-0.53	0.43
Sand (coarse)	27	0.31-0.46	0.39
Gravel (fine)	38	0.25-0.38	0.34
Gravel (coarse)	15	0.24-0.36	0.28
Silt	281	0.34-0.61	0.46
Clay	74	0.34-0.57	0.42

and with the aim of representing a reasonable approximation of future development. As the field is developed in the future, the actual location of real wells will no doubt vary in accordance with information from more detailed study of the sites. It was assumed that the simulated well fields are located in the following areas:

1. In the Western well field, within the area investigated by Italconsult (1973).
2. In the Eastern well field, within the area recommended by Howard Humphreys (1980).
3. In the areas where the estimated value of hydraulic conductivity is high and consequently has high yield potential.

Twenty-six wells were located in both well fields (Figure 12). The estimation for the number and location of wells was based on the areal extent of the productive sites and the necessity to maintain a reasonable distance between wells to avoid interference. The distance of a well location to sites of probable use was also considered in the estimate. The transmissivity values of these wells are shown in Table 5.

Pumping Rate Distribution

It should be noted that both well fields were represented by the 26 wells simulated in this study. All the wells which were drilled since the year 1970 were replaced in the model by these 26 wells. Therefore, the total water consumption for public, agricultural and industrial use from the years 1972 to 2000 was distributed among the 26 wells.

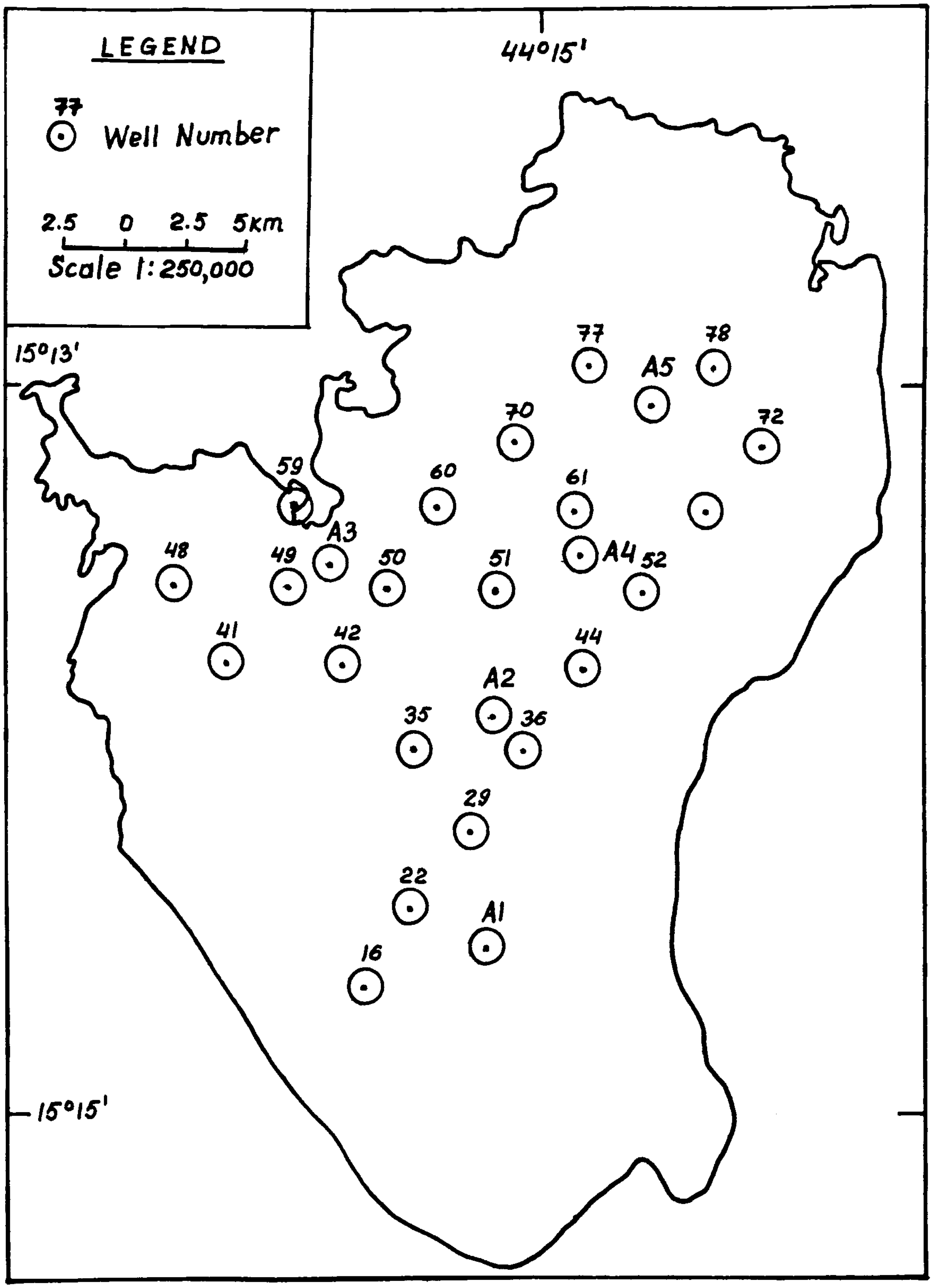

Figure 12. Location of Wells Used in This Study.

Table 5. Transmissivity Values of the Simulated Wells.

Well Number	Saturated Thickness (m)	K (m/day)	Transmissivity (m^2/day)
42	150.00	0.85	127.50
41	353.00	1.10	388.30
44	267.00	2.07	552.69
49	175.00	0.80	140.00
59	470.00	1.56	633.20
35	177.00	0.80	141.60
60	200.00	0.58	300.15
A4	145.00	2.07	594.00
A3	495.00	1.20	594.00
61	300.00	0.58	144.00
51	242.00	1.90	459.80
50	410.00	1.56	639.60
A5	150.00	0.60	90.00
62	232.00	2.07	480.24
A1	470.00	2.10	987.00
22	495.00	1.20	594.00
52	150.00	2.46	369.00
A2	150.00	0.58	87.00
70	175.00	0.80	140.00
48	470.00	1.56	633.20
16	150.00	0.50	75.00
36	375.00	1.20	450.00
77	490.00	1.20	588.00
78	330.00	0.80	264.00
72	140.00	0.45	63.00
29	180.00	2.07	372.60

Pumping rate of each well was made proportional to the transmissivity value of that well using the following methods.

First, the 1972 consumption was considered as an initial condition, then the consumption for each year was incremented by 10 percent of the previous year's consumption in order to represent the effects of population growth, and industrial and agricultural development. This value was obtained using the following equations:

$$C_T = \sum_{i=1}^{n} (C_i + aC_i) \qquad (18)$$

where

C_T = total water consumptive use (M^3)

n = 29 years

a = 0.1 = coefficient of proportionality and represents the 10% increase in annual consumptive use.

The average daily consumptive use over the 29 years ($\overline{C}_d$) was otained by dividing (C_T) by the total number of days in 29 years:

$$\overline{C}_d = C_T/29x360 \qquad (19)$$

The annual population growth was also determined using the equation (Tierney, 1979):

$$N(t) = N_o e^{Kt} \qquad (20)$$

where

$N(t)$ = the population at time t

N_o = initial population

K = growth rate = 0.025/year

The results are presented in Table 6.

Finally, the rate of pumping of each well was obtained using the following equation:

$$Q_{di} = \frac{\overline{C}_d}{W \sum_{i=1}^{w} T_i} \times \quad T_i \qquad (21)$$

where

Q_{di} = daily pumping rate of i^{th} well (M^3/day)

T = transmissivity (M^2/day)

W = 26 (number of wells)

The location of only twenty-one of the wells coincides with a nodal point of the finite element network. Therefore, the full pumping rate calculated by Equation (21) for each of these wells was assigned to the respective nodes. Where locations did not coincide with nodes, such as wells A1, A2, A3, A4 and A5, the well pumpage was distributed proportionally among the three nodes that define the element in which the well was located.

To illustrate the method of proportioning the pumping rate, consider the well located in the element shown in Figure 13. The location of the well within the element can be defined in terms of its so-called "natural coordinates" (a_1/A, a_2/A, a_3/A,), where a_1, a_2 and a_3 are the sub-regions designated in Figure 13 and A is the total area of the triangular element. The magnitude of the natural coordinates a_1/A, a_2/A, and a_3/A, corresponds to the proximity of the well at nodes 1, 2 and 3, respectively. The portion of well pumping, Q_d, which is assigned to each node increases linearly as the well approaches the

Table 6. Ground Water Extraction and Population Growth in Sana'a Basin, 1972-2000.

Year	Extraction M^3/Day	Population x 10^3	M3/day (per capita)
1972	26027.4	125.20	0.20
1973	28630.1	128.37	0.22
1974	31479.5	131.62	0.24
1975	34657.5	134.59	0.26
1976	38082.2	138.00	0.28
1977	41890.4	141.50	0.39
1978	46082.2	145.10	0.32
1979	50684.9	148.75	0.34
1980	55753.4	152.51	0.37
1981	61342.5	156.37	0.39
1982	67479.5	160.33	0.42
1983	74219.2	164.39	0.45
1984	81616.4	168.55	0.48
1985	89780.8	172.82	0.52
1986	98757.1	177.20	0.56
1987	108630.1	181.68	0.60
1988	119506.9	186.28	0.64
1989	131452.1	190.99	0.69
1990	144682.7	195.83	0.74
1991	159095.9	200.78	0.79
1992	174986.3	205.87	0.85
1993	192493.2	211.08	0.91
1994	211753.4	216.43	0.91
1995	232931.5	221.90	0.91
1996	256219.2	227.50	0.91
1997	281835.6	233.28	0.91
1998	310027.4	239.19	0.91
1999	341041.1	245.24	0.91
2000	375150.7	251.45	0.91

