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Submitted to

Brown & Root (Overseas) Ltd.
Houston, Texas

by

Utah Water Research Laboratory
Utah State University
Logan, Utah

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EXECUTIVE SUMMARY

The basic purpose of this study was to construct a finite-element computer model and give an independent appraisal of the reliability of the groundwater supply for the proposed Coastal Belt Water Project (CBWP) Well Fields at Sarir and Tazerbo. There is no doubt that ample quantities of groundwater of acceptable quality occur at the sites selected for these well fields for the estimated 50-year life of the project and longer. Of major concern is the predicted drawdown of wells and total pumping lifts throughout the 50-year period. Excessive drawdowns could cause operating costs to become prohibitively expensive.

Average drawdown in wells not including well-field interference and hydraulic friction losses at the CBWP Well Field at Sarir is expected to be only about 30 m at the end of 50 years, but the static water level is relatively deep (56 m) which makes the total pumping lift fairly high when well-field interference and other losses are added. This optimistic estimate of drawdown is based upon computer analysis for almost 7 years of pumping history of the existing Sarir South agricultural well field nearby, where the subsurface geology is believed to be quite similar to that at the proposed CBWP Well Field at Sarir. The average pumping lift, which includes many other factors besides aquifer drawdown, is estimated to be about 142 m at the end of the 50-year pumping period at Sarir and should average about 136 m during the 50 years. Interference from pumpage at the existing agricultural well fields at Sarir may be responsible for about 10 m of this predicted pumping lift.

Drawdown at Tazerbo is predicted to be about 90 m at the end of 50 years, but the static water level is only about 9 m there. Consequently

its average pumping lift should be about 133 m at the end of the 50-year pumping period and should average about 118 m during the 50 years. No appreciable interference from nearby well fields is expected in the Tazerbo area based upon presently known conditions.

Significant reductions in pumping lifts at Tazerbo and in water-collection network costs at Sarir are possible by improved well field layout and well design. Suggested improvements and estimated cost savings are presented in detail in Appendix A (especially see well-field design comparisons of Tables A-1 and A-4).

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INTRODUCTION

The vast majority of Libyan citizens live in a narrow belt of land adjoining the Mediterranean Sea where good roads, communications, and soils are found. Groundwater of the coastal belt is in short supply and usually is of poor quality. Development of the coastal belt has been impeded severely by lack of good quality water. Surface water supplies are extremely limited, but large areas of land are available for cultivation and irrigation. Vast quantities of high quality groundwater exist in the interior, both in the east and west portions of the nation. This water is a residue left mainly from the Pleistocene Epoch when the region was an extensive grassland and precipitation was considerable. Presently the inland area is a severe desert (a part of the great Sahara of North Africa) with average annual rainfall of only a few millimeters.

For many years Libyans have contemplated bringing this water from the desert to enhance municipal supplies and expand agriculture and industry in the coastal belt. The Socialist People's Libyan Arab Jamahiriya (SPLAJ or Libya) is now pressing forward with this major project, unprecedented in the history of groundwater conveyance by aqueduct.

Brown & Root (Overseas) Limited of Houston, Texas, is performing the master planning and engineering for the overall water gathering, conveyance, and distribution system of the Coastal Belt Water Project (CBWP) under the direction of the Secretariat of Land Reclamation and Agricultural Development (SLRAD). Utah Water Research Laboratory (UWRL) was selected as a subcontractor to Brown & Root to evaluate the groundwater resources in eastern Libya where groundwater will be developed initially for this project. Although groundwater studies have been made previously in this region, an independent appraisal using the latest computer modeling techniques and a longer pumping history of nearby well fields became mandatory in view of the importance and cost of the project.

UWRL was awarded this task in January 1982. After a period of model adaptation, data collection, and other preliminary work, intensive groundwater modeling and well-field design studies began in the summer of 1982. The well-field design studies were completed in February 1983 and the main appraisal of groundwater supply and reliability was finished in March 1983. This project report describes and documents the completed work, summarizes the results, and sets forth the conclusions (see page 84) of this groundwater feasibility evaluation.

DESCRIPTION OF STUDY AREA

Geography and Existing Water Use

Sites selected for initial groundwater development are in the Sarir region of Cyrenaica, the eastern-most province of Libya. The first well field to be constructed, called the Coastal Belt Water Project (CBWP) Well Field at Sarir, is to be located about 370 km south-southeast of the Gulf of Sirte at approximately 27°30' north latitude and 21°30' east longitude. The second, called the CBWP Well Field at Tazerbo, is to be located about 200 km south of the CBWP Well Field at Sarir and roughly 40 km southeast of the oasis of Tazerbo. Figure 1 is a map of the study area showing the locations of these proposed well fields, the existing well fields, and other salient geographical features. Each CBWP well field is designed to produce 350,000,000 m^3/year of groundwater. Two existing well fields (Sarir North and Sarir South, also shown on Figure 1) are already supplying water for SLRAD farming projects in the Sarir region.

The Sarir region is principally a broad, flat plain covered with coarse sand and fine gravel (this is the meaning of the word Sarir in Arabic). Except for a few scattered dunes and some other land forms of very low relief, travel in the region is unobstructed. The land surface tilts very gently to the north and east but no strongly identifiable drainages occur except along the western margin where a few intermittent streams enter the region from the Tibestis and other highlands to the west of the Sarir region. The east and southwest flanks of the region are bounded by extensive sand seas. To the north the Sarir region

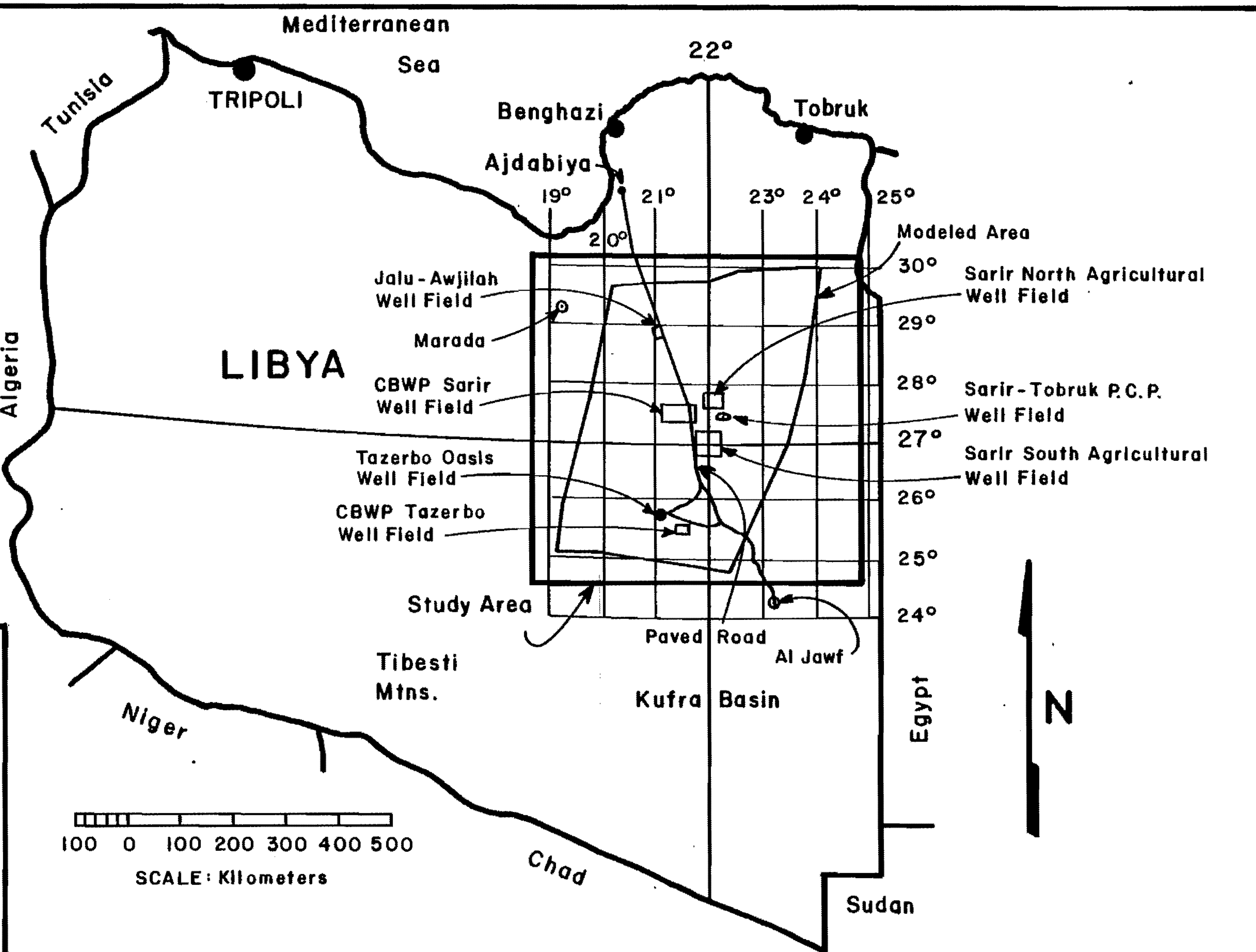


Figure 1
Location Map of
Study Area

ends in an area of low hills where a few inhabited oases are found, such as Marada, Jalu, and Awjilah. The only other historically inhabited oasis is at Tazerbo near the southwest extremity of the Sarir region.

A new paved road is nearing completion, which traverses the region from north to south and will soon connect the Sarir region to the coastal belt and to the large structural and groundwater basin to the south, called the Kufra Basin (see Figure 1). Since 1970 the Libyan government has been operating large modern farms using groundwater near Al Jawf, the principal oasis of the Kufra region.

The Kufra Basin is filled with enormous quantities of very high quality groundwater, a portion of which is flowing towards the Sarir region. This underground flow appears to be the principal source of present recharge to the Sarir aquifers. Anciently there must have been proportionately more contribution from the highlands of the west and southwest. Subsequent phases of the Coastal Belt Water Project envision the use of groundwater from Kufra. Its potential groundwater reserves of high quality water can outlast all other Libyan sources and its waters can be used to dilute and supplement waters from other regions, such as Sarir, if they ever become too saline for direct use.

A small field of 16 wells will be constructed just east of and between the two Sarir agricultural well fields. This well field will supply water to the area of Tobruk (see Figure 1) on the northeast coast of Libya. A petroleum pipeline that conveys crude oil from the Sarir Oil Field to Tobruk will be converted to a water pipeline for this purpose. Starting in 1985 this Sarir-Tobruk Pipeline Conversion Project will convey about 83,000 m^3/day from the Sarir region to the coast.

About 40 km southwest of Awjilah, 33 wells will supply water through a pipeline to 100 small farms on 600 ha adjoining Awjilah oasis. This project (the Jalu-Awjilah Agricultural Project) will require water in three stages building up from a 1983 pumping rate of about 56,000 m^3/day to 167,000 m^3/day in a few years. A small agricultural project is presently under construction at the oasis of Tazerbo. Upon completion it will pump about 55,000 m^3/day. There are 12 artesian flowing wells at Marada, where 250 ha are irrigated by an average of 8,600 m^3/day. These small well fields are shown on Figure 1.

Boundaries

The Sarir region itself is roughly 450 km long in the north-south direction and ranges up to 200 km wide. A square area of roughly 600 km on each side including the Sarir region was investigated for this groundwater modeling study. Piezometric groundwater levels and other pertinent data were collected and studied in the preparatory work of setting up the computer model. Boundary conditions for the model were the most important consideration in this regional approach. Based upon the regional data, the exact area for the computer model was selected. It is rectangular, about 500 km long in the north-south direction and about 350 km wide. Figure 1 shows the outlines of the regional study and the modeled area.

Regional Geology

The CBWP well fields will be located in the southern end of the Sirte Basin, which is a large structural basin flanking the stable African shield. The CBWP Well Field at Tazerbo is in a transitional area that separates the Sirte Basin from the Kufra Basin. There are widely divergent interpretations of the subsurface geology in the Tazerbo area because of meager exploratory drilling done there. The Sirte Basin has been much more active geologically than the relatively stable Kufra Basin.

The Sirte Basin thickens considerably from south to north due mainly to faulting and subsidence in the basement complex, which began in late Cretaceous time. Basement rocks occur about 2600 m below the land surface at the CBWP well field site at Sarir and about 2000 m at the Tazerbo site (Pallas 1980). Marine facies diminish to the south and upward in the sedimentary sequence that fills the basin. Nonmarine Mesozoic sediments will be tapped at the CBWP Well Field at Tazerbo. At Sarir a few stringers of marine sediments may lie within the producing interval and certainly marine sediments are very close below the non-marine, largely fluviatile deposits to be opened to production there.

Groundwater in the modeled area percolates generally northward passing through progressively younger formations. Paleozoic rocks crop out at the northern extremity of the Kufra Basin and dip gently to the southeast. Evidently groundwater is percolating northward through these rocks (and the overlying Mesozoic rocks) into the south extremity of the Sirte Basin where the subsurface geology is complicated and little is known about it. A few petroleum test wells drilled near Tazerbo and northward revealed about 2000 m of Paleozoic and Mesozoic sediments overlie the basement rocks and that an overlying wedge of Tertiary sediments begins at the latitude of Tazerbo and thickens and dips northward into the Sirte Basin (Pallas 1980). Deep-seated faults in the basement and overlying rocks, buried erosional surfaces, and other structural features of the pre-Tertiary rocks appear to have little effect upon the northward movement of at least the shallow, exploitable groundwater.

Groundwater at Tazerbo will be extracted principally from poorly consolidated Mesozoic sandstones composed mainly of quartz particles with virtually no saline minerals. Uppermost Oligocene, lower and middle Miocene (LMM), and some younger alluvial deposits will yield groundwater to the CBWP Well Field at Sarir (Wright 1975). The well field near Awjilah will tap the younger Calanscio aquifer of post-middle Miocene (PMM) age (Wright et al. 1979). North of Awjilah even this aquifer becomes saline, as have all the older formations before this point. The Sirte Basin continues a considerable distance to the northwest from the Sarir region, which is merely a geographic region in the southeast portion of the structural Sirte Basin.

The lower and middle Miocene (LMM) formations, comprising the main aquifer at the CBWP Well Field at Sarir and the Sarir agricultural well-field sites, dip gently and thicken slightly toward the northeast in that area. This sequence, called the Marada formation, is a series of fluviatile, medium- to coarse-grained sands with minor thicknesses of clay strata. These grade from the southwest into transitional shore-line deposits through the CBWP Sarir well field area and grade finally into marine limestones, dolomites, shales, and clays with minor thicknesses of sandstones and sands beyond that area to the northeast (Wright et al. 1974). The average thickness of the Marada formation in this vicinity is about 365 m and it dips only about 2 m/km (Wright 1975).

Because of this dip to the northeast, upper Oligocene formations will be tapped in the southwest part of the proposed CBWP Well Field at

Sarir. The Oligocene formations likewise are composed mainly of fluviatile sands with streaks of clay in the southwest part of the CBWP Sarir site where it will be tapped. Beneath the proposed producing interval it will grade vertically downward and laterally (northeastward) to marine limestones, sandstones, sandy limestones, calcarenites, sand, and shales, wherein water quality deteriorates rapidly (Wright 1975). These formations of relatively low permeability should be considered the bottom of the effective thickness of the regional fresh-water aquifer. Eocene and older sediments occur below the Oligocene and generally contain saline groundwater.

The overlying post middle Miocene (PMM) Calanscio formation also dips to the northeast. As it extends from the land surface to the top of the LMM, its thickness ranges from zero at the southwest edge of the proposed well-field site to almost 100 m at the northeast edge (Wright 1975). Most of it is above the water table and all of it will be above the producing interval, but it will be a source of water to the underlying LMM aquifer as it has been in the Sarir agricultural well fields. It is mainly a sandy, fluviatile deposit containing high quality water in most of the Sarir region. The lowering of piezometric head and the dewatering of this aquifer or the LMM can cause subsidence in time due to consolidation of the clays. This formation is the principal aquifer in the area of the 33-well Jalu-Awjilah Agricultural Project. Reworked Paleozoic and Mesozoic clastics have been the major source of the post-Eocene fluviatile and transitional deposits.

One prominent line of demarcation between marine facies on the northeast and transitional facies on the southwest appears to run from the southeast between the Sarir North and Sarir South well fields extending to the northwest just north of the proposed CBWP Sarir well field site. Thus it is inferred that the proposed new well field will have a hydrogeologic performance more like the Sarir South well field, which has shown appreciably less drawdown to date than the Sarir North well field because of the stratigraphy.

Regional Hydrology

The piezometric contours of Figure 2 were plotted by computer from observed water levels in wells and piezometers in the principal aquifer taken before major pumping began. The contours indicate there is a sizable groundwater flow entering the study area from the Kufra Basin and percolating generally northward through the region. There appears to be fairly free hydraulic communication between all the post-Eocene formations over longer periods of time although clay and other low permeability facies may impede this communication over short periods especially in the vertical dimension.

Piezometric contour maps of broader studies also indicate that only trivial amounts of groundwater recharge may be occurring in the Tibesti and other highlands west of the Kufra and Sirte Basins. Radiocarbon dating of groundwaters of these basins (Edmunds and Wright 1979) show groundwater ages ranging from 5000 years in shallow aquifers to 34,000 years in deeper aquifers. Of course there has been subsequent recharge of a relatively minor nature, but the bulk of the fresh water in the Sarir region is of prehistoric emplacement.

A very sharp increase in precipitation would have to occur to produce appreciable recharge to the Sarir region. Renewed groundwater recharge percolating into the region from the adjoining highlands

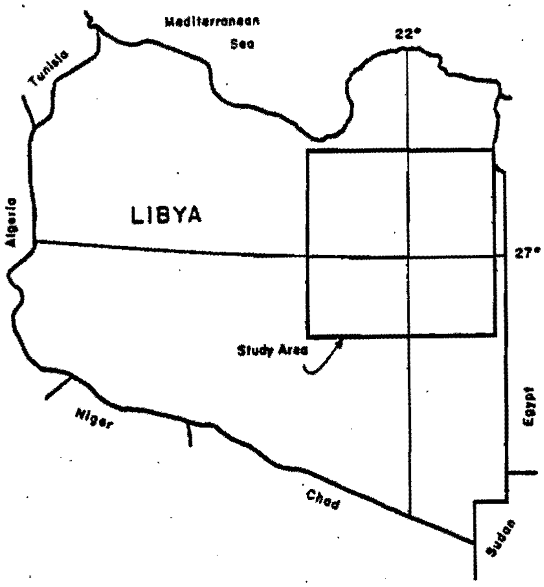
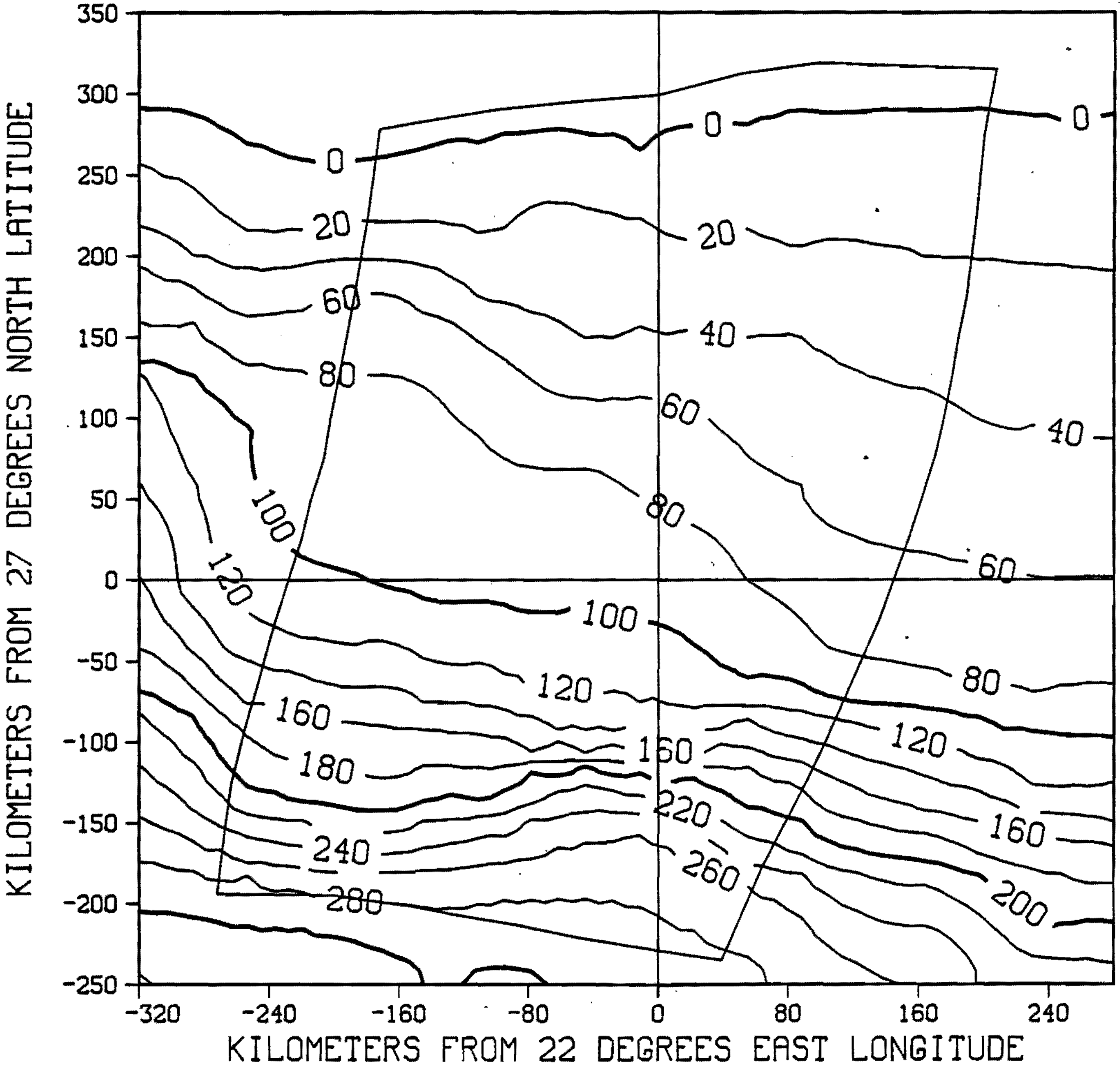


FIGURE 2
PIEZOMETRIC SURFACE IN
STUDY AREA BEFORE 1975
Contour Interval 20m



would not reach the CBWP well fields within the next 100 years because the hydraulic diffusivity of the fresh-water system is too low. Massive overland flooding along ancient drainages from the highlands could bring fresh recharge close to the well field areas, but this is most unlikely during the projected well-field life. Even then considerable time would be required for the water to infiltrate the land surface and reach the producing intervals of the wells. Hence, there is no reason to expect any significant groundwater increments from modern-day recharge. The mechanism of infiltration of flash flooding in the low lands plus relatively more rapid movement of groundwater along subsurface fluviatile channels may explain some of the irregular patterns of water quality distribution in the Sarir region.

All CBWP well field discharge will come from local groundwater storage as induced by pumpage, plus whatever may be intercepted from the regional groundwater flow. This regional underflow moving northward results from prehistoric recharge and a gradual decay of water levels up-gradient (and locally) in response to sharply reduced but fluctuating recharge during the past 5000 years. Nevertheless, the groundwater in storage and the underflow near the Sarir well fields is sufficient to supply these fields for many years. For example, assuming a specific yield of only 0.04 for the 100 m of water saturated formations above the producing interval of the Sarir South well field, those overlying formations alone contain a 50-year water supply at the present average level of discharge (400,000 m^3/day). This assumes no production from the principal aquifer nor any lateral inflow to the well field from any level.

The Sarir agricultural well fields will receive in time some water from deep percolation of excess irrigation. This water will be of greatly increased salinity depending upon the irrigation efficiency of the agricultural operations.

Petroleum exploration in the Sirte Basin has led to the delineation and development of sizable groundwater as well as oil and gas reserves. Groundwater reserves extend to great depths in the basin, but water quality generally deteriorates with depth and distance northward. The highest quality groundwater occurs at shallower more readily exploitable depths and in irregular patterns of areal distribution near the middle of the southern part of the basin. Peripheral areas of the basin generally have poor quality groundwater even at shallow depths, except in the south where the groundwater in the Tazerbo area is of very high quality. Groundwater of the adjoining Kufra Basin is of exceptionally high quality even to depths of 2000 m. In many areas of the Sarir region a thin layer of lower quality groundwater (probably a relic of the recent change to arid climate) occurs above the main body of high quality water. Below the main aquifer the water quality again is lower and continues to deteriorate with depth. Water quality is partly related to the geology of the region, because the particle size and solubility of constituent minerals in the alluvial and marine deposits affect water chemistry.

As groundwater moves northward into the rapidly thickening Sirte Basin sediments, water quality rapidly deteriorates with depth as it encounters more saline formations, but the groundwater that remains relatively shallow does not suffer rapid deterioration. The shallow groundwater encounters mainly nonsaline alluvial sediments and probably has received post-Pleistocene recharge locally at least until some time after the wet period of about 6,000 years ago which has kept it relatively fresh.

SUMMARY OF AVAILABLE DATA

Other Studies

The Institute of Geological Sciences of the Natural Environmental Research Council of Great Britain (IGS) conducted the first in-depth hydrogeologic studies in the Sarir region initially for British Petroleum Exploration Co. (Libya) Ltd. and subsequently for the Libyan government. A finite-difference model was made of the Sarir region north of the 28° parallel of latitude (Wright et al. 1974). It focused on the then proposed Jalu-Awjilah well field, which was more recently modeled by Shaath (1976) using the U.S. Geological Survey (USGS) finite-difference model. Wright and others of the IGS have continued to publish results of their subsequent studies of the region. Although they have made detailed groundwater investigations south of the 28° parallel, they have never modeled that area.

Tipton and Kalmbach, Inc., consulting engineers from Denver, Colorado, were the next to study the Sarir region. They retained Electowatt, a European consulting firm, who modeled the Sarir region and made the first well field designs for the Sarir agricultural project in 1973 and 1974. They also made a design for the Jalu-Awjilah well field.

From 1975 to 1977 Moid Ahmad of Hygronics, Inc., Athens, Ohio, redesigned the Sarir agricultural well fields and predicted their performance using the USGS model. These well fields were constructed according to his designs. He later recommended roughly the same design for the CBWP Well Field at Sarir (Ahmad, ElBakhbakhi et al. 1979) and a modified yet similar design for the CBWP Well Field at Tazerbo (Ahmad 1979) based on the same USGS model.

Meanwhile, the Engineering Consultants Group (ECG), an Egyptian consulting firm from Cairo, directed the exploration of the CBWP Sarir well field area and designed a well field using a Theis digital model and also designed the aqueduct to the coastal belt (ECG 1978). Presently Ahmad's designs for both CBWP well fields are to be used.

Base Maps

Numerous maps appear in the various reports made available for this study. However, there were discrepancies among them which had to be resolved and serious distortions were evident from the various reproduction methods used. Accordingly, an original base map of the CBWP Sarir well field and the Sarir agricultural well field area was drafted on a scale of 1:250,000. Wells, piezometers, and other features were placed on this map using a consensus of data from all other maps available.

This detailed map was photographically reduced by a professional map service to a scale of 1:1,000,000. The entire region to be modeled was then drafted on another map to incorporate the CBWP and other well fields. The model requirements did not necessitate a high degree of accuracy outside the central detailed area. This map became the basis of the groundwater model. Elements, nodes, elevations, and other physical details were mapped on it.

Many well locations are given in longitude and latitude. For groundwater modeling purposes and for consistency in plotting well locations throughout the modeled area, the center of a metric coordinate system was established on the base map at longitude 22°E and latitude

27°N. Longitude and latitude lines were drawn on the base map orthogonally only at this center point.

Several attempts were made to secure detailed topograhic maps of the study area. Air navigation charts were obtained from the United States Department of Commerce, National Oceanic and Atmospheric Administration. Topographic maps were obtained from the United States Defense Mapping Agency. Unfortunately, all of the pertinent maps had very limited topographic and relief information in the CBWP well field areas. Their use was restricted to substantiating the geographic and topographic descriptions provided in previous investigations.

Reports

Several reports were used for background information on regional groundwater geology and hydrology. The most thorough exposition was found in the principal reports of the IGS (Wright et al. 1973, 1974, and Wright 1975) and a series of subsequent publications in technical journals by IGS personnel. The Soil and Water Dept. of the SLRAD, Tripoli, was the source of several unpublished reports on the groundwater hydrology and results of exploratory work and pumping tests in the CBWP Well Fields at Tazerbo and Sarir and the Sarir agricultural area. Data of most value for the model itself were the individual well transmissivities, monthly discharges, and piezometric water levels of the Sarir agricultural well fields (Hasnain et al. 1982).

An excellent report on the water quality of the Sarir South agricultural well field was made by Hasnain (1981) and summary reports of the Sarir region were made by ElRamly (1980) and P. Pallas (1980), FAO hydrogeologists in SLRAD. These and the report of other investigations that provided the basic data necessary to establish the aquifer properties, hydraulic gradient, and depth to groundwater have been listed in the references.

By comparing the multiple sources of data and eliminating the inconsistencies, it was possible to establish for the region to be modeled a reliable data base of over 300 static water elevations, ground surface elevations, and well depths. Data, not quite so extensive but well distributed throughout the region, were geologic cross sections, chemical analyses, and aquifer pumping tests. These latter data were extremely valuable in establishing the lower boundary of the aquifers and their transmissivities, storativities, and water quality.

Well Locations and Elevations

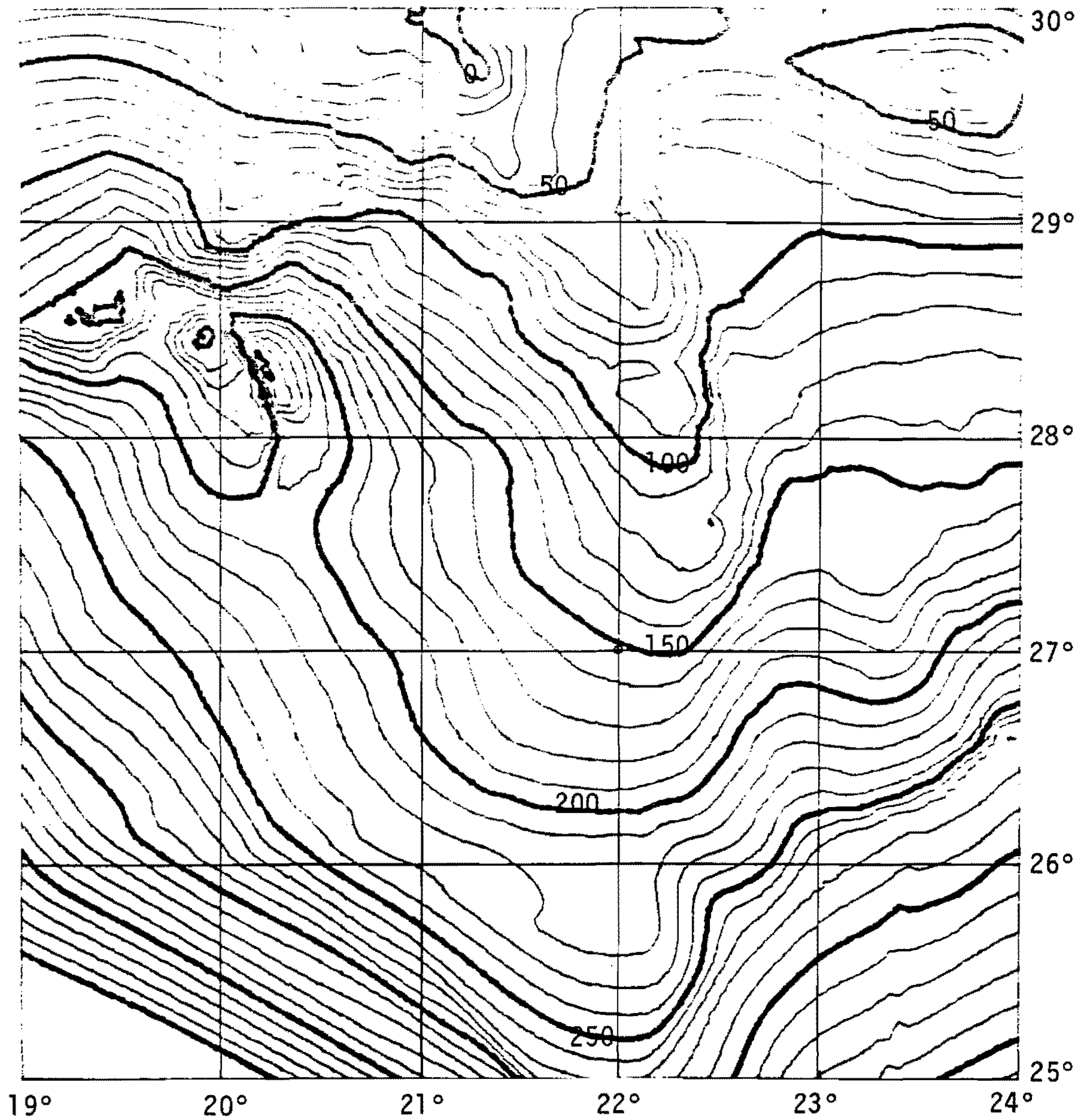
A regional water table or piezometric surface map was essential for this groundwater model of the Sarir region. Since water levels in wells are often given merely as depth from the well head or land surface, well head and topographic elevations were needed throughout the region studied. The IGS made the most extensive reconnaissance surveys and their reports contain this essential data from many points in the region. Their published topographic and piezometric maps of the region were generally of insufficient detail for direct use. They inventoried hundreds of oil wells, water wells, exploratory, and other wells as part of their assigned tasks through the years of their investigations.

