GROUND WATER SYSTEM EVALUATION FOR WADI NISAH -- SAUDI ARABIA

by

Mohammed Jamil Abdulrazzak

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STATEMENT BY AUTHOR

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SIGNED: Mohammed Jamil Abdulrazzak

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

Daniel D. Evans
DANIEL D. EVANS
Professor of Hydrology and
Water Resources

11/24/76
Date

This thesis is dedicated to
my wife, Nancy, and to my son, Bassaum,
who were my constant source of inspiration
and without whose patience and encouragement
this thesis would not have been possible.

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ABSTRACT

A detailed study of the Biyadh sandstone aquifer in the Wadi Nisah graben was conducted primarily to adopt a simple ground water model that could be used for evaluation and management of the aquifer and to study the feasibility of additional ground water withdrawal.

The model developed by Prickett has been adapted to fit the Wadi Nisah aquifer since it is simple to operate, requires less computer memory, and provides fast program execution. In light of the results obtained during the calibration, it was concluded that the model could be used for future management of the aquifer.

This study also indicated that further development of the aquifer is possible through the construction of an additional new well field at the lower end of the aquifer. A prediction analysis of the water level decline was made for the proposed well field and also for the other well fields in the area, which indicated that over a 30-year period the expected drawdown would constitute 20-30 percent of the available saturated thickness. The simulation technique used in generalizing data for rainfall, runoff, and infiltration for the Wadi Nisah area demonstrated that this procedure could be used in other areas of Saudi Arabia where only limited data are available.

CHAPTER 1

INTRODUCTION

In many areas of the world, increasing demands are being placed on ground water to meet the expanding municipal, industrial, and agricultural water needs. In areas such as Riyadh, the capital of Saudi Arabia, where ground water is the only source of water, prolonged usage and withdrawal in excess of the natural recharge have caused the water level to decline in all of the aquifers used for supply.

The City of Riyadh draws its water from two types of aquifers: the shallow formations in wadis Nisah (Biyadh formation), Namer, and Hair (Figure 1), which have good water quality (total dissolved solids = 300-600 ppm) and supply approximately 35% of the total water demand; and the deep Minjur aquifer which has a higher water salinity (1000-1500 ppm) and high temperature, and is also at a considerable depth below the ground surface (about 3000 ft).

The current national development programs which have been adopted by the Government of Saudi Arabia have caused the City of Riyadh to experience a considerably rapid expansion and, consequently, the present water supply may not be adequate in meeting the rising demand. According to a report by Doxiadis in 1969 (El-Khatib, 1974), the future water demand for the City of Riyadh is estimated in Table 1.

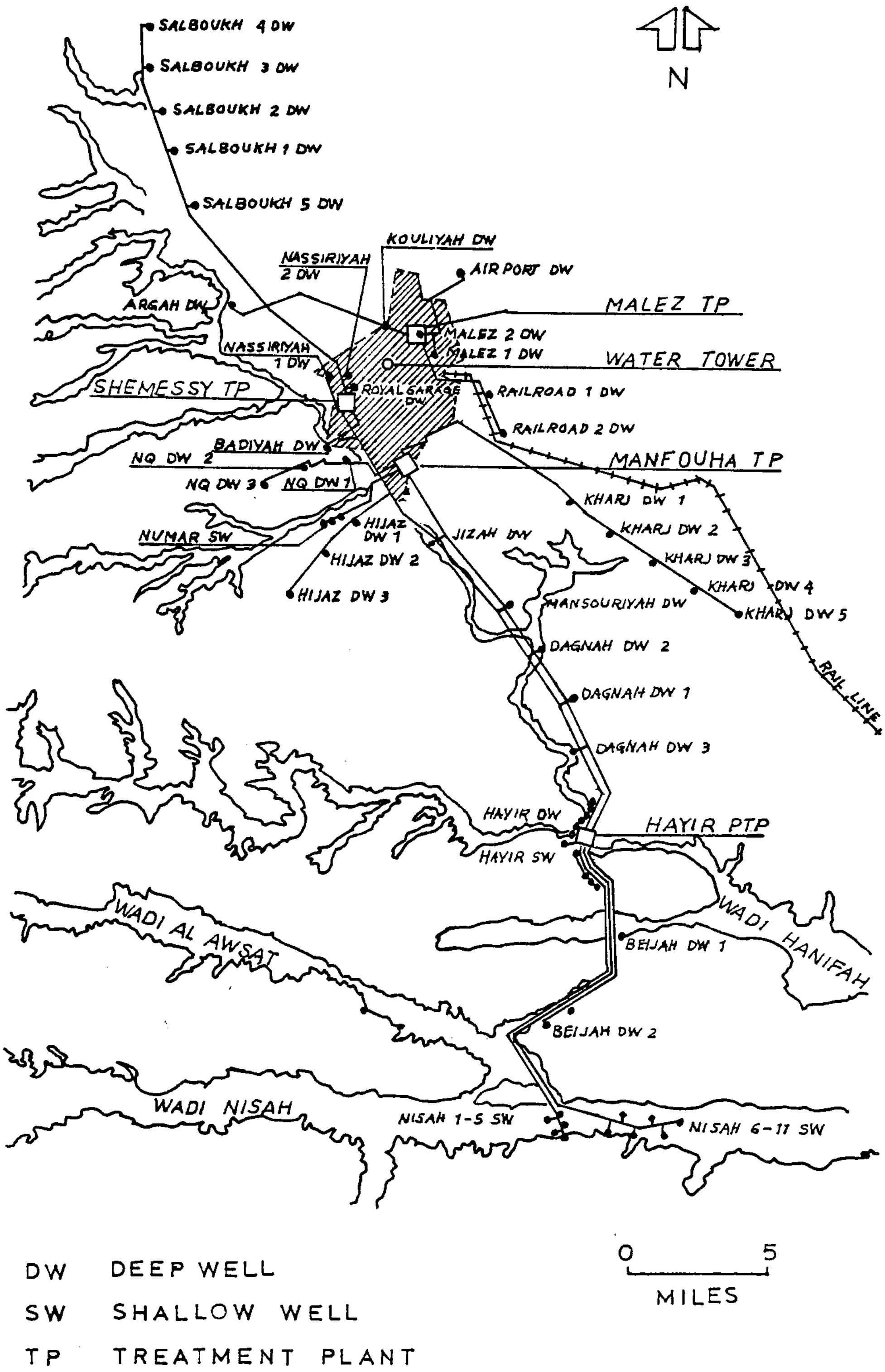

Figure 1. Well Locations. -- After El-Khatib (1974).

Table 1. Estimate of Future Riyadh Water Demand.

Year	Population	Water Demand in gpd/Capita	Total Demand in gal/day (10^6)
1970	355,000	48	18.76
1975	525,000	53	31.17
1980	625,000	58	45.70
1985	900,000	63	66.57
1990	1,050,000	69	85.86
2000	1,400,000	79	137.10

In an attempt to compensate for the increasing water demand, a ground water investigation was carried out by the Sir MacDonald consulting firm in 1972, the purpose of which was to study the feasibility of further developing the deep Minjur aquifer. In addition to this study, the government drilled six new wells in the Wadi Nisah area which started production 1975, in addition to the five wells already in use there. Further development of the Wadi Nisah aquifer appears feasible, but a more complete analysis is needed to determine the projected water level declines and to insure that the aquifer will be managed in the most efficient way.

Purpose and Scope

The main objective of this thesis is to evaluate the Wadi Nisah aquifer by the application of a ground water model which could be used to assess water development potential and as a tool for future management of the system. To do this, a relatively simple model was selected and its reliability evaluated. A corollary to the main objective is to study the feasibility of additional ground water supply from Wadi Nisah to meet the Riyadh water demands.

Location and Areal Extent of the Study Area

The following brief description of the location of the Wadi Nisah drainage basin is summarized below from works by Sogreah (1968) and Abu-Butain (1974).

The Wadi Nisah basin, which lies in the Tuwaig mountains, is about 25 miles south of Riyadh (Figure 2). The drainage basin area is about 690 square miles (1800 square kilometers) and includes the catchment area of Wadi Nisah and Wadi Awsat (Figure 3). It lies between longitudes 46° and 47° and latitudes 24°30'N and 24°00'N. The Wadi Nisah basin is bordered on the north by Wadi Hanifah and on the south by Wadi Al-Ayn and Wadi Al-Hawtah. The west border is formed by the Tuwaig mountains and the east border is near the town of Al-Kharj.

The topography changes from rolling hills adjacent to the Tuwaig escarpment in the west to the flat area of the Al-Kharj plains in the east. The elevation ranges from 3500 feet in the Tuwaig mountains to 1475 feet in the Al-Kharj area.

The Wadi Nisah Valley and its tributaries are covered by alluvium and sand dunes and are bordered on the north and south by hills ranging in height from 30 to 80 feet. The basin was subjected to tectonic activity which led to the development of major faults and grabens that run in an east-west direction. The Wadi Nisah graben is of special

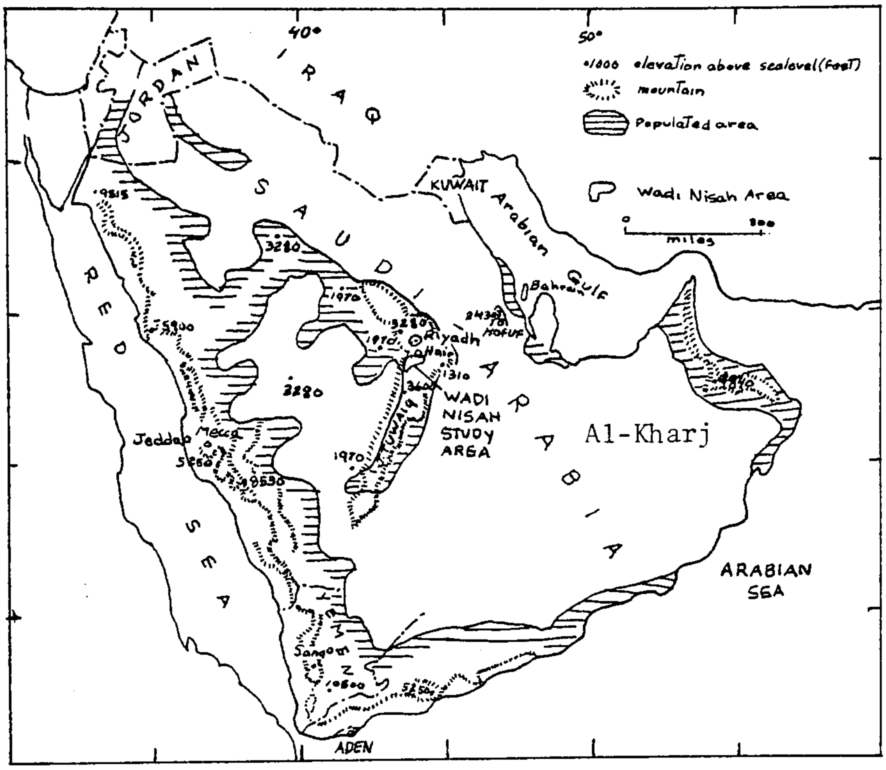

Figure 2. Location of Wadi Nisah.

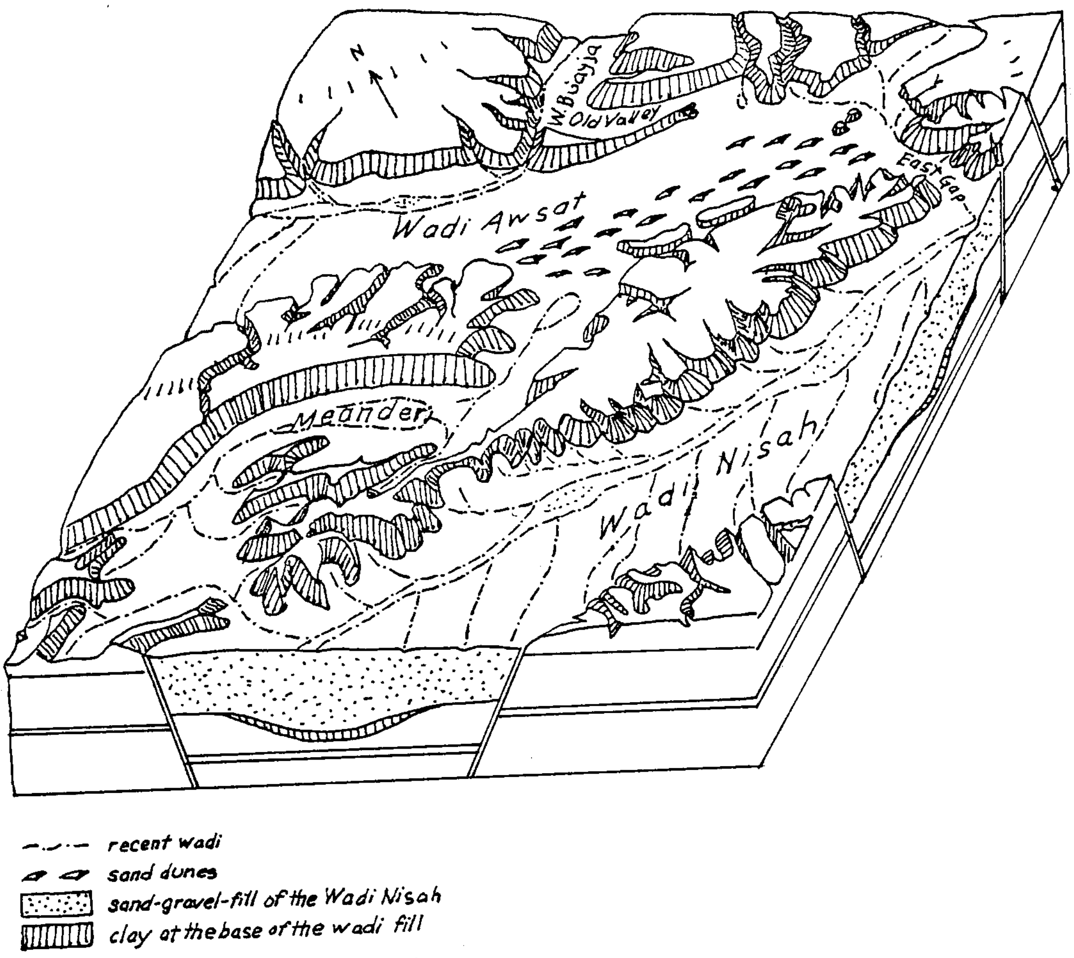

Figure 3. Recent Drainage System in the Nisah-Awsaṭ-Buayja Area.
-- After Wolfart (1960).

importance since it contains the only major aquifer in the area. The graben has an east-west dimension of approximately 70 miles and a north-south dimension varying from 1 to 2.2 miles.

CHAPTER 2

GEOLOGY AND HYDROGEOLOGY

General Geology

The Wadi Nisah basin is located within the central Arabian graben and trough system of the Arabian shelf. Previous detailed geological investigations by Wolfart (1960) and Sogreah (1968) have revealed that complex geological formations which outcrop within the Wadi Nisah drainage basin are mainly limestone and of marine origin (Figure 4). These formations belong to the geologic periods of Jurassic and early Cretaceous. The Minjur, Marrat, Druma, Tuwaig, Hanifah, Jubaila, and Arab formations belong to the Jurassic period, while the Salaiy and Biyadh formations belong to early Cretaceous. Stratigraphic description of these formations in the study area is presented in Figure 5.

Jurassic Deposits

Jurassic period deposits consist of clastic and carbonate rock. The rocks are interbedded marine shale and Arabian shelf limestone which gradually change into partly continental sandstone in the lower part of the deposit. The upper Jurassic deposits consist of limestone faces which are interrupted by the onset of evaporite environment (Burdon, 1972), which give rise to cyclic deposits of anhydrite and clean-washed lime sand and gravel. The formations which form the Jurassic period deposits are discussed below.

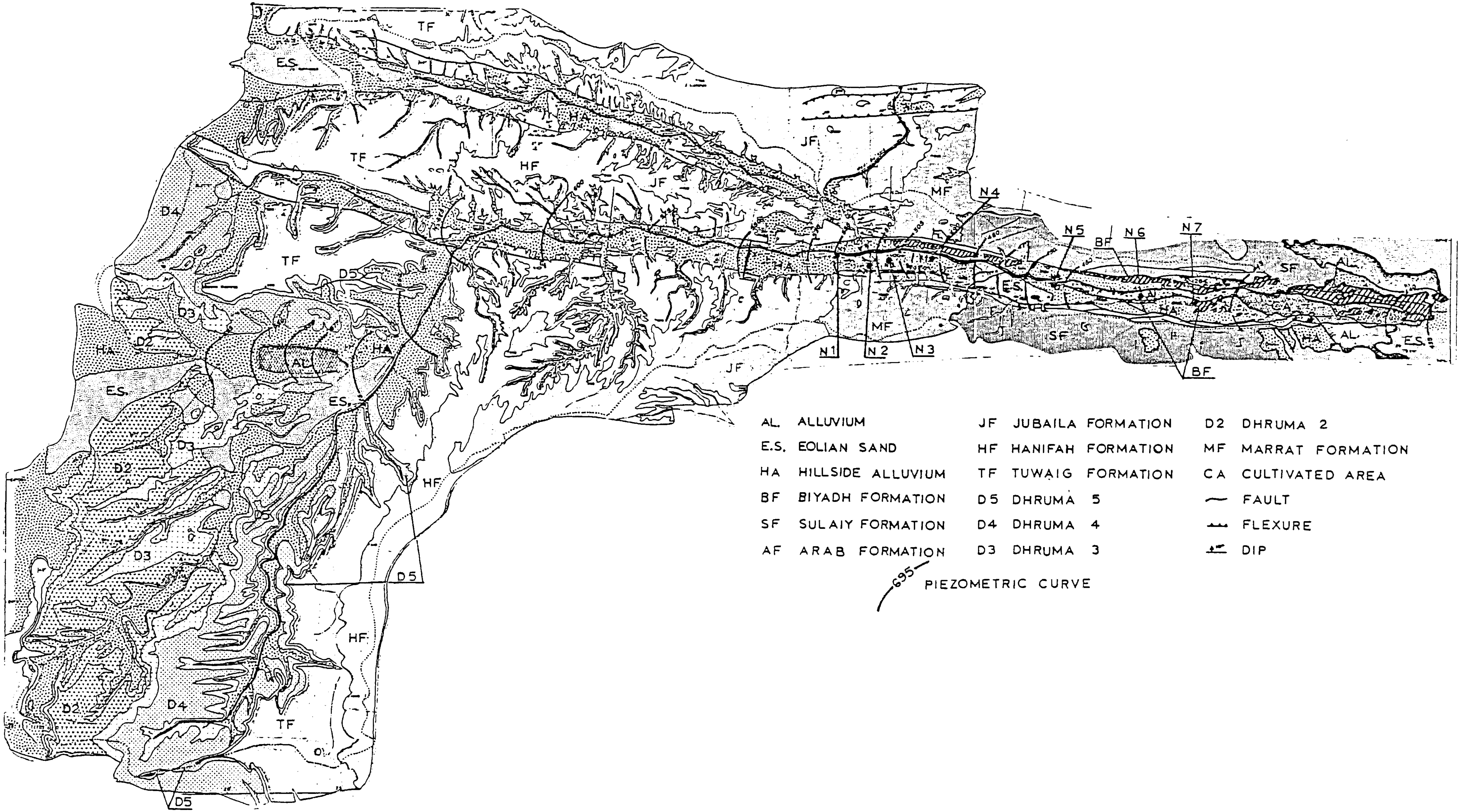

Figure 4. Geologic Map of Wadi Nisah Area. -- After Sogreah (1968).

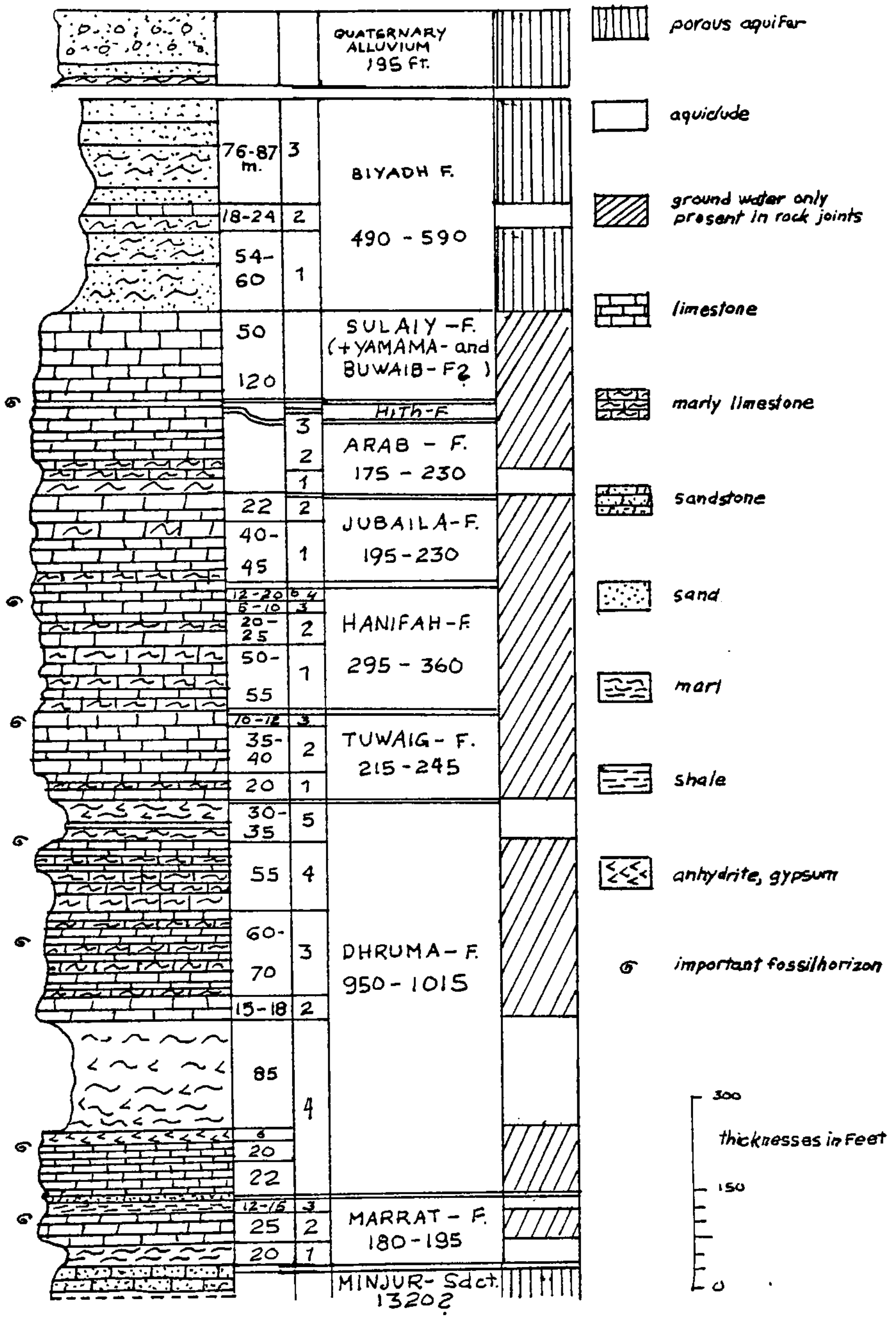

Figure 5. Stratigraphic Section. -- After Sogreah (1968).