Average Daily Extraction = 0.13 x 10^6 m^3

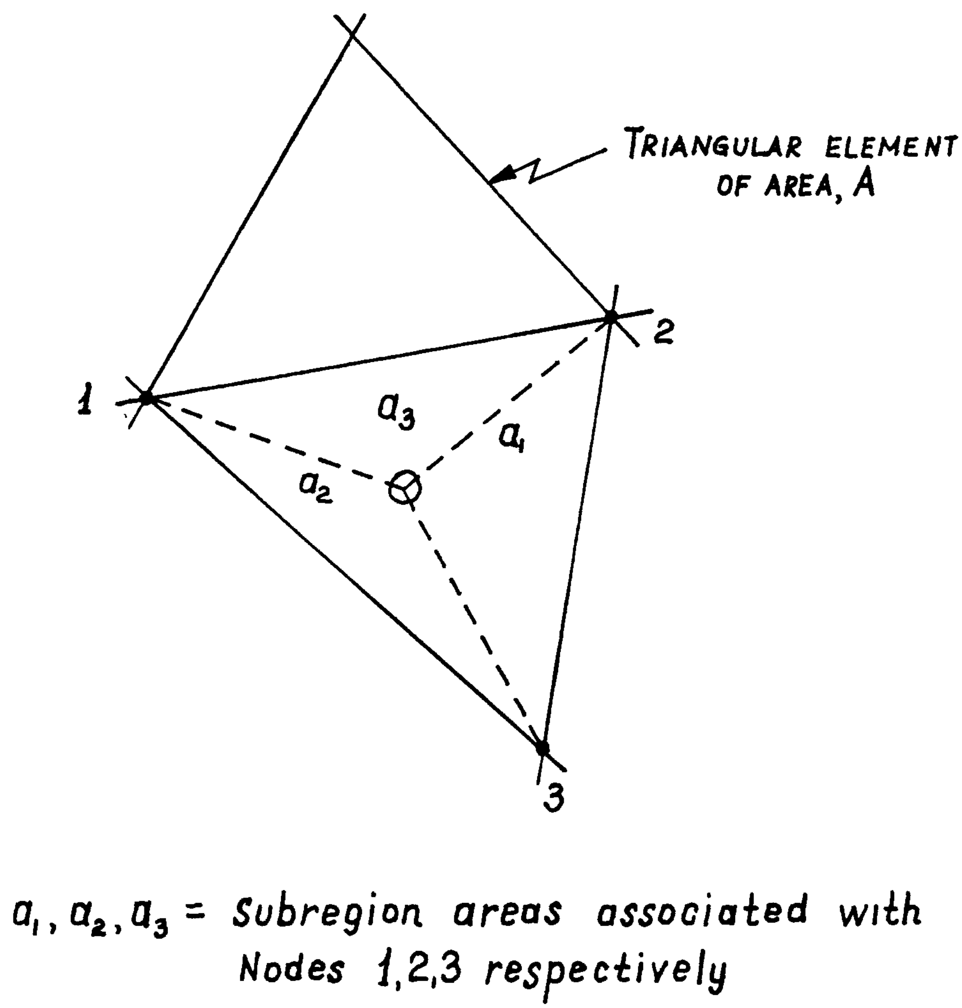

Figure 13. Finite Element Containing a Well.

node and is equal to the product of its natural coordinate and Q_d (Boggs, 1980). Therefore, the well pumpage assigned to nodes 1, 2 and 3 are $Q_d a_1/A$, $Q_d a_2/A$, and $Q_d a_3/A$, respectively.

Initial and Boundary Conditions

The initial values of head used in the input data of the model were the measured head values obtained from the water table elevation map of the Sana'a basin (Figure 14) conducted by Italconsult (1973). These values were preferred over those obtained by Howard Humphreys (1980) because they cover the entire area of the basin.

The boundary nodes of the northwest and northeast parts of the basin where the sandstone aquifer outcrops, and the southern part of the basin where regional flow to the basin occurs were specified as constant head boundaries. All other boundary nodes were not specified. Boundary node types are shown in Figures 21 and 22 (in Equipotential and Flow Lines section, Results and Discussion).

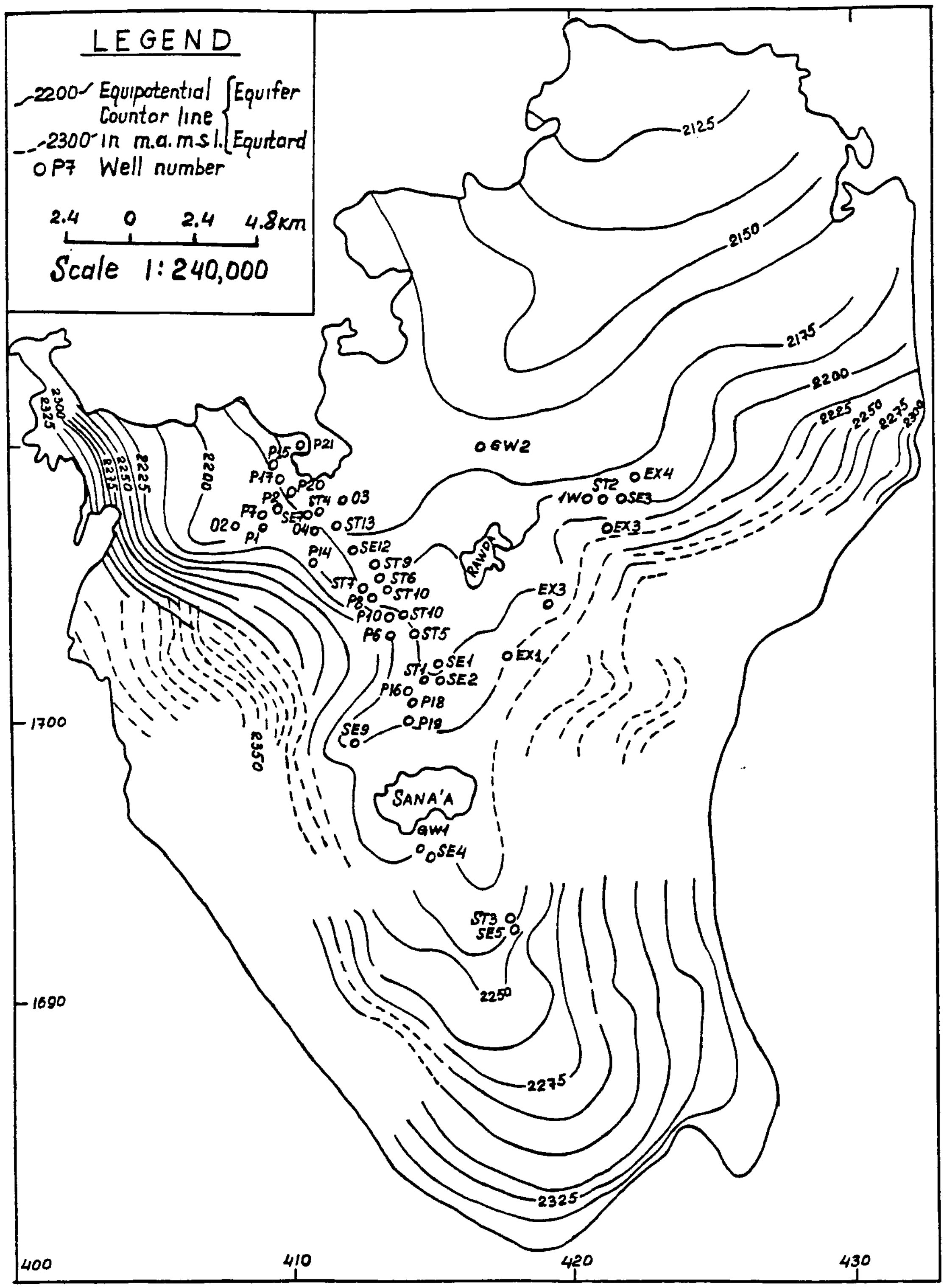

Figure 14. The 1972 Water Table Elevation Map of the Sana'a Basin (after Italconsult, 1973).

RESULTS AND DISCUSSION

In addition to simulating K values with the finite element model, simulations were made to determine the response to pumping of:

1. The upper elevation of the unconfined aquifer at each node.
2. The saturated thickness of the aquifers at each node.
3. Velocity potential and direction of flow in each element.
4. The annual head configuration at each node.
5. Volume of water in the aquifer.

The K values and the output from the model of these quantities were applied to the flow net to determine static water-level fluctuations with the basin and the overall direction and quantity of ground water flow to the basin. The results were evaluated to determine the potential of the ground water resource for meeting the needs of the Sana'a basin to assist in long-term planning.

Hydraulic Conductivity

In assigning the K values, more qualitative weight was given to those selected on the basis of geohydrology than to those selected by other methods. The K values for 29 of the 135 elements in the network were estimated by this method. It is believed that these values are fairly accurate, since they were obtained from areas where the geohydrology is known. The method of using the specific capacity of wells to estimate K values was applied to the elements which were near wells with known K values. At first, the K value of 27 elements were estimated using this method. However, the K values deterined for 5 of the elements was too high to be justified. These 5 elements were located in the southeastern part of the city where the poorly productive Trap series outcrops. The calibration process was used to estimate the K values of 84 additional elements including the five questionable elements. Initial calibration attempts indicated that a much lower K would be required for these elements. The final K values for these elements were obtained after twelve iterations of the calibration process. Generally, discrepancies were well within $\pm$ 10 meters range of the measured water-level data for eleven nodes (Figure 15).

The K values assigned to each element using the above-mentioned three methods are presented in Appendix B. Utilizing the K value obtained by these methods, a hydraulic conductivity distribution map was plotted and is presented in Figure 16.

The value of K ranged between 0.25 and 2.5 m/day. High values of K (2 to 2.5 m/day) were encountered in the central part of the study area. This is the area of the fractured sandstone and/or Trap series aquifers.

A similar high value of K (2 m/day) was found in the southwestern tip of the study area. Here, the alluvial aquifer is in contact with the Trap series, and is fractured as a result of stresses produced by the underlying Trap series.

In the northern and southeastern part of the basin, where the alluvial aquifer lies, the K value was determined to be about 1 m/day.