Piezometric, topographic, geographic, and other data were obtained from IGS, SLRAD, AGOCO (Libyan National Oil Co.), and several other sources. In some cases piezometric and land surface elevations were scaled from hydrogeologic profiles or taken from well logs. When only the depth to water was given, reference was made to the topographic map constructed for this study. This map was made by a computer analysis and plotting program using all the data obtained from the many sources. The computer program uses a subroutine to fit a smoothed ground surface to the irregularly distributed data points. The subroutine operates by calculating a continuous interpolation function in each triangle of the grid of data points on the planimetric projection of the topographic surface. A selected-size matrix containing a rectangular grid of interpolated data-point values defining the smoothed surface is then obtained. The contour subroutine uses this computed matrix of data-point values to plot a topographic contour map with any selected contour interval.

The final topographic map is not completely accurate due to the fragmentary nature of the data used, but it was the best available for this study. Very recent precise leveling has proved these old elevations to be in error by at least a few meters, but the general shape of the topography remains about the same. Moreover, as depth to water level in a well is a highly localized measurement not related to the accuracy of measurements from some distant point, the piezometric surface map may be in error by the same amount, but estimates of pumping lifts may still be fairly accurate. Figure 3 is a copy of this computer-generated topographic map.

Water Levels in Wells and Piezometers

The piezometric surface contour map of Figure 2 was plotted by the computer from historical data, taken before major pumping began in 1975. Piezometric and water-table elevations were not the same at many locations. The piezometric head in the main fresh water aquifer was



Contour Interval is 10 meters

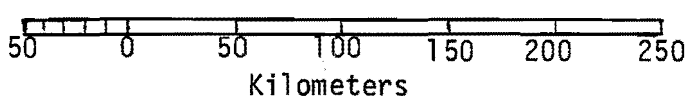


Figure 3

Topographic Contour Map of Study Area
(Drawn by Computer)

chosen for making the map in such cases. This main aquifer occurs in different parts of the geologic sequence from one locality to another, and is related more to depth below land surface than to the stratigraphy.

Static water levels were obtained at widely scattered points throughout the study area for use in the steady-state phase of the groundwater model calibration in order to obtain regional transmissivities. Additionally, time dependent water levels in the vicinity of the Sarir agricultural well fields were needed for calibration of the transient-state phase to obtain estimates of storage coefficients and leakance.

The SLRAD established 19 piezometers in the Sarir North agricultural well field and 23 piezometers in the Sarir South field. About 8 other wells and piezometers in the south field are also being monitored for water levels. Additional piezometers were completed in deeper horizons (457 m) and in shallow horizons to monitor piezometric heads below and above the main producing interval.

Piezometric levels are recorded monthly from 1975 when only a few piezometers were in operation. These data have been stored in computer files and printed out by the computer as hydrographs for the succession of piezometric levels in the main aquifer of both well fields (see Appendix C). These hydrographs for individual piezometers were extremely valuable in calibration of the model as they could be compared directly to computer generated hydrographs at nodes in the model coincident with piezometer locations. The SLRAD also furnished records of water levels within the producing wells, but these data were not used in the model.

Water Production

Fresh water is used in relatively small quantities in the various oases, oil fields, and scattered construction projects. These uses are not fully inventoried nor will they affect the performances of the CBWP well fields. All of these small water consuming operations are ignored in the regional groundwater model. A few larger water consuming projects, such as the Tazerbo and the Jalu-Awjilah agricultural well fields, are currently beginning operation in the Sarir region. They are taken into account in the model along with the Sarir North and Sarir South well fields because of the possibility of mutual interference with the CBWP well fields.

SLRAD has provided monthly records of well discharge and other hydrologic data of the Sarir North and Sarir South well fields. Well discharge for the agricultural projects is not steady. Two crops per year are grown with interim periods of harvesting and planting wherein no well discharges occur. This highly fluctuating pumpage pattern also varies in time and space depending upon many localized operational conditions. Only a computer can efficiently handle all of the computational ramifications of this widely variant discharge pattern.

Pumpage began in the Sarir South agricultural well field in May of 1975 with only a few wells producing. Through the years the farming operation was expanded until currently there are about 157 wells producing an average of 313,000 m^3/day. Sarir North started in December of 1980 with 66 wells pumping, and now 81 wells are producing an average of 240,000 m^3/day. It is assumed for modeling purposes that these levels of production will remain about the same or somewhat higher in the future.

Discharge figures of SLRAD are taken to be accurate as recorded. Flowmeter and other corrections are assumed to have been made. Now and then discrepancies have been noted between the recorded discharges and the cumulative discharge figures. Then the most consistent values had to be adopted over others in the absence of confirming figures.

It was assumed that the well discharges are the net draft on the aquifer or that irrigation efficiency is so high that effectively no water is returning to the aquifer. Of course deep percolation from excess irrigation will reach the semiconfining water-bearing horizons first and simply add to the longevity of the vertical drainage into the main aquifer from above. This return flow may be highly saline depending upon the irrigation efficiency and should be kept to a minimum to avoid salinity buildup from recirculation of used groundwater. The CBWP well fields will not have this hazard because all the water will be exported from the sites.

Pumping Tests

Every well in the Sarir agricultural well fields was given at least a 12-hour step-drawdown test. Specific capacities of the wells and aquifer transmissivities were calculated from the results of the tests. A few special tests were conducted on these wells, the piezometers, and other test wells. Transmissivities and storage coefficients were obtained from the special tests. The SLRAD has provided these data and pumping test results from the CBWP well field exploration wells. Pumping test data were also found in the IGS and a few other reports.

Average transmissivity of the Sarir North well field (82 wells and one piezometer) is 1360 m^2/day and at the Sarir South field (147 wells and 8 piezometers) transmissivities average 1300 m^2/day. These values are based upon short term (maximum 24 hours) drawdown and recovery tests and consequently represent only the average transmissivities of the formations immediately surrounding the producing intervals of the individual wells. Average storage coefficients of the main aquifer in both well fields are about 5 x 10^{-4} based on the special pumping tests.

The Sarir North well field has a zone of relatively high permeability aquifer, called the Sarir Channel, trending north-south through the middle of the well field (Ahmad 1978). It does not occur in the Sarir South field, but transmissivities in that field increase from southeast to northwest as a general trend. Transmissivities in the Sarir North agricultural field are relatively low except for those determined within the Sarir channel. The average transmissivity at 70 wells outside of the channel is only about 785 m^2/day, but within the channel the average is 4440 m^2/day at 12 wells and one piezometer. Although the overall average transmissivity is higher than that of the Sarir South field, the productivity of the north field is not nearly as good as the south field because of the poor distribution of transmissivities and variable stratigraphic conditions.

Transmissivities estimated from short term pumping tests were of value in estimating the hydraulic conductivity (an aquifer property related to its permeability) of the aquifer materials tapped by a well. The Sarir agricultural well fields produce from the interval between 150 m and 300 m below the land surface. Thus the average hydraulic conductivity of the main producing interval in the Sarir South field is about 8.7 m/day (transmissivity divided by the thickness of the aquifer tested).

Since there are water bearing formations both above and below the main producing interval that are believed to be in hydraulic communication, the well field taps a much thicker water bearing section than the 150-m producing interval. Due to the lenticularity of these mainly fluviatile deposits whose bedding is nearly horizontal, hydraulic communication within them is retarded especially in the vertical direction. Water entering the wells from above and below is delayed significantly in time by aquifer materials of lower vertical permeability and by the tortuous paths along which it may have to pass occasionally. After longer periods of time, discharge from such partially penetrating wells is sustained by delayed flow from above and below the producing interval. The wells behave as if they are producing from a much larger transmissive thickness than their short-term pumping tests would suggest. This effective long-term transmissivity is often called a regional transmissivity, and the 50-year performance of the Sarir well fields will depend much more upon the regional transmissivity than those obtained from the short-term pumping tests of partially penetrating wells.

Pumping tests were performed at six wells in the area tested for the CBWP Well Field at Sarir. Transmissivities obtained from these tests ranged from 1090 m^2/day to 6300 m^2/day. Hydraulic conductivities were about 15 m/day. Storage coefficients ranged from 5×10^{-4} to 3×10^{-2} in these tests.

In the Tazerbo CBWP area eight pumping tests were made at six locations. Transmissivities ranged from 180 m^2/day to 4500 m^2/day and storage coefficients ranged from 3×10^{-4} to 5×10^{-2}. Again these values are not representative of long-term regional aquifer response to pumpage.

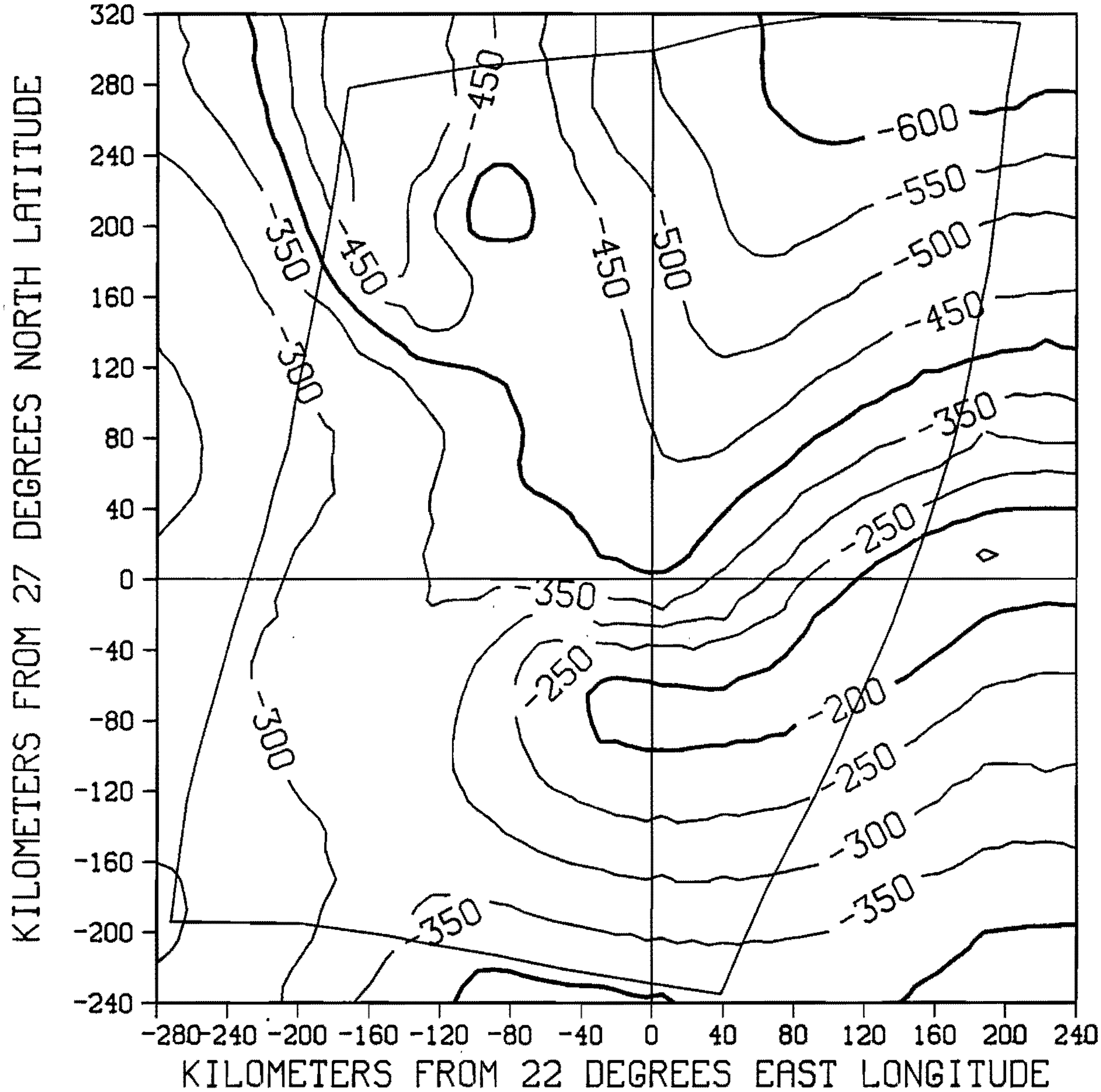
At the 33-well Jalu-Awjilah Agricultural Project transmissivities range from about 1000 m^2/day to about 2000 m^2/day and storage coefficients range from 10^{-5} to 2×10^{-2}. At the Marada agricultural project transmissivities range from 500 m^2/day to 2080 m^2/day and storage coefficients range from 6×10^{-3} to 0.4. The foregoing figures of pumping test results were taken from ElRamly (1980, Table 16).

Field Estimates of Aquifer Parameters

Before entering the modeling phase of the study it was necessary to estimate aquifer parameters from available field data. The first step in the calibration was to construct a "steady-state" piezometric surface map, and to evaluate the appropriate geometric/geologic factors of the regional aquifer. The geometric factors include aquifer bottom elevation, aquifer thickness, horizontal extent of the aquifer including the location of no-flow boundaries, constant head, and constant flux boundaries.

The piezometric surface map shown on Figure 2 was constructed using water level observations obtained prior to major groundwater development in the region (pre-1975 levels). Much of this early information was obtained from a report by Wright and Edmunds (1969). For much of the region enough observations were available so the steady-state piezometric surface map is quite adequate; however, the extreme southwestern corner of the study region contained very sparse observations and the contours there should be considered approximate. Again using the computer controlled plotter, the aquifer bottom elevation contour map, Figure 4, was prepared on the basis of interpretation of the extensive lithologic logs available in the region.

FIGURE 4: AQUIFER BOTTOM
ELEVATION CONTOUR MAP
Contour Interval 50m



Flow net analysis was then performed manually to estimate flow lines (streamlines), and to transfer aquifer transmissivity (T) or hydraulic conductivity (K) along stream tubes from regions of known T or K to regions without pumping test information. Assuming steady flow, the flux through a single stream tube is constant and thus by continuity the flux between adjacent regions along the stream tube can be written as

$$T_1 \frac{\Delta h_1}{\Delta s_1} \Delta w_1 = T_2 \frac{\Delta h_2}{\Delta s_2} \Delta w_2 = Q = \text{constant}$$

where Q is the steady volumetric flow rate through the aquifer; Δh is the head drop over Δs, the axial distance along the stream tube, Δw is the stream tube width; and T is the transmissivity. This expression allows estimation of the transmissivity or hydraulic conductivity field in regions of unknown T or K. Hydraulic conductivity is estimated with the following expression (where $T = Kb$, and b is aquifer thickness)

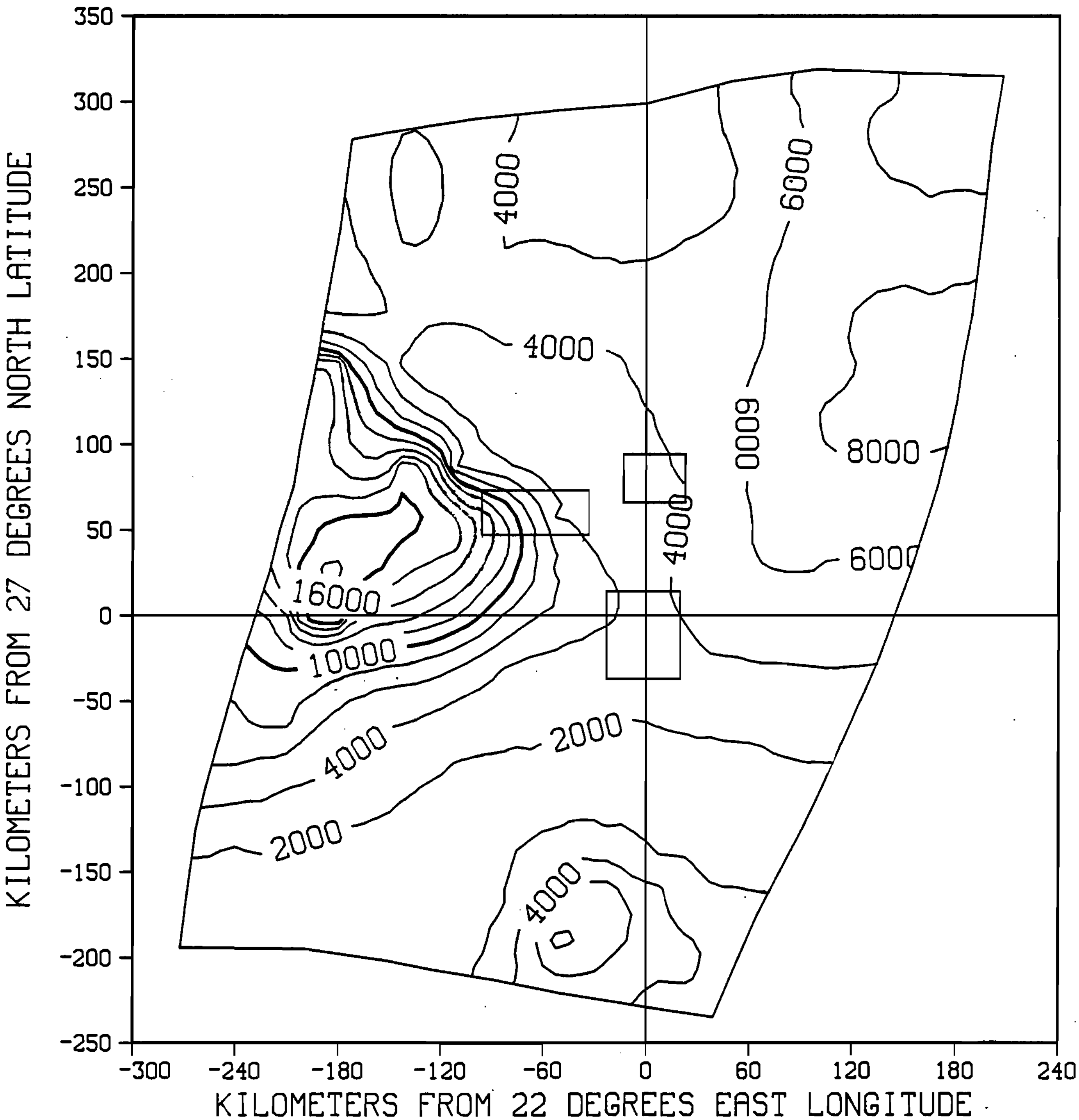
$$K_1 = \frac{b_2}{b_1} \left[\frac{\Delta w_2}{\Delta w_1} \frac{\Delta h_2}{\Delta h_1} \frac{\Delta s_1}{\Delta s_2} \right]$$

This was done for the modeled region and the estimated results from this manual calculation are shown in Figure 5. It should be emphasized that this approximate technique is only used as an initial guess of the transmissivity or hydraulic conductivity field of the region. This initial guess, however, is necessary to begin the steady-state model calibration. During this calibration, as seen later, the initial hydraulic conductivity field was adjusted so that the observed and predicted piezometric surface contours have a satisfactory comparison.

FIGURE 5

ESTIMATED TRANSMISSIVITY CONTOUR MAP

IN CUBIC METERS PER DAY PER METER



Water Quality Analyses

Chemical analyses of water from Sarir agricultural wells, CBWP test wells, and other wells scattered throughout the region were obtained from the SLRAD, IGS, and other reports. Water quality maps were made by IGS (Wright 1975) and SLRAD (ElRamly 1980 and Ahmad, ElBakhbakhi et al. 1979), but detailed information is lacking near the proposed CBWP well-field sites. Nevertheless, enough water quality data are available to assure that the CBWP Well Fields at Sarir, when constructed, will produce water of total dissolved solids (TDS) no greater than about 1200 milligrams per liter (mg/l) and at Tazerbo it should be less than 500 mg/l TDS.

Water of inferior quality occurs above, below, and surrounding the producing intervals of the Sarir well fields. This is of no immediate hazard to the water quality of the existing or proposed well fields, but in time some deterioration will take place. Groundwater from the CBWP Well Field at Tazerbo, because of its high quality, will tend to reduce salinity by dilution. Ultimately groundwater from Kufra also could be used in the system to dilute salinities as well as to supplement the supply to the coastal belt. Water quality in the Tazerbo area appears to be satisfactory all around the proposed CBWP well field site. Water quality distribution in the Sarir area is shown in Figure 6 as a contour map of electrical conductivity of water found in the principal aquifer.

It is extremely important in the CBWP Well Field at Sarir that a few piezometers be completed below the producing interval to monitor vertical gradients and water-quality variations in the vertical direction, especially since this field will be drilled considerably deeper (450 m) than the Sarir agricultural well fields (300 m).

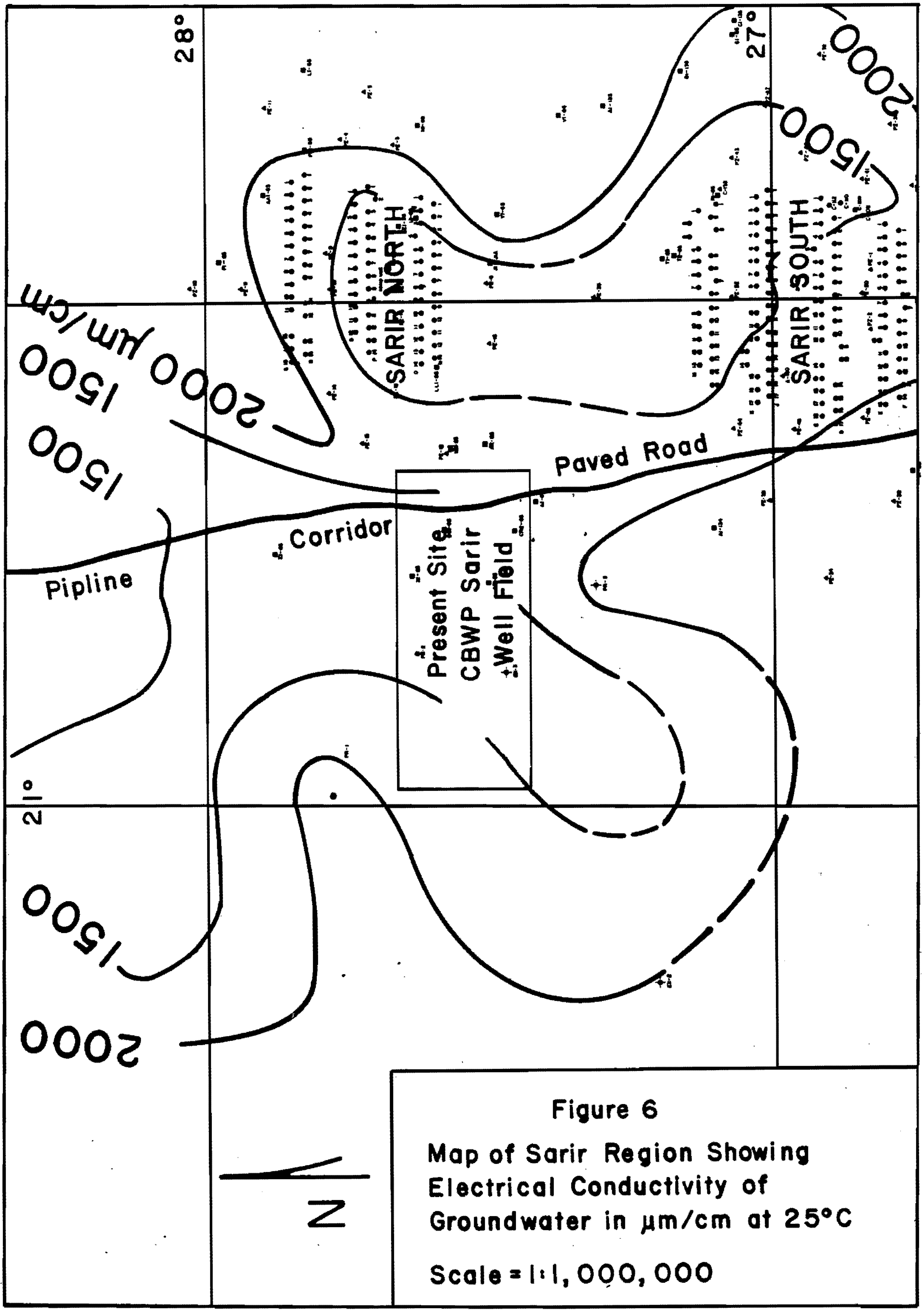


Figure 6

Map of Sarir Region Showing Electrical Conductivity of Groundwater in µm/cm at 25°C

Scale = 1:1,000,000

According to a report by Hasnain (1981), there has been rather insignificant water quality deterioration in the Sarir South agricultural well field. Water quality variations in time at the CBWP well field site at Sarir should be similar to those at Sarir South. It would be premature to attempt computations to predict water quality deterioration for the CBWP Well Field at Sarir until a few years of piezometric and water quality histories are obtained after pumpage begins. Water of inferior quality appears to be nearer to the Sarir agricultural well fields than to the CBWP Sarir well field site. The thin lens of lower quality water which occurs above the producing intervals near the water table may cause a salinity buildup as it is finally pumped from the wells. The biggest threat after several years is from the relatively large quantities of low quality water both below and at some distance laterally from the producing intervals of the well fields.

NUMERICAL MODELS OF THE PROJECT AREA

Selection and Description of the Computer Program

Computer models in regional groundwater studies have become an important tool for the analysis of groundwater development plans. The computer model allows the hydrogeologist to synthesize complex hydrologic and geologic field data into a coherent framework, leading to a better understanding of the natural system. The model allows one to test the sensitivity of "errors" in aquifer parameters, to examine alternative hypotheses about aquifer boundary conditions, and to evaluate local or basinwide fluxes through the system. An especially important aspect of computer models lies in the facility by which alternative development plans can be examined under a variety of assumptions concerning the distribution of aquifer parameters, pumping, recharge and leakage in both space and time.

The finite element method, as an alternative to finite differences, has increased in popularity and gained considerable attention in recent years. It has been developed into a powerful numerical procedure for solving a broad spectrum of problems in engineering and the applied sciences. Its uses range through analysis of structures, stress analysis of machine components, heat transfer in complicated thermal systems, flow of fluids, vibrating systems, and the determination of water movement both in the unsaturated and saturated zones in groundwater aquifers.

Finite differences and finite elements as numerical methods for obtaining approximate solutions to field problems such as flow in groundwater aquifer systems each have their advantages. Finite differences are conceptually much simpler and for rectangular regions with constant grid increments are simpler to implement in a computer algorithm. Finite element methods have the advantage that certain boundary or other conditions are handled naturally and do not require special formulas as are needed in finite differences. The size of the finite elements can be varied readily, so that it is easy to use much smaller elements in regions where rapid changes of the dependent variable occur and use large elements where variations are smaller or where accuracy is not needed. In finite differences nonrectangular regions are not conveniently modeled and when they are, the computer program may still waste storage for a rectangular region that completely contains the actual region. Finite elements can conveniently be adapted to any region with straight or curved boundaries. Heterogeneity in aquifer properties is also more readily accommodated by finite elements than by finite differences. A disadvantage of finite elements is that a second-order approximation or a three-dimensional solution increases considerably the effort in the formulation and the solution.

Although a large number of regional aquifer models are available, in this study a finite element aquifer code, AQUIFEM, was adopted which was developed at the Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Massachusetts Institute of Technology. The code is oriented towards the most common situation encountered by the hydrogeologist: a two-dimensional, approximately horizontal aquifer of large areal extent (with a two-layer option to model leaky aquifers).

A copy of the AQUIFEM User's Manual has been included in Appendix B (issued under separate cover in only a few copies). Appendix B gives a listing of the program code as modified by UWRL and a detailed description of its use is given in a special section in Appendix B, as comments in the program itself, and in the User's Manual. Appendix D (issued under separate cover) is a computer readable tape of the modified program, the regional and Sarir South models, and the production and piezometric data as used in these models.

AQUIFEM (Aquifer Finite Element Model) uses a Galerkin finite element technique for which anisotropic, heterogeneous, phreatic or confined, leaky or non-leaky aquifers under transient or steady state conditions can be modeled. A change of aquifer status from confined to phreatic, or vice-versa, is also allowed. Time varying boundary conditions may be used, where specified heads or specified point, lateral or areal recharge or discharge rates are given. With the proper combinations of these boundary conditions, the code can model pumping wells, recharge wells, constant drawdown flowing wells, springs, drains, excavation dewatering, groundwater discharge to surface depressions, evapotranspiration, the effects of geologic faults, and the exchange of water between the aquifer and fully or partially penetrating surface water bodies. AQUIFEM can also be used to examine certain two-dimensional vertical cross-sectional views of an aquifer.

The finite element approach has been adopted for this computer code because, compared to the finite difference method, it: 1) requires fewer node points to represent the discretized aquifer to the same level of accuracy, thus cutting down on execution, storage and input/output costs; and 2) reproduces the complex geometry of groundwater aquifers more conveniently and more accurately.

Although the final results of finite difference and finite element codes are generally not significantly different, in the case of mass transport the finite element technique performs significantly better for both computational efficiency and accuracy.

Auxiliary Models

One use of the AQUIFEM program was to model the present design (arrangement of wells) of the CBWP Well Field at Sarir. The well field model was first established as part of a completely hypothetical aquifer, but was later modeled in the aquifer of the CBWP Sarir well field area as determined by the regional steady-state model.

When alternative designs of the well field were to be studied, the Theis model (summation of the drawdowns of all the wells in the region as given by the Theis equation) was used because it was so much easier to apply repeatedly to numerous alternative well field layouts. AQUIFEM can be used to simulate well field performance once the final well field design is known. Each model has its advantages and disadvantages, but for long-term monitoring of the well field and continued use of the model, the AQUIFEM program is preferable. The Theis model was used many times to test the relative value of several different hypothetical well-field layouts, various well spacings, and various numbers of wells to produce the total flow requirement. A pipe network optimization program (NETWK) also was used with the Theis aquifer model to assist in well field design for both CBWP Sarir and Tazerbo well fields (see Appendix A).

Another AQUIFEM model was made to assist in calibration of the regional model. This was a model of the Sarir South agricultural well field operated alone in its local environment. With more than 6 years of production history and piezometer records available, an excellent opportunity was afforded to make a detailed study of this well field and obtain reliable aquifer parameters for prediction purposes. The

Sarir North well field was left out because it has affected only slightly the water levels of one piezometer (Pz. 33, between the two fields) in the vicinity of the Sarir South field.

The model of the Sarir South field was run after regional transmissivities and other aquifer characteristics were determined from the regional steady-state model. Given these characteristics from the steady-state model, storage coefficients, leakance, and still other aquifer characteristics could be determined more readily from the 7-year transient-state model in the vicinity of the Sarir South field. Most of the water well and practically all of the piezometer sites were located at nodes in this model. Thus true aquifer head and water extraction distributions were simulated accurately in space and time. Boundaries were selected so remote from the center of pumpage that boundary conditions could not seriously affect the results at the well field sites. Unconfined, partially confined, and confined aquifer parameters were tested in the model for the best simulation of the historical aquifer behavior. Aquifer characteristics obtained from this detailed study were then used in the transient-state regional model for predicting aquifer behavior in the Sarir South well field and other geologically similar areas in the modeled region.

Calibration of the model of the Sarir South field was achieved by modifying the output subroutine in the AQUIFEM fortran code. This modification permitted water level elevation versus time data to be printed separately from the normal AQUIFEM output. Since the grid system for the Sarir South field model was selected to correspond exactly with piezometer and production well locations, the output water level elevations from the model could be compared with the actual piezometer hydrographs.

Actual piezometer data for 23 piezometers in the Sarir South field were plotted employing the computer graphics capability of the DISSPLA (copyright of Integrated Software Systems Corporation 1981) package implemented on the Utah State University VAX 11/780 computer. Similar elevation and time scales were selected for the model output data. These data were then plotted using the same DISSPLA routines and the two sets of graphs (one of actual and one of simulated data) were compared.