Minjur Formation. Minjur sandstone outcrops only in the extreme southwestern part of the Nisah area. The formation consists of quartzitic sandstone with small amounts of conglomerate and shale of continental origin. The sandstone is typically white to brown, medium grained, and poorly sorted. Its maximum thickness was encountered outside the study area (near Riyadh) and gradually decreased southward. At Riyadh, several high-capacity production wells tapped the formation, producing water of good quality. In the Wadi Nisah area, the Minjur formation has not been explored due to its great depth and the water may be of poor quality, as observed in the Al-Kharj area.

Marrat Formation. This formation also outcrops only in the southwestern part of the Wadi Nisah area. It consists of lower marine sediments and upper terrestrial sediments. In the lower part are layers of marl and limestone and the upper part is hard sandstone. This formation produces only small amounts of water in the outcrop area.

Dhruma Formation. This formation occupies the whole western and southwestern part of the Nisah area. It consists of an alternating bedding of various limestone, dolomite, gypsum and anhydrite, and marl materials. It is approximately 1,000 feet thick. It is divided into three members of upper, middle, and lower. The lower unit consists of shale with some limestone and gypsum, the middle unit is limestone, and the upper unit is shale with some limestone. This formation is known to be a potential aquifer only in the carbonate sandstone faces south of Riyadh outside the study area.

Tuwaig Formation. This formation outcrops in the western part of the study area. It consists of coral-bearing, dense, pure limestone. Coral colonies which were subjected to weathering are often dolomitized and coated with black-brown, Fe-Mn precipitation. This formation is not known to be a water producing aquifer.

Hanifah Formation. This formation outcrops in the north of the Nisah area. The continuity of the Hanifah formation is disturbed by the Wadi Nisah graben. The Wadi Nisah graben slices through the backbone of the Tuwaig formation which underlies the Hanifah formation. The formation consists of brown oolitic limestone and alternating beds of brown platy dolomite and marl limestone. Shallow hand-dug wells have tapped this formation in the outcrop belt near the surface where the permeability and porosity of the rock developed through weathering allows storage for a small water yield.

Jubaila Formation. This formation outcrops in the middle of the Nisah area and is disturbed by the graben fault. It consists of very resistant limestone and dolomite. It produces small quantities of water outside the study area where weathering and joint systems allow the storage of water.

Arab Formation. It outcrops in the middle of Wadi Nisah on both sides of the graben fault. This formation shows the effect of slumping, which was caused by the removal of anhydrite beds, and the subsequent collapse of the carbonate units left behind. There is little knowledge of the basic rock types. The formation consists of grey limestone, part marls, and platy anhydrite. Large amounts of water are being produced from this formation in the Al-Kharj area (east of the study area) through two sink holes. The water quality indicates a high saturation of calcium carbonate.

Cretaceous Deposits

The Cretaceous period deposits consist of a thin basal limestone, succeeded by a thick deposit of mainly continental sandstone. The sandstone is mainly coarse and crossbedded with some interbedded shale and siltstone and thin limestone layers. Formations making up the Cretaceous deposits are described below.

Salaiy Formation. This formation outcrops in the eastern part of Wadi Nisah, and it consists of oolites and compacted limestone. The complete sequence of this formation is not completely present in Wadi Nisah and their subdivision is difficult to identify due to the lack of good exposure. It is composed of light, platy limestone with brown colites. The limestone is hard and compacted. It is not known to be a water producing formation.

Biyadh Formation. It is the only one of the formations that can be traced over a great distance throughout Saudi Arabia. At a typical section, it is 1475 feet thick and reaches a maximum thickness of 2132 feet at Bani Al-Labab (20°42'N), where its thickness gradually decreases as it progresses northward. In the Wadi Nisah area, it is only preserved in the graben fault. The lower three-fourths of this formation consists of light-colored, crossbedded quartz sandstone with a little interbedded shale. The upper fourth consists of coarse-grained, crossbedded sandstone containing abundant pebbles of white quartz. This formation is one of the major aquifers in Saudi Arabia. Many production wells tap the Biyadh aquifer in the Wadi Nisah graben. The thickness of the aquifer ranges from 263 to 1150 feet throughout the graben. The transmissivity of the aquifer ranges from 30,000 to more than 100,000 gpd/ft. The water quality in the Wadi Nisah graben is good (300-900 ppm); however, it deteriorates progressively eastward, reaching 6000 ppm in the eastern part of Saudi Arabia. Water from the Biyadh aquifer is being injected into the oil reservoir there.

Quaternary Deposits

Quaternary deposits are alluvial, underlying the main channels and thin tributaries of Wadi Nisah and Awsat. The alluvial fill is underlined by a relatively thin clay bed. The alluvial deposit consists of aeolin quartz, sand, and pebbles underbedded with layers of sandstone and limestone boulders. The limestone boulders are present only on the upper part of the fill and the thickest parts of the alluvium deposit is a shallow aquifer and is recharged during periods of heavy rainfall.

Structure of the Wadi Nisah Area

The Tuwaig mountains, which are located west of the study area, are dissected by a system of parallel major faults and grabens running in an east-west direction. One of the major grabens is that of Wadi Nisah, which coincides with the present valley of Wadi Nisah. The Wadi Nisah graben is a linear feature which generally trends N85°W. It is bounded on the north and south by normal faults which dip under the down-dropped floor at 60 to 70° (Figure 6). Another graben is the Awsat, which is

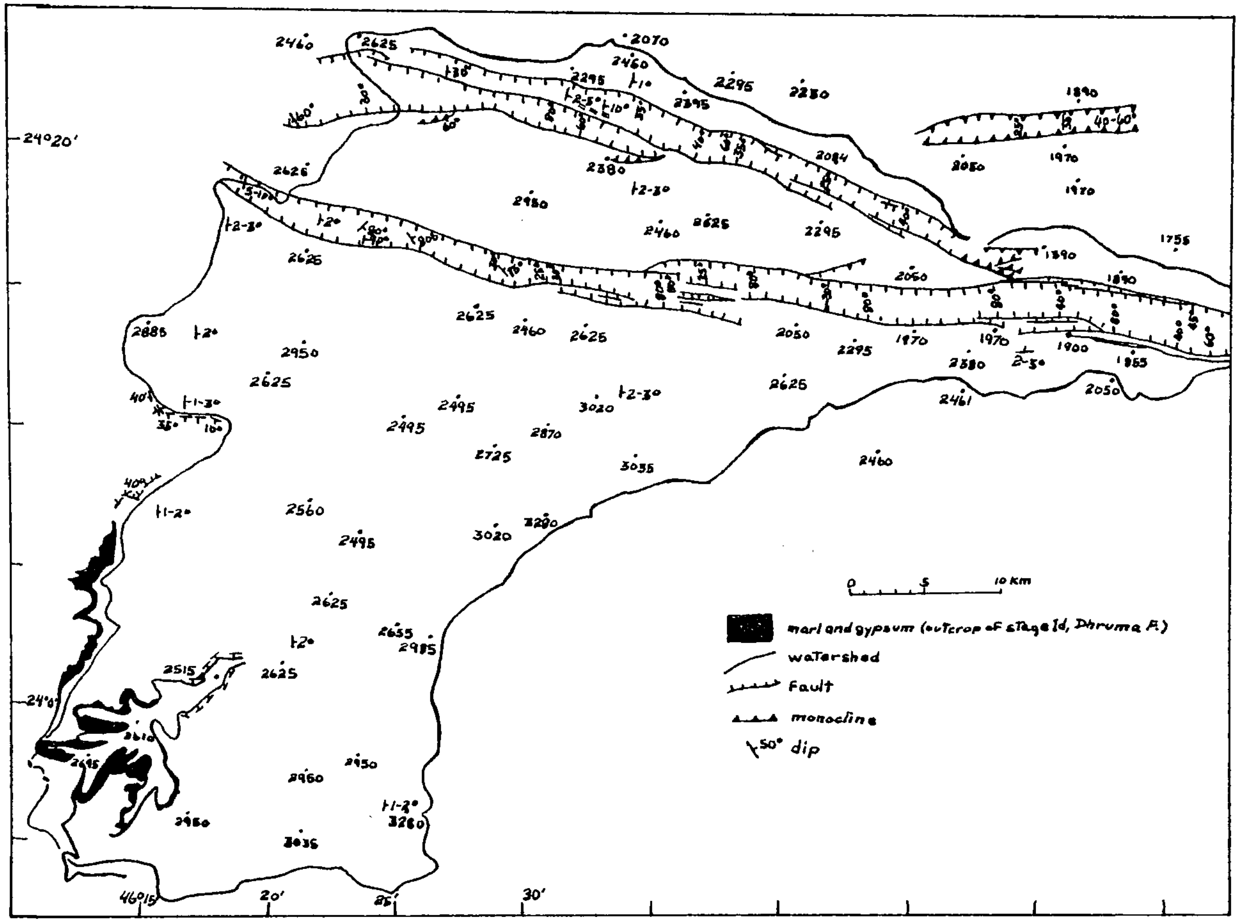

Figure 6. Structural Map of Wadi Nisah Area. -- After Wolfart (1960).

located northwest of the western part of Wadi Nisah. The Awsat graben branches out from Wadi Nisah and extends almost 55 miles northwestward with a trend of N68°W.

Aramco geologists have studied the area and their research shows that the tectonic movements which caused the subsidence in this area may have taken place between the upper Cretaceous and the Tertiary periods. In addition, small subsidences may also have occurred during the recent Quarternary period. The amount of displacement in the western part of the graben was determined by studies performed by Powers et al. (1966), where the lower Arab formation was downthrown against the Hanifah formation and the upper Hanifah formation dropped against the upper Dhruma formation (the amount thrown is shown in Table 2). The downthrown blocks

Table 2. Magnitude of Throw in Wadi Nisah Graben. -- After Sogreah (1968).

Location	Distance West of Abraq Firzan (mi)	Magnitude of Throw (ft)
Al-Kharj plain (Abraq Firzan Swaidah	0.00	380-460
Wadi Awsat	8.1	656-820
	15.5	1295-1395
Wadi Awsat	24.8	1148-1279
Riyadh water supply well field	31.1	853-984
	40.4	856-787
	52.8	1075 (approx.)
Western end of graben	68.3	0

are partly split by subsidiary faults and partly folded. Drag effects are found in the limestone rocks on both sides of the graben and are visible as far as 0.6 miles back from the edge of the trough. In the immediate vicinity of the fault plane, local intense drag was found. The limestones present on both sides of the graben are often split into large blocks which dip toward the graben as much as 20°. The limestone is very fissured and jointed (Sogreah, 1968).

Geophysics

An electric resistivity survey was conducted throughout the length of the Wadi Nisah graben in order to determine the western boundary of the water-bearing Biyadh sandstone aquifer and also to delineate the structure and variation in thickness. Thirty electrical soundings were made by Sogreah (1968) which indicated that the Biyadh sandstone aquifer wedges out between the alluvium and the underlying Sulaig limestone formation at about 3-3.5 miles upstream of the Wadi Awsat confluence. The thickness of the Biyadh formation increases in a downstream direction and reaches about 590 feet at the production wells PW_1 and PW_2 (Figure 7). The electric survey indicated two areas with great thickness; one area is located just east of the Riyadh water supply well field (590 feet), and the other is located between Suwaidah and Gauwid Firzan (820 feet in thickness). These two delineated areas, where the upper part of the Biyadh formation has its greatest thickness, are made up of pure sand and have good water quality.

The geophysical survey also revealed that the Biyadh formation's upper part consists of a series of sandy horizons alternating with three

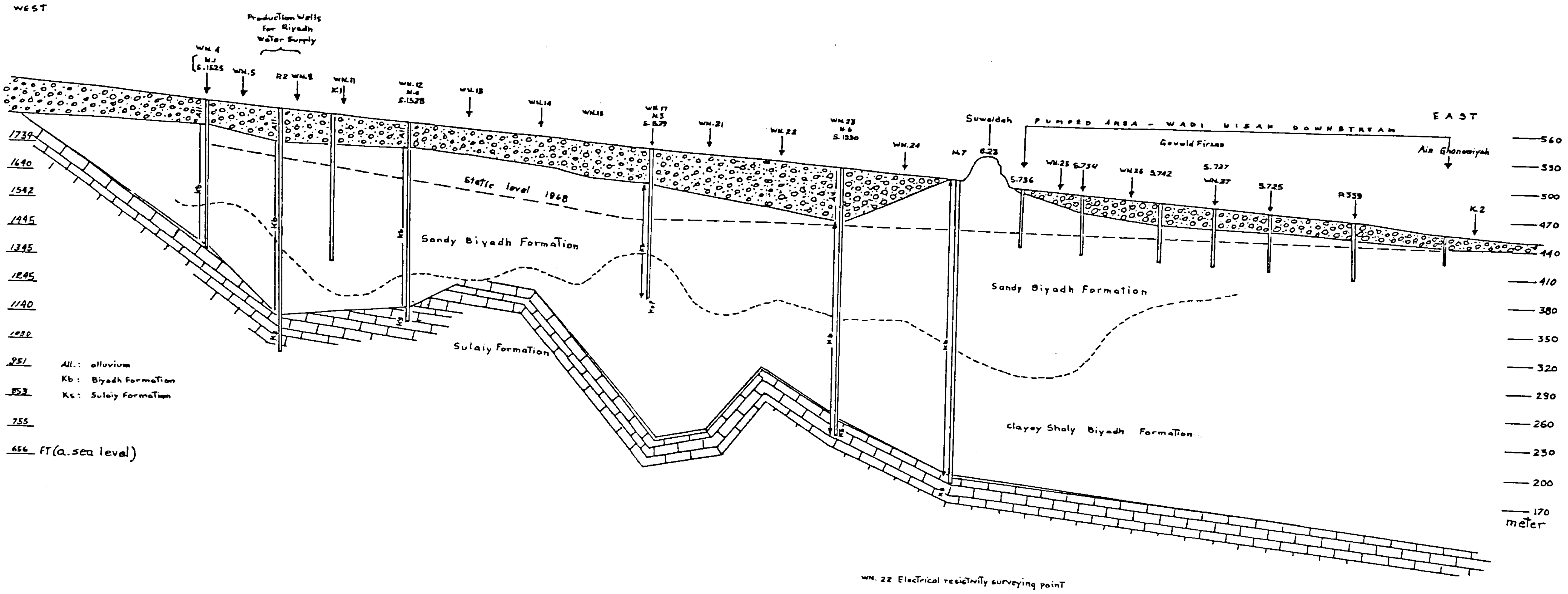

Figure 7. Longitudinal Profile of Wadi Nisah Aquifer. -- After Sogreah (1968).

shale layers. The shale layers become thicker at the lower part of the formation. Even though the thickness of the formation increases greatly in a downstream direction, the percentage of shale increases considerably which causes a deterioration of water quality.

Along the edges of the graben, the faults divide the formation into blocks which are increasingly downthrown closer to the axis. As a result, the aquifer thickness decreases greatly at the edge, which creates a stairway structure (Figure 8).

Hydrogeology

There are two aquifers in the study area: the alluvial aquifer and the Biyadh sandstone aquifer (Sogreah, 1968). The alluvial aquifer is located in the sand-gravel deposits of the Wadi Nisah main channel. It is an unconfined aquifer where the water level responds significantly to the amount of precipitation. The aquifer thickness varies throughout the study area, reaching a maximum thickness of 200 feet in the middle of the graben. In the upper part of the catchment area, near the Al-Jufayr and the Khasham Al-Atark plains, it is between 100 and 130 feet thick. A few hand-dug and drilled wells were sunk into the alluvium and underlying fractures Dhruma limestone formation and are being pumped regularly. The estimated annual yield from the above wells is 2×10^3 acre-feet. The alluvial aquifer in the Wadi Nisah graben is dry most of the time, except during flood season, and the water table along most of the length of the wadi can be found in the underlying Biyadh sandstone formation, which is the main aquifer in the graben fault. The Biyadh aquifer receives its

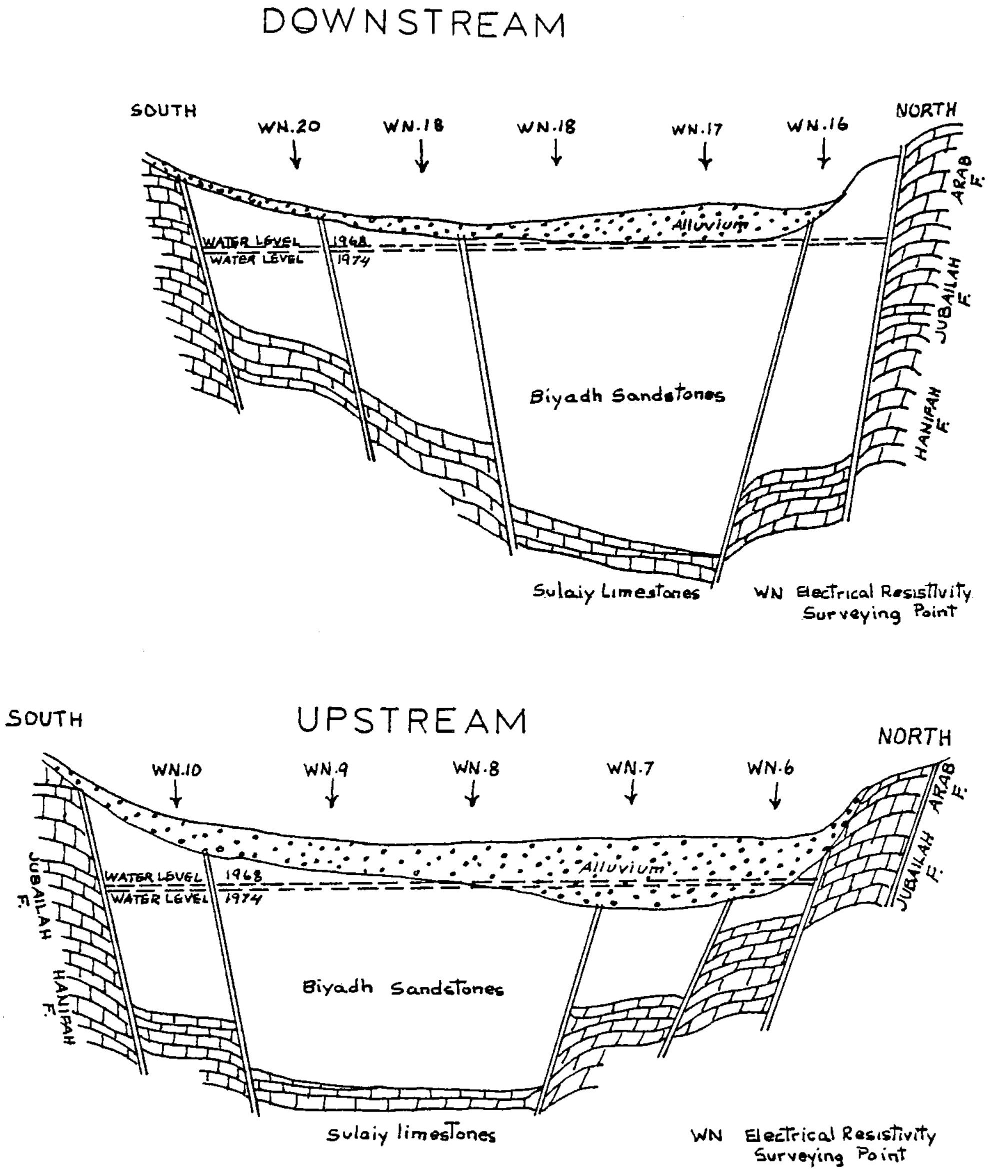

Figure 8. Cross-Section of Wadi Nisah. -- After Sogreah (1968).

recharge from the overlying alluvial aquifer where flood waters infiltrate during rainy periods.

Samples taken during drilling in Wadi Nisah indicated that the Biyadh formation is made up of 70% medium to coarse-grained sand with an average effective grain size of 0.006 inches and a uniformity coefficient of 0.14 inches (Wolfart, 1960). Drill cuttings indicated that the Biyadh formation is very heterogeneous; the 0.02 inch fraction is between 15 and 65% for samples from various depths. The lithological logs of production wells PW_1 and PW_2 show about 195 feet of pebbly and silty alluvium and the water level was 174 feet, which proves that the alluvium is water bearing. The log also indicated that the Biyadh formation is divided into two aquifers separated by a 65-foot layer of marl limestone and farily clayed marl. The upper aquifer is 240-280 feet of sand with a little shale. The lower aquifer is 180-215 feet of sand interbedded with numerous siltstone and shale beds. This formation extends under the Al-Kharj plain where there is continuous underground water flowing eastward. Sulaig limestone of low permeability underlies the Biyadh aquifer. The thickness of the aquifer decreases laterally due to the stairway structures which were caused by the faulting. The limestone adjacent to the graben fault is believed to act as a reservoir since it has fissures and joints and solution openings.

The ground water in the Biyadh aquifer flows from the west to the east. According to 1974 water level data, the hydraulic gradient varies from 0.006 at the upper part of the aquifer near the Riyadh well field, to 0.0001 at the lower part of the aquifer near Suwaidah. The low hydraulic gradient at Suwaidah indicates a high transmissivity value, assuming that the pumpage of the aquifer, mentioned in Sogreah's report of 1968, remains the same or is only slightly increased. The 1974 average hydraulic gradient along the length of the aquifer is about 0.0027.

Ground water could be moving from the edge of the graben to the Biyadh aquifer (Sogreah, 1968). Water infiltrating during the rainy season is believed to be stored in the faulted, fissured limestone on both sides of the graben. During the period when the recharge amount is great, water probably moves from the Biyadh sandstone and overlying alluvium to the fractured limestone. When the recharge is low or when water is being pumped, which causes the water table to decline, the water moves from the limestone into the aquifer. No information is available about the capacity of storage or transmissivity of the fractured limestone.