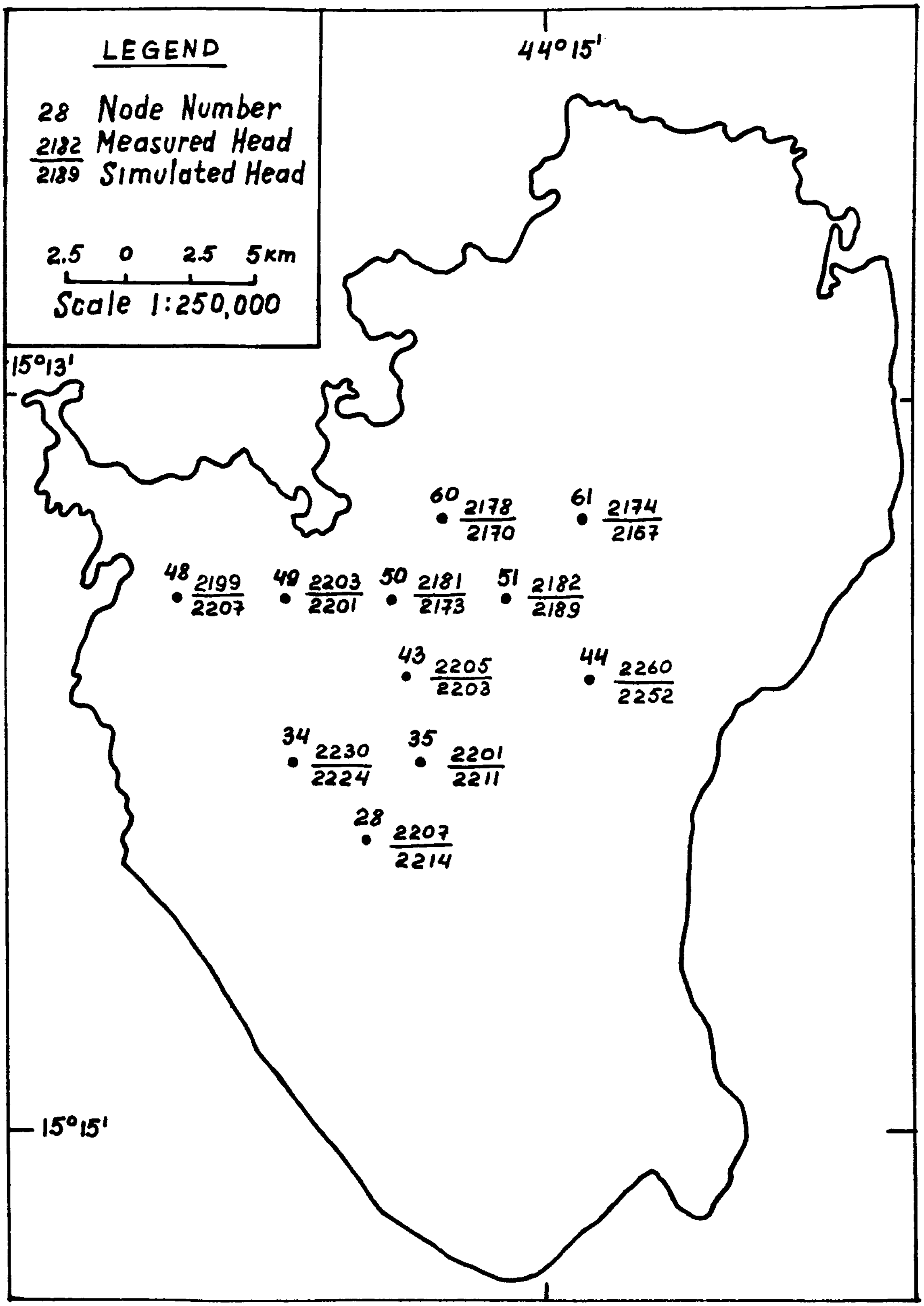

Figure 15. Discrepancies Between Simulated and Measured Head for the Year 1979.

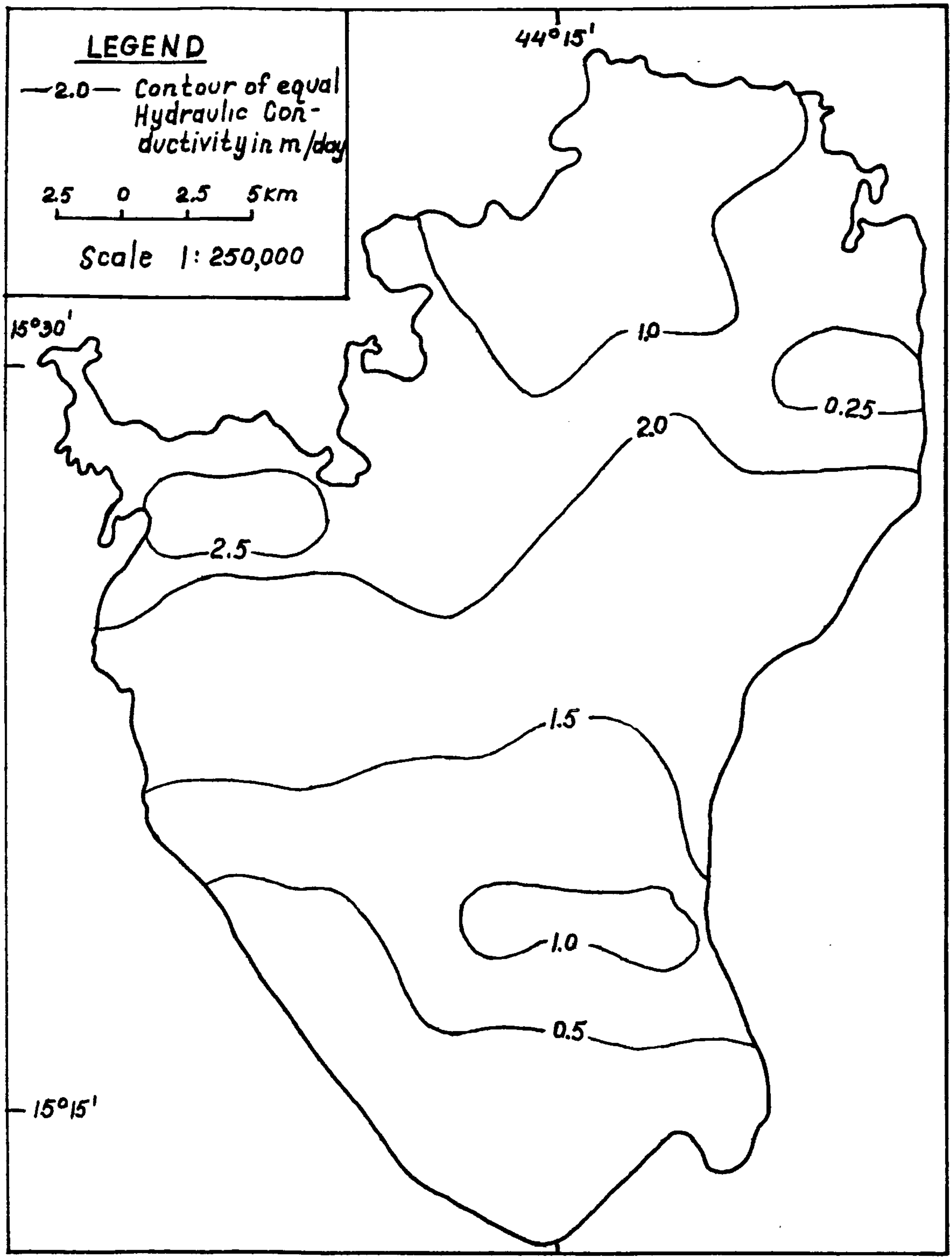

Figure 16. Hydraulic Conductivity Distribution Map of the Sana'a Basin.

The lowest value of K (0.25 m/day) was located in areas where the sandstone aquifer with primary permeability outcrops.

In summary, the final K values using the three methods were consistent with what is known or suspected about the hydrogeological conditions of the area. Inasmuch as the K values within the study area were estimated, it is possible that the magnitude of the values obtained may be off by a constant factor, but their relative distribution is believed to be reasonably accurate.

Static Water-Level Fluctuations

The performance of the 26 wells simulated in the study was examined to determine possible water-level fluctuations. The behavior of each well in response to pumping is presented in Figures 17, 18 and 19. The analyses indicated that for the 1972-1983 period the average annual decline of water levels ranged from between 0 and 1.61 meters; for the 1983-2000 period the average annual water-level decline was less and ranged between 0 and 0.91 meters. The lower decline in the latter period could be due to the aquifer approaching a steady state condition.

The program was run for 120 years with the same input data used for the 29-year period. The purpose was to determine when the aquifer might reach a steady state condition. The trial showed that the aquifer would reach this condition after 76 years if the annual water consumption was held constant. If it is assumed that the demand for water will increase by 50 percent over the 76-year period, then the aquifer might reach a steady state condition in about 38 years.