After adjustments based on several runs, an optimal set of aquifer parameters was determined. The flexibility of the AQUIFEM model permitted rapid computer simulation of unconfined, confined, and leaky aquifers. Graphical results for each type of model were then compared to the actual piezometer data, and optimal parameters were determined for each case.

For the 23 piezometers in the South field, a few could be duplicated best through time by an unconfined aquifer simulation, a few could be duplicated best in time by a confined aquifer, but the best model simulation was usually a leaky aquifer representation. Hydrographs of water levels in the 23 piezometers are given in Appendix C (issued under separate cover with Appendix B in only a few copies) and the computer-generated hydrographs are also given in companion graphs to show the degree of duplication attained by unconfined, confined, and leaky aquifer model simulations.

The effectiveness of a well field depends not only upon pumping lifts within wells, but also upon the costs and layout of the water-gathering network of piping which conveys the water to the head of the aqueduct to the coastal belt. A pipe network and design program (NETWK) developed at Utah State University was used in conjunction with the aquifer model results to obtain optimum network designs for the various alternative well field designs considered. This program uses the Darcy-Weisbach equation for estimating pipe friction losses. Estimated unit costs of installed pipe of various sizes and energy costs were furnished by Brown & Root. The network program calculates the optimum slope of the hydraulic grade line and pipe sizes and lengths for minimum costs of pumping. Pumping lifts are also included in the calculations. Numerous well field configurations were compared using this model (see Appendix A).

Data Preparation

The AQUIFEM model requires extensive data that must be organized into computer readable files prior to beginning any simulation. Principally these data can be divided into five separate groups:

1. Program options

These data consist of specifying the type of aquifer (confined, unconfined, leaky), the number of nodes and elements, and specialized conditions to expect such as constant head nodes.

2. Geometry data

This consists of the coordinates of all the nodes and what is called connectivity data, the three nodes that comprise the vertices of each triangular element.

3. Property data

Under this category all of the aquifer property data are organized. The file could be as simple as a regional value of hydraulic conductivity, storativity, and thickness for the entire aquifer. A complex file of nodal properties or even elemental properties can be prepared.

4. Boundary data

Since the AQUIFEM model is formulated on the numerical solutions to partial differential equations, the boundary conditions file is extremely important. This file contains information concerning constant head, constant flux, and no flow boundaries as well as discharge information for individual nodes or elements.

5. Output control data

This file specifies the time increment for output data. It can vary from hours up to years dependent on the desired precision.

It was necessary to write a number of data handling support programs that would organize the raw researched data into files compatible with AQUIFEM model input. Some examples of these are interpolation programs for ground surface, water surface, and aquifer bottom elevations, hydraulic conductivity calculation programs given variable transmissivity and thickness, and discharge data conversion programs to permit various time step selection.

Selection of the Grid System

In general the selection of the node points and element locations within the aquifer domain depend on the particular aquifer under study, the purpose of the investigation, and the quality of field data concerning geometry, aquifer properties, boundary conditions, and cost constraints.

For the AQUIFEM model it is possible to vary the element size over the study area. This allows increased accuracy of piezometric head simulations in zones of large hydraulic gradients simply by increasing the number of nodes and elements in the zone. For zones of relatively small piezometric head variations it is reasonable to use a larger node spacing thus producing larger elements.

The regional aquifer grid was prepared as follows:

1. The geometry of the aquifer domain was sketched on the regional piezometric surface map by drawing the limiting flow lines (outer boundaries) along the east and west margins of the region. These limiting flow lines are orthogonal to the piezometric contour lines, and are considered to be the "effective lateral boundaries" of the flow system. They are taken to be "no-flow" boundary conditions in the model. The aquifer boundaries at the northern and southern part of the study region coincide with existing piezometric contours, and were initially considered to be "constant head" boundary conditions during the steady-state calibration.

2. Nodes and elements were then roughly sketched in along bands from west to east which were scaled so as to increase the node density in the well field regions and decrease the density in outlying regions. The nodes were then connected to form triangles. The triangles were designed so that the length to width ratio never exceeded five to one, because numerical computation problems can arise for extremely acute triangles.

3. Since the efficient design of the grid system is directly related to size and bandwidth of the system of equations to be solved, the "rough" grid design was then adjusted several times to reduce the bandwidth of the matrix and thus improve computational efficiency and cost (see User's Manual, Appendix B, for details).

Figure 7 is a plot of the initial grid system used in the regional model. This was modified very slightly so that a few nodes in the Sarir North well field would coincide with piezometers there. Plate I shows

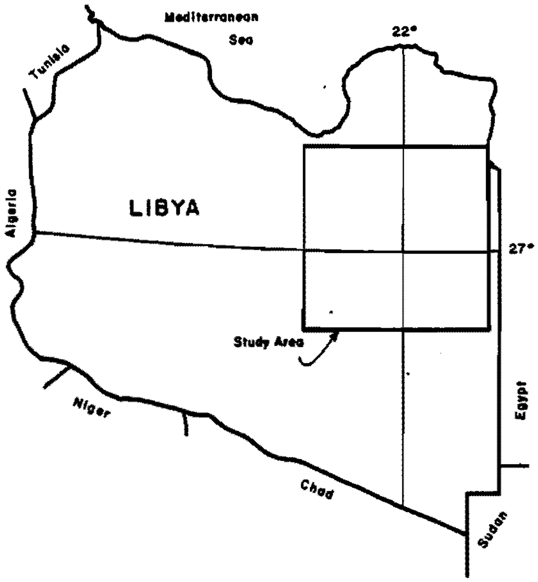
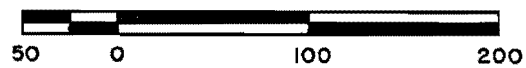
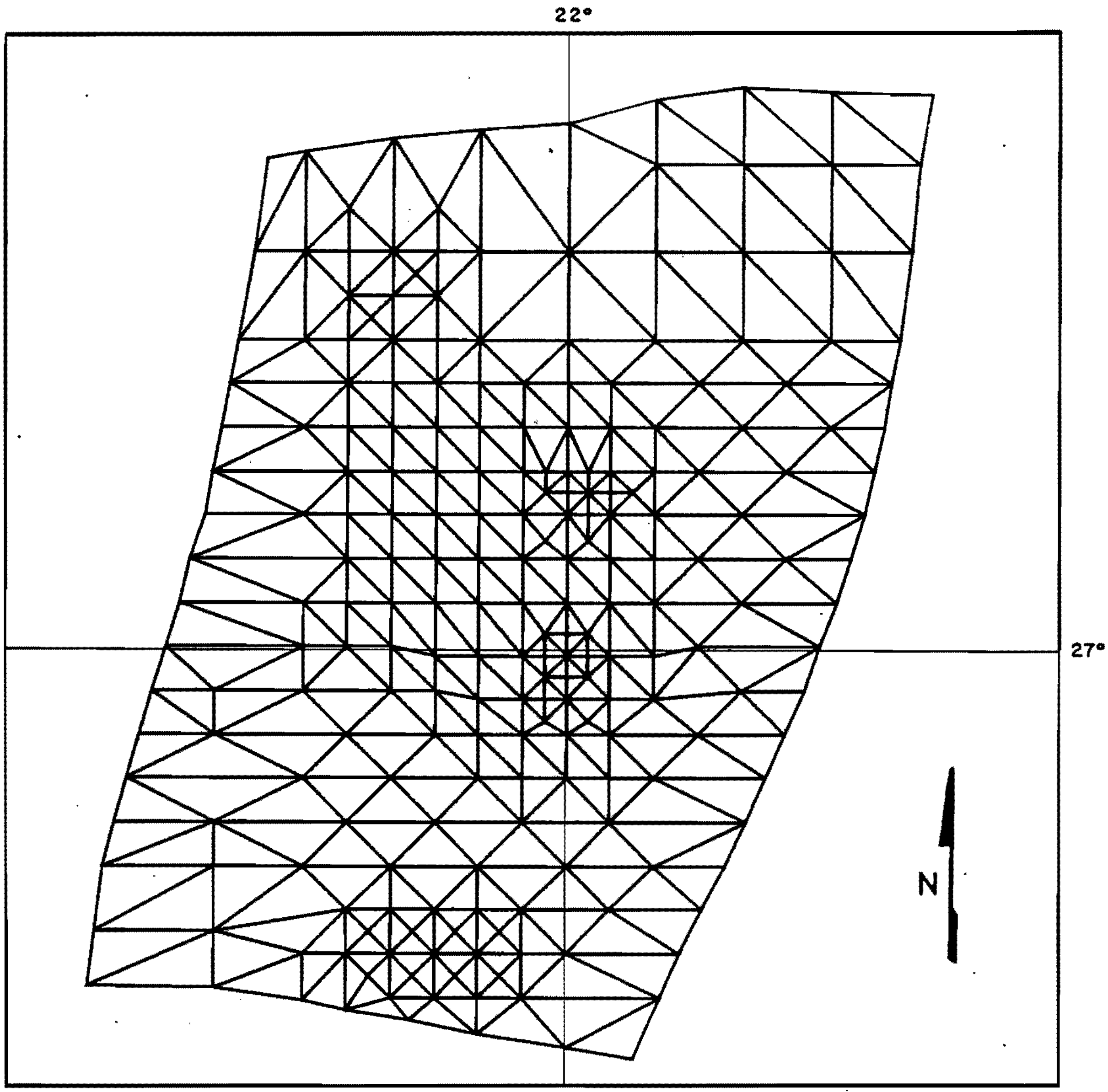


Figure 7: FINITE ELEMENT GRID FOR COMPUTER SIMULATION

November 1982





the final finite-element grid system used for the regional model. All of the node and element numbers are shown.

Selection of a Time Step

The accuracy of a finite element solution for any unsteady problem depends on both spatial and temporal discretization. Large time steps lead to cheap but inaccurate solutions, whereas small time steps give better accuracy and greater computational costs. The ideal situation is to use the largest possible time step that does not seem to significantly change the solution. After some trials, a 90-day time step was found to be the most practical for the 7-year calibration runs. Using a cubic spline fit of the 90-day aquifer head data, the computer generated curves duplicated the 30-day piezometer head plots quite well.

Time steps longer than 90 days were mandatory in the 50-year predictions of the regional model. AQUIFEM features several options for time-stepping which are convenient to use. Time steps can be held constant or accelerated as the solution progresses. In this latter option small time steps initially capture the rapid changes which occur immediately after any stress and then larger time steps are adequate at later times when the response varies slowly. In the 50-year regional study, time-stepping is done in a multiplicative manner. The initial time step, chosen to be 90 days, is increased after every time step by 1.15 times. That is, the consecutive time steps in days are 90.0, 103.5, 119.0, 136.9, etc., yet the output can be obtained for any desired times not necessarily geared to the foregoing time steps.

Well Locations

Individual wells largely had to be ignored in the regional model since it was not feasible to assign a node of the model to every well.

Computational time and computer storage would have been immense, if not prohibitive, for such a detailed model and there probably would be little added predictive capability of the model. Individual well sites are not known exactly for the proposed CBWP and other well fields yet to be constructed. Well locations in the Sarir and Jalu-Awjilah agricultural well fields are the only ones presently known with a modest degree of accuracy.

When estimating the effects of one well field upon another, precise well locations are not needed. Groups of about 6 to 8 wells were contained in the individual finite elements of the existing Sarir well fields, and this representation was adequate for the regional model. Several nodes of the regional model were placed at the geographical locations of piezometers in the Sarir North and Sarir South well fields. This enabled overlapping, independent calibration of the two models (Sarir South field and regional) to be made using the historical well performance and piezometric data of both well fields.

In the model of the Sarir South well field, nodes were placed at almost all of the production well and piezometer sites. A very detailed simulation was made of the historical performance of the Sarir South well field to determine aquifer characteristics. The results of this detailed determination agreed very closely with the aquifer characteristics of the South field obtained from short-term calibration runs of the regional model. While precise well locations are of value in extremely detailed groundwater studies, such precision is not needed in regional model studies. Well locations scaled from available maps were of sufficient accuracy for the detailed as well as the regional modeling of this study. Corrections in well locations made in the regional model for convergence of longitude lines northward were probably unnecessary.

Well Depths

Depths of wells and intervals open to production in the Sarir well fields were not known until very late in this study. However, the approximate overall producing interval of some wells was known early in the study and this provided sufficient information for the modeling to proceed. Groundwater models generally are formulated with the assumption that production wells are fully penetrating the aquifer and that piezometers represent the average head of a fully penetrating well in the aquifer.

The Sarir agricultural well fields produce from the interval between 150 m and 300 m below ground level and the CBWP well fields are to produce from the interval between about 160 m and 450 m. These values were not used in the models directly. The models assume full aquifer penetration, which is not achieved in either case. A small correction must be made for partial penetration when final interpretation is made of the models' results. Some calculations were made to estimate the effects of partial penetration in the Sarir area. Depending upon which formula is used, estimates of additional drawdown caused by partial penetration of wells range from 0.5 m up to about 4 m for the CBWP Sarir well field site. In the final calculations 2 m was used for both CBWP Sarir and Tazerbo well fields (see Appendix A).

Many of the Sarir agricultural wells have nonperforated sections of casing within the overall producing interval of 150 m to 300 m below ground level. No estimates nor corrections were made of the vertical convergence losses due to this feature of the well design. The blank sections are believed to be opposite clays or other nonproductive deposits wherein such losses would be of no consequence. It is suggested in Appendix A that this practice be discontinued for the CBWP well fields.

Water Well Production Rates Through Time

Discharge data of the Sarir South and Sarir North agricultural well fields were placed into computer files to be used in the ground-water models. Much difficulty was encountered in transcribing from the original data sheets because of the exceptionally poor quality of reproduction. In December 1981 the method of recording discharge figures was changed, and the monthly observations had to be smoothed individually by wells to suppress the artificial irregularity that resulted. Fortunately there are sufficient data following the irregularity in time that it should have no significant effect on the modeling results.

The discharge data were then reduced to 10-day time intervals to avoid the small problems created by an irregular number of days in the months and years involved and to facilitate the selection of time-step lengths in the models. This way it was very easy to select any convenient time step for use in the models as long as it was a multiple of 10 days. The beginning day for modeling purposes was arbitrarily selected as January 1, 1975. This starting date gives the model some time steps to be sure a steady-state condition has been reached before discharges from the Sarir South well field are imposed.

For the regional analysis of the aquifer all of the proposed well fields and the existing well fields were assigned water production rates consistent with their respective development plans.

As a basis for the 50-year model prediction (60 years starting from January 1, 1975), the various well fields were assigned production rates and starting dates as shown below.

Well Field	Production Rate (m^3/day)	Date
Sarir North	275,000	January 1983
Sarir South	400,000	January 1983
Jalu-Awjilah	56,000	January 1983
Jalu-Awjilah	112,000	January 1984
Jalu-Awjilah	167,000	January 1985
Tazerbo Oasis	55,000	January 1984
Sarir-Tobruk P.C.P.	83,000	March 1985
CBWP Sarir	1,000,000	January 1987
CBWP Tazerbo	1,000,000	October 1988

These production rates were incorporated into the regional aquifer model in an attempt to be as realistic as practical, relative to the starting times of the various proposed well fields. Historical production data were used for the Sarir North and Sarir South well fields from 1975 through 1982.

These discharges were divided among a number of grid elements for computation purposes. Elements 167 through 172 were assigned to the CBWP Well Field at Sarir and elements 372 and 373 were assigned to the CBWP Well Field at Tazerbo. This elemental distribution of the discharge conforms to the expected geographical area in which each well field will be constructed. Well distribution in elements is shown in Plate I for the Sarir North and Sarir South well fields.

Boundary Conditions

In this report, the term "boundary conditions" is used to represent the groundwater flow and/or head conditions at the boundaries of the modeled area, the draft from the aquifer in the form of pumping from wells, and the heads in the adjacent (overlying water-table) aquifer while modeling as a leaky aquifer. The geometry of the study area which is approximately rectangular, allows identification of the boundaries as north, south, east, and west.

A constant head boundary was used at the north. Heads along this boundary were set at zero mean sea level (MSL) for the steady-state calibration with zero pumping discharge assumed. The model diverged slightly from this setting, but this had no effect upon the CBWP well-field predictions.

Constant heads were assumed to exist along the southern boundary during steady and transient calibrations due to their distance from the well fields. During steady-state calibration, heads at all nodes along the boundary were set equal to 300.0 m above MSL. For transient calibration, these head values were updated before any pumping began using the static water level map.

When pumping begins at the CBWP Well Field at Tazerbo, it will significantly affect the heads in the south boundary. When this happens, the assumption of a constant head boundary at the south no longer will be valid. The boundary condition at the south was, therefore, changed to a constant-flux boundary to represent a constant recharge as determined by the steady-state model. The model produced slight variations in head as a result. This is considered the best treatment for this south boundary located near the CBWP Well Field at Tazerbo.

The constant flux values for an unconfined aquifer were obtained from boundary flux values of the steady-state model with the constant head boundary condition. For a leaky aquifer, the values for constant flux were obtained from the unsteady-state solution at time = 0 with a constant head boundary condition. Total flux into the aquifer from the south boundary for the unconfined case was 633,000 m^3/day and for the leaky aquifer case it was 403,500 m^3/day. The constant fluxes at each elemental side of the south boundary have been calculated to be:

Nodes of elemental side	Constant flux into the aquifer (m^3/day/m) Unconfined	Leaky
206-207	1.80	0.77
207-220	1.47	0.53
220-221	1.02	0.43
221-231	1.09	0.79
231-232	2.37	1.95
232-233	2.97	2.41
233-234	3.05	2.07

As the leaky model implies no horizontal flow in the top 100 m of the regional aquifer (the leaking portion of the aquifer), the true inflow into the Sarir region is probably very close to the value obtained in the unconfined case. Thus 650,000 m^3/day represents the best estimate of groundwater underflow into the modeled area that might be considered as recharge.

The east and west boundaries of the modeled area were chosen such that they coincide with the stream lines obtained from the static water level map. This makes both of them zero-flux boundaries and they were so maintained for the entire study. During the 50-year prediction, these boundaries showed no significant drawdown. Therefore, this assumption was justified.

Steady-state calibration then was performed for the conditions before any pumping began. The well discharge data for the 7-year transient calibration (1975-82) were obtained from available well records. The discharge data were calculated for 90-day periods for each element by summing up discharges from individual wells in the elements (m^3/day/element). This required minor modifications in the AQUIFEM code, which accepts element fluxes as volume per unit time per unit area (in this case, $m^3/day/m^2$).

The transient calibration for the 7-year period (1975-1982) was done assuming a leaky main producing aquifer with a water table condition in the overlying semi-confining layer (adjacent aquifer). The head in the adjacent aquifer was set equal to the static water level elevation so that the piezometric surface of the confined aquifer and the water table coincided at time zero. Heads in the adjacent aquifer (or the water table surface) were assumed to remain unchanged during the transient calibration. This assumption was supported by the observed changes in shallow aquifer piezometers of less than 1 m over the 6 years of pumping from the deep aquifer. This kind of constant head in the adjacent aquifer gives a continuous source of downward leakage into the confined but leaky aquifer. The leakage increases with increasing drawdown of the piezometric surface or with increased pumping from the confined, deeper aquifer until, theoretically, all of the pumpage is supplied by water leaking into the main aquifer from the adjacent aquifer.

However, it is believed that the adjacent upper aquifer cannot continue indefinitely to be a constant source of leakage into the semi-confined aquifer, especially since pumping from the main aquifer will continue at a much higher rate after the new well fields become operational. The water table aquifer will deplete slowly over a period of time as piezometric heads drop continuously. The rate of decline of water table levels (adjacent aquifer heads) can be modeled under different assumptions. Linear and exponential patterns of decline over time were tried during the 50-year prediction runs. The rates of decline were also varied spatially such that the decline was faster near the well fields with higher pumping. After several trials of different mathematical formulations, an exponential decline of the water table in the adjacent overlying aquifer was selected as best approximating field conditions.

CALIBRATION OF THE MODEL

Calibration of the aquifer simulation model was done in two stages with constant-head boundaries at north and south and zero-flux boundaries at east and west margins. A steady-state calibration initially assuming phreatic conditions was done for early 1975 by matching the physically measured static water-level contours with the simulated water-level contour map. A computer generated map showing simulated steady-state water level contours is given in Figure 8. This compares very closely to the physical piezometric contour map of Figure 2. The parameter adjusted during the steady-state calibration was the hydraulic conductivity (K) and from these adjusted values the transmissivity values throughout the modeled area were obtained.

The steady-state solution for the year 1975 with the leaky aquifer model using the K values obtained above was found to be very close to the one obtained from phreatic formulation.

Transient calibration of the regional model for the 7-year period (1975-1982) was later performed with a leaky aquifer formulation. The criteria for calibration were to compare the simulated and observed hydrographs at several piezometer locations in Sarir agricultural well field area. The piezometers used for comparison were PZ 10, PZ 15, and PZ 17 in the Sarir North area, and PZ 32, PZ 33, PZ 39, PZ 49, PZ 50, and PZ 52 in the Sarir South area.

The leakance (K'/B' where K' is the hydraulic conductivity and B' is the thickness of the semi-confining layer or adjacent aquifer) and storage coefficient parameters around the selected nodes were adjusted to get a

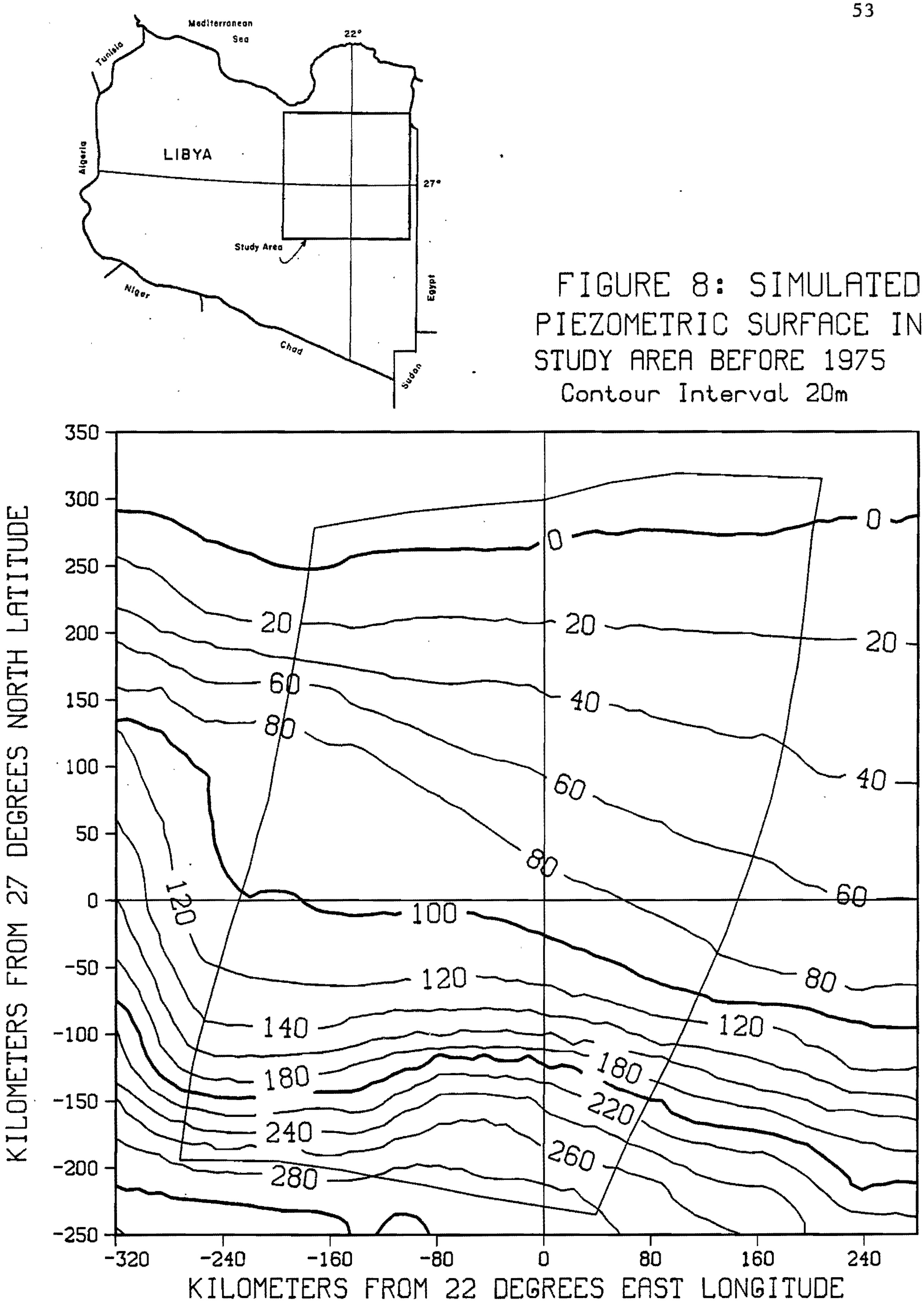


FIGURE 8: SIMULATED PIEZOMETRIC SURFACE IN STUDY AREA BEFORE 1975
Contour Interval 20m

good match between the physically observed and computer simulated hydrographs. This process was time consuming requiring many computer runs with different combinations of leakance and storage coefficients to obtain a good match between observed and simulated hydrographs. As mentioned before, a similar confirming calibration was made using the auxiliary model of the Sarir South well field. The simulated and observed hydrographs for some of the piezometers are shown in Figures 9 through 12 as examples. Many others are given in Appendix C.

FIGURE 9
PIEZOMETER 52
OBSERVED AND SIMULATED HYDROGRAPHS

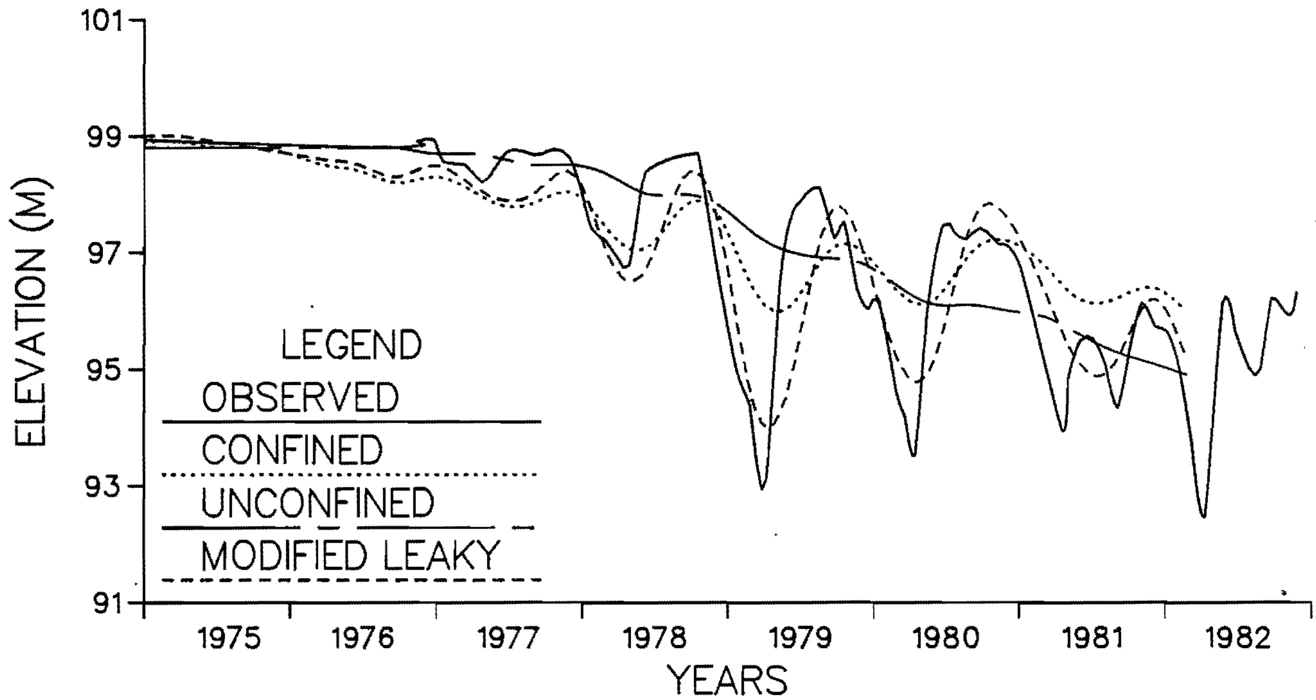


FIGURE 10
PIEZOMETER 48
OBSERVED AND SIMULATED HYDROGRAPHS

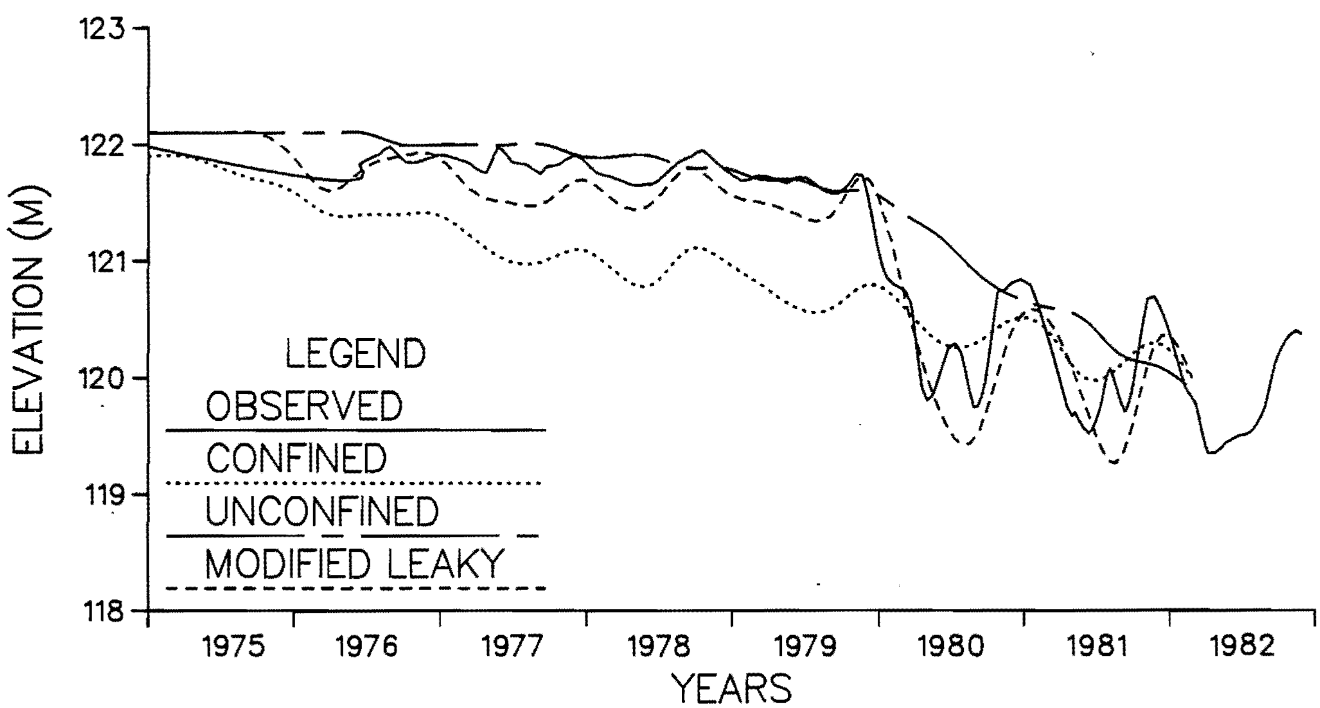


FIGURE 11
PIEZOMETER 17
OBSERVED AND SIMULATED HYDROGRAPHS

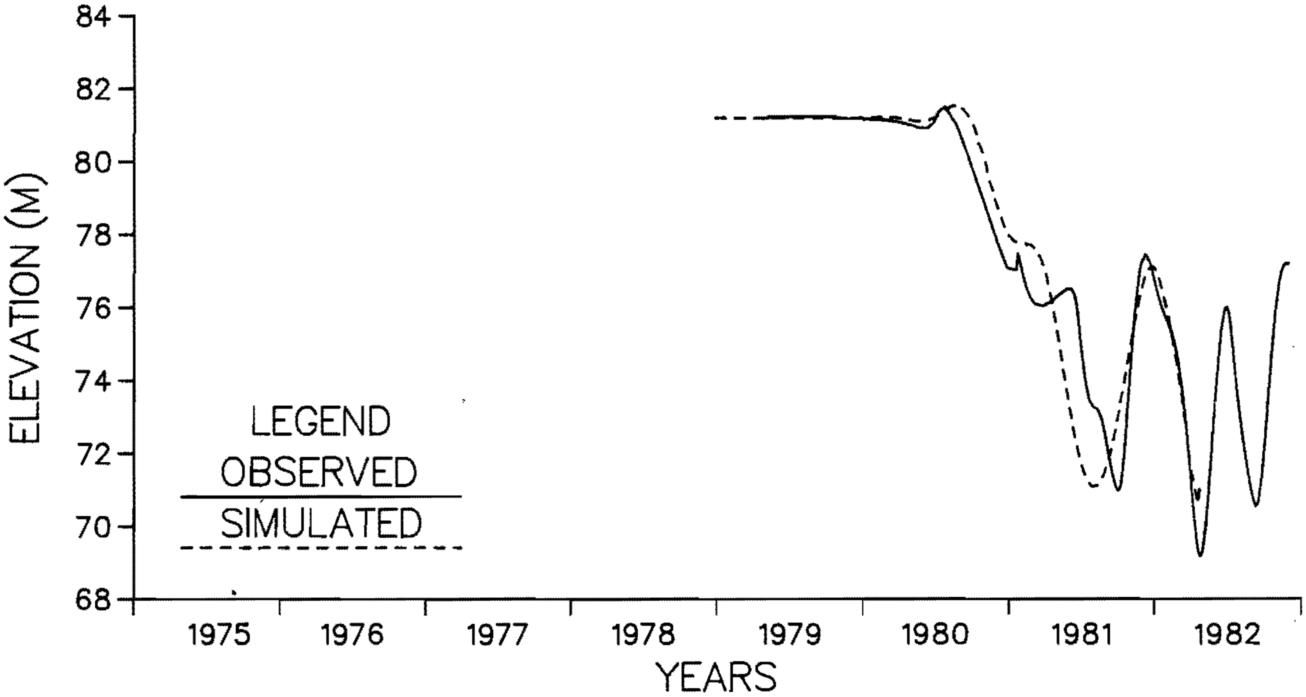
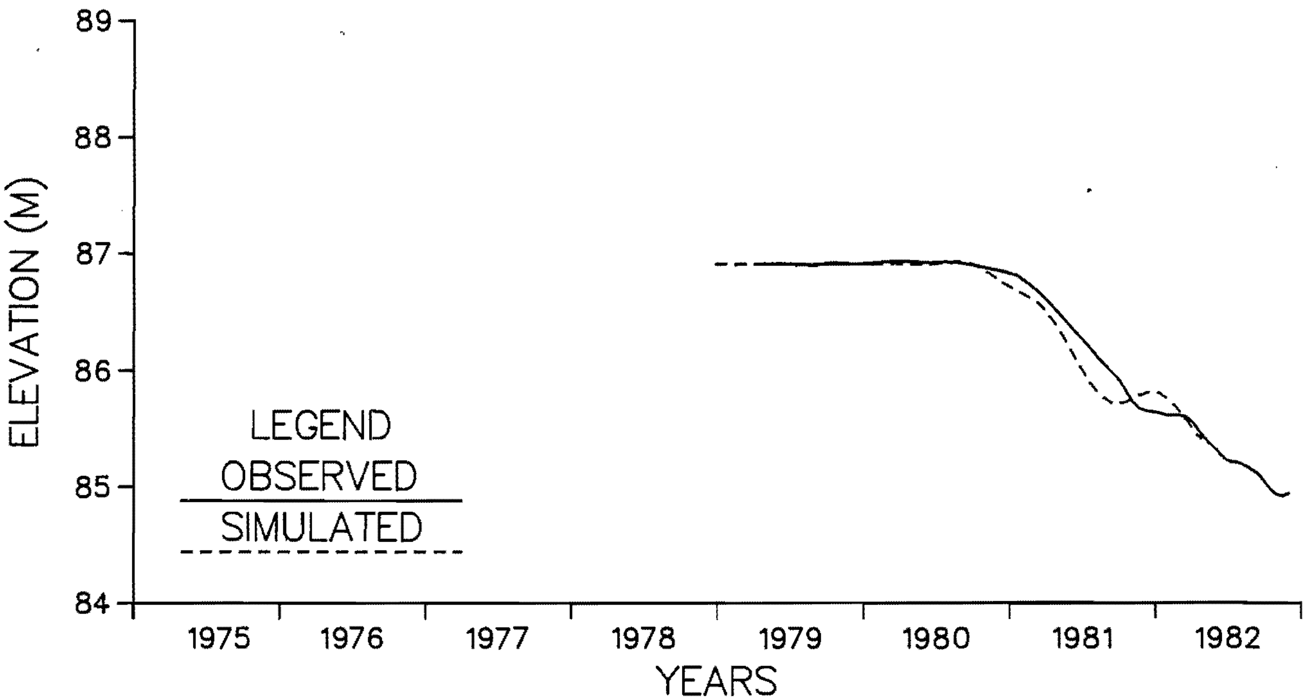