The water pumped from the middle of Wadi Nisah appears to be 6000 years old, as determined by C_{14} measurement (Sogreah, 1968). The average ground water velocity before exploitation of the aquifer was about 3.3 to 6.6 feet per year. The velocity in a localized area can be much greater or less than the above value depending on the permeability, hydraulic gradient, and the porosity of the aquifer. Near a pumping well, the velocity will be much higher due to a steep hydraulic gradient.

Pumpage

Development of ground water in Wadi Nisah was started in 1960 for a few farms which are located between Suwaidah and Gawaid Firzan (downstream; see Figure 7). After the completion of the five wells at the confluence of Wadi Nisah and Awsat by the City of Riyadh, pumping started in 1963 and continued to the present time. The annual volume of water extracted was 1.6×10^3 acre-feet in 1967 and production was increased to 4.4×10^3 acre-feet in 1968 in order to meet the rising demand. Pumpage was increased again in 1974 to 8.4×10^3 acre-feet after the completion of six additional wells just 2.3 miles downstream from the existing well field. Agricultural pumpage by private small farms also increased in 1968, reaching an estimated volume of 8.4×10^3 acre-feet. About 50% of the water used for agriculture is expected to be lost by evapotranspiration and the rest infiltrates back to the ground water reservoirs. It should be noted that the ground water pumpage is mainly from the Biyadh aquifer.

The hydrograph for the observation wells in the Biyadh aquifer shows a steady decline in ground water level. Since 1964, when the pumping began, the Riyadh well field water level has declined at a rate of 2.13 feet per year. However, the increase in pumpage in 1973 increased the water level decline to 2.74 feet per year. Table 3 shows the water level variation in the Biyadh aquifer between 1968 and 1974 (Abu-Butain, 1974).

Water level contour maps were constructed for the pumping center at the Riyadh well field for the years 1968 and 1974 (Figures 9 and 10). Studies of these maps indicate high transmissivity values in the area between observation well N_1 and production well P_2. The high transmissivity in this area could be attributed to the presence of a fractured zone, which was caused by faulting, or by a buried channel. Brown and

Table 3. Water Levels for the Wells in Wadi Nisah. -- After Abu-Butain (1974).

Well No.	Elevation above Sea Level (ft)	Depth (ft)	Water Level (ft) 1968 Water Level Elevation (ft)	Water Level (ft) 1974 Water Level Elevation (ft)
X.1	1833.5	541.4	1654.0	1640.9
X.12	1860.3	721.8	1689.7	1676.6
WP.1	1866.2	836.7	1653.6	1640.5
WP.2	1847.3	830.1	1650.1	1630.8
WP.3	1844.3	492.2	1655.8	1628.3
WP.4	1853.3	529.0	1658.5	1638.2
WP.5	1853.3	792.0	1626.9	1606.2
N.1	1878.7	521.8	1723.5	1716.1
N.2	1852.2	838.1	1675.7	1662.5
N.3	1838.8	377.3	1662.8	1646.3
N.4	1807.0	698.8	1610.5	1599.6
N.5	1738.9	515.1	1490.9	1485.9
N.6	1664.6	922.0	1465.5	1459.9
N.7	1633.2	1033.2	1463.7	1457.7

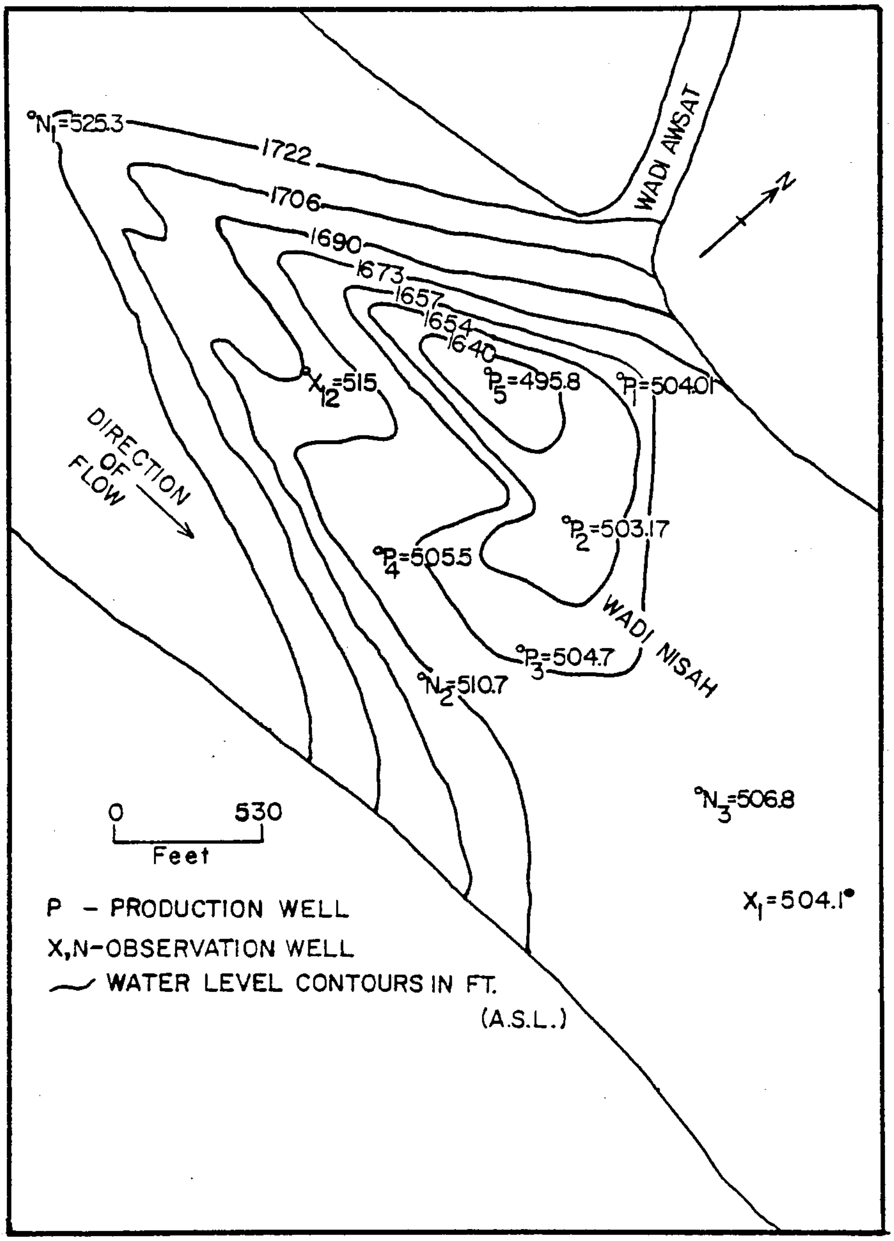

Figure 9. Water Level Map of Riyadh Well Field, 1968.

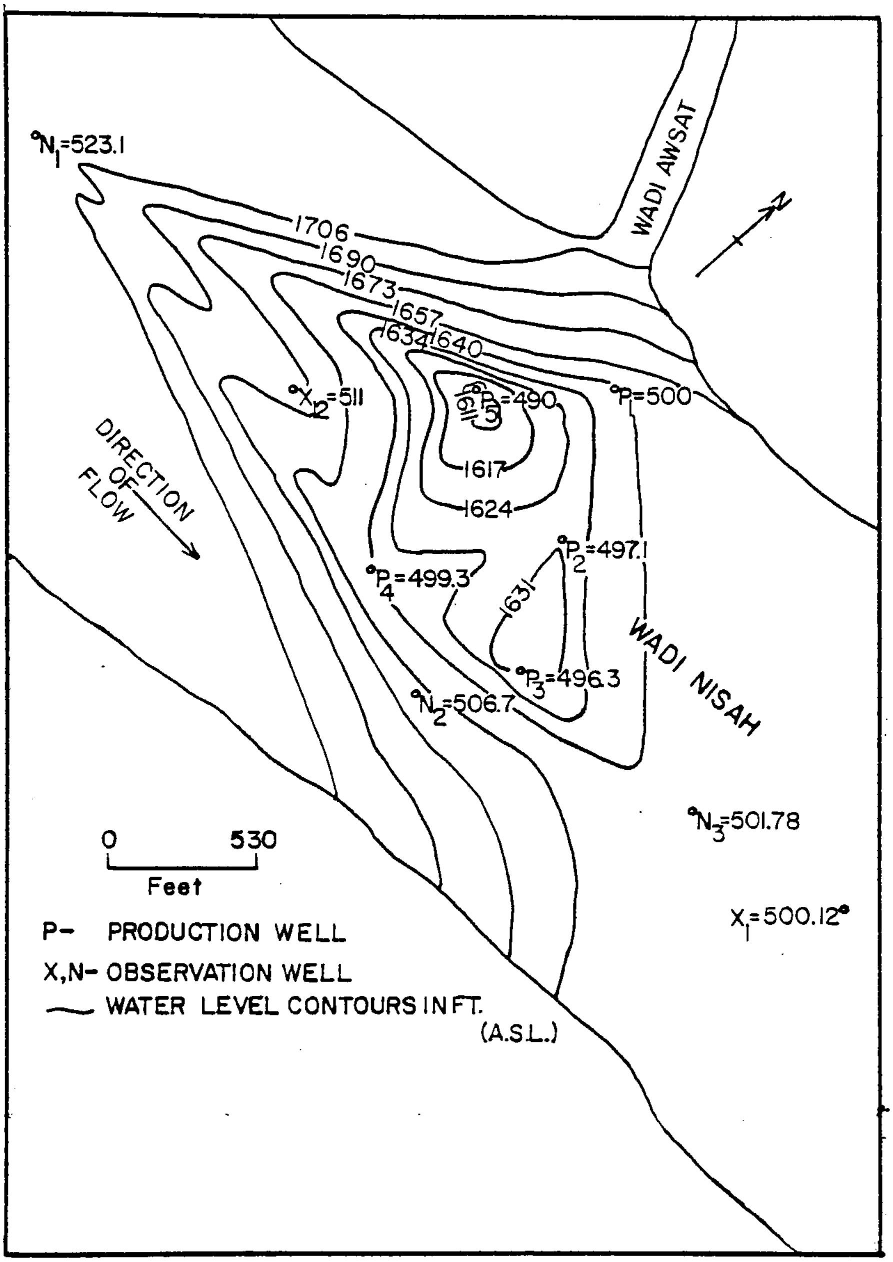

Figure 10. Water Level Map of Riyadh Well Field, 1974.

Lough (1963) and Sogreah (1968) performed two pumping tests on wells X_2 and P_2 in the Riyadh well field to determine the aquifer parameters, but since these tests were of short duration the values obtained cannot be considered representative of the transmissivity and storage coefficients of the aquifer. In order to arrive at an average aquifer parameter, a drawdown map (Figure 11) was drawn based on the water level contour maps of 1968 and 1974. A drawdown graph was then constructed using the map, assuming that the five production wells representing the pumping center were pumped continuously for a period of six years (1968-1974). Thus, the estimated aquifer transmissivity is 92×10^3 gpd/ft, and the storage coefficient is 2.7×10^{-2} (Figure 12).

Chemical Quality

The chemical quality of ground water is an important aspect to consider when planning the development of water supplies for industrial, agricultural, and human use. Ground water quality is influenced both by the sub-surface physical environment and by the environment where recharge takes place. The quality of a ground water supply is often just as important as the quantity -- the required quality being dependent on usage.

The ground water quality of Wadi Nisah is generally good, except in the areas near the Al-Kharj plain. Many samples have been collected from the production wells of the Riyadh water supply and analyzed. Representative results are given in Table 4 (Abu-Butain, 1974). They are within the maximum limits set by the U. S. Public Health Service (1962) for potable water. The water quality samples indicated that the total

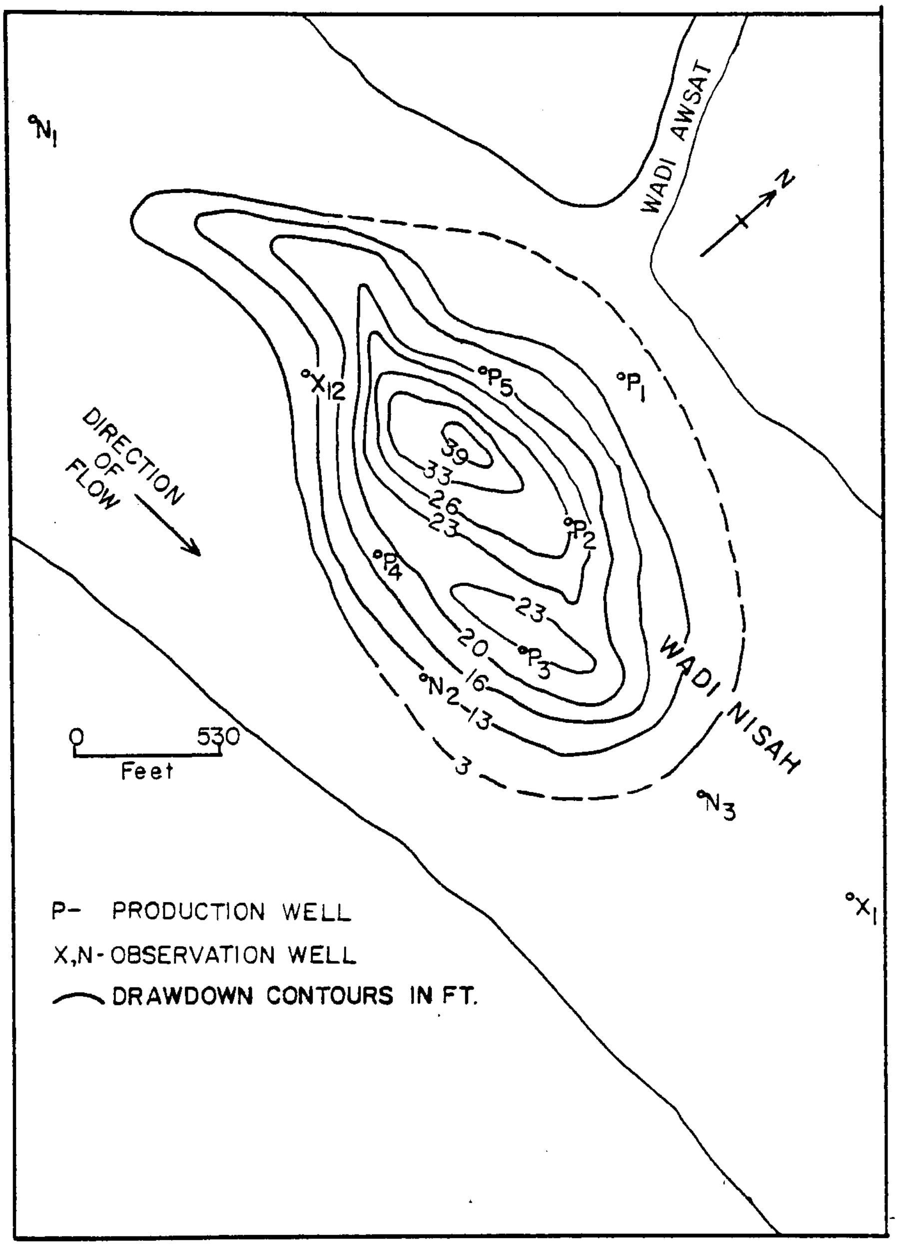

Figure 11. Drawdown Map of Riyadh Well Field, 1968-1974.

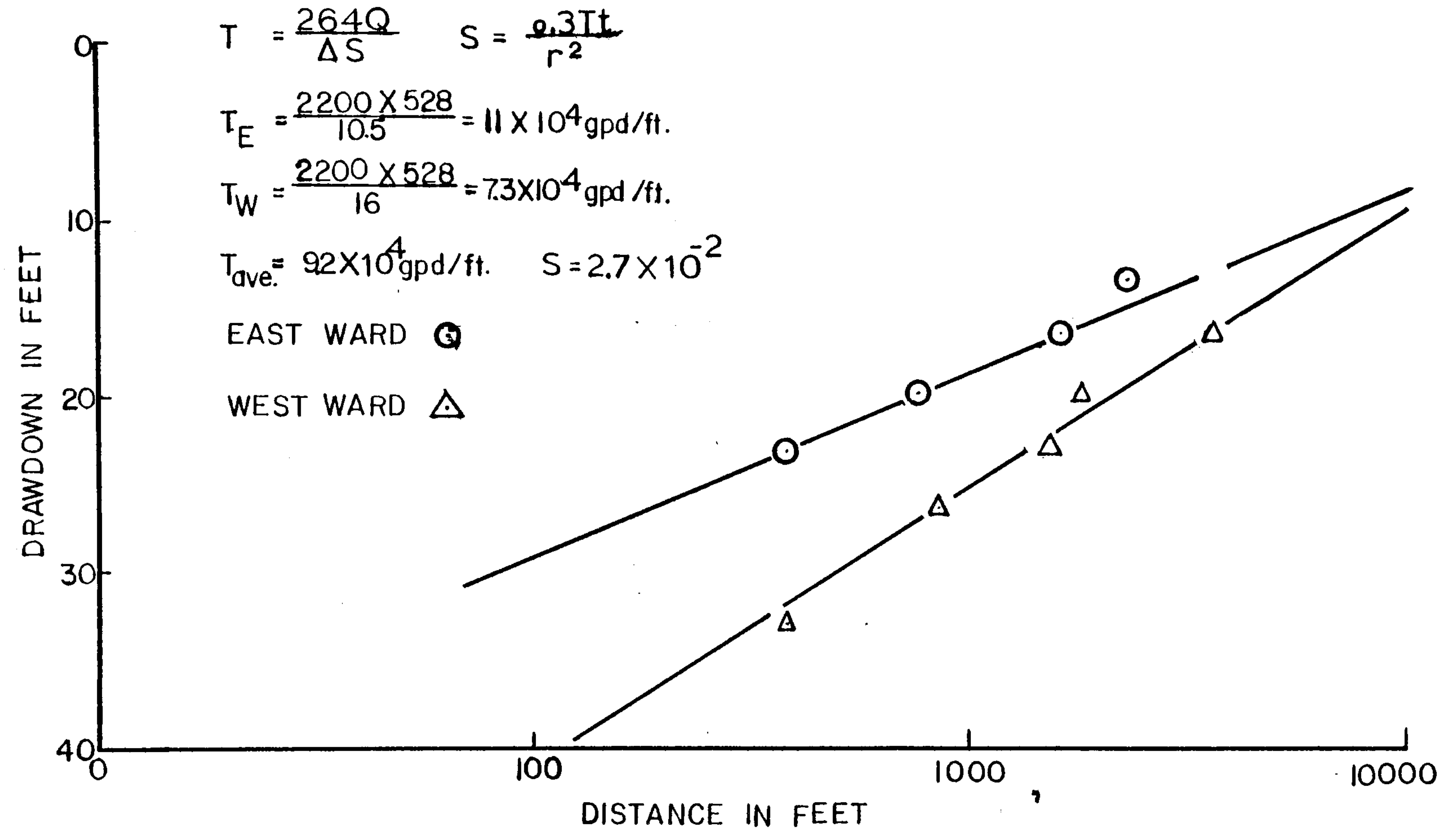

Figure 12. Distance Drawdown Graph of Riyadh Well Field.

Table 4. Chemical Analyses of Water from Wadi Nisah Pumping Area, 1975. -- After Abu-Butain (1974) and Biokat (1975).

Well No.	E.C. (micro/cm)	T.D.S.	pH	Cations			Anions				
				Ca	Mg	Na	HCO_3	Cl	NO_3	SO_4	F
P.1	550	456	7.4	68	21.9	27.4	182.4	87	13.2	86	0.5
P.2	490	427	7.2	64	18.3	28.1	178.1	57	15.4	66	0.4
P.3	480	410	7.8	56	20.7	25.3	187.9	43	13.2	66	0.4
P.4	490	410	7.4	64	19.5	18.4	185.4	39	13.2	70	0.4
P.5	530	404	7.6	52	22.0	23.0	186.7	51	17.6	51	0.5
P.6	570	454	7.6	68	25.6	20.7	197.6	60	13.2	69	0.4
P.8	515	435	7.7	60	19.5	29.9	192.6	43	15.4	74	0.5
P.9*	515	409	7.6	62	21.9	15.4	174.5	43	4.4	88	0.0
P.10	520	451	7.6	64	22.0	29.9	190.3	50	8.8	85	0.4
P.11	490	422	7.6	62	19.5	25.3	183.6	43	11.0	78	0.4

*1974 data.

dissolved solids increased in a downward direction, showing that the recharge of the aquifer takes place mainly in the upper part of the Wadi Nisah graben. The total salinity of the water samples ranged from 300 to 840 ppm. The principal cations are Ca, Mg, and Na. Bicarbonate, sulfate, and chloride are the important anions. The iron concentration is about 0.02. The chloride concentration ranges from 35 to 60. The hardness ($CaCO_3$) is generally less than 100 ppm and decreases as the depth decreases. The pH ranges from 7.3 to 8.4, which indicates that the water should not cause corrosion problems. The fluoride content ranges from 0.3 to 0.5, which is below the permissible limit. The average water temperature is approximately 79°F.

As mentioned previously, in overall chemical quality, the water is good; however, contamination may take place in the lower part of the Wadi Nisah graben due to use of fertilizers in agriculture and septic tanks in the villages.

CHAPTER 3

REGIONAL CLIMATE AND HYDROLOGY

General

Saudi Arabia's climate is mainly continental and sub-tropical. The northern and southern regions of the country are influenced, respectively, by the Mediterranean depressions and their associated cold fronts, and by the southwest monsoon. The prevalent air mass over Saudi Arabia is continental and tropical throughout the year. From October to May, the prevalent air masses are the continental polar air, which develops over central Asia, the Maritime polar air, which develops over the Atlantic Ocean and moves eastward over Europe, and the Mediterranean and continental tropical air, which build up over the Sahara desert. From June to September, the dominant air masses are the thermal low pressure tropical air which covers the area from northwestern India to North Africa, and the Maritime tropical air mass which develops over the Indian Ocean and the Arabian Sea (Al-Blehed, 1975).

The general climatic features of the Wadi Nisah study area are hot, dry summers, mild winters, and low precipitation. Meteorological data are not available for the study area; the nearest data sources being the meteorological stations at Riyadh (latitude 24°39', longitude 46°43', elevation 1850 ft) and Al-Kharj (latitude 24°10', longitude 47°24', elevation 1410 ft). The data for the Riyadh and Al-Kharj stations have been collected since 1964 and 1966, respectively.