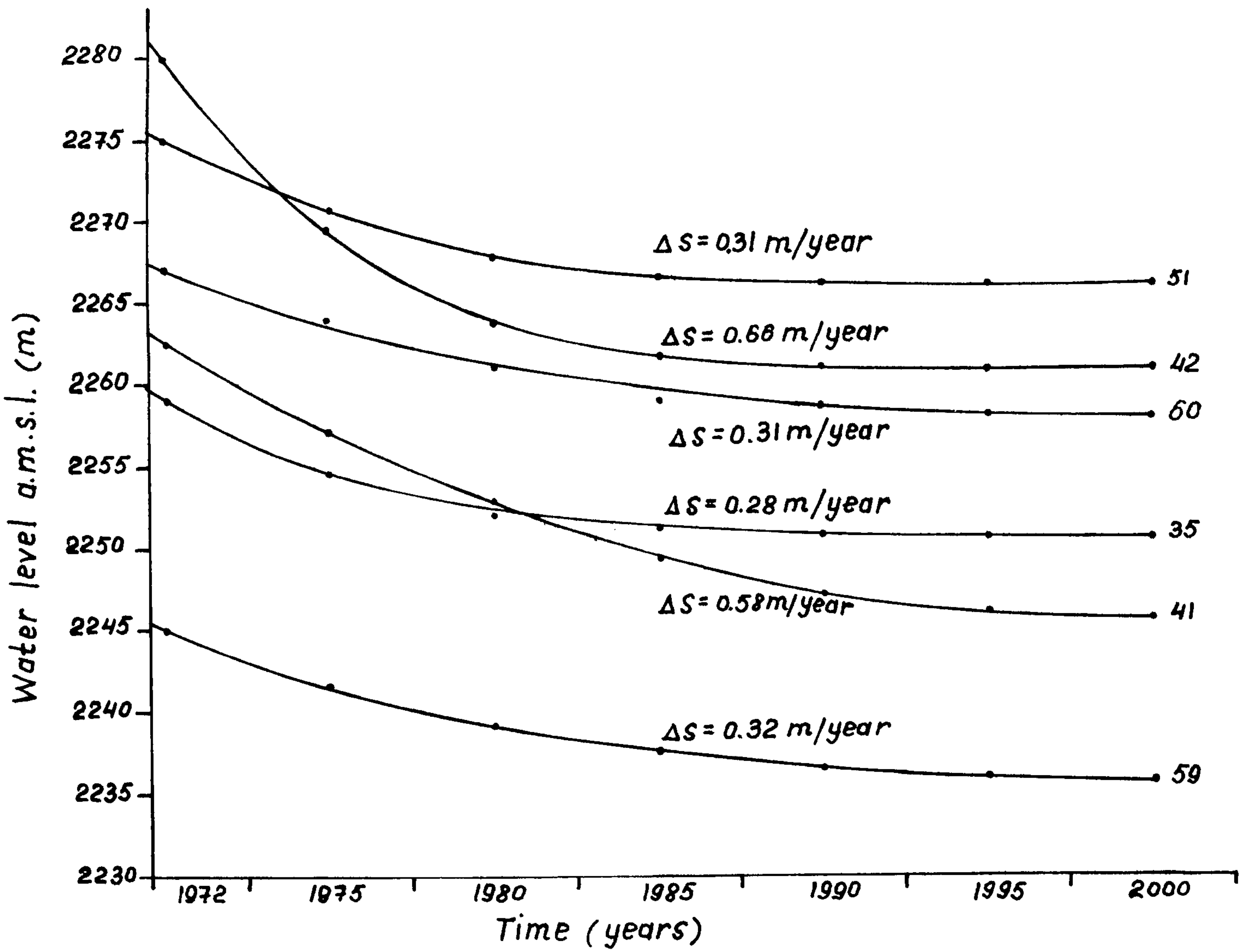

Figure 17. Static Water Level Fluctuation in Wells 35, 41, 42, 51, 59 and 60.

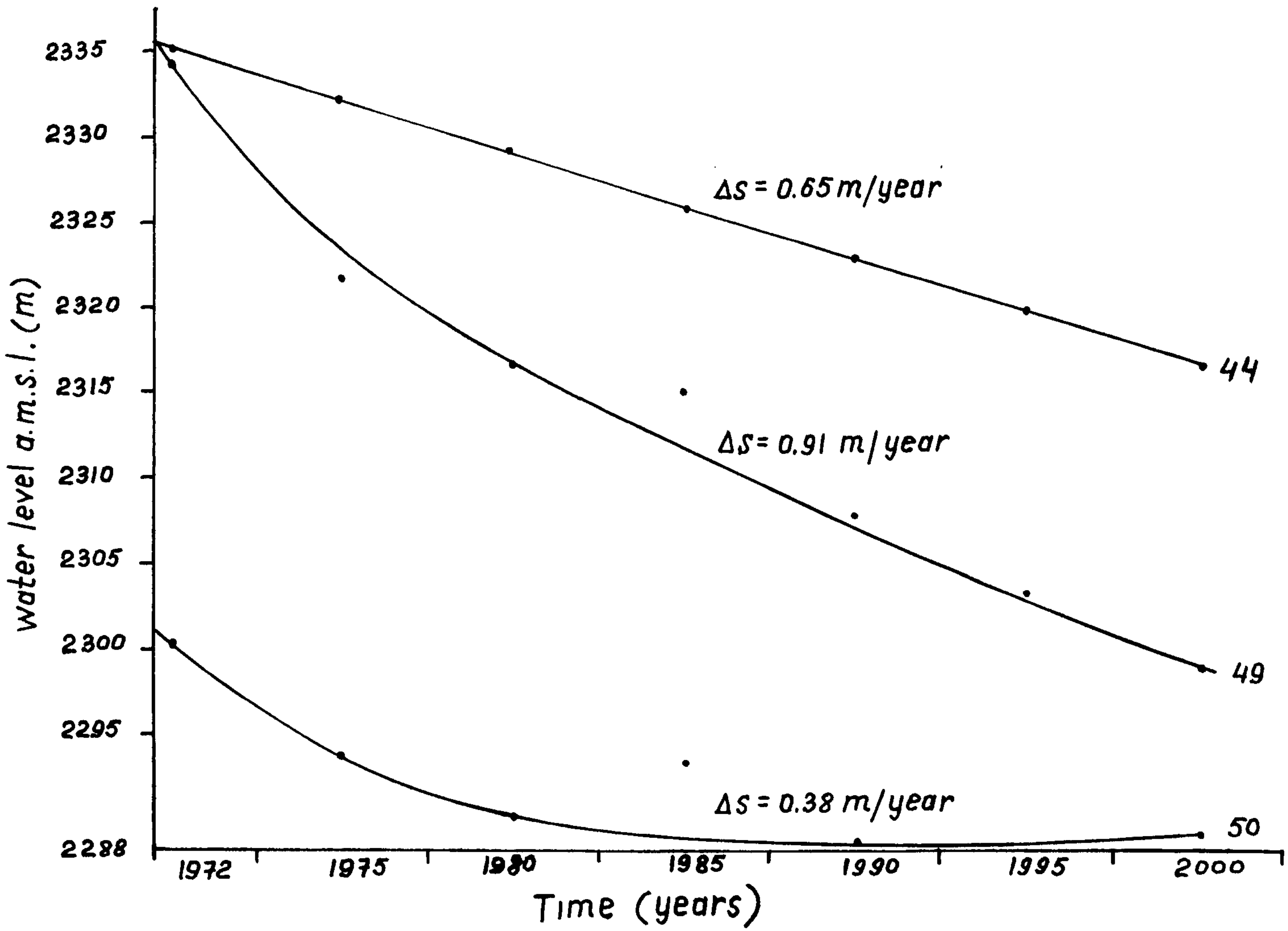

Figure 18. Static Water Level Fluctuations in Wells 44, 49 and 50.

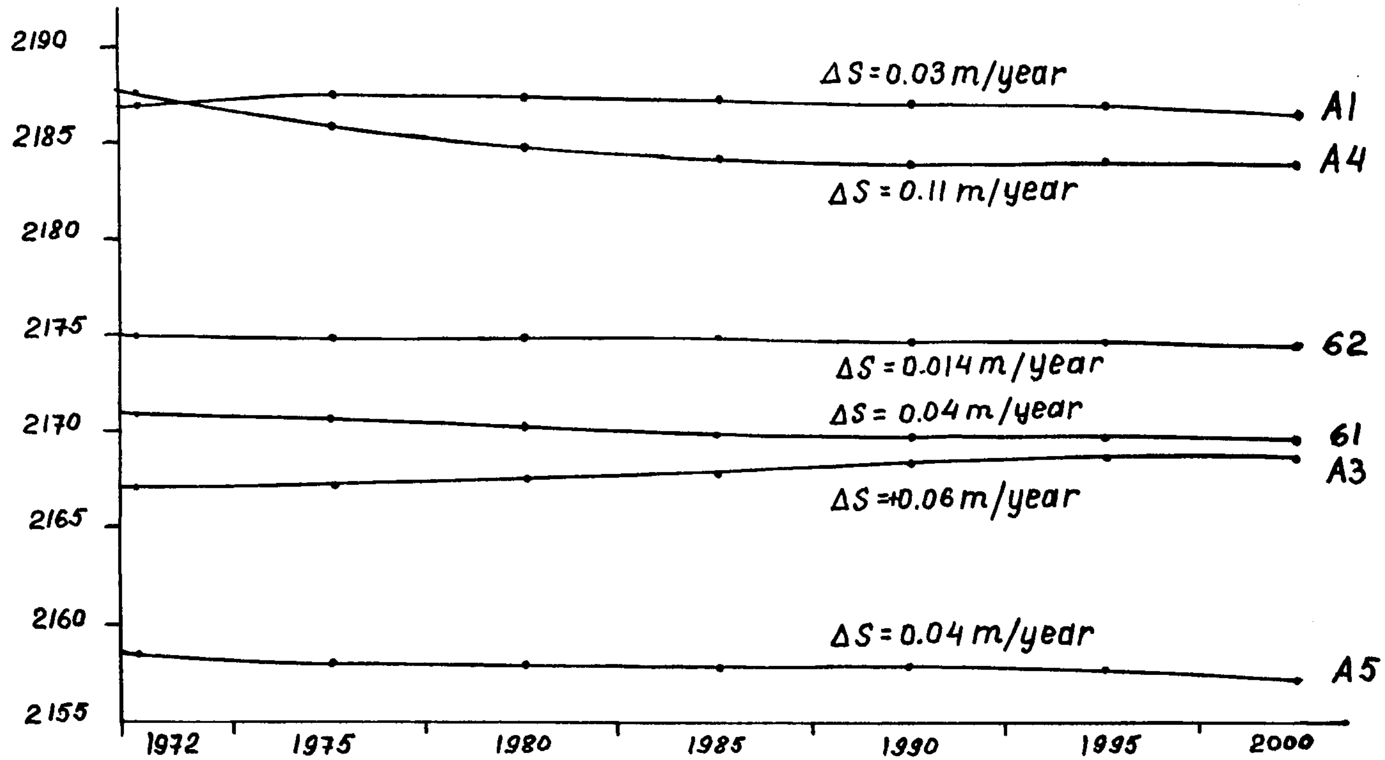

Figure 19. Static Water Level Fluctuation in Wells A1, A3, A4, A5, 61 and 62.

It should be noted that the maximum annual decline in head occurred in wells 49, 42, 44 and 41 and ranged between 0.7 and 1.00 meters. The question is whether the observed decline is due to the lack of replenishment in the basin or due to the high rates of pumping.

The first possibility can be ignored because recharge was assumed to be constant (0.000025 m/day). Since the maximum decline occured in wells where there was a high rate of pumping and the observed decline appears to differ in different areas of the basin, it is quite possible that the water-level decline is due more to the local pumping than to the lack of replenishment.