FIGURE 12
PIEZOMETER 15
OBSERVED AND SIMULATED HYDROGRAPHS



MODEL PREDICTIONS BY DYNAMIC SIMULATION

After completion of the calibration phase, the prediction runs were made for the regional aquifer model over a 60-year period that started January 1, 1975. Although calibration indicated that the leaky aquifer model provided the best match between observed and simulated drawdown for the first 7 years, a series of regional model predictions were performed for the following cases:

1) The classical leaky aquifer with constant adjacent heads in time.

2) A modified leaky aquifer where adjacent heads were gradually reduced using an exponential decay over a 20-year period starting 5 years after pumping begins locally, after which phreatic conditions prevail for the final years of the simulation. These modified leaky aquifer runs were made to simulate the dewatering of the upper semi-confining layer and leakage from its extensive silt and clay layers.

3) A completely phreatic aquifer simulation over the 60-year period.

4) A completely confined aquifer simulation over the 60-year period.

These multiple runs were valuable in assessing the overall range of possible drawdown conditions under a wide variety of model assumptions, and in testing the robustness of model assumptions used. Pumping figures were assumed to be constant over the prediction period at previously estimated levels.

Figures 13-17 illustrate the model predictions for piezometric elevation head at 5 nodal points over the 60-year interval in and around the Sarir well fields. A 60-year model run was chosen starting in 1975 to yield about a 50-year prediction for the CBWP well fields yet to be constructed. The model predictions were made for four different aquifer assumptions with the symbols: L = leaky aquifer, P = phreatic aquifer, ML = modified leaky aquifer, and C = confined aquifer simulations.

Figure 13 gives the results for the regional model node number 92, located near the camp well in the center of the Sarir North agricultural well field (see Plate I). The net drawdown for the leaky aquifer is only 11 m as shown by the curve labeled L. This relatively small drawdown illustrates the unrealistic behavior of the classical leaky aquifer model for long-term predictions. The drawdown stabilizes very early in the pumping history, because the constant-head condition in the adjacent aquifer essentially acts as a very large, perpetual source of recharge to the main aquifer. At the other extreme, the assumption of a completely confined aquifer affects the long term drawdown as shown by the curve labeled C. The net drawdown in this case of 49 m can be considered excessive since the model allows no leakage from the adjacent lower-permeability beds.

The model gives approximately the average drawdown of the elements surrounding a nodal point including interference from all other wells in the area. A well at this point probably would draw down approximately 5 m in addition (determined by the Theis model) because of its own individual self drawdown. This will be true generally for all the Sarir well fields. These long-term predictions include well field interference but not well losses nor other corrections including partial penetration.

The assumption of a phreatic aquifer (curve P) with no recharge over the complete prediction period gives an intermediate drawdown of 38 m in the Sarir North field. The modified leaky aquifer (dashed curve labeled ML) gives a drawdown of 42 m. In this latter case the adjacent aquifer heads were gradually reduced exponentially over 20 years starting 5 years

FIGURE 13
PIEZOMETRIC HEAD PREDICTIONS
NODE 92, SARIR NORTH WELL FIELD

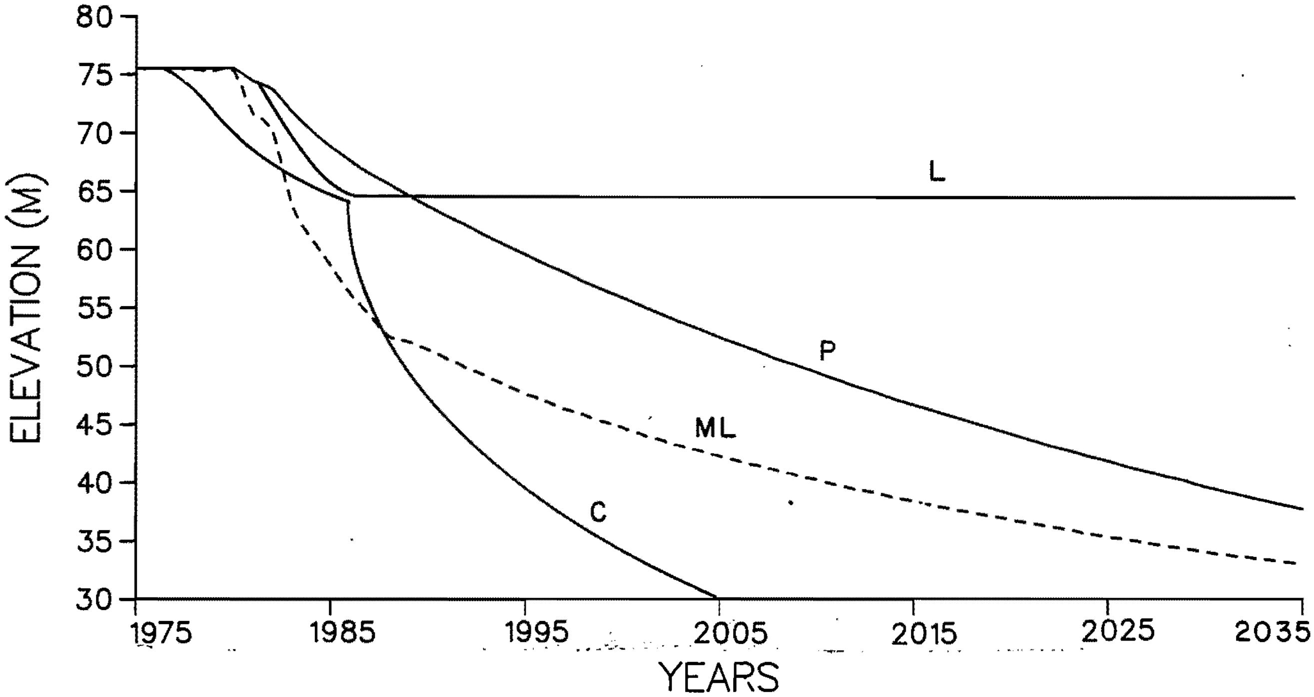
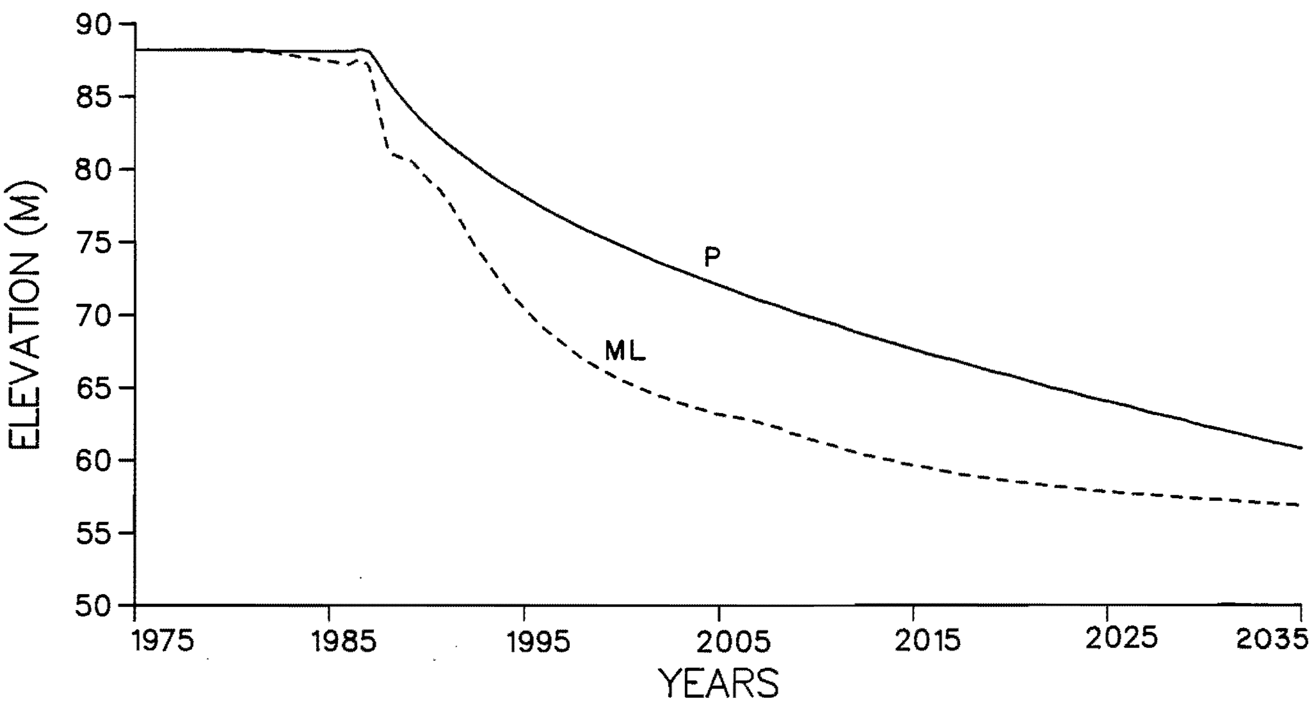


FIGURE 14
PIEZOMETRIC HEAD PREDICTIONS
NODE 87, CBWP WELL FIELD AT SARIR



after the start of pumping. After the upper adjacent aquifer was completely drained (at the end of 25 years), the main aquifer became phreatic with no water coming from the adjacent aquifer.

Figures 14 and 15 illustrate the 60-year prediction (50 years after start of pumping) in the CBWP Well Field at Sarir. In Figure 14 regional model node 87 (see Plate I for location) gives predicted drawdowns of P = 28 m and ML = 32 m after 50 years of pumping. Results for node 106 in Figure 15 are L = 7 m, P = 34 m, ML = 39 m, and C = 61 m. Note that these are average heads in the aquifer and that wells at these sites will draw down further due to self drawdown, partial penetration, and well losses. The 1,000,000 m^3/day discharge was taken from elements numbered 167 through 171 and half of element number 172 in the regional model (see Plate I). The average drawdown predicted by nodes 87 and 106 for the modified leaky case is about 36 m which includes about 11 m of drawdown due to well field interference.

Figure 16 gives the 60-year prediction for node 123 located at the site of Piezometer 33 (see Plate I) between the Sarir North and Sarir South well fields. The phreatic (P) and modified leaky (ML) simulations show drawdowns, due to interference from all the nearby well fields, of 31 m and 37 m respectively. Again the confined (C) and leaky aquifer (L) simulations give extremes of 56 m and 9 m respectively.

Figure 17 is the 60-year prediction for the Sarir South well field as indicated by node 155 located in the middle of the field beside Piezometer 50 (see Plate I). Again the phreatic and the modified leaky simulations are reasonably consistent (30 m and 34 m respectively), while the leaky aquifer results in only 6 m of drawdown and the confined prediction is 58 m. Figure 18 shows the 60-year predictions for node 186

FIGURE 15
PIEZOMETRIC HEAD PREDICTIONS
NODE 106, CBWP WELL FIELD AT SARIR

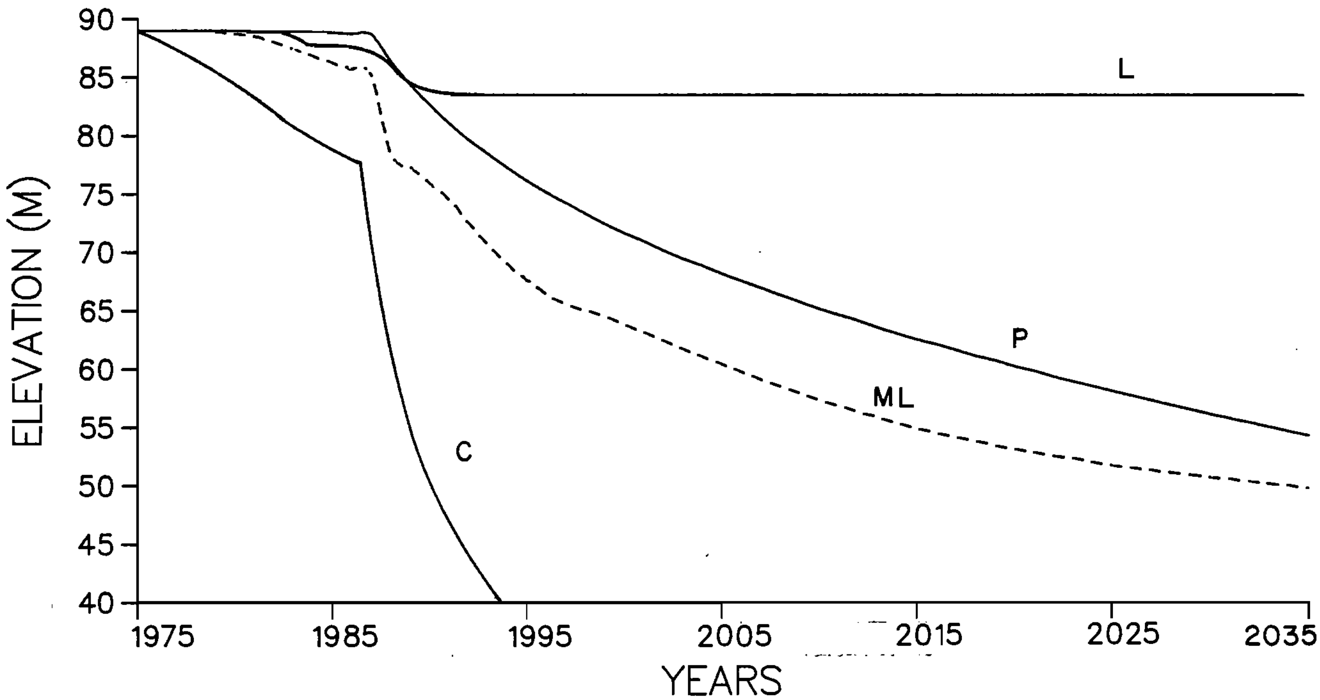


FIGURE 16
PIEZOMETRIC HEAD PREDICTIONS, PZ33
NODE 123, BETWEEN SARIR NORTH AND SARIR SOUTH WELL FIELDS

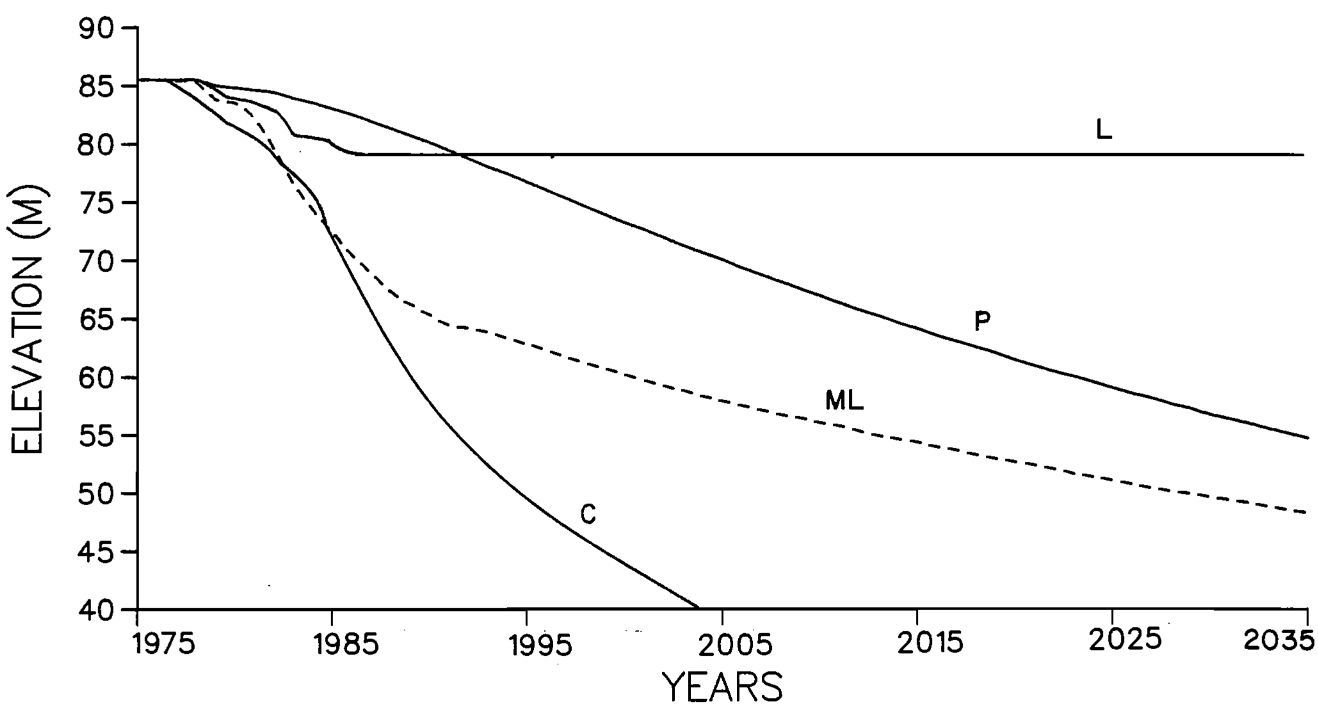


FIGURE 17
PIEZOMETRIC HEAD PREDICTIONS
NODE 155, SARIR SOUTH WELL FIELD

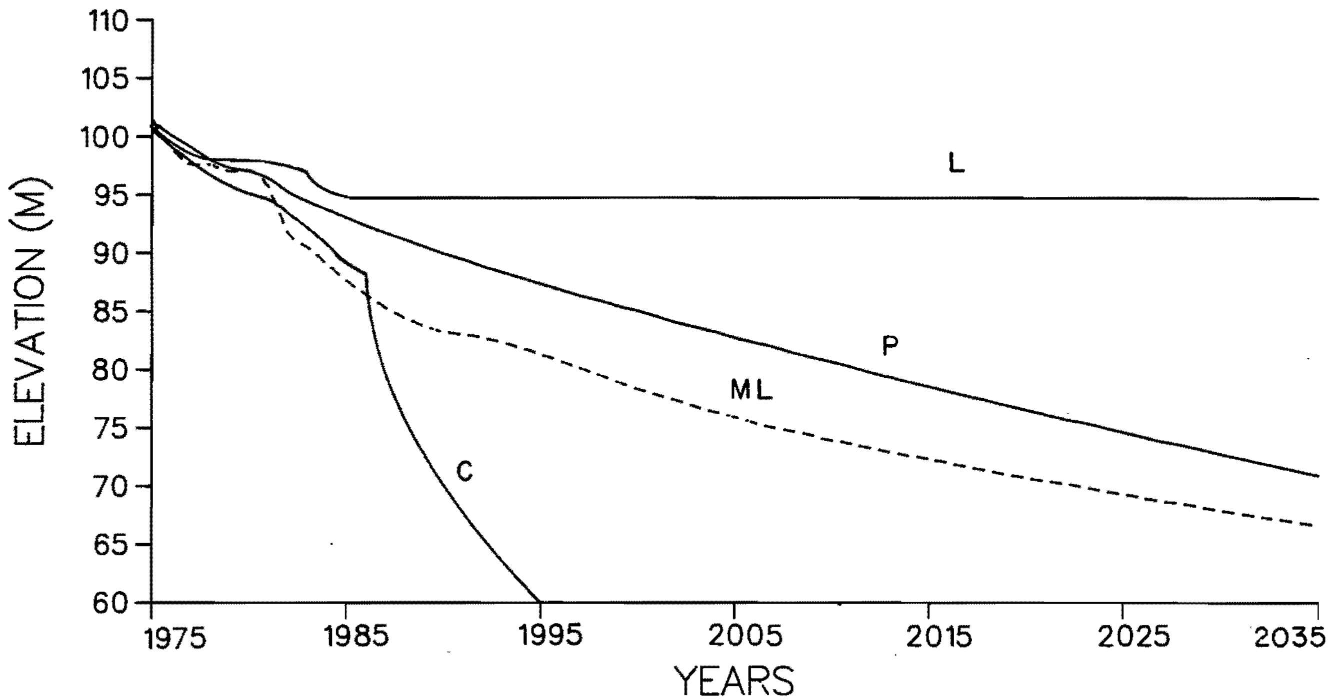
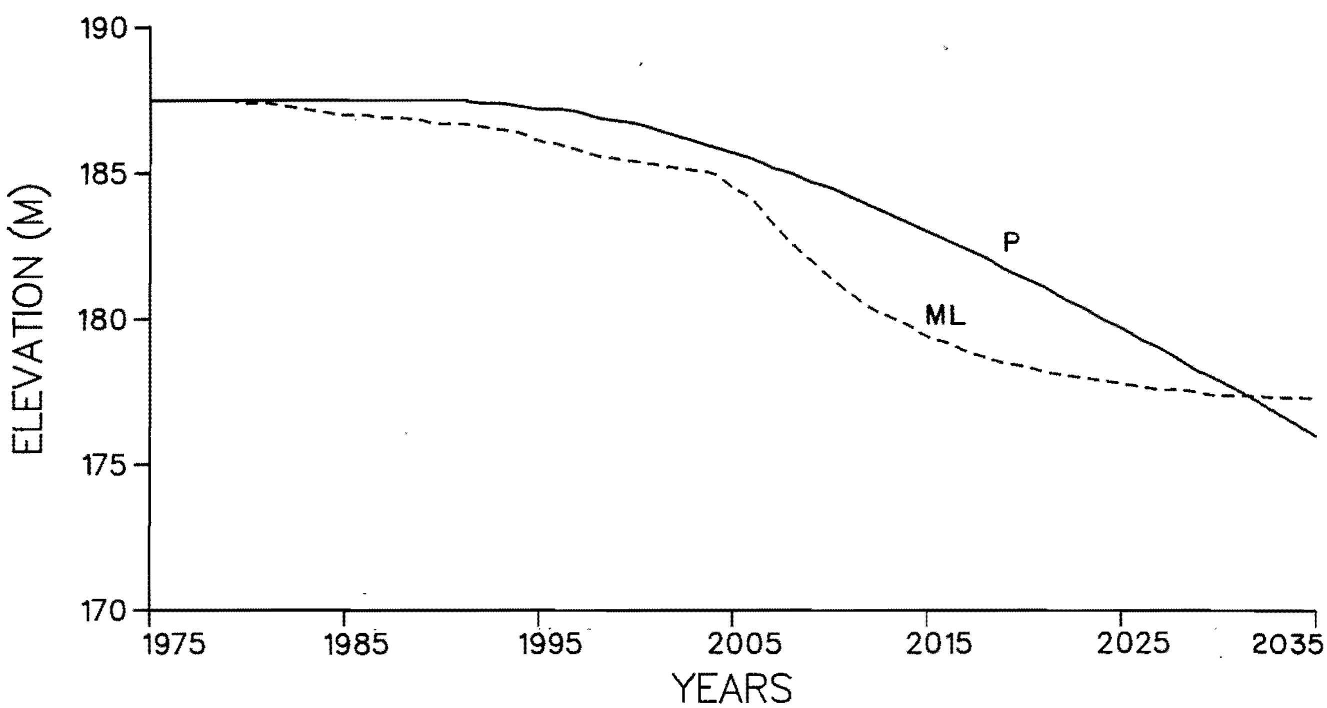


FIGURE 18
PIEZOMETRIC HEAD PREDICTIONS
NODE 186, BETWEEN SARIR SOUTH AND CBWP TAZERBO WELL FIELDS

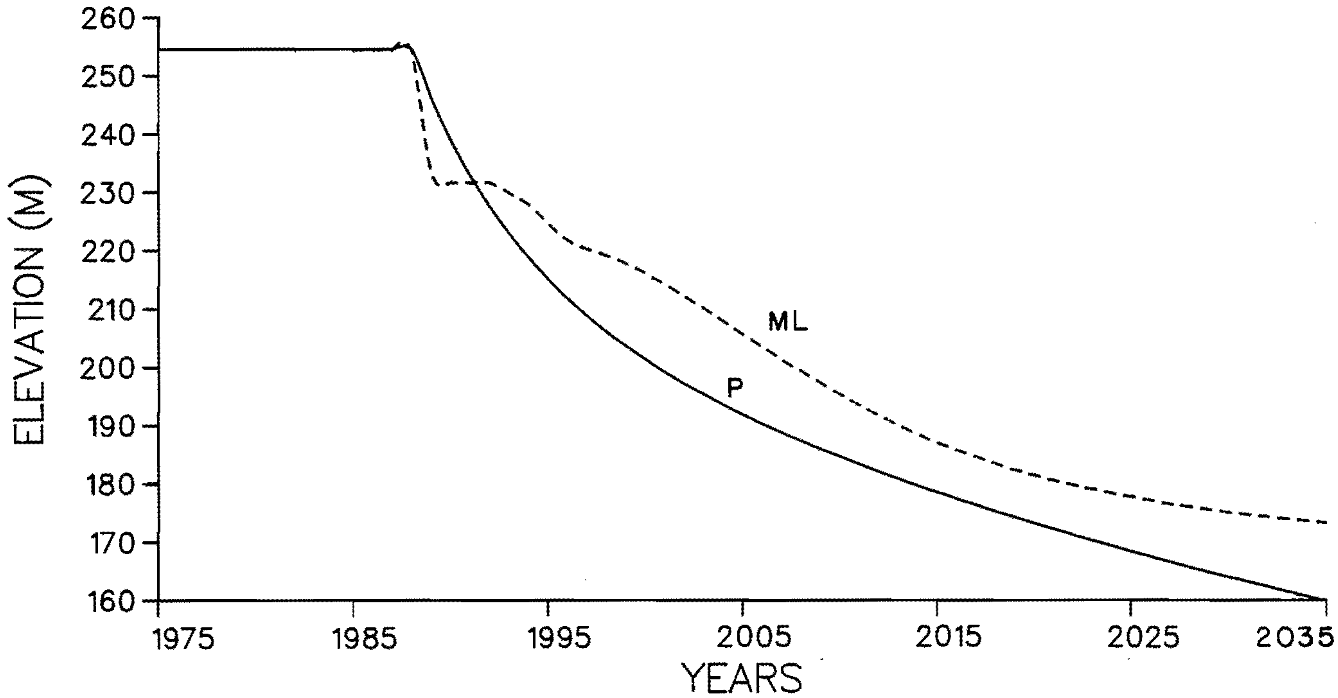


located between the Sarir South well field and the CBWP Well Field at Tazerbo (see Plate I). Results are similar to the foregoing except drawdowns are not severe (P = 12 m and ML = 10 m) because of the distance from pumping centers.

These results indicate that the phreatic model and the modified-leaky model will provide a reasonably good prediction of future conditions. The ordinary leaky aquifer model with an infinite supply of vertical downward leakage is totally unsuitable for long term predictions, and will underestimate drawdowns by a significant amount. The confined aquifer predicts unwarranted large drawdowns which are believed to be overly pessimistic. These extremes may be considered as maximum and minimum limits of these predictions. The modified-leaky aquifer simulation produces slightly more drawdown than the phreatic case and thus would be the most appropriate model for a conservative prediction of well-field performance. The values of drawdown thus obtained are the ones used for the regional drawdown in the prediction of future well field performance in this report.

Figure 19 shows the 60-year prediction (50-year drawdown) for the CBWP Well Field at Tazerbo located at node 202 with discharge from elements 372 and 373 on the regional model (see Plate I). In this case the phreatic prediction showed more drawdown than the modified leaky simulation. The extremely small dimensions of the present well field layout, the lack of geohydrologic data, and the large discharge of the proposed well field detract from the modeling accuracy in this area. A separate model with smaller elements should be constructed or a large number of elements should be added in this area once the final well field design is selected. This will give the needed resolution power for this

FIGURE 19
PIEZOMETRIC HEAD PREDICTIONS
NODE 202, CBWP WELL FIELD AT TAZERBO



portion of the regional model. The 50-year drawdown indicated by the modified leaky simulation for the CBWP Well Field at Tazerbo is about 81 m to which must be added self drawdown (about 9 m after 50 years, obtained by Theis model), partial penetration (2 m), and well loss corrections.

EVALUATION OF THE MODEL SYSTEM

Piezometric-Surface Contour Maps

Figures 20 and 21 represent computer generated contour maps of the Sarir area showing the cones of depression for the Sarir well fields under certain hypothetical conditions. These maps represent an optimistic prediction assuming the whole regional aquifer will behave ultimately as a phreatic or a water-table aquifer. This is probably the way it will behave, but for the present the estimate is for about 5 m more drawdown (using the modified leaky simulation) to take place at the CBWP Well Field at Sarir after 50 years of pumping.