Air Temperature

The air temperature ranges from a low of 28°F in the winter months to over 115°F in the summer. The mean annual temperature is 75-77°F. The mean temperature in January is 54-57°F, while in July it is 91°F. Table 5 shows the mean monthly and annual air temperatures as recorded by the Riyadh and Al-Kharj stations. The maximum and minimum air temperatures for Riyadh only are shown in Table 6; the Al-Kharj record showed almost identical readings.

Wind

A northwesterly wind prevails through the year. North winds are more frequent during the summer than during the remainder of the year. The mean monthly wind speed for Riyadh is 3.2 miles per hour, while for Al-Kharj the average is 1.0 mile per hour. High velocity winds usually occur during the month of July, as can be seen in the chart for mean monthly wind speeds (Table 7).

Evaporation

As the study area is characterized by hot, dry air, evaporation losses from water surfaces are high. The mean monthly evaporation rate from a class A evaporation pan is 9.1-10.1 inches, as recorded by the two nearest stations (Riyadh and Al-Kharj). The total annual evaporation rate is 108.6-121.2 inches for Riyadh and Al-Kharj. The evaporation rate at Al-Kharj is higher than that at Riyadh, which corresponds to the higher temperature. The maximum evaporation rate takes place during the month of July and the minimum in December. Table 8 shows the total monthly evaporation rates in inches.

Table 5. Mean Monthly and Annual Air Temperature (°F).

Month	Riyadh	Al-Kharj
J	56.7	54.3
F	60.6	58.5
M	69.1	68.0
A	75.9	76.7
M	86.2	85.5
J	90.0	89.2
J	91.6	91.6
A	91.4	91.0
S	86.4	85.8
O	81.8	76.5
N	70.7	65.8
D	61.3	57.4
Annual	76.8	75.0

Table 6. Maximum and Minimum Air Temperature for Riyadh (°F).

Month	Maximum	Minimum
J	83.3	30.3
F	89.6	32.0
M	96.3	43.3
A	103.6	48.3
M	112.3	61.2
J	114.1	63.7
J	114.6	66.4
A	114.6	66.3
S	110.3	59.2
O	102.9	48.9
N	94.3	40.2
D	84.9	28.5
Annual	101.7	49.0

Table 7. Mean Monthly Wind Speed (Miles per Hour).

Month	Riyadh	Al-Kharj
J	3.38	1.20
F	3.41	1.20
M	3.75	1.30
A	3.91	0.95
M	3.66	0.91
J	3.54	1.24
J	4.50	1.41
A	3.23	0.89
S	2.78	0.85
O	2.32	0.52
N	2.26	0.89
D	2.74	1.04
Annual	3.25	1.03

Table 8. Class A Pan Evaporation.

Month	Riyadh	Al-Kharj
J	3.8	4.5
F	5.1	5.6
M	8.1	8.5
A	9.3	9.7
M	12.2	13.7
J	14.1	15.4
J	14.9	16.3
A	13.8	15.4
S	11.0	12.3
O	8.0	9.2
N	4.8	5.7
D	3.5	4.4
Annual	9.1	10.1
Total	108.6	120.7

Relative Humidity

The humidity in the Riyadh and Al-Kharj areas varies annually from a low of 18% in July to 52% in January. The mean annual relative humidity for Riyadh is 37% and 40% for Al-Kharj. The mean monthly values from November to April are higher as compared with the remainder of the year, which corresponds directly to the increased rainfall. Table 9 shows the mean monthly relative humidity for these two areas.

Precipitation

The Wadi Nisah area experiences Mediterranean winter precipitation resulting from a frontal system that usually travels eastward along the Mediterranean sea from the Atlantic Ocean and then moves inland. The rainfall is cyclonic in nature and its distribution is irregular. The average duration of a rain shower on any given day would not likely exceed four hours; however, the presence of a low pressure system over the area would influence this estimate (Al-Blehed, 1975). The mean annual precipitation at Riyadh and Al-Kharj is 2.4 and 3.4 inches, respectively, and falls mainly during the period from December through April (Table 10). Precipitation very seldom falls between June and October. The maximum annual precipitation at Riyadh was 8.5 inches (1964) and the minimum was 1.1 inches (1966). The maximum daily recorded precipitation was 1.5 and 1.6 inches for Riyadh and Al-Kharj, respectively.

Statistical analysis of the Riyadh precipitation records was made so that the findings could be used as a basis for rainfall simulation. The objectives of the simulations were to predict future rainfall

Table 9. Mean Monthly Relative Humidity (Percent).

Month	Riyadh	Al-Kharj
J	52	52
F	45	47
M	38	45
A	38	40
M	30	28
J	21	17
J	20	18
A	20	20
S	21	22
O	29	29
N	44	43
D	50	48
Annual	34	34

Table 10. Mean Monthly Precipitation (Inches).

Month	Riyadh	Al-Kharj
J	0.72	0.51
F	0.28	0.66
M	0.57	0.67
A	0.96	0.66
M	0.29	0.06
J	0.00	0.00
J	0.00	0.00
A	0.00	0.00
S	0.00	0.00
O	0.00	0.00
N	0.13	0.04
D	0.42	0.18
Annual	3.37	2.43

distribution in the study area so that the recharge to the Biyadh aquifer could be estimated, and also so the data generation procedure could be used to extend the records of other precipitation stations which only have limited data.

The simulation technique is a statistical process using the Monte Carlo method, which refers to a process by which data are produced synthetically by some form of random number generation. To describe the random process, rainfall probability models were used which are event-based and are characterized by at least two random variables and their distributions. These random variables are the number of events per unit of time, the rainfall depth per event, and the inter-arrival time between events. An event is defined as consecutive days of rainfall in which at least 0.04 inches (1 mm) of rain, as measured by a rain gauge, occurred each day. An analysis showed that the mean number of events per season (six months, from December to May) is 5 and the frequency is assumed to fit a Poisson distribution.

The mean rainfall depth per event is 0.46 inches and the mean inter-arrival time between events is 23 days. The frequencies of both of the above distributions fit gamma distributions (Figures 13-16). Statistical parameters (mean and variance) were then calculated for the precipitation data, and parameters for the probability models were estimated by the method of moments from the precipitation statistics. Monte Carlo techniques were used to simulate 100 years of rainfall data. The generated rainfall data were later used as an input for runoff infiltration simulation for a period of 100 years.

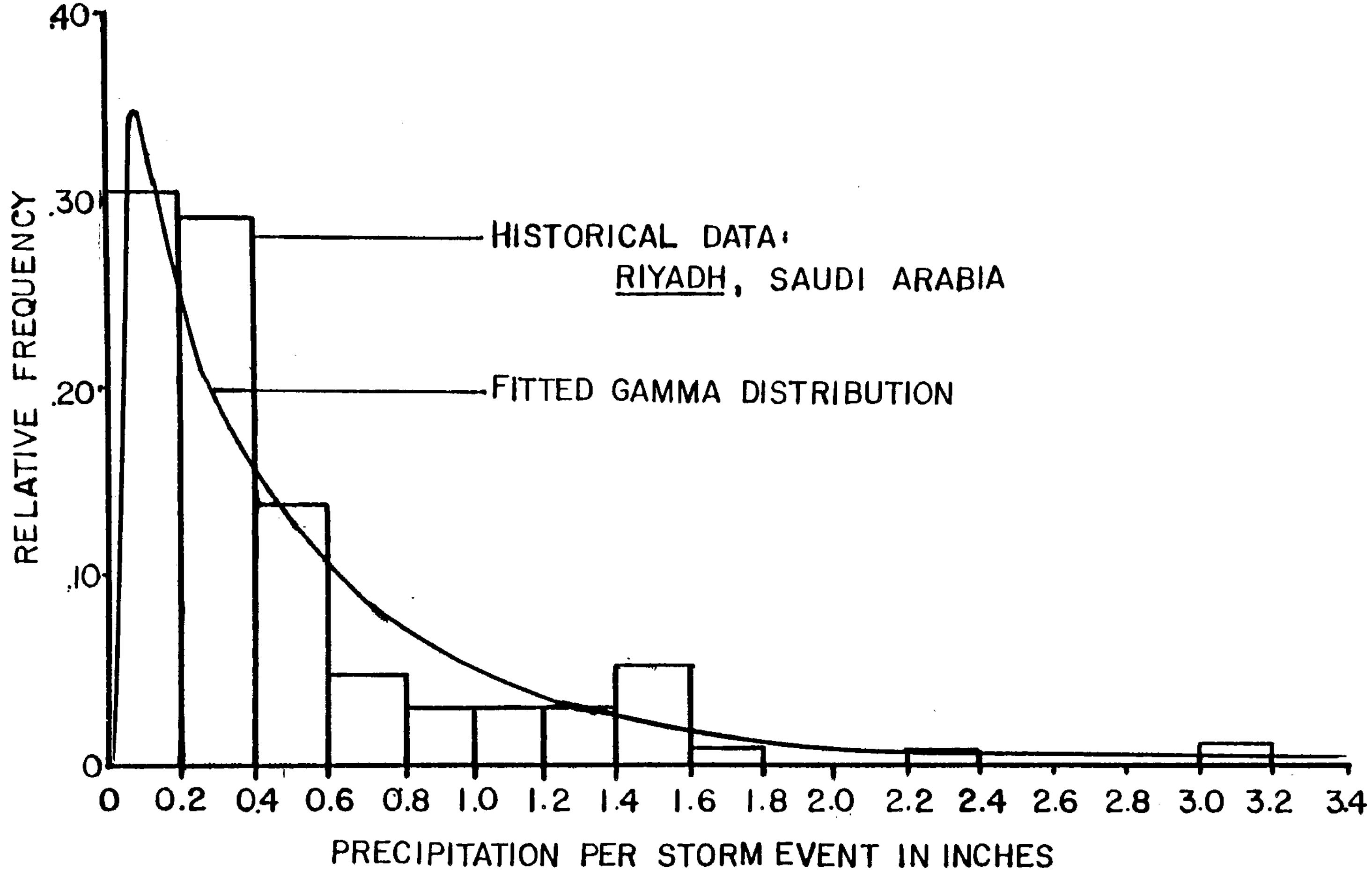

Figure 13. Histogram of Storm Precipitation and Fitted Gamma Distribution.

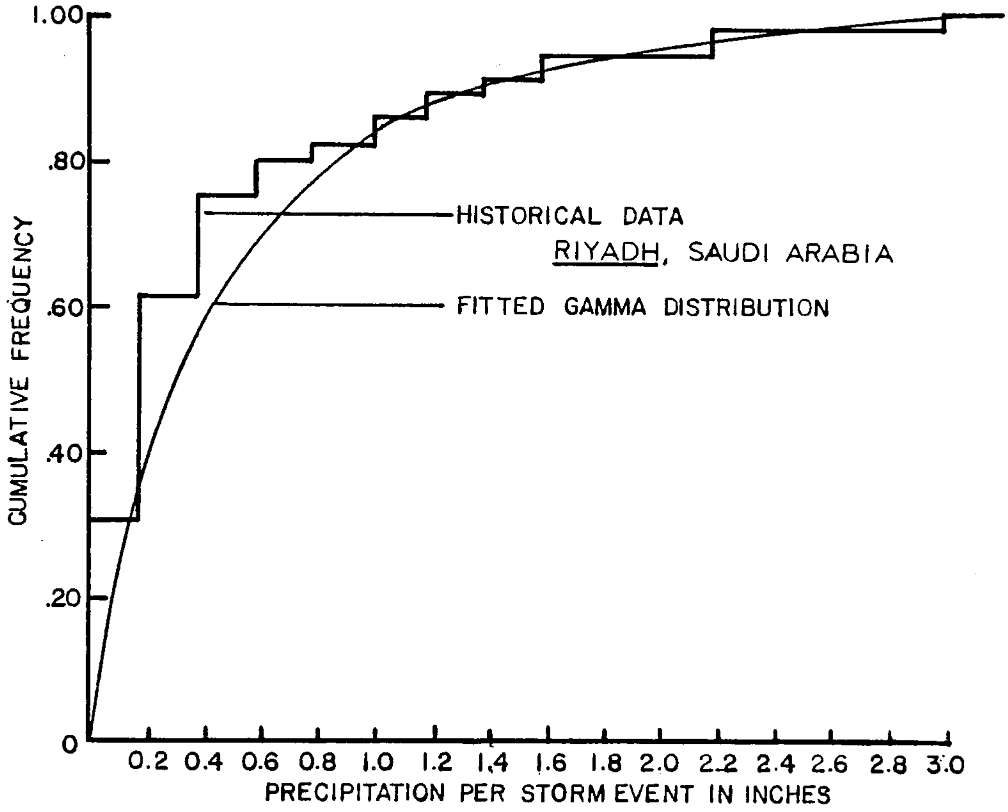

Figure 14. Probability Distribution of Storm Precipitation Being Equal to or Less than a Specific Amount.

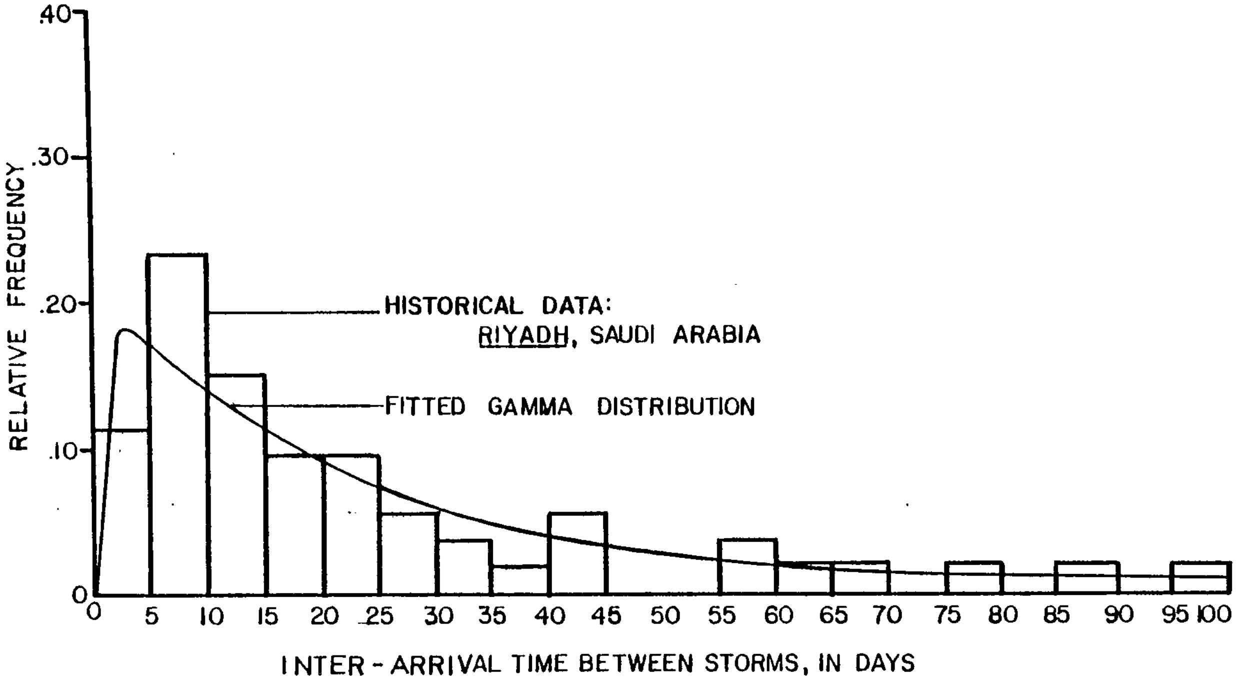

Figure 15. Histogram of Inter-Arrival Time between Storms and Fitted Gamma Distribution.

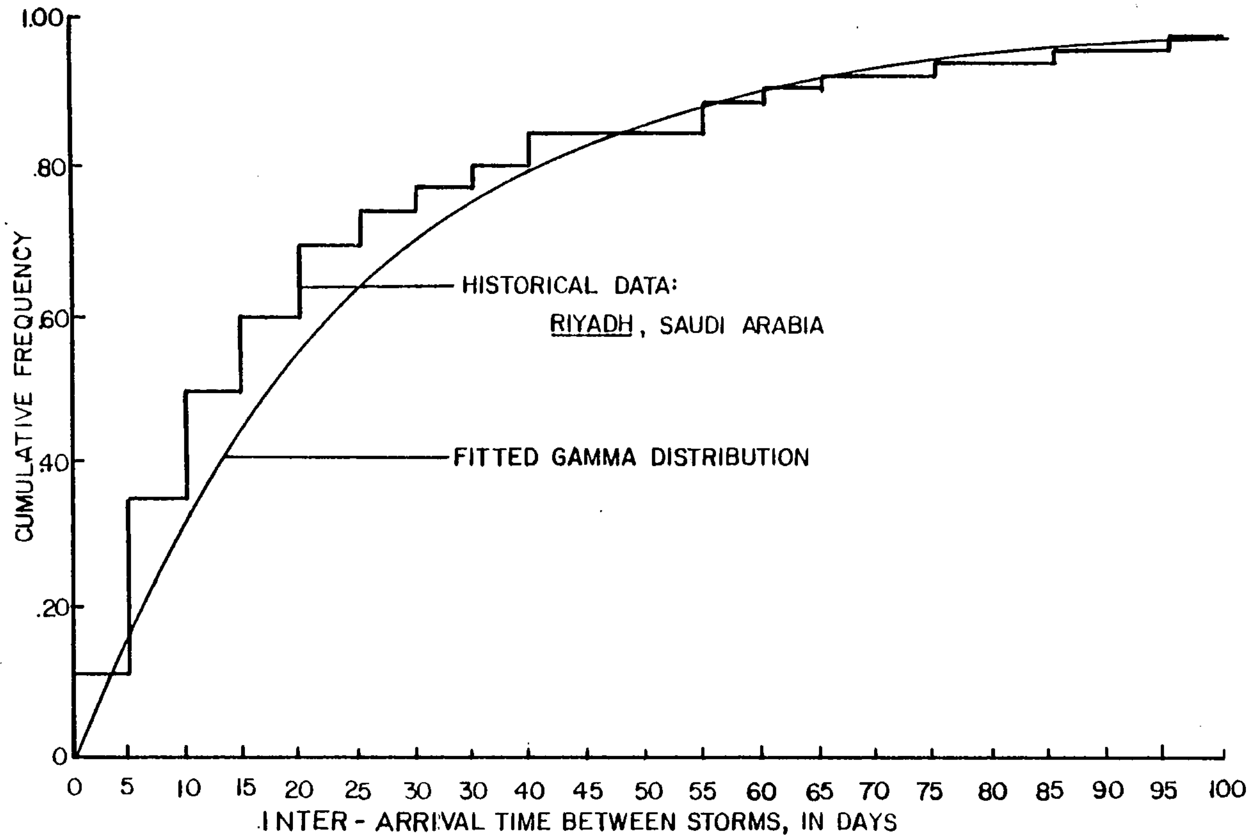

Figure 16. Probability Distribution of Inter-Arrival Time between Storms Being Equal to or Less than a Giver Number of Days.

Hydrology

Surface Water

Since there are no perennial streams in the study area, flood flow constitutes the only source of surface water. Flood flow data are not available for the study area itself as a gauging station has not, as yet, been established. Based on flood flow studies (Sogreah, 1968) of adjacent basins with similar hydrological conditions, it was concluded that flood flow in Wadi Nisah will be irregular and only heavy rain of sufficiently long duration (which represents about 60% of the average annual rainfall) generates flow large over the entire length of the Wadi Nisah area. In addition, numerous small floods are estimated to be frequent in the upper and middle parts of the catchment basin as well as in the small side wadis which flow into the graben. The annual surface runoff of the entire catchment was approximated at 8,100 acre-feet (Sogreah, 1968).

The above discussion indicates that the flood flow volume and timing which are needed to estimate the recharge to the aquifer are not accurately known and the reported values are merely from speculation. In attempting to arrive at estimated flood flow values for Wadi Nisah, one of several runoff estimation methods can be used. These methods are as follows: the Soil Conservation Service method (SCS), the rational method, and the Colorado State University method. The SCS method was chosen for this study since it is based on basin characteristics. The SCS method was originally developed for humid regions but it has recently been applied in arid regions. The general runoff estimation equation for surface flow for a given storm is shown below:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S}$$

where

Q = storm runoff in inches,

P = storm rainfall in inches, and

S = a watershed factor which reflects the infiltration characteristics of the study area and is expressed in inches.

The watershed factor (S) is related to a watershed index shown by the following equation:

$$W(CN) = \frac{1000}{10 + S}$$

The watershed index, sometimes designated a runoff curve number, depends on the general hydrological conditions of the study area, soil type, type of land use or cover, and the antecedent moisture at the start of the storm period which generated runoff.

Most of the rocks that outcrop in the Wadi Nisah area are limestone which can be classified as soil type C. The characteristics of soil type C are shallow soil having below-average infiltration when thoroughly wetted. Row crops with poor rotation were assumed to be the main form of land use in the area (Chow, 1964) and runoff curve number values of 75, 85, and 95 were selected to respectively represent the antecedent moisture conditions one, two, and three (see Appendix A). The runoff volumes were estimated for the study area at a point approximately 200 feet from the upper boundary of the Biyadh aquifer so that recharge to the aquifer could be estimated. Also, based on studies of runoff infiltration characteristics in the adjacent Wadi Hanifah basin, an infiltration coefficient of 0.65 of the runoff volume was assumed for Wadi Nisah.

A Fortran computer program was written by Mr. Heckman of the Department of Watershed Management of The University of Arizona which implemented the SCS method for simulating runoff using generated rainfall data (Appendix A). In addition, the program also estimated infiltration volumes based on an assumed runoff-infiltration coefficient of 0.65. An analysis of the simulated runoff volume showed that the mean flow was 8630 acre-feet and this cumulative distribution is shown in Figure 17.