Wells A5, 61, 62, A1 and A4 showed almost no decline in water levels. The possible reasons for this behavior are that the pumping rate in these wells is low and/or the wells are located in the vicinity of the constant head boundaries. The drawdowns after 29 years of pumping are shown in Figure 20. Note that there is a maximum decline of about 30 meters from the city of Sana'a, extending northward to Rawda and the airport. This decline was expected since the most intensive pumping was simulated for this area to match the actual pumping rates.

Previous studies reported that the maximum decline in head occurred between Sana'a and Rawda at a rate of 2 to 3 m/year, and in other locations the rate was between 0.25 and 1.5 m/year. These values contrast somewhat with values of 0 m/yer and 1.00 m/year obtained in this study. In this study the pumping was distributed between both Eastern and Western well fields in contrast to the previous studies

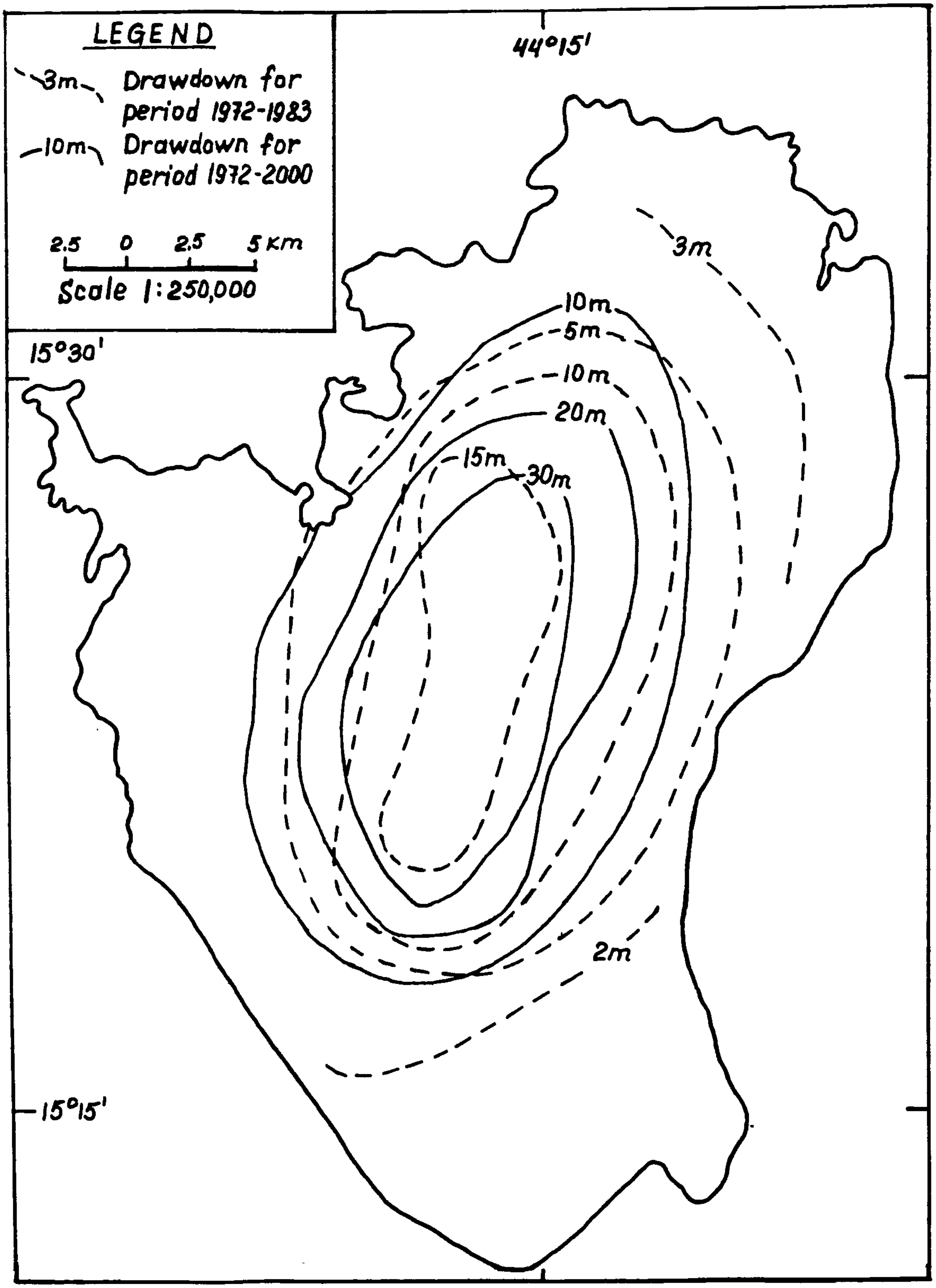

Figure 20. Projected Areal Drawdown in the Sana'a Basin for Periods 1972-1983 and 1972-2000.

which concentrated almost entirely in the Western well field. As a result the projected water-level decline is lower in the present study.

Equipotential and Flow Lines

A flow net, which is a graphical illustration of a flow pattern, is composed of two families of lines or curves. One family of curves, called equipotential lines, represents contours of equal head of an aquifer, i.e., the potentiometric surface for a confined aquifer or the water table for an unconfined aquifer. Intersecting the equipotential lines at right angles is another family of curves representing the streamlines, which indicate the path followed by a particle of water as it moves through the aquifer.

Figures 21 and 22 were constructed using the values of head simulated for 1983 and 2000. The head configuration of 1983 responds to the amount of pumping in the basin as it did for all years of the 29-year simulation period. The direction of flow changed somewhat during the 29-year period, but it was generally from the northeast, northwest and south and converged toward the wadi bed in the central part of the basin where the elevation of the land surface is lower and the consumptive use is high. This convergent pattern indicates that the mountain ranges are major intake areas for ground water recharge. A pronounced cone of depression is centered in the vicinity of Sana'a and Rawda due to the high pumping rates. Flow from the central basin is toward the north.

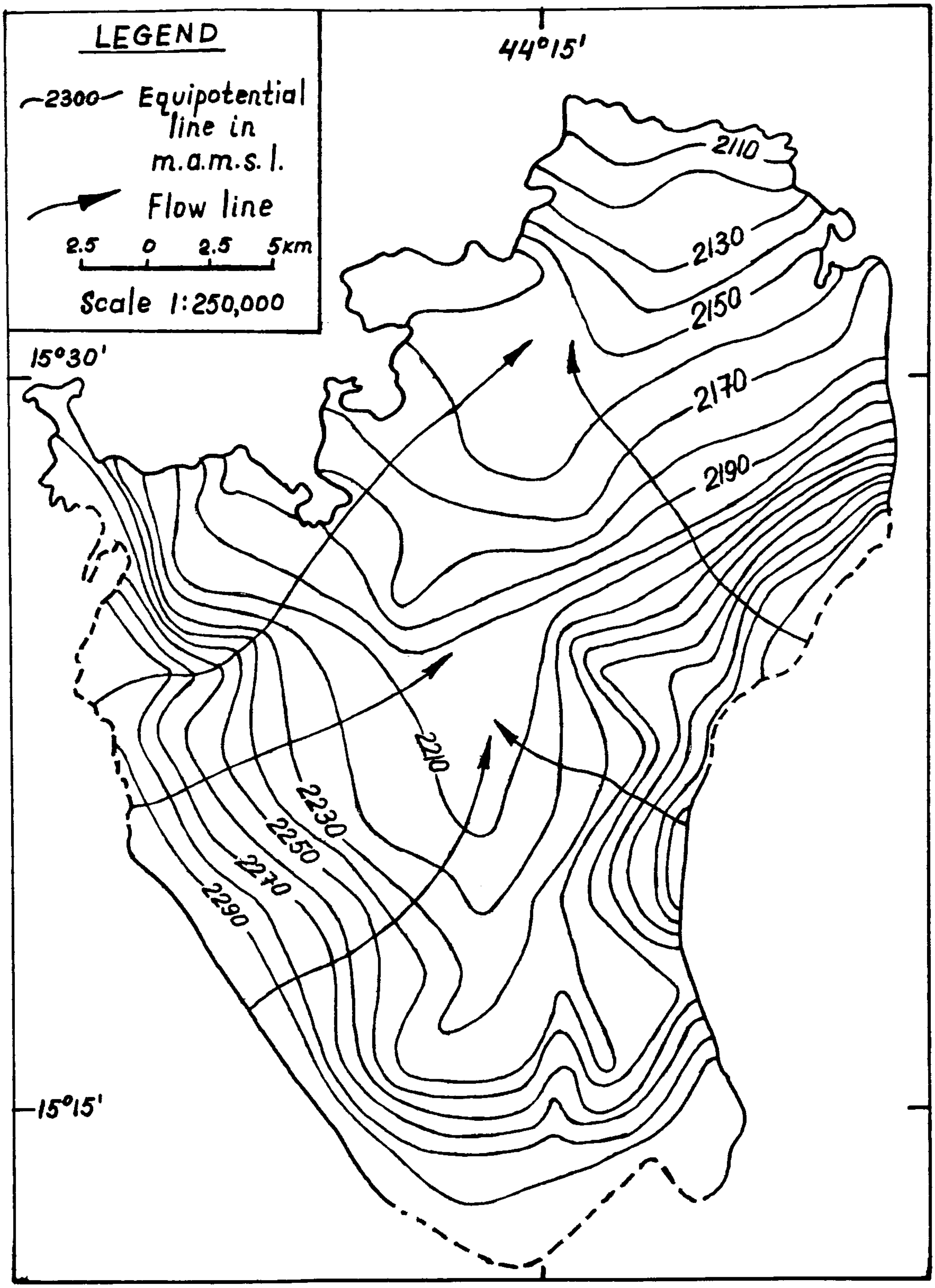

Figure 21. Equipotential and Flow Lines of the Sana'a Basin Aquifers for the Year 1983.