Figure 20a shows the estimated drawdown for the year 2035 if the Sarir North and Sarir South well fields continue pumping and the CBWP Well Field at Sarir does not pump at all. This map gives an estimate (for a phreatic aquifer) of how much the well field interference may be in the CBWP well field site as generated by the Sarir North and Sarir South well fields. It appears to be about 11 m on the average for this case. Figure 20b shows the estimated drawdown for the year 2035 if the CBWP Well Field at Sarir were pumped alone for 50 years.

Figure 21 shows the estimated drawdown by the year 2035 if all three Sarir well fields are pumped continuously as now planned for the remainder of the 60-year period in the hypothetical phreatic aquifer. A maximum of 35 m drawdown will take place at the east end of the CBWP well field because of the interference from the other two well fields. A large area between these three well fields will be dewatered as a result of the prolonged pumpage.

FIGURE 20a. PREDICTED REGIONAL DRAWDOWN OF SARIR NORTH AND SARIR SOUTH WELL FIELDS

PHREATIC CASE

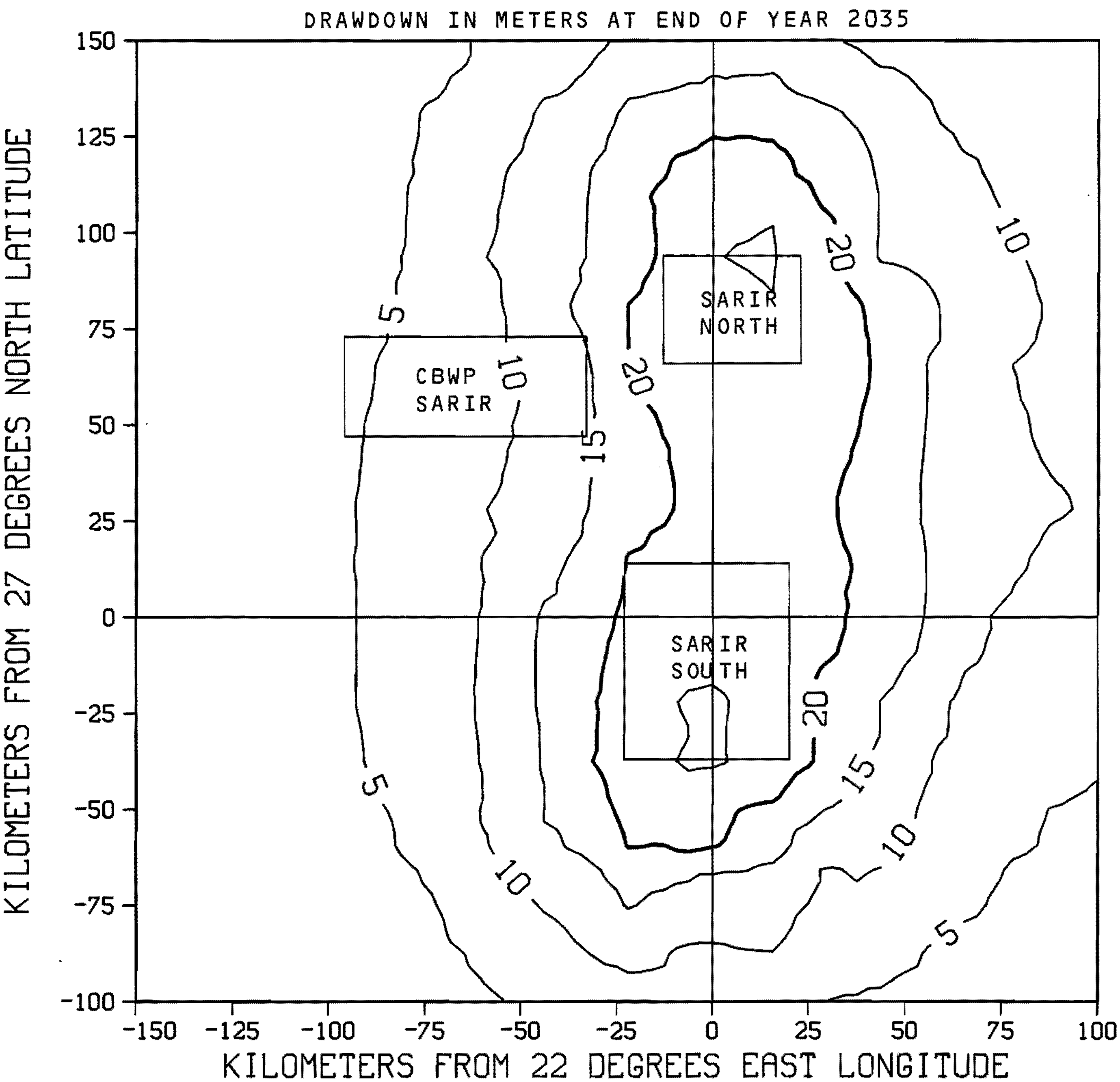


FIGURE 20b. PREDICTED REGIONAL DRAWDOWN OF CBWP WELL FIELD AT SARIR

PHREATIC CASE

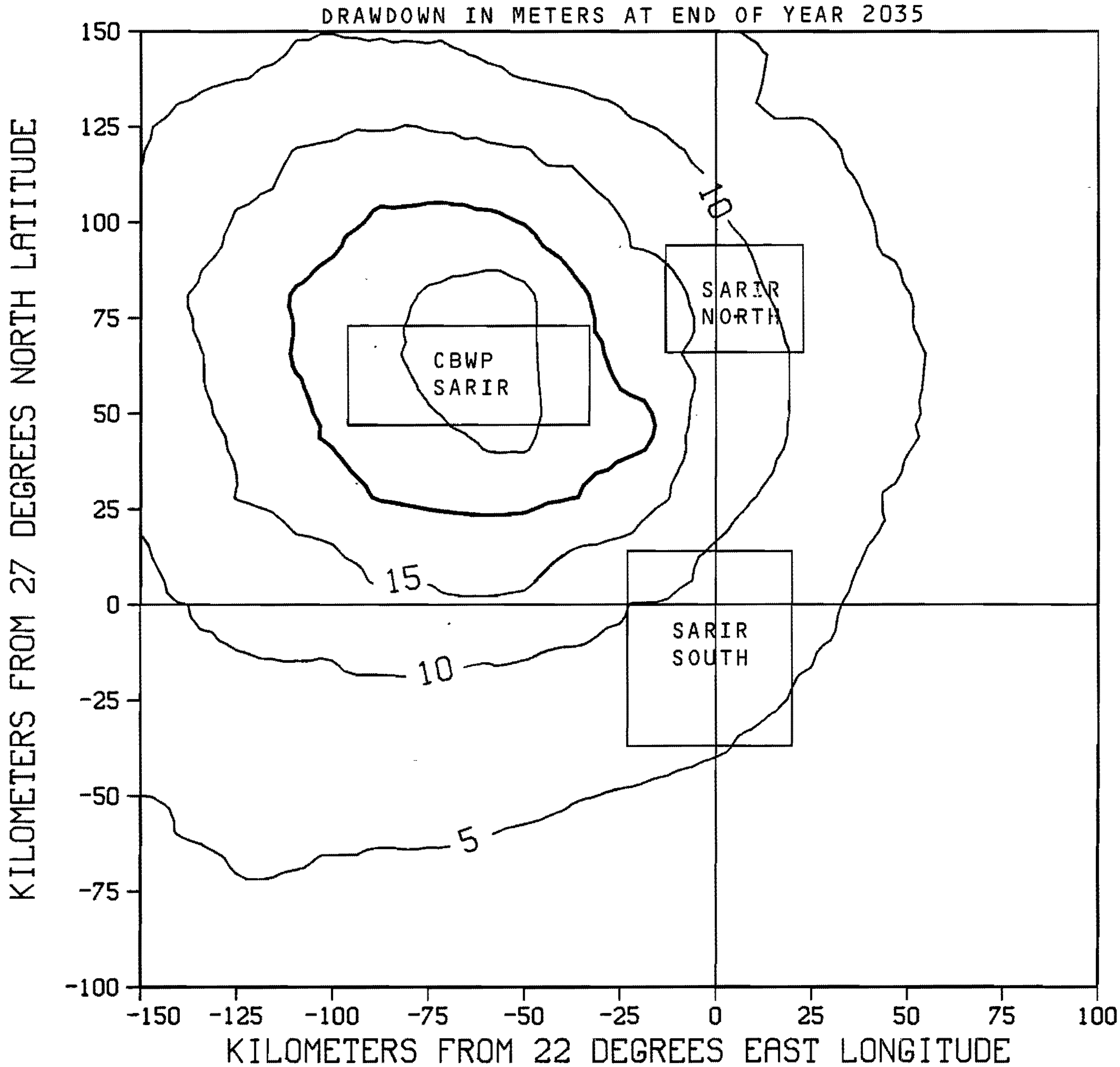
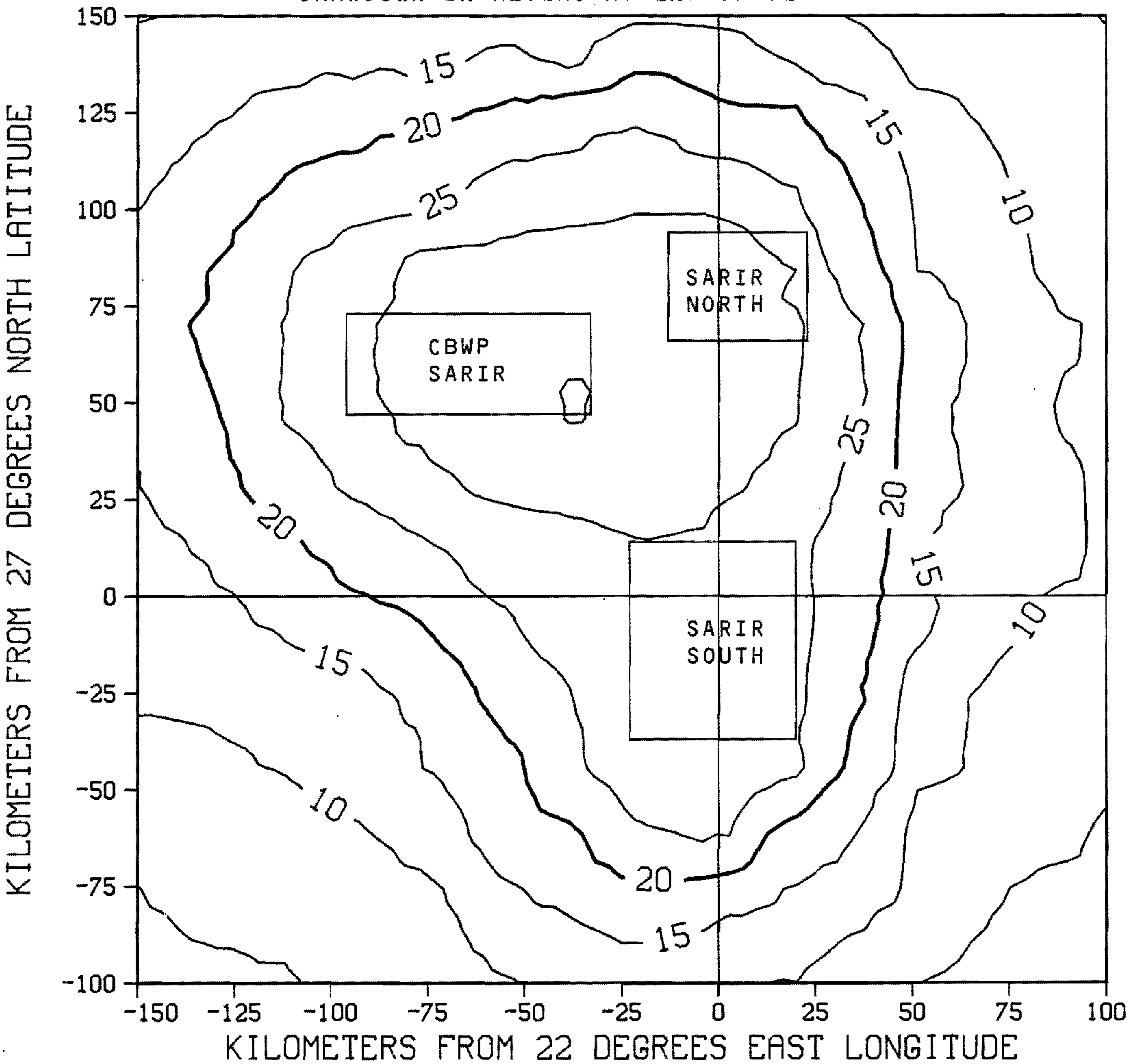


FIGURE 21. PREDICTED REGIONAL DRAWDOWN OF CBWP SARIR, SARIR NORTH, AND SARIR SOUTH WELL FIELDS

PHREATIC CASE

DRAWDOWN IN METERS AT END OF YEAR 2035



The modified leaky prediction shows a few meters more drawdown over the same period, thus the prediction for the CBWP Well Field at Sarir is for the greater drawdown. Hopefully, the ultimate drawdown will be more like Figure 21 depicts for an unconfined aquifer. It must be remembered that the model gives only an average piezometric surface throughout the area of the well fields. Individual pumping wells make dimples in this surface due mainly to their self drawdown. Also hydraulic friction within the wells causes the pumping level to be even deeper than the bottom of the dimple. These and other corrections are needed to arrive at an estimated pumping lift for a well field as is explained in Appendix A.

Accuracy of Results

For the predicted drawdown, the modified leaky simulation was used, but this is still only an estimate based upon 7 years of pumping history of the existing well fields and a computer model prediction based upon aquifer characteristics determined in several ways (calibration runs, steady-state modeling, pumping tests, etc.). As time passes, the model should be up-dated and new predictions made. The model predictions may diverge in the future from these present predictions, even though they are based upon the best data and modeling techniques presently available. Any divergence should certainly stay within the predictions shown graphically on Figures 13 through 19 representing the purely leaky aquifer simulation (L) and the wholly confined aquifer simulation (C).

Sensitivity Studies

To effectively calibrate the main AQUIFEM model, the auxiliary model of the Sarir South agricultural well field was used to see what effect the local variation of aquifer parameters had on the overall drawdown. Of great value to these efforts was the flexibility of the AQUIFEM program to simulate confined, unconfined, and leaky aquifer situations. The water-level time histories (hydrographs) for 23 piezometers of the Sarir South well field were most useful.

The wells in the Sarir South field are operated cyclicly conforming to the irrigation and harvesting needs. The resulting hydrographs of water level versus time for any piezometer in or near the well field exhibit dips and rises coinciding to the on-off utilization of the groundwater.

By varying the principal aquifer parameters of transmissivity, storage coefficient or storativity, and leakance, the location and amplitude of the fluctuations could be duplicated quite easily when the actual pumping rates from 1975 to 1982 were used in the Sarir South model.

Variations in the storage coefficient were found to relate more to the amplitude of the rises and dips in the hydrographs and have little relationship to the drawdown trend. Variation in the transmissivity was found to relate to the overall drawdown trend and have very little effect on the seasonal fluctuations. The leakage term had an effect similar to the transmissivity, that is, strongly affecting the drawdown trend and barely influencing the short term changes.

A systematic series of 24 computer simulations were run for the Sarir South well field progressing through a planned sequence of aquifer parameter variation, each time using the actual discharge data. The best fit of the piezometric field data for each case of confined, leaky, and unconfined simulation is illustrated in the graphs of Appendix C and Figures 9 and 10. Those results were then extended from the smaller model of the Sarir South well field to the regional aquifer model. Similar techniques of graphical comparison and parameter variation were used to calibrate the regional model using Sarir North and Sarir South well field data.

PERFORMANCES OF THE WELL FIELDS

Alternative Well Field Designs

In the layout of a well field wherein a water gathering network of pipes is required, many things must be considered besides drawdown in wells, mutual well interference and other aquifer related items. Paramount among these other considerations are initial costs of wells, pumps, appurtenances, pipelines, power lines, and roads as well as operation and maintenance costs. Reduction of hydraulic friction inside wells and pipelines is equally as important as reducing drawdown in an aquifer (another form of hydraulic friction) because they both affect pumping costs the same way. Wider well spacing reduces drawdown and lifting costs, but it usually increases pipeline costs and hydraulic friction in the pipe network. Increased pipe diameters will reduce pumping costs but larger pipes are more expensive. These and several other counteracting design features must be optimized for a more efficient well field design.

The present designs of the CBWP well fields at Sarir and Tazerbo are mutually inconsistent and each can be improved in different ways. For example, the Sarir well field can be spread out and yet use less pipe and fewer wells. This and a few other suggested modifications could lead to a savings of roughly $116,000,000 over the life of the well field. Figure 22 is a map of the Sarir region showing the present and suggested well field designs with individual wells and the pipeline networks shown diagrammatically. A similar amount could be saved at the Tazerbo well field by another set of similar suggestions, which includes spreading out this extraordinarily compact layout. Figure 23 is a map of

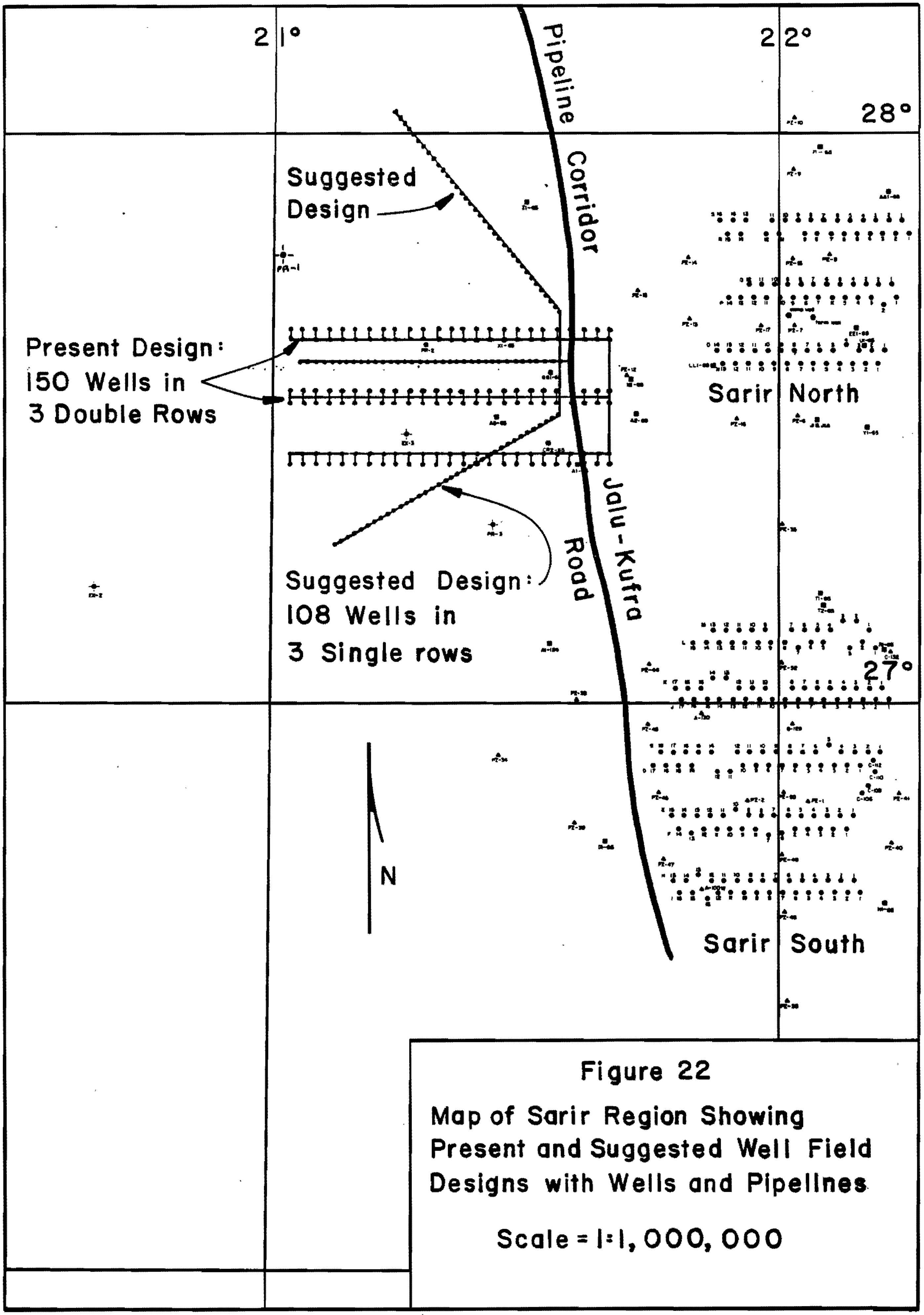


Figure 22

Map of Sarir Region Showing Present and Suggested Well Field Designs with Wells and Pipelines

Scale = 1:1,000,000

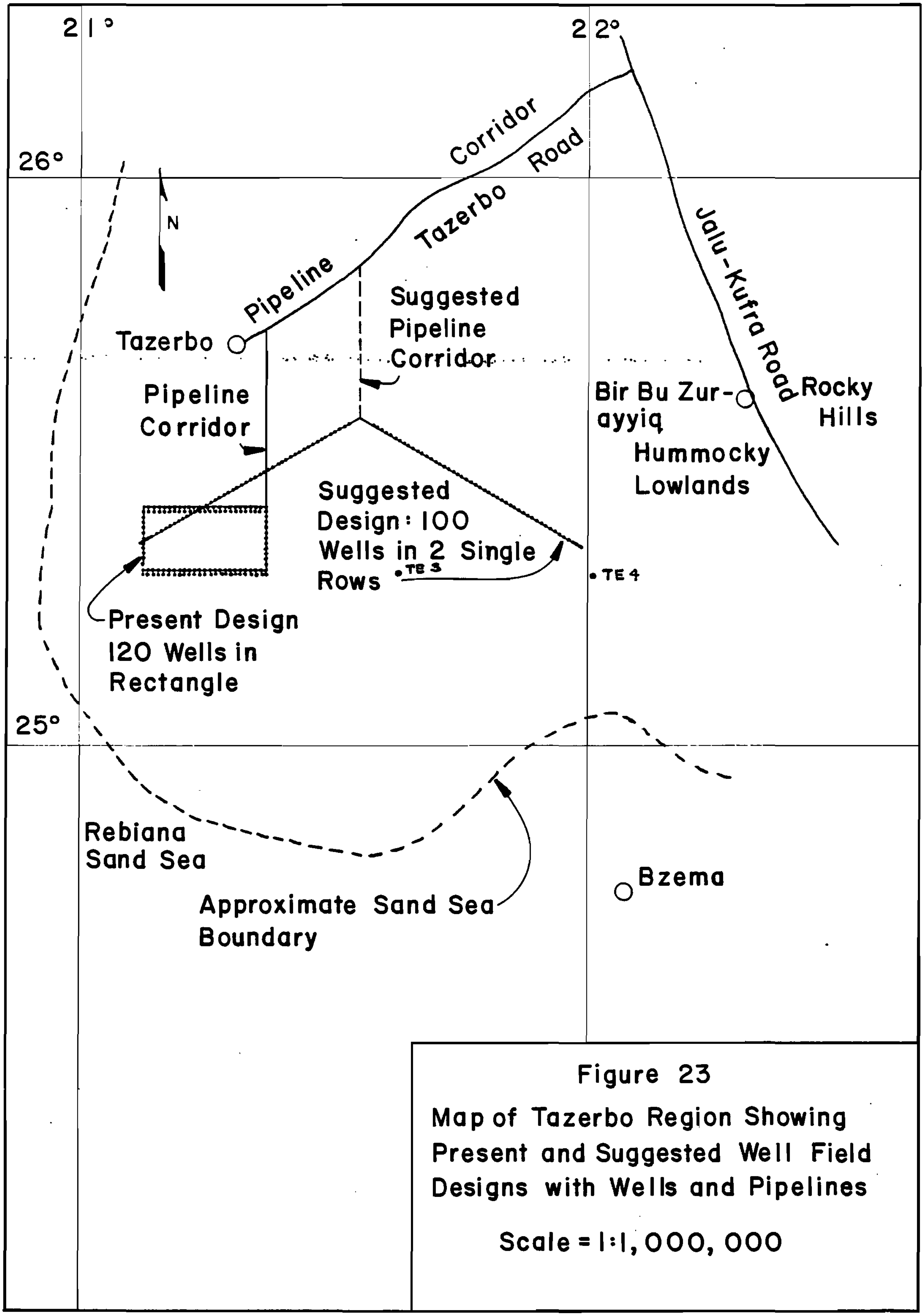


Figure 23

Map of Tazerbo Region Showing Present and Suggested Well Field Designs with Wells and Pipelines

Scale = 1:1,000,000

the Tazerbo region showing the present and suggested well field designs. These suggestions, and the physical and economic principles supporting them, are explained in Appendix A. These suggested designs are not intended to violate any governmental water well policies, but are presented in a constructive spirit with the hope that they or at least the principles supporting them will be adopted for the final well field layout.

Useful Life of the Well Fields

The Sarir region is endowed with enormous quantities of high quality groundwater where the two CBWP well fields have been located. Even though this water is not being replenished at rates comparable to the planned extractions, there is more than ample water in drainable storage to supply these fields for their designed 50-year life. For example, if the Sarir well field is fanned out as suggested, it will enclose an area of about 2400 km^2, and assuming a specific yield of 0.05 for the nearly 100 m of aquifer overlying the main aquifer, almost 70 percent of the 50-year extractions may come from dewatering of the overlying aquifer. At least another 10 percent will come from regional underflow from the south into the area. The remaining 20 percent will be obtained readily by dewatering of the main aquifer and from elastic expansion of the affected groundwaters within and surrounding the well field. This is not necessarily the way water will be extracted, but is given only to illustrate the large amount of water locally in storage throughout the region.

Aquifer drainage patterns are highly dependent upon local stratigraphic conditions within the aquifers developed. The optimistic predictions of this report are based mainly upon the extremely favorable behavior of the

Sarir South well field. This is a true history of 7 years, which is long enough to give assurance of its future behavior and that of the CBWP well field to be placed in virtually the same stratigraphic setting.

The CBWP Well Field at Tazerbo will not be in the same stratigraphic sequence as the Sarir well field, but analogous geologic conditions exist there. The aquifer material is of considerably greater age and may be of somewhat lower permeability and specific yield, but it is believed that a drainable water-table aquifer overlies the main aquifer and this similar stratigraphic condition will enable the CBWP Well Field at Tazerbo to perform nearly as well as the one at Sarir. Moreover, the Tazerbo well field will not have increased drawdown resulting from nearby well fields producing from the same aquifer, based upon presently known conditions.

After 50 years, these well fields will continue producing and continue along whatever pumping-level trend they are following at the time. There will be no sudden stoppage of water, but at some time the ever increasing pumping lifts may render the operation too costly. By that time supplemental well fields could be in operation and the original ones perhaps could continue at a lower, more economic pumping rate.

Location of the CBWP Well Fields

The CBWP well fields have been located at excellent sites based upon what is presently known of the regional geohydrology. The aquifers of the two sites are mainly composed of unconsolidated sands with reasonably high specific yields. Their relatively low permeabilities are largely compensated for by their large thicknesses. Almost 300 m of aquifer section will be opened to production in the wells and there are additional contributing aquifers above and below the main producing intervals.

The proximity of a drainable phreatic aquifer is probably the chief advantage these two well field sites have. This stratigraphic feature probably has the greatest influence upon the future pumping lifts and economic life of the well fields. Drainable water table aquifers are believed to be present within both well field sites, thus their sustaining effects will be felt almost immediately from the beginning of pumpage, as has occurred at the Sarir South well field. Even if such aquifers are some distance away, their effects will be beneficial (in diminishing strength with distance).

More prolific aquifers occur in the Sarir region, such as the sizable streak of highly permeable aquifer that trends through the Sarir North well field, but finding them may be more costly than the advantage they may give in more effective wells and reduced drawdown. The relatively poor aquifers on either side of the permeable streak caused the overall performance of the Sarir North well field to be worse than the Sarir South well field, which has no such streak. Aquifer transmissivities of the Sarir South well field increase across that field in the direction of the CBWP well field site at Sarir and the regional steady-state model results indicated that this trend continues into the site. If this trend is confirmed during the construction of the CBWP Well Field at Sarir, then the foregoing well field predictions are assured.

The main disadvantage in the CBWP well field site at Sarir is that it will experience about 11 m of interference from the two agricultural well fields in 50 years as well as cause interference upon them. Unfortunately the location of the CBWP well field is quite firmly fixed by water quality constraints. A little freedom still remains for some movement in that respect by extending further into areas of high quality groundwater and away from the existing well fields. One logical area where development could be made is in the lobe of high quality water shown on Figure 6 in the vicinity of 28°N latitude and 21°E longitude. Although it is too late to test and appraise this area for the present well field site, it is probably the best area to consider if the well field is ever expanded to increase its yield. The smaller lobe extending to the southwest of the present site might also be developed further if some future need arises. The site of the CBWP Well Field at Sarir is then a compromise between water quality, geology, well field interference, and other considerations. See Appendix A for further remarks on the location of this well field.

The CBWP Tazerbo well field site is good so far as the known geohydrology is concerned. Water quality is probably very high throughout the Tazerbo area. All water samples taken from the main aquifer out of the SLRAD test wells had TDS less than 510 mg/l (ElRamly 1980). A wedge of Tertiary sediments tends to confine the aquifers north of the latitude of Tazerbo Oasis, thus the CBWP well field should remain safely south of there. The Rebiana sand sea borders the area about 20 km to the west and about 40 km to the south of the present CBWP Tazerbo well field site. It is suggested that the Tazerbo well field be moved about 25 km to the northeast and spread out to reduce the intense mutual well interference inherent in the present design (see Figure 23). Substantiation of this is explained in Appendix A. Except for the possibility of encountering lower permeability aquifers or some unknown hydraulic barriers, there appears to be no other reasons for not making this move and expansion of well spacing. A few test wells are recommended if this repositioning of the well field is adopted. They could be positioned at locations where they would become premanent production wells or piezometers if the tests prove moving the well field will be beneficial.

Interference Between Well Fields

When two or more well fields are pumping simultaneously, they affect each other by causing additional drawdown because their cones of depression are superposed upon each other. Figures 20a and 20b illustrate this very well by showing the drawdown caused by the pumping of a well field in the area surrounding it. Figure 21 shows how these cones of depression are superposed. The drawdown indicated at any point on Figure 21 is the sum of the two drawdowns indicated at the same points on Figures 20a and 20b. This is the reason for separating well fields as far apart as is practical.

The CBWP Well Field at Tazerbo will experience no significant interference from the well field now under construction at Tazerbo Oasis. However, the Tazerbo Oasis well field could be strongly affected by the CBWP well field. This is another reason for moving and spreading out the CBWP Well Field at Tazerbo to the northeast from its present site (see Figure 23).

Changes in Water Quality

Water quality in the Sarir South agricultural well field has remained virtually unchanged in the 6 years of production history despite the close proximity of lower quality water to the east and south (Hasnain 1981). This is believed to have happened because pumping levels have not declined sufficiently to induce appreciable quantities of groundwater to enter the well field laterally. Inflow to the Sarir South wells has been sustained largely by the dewatering of unconfined aquifers above the main producing interval. After many years, this added source of water above the main aquifer will be depleted and proportionately more and more water will be induced into the wells from surrounding areas and from deeper aquifers.

A somewhat more immediate hazard to the water quality of the Sarir South agricultural field may be the layer of inferior quality water just below the regional water table and the deep percolation of irrigation return flow that will combine with it. If this mixture should happen to break through the higher quality groundwater via stratigraphic irregularities, water quality deterioration could be accelerated in an unpredictable fashion. Deep percolation from excess irrigation waters can be highly saline depending upon procedures of the irrigation project.

Not much is known about the shallow layer of inferior quality groundwater in the CBWP Sarir well field area. Moreover, there will be no hazard from deep percolation of irrigation return flows.

Presently it appears that the main threat to water quality deterioration at the CBWP Well Field at Sarir may come from the added depth of the wells. This hazard can be partially assessed as the wells are constructed and tested, but for the long term, deep piezometers must be constructed below the pumping centers to monitor vertical gradients and water quality variations. It is premature at this time to predict water quality variations in the CBWP well fields except to note that they are constructed in areas known to be of the highest quality water in the region. It is most important that adequate data are collected to evaluate this potential problem before and during early well-field production.