Recharge

All ground water recharge is derived by infiltration of precipitated water. Wolfart (1960) estimated that 3.5 inches of the annual precipitation falls on the Wadi Nisah catchment (an area of 565 square miles) and 0.18 inches, or 5 percent, of the rainfall (6.5 thousand acre-feet) contributed to the recharge of the ground water table. The rest was lost by evaporation and overland flow runoff. His estimate was based on studies which were conducted in the adjacent Wadi Hanifah which has similar morphological conditions to Wadi Nisah. Wadi Awsat, which joins Wadi Nisah, could also contribute an estimated amount of 1200 acre-feet of water to recharge, but it is believed that a ground water divide exists at the confluence of the two wadis which indicates that part of the recharge flow went to Wadi Buaija and the rest went to Wadi Nisah. Sogreah's (1968) estimate of surface runoff for Wadi Nisah was 8100

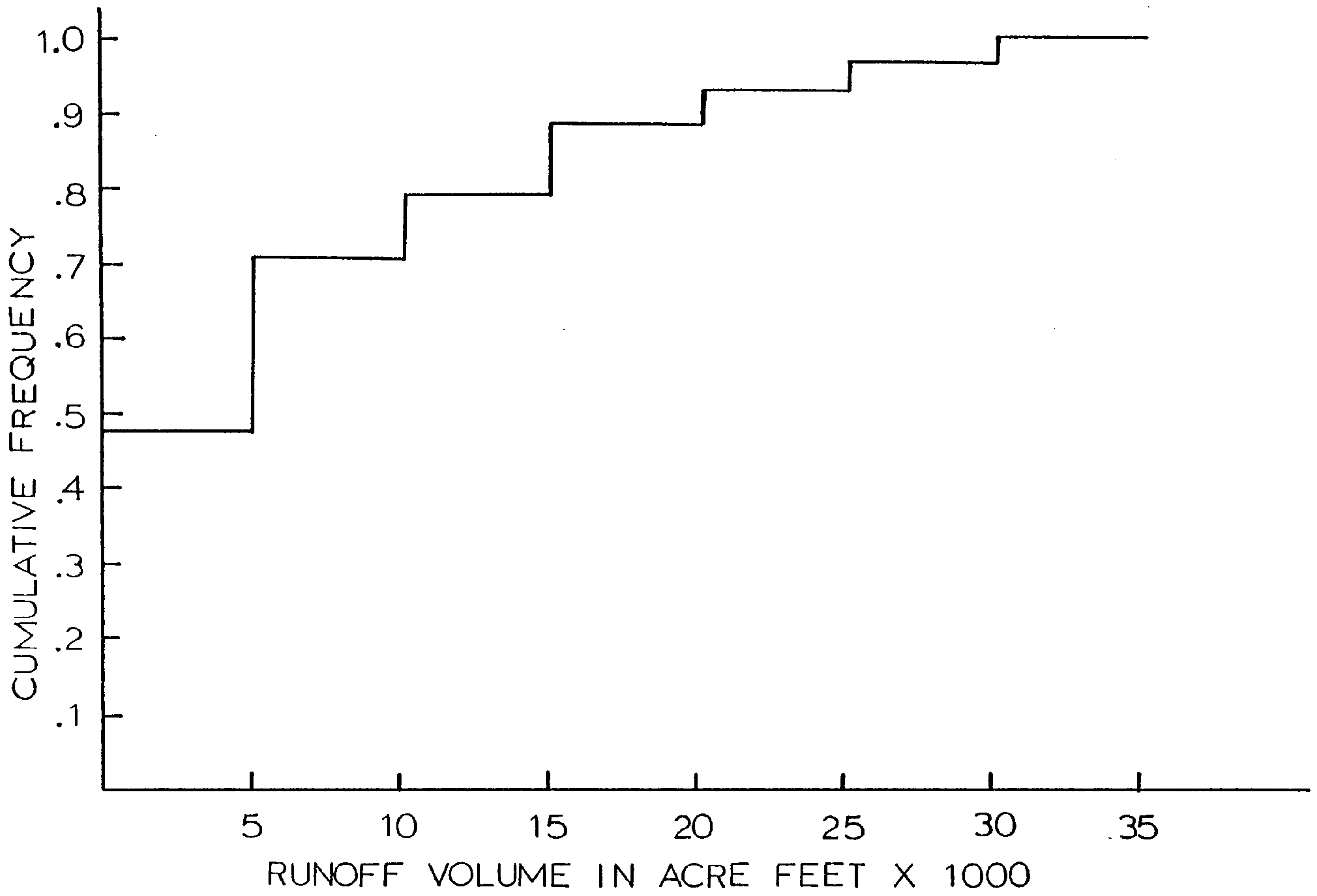

Figure 17. Cumulative Frequencies of Simulated Flood Flow.

acre-feet annually and taking into consideration the type of material making up the wadi bed where most of the recharge takes place, the average recharge was approximated at about 2400 acre-feet per year. However, the infiltration value produced from a 100-year runoff simulation indicates that the mean annual value would be about 5800 acre-feet per year which was assumed by the author to represent the future recharge value to the Biyadh sandstone aquifer in Wadi Nisah. Figure 18 shows the cumulative distribution of the 100-year simulated infiltration.

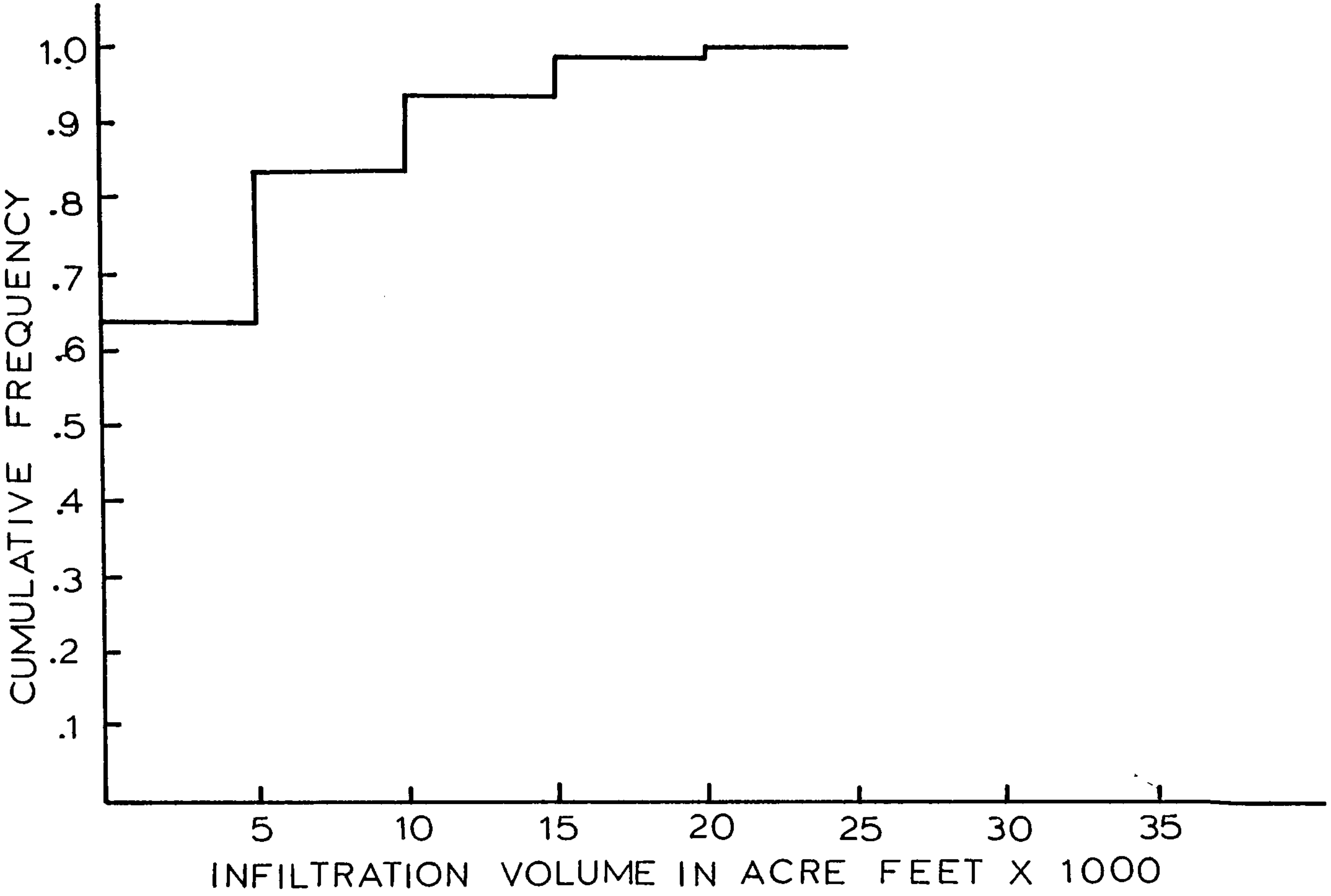

Figure 18. Cumulative Frequencies of Simulated Recharge.

CHAPTER 4

GROUND WATER MODEL

General

The requirements for the development of new water resources and the extension and optimum use of existing developed resources have led many investigators in the past two decades to develop many physical and mathematical models to simulate ground water flow and distribution. Physical models are simple, constructed scale models which resemble the actual ground water system, such as sand boxes, Hele-Shaw, and electrical conductivity and resistance capacity models. All of these models have limited capabilities and limited use as a basin-wide modeling device for ground water aquifers due to their complicated construction and operation procedures and lack of versatility. Mathematical models are currently being used more frequently to simulate aquifer systems. A mathematical model may be defined as a mathematical expression that describes the geohydrologic system and study. Mathematical modeling of an aquifer system consists of working with the appropriate differential equations and their associated boundary conditions, collection of the physical parameters of the system, and acquisition of historical status of the system for verification of the adequacy of the model. Manipulation of these models was originally done with electric analog techniques. The development of digital computers with large memories and higher computational speeds have led many investigators to adopt the models for digital treatment. The hybrid computer combines some of the more useful features of both the digital and analog computers, which also come into limited use in some applications (Vemuri and Karplus, 1969).

The most common ground water equation considered for aquifer simulation with the aid of a digital computer is the partial differential equation governing the non-steady state, two-dimensional flow of ground water in an elastic, isotropic, and non-homogeneous porous medium. The partial differential equation can be stated as follows:

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right) = S\frac{\partial h}{\partial t} + W(x,y,t) \qquad [1]$$

where

T = aquifer transmissivity (L^2/T),

S = aquifer storage coefficient (dimensionless),

W = source and sink term (L/T),

h = total hydraulic head (L),

t = time, and

x,y = rectangular coordinates.

In water table aquifers, transmissivity is a function of head. The flow equation may be expressed as:

$$\frac{\partial}{\partial x}\left(K_x b\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y b\frac{\partial h}{\partial y}\right) = S_y\frac{\partial h}{\partial t} + W(x,y,t) \qquad [2]$$

where

K = hydraulic conductivity (L/T),

S_y = aquifer specific yield (dimensionless), and

b = aquifer saturated thickness (L).

There is no general solution to the above equations; however, by use of a finite difference approach, a numerical solution can be obtained. The finite difference approach involves replacing the continuous aquifer parameters with an equivalent set of discrete elements (Prickett and Lonnquist, 1971) when a digital computer is used, both space and time variables being treated as discrete parameters. Then the equation governing the flow of ground water is written in finite differential form.

There are two methods that can be used for deriving the finite difference equation of the ground water flow. The first method is from a physical standpoint and involves the use of Darcy's law and the principle of conservation of mass. The second method involves a mathematical treatment where the finite difference approximations are substituted for the derivatives of equation [1]. Both methods lead to the same finite difference approximation form (Prickett, 1975).

In order to apply finite difference techniques to an aquifer system, it is necessary to define the extent of the aquifer or the portion of the aquifer that is to be modeled. Then the region to be analyzed is subdivided into grids having either uniform or variable spacing. The intersections of the grid lines are called nodes and are referenced as a column (i) and row (j) coordinate system, colinear with x and y directions, respectively (Prickett, 1975). The rectilinear finite difference grids are not mandatory, however, as Tyson and Weber (1964) used a grid made up of various sizes of polygons where the nodes could be placed at the location of pumpage and exactly along irregular boundaries.

Most of the existing ground water models use the finite difference approach in solving the equations of ground water flow. Some of these models were developed by Prickett and Lonnquist (1971); Tyson and Weber (1964); Gates (1972); and Knowless, Claborn, and Wells (1971), who used a revised version of the Tyson and Weber model. The basic differences between these models are the finite difference forms used in approximating the differentials of equation [1] and the methods of solving them. The Tyson-Weber model uses the backward difference-implicit procedure (Prickett, 1975), while the revised Tyson-Weber model (Knowless et al., 1971) uses the Crank-Nicholson procedure known as central difference. Both of these models use Gauss-Seidel iteration procedure to solve the system of equations and the Theissen polygons method to discretize the aquifer properties. The ground water model developed by Prickett and Lonnquist (1971) and the Tucson basin model (Gates, 1972) use the alternating direct implicit method which is used to reduce large sets of simultaneous equations down to a number of small sets. These models use uniform grid spacing.

The Prickett model has been chosen for this study rather than the other models because of the advantages listed below:

1. Simplicity and availability of program listing.
2. Easier problem set-up and revision.
3. Ability to solve a wide range of problems.
4. Rectangular node system requires less computer memory and provides faster program execution.

The Ground Water Model

The ground water model used was developed by Prickett and Lonnquist (1971). The aquifer simulation program was coded in Fortran IV and was written for use on an IBM 360 system, but was modified so it could be used on a CDC 6400 system. The model is based on solving the partial differential equation (equation [1]) of ground water flow, written in finite difference form, for every node of the digital model. This is shown as follows:

$$\frac{T_{i-1,j,2}(h_{i-1,j} - h_{i,j})}{\Delta x^2} + \frac{T_{i,j,2}(h_{i+1,j} - h_{i,j})}{\Delta x^2} + \frac{T_{i,j,1}(h_{i,j+1} - h_{i,j})}{\Delta y^2}$$

$$+ \frac{T_{i,j-1,1}(h_{i,j-1} - h_{i,j})}{\Delta y^2}$$

$$= \frac{S_{i,j}(h_{i,j} - h\phi_{i,j})}{\Delta t} + \frac{Q_{i,j}}{\Delta x \Delta y} \qquad [3]$$

where

$h\phi_{i,j}$ = calculated head at node (1,j) at the end of the previous time increment,

$\Delta x \Delta y$ = grid spacing,

$T_{i,j,1}$ = aquifer transmissivity between node (i,j) and node (i,j+1) toward the east,

$T_{i,j,2}$ = aquifer transmissivity between node (i,j) and node (i+1) toward the south, and

$h_{i,j}$ = calculated head at the end of time increment measured from an arbitrary reference elevation at node (i,j).

Equation [3] is rearranged in order to make it easier to solve node equations by columns and rows. It was assumed that the finite difference grid is made up of squares and that $\Delta y = \Delta x$. Then the equation is written in two forms, one for solving the node equation by columns, and the other for solving the equation by rows. The column equation is shown below (Prickett, 1975):

$$- T_{i,j-1,1}h_{i,j-1} + h_{i,j}(T_{i-1,j,2} + T_{i,j,2} + T_{i,j,1} + T_{i,j-1,1} + S_{i,j}\frac{\Delta x^2}{\Delta t}) - T_{i,j}h_{i,j+1} = (S_{i,j}\frac{\Delta x^2}{\Delta t})\,h\phi_{i,j} - Q_{i,j} + T_{i-1,j,2}h_{i-1,j} + T_{i,j,2}h_{i+1,j} \qquad [4]$$

Equation [4] is of the form:

$$AA_j h_{i,j-1} + BB_j h_{i,j} + CC_j h_{i,j+1} = DD_j$$

where

$$AA_j = T_{i,j-1,1}$$

$$BB_j = T_{i-1,j,2} + T_{i,j,2} + T_{i,j,1} + T_{i,j-1,1} + S_{i,j}\frac{\Delta x^2}{\Delta t}$$

$$CC_j = - T_{i,j,1}$$

$$DD_j = (S_{i,j}\frac{\Delta x^2}{\Delta t})\,h\phi_{i,j} - Q_{i,j} + T_{i-1,j,2}h_{i-1,j} + T_{i,j,2}h_{i+1,j}.$$

Similar equations can be written for rows calculation.

To account for water table conditions where gravity drainage of the interstices decreases the saturated aquifer thickness and transmissivity, the model could be modified by assigning the values of hydraulic conductivity and the aquifer bottom elevation to each node of the model. The transmissivity of the aquifer can be approximated for each column and row with the following formulas:

$$T_{i,j,2} = PERM_{i,j,2} \sqrt{(h_{i,j} - Bot_{i,j})(h_{i+1,j} - Bot_{i+1,j})}$$

$$T_{i,j,1} = PERM_{i,j,1} \sqrt{(h_{i,j} - Bot_{i,j})(h_{i,j+1} - Bot_{i,j+1})}$$

where

PERM = hydraulic conductivity of the aquifer, and

Bot = aquifer bottom elevation.

Appendix B shows the simulation program and the computer job set-up.

The alternating direction implicit method is used to solve the set of simultaneous node equations for every column and row by applying the B and G arrays, which are shown below:

$$G_N = (DD_N - AA_N G_{N-1})/(BB_N - AA_N B_{N-1})$$

$$B_N = CC_N/(BB_N - AA_N B_{N-1})$$

N = i for row calculations and j for column calculations

Wadi Nisah Aquifer Set-Up

The dimension of the Wadi Nisah aquifer was approximated from a geological map developed by Sogreah (1968) (see Figure 4). A square finite difference grid was superimposed over the map of the aquifer. The grid divided the aquifer into 697 nodal areas of 0.11 square mile each, spaced 0.33 mile apart (1750 feet). The boundary of the aquifer is approximated in a stepwise fashion, as shown in Figure 19.

Input Data

The required input consists of water level, bottom elevation of the aquifer, coefficient of storage, transmissivity, hydraulic conductivities, pumpage, and recharge data. The water level data were obtained

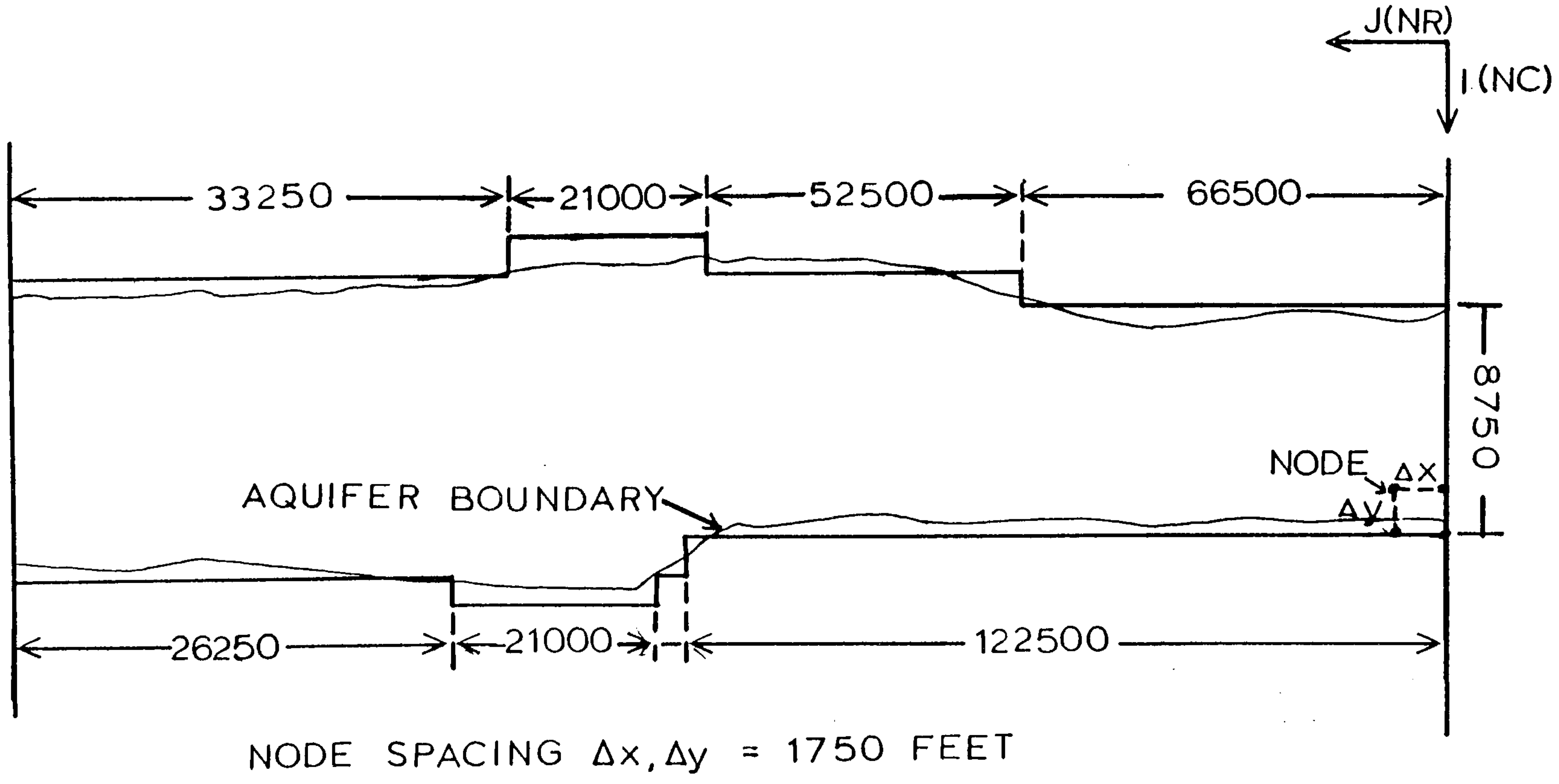

Figure 19. Discretized Map of Wadi Nisah Aquifer.

from regular monitoring of five production wells and nine observation wells scattered along the length of the wadi. The water level contour map prepared by Sogreah (1968) was used as the initial water level for model calibration; however, it was not too reliable since it depended on only a few observation wells.

The proposed model required that the head at each node be referred to a reference datum. The water level elevation at the first two nodes of the model was assumed to represent the reference datum and the drop of the water level throughout the length of the aquifer is represented by a negative value. The 1968 water level data were used as the initial heads to the model.

The aquifer bottom elevations were referenced to the water level datum. The bottom elevations for each node of the model were estimated from the longitudinal section of Wadi Nisah that was established from the geophysical survey (Sogreah, 1968).

The storage coefficient of 0.16, arrived at by Sogreah (1968) and used for the model, is assumed to be constant over the whole Wadi Nisah aquifer because few data are available to show its variability. The storage coefficient of the aquifer is equivalent to a specific yield because the aquifer in the graben is unconfined. Aquifer tests in the study area commonly indicate that the storage coefficient is less than 0.014, probably because the tests were performed for short pumping periods, on the order of hours, and delayed drainage causes the water level decline to be too great and, thus, the calculated coefficients to be too small.

Aquifer tests in the study area indicate great variation in transmissivity values ranging from 26,000 gpd/ft to more than 300,000 gpd/ft, which can be attributed to the heterogeneity of the Biyadh aquifer materials, and also the fact that the tests were of short duration. Since the available transmissivity values are few and thus cannot give a representative value for the aquifer, some limitations will result in the modeling of the aquifer.