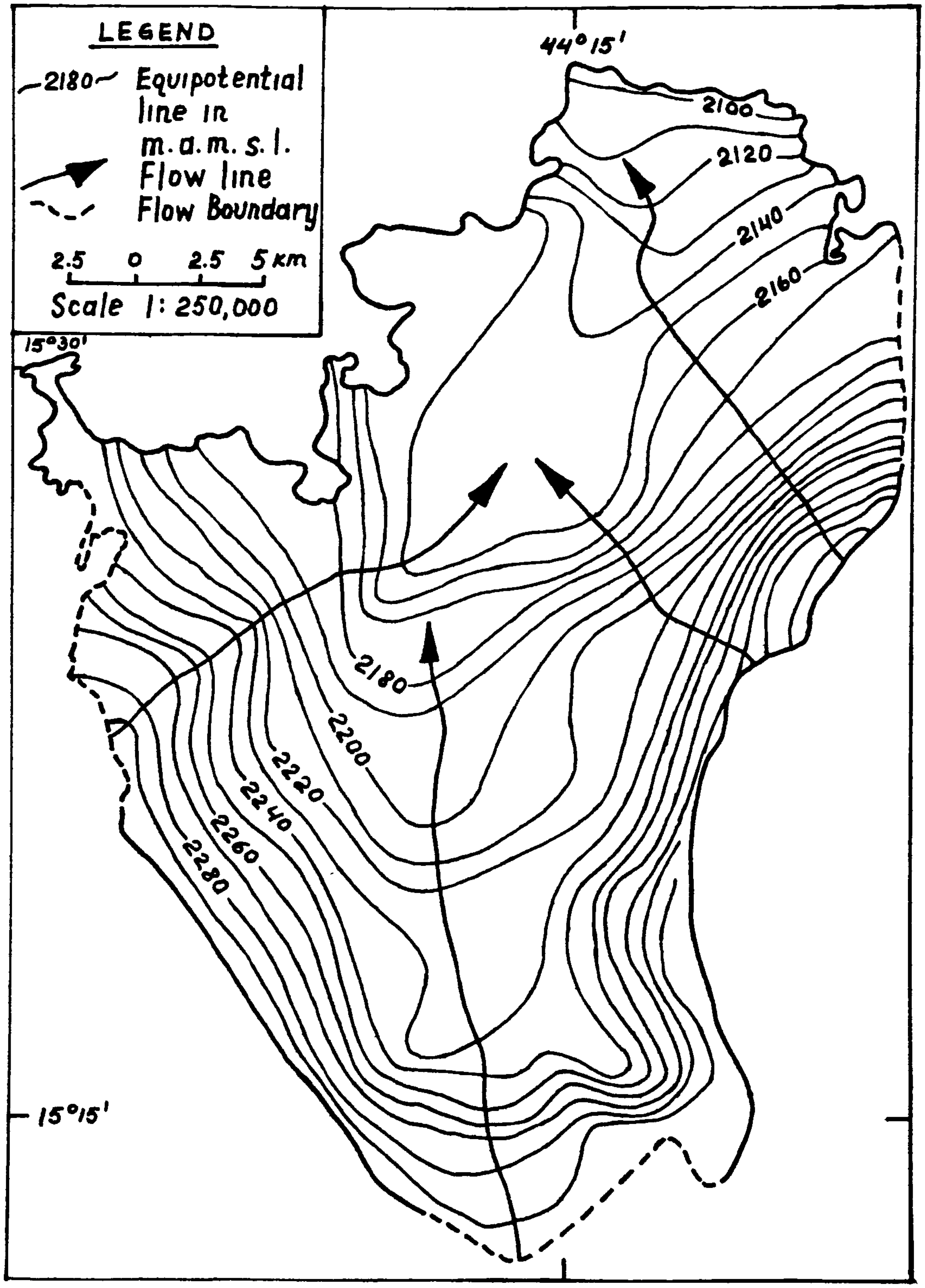

Figure 22. Equipotential and Flow Lines of the Sana'a Basin Aquifers for the Year 2000.

Rate of Ground-Water Flow

The rate of ground water flow was estimated from Figure 21. The flow was calculated along the northwestern, southern and northeastern boundary of the basin from which the main flow occurred. The length of the flow was estimated at 15.8 km in the northwest, 15.1 km in the south and 11 km in the northeast. The hydraulic gradients for the northwestern, southern and northeastern boundary were 0.020, 0.015 and 0.010, respectively. The flow within each boundary was then calculated using Darcy's ground-water flow equation:

$$Q = LIT \qquad (22)$$

where

Q = flow rate (m^3/day)

L = length of the flow (m)

I = hydraulic gradient (m/m)

T = transmissivity (m^2/day)

The results are summarized in Table 7. From this table, it is seen that the total flow to the basin is 0.20×10^6 m^3/day. The method used in calculating ground water flow does not distinguish between the long-term situation and the short-term variations of replenishment which may or may not exceed the long-term mean. This is particularly relevant in the Sana'a area where recharge does not seem to be uniformly distributed over time. Therefore, in times when short-term replenishment is less than the calculated ground water flow, replenishment may be temporarily derived from aquifer storage. That is, short-term mining of the aquifer could take place. The 200 mm

Table 7. Estimation of Total Ground-Water Flow to the Sana'a Basin.

Location	Constant Boundary Nodes	K (m/day)	b (m)	T (m^2/day)	$\overline{T}$ (m^2/day)	L(m) x 1000	$\frac{dh}{dl} = I$	Q(m^3/day) x 10^6
Northwestern Boundary	56	1.20	220	264				
					244.5	4.6	0.02	0.0225
	47	0.90	250	225				
					280.5	3.5	0.02	0.0196
	39	1.60	210	336				
					310.5	4.3	0.02	0.0267
	32	0.95	300	285				
					292.5	3.4	0.02	0.0199
	26	1.00	300	300				
Southern Boundary	1	0.98	200	196				
					210.5	4.2	0.015	0.0133
	2	0.90	250	225				
					235.0	4.5	0.015	0.0159
	3	0.98	250	245				
					180.5	3.5	0.015	0.0095
	8	0.40	290	116				
					210.0	2.9	0.015	0.0091
	4	0.95	320	304				
Northeastern Boundary	64	1.40	250	350				
					555.0	4.0	0.01	0.0222
	54	1.90	400	760				
					572.0	3.5	0.01	0.0200
	46	1.20	320	384				
					472.0	4.0	0.01	0.0189
	38	1.60	350	560				
Total flow to the basin =								0.20×10^6
By introducing 25% safety factor, the reduced flow =								0.15×10^6 m^3/day

average annual rainfall in the last 10 years has been less than the long-term average of 325 mm. It would be unwise to abstract an amount equal to the estimated long-term lateral replenishment. The total abstraction should not perhaps exceed 75 percent of the calculated ground-water flow. Therefore, the calculated flow 0.20×10^6 m/day would be reduced to 0.15×10^6 m^3/day.

Moreover, the ground-water equation (22) is very sensitive to variations in the values of transmissivity and hydraulic gradients, especially in areas similar to Sana'a basin, where the geohydrological structure is complicated and where the hydrological parameters are imperfectly known. However, a maximum effort was made in this study to investigate the entire basin with as small an error as possible.

Howard Humphreys (1980) estimated the ground-water flow to the Western and Eastern well field to be 0.085×10^6 and 0.078×10^6 m^3/day, respectively, with a total flow to both well fields of 0.16×10^6 m^3/day, but the method used in estimating the value for the Eastern well field was not presented in Howard Humphreys' report. The present study determined the total flow to the basin to be 25 percent higher than the previous estimates. There is no way to account for this discrepancy since the methodolcgy used in the Howard Humphreys' study is unknown.

Ground-Water Extraction

In this study the total extraction from 1972 to 2000 was estimated to be 1.3×10^9 m^3 and the average daily extraction over the 29 years was 0.13×10^6 m^3 (Table 6). The method used to estimate these values was discussed under pumping rate distribution in the Methods section. Pumping rate distribution of the simulated wells are presented in Appendix C. This extraction included present and future uses by the public, industry and agriculture. Approximately 40 percent of the total extraction is presently used for public consumption, 10 percent for industry and about 40 to 50 percent for agriculture. Previous studies showed that the daily consumption averaged only about half the amount (0.07×10^6 m^3) calculated in this study. However, the previous estimates did not consider future increases in population and agriculture, but assumed a constant demand. The previous studies also assumed that water would not be used for agriculture, but rather only for public consumption. Furthermore, these studies recommended restriction of the well fields only for public consumption. This is perhaps a good recommendation; but with present population growth, the absence of adequate controls on ground water use, and the necessity for industry and agriculture, it is not completely realistic.

CONCLUSIONS AND RECOMMENDATIONS

This study was designed to explore the feasibility of conjunctive use of the Western and Eastern well fields in the Sana'a basin in order to determine effects of ground water on future water supplies up to the year 2000. A preliminary appraisal of the ground-water potential and its state of development was made.

The most productive areas for ground water exploitation were found in the Cretaceous sandstone and particularly in the vicinity of the contact between tertiary lava flows and the sandstone where dense fracturing occur. Cretaceous sandstone, alluvial deposits and the Trap series form a generally continuous aquifer complex in the Sana'a basin with a combined thickness of several hundred meters.

Ground water flow to the Sana'a basin was estimated at 0.15×10^6 m^3/day. Ground water extraction, averaged for 29 years, was estimated at 0.13×10^6 m^3/day. These results showed that ground water resources in the basin are adequate to carry out the projected demand up to year 2000 if the following assumptions hold:

1. The proposed well fields are successful in terms of productivity.
2. The annual consumptive use does not increase by more than ten percent.
3. The well fields will be operated efficiently and protected against other uncontrolled spontaneous development.

If these assumptions do not hold, the promising Jurassic Kohlan sandstone which is located in the Sana'a basin should be examined very closely to determine its degree of productivity for possible future development.

In the period 1972 to 1983, ground water levels declined at a rate of about 1.50 m/year in the main pumping areas and about 0.2 m/year in areas outside of this range of abstruction. In the central part of the basin, the maximum projected drawdown for this period was 15 meters and the minimum drawdown was 2 to 3 meters.

In the period 1972 to 2000, ground water levels were projected to decline at a rate of about 1.10 m/year in the main pumping areas and about 0.15 m/year in areas outside this range of abstraction. In the central part of the basin, the maximum projected drawdown over 29 years was 30 meters and the minimum was about 5 to 10 meters. It must be expected that any further increase of ground water abstraction greater than the estimated amount would immediately result in a further decline of ground water levels. This would cause a considerable increase in investment and operational costs.