Two exploratory wells (EX-3 and PR-2) constructed within the present confines of the CBWP Well Field at Sarir yielded water of less than 1000 milligrams per liter (mg/l) of total dissolved solids (TDS) in the proposed producing interval between 150 m and 450 m. However, nearby test wells PR-1 and PR-3 yielded water of 1600 mg/l TDS and 1324 mg/l TDS respectively within the same interval (ElRamly 1980). This is not to discourage the use of 450-m wells, but only to point out that some risk is involved, that adequate data must be collected during construction, and that slight modifications may have to be made as a result of new water quality or other data collected at that time. Salinity of water at the CBWP Sarir Well Field at Sarir should be less than 1200 mg/l TDS.

Based on existing reports (including ElRamly 1980), groundwater quality at Tazerbo is very high and there is little danger of deterioration in time. TDS of all deep Mesozoic aquifer water samples obtained there was generally below 500 mg/l. Tazerbo groundwater could be used effectively in diluting the poorer quality of the Sarir water by commingling the waters of the Ajdabiya holding reservoir and thus will help offset any salinity buildup that might occur at the CBWP Well Field at Sarir.

Possible Subsidence Effects

The lithology of the study area suggests that there is considerable potential for land subsidence as piezometric heads decline over time.

Subsidence potential is directly related to percent and distribution of clay interbeds underlying each of the well field sites. The final report of the IGS Jalu-Tazerbo Project (Wright 1975) provides detailed lithologic logs which indicate that substantial clay beds are present in the PMM and LMM sediments, which comprise the main aquifers of the CBWP Sarir well field and the Sarir agricultural well fields. For example, clay beds appear to make up about 30 percent of the total saturated thickness in the vicinity of the CBWP Sarir well field (Wright 1975, Figure 13).

Declining piezometric heads cause intergranular stresses to increase within an aquifer. Clays cannot sustain this loading and entrained water is squeezed from them. Reduced aquifer head may accelerate the consolidation, but it is a very slow process due to the extremely low permeability of clay. Over a period of years, however, subsidence can become large.

Although it was not the purpose of the present study to examine subsidence related to groundwater withdrawals, it is probable that subsidence may become a factor in the long term operation of the well fields. Normally subsidence is of little consequence even in heavily pumped areas, but occasionally it can become very serious. The most common effects are land subsidence around well heads and differential settlement of the land surface across the countryside. Ruptured pipes and connections can be avoided because subsidence usually takes place very slowly and can be detected before serious damage occurs. A moderately precise leveling network of well-head foundations, piezometer heads, key points on the pipeline network, and whatever surveying monuments are used during the construction phase should be established and releveled every year or two to detect incipient differential settlement. Also the flexible couplings used at well heads and pipeline thermal expansion joints can be installed propitiously to accommodate some differential settlement.

CONCLUSIONS

1. The aquifers at CBWP Well Field at Sarir have about the same hydrologic properties as those at Sarir South agricultural well field, but not necessarily the same as those at the Sarir North field. This is justification for modeling the CBWP Well Field at Sarir based upon aquifer characteristics similar to those determined for the Sarir South well field aquifers from a preliminary model simulation of the Sarir South field's 7-year production history. Regional model calibration also supports the similar relationship of these two areas.

2. The CBWP well fields are properly located in areas where dewatering of overlying unconfined aquifers will minimize pumping lifts. The repositioning of these well fields suggested in this report will not take them from these more favorable areas.

3. Water quality deterioration should not be a serious problem in the CBWP Sarir and Tazerbo well fields, but an adequate water quality monitoring program is essential for both of them. The more immediate hazard to water quality deterioration is upwelling from below the producing intervals. The monitoring program must include piezometers that monitor groundwater heads and quality below 450 m, especially in the CBWP Well Field at Sarir.

4. Aquifers of the CBWP well fields will behave in the long term as unconfined aquifers with strong delayed drainage effects. Heterogeneity and lenticularity of the fluviatile sediments that compose the local aquifers will cause partial confinement, perching, and highly irregular flow paths, which will greatly impede the flow of groundwater into the wells from horizons not opened directly to production. The

opening to production of only a portion of the total effective aquifer thickness forces flow to cross bedding planes in the direction of normally lowest permeability, even in the more permeable beds.

5. Delayed drainage in the prediction of CBWP well field aquifer performance is best simulated by a leaky but depletable aquifer in the initial phases of water production followed by an unconfined flow regime lasting for the balance of the well field's life. The specific yield of the aquifer may apparently increase in time giving more optimistic predictions in future years of monitoring. Modeling of delayed drainage for application to this groundwater model by modified leaky aquifer methods should be considered approximate. Groundwater models based upon delayed drainage have not yet been developed. Therefore, these conventional approximations of modified leaky and phreatic combinations have been used.

6. Detailed analysis of the Sarir South agricultural well field production history revealed that aquifer behavior there could be best simulated by a leaky aquifer having an average leakance of 2.5×10^{-5} per day and a storativity of 0.001. The 7-year aquifer performance also was simulated closely by an unconfined aquifer having a specific yield of 0.035 (a value of 0.04 was then used in the 50-year predictions). Finally it was simulated again fairly closely by a confined aquifer having a storativity of 0.005 and a transmissivity of 20,000 m^2/day. Transmissivities for the leaky and unconfined cases varied throughout the region as determined by the steady-state calibration of the regional model.

7. Fifty-year predictions of CBWP well field performance could not be based upon leaky aquifer theory without artificially tapering

off the leakage during the first 25 years of pumpage, thereafter the aquifer behavior was simulated by unconfined aquifer theory. The regional model demonstrated that a classical leaky aquifer solution is unsuitable for long-term predictions.

8. Regional drawdown at the CBWP Well Field at Sarir was estimated to be 25 m at the end of the 50-year period, but average drawdown in the wells themselves would be about 30 m, not counting well losses or well field interference. This well field drawdown will be increased by a maximum of about 11 m due to continued pumpage of the Sarir agricultural well fields, and by another 15 m of fluid-friction losses within the wells and aquifer, for a total of 56 m.

An improved layout and well design is suggested for the CBWP Well Field at Sarir not to improve the drawdown but to improve the pipe network and operation costs. The CBWP Sarir field should be repositioned to the west of the paved Jalu-Kufra road and the proposed pipeline corridor to reduce well field interference from the existing well fields at Sarir.

9. Regional drawdown at the CBWP Well Field at Tazerbo was estimated to be 81 m at the end of 50 years, but average drawdown in the wells themselves would be about 90 m, not counting well losses and other considerations. There will be no significant interference from other known well fields in the Tazerbo region, but well losses and other frictional losses will then cause an effective drawdown of 106 m at the end of 50 years. A modified well field layout and well design is suggested in this report to bring this anticipated drawdown more in line with that of the CBWP Well Field at Sarir.

10. The estimated underflow of groundwater coming from the south and flowing through the modeled area is about 650,000 m^3/day. Although this is not strictly a result of modern-day recharge, it may be considered as such for it will continue throughout the lifetime of the proposed well fields.

11. There are ample quantities of groundwater of satisfactory quality to sustain the proposed CBWP well fields at Sarir and Tazerbo, each producing 350,000,000 m^3/year, for considerably longer than the 50-year design life. Total dissolved solids of the water produced at Sarir should be about 1,200 mg/l and should be less than 500 mg/l at Tazerbo.

12. Should it ever become necessary to increase the yield of the CBWP Well Fields at Sarir and Tazerbo each to 1,800,000 m^3/day, it is extremely doubtful that the presently design well fields could sustain the increased yields. The wells especially are underdesigned and the well spacing is too close.

Well fields designed like those suggested could produce increased amounts, but it is preferred that more wells be added to extend the rows of single wells, thus spreading out the added well interference into more remote areas. If the added production must be obtained from the presently suggested number of wells, the wells should be redesigned and the rows of wells lengthened somewhat now in order to produce the increased yields more efficiently when the need arises. It is not feasible to simply increase the production of a well field by such a large amount without paying some penalties. Planning ahead for such an alternative could produce overall savings that may be of benefit even if the increased yield is not required.

REFERENCES

Ahmad, M. U. 1978. Discovery of an Ancient Underground Channel in the North Sarir well field, Libya. In: Symposium of Investigation, Exploration, and Economy of the Underground Waters. Zagreb, Yugoslavia.

Ahmad, M. U. 1979. A Design of Tazerbo Well Field. SARLD Department of Water and Soil, Tripoli, Libya. (Unpublished)

Ahmad, M. U., M. ElBakhbakhi, M. Husnain, and S. Ahmed. 1979. A Hydrogeology of Sarir Transportation Scheme. SPLAJ, SARLD Department of Water and Soil, Tripoli, Libya, 10 December 1979. (Unpublished)

Benfield, A. C. 1973. Preliminary Assessment of Post-oligocene Sediments in Region North of Latitude 27°20'N. Institute of Geological Sciences, London, England. (Unpublished)

Edmunds, W. M., and E. P. Wright. 1979. Groundwater Recharge and Palaeoclimate in the Sirte and Kufra Basins, Libya. Journal of Hydrology, 40:215-241, Amsterdam, The Netherlands.

ECG Engineering Consultants Group. 1978. Hydroagricultural Development of the Sirte and Sarir Areas, Phase 1, Final Technical Report, to Secretariat of Dams and Water Resources, SPLAJ (Unpublished). Cairo, Egypt.

ElRamly, I. M. 1980. Water Resources Atlas for Al Kufra and Sirt Basins. SARLD Department of Water and Soil, Tripoli, Libya. (Unpublished)

Hassan, S. A. 1976a. Map of South Sarir Well Field Layout. SARLD Kufra and Sarir Authority, Libya. (Unpublished)

Hassan, S. A. 1976b. A Brief Note on Water Resources Conditions in Sarir and Tazerbo Regions. SARLD Department of Soil and Water, Tripoli, Libya. (Unpublished)

Hassan, S. M. 1979. Hydrogeological Cross Sections 1 and 2: North Sarir Area. SARLD Department of Water Soil, Tripoli, Libya. (Unpublished)

Hasnain, S. M. 1981. Sarir Southern Field Water Quality and Changes Due to Pumping. SARLD Department of Water and Soil, Tripoli, Libya. (Unpublished)

Hasnain, S. M., S. A. Hasan, S. A. Ahmed, et al. 1982. Monthly Data for Sarir North and South Production Wells from 1975 to 1982. SARLD, Department of Water and Soil, Tripoli, Libya. (Unpublished)

Pallas, P. 1980. Water Resources of the Socialist People's Libyan Arab Jamahiriya. In: The Geology of Libya, Volume II, by M. J. Salem and M. T. Busrewil (editors), Academic Press, London.

Shaath, S. K. 1976. Quantitative Analysis for Jalo-Augila Project. Unpublished MS Thesis, Ohio University, Athens, Ohio, U.S.A.

Wright, E. P. 1975. Jalu-Tazerbo Project: Phase 2, Final Report. Institute of Geological Sciences, London, England. (Unpublished)

Wright, E. P., and W. M. Edmunds. 1969. Hydrogeological Studies in Central Cyrenaica, Libya. Institute of Geological Sciences, London, England. (Unpublished)

Wright, E. P., et al. 1973. Jalu-Tazerbo Project: Phase 1 Interim Report. Institute of Geological Sciences, London, England. (Unpublished)

Wright, E. P., et al. 1974. Jalu-Tazerbo Project: Phase I Final Report. Institute of Geological Sciences, London, England. (Unpublished)

Wright, E. P., et al. 1982. Hydrogeology of the Kufra and Sirte Basins Eastern Libya. Quarterly Journal of Engineering Geology, 15:83-103. The Geological Society, London, England.

APPENDIX A

COASTAL BELT WATER PROJECT

WELL FIELD DESIGN AT SARIR AND TAZERBO

INTRODUCTION

As a supporting part of the main effort of modeling the principal groundwater aquifer in the Sarir-Tazerbo region by Utah Water Research Laboratory, a study was made of the design of the presently proposed CBWP Well Field at Sarir. A study was also performed for the proposed CBWP Well Field at Tazerbo with generally similar conclusions. Considerably less is known about the geohydrology of the Tazerbo region and caution must be used when extrapolating into relatively untested areas. The problem of well field design is complicated because many diverse factors must be considered, such as aquifer characteristics, water quality, well design, power supply, topography, collection pipe networks, and well interference.

The basic purpose of each proposed CBWP well field is to produce 350,000,000 m^3/year for multiple uses in the coastal belt of northern Libya. Well field design should aim to accomplish this at minimum overall cost and within water quality requirements. Presently the designs of both proposed CBWP well fields at Sarir and Tazerbo have been established and their sites specified by the Soil and Water Department of SLRAD. A review of the design and location of these fields was needed to produce an independent appraisal of their future performance within the framework of the regional groundwater study. A few basic modifications to these well field designs and locations are recommended as a result of this study. Essentially the modifications consist of a fanning-out of the main lines of wells to reduce the pumping lifts attributable to interference, the elimination of double rows of wells to reduce pipeline and maintenance costs, an improvement in well design, and a reduction in the number of wells. Also a repositioning of the well fields is suggested to reduce interference between well fields and to reduce pipeline and access costs.

CBWP WELL FIELD AT SARIR

Present Design

This well field presently is designed to yield 350,000,000 m^3/year utilizing 150 wells, each capable of producing 80 liters per second (lit/sec). Each well is expected to average 74 lit/sec for the life of the project. This margin allows 8 percent down time for maintenance or repairs. Some wells may produce more and others less than the quota depending upon individual well, aquifer, and pump characteristics. The wells are equally spaced at 2.6-km intervals in the east-west direction along three, parallel, double rows or a total of 6 rows of 25 wells each (see Figure 22). In each of the three double rows a main collector pipe runs east-west a distance of about 62.4 km and small collector pipes connect the individual wells to it in the north-south direction. North-south distance between wells in the same double row is 2.16 km. North-south distance separating adjacent double rows is 10 km. This distance is spanned by two larger collector pipes at the end of the well field where the water will be collected in a header tank before entry into the principal pipeline to the coastal belt. The overall north-south dimension of the well field is taken to be 26.48 km (3 times 2.16 km plus 2 times 10 km).

Individual well yields, well spacing, and general layout of the proposed CBWP Sarir well field are similar to those same characteristics of the neighboring Sarir agricultural project well fields. Although the general design may have been successful for the farming operation, it may not be the best for the new CBWP well fields where pipeline networks are involved. Furthermore, there are some irreconcilable differences in the present designs of the two CBWP well fields. Among these differences are: wells of the Tazerbo well field are much more compactly spaced and are fewer in number to produce the same total amount of water, the overall screened lengths in the CBWP wells are to be nearly double those of the existing agricultural well fields, 8 5/8" outside diameter (O.D.) wire-wrapped screens are specified for all wells in the proposed CBWP Well Field at Sarir, and it is assumed that the same screens will be specified for the CBWP Well Field at Tazerbo. Note that drill bit and well casing manufacturers have not fully adopted the metric system. Therefore, well and pipe diameters are still expressed in the English system of measurement.

Overall screened interval for wells of the CBWP Well Field at Sarir will average about 280 m and it is believed that the screened length will be about the same at Tazerbo. The existing Sarir agricultural well fields have screened intervals up to 150 m and the average well yield is 76 lit/sec. Such a drastic change in well design is probably aimed at improving well productivity, yet no significant increase in pumping rate is specified at Sarir, while it is at Tazerbo. Exploratory well pumping test data indicate there is little difference in aquifer characteristics between Sarir and Tazerbo. The large difference in well spacing and number of wells at each site is an enigma, based upon available geo-hydrological data.

Number of Wells

The Egyptian consulting firm that originally designed the CBWP Well Field at Sarir, Engineering Consultants Group (ECG), recommended a design with 230 wells spaced at 1-km intervals along main collector pipelines branching at various angles in a complicated tree-like pattern. Each well was to produce 50 lit/sec and about 265 km of collector pipelines were required. The collection point was to be about 50 km west of what is now the paved Jalu-Kufra road and the CBWP pipeline corridor. Apparently less emphasis was placed upon distance from paved road, maintenance costs, and groundwater quality in their well field layout and site selection.

Although more wells, spread as far apart over as large an area as possible, will minimize pumping costs, the costs of wells, interconnecting pipelines, and hydraulic friction losses in those pipelines and wells must be considered because all of these factors contribute to the overall costs of the project. With well spacing of 0.7 km or more, the cost of interconnecting pipelines exceeds the costs of the wells and increased hydraulic friction losses in the pipelines may offset the reduced pumping lifts achieved by wider well spacing. Thus, a reduced number of wells involving a minimum of interconnecting pipelines, a more efficient well design, and direct access to the paved road and pipeline corridor would constitute a more economical design.

In order to distinguish between the effects of using 150 wells or 120 wells as now planned for the CBWP Sarir and Tazerbo well fields respectively, the main consideration is the effective area drained (or the spacing and total length of the lines of equally spaced wells). The average drawdown in a line sink created by a row of pumping wells depends more upon the average extraction rate per kilometer of the line sink than it does upon the number of wells employed to produce the desired amount of water.

If the length of the rows of wells is kept at 62.4 km and 108 wells instead of 150 wells are used to produce 1,000,000 m^3/day, then the increased mutual interference between wells is only about 0.7 m per well on the average. A computer model using the Theis equation to solve numerous hypothetical well field layouts was used to obtain all estimates of relative values of drawdown presented in this appendix. Results were reconciled with the regional AQUIFEM model in the cases of the present CBWP well field designs. An average value of drawdown during a 50-year pumping period is estimated for these comparisons. Some details of this model are presented at the end of this appendix.

Any reduction in total number of wells implies an increased discharge per well and an accompanying increased hydraulic friction within each well if the well diameter is constant. Improved well design can compensate for this as will be discussed in a later section. When reducing from 150 to 108 wells an increase in hydraulic friction within each well of a little over 1 m will result, giving a total increased pumping lift including well interference of about 2 m. The potential saving of about $25,000,000 in costs of well construction, pumps, and appurtenances is worth more than the penalty of increased pumping lift costing roughly $86,000 per year.

The Soil and Water Department of SLRAD estimates wells for the CBWP will cost $363,000 each. Estimated total cost of 80-lit/sec wells including pumps and appurtenances is $680,000 and cost of 111-lit/sec wells is $715,000 assuming drilling costs are not increased as will be explained later in this report. These are minimum installed capacities of the wells, which allow about an 8% margin to compensate for down time and reduced efficiencies of wells. A reduction to 108 wells for the

Sarir well field is suggested. These wells (111-lit/sec installed capacity) are expected to produce an average of 102.8 lit/sec each for the life of the well field.

Position of Well Field

Although 50 km separate the existing Sarir North and Sarir South well fields, the proposed site of the CBWP Well Field at Sarir is only 40 km from the Sarir South well field and less than 20 km from the Sarir North well field. Mutual interference between these major well fields should be kept to a minimum. To minimize well field interference, probably the best position for the new CBWP well field is about 50 km to the north-northwest in the vicinity of 21° east longitude and 28° north latitude, but such an extreme move is not practical at this late stage of the project, and there may be some unforeseen disadvantages. This area may be considered as the site of some future expansion of the CBWP Sarir well field, however.

Repositioning of the well field somewhat to the west will reduce mutual interference between well fields and will slightly reduce pumping lifts required to get the water into the pipeline from the aquifer. Furthermore, a move of about 9.5 km westward and about 6.5 km northward will locate all of the well-field operations west of the paved Jalu-Kufra road and the CBWP pipeline corridor and simplify construction, operation, and maintenance in the future.

Extraction of the best possible quality of water is a prime objective. Figure A-1 is a map showing the distribution of water quality in the principal aquifer of the Sarir region as measured by electrical conductivity of the groundwater. This map is a compilation of data from

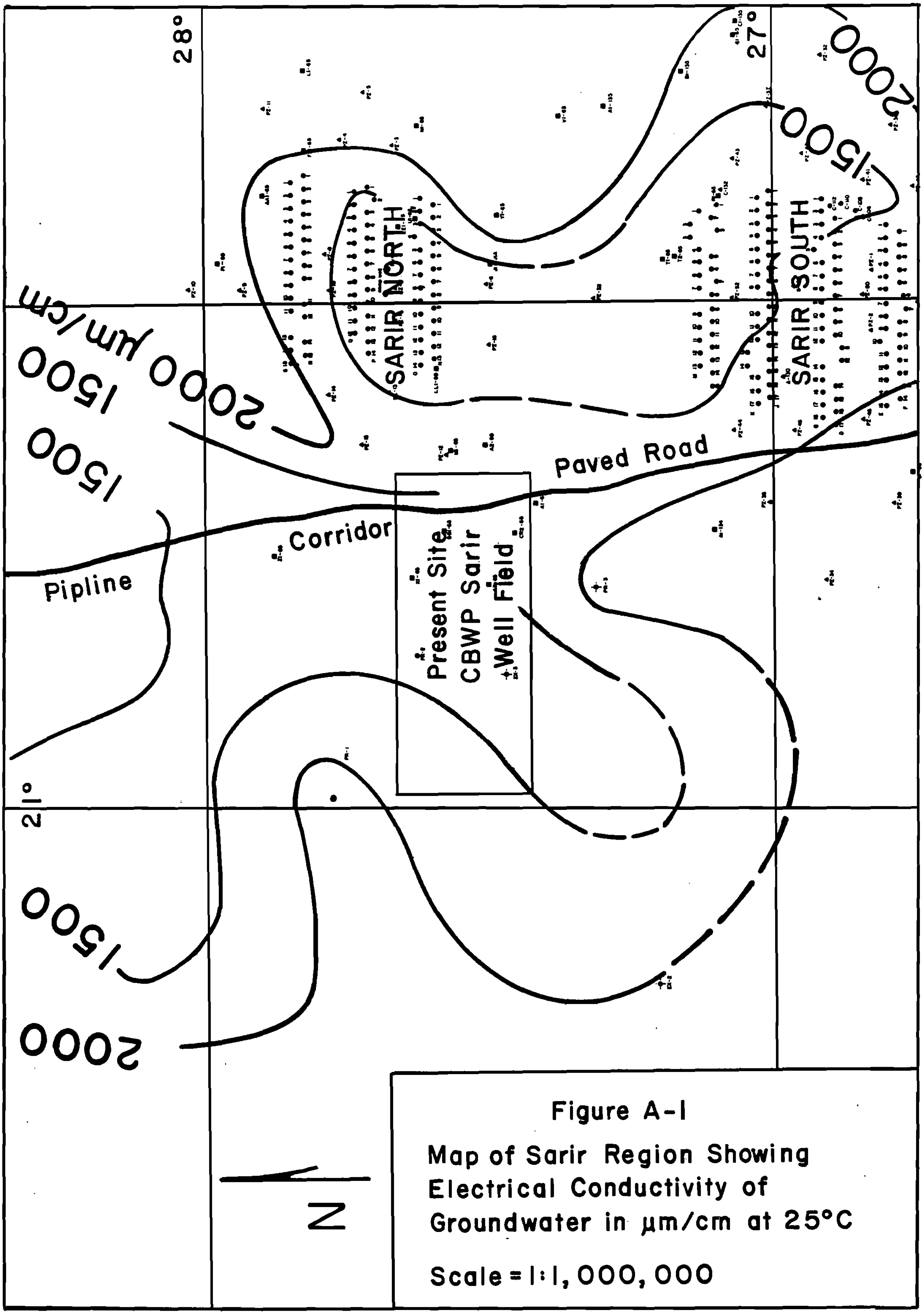


Figure A-1

Map of Sarir Region Showing Electrical Conductivity of Groundwater in μm/cm at 25°C

Scale = 1:1,000,000

several sources, including the report of Ahmad, ElBakhbakhi, and others (1979, Figure 5), and the final IGS report (Wright 1975, Figure 25). Also shown are the present proposed location of the CBWP Well Field at Sarir, the new paved road, and the pipeline corridor that parallels the road on its west flank. The present site for the new well field is in an area of high quality water. A move to the west will not cause a significant reduction in water quality, especially not if the well field is expanded into areas of higher quality as suggested below.

Figure A-2 is a topographic map showing approximate land surface elevations in the Sarir region. This map was compiled mainly from petroleum exploration data. Inasmuch as the pipeline corridor has been selected alongside of the paved Jalu-Kufra road and at least 160 m of elevation head are required for the desired quantity of water to flow to the coastal belt solely under the force of gravity, wells situated at somewhat higher elevations are not detrimental provided their surface elevations do not significantly exceed the elevation of the hydraulic grade line of the collection network, in which case some energy may be wasted in pumping water higher than necessary.

Energy requirements are determined mainly by vertical pumping lifts and the head required to move the water horizontally from the water supply wells into the pipeline header tank. If a minimum slope of 0.0003 is assumed for the hydraulic grade line in the suggested collection pipe network, then well-head elevations ranging linearly from about 162 m near the pipeline intake to about 183 m at the network extremities result in no wasted energy. Apparently, the land surface rise to the west of the pipeline corridor does not exceed those limits. As new land surface elevations have been obtained in the region, this topographic map may

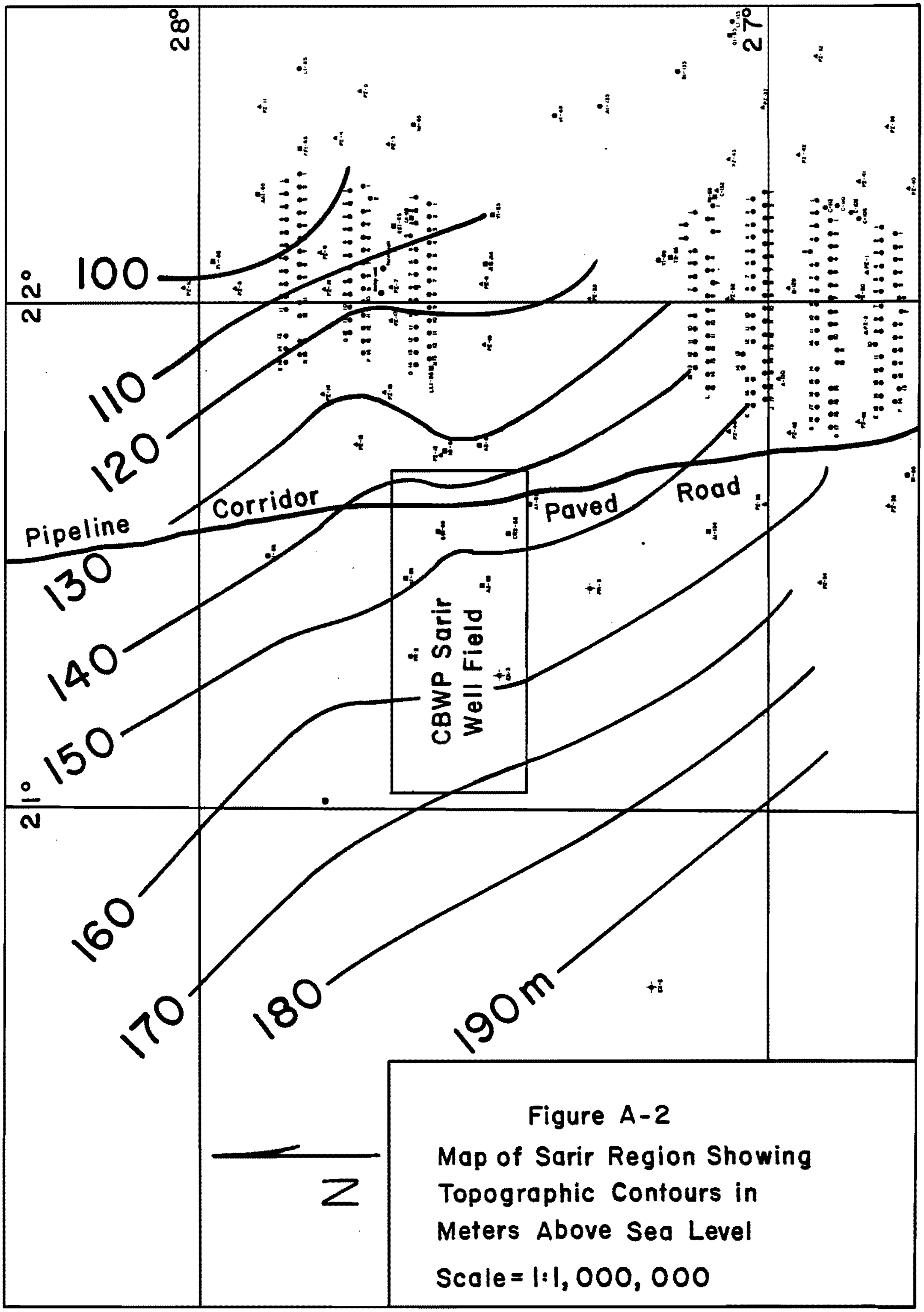


Figure A-2
Map of Sarir Region Showing Topographic Contours in Meters Above Sea Level
Scale= 1:1,000,000

have to be corrected accordingly. Nevertheless, corrected land surface elevations would have to exceed the foregoing hydraulic grade line elevations before energy will be wasted. If the present well field design network is used with its optimum hydraulic grade line slope of 0.0005, then correspondingly higher land surface elevations are tolerable.

Figure A-3 is a map showing the elevation of the piezometric surface in the Sarir region. A flattening of the piezometric surface (implying larger transmissivity) takes place in the latitude of the CBWP well field. Consequently, any reasonable move of the proposed well field westward results in a slight decrease in pumping lift to get the water from the water table to the fixed elevation of the water level in the header tank at the pipeline intake. A repositioning of the well field westward results in a few meters reduction of pumping lifts for two reasons: 1) higher piezometric surface and 2) less well field interference by moving away from the existing agricultural well fields. The remaining considerations have to do with minimizing drawdown below the water table and minimizing hydraulic friction losses in the wells and the pipeline collection network.