The transmissivity value of 92,000 gpd/ft arrived at by the author will be used as an initial value for the model, since it is based on the flow net analysis of the Riyadh well field, which could be considered a long-term pumping test. It should be noted that the model assigns a south and east direction transmissivity value to each node but due to lack of data the transmissivity for each node will be assumed constant for all directions in this study.

The pumpage data used in the model consists of values for the Riyadh well field and values for the agricultural pumpage in the lower part of the aquifer. The average pumpage value for a period of six years at the Riyadh well fields (Abu-Butain, 1974) was used in the model. As far as agricultural pumpage is concerned, no pumping data nor well locations are available. The 1968 pumpage estimates made by Sogreah are available and some projections, based on those values, were used in the model.

Recharge data are not available, since hydrological studies were not made for the Wadi Nisah area. Sogreah (1968) estimated the recharge based on observations of adjacent basins, which amounts to an average value of 2400 acre-feet/year.

In order to simplify the model, the average annual recharge is assumed to be uniform during the period of simulation (1968-1974). The recharge was estimated to be taking place in the upper portion of the aquifer close to the present Riyadh well field where the present cone of depression will induce higher ground water flow into the pumping center. The mean annual recharge of 5800 acre-feet obtained from the rainfall-runoff simulation seems to give better calibration results for the model, which could indicate that the aquifer recharge value is higher than the estimated value. Recharge values along the aquifer boundaries were assumed to be negligible, and transmissivity values of zero were assigned for these boundaries.

Calibration of the Model

After initial estimates were made for the aquifer parameters, initial conditions and input at each of the 692 nodes, the model was calibrated by adjusting these estimates until the model reproduced historical water level changes for the period from 1968 to 1974. The six-year calibration period was chosen because it was the longest period where input data to the model were available. In calibrating the model, only measured values of water level elevations at the observation sites were used. It should be emphasized that the observation wells are poorly distributed over the aquifer, and water levels reproduced in areas where no wells exist are likely to be unreliable. Adjustment of the other parameters of the model during the calibration procedure was done, to a large extent, by trial and error. The parameters that were adjusted were the transmissivity, recharge, and agricultural pumpage in the downstream portion of the aquifer. The initial transmissivity was 92,000 gpd/ft, but this figure had to be decreased in the central area of the aquifer and increased again in the downstream area of the aquifer in order to give water level values close to the historical records.

A comparison is made between the historical and simulated water change for the period from 1968 to 1974 (Table 11), which shows a fair

Table 11. Comparison between Actual and Simulated Water Level.

Well No.	Water Level Change 1968-1974	Simulated Model Values
X.12	-13.1	-18.5
WP_1	-13.2	-19.2
WP_2	-19.7	-24.1
WP_3	-27.6	-29.1
WP_4	-20.3	-25.6
WP_5	-22.1	-28.9
N.1	- 7.4	- 9.2
N.2	-13.2	-16.2
N.3	-16.5	-20.1
N.4	-10.9	-13.1
N.5	- 5.0	+ 3.2
N.6	- 5.6	- 3.5
N.7	- 6.0	-10.2

match for the upper and lower part of the aquifer, excepting the middle part of the aquifer where a steep water level gradient exists. It seems that the model is not capable of simulating steep water table gradients, as is the case in the middle portion of the Wadi Nisah aquifer which produced water level values far from the historical data. The adjusted input model data which achieved a reasonable calibration are shown in Appendix B.

Based on the limited available hydrological data, it is believed that the proposed model can be used to evaluate the future ground water situation in the Wadi Nisah area; however, additional hydrogeological data are needed for refinement of the model so better calibration of the model can be achieved.

CHAPTER 5

QUANTITATIVE ASSESSMENT

The hydrogeological study of the Wadi Nisah graben indicates that the Biyadh sandstone aquifer could be further developed. There are currently eleven wells, as mentioned previously, in the area which form two pumping centers located 2.1 miles apart. The five wells of the older pumping center at the confluence of wadis Nisah and Awsat were studied and the water level decline was predicted for the next 30 years (from 1974), assuming that there would be no increase or decrease of the original pumping rate of 450 gpm per well throughout this period. Also, an analysis of the six newer wells representing the second pumping center was made, assuming that the wells followed a linear path through the middle of the aquifer and were spaced 2300 feet apart (El-Khatib, 1974). The pumpage for these wells was assumed to be 500 gpm for each.

After careful studies, it was concluded that a new well field could be developed in the middle of lower Wadi Nisah. The proposed well field should be about 9 miles downstream from the existing Riyadh water supply well field, and should be located between the existing observation wells N5 and N7 (Figure 7, geophysical survey point WN17 and WN24). The site was selected based on the geophysical profile which indicated that the location would have an average thickness ranging from 790 to 935 feet. The available aquifer thickness indicates that pumping can be achieved without significantly dewatering the aquifer. This new well field could have ten wells of 16-inch diameter.

In order to make water decline prediction analyses for the existing and proposed well fields, the Theis equation was used to calculate the predicted drawdown independently of the computer model since, by using the average transmissivity values arrived at by pumping tests (92,000 gpd), the results would show a more conservative estimate than the higher transmissivity values obtained through the model (180,000 gpd). Also, the analysis was made for the actual location of the proposed wells, since the well locations would not coincide with the nodal points of the model. To evaluate the effects of the boundaries (two parallel graben walls), the image well theory was used (Ferris et al., 1962). The presence of this boundary leads to an increase in the drawdown at the well field. As the cones of depression spread, they are reflected from the boundaries. Although, with sufficient, precise data, the iteration of the model would account for this effect, independent calculations for a series of image wells was used to evaluate the total drawdown at any point. These calculations indicated that more than five image wells would be needed on each side of the graben in order to have a small signigicant effect, but for practical reasons only three image wells on each side were used.

In order to decide on the rate of pumpage per well, a distance drawdown analysis using the Theis non-equilibrium equation was made (Figure 20) so that a reasonable drawdown value could be selected. Also, analysis of the step drawdown tests made for the newly completed wells

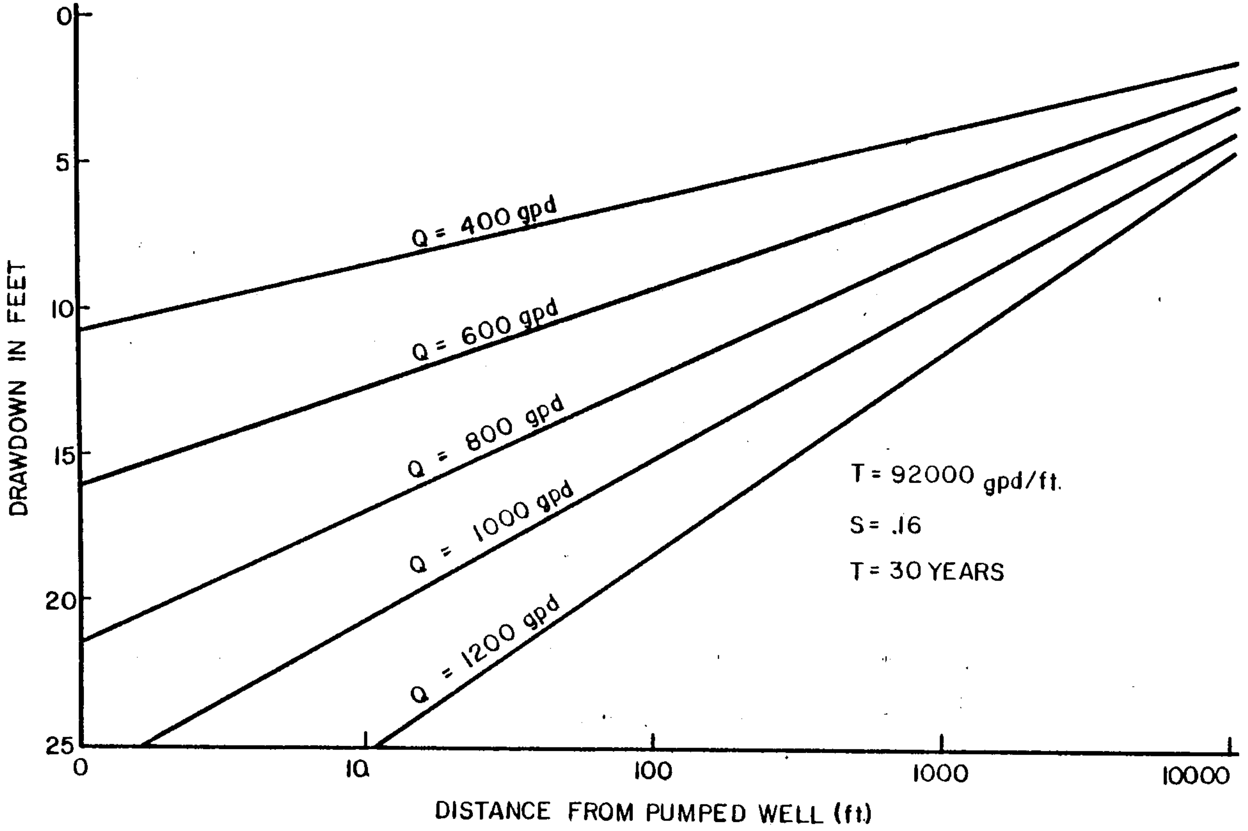

Figure 20. Distance Drawdown Graph for Wadi Nisah Biyadh Aquifer.

R69, 70, and 71 show that if the well is properly constructed and being pumped at a rate of 1000 gpm per well, the well loss will be small compared to the total drawdown (Appendix C). From the above analysis, it was decided that the pumping rate for each of the proposed wells should be 1000 gpm.

In deciding on optimal well spacing, the image well theory was used to calculate steady-state drawdown by pumping a production well at 1000 gpm. The analysis indicates that the well spacing should be 4000 ft for the drawdown to be minimal. The wells should be located in a straight line approximately one-third of the way into the graben where the thickness is greatest (Figure 21).

Drawdown contour maps were drawn for the proposed well field, based on calculations by the analytical method, assuming that recharge during the flood season does not reach that part of the aquifer; however, the recharge was considered in the analysis of the pumping effect on the Riyadh well field. Also, drawdown contour maps were drawn for the old and new Riyadh water supply well fiels, as shown in Figures 22 and 23, respectively. The maximum drawdown at the center of the proposed well field is 200 feet (Figure 24). It seems that 200 feet of drawdown in 30 years is an acceptable amount. The thirty-year drawdown will be 25 percent of the available saturated aquifer thickness.

Well Design Criteria

In order to determine certain criteria in designing a well, a sieve analysis must be done at different levels of the aquifer. Figure 25 shows grain size distribution of observation well N6 which is

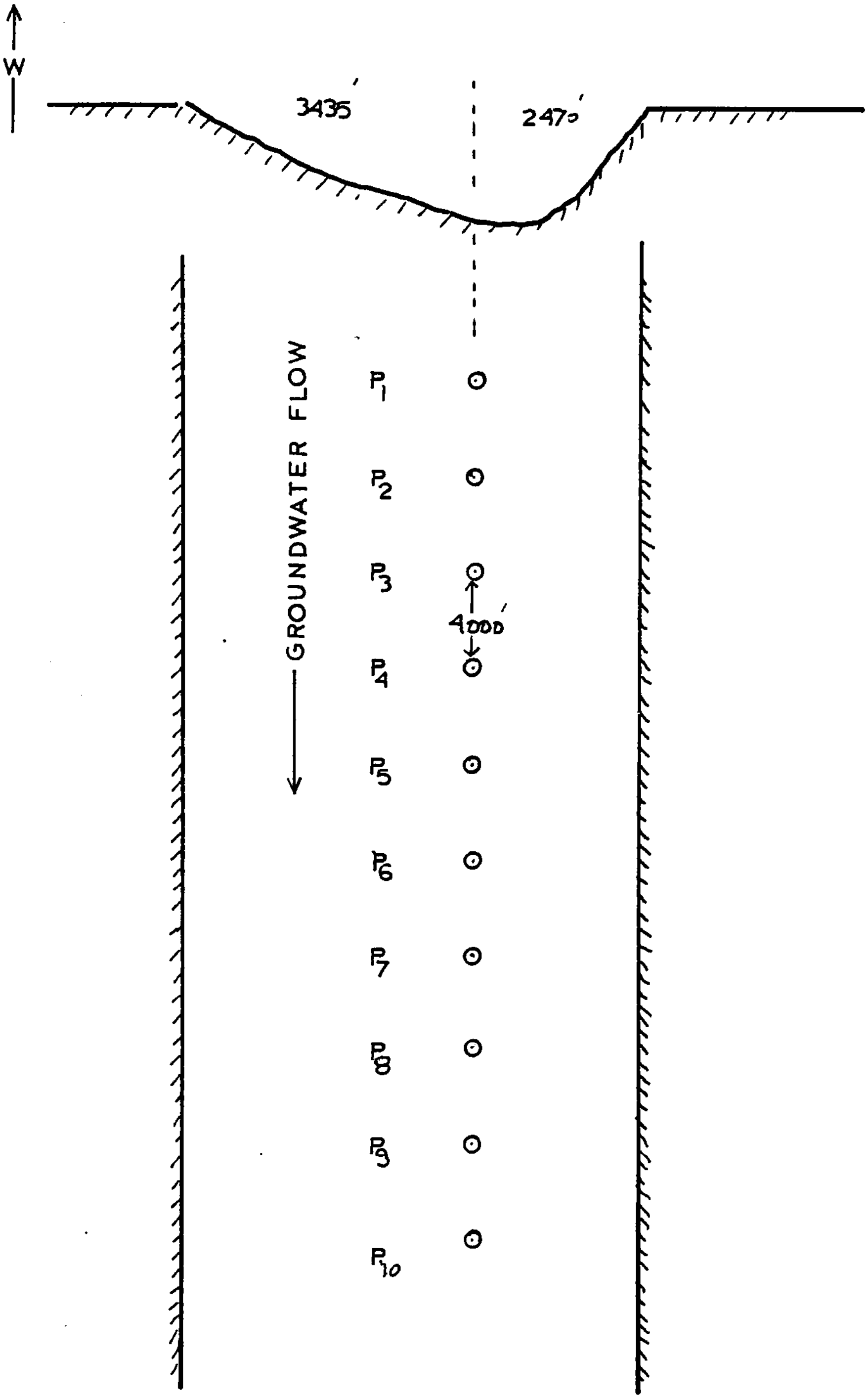

Figure 21. Schematic Diagram of the Proposed Well Field.

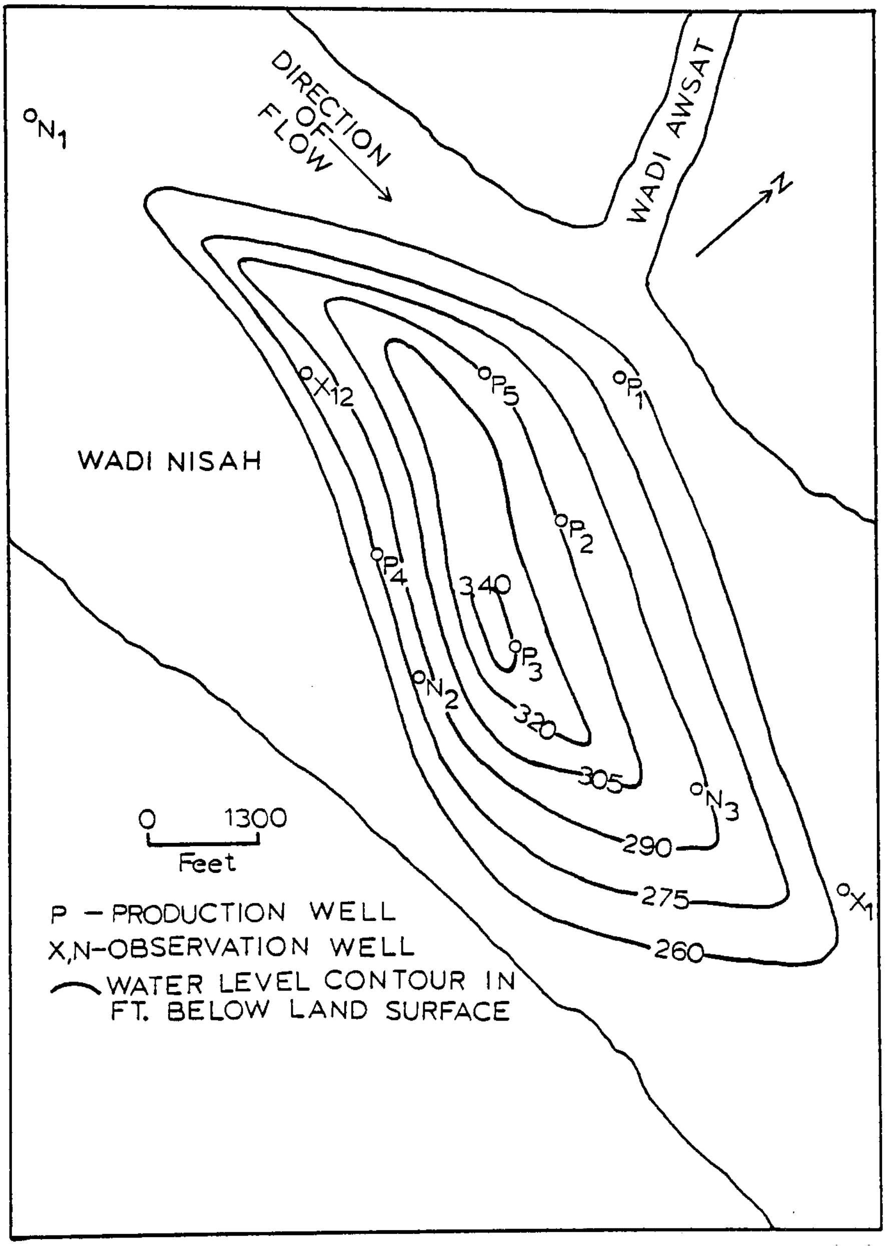

Figure 22. Predicted 30-Year Water Level Decline for Riyadh Well Field.

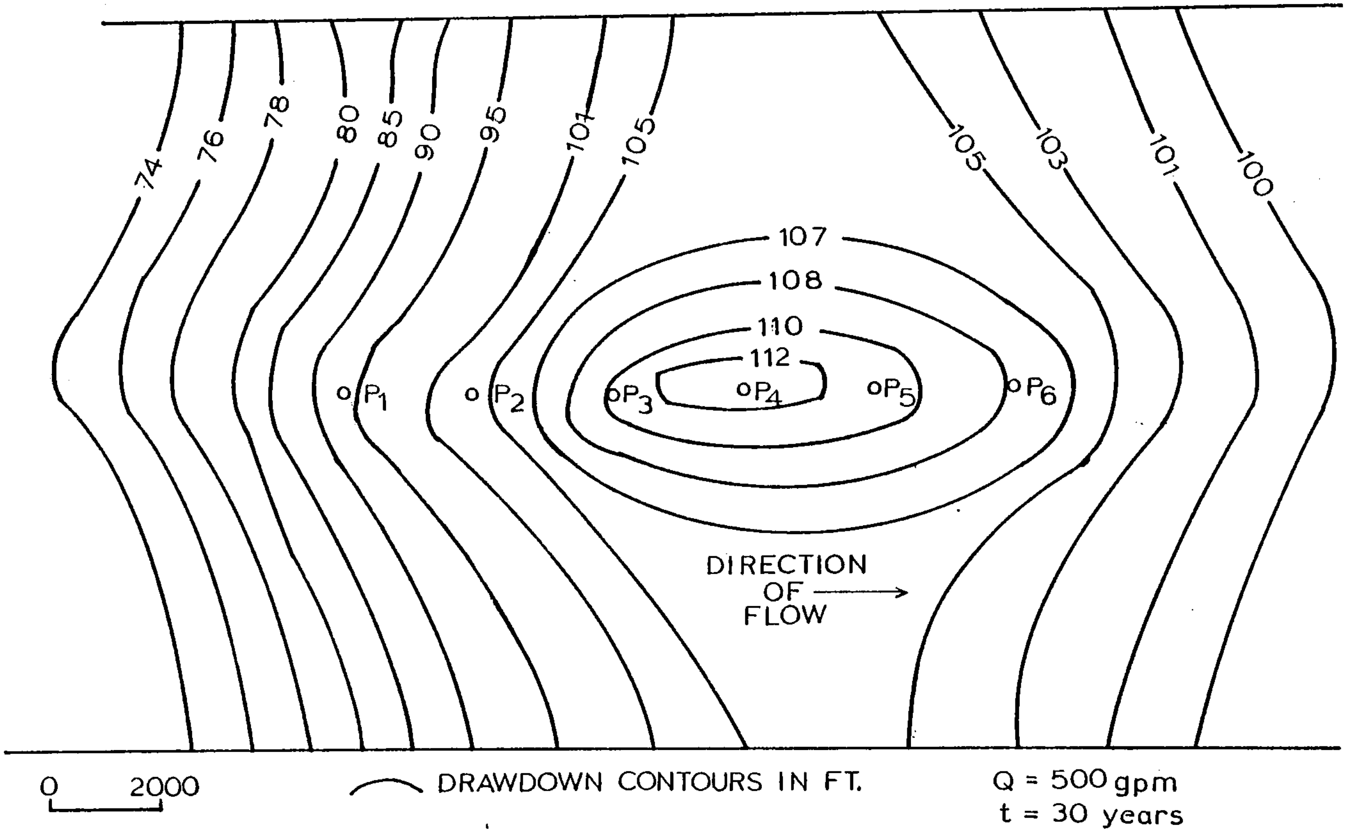

Figure 23. Predicted 30-Year Drawdown at the Six New Wells.