The finite element model used in this study developed by Contractor (1981) gave results within about $\pm$ 10 meters range of the actual measured heads of 1979, and this error could be due in part to inaccuracies in the input data. The model enables the exploration of alternative options for the development of the ground water resource in the Sana'a basin, and was used to predict future conditions of the resource under a variety of constraints. An important use of the model is to indicate areas where more information is needed and where the most efficient future development might be made.

At present, control of ground water extraction by a higher-level supervising organization would be urgently required in order to prevent overexploitation of the ground water resouces of the basin. Furthermore, the recording of ground water levels and rainfall in the Sana'a basin should be conducted regularly.

APPENDIX A

HYDROGEOLOGICAL PARAMETERS OF WELLS DRILLED IN THE SANA'A BASIN

Table A-1. Hydrogeological Parameters of Wells Drilled in the Sana'a Basin.

Well No.	Aquifer	Total Depth (m)	K (m/day)
SE1	Sandstone	306.00	2.00
SE2	Sanestone	250.50	1.56
SE3	Sandstone	300.00	2.42
SE4	Trap Basalt	350.00	0.58
SE5	Alluvium	151.00	1.00
SE6	Sandstone	132.00	0.10
SE7	Sandstone	208.00	2.17
SE8	Sandstone	99.50	?
SE9	Basalt	166.00	0.58
ST1	Sandstone	250.00	2.6
ST2	Sandstone	88.50	2.42
ST3	Alluvium	167.50	0.80
ST4	Sandstone	200.00	0.70
ST5	Sandstone	200.00	0.20
ST6	Sandstone	128.00	1.00
ST7	Sandstone	200.00	18.15?
1W	Sandstone	?	2.42
GW-1	Sandstone	184.00	0.90
GW-2	Sandstone	181.00	0.90
P1	Sandstone	177.00	3.68
P6	Sandstone	220.00	0.60
P7	Sandstone	191.00	1.15
P8	Sandstone	215.00	0.90
P9	Sandstone	158.00	3.78
P10	Sandstone	220.00	0.30
P14	Sandstone	222.00	1.50
P15	Sandstone	153.00	1.18
P16	Basalt/Sandstone	220.00	6.30
P17	Sandstone	165.00	1.45
P13	Alluvium/Sandstone	220.00	0.90
P18	Sandstone	225.00	3.20
P19	Alluvium/Sandstone	225.00	0.80
P20	Sandstone	200.00	1.40
P21	Sandstone	209.00	0.64
02	Sandstone	98.00	12.33
03	Sandstone	202.00	0.80
04	Sandstone	117.01	0.20
05	Sandstone	202.00	0.60
011	Sandstone	220.00	0.10
012	Sandstone	214.00	0.10
EX1	Sandstone	137.00	48.00
EX2	Sandstone	202.00	0.32
EX3	Sandstone	200.00	0.20

Table A-1. -- Continued

Well No.	Aquifer	Total Depth (m)	K (m/day)
EX4	Sandstone	202.00	0.76
ST8	Sandstone	200.00	2.10
ST9	Sandstone	200.00	2.10
ST10	Sandstone	200.00	2.70
ST11	Sandstone	200.00	0.50
ST12	Sandstone	200.00	1.10
ST13	Sandstone	200.00	0.95

APPENDIX B

K VALUES OBTAINED USING SUBJECTIVE HYDROGEOLOGICAL INTERPOLATION, SPECIFIC CAPACITY OF WELLS, AND CALIBRATION TECHNIQUE

Table B-1. K Values Obtained Using Subjective Hydrogeological Interpolation.

Element Number	Aquifer Characteristics	K (m/day)
33	Trap series and sandstone obtained from G.C.S. A-A'	0.58
49	Alluvium and S.S. fractured similar to well SE 1	2.00
71	S.S., fractured, similar to wells SE 7, obtained from G.C.S.A-A'	2.10
74	S.S., fractured similar to wells EX3, SE3, obtained from G.C.S. A.A'	2.10 1.10
77	S.S., fractured, similar to wells SE7, P15	1.65
80	S.S., fractured, similar to wells SE3, EX3, obtained from B.C.S. A.A'	1.50
85	S.S., fractured, similar to wells P15, P17, P21, SE7	2.07
87	S.S., primary permeability and Trap series, similar to wells GW1, 2	1.00
88	S.S., fractured, similar to well SE3	2.40
96	S.S. and alluvium, similar to well P21	0.90
98	S.S. and alluvium, similar to well P21	1.10
99	S.S., fractured, obtaned from G.C.S.A-A'	2.10
103	S.S., with primary permeability, obtained from G.C.S.C-C'	0.24
104	S.S., with primary permeability, obtained from G.C.S.C-C'	0.24
106	S.S., with primary permeability, obtained from G.C.S.C-C1'	0.24
107	S.S., with primary permeability, obtained from G.C.S.A-A'	0.24
108	S.S. with primary and secondary permeability	1.00
110	Alluvium, S.S. fractured	0.90
111	S.S., primary permeability	0.24
113	S.S., fractured due to lava flow	1.60
115	S.S., primary permeability	0.24
116	S.S., primary permeability	0.24
118	Alluvium with S.S. with primary permeability	0.24
119	Alluvium, S.S. and limestone	1.10
122	Alluvium, S.S. and limestone	1.10
123	Alluvium, S.S. and limestone	1.10
126	Alluvium, S.S. and limestone	1.10
131	Alluvium and fractured sandstone	1.10
134	Alluvium and fractured sandstone	1.10

G.C.S. = Geological Cross-Section.
S.S. = Sandstone.
T.S. = Trap Series.

Table B-2. K Values Obtained Using Specific Capacity of Existing Nearby Wells.

Element Number	Aquifer	Wells Used For Estimating K	K (m/day)
23	Alluvium	GW1	0.48
25	Alluvium	ST3	0.76
29	Alluvium	SE5, ST3	0.76
39	Trap series	SE4	1.65
48	Trap series	SE9	1.48
49	Trap series	P18	1.60
54	Sandstone	P16, ST1	2.50
55	Sandstone	SE2	1.09
60	Sandstone	P10	1.09
61	Sandstone	EX1	2.20
65	Sandstone	SE6	1.55
66	Sandstone	ST10	1.49
67	Sandstone	EX2	1.19
72	Sandstone	P8, ST9	1.19
73	Sandstone	ST10	1.19
78	Sandstone	02, P7	2.19
79	Sandstone	ST13, ST4, ST12	0.81
81	Sandstone	IW, ST2, SE3	1.47
86	Sandstone	P7, P20, P15	1.47
89	Sandstone	EX4	1.46
95	Sandstone	P21, P15	1.46
97	Sandstone	GW2	1.14

Total = 22

Table B-3. K Values Obtained by Calibration Technique.

Element Number	Aquifer	K (m/day)
1	Fractured sandstone	1.54
2	Fractured S.S. and Trap series	0.90
3	Trap series and fractured sandstone	0.90
4	Trap series, dike, and fractured S.S.	0.90
5	S.S., primary permeability, T.S.	0.24
6	S.S., primary and secondary permeability	0.90
7	Trap series	0.58
8	Trap series	0.58
9	S.S., primary permeability and Trap series	0.58
10	S.S., fractured due contact	2.00
11	Trap series	0.58
12	Trap series	0.58
13	Trap series	0.58
14	Trap series	0.58
15	Trap series	0.58
16	Trap series	0.58
17	Trap series	0.58
18	Trap series	0.58
19	Trap series	0.58
20	Trap series	0.58
21	S.S., fractured and Trap series	0.75
22	S.S. primary permeability	0.65
24	S.S., Trap series	0.58
26	Alluvium	0.70
27	Alluvium	0.70
28	Alluvium	0.70
30	Sandstone primary permeability and Trap series	0.60
31	Alluvium	0.70
32	Trap series	0.58
34	Trap series	0.58
35	Trap series	0.58
36	S.S. fractured and Trap series	1.40
37	S.S. and alluvium	1.10
38	S.S. fractured	2.20
40	S.S. and Trap series	1.60
41	S.S. fractured and Trap series	1.50
42	S.S. and Trap series	1.60
43	S.S. fractured	2.10
44	S.S. fractured and alluvium	1.90
45	Alluvium and S.S. fractured	1.75
46	Alluvium and S.S. fractured	1.75
47	Trap series	0.58
50	Alluvium and S.S.	1.56
51	S.S. fractured, alluvium	2.10

Table B-3. -- Continued

Element Number	Aquifer	K (m/day)
52	Trap series	0.58
53	Trap series and S.S.	0.70
56	Alluvium and sandstone fractured	1.60
57	Alluvium and sandstone fractured	1.60
58	Alluvium and sandstone fractured	1.60
59	Sandstone and Trap series	0.90
62	S.S. fractured and Trap series	2.10
63	S.S. fractured and Trap series	2.10
64	Sandstone fractured	2.50
68	S.S. primary and secondary permeability	0.90
69	S.S. fractured and Trap series	2.10
70	S.S. fractured and Trap series	2.10
75	S.S. primary permeability and Trap series	1.10
76	S.S. fractured and Trap series	2.10
82	S.S. fractured and Trap series	2.10
83	S.S. fractured and Trap series	2.10
84	S.S. fractured and Trap series	1.60
90	S.S. fractured and Trap series	1.70
91	S.S. fractured and Trap series	2.10
92	S.S. fractured and Trap series	2.10
93	S.S. fractured and Trap series	2.10
94	S.S. fractured and Trap series	2.10
100	S.S. fractured and Trap series	2.10
101	S.S. fractured and Trap series	2.10
102	S.S. fractured and Trap series	2.10
105	S.S. fractured and Trap seris	2.10
109	Sandstone and Trap series	1.10
112	Trap series	0.58
114	S.S. primary permeability and Trap series	0.90
117	S.S. primary permeability and Trap series	0.90
120	Alluvium and sandstone	0.75
121	Sandstone and limestone	0.50
124	Alluvium and sandstone	0.65
125	Alluvium and sandstone	0.75
127	Alluvium and sandstone	0.75
128	Alluvium and sandstone	0.75
129	Alluvium and sandstone	0.75
130	Alluvium and sandstone	0.75
132	Alluvium and sandstone	0.75
133	Alluvium and Trap series	0.93
135	Alluvium and Trap series	0.93
84 Total		

APPENDIX C

PUMPING RATE DISTRIBUTION OF THE SIMULATED WELLS FOR THE PERIOD 1972-2000

Table C-1. Pumping Rate Distribution of the Simulated Wells for the Period 1972-2000 (m^3/day).