Well Field Configuration

An effective way to minimize mutual well interference between wells is to spread them over a larger area. This can be done for the CBWP well fields by spreading out the main collection pipes radially from their ends near the pipeline intake. The wells will remain in areas of high quality groundwater and no additional main pipelines will be required. Figure A-4 is a map showing the suggested new design of the CBWP Well Field at Sarir (see also Figure 22). The well field has been

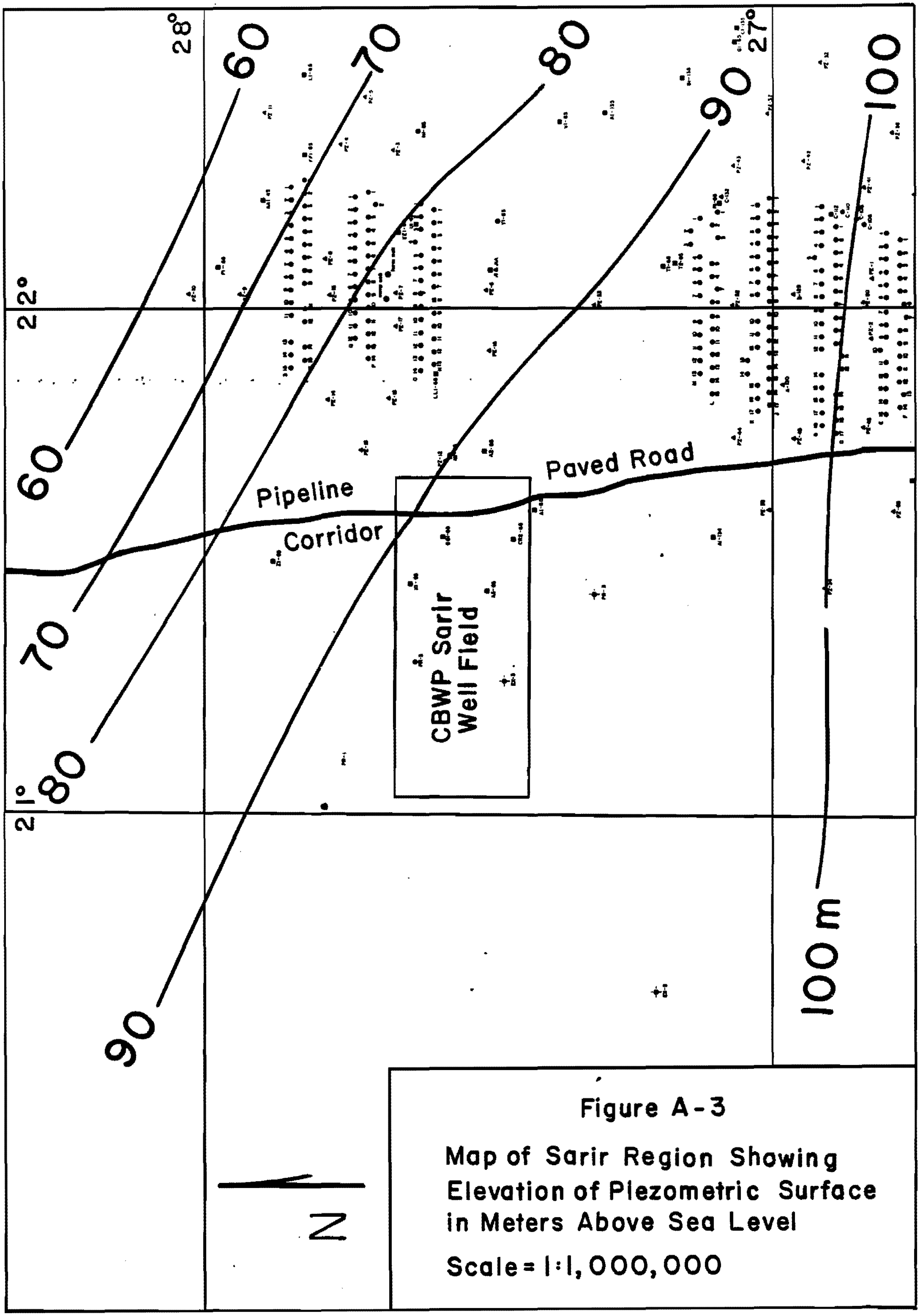


Figure A-3

Map of Sarir Region Showing Elevation of Piezometric Surface in Meters Above Sea Level

Scale = 1:1,000,000

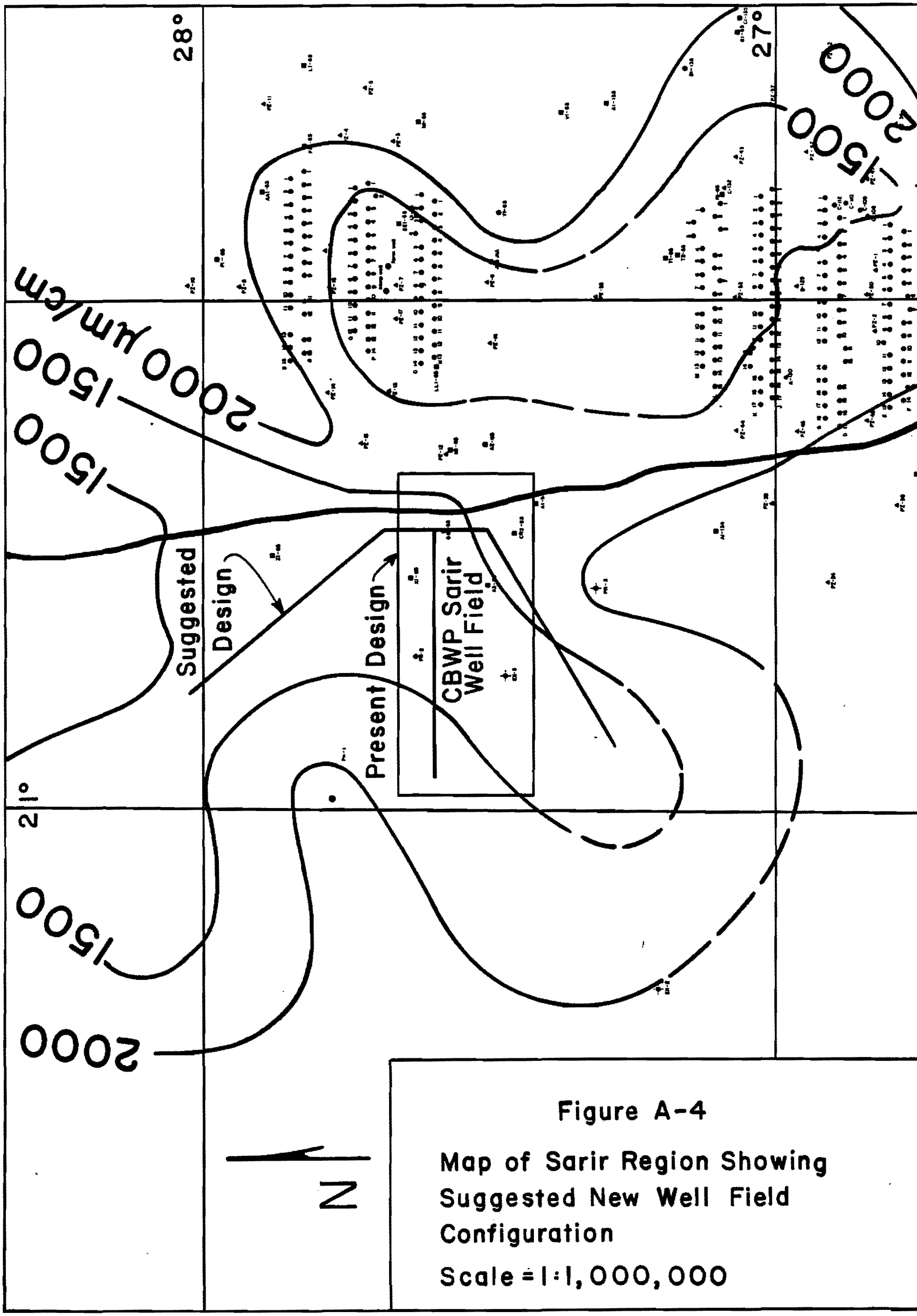


Figure A-4

Map of Sarir Region Showing Suggested New Well Field Configuration

Scale = 1:1,000,000

translated 9.5 km west and about 6.5 km north from its present position. The main north-south gathering line at the east end of the field will be about 2.1 km west of the paved Jalu-Kufra road and the main east-west gathering line and the line which empties into the pipeline header tank will pass about 2.43 km north of the petroleum test well GG1-65. The middle main gathering line will remain in its original east-west direction, but the southern main line will be rotated about 30° to the southeast with its eastern extremity fixed as shown in Figure A-4. Similarly the northern main line will be rotated to the northeast about 50° as shown. These degrees of rotation are necessary to obtain the highest water quality in the area as illustrated in Figure A-4.

The potential drawbacks to this configuration are the unlikely possibilities of encountering aquifers of significantly lower permeability or lower quality groundwater than expected to the north. Otherwise well field conditions should be the same or improved. One advantage of moving the northern line of wells is its increased distance from the test well PR1, which produced relatively low quality water (1600 mg/lit TDS).

The major benefit of this suggested design is a permanent reduction in mutual well interference between wells within this field besides the reduced interference between the existing major well fields and this field. The reduction in interference from existing well fields is on the order of 2 m. Nevertheless, the between-field interference could still be as much as 11 m in 50 years even with the 2-m reduction. The average between-field interference will be about 7 m during the 50-year life of the CBWP Well Field at Sarir.

The reduction in mutual interference between wells within the suggested well field compared to the present well field would be almost

10 m for the life of the well field (assuming the same number and spacing of wells). Based upon the present estimated cost of power at Sarir ($0.03/kw-hr), these simple modifications of spreading out the well field layout would save about $430,000 annually for the life of the field.

Well Spacing

The concept of using well pairs spaced 2.16 km apart at 2.6 km intervals along main collection lines appears to have no advantage over single wells spaced at 1.3 km intervals along those same main lines. Using this new suggested design, the increased well interference is only about 0.4 m, but the elimination of the 1.08 km of pipeline for each well reduces the friction losses in the pipeline by about the same amount, producing no net change in mean pumping head. While there is no net improvement in hydraulics, the elimination of 160 km of network pipelines saves approximately $26,000,000. Furthermore, the elimination of the maintenance costs on the pipeline, roads, and power lines, the reduction in travel time for all other surveillance work on the wells, and many other savings will be realized.

With the suggested 36 wells equally spaced in single rows along three fanned-out main collector lines, the length of these main lines may be considered. In this case reduced capital investment in the main lines and concomitant reduced hydraulic friction losses must be weighed against increased mutual interference between wells if main lines are shortened. A shortening of the main lines by 12.4 km from the present 62.4 km would result in an increase of mutal interference on each well of about 4 m. The elimination of 12.4 km of pipeline from each main line would eliminate almost 2 m of hydraulic friction loss from each main line, and save a total of about \$27,000,000 in capital investment. The net increase in pump lift of roughly 2 m could result in about \$86,000 increase in annual energy costs. Thus a reduction of main line lengths to 50 km is recommended. Although further reductions are economically advisable, restraint should be used in significantly increasing drawdowns and reducing the effective drainage area of the well field and its ability to intercept underflow from the south. Well field life, water quality deterioration, and other ramifications may make the overall economics of further reducing main lines less attractive.

Additional refinements in well spacing using constant main line lengths could be made in an attempt to equalize pumping lifts. Wells at the remote extremities of main lines suffer less from mutual well interference, therefore, they could be spaced closer together and internal wells could be spaced further apart. Differences in drawdown up to 15 m could exist between innermost and outermost wells in the present design assuming a homogeneous aquifer and other conditions are equal. Topographic elevations and hydraulic grade line elevations would have to be considered for each well. Individual well characteristics determined after wells are completed may result in unforeseeable differences in pumping lifts despite the careful spacing of wells and render such a refinement of less practical benefit. Nevertheless, the savings in operation and maintenance costs probably make the relatively inexpensive exercise worthwhile, as at least a first approximation to help make pumping lifts more uniform. Even anticipated well field interference and hydraulic grade line elevation could be taken into account if desired. More uniform pumping lifts can result in more uniform equipment and greater efficiency of operation and maintenance.

Well Design

The well specifications for the CBWP Well Field at Sarir issued in Febuary 1981 are generally an excellent water well design. However, there are a few improvements that can be made in the well screen design, which will significantly reduce pumping costs and prolong well field life regardless of which well field design is constructed.

Wire-wrapped continuous slot screens of 8 5/8" O.D. ranging up to 290 m per well have been specified. While these screens are the very best for transmitting large quantities of water per unit length of screen from highly permeable aquifers, a misapplication is implied when only 80 lit/sec are planned to be extracted from up to 290 m of screen per well. The Sarir aquifers are not highly permeable and the required yield per meter of screen is only 0.28 lit/sec. The capacity of the specified screens is more than 20 times greater than the design requirement.

Less expensive screens with lower open inlet areas are certainly appropriate for this application. Slotted fiberglass and louvered stainless steel screens have been used successfully in the existing Sarir and Kufra well fields. Either of these two alternative screen types are recommended, but the 304 stainless steel louvered screens probably have superior joint and wall strength properties for the unusually long sections specified. Type 304 stainless stell is recommended.

Screen diameters are more important than the type of screens used. Internal screen diameters control mainly the amount of hydraulic friction losses within the screens, known as well losses. It is strongly recommended that 12 3/4" O.D. screens be used instead of the 8 5/8" O.D. screens specified. A recommended 21" diameter hole will have to be drilled and gravel packed instead of the 17 1/2" hole specified, but with reverse rotary drilling, this should not appreciably increase construction costs as this size can be drilled in one step the same as 17 1/2" hole. The cost of 12 3/4" O.D. 304 stainless steel louvered screen with welded couplings is probably less than the cost of 8 5/8" O.D. 304 stainless wire-wrapped screens. There is no need to blank off the clay beds when inexpensive louvered perforations are used. Thus a superior well can be obtained at probably no increase in construction costs.

Welded couplings are recommended over specially cut API (American Petroleum Institute specifications) threaded couplings of stainless steel. When compatible stainless welding rods are used and double welded, the welded couplings give nearly full strength joints. Stainless steel threaded joints often gall and cannot give full strength joints whether they gall or not. The cost of API threaded stainless couplings is about $400 per joint for 12 3/4" O.D. pipe.

The main benefit of 12 3/4" O.D. screens will be a substantial reduction in well losses for the life of the well field. Well losses commence the instant pumping begins, for they are related to well discharge rather than aquifer properties. Estimated well losses or pumping lifts attributable to the use of 8 5/8" O.D. well screens are expected to average about 10 m per well, whereas those for 12 3/4" O.D. screens are expected to average as low as 2 m when 150 wells are pumped. If fiberglass screens are used, the well losses could be even less due to their unusual wall smoothness.

If the total number of wells is reduced to 108 as recommended, then each well will produce an average of 107 lit/sec. The well loss using 12 3/4" O.D. screens at that discharge will be about 3 m. These figures are taken from pipe friction tables for standard pipes with some modification. The full discharge is normally taken to traverse 1/3 of the screen length. In practice, however, well losses in screens are usually much larger than theoretical pipe friction values due to roughness factors and the entry of water causing turbulence not considered in pipe friction tables. Accordingly, division by 3 was not done in this case. Wells at the existing Sarir well fields have well losses of about 6 m to 7 m and have approximately half the screen length anticipated for the CBWP well fields. Therefore, screen losses could be around 10 m to 11 m for the CBWP well fields if 8 5/8" O.D. screens are used. The reduction in well loss in using 12 3/4" O.D. screens would be about 85% for the same discharge rate, using pipe friction-loss tables. Thus, the possible reduction in well loss could be 8 m to 9 m in the CBWP Well Field at Sarir if 150 wells are used, or 7 m to 8 m if 108 wells are used. If 7 m in well loss are saved per well, a savings in energy costs of about $300,000 per year for the life of the well field could result.

Deeper Piezometers

An important consideration with regard to the long term water quality in each of the Sarir well fields is the effect of vertical flow from strata below the main (LMM) aquifer. According to Hasnain (1981), at depths below land surface greater than 400 m in existing well fields the TDS concentration may exceed 3000 to 4000 mg/lit. As pumping in the Sarir region continues, it is possible to induce the low quality water to move vertically upwards into the producing interval.

The CBWP Well Field at Sarir is situated in an area of high quality water and should yield water of comparable quality to that of the existing well fields at Sarir. However, all the new wells are to be drilled to 450 m rather than 300 m as was done in the existing fields. Inasmuch as water of lesser quality exists at depth below the CBWP well field area, these deeper wells may accelerate the up-coning of more saline waters to the ultimate detriment of the well field. For example, exploratory well Ex-3 yielded exceptionally high quality water of 770 mg/lit dissolved solids at 319 m well depth, but at 487 m the dissolved solids were 1850 mg/lit. This marginal quality water is less than 40 m below the proposed producing interval of the CBWP Well Field at Sarir. Near the middle of the field, however, water of much higher quality (970 mg/lit) was found in test well PR 2 at depths below 600 m. Wide variations in water quality are found both horizontally and vertically in the Sarir region. Well field layout may have to be altered somewhat during construction if an unexpected low quality water is found.

The parameters which control the vertical flux of water are: the vertical hydraulic gradient, which will gradually increase as pumping continues, and the vertical hydraulic conductivity of the strata immediately below the pumping wells where lowering of head will be greatest. Interpretation of the significance of vertical flow cannot be quantitatively addressed unless data are available from deeper piezometers at the same location as main aquifer piezometers.

Without piezometer clusters which include a deeper piezometer (greater than 450 m) it is impossible to determine local vertical gradients, from which vertical hydraulic conductivities and vertical flows could be determined. Therefore, it is recommended that at least three deeper piezometers be installed adjacent to presently planned piezometers within the proposed CBWP well fields. Deep piezometers are only necessary within the confines of a well field where vertical flow is expected to be strongest and potentially most detrimental. Flow will remain essentially horizontal in the adjacent regions and thus deep piezometers are not necessary at remote locations. This field information will be necessary before an appropriate multi-dimensional model can be adequately calibrated for a given site to assess potential water quality deterioration.

Partial Penetration of Aquifer

When the well screen does not extend through the full thickness of an aquifer, the well is said to be partially penetrating and the drawdown is greater than for a fully penetrating well because of the crowding of the flow near the well. The shorter the screen, the greater will be the increase in drawdown near the well, but the effect on the flow pattern is negligible beyond a radial distance larger than 1/2 to 2 times the aquifer thickness, depending on the amount of penetration.

Since the aquifer properties are reasonably constant in each well field and the same well design is proposed for all the wells, the additional drawdown due to partial penetration will be about the same for each well. Thus for design purposes in the CBWP well fields, partial penetration is viewed as adding the same constant amount of drawdown at every well.

For the CBWP Well Field at Sarir the increased drawdown is estimated to be somewhere between 0.5 m and 4 m. A value of 2 m was used in all cases for these well field design comparisons. The greatly increased screen lengths in the CBWP well fields will do much to minimize the potential effects of partial penetration.

Pipeline Water Gathering Networks

An integral part of any well field design is the network of pipelines, which collect water from each well and transmit it to the header tank at the intake of the main pipeline conveying water from the well field. Hydraulic friction losses occur in this network of pipelines as they do in the wells. The cost of network pipelines is very high. Thus, an optimization is required in well field design taking into account all aspects of land surface and subsurface conditions. A computer model, NETWK, developed at Utah State University was used to optimize the pipeline gathering network that used data from the Theis aquifer model. The two models were not operated together as some scientific judgment was required to interface the models.

Numerous runs were performed of both the aquifer and pipeline models to evaluate the effect of each step in the well field design, but only the computer results appraising the present well field design and the final suggested design are presented in this report. The reasoning and valuation of each step was given in the foregoing text, but a summary of the results is given below.

Table A-1 is a summary for comparison of the estimated costs and other factors related to both well field designs. Present-day costs of installed pipelines, water well pumps and appurtenances, and power costs were furnished by Brown & Root (Overseas) Limited. Cost of well construction was furnished by the Soil and Water Department of the SLRAD.

A 50-year life was assumed in the calculations for the well field. Actually the water supply will last much longer than that. The amortization or discount rate was fixed at 0% for the purposes of this comparison. This fiscal policy infers there is no difference between lending and

Table A-1. Comparison of alternative well field designs for the CBWP Well Field at Sarir.

Design Characteristic	Present Design	Suggested Design	Difference
Number of wells	150	108	-42
Cost of wells (in millions of dollars)	54.4	39.2	-15.2
Cost of pumps and appurtenances (in millions of dollars)	47.6	38.0	-9.6
Cost of electrical distribution system (in millions of dollars)	99.3	93.6	-5.7
Length of pipe in network (in kilometers)	369.2	172.3	-196.9
Cost of pipe network installed (in millions of dollars)	185.5	139.7	-45.8
Hydraulic gradient in pipe network	0.0005	0.0003	-0.0002
Energy required in pipe network (in million kw-hr/year)	25	12	-13
Energy required in vertical lift (in million kw-hr/year)	170	157	-13
Average drawdown alone (in meters)	25	24	-1
Total well losses (in meters)	12.8	5.8	-7.0
Average pumping head (in meters)	136	119	-17
Annual power costs at $0.03/kw-hr (in millions of dollars)	5.87	5.08	-0.79
Present worth of development and power costs at 0% rate-of-return (in millions of dollars)	680.3	564.5	-115.8

inflation rates. Power costs were fixed at $0.03/kw-hr for these calculations. Pump efficiency of 78% and motor efficiency of 88% were used for an overall wire-to-water efficiency of 68.6%. If other values are assumed, the estimated power costs may be adjusted in direct proportion. The initial costs of operational structures and roads and the overall maintenance and operation were not included in this summary. It was assumed that the sum of these cost items would also be in favor of the suggested well field design. Also not included is the reduction in well field interference of about 2 m, which should be about equal for both designs and should save about $86,000 annually just for moving either field 11.5 km west-northwestward. Not shown in the drawdown estimates are 10 m for 50-year average well field interference and 2 m for partial penetration effects. Included in the well losses are 2.6 m for estimated column pipe and well head losses. These latter three values are considered to be the same for both well field designs, and assume that proportionately large diameter column pipes are used for the larger pumps of the suggested designs. Average drawdown for both designs is about the same, but the savings come in using fewer, more efficient wells and less connecting pipelines.

The suggested design shows an estimated annual savings in power costs of $790,000 and a reduction in initial capital investment of $76.3 million. The table shows that at a power cost of $0.03 per kw-hr, a decrease of 1 m in average pumping lift would save about $43,000 annually.

The average pumping head of the present design of 136 m includes the following averaged components; aquifer drawdown 25 m, well losses 10.2 m, column pipe losses 2.6 m, well field interference 10 m, partial penetration losses 2 m, lift from original static water level to land surface 56.1 m, height of header tank above ground level 12.8 m, and hydraulic friction in pipe network 17.8 m. These are 50-year averages, which will physically occur at about the 21st year. At the end of 50 years the total average pumping head is estimated to be about 6 m greater. Pumping lifts at innermost wells may be 6 m more and at outermost wells they may be 8 m less. The average pumping head for the present design is estimated to be 111 m at the end of the first year, 122 m at the end of 5 years, and at the end of each 5 decades of project life it is estimated to be as follows: 128 m, 135 m, 139 m, 141 m, and 142 m. For the suggested design the average pumping head is estimated to be 94 m at the end of 1 year, 105 m at the end of 5 years, 111 m at the end of 10 years, 118 at the end of 20 years, 121 m at the end of 30 years, 123 m at the end of 40 years, and 125 m at the end of 50 years of pumping. Note that these are calculated estimates and their accuracy is discussed in the main report. Recent corrections for depth to static water level based on new surveys also may affect these estimates.

Table A-2 is a summary of the computed lengths and costs of the optimum pipeline segments for both well field designs. Numerous computer model runs were made to arrive at these designs. It was found that for the present well field design, a slope of the hydraulic grade line of 0.5 m/km gave the least expensive option, whereas for the suggested design a slope of 0.3 m/km was best. Of course these optimal values vary with estimated power costs. Appreciably higher power costs force these slopes downward.

For the suggested design a 20-m length of 360 mm I.D. (inside diameter) pipe was added to the layout to connect each well head to the

Table A-2. Details of optimum collection pipe networks for alternative Sarir well field designs.

Pipe size (ID) in millimeters	Present Design: Pipe length in kilometers	Present Design: Pipe cost (installed) in millions of dollars	Suggested Design: Pipe length in kilometers	Suggested Design: Pipe cost (installed) in millions of dollars
360	159.8	25.9	2.16	0.35
565	7.8	1.9	4.29	1.05
720	7.8	2.4	4.29	1.31
870	7.8	2.9	4.29	1.58
1025	7.8	3.4	8.58	3.69
1170	15.6	10.2	8.58	5.63
1320	23.4	17.3	12.87	9.52
1475	15.6	12.8	12.87	10.58
1600	31.2	24.6	17.16	13.52
1800	39.0	34.2	25.74	22.57
2000	53.4	49.9	25.74	24.04
2200	-	-	45.74	45.83
Totals	369.2	185.5	172.3	139.7

main pipeline leaving enough room for unimpaired access by well maintenance equipment. Table A-3 gives the layout of main-line pipes in the networks for both well field designs. Pipe size distribution is the same for all main lines due to regularity and symmetry of both designs. There are only two main collector pipes at the end of the system which unite directly with the center lateral line before the water enters a short segment (1.3 km) of 4000 mm I.D. pipe and flows thence to the header tank serving the main conveyance pipeline.

Table A-3. Pipe size distribution in collection networks for alternative Sarir well field designs.

Segment Location	Pipe ID in mm	Present Design Segment Length in km	Suggested Design Segment Length in km
Well head	360	2.16	0.02
Most remote	565	2.60	1.43
	720	2.60	1.43
	870	2.60	1.43
	1025	2.60	2.86
	1170	5.20	2.86
	1320	7.80	4.29
	1475	5.20	4.29
	1600	10.40	5.72
	1800	13.00	8.58
	2000	10.40	8.58
End lateral	2200	-	8.58
End network	2000	11.08	-
End network	2200	-	10.00

Note: 1) All three main lateral collection lines are the same.
2) Both main end collection lines are the same.
3) Pipe sizes less than 1600 mm ID are constructed of cement-lined grade B steel pipe. Pipe sizes of 1600 mm ID and larger are of prestressed concrete cylinder pipe.

CBWP WELL FIELD AT TAZERBO

Present Design

The present design of the CBWP Well Field at Tazerbo features a very small cluster of wells on 1-km spacing (in both directions) with two double rows of wells in the east-west direction which are bounded or connected on their ends by north-south single rows of wells (see Figure 23). This is a radical departure from the design of well fields at Sarir and will cause excessive mutual well interference.

The range of values of aquifer characteristics from pumping tests on Tazerbo test wells is about the same as that for test wells at the CBWP Well Field at Sarir. For example, the average transmissivity of seven short-term pumping tests made at exploratory wells in the Tazerbo CBWP area is 2220 m^2/day and the average from three long term pumping tests at Sarir CBWP area is 2878 m^2/day. Average storativities of those tests differed by only a factor of about 2 from one area to the other. Therefore, there is no reason for the Tazerbo well field density to be so much different from the Sarir well field. Consequently, the suggested design for the CBWP Well Field at Tazerbo is essentially the same as that for Sarir, except the center main collector line is removed, and all the reasoning and calculations used in the preceding discussion on Sarir applies to Tazerbo.

Suggested Design

Groundwater quality is believed to be of very high quality throughout the Tazerbo area. Therefore, the well field layout is not constrained by a water quality distribution pattern and an inverted "V" pattern consisting of only 2 main lines rotated 120° apart is recommended. The axis of symmetry should be oriented in the north-south direction with the pipeline header tank at the north end of the system. The whole well field should be displaced about 25 km to the northeast from its present position (see Figure 23). This, in combination with fanning-out the field, will reduce its strong interference with the Tazerbo Oasis agricultural project well field now under construction and other groundwater supplies at the oasis. Also a savings of $45,000,000 will be made in pipeline installation costs ($1.8 million/km) and a further savings in energy costs of about $4700/year per km moved ($5,900,000 in 50 years) by reducing the distance the principal conveyance pipeline must extend northward to reach the coastal belt.

About 40 km and beyond to the northeast of the present Tazerbo site, the aquifer is known to be confined but probably is leaky as is the Sarir North well field area. It is believed that the 25-km move to the northeast will not seriously detract from the productivity of the well field by placing it into a strongly confined aquifer system. However, two test wells (TE-3 and TE-4) to the east of the present site of the CBWP Well Field at Tazerbo indicated the aquifers there have low hydraulic conductivities. These tests probably were not representative of that area, but further testing should be done in the area north and east of the present site if the suggested design is to be adopted. The geology of the entire Tazerbo area is not known as well as it should be. It is a transitional area between the Kufra and Sirte basins, where the geology may be very complicated and could affect groundwater movement in unexpected ways.

Pipeline Water Gathering Networks

Comparison of design features between the present design and the suggested design will be similar but not the same as for the CBWP Well Field at Sarir. All factors should favor the suggested design except main lines will have to be spread out and lengthened for a much more economical aquifer drainage pattern. Table A-4 is a comparison of design characteristics of the present and suggested CBWP Well Fields at Tazerbo. Explanation for this table is much the same as was used for Table A-1. A new line item was added to show the savings in costs of 25 km of 4000 mm I.D. conveyance pipeline and in power costs associated with the 25 km reduction in power lines over 50 years.

Table A-5 is a summary of the computed lengths and costs of the optimum pipeline segments for both well field designs. Table A-6 gives the distribution of the various pipe sizes and lengths for both well-field designs.

The present Tazerbo well field design entails a rectangular main-line configuration. It was arbitrarily decided to place the system's discharge point at the header tank at the northeast corner of the rectangular system (for minimum length of main conveyance pipeline) and to break the loop at the southwest corner. This yields two main laterals that will receive water from 60 wells each. One lateral (NW) will gather water first from the 10 wells on the remote west end of the well field and then gather water from the 50 wells along the north flank. The other lateral (SE) will gather water first from the 50 wells on the remote south flank and then gather water from the 10 wells on the east end of the field just before combining with the flow of the first lateral preparatory to discharge into the header tank. Pipe sizes and lengths

Table A-4. Comparison of alternative well field designs for the CBWP Well Field at Tazerbo.

Design Characteristic	Present Design	Suggested Design	Difference
Number of wells	120	100	-20
Cost of wells (in millions of dollars)	43.6	36.3	-7.3
Cost of pumps and appurtenances (in millions of dollars)	42.9	35.8	-7.1
Cost of electrical distribution system (in millions of dollars)	58.3	72.4	+14.1
Length of pipe in network (in kilometers)	119	100	-19
Cost of pipe network installed (in millions of dollars)	75.0	92.8	+17.8
Reduced main conveyance pipeline and power costs (in millions of dollars)	0	-50.9	-50.9
Hydraulic gradient in pipe network	0.0003	0.0003	0
Energy required in pipe network (in million kw-hr/year)	7	10	+3
Energy required in vertical lift (in million kw-hr/year)	161	111	-50
Average drawdown alone (in meters)	75	45	-30
Total well losses (in meters)	13.6	7	-6.6
Average pumping head (in meters)	118	83.6	-34.4
Annual power costs at $0.03/kw-hr (in millions of dollars)	5.04	3.62	-1.42
Present worth of development and power costs at 0% rate-of-return (in millions of dollars)	471.8	367.4	-104.4

Table A-5. Details of optimum collection pipe networks for alternative Tazerbo well field designs.

Pipe size (ID) in millimeters	Present Design: Pipe length in kilometers	Present Design: Pipe cost (installed) in millions of dollars	Suggested Design: Pipe length in kilometers	Suggested Design: Pipe cost (installed) in millions of dollars
360	-	-	-	-
565	49	12.01	1.0	0.25
720	2	0.61	1.0	0.31
870	3	1.10	1.4	0.52
1025	3	1.29	3.6	1.55
1170	3	1.97	4.0	2.62
1320	4	2.96	4.0	2.96
1475	4	3.29	6.0	4.93
1600	4	3.15	6.0	4.73
1800	6	5.26	12.0	10.52
2000	8	7.47	12.0	11.21
2200	10	10.02	16.0	16.03
2400	11	11.81	16.0	17.18
2600	12	14.08	17.0	19.94
Totals	119	75.0	100	92.75

Table A-6. Pipe size distribution in collection networks alternative for Tazerbo well field designs.

Pipe ID in mm	Present Design		Suggested Design	
	NW Main Lateral Segment Lengths in km	SE Main Lateral Segment Lengths in km	West Main Lateral Segment Lengths in km	East Main Lateral Segment Lengths in km
565	1	-	0.5	0.5
720	1	1	0.5	0.5
870	2	1	0.7	0.7
1025	2	1	1.8	1.8
1170	2	1	2.0	2.0
1320	3	1	2.0	2.0
1475	2	2	3.0	3.0
1600	2	2	3.0	3.0
1800	3	3	6.0	6.0
2000	4	4	6.0	6.0
2200	5	5	8.0	8.0
2400	5	6	8.0	8.0
2600	3	9	8.5	8.5
Total Length	35	36	50	50

Note: 1) The NW main lateral also has 23 segments of 1 km each connecting individual wells to the lateral from the row of wells 1 km south of the wells on the north boundary of the well field.

2) The SE lateral has 25 segments of 1 km each along the south boundary.

are given for both laterals beginning at the lateral extremities of the southwest corner of the well field, where a 1-km segment at the southern extremity of the east end of the field was not placed into the system.

Components of the average 50-year pumping head of 118 m are estimated for the present design to be as follows: drawdown 75 m, depth to static water levels 9 m, well losses 11 m, column pipe losses 2.6 m, partial penetration effects 2 m, elevation of water level in header tank 12.8 m above ground level, fluid friction in pipe network 5.6 m. Note that these are 50-year estimated average values which will prevail near the end of 21 years. All of these component values are expected to remain reasonably constant in time except drawdown, which varies roughly as the logarithm of time (if confined aquifer conditions prevail). The average pumping head for the present design is estimated to be 65 m at the end of the first year, 93 m at the end of 5 years, and at the end of each 5 decades of project life it is estimated to be as follows: 105 m, 117 m, 124 m, 129 m, and 133 m. It is estimated to be 49 m, 67 m, 75 m, 83 m, 88 m, 91 m, and 93 m respectively at the end of 1 year, 5 years, 10 years, 20 years, 30 years, 40 years, and 50 years for the suggested design.

Both main laterals are identical for the suggested design. They converge at the main aqueduct header tank. For the sake of reducing interference at the wells nearer the header tank and increasing drawdown a little more at the lateral extremities, the spacing of the most remote 4 wells was reduced to 0.5 km, then the next one was spaced at 0.7 km, then one at 0.8 km, then all the rest were left on 1.0 km spacing, leaving 3 km with no wells on each lateral next to the header tank. This is only a first step towards equalizing drawndown in wells and further optimization could be made.

The suggested design will cost about $104 million less on the basis of calculations used. The suggested design is superior as a method of aquifer development. This design or a similar one should be adopted for this latter reason alone.

THEIS AQUIFER MODEL

To compare the effects on drawdown of various well field designs, a Theis model was set up and run on the computer. This is a very simple model based upon use of the equation derived by C. V. Theis in 1935, which has been in use for analytical groundwater computations for many years. It is much more versatile than the big computer models when testing various well field designs.

In essence the model calculates the self drawdown of a well and adds to it the calculated interference drawdown attributable to every other well in the hypothetical well field layout. It repeats this process for as many wells or for any other points of interest as needed. This model used the first six terms of the infinite series equation to calculate values of the well function. When the function argument, u, was greater than 1, the well function was computed by numerical integration of the well function integral. For a well field of 150 wells, the model would make 150 times 150 computations for drawdown plus all the auxiliary calculations needed.