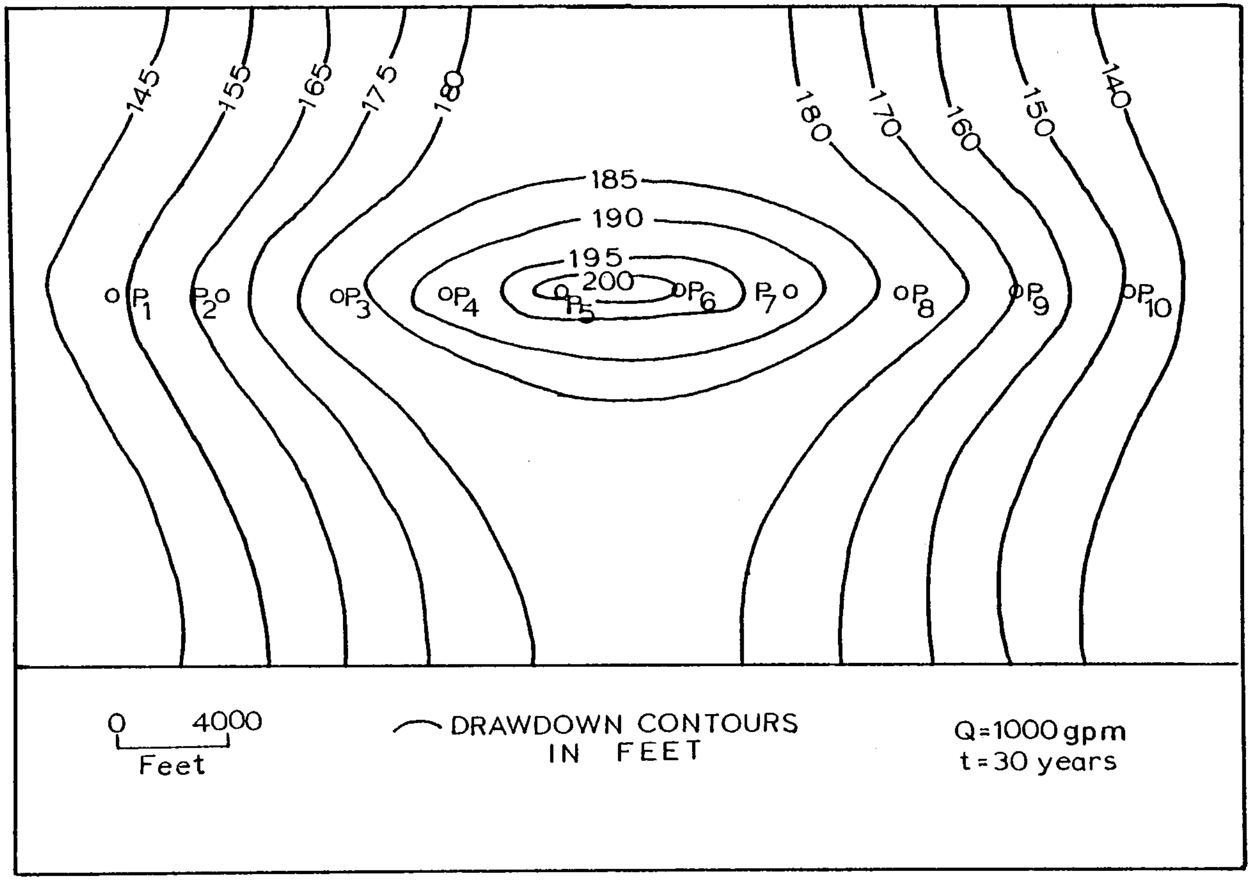

Figure 24. Predicted 30-Year Drawdown at the Proposed Well Field.

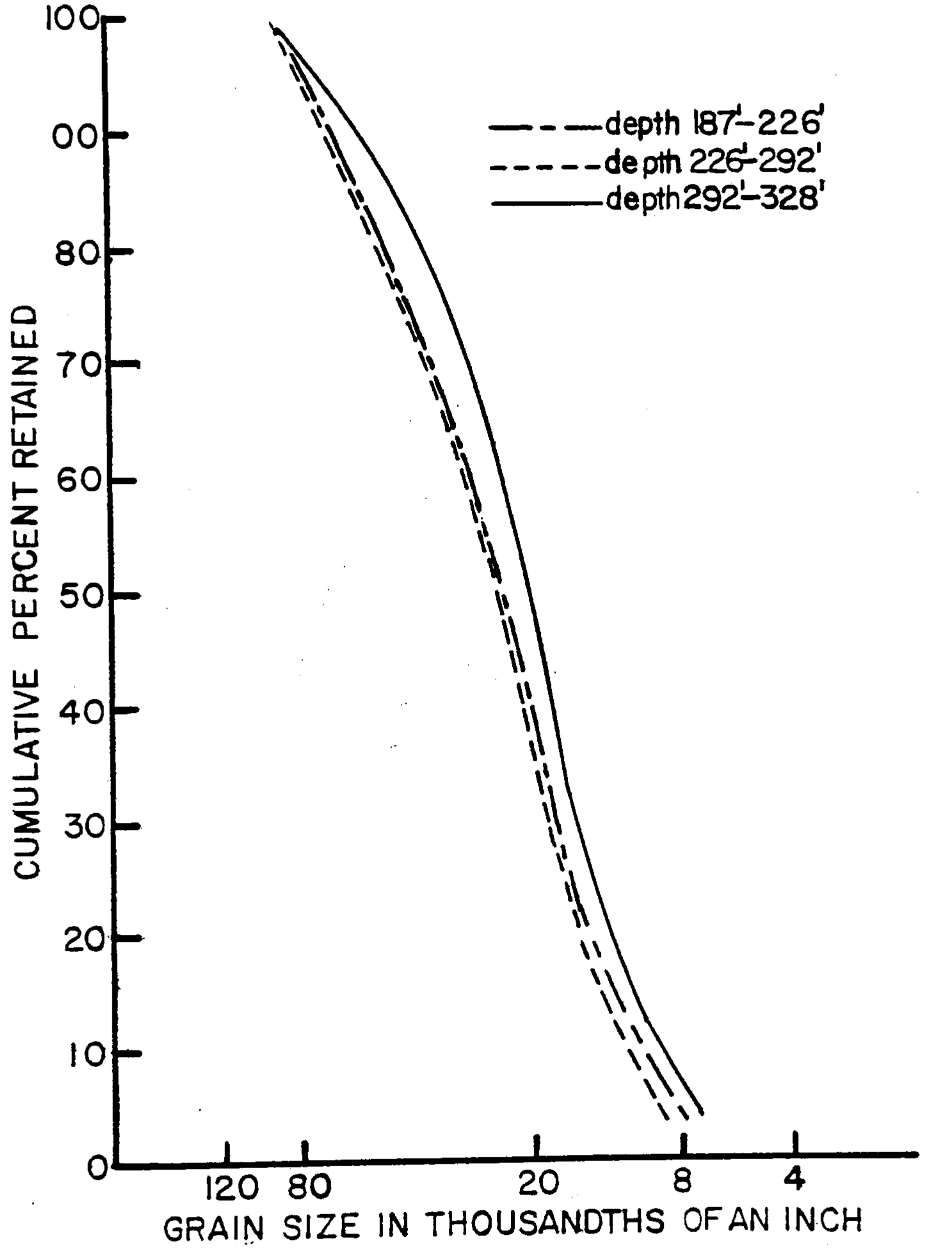

Figure 25. Grain Size Distribution Curve. -- After Wolfart (1960).

at the edge of the proposed well field. The curve indicates that the formation consists of uniform material and the "S" shape of the curve may indicate high porosity. The D50 size for the aquifer was 20/1000. Therefore, the slot size should be 0.02 inches.

Casing perforations should be machine cut using a milling machine. Each cut should be vertical, 3 inches long, and 0.02 inches in width. The distance between slots in a row around the casing should be 6 inches, and alternating rows should be staggered. For a 20-inch casing, they will provide 17.2 square inches of open area per running foot. The length of the perforated casing should be about one-third of the available saturated thickness.

The wells should extend to a depth of 965 to 1100 feet from the land surface, depending on the thickness of the aquifer. The screen should be placed in the lower portion of the aquifer. The lift needed to extract the water is 480 feet.

Well Construction

The wells should be cable-tool drilled so that more complete information about the aquifer can be obtained. The formation should be sampled at ten-foot intervals so that a lithological log can be established.

Each well should be developed by surge plungers. The water is surged to loosen the fines from the soil material and the water carries the fines upward so they can be removed. This method is particularly good for sand and gravel aquifers. A solid surge plunger should be used.

The wells should be grouted to prevent contamination by placing cement grout in the annular space outside the casing. Concrete surface covers should be put around the production wells, sloping away from the wells. The final step should be to thoroughly disinfect the wells using a chlorine solution.

CHAPTER 6

PRACTICAL APPLICATION OF THE PROPOSED MODEL

The ground water model (Prickett, 1975) used in this research could be successfully applied to many of the existing aquifers in Saudi Arabia. The model is simple enough that anyone with basic knowledge of computer programming can use it. Various modifications can be added to the main program that allow incorporating additional features, such as special types of printouts, variable pumping rate, leaky artesian conditions, induced infiltration, ground water evapotranspiration, and conversion from water table to artesian conditions.

Areas in which the model can be used immediately are Wadi Khalis, which is one of the main aquifers which supplies the City of Jeddah, Wadi Nijran, and Wadi Bisah, where future agricultural development is planned.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

The study shows that the Prickett ground water model can be applied to the development and management of the Wadi Nisah aquifer. It is shown that the Biyadh aquifer in Wadi Nisah is suitable for large-scale development of ground water and is capable of satisfying part of the water demand for the City of Riyadh. The chemical quality of the water is good, with the total dissolved solids around 500 ppm. This water can also be used to dilute the water pumped from deeper aquifers. The proposed well field site that was chosen will cause the least interference with the other wells in the area; however, the cost of pipes for the transport of the water from each well will be high, as the wells are spaced 4000 feet apart. It should be noted that the effect of agricultural pumpage in the lower part of the study area was not considered as no data were available. Pumping the ten wells, which will produce 1000 gpm each, will cause the water level to drop by 200 feet in a period of 30 years, which is a reasonable drawdown as compared to the available aquifer's saturated thickness.

Initially, one production well and two observation wells should be built. The production well should be located in the center of the well field and the observation wells should be located 500 and 1500 feet from the production well. An aquifer test should then be carried out, preferably lasting longer than a week, in order to determine the aquifer's characteristics and the effect of the boundary condition. At least twelve observation wells from 4 to 6 inches in diameter should be drilled throughout the Wadi Nisah area in order to monitor future water level declines, evaluate the negative boundary conditions, and assess the recharge volume to the aquifer. Two of these observation wells should be located upstream of the existing well field, three within the well field, two between the present well field and the proposed field, four within the proposed well field, and one downstream, close to the Al-Kharj plain. All of these wells, in addition to the existing wells, should be equipped with automatic water level recorders. The data monitoring program should include the agricultural area in the eastern portion of the Wadi Nisah aquifer in order to evaluate its effect on the aquifer system. The collected water level data should be reassessed annually in order to evaluate the effects of the pumping regime on the aquifer. Adjustment of the pumping rates should be made whenever necessary in order to manage the ground water aquifer in the best possible way.

Three automatic rain gauges should be installed in the catchment area of Wadi Nisah and flood flow should be gauged, which will assist in evaluating the recharge to the ground water aquifer. Originally, a long-term recharge estimate was made for the Wadi Nisah aquifer based on the 100-year simulated rainfall-runoff values, which showed a mean annual recharge value of 5800 acre-feet, which was assumed to represent the future recharge value of the aquifer; however, a special detailed study concerning annual recharge should be carried out in order to arrive at an accurate value and explore the possibilities of artificial recharge through the construction of small check dams. The simulation technique should be used to estimate the recharge for any area in Saudi Arabia with limited data.

In the future, the Government of Saudi Arabia should prohibit any unauthorized drilling in the Wadi Nisah area so that the ground water will be reserved for the City of Riyadh. The few farms located downstream should either be bought by the government so that pumping can be controlled, or pumping limits should be imposed. With the aid of a ground water model, the government will be able to put more emphasis on the management of the available water resources and will be able to devise water plans for optimum water use.

APPENDIX A

COMPUTER PROGRAM FOR RAINFALL AND RUNOFF SIMULATION

In the course of the investigation a computer program was used for rainfall and runoff simulation, which consists of a main program and two subroutines. The program simulated rainfall data based on the statistical parameters of the historical precipitation data. The program is written in such a way that it sums up the amount of rainfall received five days prior to any runoff and selects the antecedent moisture condition according to the following:

Rain in previous 5 days (cm)	Antecedent moisture condition	S (mm)
less than 13	I	84.0
1.3 - 2.6	II	34.5
more than 2.6	III	13.5

Based on the antecedent moisture, a watershed factor (S) is calculated which is used in calculating the runoff volume. A runoff-infiltration coefficient of 0.65 was calculated so the infiltrated flood volume could be calculated. It should be noted that the metric system was used during the simulation procedures and the results were then converted to the English system in the text. The program listing is shown on the following pages.

```
      PROGRAM LHHJR
      COMMON T(120),RAIN(100),P5(6)
      PAUSE
      READ(5,1000)(RAIN(I),I=1,100)
 1000 FORMAT(E12.6)
      PAUSE
      READ(5,1000)(T(I),I=1,120)
      WRITE(2,1010)
 1010 FORMAT(//,"ENTER CONSTANT K, SEED, AND YEARS TO RUN ...")
      READ(1,*)K,L,LY
      WRITE (2,1020)
 1020 FORMAT(///,"YR  DAY PPT AMC    Q  M'3       INF M'3",//)
      DO 300 ISEA=1,LY
      CALL ZER
      DO 11 I=1,120
      IN=I
      IF(T(I)-R) 11,12,12
   11 CONTINUE
   12 IDAY=-IN
   13 IF(IDAY) 14,14,17
   14 CALL RNDOM(K,L,R)
      DO 15 I=1,120
      IN=I
      IF(T(I)-R) 15,16,16
   15 CONTINUE
   16 IDAY=IDAY+IN
      GO TO 13
   17 IF(IDAY-130) 25,25,200
   25 CALL RNDOM(K,L,R)
      DO 30 I=1,100
      M=I
      IF(RAIN(I)-R) 30,35,35
   30 CONTINUE
   35 PPT=FLOAT(M)
      SUM5=0.0
      FILT=0.0
      Q=0.0
      IF(IN-5) 45,45,40
   40 CALL ZER
      GO TO 90
   45 IF(IN-1) 65,65,50
   50 JJ=IN-1
      DO 60 I=1,JJ
      DO 55 J=1,5
      P5(J)=P5(J+1)
   55 CONTINUE
   60 CONTINUE
```

```
  65  DO 70 I=1,5
      SUM5=SUM5+P5(I)
      P5(I)=P5(I+1)
  70  CONTINUE
  72  IF(SUM5-13.0) 90,75,75
  75  IF(SUM5-26.0) 85,85,80
  80  S=13.462
      GO TO 92
  85  S=34.544
      GO TO 92
  90  S=34.532

      IF(PPT-0.2*S) 100,100,95
  95  Q=(((PPT-0.2*S)**2.0)/(PPT+0.S*S)*1.1E+6
      FILT=Q*0.65
 100  IP=IFIX(PPT)
      IAMC=IFIX*SUM5)
      WRITE(2,1030) ISEA,IDAY,IP,IAMC,Q,FILT
1030  FORMAT(4(I3,IX),2(E12.5,1X)
      GO TO 4
 200  WRITE(2,1040)
1040  FORMAT(//)
 300  CONTINUE
      STOP
      END
      SUBROUTINE RNDOM(K,L,R)
      L=L*K
      R=FLOAT(L)
      R=R/32767.0
      IF(R) 5,10,10
   5  R=-R
  10  RETURN
      END
      SUBROUTINE ZER
      COMMON FILL(220),P5(6)
      DO 10 I=1,6
      P5(I)=0.0
  10  CONTINUE
      RETURN
      END
      ENDS
```

APPENDIX B

GROUND WATER COMPUTER PROGRAM

The program listing developed by Prickett and Lonnquist (1971) was used in this study. The program was written in such a way that it would work with any consistent set of units. In this study, the gallon-day-foot system was used. A storage factor was introduced to adjust the storage coefficient so a consistent unit could be achieved. The storage factor is as follows:

$$SFi = 7.48S\ \Delta x \Delta y$$

where

SFi = storage factor for node located at node i of the model, in gallons/foot;

S = storage coefficient of the aquifer;

7.48 = number of gallons in a cubic foot of water; and

$\Delta x \Delta y$ = finite difference grid interval, in feet, for Wadi Nisah model:

$$\begin{aligned} SF_1 &= 7.48 \times 0.16 \times 1750 \times 1750 \\ &= 36 \times 10^5 \end{aligned}$$

Parameter, default, and node cards have to be prepared according to the format statement in the program. The default value card provided data for simulating a number of columns by a number of row aquifer systems. For Wadi Nisah, the aquifer properties were discretized by 10 columns and 99 rows. The parameter value card provided data (step, delta, and error) on the desired simulation time and allowable error during the calculation of head. For the Wadi Nisah model, the delta value was 120 days and the number of steps was 18, to achieve a simulation for a period of 6 years. The allowable error was set at 50 feet since the available hydrological data were not reliable.