Well No.	42	41	44	49	59	35	60	A4	A3
July									
1972	192.96	257.3	188.1	385.1	988.9	1714.1	1965.0	2645.2	1575.8
1973	212.4	283.0	207.0	424.5	1088.6	1885.5	2161.5	2909.7	1733.4
1974	233.28	311.3	227.65	467.00	1197.4	2074.1	2377.6	3200.6	1906.8
1975	257.0	342.4	250.4	513.7	1317.1	2281.5	2615.4	3520.7	2097.4
1976	282.2	376.7	275.5	565.0	1448.9	2509.7	2877.0	38728	2307.2
1977	310.3	414.3	303.0	621.5	1593.7	2760.6	3164.6	4260.1	2537.9
1978	342.0	455.8	333.3	683.7	1753.1	3036.7	3481.1	4686.1	2791.7
1979	375.84	501.4	366.6	752.0	1928.4	3340.4	3829.2	5154.7	3070.9
1980	413.3	551.5	403.3	827.3	2121.3	3674.4	4212.1	5670.2	3378.0
1981	455.0	606.6	443.6	910.0	2333.4	4041.8	4633.3	6237.2	3715.7
1982	500.4	667.3	488.0	1000.0	2566.7	4446.0	5096.6	6860.9	4087.3
1983	550.0	734.0	536.8	1101.0	2823.4	4890.6	5606.3	7547.0	4496.1
1984	605.5	807.0	590.5	1211.0	3105.8	5379.7	6166.9	9131.9	4945.7
1985	666.0	888.0	649.5	1332.0	3416.3	5917.6	6783.6	10045.1	5440.2
1986	732.24	977.0	714.4	1466.0	3758.0	6509.4	7462.0	11049.6	5984.2
1987	805.7	1074.7	785.9	1612.0	4133.8	7160.3	8208.2	12154.5	6582.6
1988	886.3	1182.2	864.5	1773.0	4547.1	7876.4	9029.0	13370.0	7240.9
1989	974.9	1300.0	950.9	1951.6	5001.86	8664.0	9931.9	14707.0	7965.0
1990	1072.0	1430.4	1046.0	2146.0	5502.0	9530.4	10925.1	16177.7	8761.5
1991	1179.4	1573.5	1150.6	2360.0	6052.2	10483.5	12017.6	17795.4	9637.6
1992	1297.4	1730.8	1265.7	2596.0	6657.5	11531.8	13219.4	19575.0	10601.4
1993	1427.0	1903.9	1392.3	2856.0	7323.2	12685.0	14541.3	21532.5	11661.6
1994	1570.3	2094.3	1531.5	3141.5	8055.5	13953.5	15995.4	23685.1	12827.7
1995	1727.3	2303.7	1684.6	3456.0	8861.1	15348.8	17595.0	26054.3	14110.5
1996	1900.0	2534.1	1853.1	3801.1	9747.2	16883.7	19354.5	28659.7	15521.5
1997	2089.4	2787.5	2038.4	4181.0	10721.9	18572.1	21289.9	31525.7	17073.7
1998	2298.96	3066.2	2242.2	2499.0	11794.1	20429.3	23418.9	34678.2	18781.1
1999	2528.6	3372.8	2466.5	5059.4	12973.5	22472.2	25760.8	38146.1	20659.2
2000	2781.4	3710.0	2713.1	5565.4	14270.9	24719.4	28336.9	41960.7	22725.1

Table C-1. -- Continued

Well No. 61		51	50	A5	62	A1	22	52	A2
July									
1972	1206.0	1591.9	1591.5	1809.0	1232.3	1287.2	804.4	998.6	238.6
1973	1326.6	1751.1	1751.1	1989.9	1355.5	1415.9	884.8	1098.5	262.5
1974	1459.3	1926.2	1926.2	2188.9	1491.0	1557.5	973.3	1208.3	288.7
1975	1605.2	2118.8	2118.8	2407.8	1640.1	1713.3	1070.7	1329.1	317.6
1976	1765.7	2330.7	2330.7	2648.6	1804.2	1884.6	1177.7	1462.1	349.4
1977	1942.3	2563.8	2563.8	2913.4	1984.6	2073.1	1295.5	1608.3	384.3
1978	2136.5	2820.1	2820.1	3204.8	2183.0	2280.4	1425.1	1769.1	422.7
1979	2350.2	3102.2	3102.2	3525.2	2401.3	2508.4	1567.6	1946.0	465.0
1980	2585.2	3412.4	3412.4	3877.8	2641.5	2759.2	1725.4	2140.6	511.5
1981	2843.7	3753.6	3753.6	4262.5	2905.6	3035.2	1896.7	2354.7	562.7
1982	3128.1	4129.0	4129.0	4692.1	3196.2	3338.7	2086.4	2590.1	618.9
1983	3440.9	4541.9	4541.9	5161.3	3515.8	3672.5	2295.1	2849.1	680.8
1984	3785.0	4996.1	4996.1	5677.4	3867.4	4034.8	2524.6	3134.0	748.9
1985	4163.5	5455.7	5455.7	6245.2	4254.1	4443.8	2777.0	3447.4	823.8
1986	4579.9	6045.2	6045.2	6869.7	4679.5	4888.2	3054.7	3792.2	906.2
1987	5037.9	6649.8	6649.8	7556.6	5147.5	5377.0	3360.2	4171.4	996.8
1988	5541.6	7314.7	7314.7	8312.3	5662.2	5914.7	3696.2	4588.5	1096.5
1989	6095.8	8046.2	8046.2	9143.5	6228.4	6506.1	4065.8	5047.4	1206.1
1990	6705.4	8850.8	8850.8	10057.9	6651.3	7156.7	4472.4	5552.1	1326.8
1991	7375.9	9735.9	9735.9	11063.7	7536.4	7872.4	4919.17	6107.4	1459.4
1992	8113.5	10709.5	10709.5	12170.0	8290.1	8659.7	5411.6	6718.1	1605.4
1993	8924.9	11780.5	11780.5	13387.1	9119.1	9525.6	5952.8	7389.9	1765.9
1994	9817.4	12958.5	12958.5	14725.8	10031.0	10478.2	6548.1	8128.9	1942.5
1995	10799.1	14254.4	14254.4	16198.3	11034.1	11526.0	7202.9	8941.8	2136.7
1996	11879.0	15679.8	15679.8	17818.2	12137.5	12678.6	7923.1	9835.9	2356.4
1997	13066.9	17247.8	17247.8	19600.0	13351.2	13946.5	8715.5	10819.5	2585.5
1998	14373.6	18972.5	18972.5	21560.0	14686.3	15341.1	9587.0	11901.5	2844.0
1999	15811.0	20869.8	20869.8	23716.0	16155.0	16875.2	10545.7	13091.6	3128.4
2000	17392.1	22956.8	22956.8	26087.6	17770.5	18562.8	11600.3	14400.8	3441.2

Table C-1. -- Continued

Well No.	70	48	16	36	77	78	79	29
July								
1972	1481.2	1040.6	141.50	1055.38	170.45	707.52	375.20	379.49
1973	1629.32	1144.77	155.65	1160.92	187.49	778.27	412.72	417.44
1974	1792.3	1259.18	171.22	1277.01	206.24	856.10	453.99	459.18
1975	1971.5	1385.10	188.34	1404.72	226.87	941.71	499.39	505.o0
1976	2168.6	1523.6	207.18	1545.19	249.55	1035.88	549.33	555.61
1977	2385.46	1675.97	227.89	1699.71	274.51	1139.47	604.26	611.17
1978	2624.01	1843.57	250.68	1869.68	301.96	1253.41	664.69	672.29
1979	2886.4	2027.9	275.75	2056.64	332.15	1378.75	731.16	739.51
1980	3175.05	2230.71	303.33	2262.31	365.37	1516.63	804.28	813.47
1981	3492.55	2453.79	333.66	2488.54	401.91	1668.29	884.70	894.81
1982	3841.8	2699.16	367.02	2737.39	442.10	1835.12	973.17	984.29
1983	4225.99	2969.08	403.73	3011.13	486.31	2018.63	1070.49	1082.72
1984	4648.59	3265.99	444.1	3312.25	534.94	2220.5	1177.54	1191.00
1985	5113.45	3592.59	488.51	3643.47	588.43	2442.54	1295.29	1310.1
1986	5624.79	3951.85	537.36	4007.82	647.28	2686.8	1424.82	1441.11
1987	6187.27	4347.03	591.10	4408.6	712.00	2955.48	1567.31	1585.22
1988	6806.00	4781.73	650.21	4849.46	783.20	3251.03	1724.04	1743.74
1989	7486.6	5259.91	715.23	5334.41	861.52	3576.13	1896.44	1918.11
1990	8235.25	5785.9	786.75	5867.85	947.68	3933.74	2086.08	2109.92
1991	9058.78	6364.49	865.43	6454.63	1042.44	4327.12	2294.69	2320.91
1992	9964.66	7000.9	951.97	7100.1	1146.69	4759.83	2524.16	2553.01
1993	10961.12	7701.03	1047.16	7810.11	1261.36	5235.81	2776.58	2808.31
1994	12057.24	8471.13	1151.88	8591.12	1387.49	5759.39	3054.24	3089.14
1995	13262.96	9318.25	1267.07	9450.23	1526.24	6335.33	3559.66	3398.05
1996	14589.26	10250.07	1393.78	10395.25	1678.87	6968.86	3695.63	3737.86
1997	16048.18	11275.08	1533.15	11434.78	1846.75	7665.75	4065.19	4111.64
1998	17653.00	12402.59	1686.47	12578.25	2031.43	8432.33	4471.71	4522.80
1999	19418.3	13642.85	1855.12	13836.08	2234.57	9275.56	4918.88	4975.09
2000	21360.13	15007.13	2040.63	15219.69	2458.03	10203.11	5410.77	5472.59

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