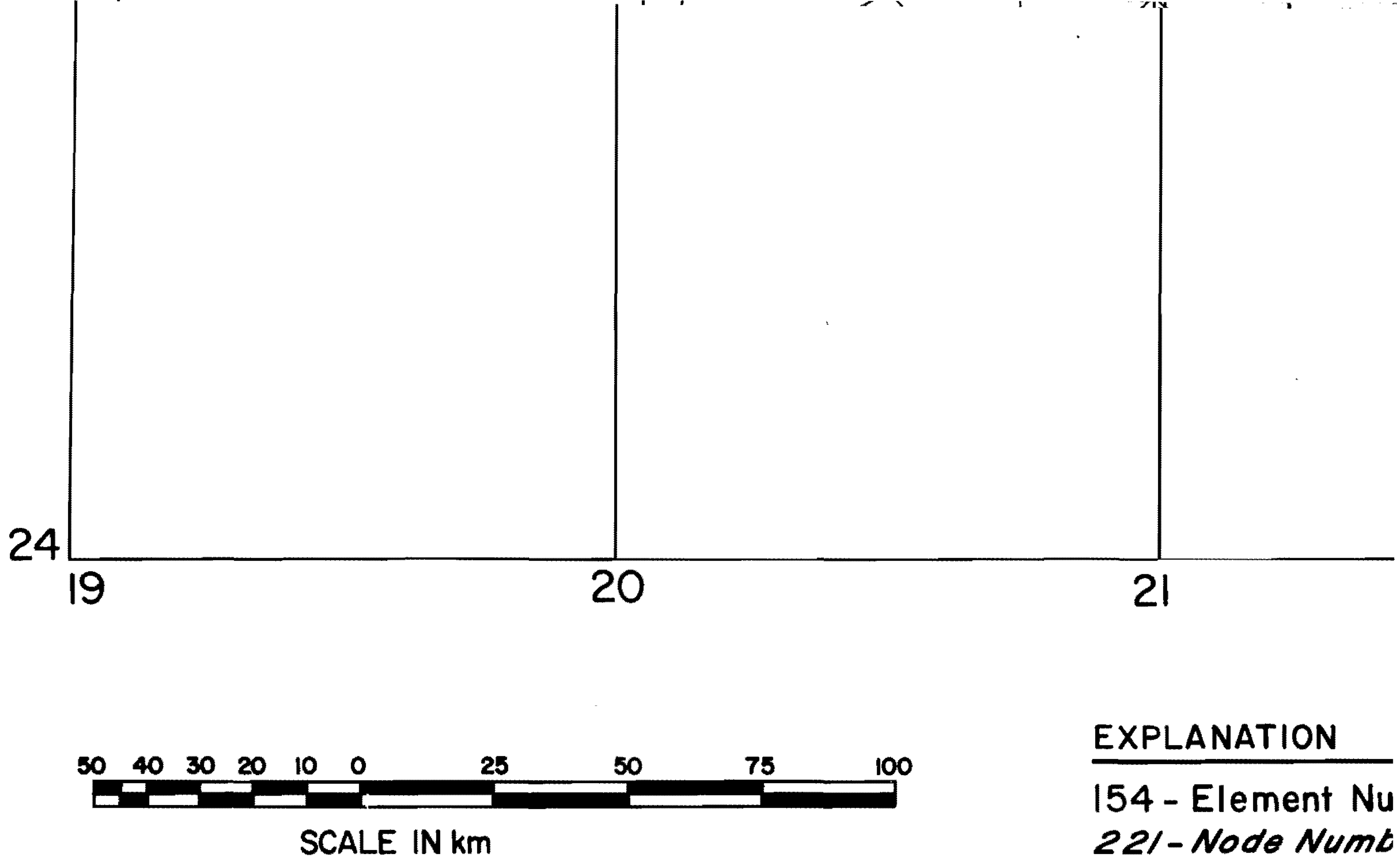
This model is intended to give anticipated well field drawdowns as a first approximation only and its accuracy depends heavily upon choice of parameter values for aquifer characteristics. Since no pumping history is available for these hypothetical well field layouts, this model could not be calibrated. This model has one advantage over the others in that once calibrated, it gives physically more realistic values of drawdown at each well, while other models tend to average out drawdowns more from node to node and give local drawdowns between wells.

For this simple model, the aquifer was treated as being confined, but having a reasonably large storativity to simulate the delayed drainage or leakage of the semi-confined aquifers believed to be present at Sarir and Tazerbo. A transmissivity of 5000 m^2/day was selected as a reasonable estimate of this parameter at Sarir (4000 m^2/day used at Tazerbo) based upon results of the steady-state and transient-state calibrations of the finite element regional model and its 50-year predictions. A storativity of 0.04 was selected as an estimate of specific yield at Sarir based upon performance of the Sarir South well field in the regional model and 0.03 was used for Tazerbo. Although initially the aquifer will behave as though it has a smaller storage coefficient, in the long term it will behave as a water-table aquifer of possibly a higher specific yield than 0.04.

All Theis model calculations were run for a 50-year period of time. Drawdowns became such that the transmissive thickness of the hypothetical aquifer was reduced to the point of invalidating the Theis equation, but the conservative estimate of transmissivity was intended to compensate for this. It was found that the average drawdown for each well for the 50-year period was almost the same as the 21-year calculated drawdown. The drawdowns given in the foregoing sections as representing 50-year estimated averages were taken from the AQUIFEM model modified leaky aquifer simulation. The Theis model calculations matched the AQUIFEM results for the present well field designs fairly well, but the Theis model results had to be used for the suggested designs. Nevertheless, relative values or comparative improvements of one well field design over another are believed to be reasonably dependable and are based on fair treatment in the modeling process.

A few constant values for fluid friction losses within wells were added to drawdowns estimated for each well. First, a screen loss of 10.2 m was added to represent an estimate of well or screen losses for 8-5/8" O.D. screens. This was obtained by averaging the screen losses of almost 100 wells in the Sarir North and Sarir South well fields (6.7 m) and multiplying that by the estimated increase in length of screens and casings below the average initial pump settings for the CBWP well fields (152%). The reduction in screen losses (7 m) in going from 8 5/8" screens to 12 3/4" screens was estimated from the use of standard tables for hydraulic friction losses in pipes. Second, column-pipe friction losses were estimated to be 2.6 m based upon some records from Kufra wells as such values from Sarir were not available. Third, an estimated 2 m was added to represent the effects of partial penetration (not strictly a well loss) . This value could be larger since the formulae apply to homogeneous aquifers. However, due to the conservative estimate for transmissivity and the relatively large thickness to be opened to production in the CBWP well fields, this value is considered reasonable and, as it is applied equally to all alternative well field designs, there is no bias in this factor. Thus, a total well loss and partial penetration loss of 14.8 m was estimated for wells using 8 5/8" O.D. screens and 7.8 m was estimated for wells using 12 3/4" O.D. screens.

Many different well field configurations were simulated to arrive at one of more practical worth. Only the first and last are summarized in this report. There may be others that could be suitable depending upon personal preferences or governmental water well policies.



EXPLANATION

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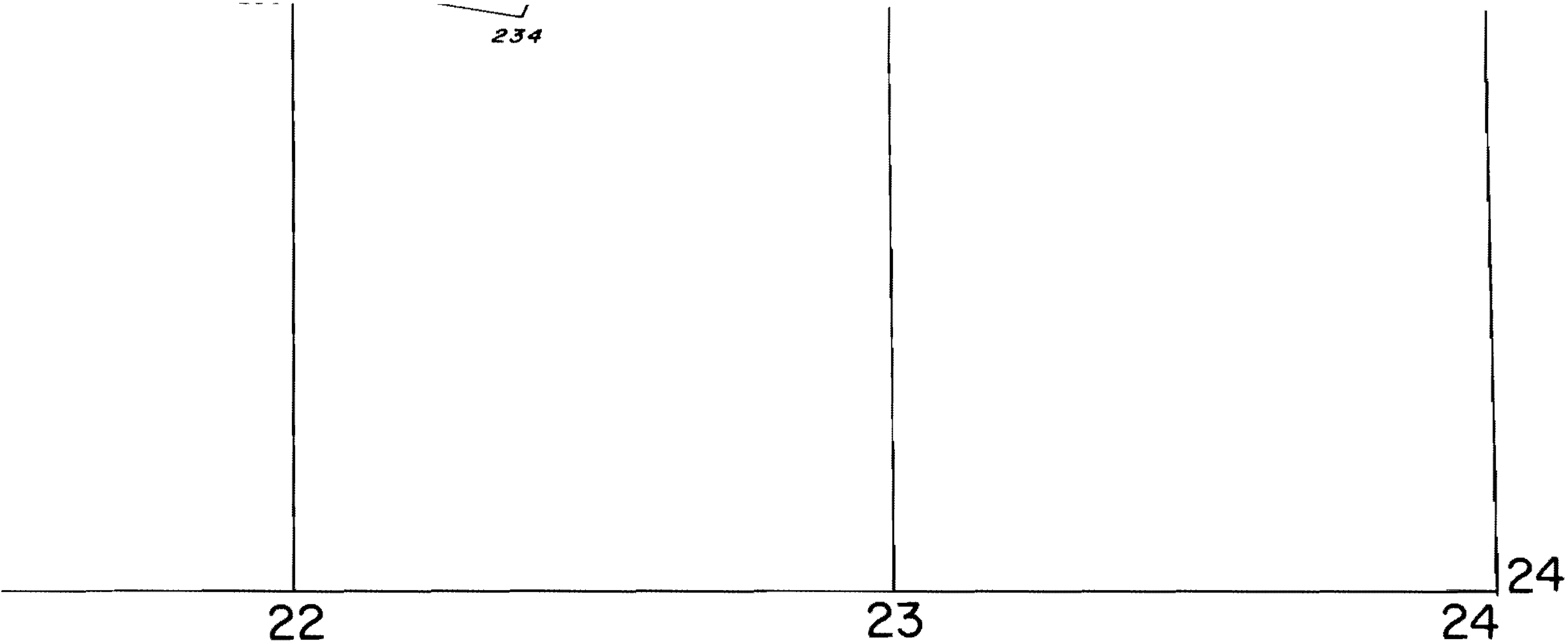
221 - Node Numb



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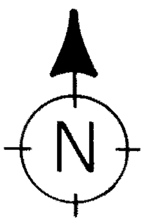
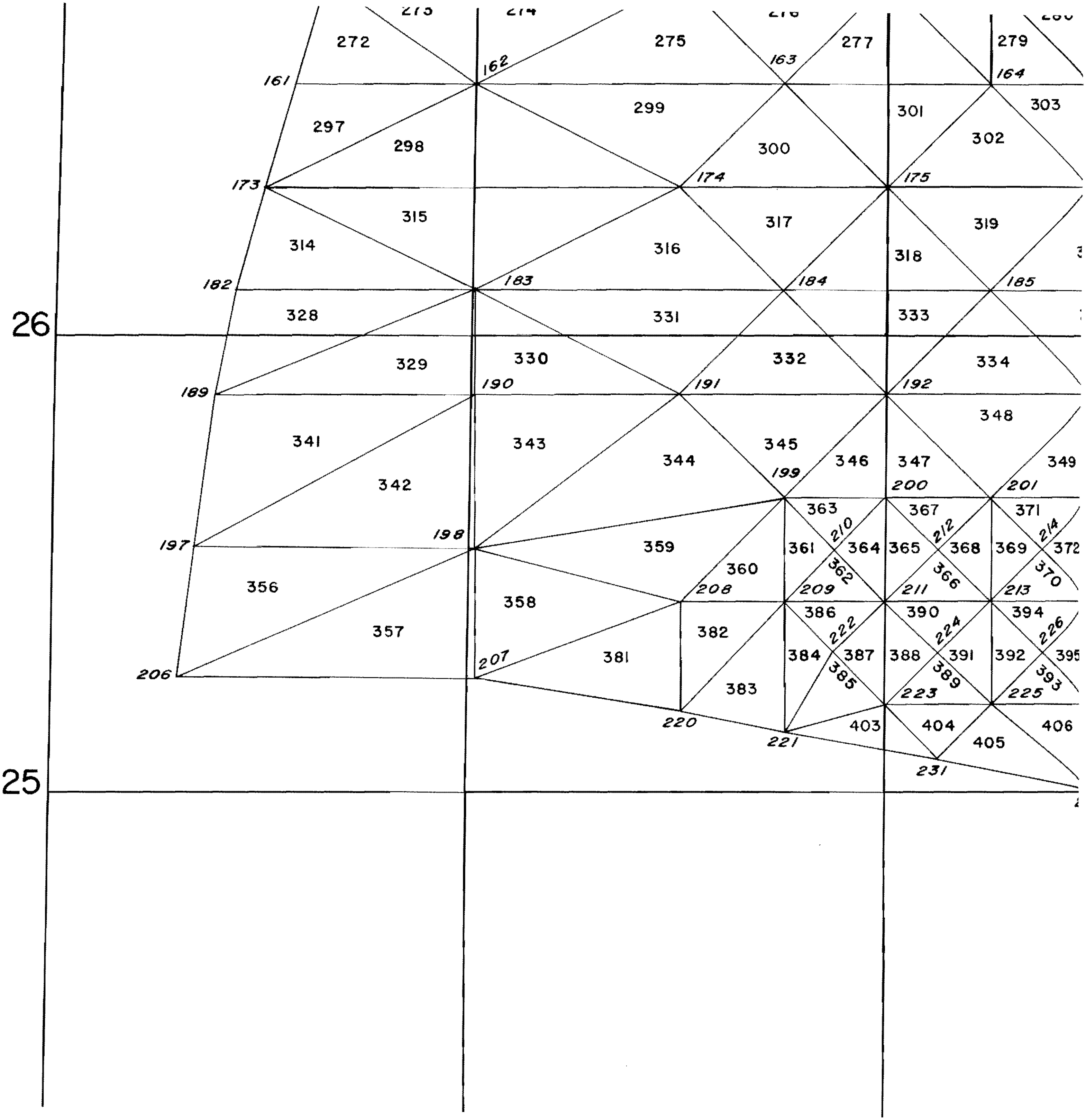


PLATE I

Map Showing Finite Element Grid Used for Groundwater Model of Sarir-Tazerbo Region

Utah Water Research Laboratory, Logan, Utah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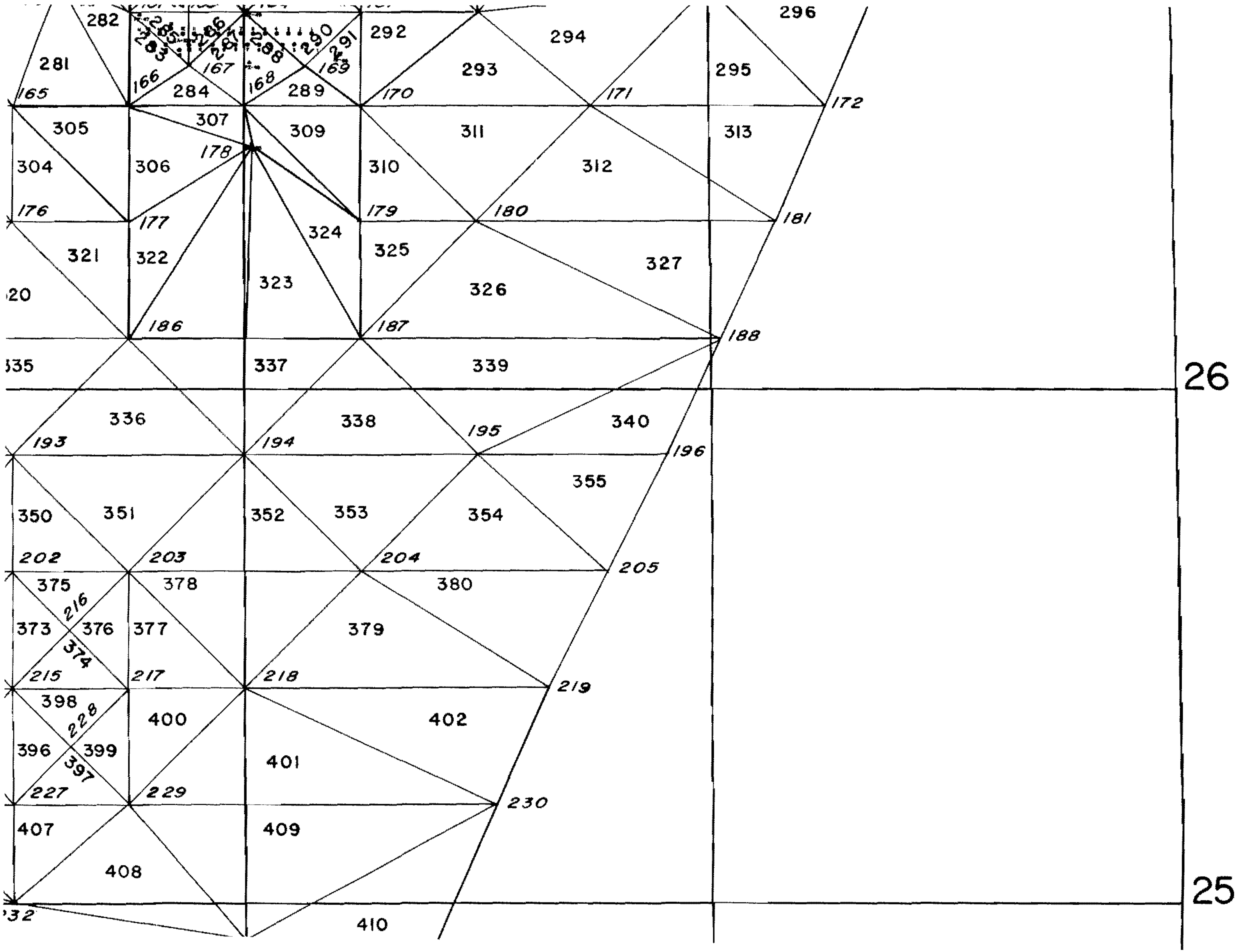

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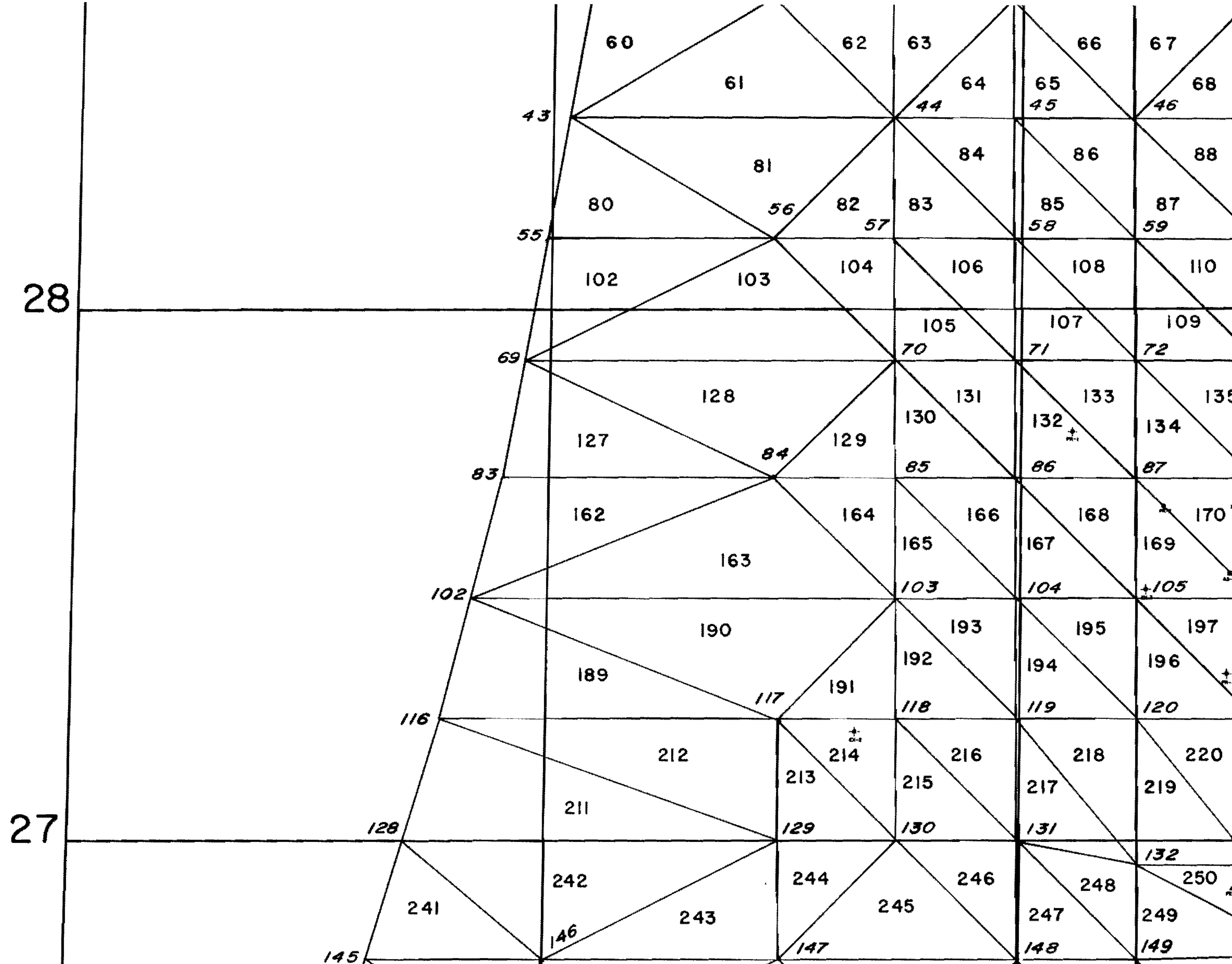

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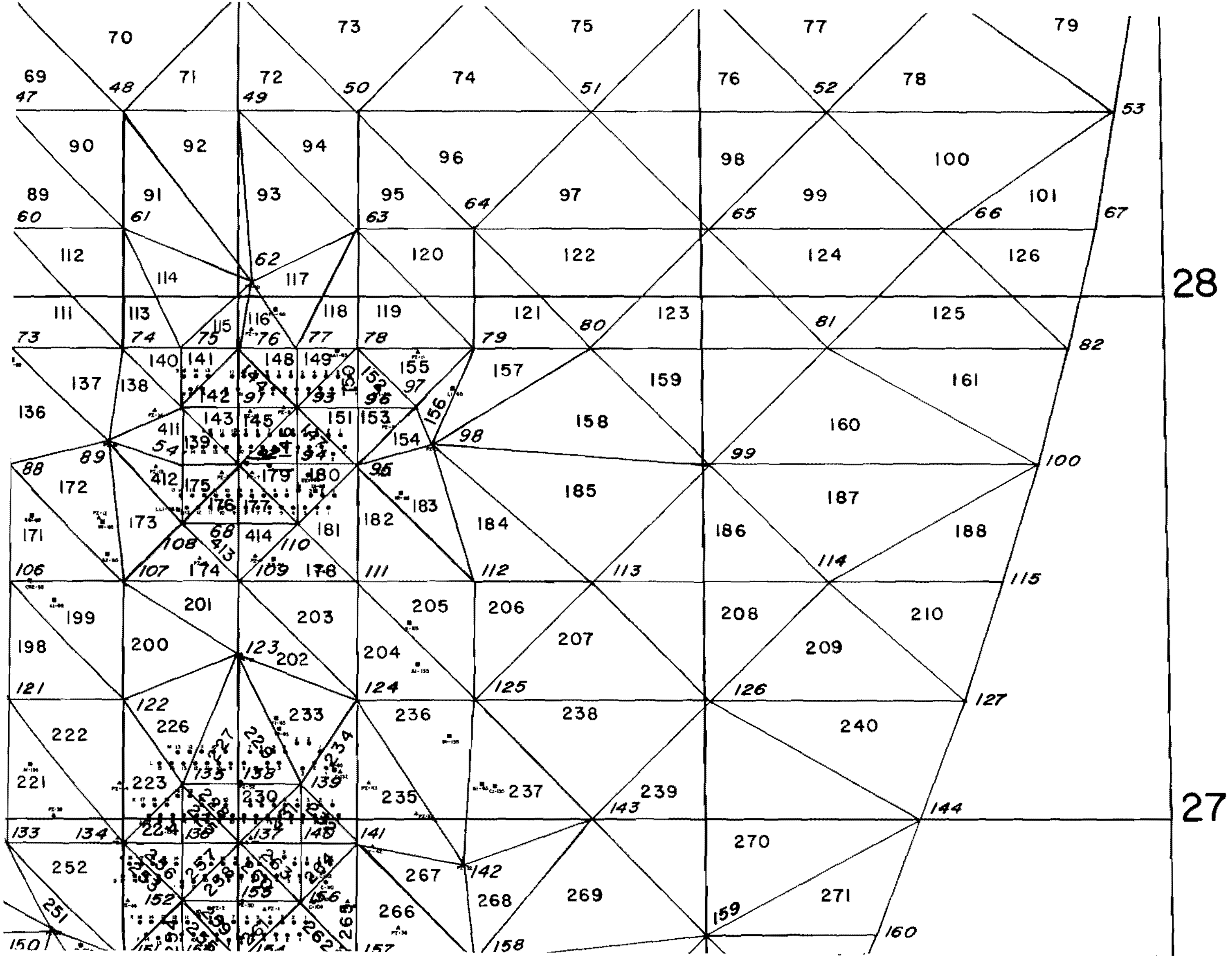

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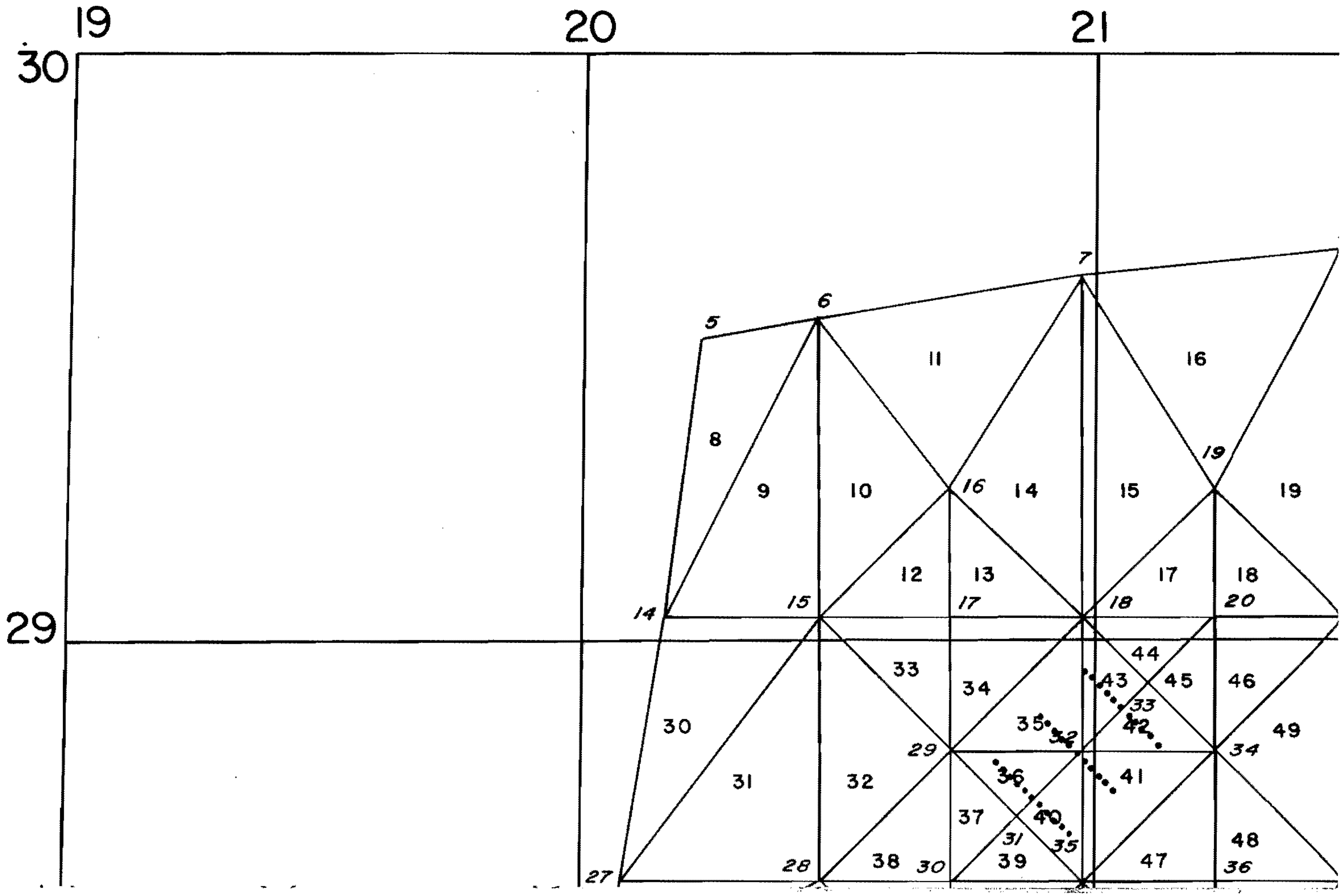
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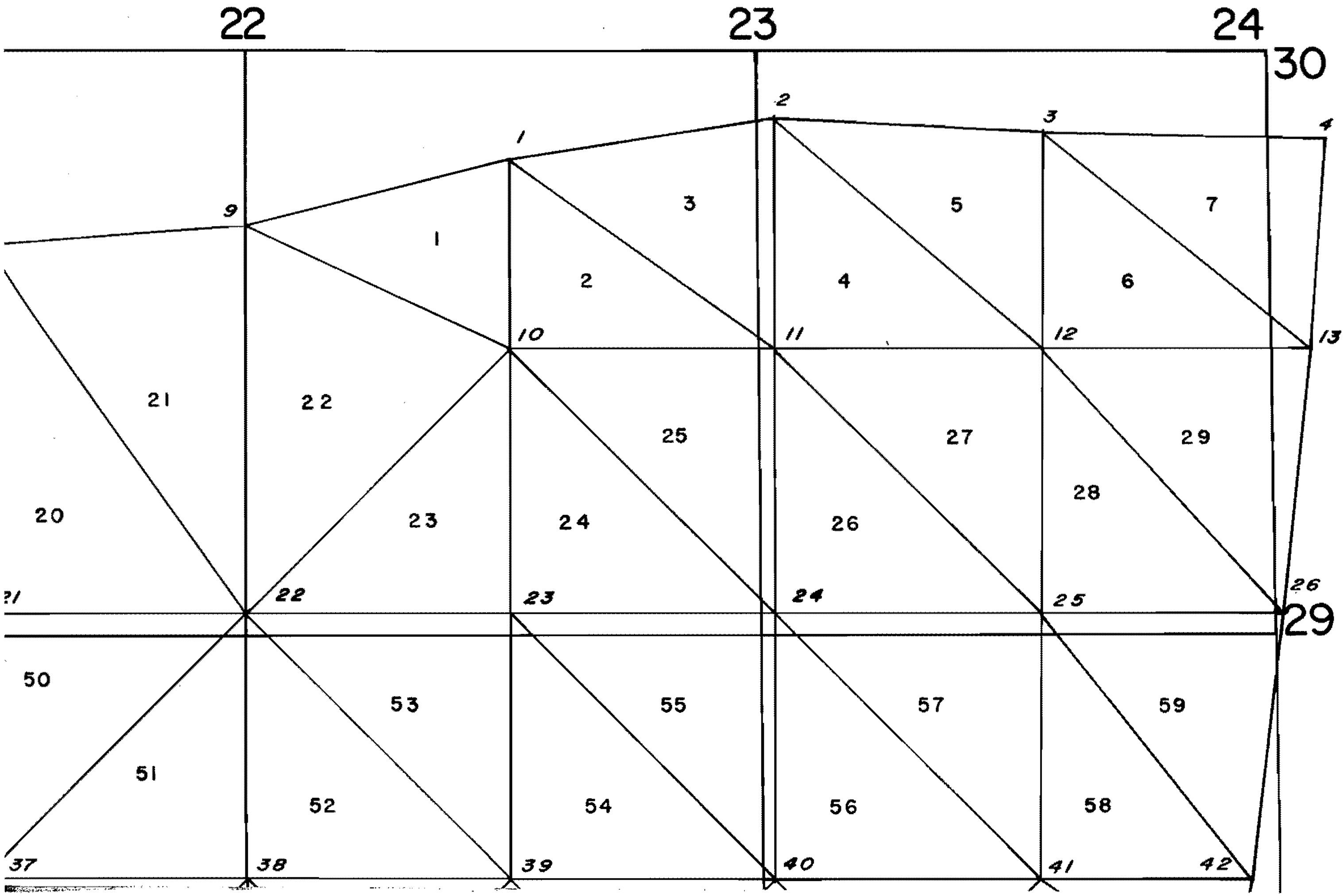

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