A node card deck was prepared for each node of the Wadi Nisah aquifer. The node cards contained the location of the node, the transmissivity of the node in the eastern and southern directions (which was assumed to be the same for both directions), the storage factor, the water level elevation from a reference datum, the discharge or recharge, the hydraulic conductivity, and the bottom elevation of the aquifer at that node measured from a reference datum. The program list and sample of input are shown on the following pages.

```
PROGRAM UADM (INPUT,OUTPUT,TAPE1=INPUT,TAPE2=OUTPUT)

UNIVERSITY OF ARIZONA DRAWDOWN MODEL--A MODIFIED VERSION OF THE
ILLINOIS STATE WATER SURVEYS FINITE DIFFERENCE AQUIFER SIMULATION MODEL
REFERENCE--ILLINOIS STATE WATER SURVEY BULLETIN 55
BY PRICKETT AND LONNQUIST  (1971)


DEFINITION OF VARIABLES
I-----------MODEL COLUMN NUMBER
J-----------MODEL ROW NUMBER
HO(I,J)-----HEADS AT START OF TIME INCREMENT (I,J)
H(I,J)------HEADS AT END OF TIME INCREMENT (FT)
SF1(I,J)----STORAGE FACTOR (GAL/FT)
Q(I,J)------CONSTANT WITHDRAWAL RATES (GPD)
P(I,J,2)  AQUIFER HYDRAULIC CONDICTIVITY EAST OF NODE
 -Q(I,J)   CONSTANT  RECHARGE  RATE (GPD)
T(I,J,1)----AQUIFER TRANSMISSIVITY SOUTH OF NODE (GPD/FT)
T(I,J,2)----AQUIFER TRANSMISSIVITY EAST OF NODE (GPD/FT)
AA,BB,CC,DD-COEFFICIENTS IN WATER BALANCE EQUATIONS
NSTEPS------NO. OF TIME INCREMENTS
DELTA-------TIME INCREMENTS (DAYS)
ERROR-------SUM OF HEAD CHANGES FOR ALL NODES DURING AN ITERATION (FT)
NC----------NO. OF COLUMNS IN MODEL
NR----------NO. OF ROWS IN MODEL


JOB SETUP FOR UNIVERSITY OF ARIZONA DRAWDOWN MODEL (UADM)

JOB CARD
FTN.
LGO.
789
PROGRAM DECK
789
PARAMETER CARD
  NSTEPS  COL  1-6  RIGHT JUSTIFIED  (RJ)
  DELTA COL 7-12
  ERROR COL 12-18
NODE CARDS
  I  COL 1-3 RJ
  J  COL 4-6 RJ
  T1 COL 7-12
  T2 COL 13-18
H  COL  23-26
Q  COL  27-32
SF   COL  51-56
P1   COL  63-68
 BOT  COL  75-80
P2   COL  69-74
6789


/// NOTE 1 ///  ALL SPECIFIED FIELDS OF THE PARAMETER, DEFAULT, AND
NODE CARDS MUST CONTAIN PUNCHED VALUES

/// NOTE 2 /// THE MAXIMUM DIMENSION OF THE NODAL GRID IS 50 COLUMNS BY
ANY SPECIFIED NUMBER OF ROWS
```

```
C     /// NOTE 3 /// THE PRINTOUT CONTAINS A MAXIMUM OF 25 COLUMNS PER PRINTER
C     PAGE

C     /// NOTE 4 /// THE PRINTOUT FOR COLUMNS 26 THROUGH TOTAL NUMBER OF
C     COLUMNS WILL FOLLOW THE OUTPUT OF COLUMNS 1-25

C     /// NOTE 5 /// THE PRINTOUT NODAL SPACING IS SQUARE--ALLOWING DIRECT
C     CONTOURING ON THE OUTPUT

C     /// NOTE 6 /// THE DIMENSION CARD MUST ALLOW SUFFICIENT VARIABLE STORAGE
C     AREA FOR THE GEOMETRY OF THE PROBLEM
C     THE DIMENSION IS READ (ROW,COLUMN)


      DIMENSION H(10,99),HO(10,99),
     1SF1(10,99),Q(10,99),T(10,99,2),
     2B(99),G(99),DL(10,99)
     3,PERM(10,99,2),BOT(10,99)

C     READ PARAMETER CARD AND DEFAULT VALUE CARD

      READ(1,20) NSTEPS,DELTA,ERROR,NC,NR
20    FORMAT(I6,2F6.0/2I6)

C     READ NODE CARDS

    3 READ 4  ,I,J,T(I,J,1),
     1T(I,J,2),H(I,J),Q(I,J),
     2SF1(I,J),PERM(I,J.1),PERM(I.J,2),BOT(I,J)
4     FORMAT(2I3,2F6.0,4X,1F4.0,1F6.0,18X,1F6.0,6X.3F6.0)
      IF(EOF(1))5,3

C     PRINT PUMPING RATES

5     DO6 I=1,NC
      DO6 J=1,NR
6     Q(I,J)=Q(I,J)/1000.
      IF(NC.GT.25) NNC=25
      IF(NC.LE.25) NNC=NC
      PRINT 7
7     FORMAT(1H1,*PUMPING RATES DIVIDED BY 1000*)
      PRINT 8,(I,I=1.NNC)
8     FORMAT(/,4X,25I5)
      DO 14 J=1,NR
      PRINT9, J,(Q(I,J).I=1,NNC)
9     FORMAT(// ,I3,1X,25F5.0)
14    CONTINUE
      PRINT 8,(I,I=1,NNC)
      IF(NC.LE.25) GO TO 12
      PRINI 7
      PRINT 10,(I,I=26,NC)
10    FORMAT(/,   25I5,/)
      DO 15 J=1,NR
      XJ=J
      PRINT 11,(Q(I,J),I=26,NC),XJ
11    FORMAT(// ,26F5.0)
15    CONTINUE
      PRINT 10,(I,I=26,NC)
12    DO 13 J=1,NR
      DO 13 I=1,NC
```

```
13    Q(I,J)=Q(I,J)*1000.

C     START OF SIMULATION

50    TIME=0
      DO 340 ISTEP=1,NSTEPS
      TIME=TIME+DELTA

C     PREDICT HEADS FOR NEXT TIME INCREMENT

      DO 70 I=1,NC
      DO 70 J=1,NR
      D=H(I,J)-HO(I,J)
      HO(I,J)=H(I,J)
      F=1.0
      IF(DL(I,J).EQ.0.0)GO TO 60
      IF(ISTEP.GT.2)F=D/DL(I,J)
      IF(F.GT.5)F=5.0
      IF(F.LT.0.0)F=0.0
60    DL(I,J)=D
      H(I,J)=H(I,J)+D*F
   70 IF(H(I,J).LE.BOT(I,J))H(I,J)=BOT(I,J)+0.01

C     REFINE ESTIMATES OF HEADS BY IADI METHOD

      ITER=0
80    E=0.0
      ITER=ITER+1
C     TRANMUSSUVUTY CONTROL
      DO83I=1,NC
      DO83J=1,NR
      IF(I.LT.NC)T(I,J,2)=PERM(I,J,2)*SQRT((H(I,J)-
     1BOT(I,J))*(H(I+1,J)-BOT(I+1,J)))
 83   IF(J.LT.NR)T(I,J,1)=PERM(I,J,1)*SQRT((H(I,J)-
     1BOT(I,J))*(H(I,J+1)-BOT(I,J+1)))

C     COLUMN CALCULATIONS

      DO 190 II=1,NC
      I=II
      IF(MOD(ISTEP+ITER,2).EQ.1) I=NC-I+1
      DO 170 J=1,NR

C     CALCULATE B AND G ARRAYS

      BB=SF1(I,J)/DELTA
      DD=HO(I,J)*SF1(I,J)/DELTA-Q(I,J)
      AA=0.0
      CC=0.0
      IF(J-1)90,100,90
90    AA=-T(I,J-1,1)
      BB=BB+T(I,J-1,1)
100   IF(J-NR)110,120,110
110   CC=-T(I,J,1)
      BB=BB+T(I,J,1)
120   IF(I-1)130,140,130
130   BB=BB+T(I-1,J,2)
      DD=DD+H(I-1,J)*T(I-1,J,2)
140   IF(I-NC)150,160,150
150   BB=BB+T(I,J,2)
```

```
      DD=DD+H(I+1,J)*T(I,J,2)
160   W=BB-AA*B(J-1)
      B(J)=CC/W
170   G(J)=(DD-AA*G(J-1))/W

C     RE-ESTIMATE HEADS

      E=E+ABS(H(I,NR)-G(NR))
      H(I,NR)=G(NR)
      N=NR-1
180   HA=G(N)-B(N)*H(I,N+1)
      E=E+ABS(HA-H(I,N))
      H(I,N)=HA
      N=N-1
      IF(N.GT.0)GO TO 180
      DO 190 N=1,NR
      IF(H(I,N).GT.BOT(I,N))GO TO 190
      E=E+BOT(I,N)+0.01-H(I,N)
      H(I,N)=BOT(I,N)+0.01
190   CONTINUE

C     TRANSMISSIVITY CONTROL
      DO 193 J=1,NR
      DO 193 I=1,NC
      IF(I.LT.NC)T(I,J,2)=PERM(I,J,2)*SQRT((H(I,J)-
     1BOT(I,J))*(H(I+1,J)-BOT(I+1,J)))
 193  IF(J.LT.NR)T(I,J,1)=PERM(I,J,1)*SQRT((H(I,J)-
     1BOT(I,J))*(H(I,J+1)-BOT(I,J+1)))
C     ROW CALCULATIONS

      DO 300 JJ=1,NR
      J=JJ
      IF(MOD(ISTEP+ITER,2).EQ.1) J=NR-J+1
      DO 280 I=1,NC
      BB=SF1(I,J)/DELTA
      DD=HO(I,J)*SF1(I,J)/DELTA-Q(I,J)
      AA=0.0
      CC=0.0
      IF(J-1)200,210,200
200   BB=BB+T(I,J-1,1)
      DD=DD+H(I,J-1)*T(I,J-1,1)
210   IF(J-NR)220,230,220
220   DD=DD+H(I,J+1)*T(I,J,1)
      BB=BB+T(I,J,1)
230   IF(I-1)240,250,240
240   BB=BB+T(I-1,J,2)
      AA=-T(I-1,J,2)
250   IF(I-NC)260,270,260
260   BB=BB+T(I,J,2)
      CC=-T(I,J,2)
270   W=BB-AA*B(I-1)
      B(I)=CC/W
280   G(I)=(DD-AA*G(I-1))/W

C     RE-ESTIMATE HEADS

      E=E+ABS(H(NC,J)-G(NC))
      H(NC,J)=G(NC)
      N=NC-1
290   HA=G(N)-B(N)*H(N+1,J)
```

```
      E=E+ABS(H(N,J)-HA)
      H(N,J)=HA
      N=N-1
      IF(N.GT.0)GO TO 290
      DO 300 N=1,NC
      IF(H(N,J).GT.BOT(N,J))GO TO 300
      E=E+BOT(N,J)+0.01-H(N,J)
      H(N,J)=BOT(N,J)+0.01
300   CONTINUE

C     PRINT RESULTS
      IF(E.GT.ERROR) GO TO 80

      IF(NC.GT.15) NNC=15
      IF(NC.LE.25) NNC=NC
      WRITE(2,310)TIME,E,ITER
310   FORMAT (1H1,* TIME =*,F8.2,* DAYS   ERROR =*,E20.7,*  ITERATIONS =
     2*,I5)
      PRINT 8,(I,I=1,NNC)
      DO 360 J=1,NR
      PRINT 320, J,(H(I,J),I=1,NNC)
320   FORMAT(//,I3,2X,  15F7.1)
360   CONTINUE
      PRINT 8,(I,I=1,NNC)
      IF(NC.LE.25) GO TO 340
      WRITE(2,310) TIME,E,ITER
      PRINT 10,(I,I=26,NC)
      DO 350 J=1,NR
      XJ=J
      PRINT 330, (H(I,J),I=26,NC),XJ
330   FORMAT(//,1X,  26F5.1)
350   CONTINUE
      PRINT 10,(I,I=26,NC)
340   CONTINUE
      STOP
      END
```

```
LFN = Y

      18  120.     50
      10    99
   1   1   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   2   1   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   3   1   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   4   1  18E4   18E4      0.0    0.0            36E5       9000   9000    -20
   5   1  18E4   18E4      0.0    0.0            36E5       9000   9000    -20
   6   1  18E4   18E4      0.0    0.0            36E5       9000   9000    -20
   7   1  18E4   18E4      0.0    0.0            36E5       9000   9000    -20
   8   1  18E4   18E4      0.0    0.0            36E5       9000   9000    -20
   9   1  18E4    0.0      0.0    0.0            36E5       9000    0.0    -20
  10   1   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   1   2   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   2   2   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   3   2   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   4   2  92E3   92E3       -2    0.0            36E5       1840   1840    -52
   5   2  92E3   92E3       -2    0.0            36E5       1840   1840    -52
   6   2  92E3   92E3       -2    0.0            36E5       1840   1840    -52
   7   2  92E3   92E3       -2    0.0            36E5       1840   1840    -52
   8   2  92E3   92E3       -2    0.0            36E5       1840   1840    -52
   9   2  92E3    0.0       -2    0.0            36E5       1840    0.0    -52
  10   2   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   1   3   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   2   3   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   3   3   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   4   3  92E3   92E3       -5    0.0            36E5       1082   1082    -90
   5   3  92E3   92E3       -5    0.0            36E5       1082   1082    -90
   6   3  92E3   92E3       -5    0.0            36E5       1082   1082    -90
   7   3  92E3   92E3       -5  -27E4            36E5       1082   1082    -90
   8   3  92E3   92E3       -5    0.0            36E5       1082   1082    -90
   9   3  92E3    0.0       -5    0.0            36E5       1082    0.0    -90
  10   3   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   1   4   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   2   4   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   3   4   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   4   4  92E3   92E3       -7    0.0            36E5        780    780   -125
   5   4  92E3   92E3       -7    0.0            36E5        780    780   -125
   6   4  92E3   92E3       -7    0.0            36E5        780    780   -125
   7   4  92E3   92E3       -7  -27E4            36E5        780    780   -125
   8   4  92E3   92E3       -7    0.0            36E5        780    780   -125
   9   4  92E3    0.0       -7    0.0            36E5        780    0.0   -125
  10   4   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   1   5   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   2   5   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   3   5   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   4   5  92E3   92E3      -10    0.0            36E5        634    634   -155
   5   5  92E3   92E3      -10    0.0            36E5        634    634   -155
   6   5  92E3   92E3      -10    0.0            36E5        634    634   -155
   7   5  92E3   92E3      -10  -27E4            36E5        634    634   -155
   8   5  92E3   92E3      -10    0.0            36E5        634    634   -155
   9   5  92E3    0.0      -10    0.0            36E5        634    0.0   -155
  10   5   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   1   6   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   2   6   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   3   6   0.0    0.0      0.0    0.0            36E3        0.0    0.0     -5
   4   6  92E3   92E3      -12    0.0            36E5        517    517   -190
   5   6  92E3   92E3      -12    0.0            36E5        517    517   -190
   6   6  92E3   92E3      -12    0.0            36E5        517    517   -190
   7   6  92E3   92E3      -12  -27E4            36E5        517    517   -190
```

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 8  6   92E3   92E3     -12    0.0          36E5          517    517   -190
 9  6   92E3    0.0     -12    0.0          36E5          517    0.0   -190
10  6    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 1  7    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 2  7    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 3  7    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 4  7   92E3   92E3     -14    0.0          36E5          447    447   -220
 5  7   92E3   92E3     -14    0.0          36E5          447    447   -220
 6  7   92E3   92E3     -14    0.0          36E5          447    447   -220
 7  7   92E3   92E3     -14  -27E4          36E5          447    447   -220
 8  7   92E3   92E3     -14    0.0          36E5          447    447   -220
 9  7   92E3    0.0     -14    0.0          36E5          447    0.0   -220
10  7    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 1  8    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 2  8    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 3  8    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 4  8   92E3   92E3     -16    0.0          36E5          385    385   -255
 5  8   92E3   92E3     -16    0.0          36E5          385    385   -255
 6  8   92E3   92E3     -16    0.0          36E5          385    385   -255
 7  8   92E3   92E3     -16  -27E4          36E5          385    385   -255
 8  8   92E3   92E3     -16    0.0          36E5          385    385   -255
 9  8   92E3    0.0     -16    0.0          36E5          385    0.0   -255
10  8    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 1  9    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 2  9    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 3  9    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 4  9   92E3   92E3     -18    0.0          36E5          326    326   -300
 5  9   92E3   92E3     -18    0.0          36E5          326    326   -300
 6  9   92E3   92E3     -18    0.0          36E5          326    326   -300
 7  9   92E3   92E3     -18  -27E4          36E5          326    326   -300
 8  9   92E3   92E3     -18    0.0          36E5          326    326   -300
 9  9   92E3    0.0     -18    0.0          36E5          326    0.0   -300
10  9    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 1 10    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 2 10    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 3 10    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 4 10   92E3   92E3     -21    0.0          36E5          302    302   -325
 5 10   92E3   92E3     -21    0.0          36E5          302    302   -325
 6 10   92E3   92E3     -21    0.0          36E5          302    302   -325
 7 10   92E3   92E3     -21  -27E4          36E5          302    302   -325
 8 10   92E3   92E3     -21    0.0          36E5          302    302   -325
 9 10   92E3    0.0     -21    0.0          36E5          302    0.0   -325
10 10    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 1 11    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 2 11    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 3 11    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 4 11   92E3   92E3     -23    0.0          36E5          277    277   -355
 5 11   92E3   92E3     -23    0.0          36E5          277    277   -355
 6 11   92E3   92E3     -23    0.0          36E5          277    277   -355
 7 11   92E3   92E3     -23  -27E4          36E5          277    277   -355
 8 11   92E3   92E3     -23    0.0          36E5          277    277   -355
 9 11   92E3    0.0     -23    0.0          36E5          277    0.0   -355
10 11    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 1 12    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 2 12    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 3 12    0.0    0.0     0.0    0.0          36E3          0.0    0.0     -5
 4 12   92E3   92E3     -25    0.0          36E5          271    271   -365
 5 12   92E3   92E3     -25    0.0          36E5          271    271   -365
 6 12   92E3   92E3     -25    0.0          36E5          271    271   -365
 7 12   92E3   92E3     -25  -27E4          36E5          271    271   -365
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 8 12   92E3   92E3     -25    0.0            36E5     271    271   -365
 9 12   92E3    0.0     -25    0.0            36E5     271    0.0   -365
10 12    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 1 13    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 2 13    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 3 13    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 4 13   92E3   92E3     -28    0.0            36E5     345    345   -420
 5 13   92E3   92E3     -28    0.0            36E5     345    345   -420
 6 13   92E3   92E3     -28    0.0            36E5     345    345   -420
 7 13   92E3   92E3     -28  -27E4            36E5     345    345   -420
 8 13   92E3   92E3     -28    0.0            36E5     345    345   -420
 9 13   92E3    0.0     -28    0.0            36E5     345    0.0   -420
10 13    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 1 14    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 2 14    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 3 14    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 4 14   92E3   92E3     -30    0.0            36E5     230    230   -420
 5 14   92E3   92E3     -30    0.0            36E5     230    230   -420
 6 14   92E3   92E3     -30    0.0            36E5     230    230   -420
 7 14   92E3   92E3     -30  -27E4            36E5     230    230   -420
 8 14   92E3   92E3     -30    0.0            36E5     230    230   -420
 9 14   92E3    0.0     -30    0.0            36E5     230    0.0   -420
10 14    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 1 15    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 2 15    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 3 15    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 4 15   92E3   92E3     -32    0.0            36E5     205    205   -480
 5 15   92E3   92E3     -32    0.0            36E5     205    205   -480
 6 15   92E3   92E3     -32    0.0            36E5     205    205   -480
 7 15   92E3   92E3     -32  -27E4            36E5     205    205   -480
 8 15   92E3   92E3     -32    0.0            36E5     205    205   -480
 9 15   92E3    0.0     -32    0.0            36E5     205    0.0   -480
10 15    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 1 16    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 2 16    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 3 16    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 4 16   92E3   92E3     -34    0.0            36E5     191    191   -515
 5 16   92E3   92E3     -34    0.0            36E5     191    191   -515
 6 16   92E3   92E3     -34   61E4            36E5     191    191   -515
 7 16   92E3   92E3     -34  -27E4            36E5     191    191   -515
 8 16   92E3   92E3     -34    0.0            36E5     191    191   -515
 9 16   92E3    0.0     -34    0.0            36E5     191    0.0   -515
10 16    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 1 17    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 2 17    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 3 17    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 4 17   92E3   92E3     -36    0.0            36E5     182    182   -540
 5 17   92E3   92E3     -36   61E4            36E5     182    182   -540
 6 17   92E3   92E3     -36   61E4            36E5     182    182   -540
 7 17   92E3   92E3     -36  -27E4            36E5     182    182   -540
 8 17   92E3   92E3     -36   61E4            36E5     182    182   -540
 9 17   92E3    0.0     -36    0.0            36E5     182    0.0   -540
10 17    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 1 18    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 2 18    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 3 18    0.0    0.0     0.0    0.0            36E3     0.0    0.0     -5
 4 18   92E3   92E3     -38    0.0            36E5     170    170   -580
 5 18   92E3   92E3     -38    0.0            36E5     170    170   -580
 6 18   92E3   92E3     -38   61E4            36E5     170    170   -580
 7 18   92E3   92E3     -38  -27E4            36E5     170    170   -580
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 8 18  92E3  92E3    -38    0.0          36E5      170   170  -580
 9 18  92E3   0.0    -38    0.0          36E5      170   0.0  -580
10 18   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 1 19   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 2 19   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 3 19   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 4 19  92E3  92E3    -42    0.0          36E5      161   161  -615
 5 19  92E3  92E3    -42    0.0          36E5      161   161  -615
 6 19  92E3  92E3    -42    0.0          36E5      161   161  -615
 7 19  92E3  92E3    -42  -27E4          36E5      161   161  -615
 8 19  92E3  92E3    -42    0.0          36E5      161   161  -615
 9 19  92E3   0.0    -42    0.0          36E5      161   0.0  -615
10 19   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 1 20   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 2 20   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 3 20   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 4 20  92E3  92E3    -46    0.0          36E5      152   152  -650
 5 20  92E3  92E3    -46    0.0          36E5      152   152  -650
 6 20  92E3  92E3    -46    0.0          36E5      152   152  -650
 7 20  92E3  92E3    -46  -27E4          36E5      152   152  -650
 8 20  92E3  92E3    -46    0.0          36E5      152   152  -650
 9 20  92E3   0.0    -46    0.0          36E5      152   0.0  -650
10 20   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 1 21   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 2 21   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 3 21   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 4 21  92E3  92E3    -50    0.0          36E5      156   156  -640
 5 21  92E3  92E3    -50    0.0          36E5      156   156  -640
 6 21  92E3  92E3    -50    0.0          36E5      156   156  -640
 7 21  92E3  92E3    -50    0.0          36E5      156   156  -640
 8 21  92E3  92E3    -50    0.0          36E5      156   156  -640
 9 21  92E3   0.0    -50    0.0          36E5      156   0.0  -640
10 21   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 1 22   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 2 22   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 3 22   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 4 22  92E3  92E3    -54    0.0          36E5      157   157  -640
 5 22  92E3  92E3    -54    0.0          36E5      157   157  -640
 6 22  92E3  92E3    -54    0.0          36E5      157   157  -640
 7 22  92E3  92E3    -54    0.0          36E5      157   157  -640
 8 22  92E3  92E3    -54    0.0          36E5      157   157  -640
 9 22  92E3   0.0    -54    0.0          36E5      157   0.0  -640
10 22   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 1 23   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 2 23   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 3 23   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 4 23  92E3  92E3    -60    0.0          36E5      160   160  -635
 5 23  92E3  92E3    -60    0.0          36E5      160   160  -635
 6 23  92E3  92E3    -60    0.0          36E5      160   160  -635
 7 23  92E3  92E3    -60    0.0          36E5      160   160  -635
 8 23  92E3  92E3    -60    0.0          36E5      160   160  -635
 9 23  92E3   0.0    -60    0.0          36E5      160   0.0  -635
10 23   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 1 24   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 2 24   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 3 24   0.0   0.0    0.0    0.0          36E3      0.0   0.0    -5
 4 24  92E3  92E3    -73    0.0          36E5      167   167  -625
 5 24  92E3  92E3    -73    0.0          36E5      167   167  -625
 6 24  92E3  92E3    -73    0.0          36E5      167   167  -625
 7 24  92E3  92E3    -73    0.0          36E5      167   167  -625
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 8 24   92E3   92E3      -73    0.0               36E5       167    167   -625
 9 24   92E3    0.0      -73    0.0               36E5       167    0.0   -625
10 24    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 1 25    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 2 25    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 3 25    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 4 25   92E3   92E3      -87    0.0               36E5       172    172   -620
 5 25   92E3   92E3      -87    0.0               36E5       172    172   -620
 6 25   92E3   92E3      -87    0.0               36E5       172    172   -620
 7 25   92E3   92E3      -87    0.0               36E5       172    172   -620
 8 25   92E3   92E3      -87    0.0               36E5       172    172   -620
 9 25   92E3    0.0      -87    0.0               36E5       172    0.0   -620
10 25    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 1 26    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 2 26    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 3 26    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 4 26   92E3   92E3     -101    0.0               36E5       179    179   -615
 5 26   92E3   92E3     -101    0.0               36E5       179    179   -615
 6 26   92E3   92E3     -101    0.0               36E5       179    179   -615
 7 26   92E3   92E3     -101    0.0               36E5       179    179   -615
 8 26   92E3   92E3     -101    0.0               36E5       179    179   -615
 9 26   92E3    0.0     -101    0.0               36E5       179    0.0   -615
10 26    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 1 27    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 2 27    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 3 27    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 4 27   18E4   18E4     -114    0.0               36E5       359    359   -615
 5 27   18E4   18E4     -114    0.0               36E5       359    359   -615
 6 27   18E4   18E4     -114    0.0               36E5       359    359   -615
 7 27   18E4   18E4     -114    0.0               36E5       359    359   -615
 8 27   18E4   18E4     -114    0.0               36E5       359    359   -615
 9 27   18E4    0.0     -114    0.0               36E5       359    0.0   -615
10 27    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 1 28    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 2 28    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 3 28    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 4 28   18E4   18E4     -120    0.0               36E5       371    371   -605
 5 28   18E4   18E4     -120    0.0               36E5       371    371   -605
 6 28   18E4   18E4     -120    0.0               36E5       371    371   -605
 7 28   18E4   18E4     -120    0.0               36E5       371    371   -605
 8 28   18E4   18E4     -120    0.0               36E5       371    371   -605
 9 28   18E4    0.0     -120    0.0               36E5       371    0.0   -605
10 28    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 1 29    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 2 29    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 3 29    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 4 29   18E4   18E4     -126    0.0               36E5       388    388   -590
 5 29   18E4   18E4     -126    0.0               36E5       388    388   -590
 6 29   18E4   18E4     -126    0.0               36E5       388    388   -590
 7 29   18E4   18E4     -126    0.0               36E5       388    388   -590
 8 29   18E4   18E4     -126    0.0               36E5       388    388   -590
 9 29   18E4    0.0     -126    0.0               36E5       388    0.0   -590
10 29    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 1 30    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 2 30    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 3 30    0.0    0.0      0.0    0.0               36E3       0.0    0.0     -5
 4 30   18E4   18E4     -132    0.0               36E5       411    411   -570
 5 30   18E4   18E4     -132    0.0               36E5       411    411   -570
 6 30   18E4   18E4     -132    0.0               36E5       411    411   -570
 7 30   18E4   18E4     -132    0.0               36E5       411    411   -570
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 8 30   18E4   18E4    -132    0.0            36E5         411    411   -570
 9 30   18E4    0.0    -132    0.0            36E5         411    0.0   -570
10 30    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 1 31    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 2 31    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 3 31    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 4 31   18E4   18E4    -138    0.0            36E5         437    437   -550
 5 31   18E4   18E4    -138    0.0            36E5         437    437   -550
 6 31   18E4   18E4    -138    0.0            36E5         437    437   -550
 7 31   18E4   18E4    -138    0.0            36E5         437    437   -550
 8 31   18E4   18E4    -138    0.0            36E5         437    437   -550
 9 31   18E4    0.0    -138    0.0            36E5         437    0.0   -550
10 31    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 1 32    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 2 32    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 3 32    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 4 32   18E4   18E4    -144    0.0            36E5         460    460   -535
 5 32   18E4   18E4    -144    0.0            36E5         460    460   -535
 6 32   18E4   18E4    -144    0.0            36E5         460    460   -535
 7 32   18E4   18E4    -144    0.0            36E5         460    460   -535
 8 32   18E4   18E4    -144    0.0            36E5         460    460   -535
 9 32   18E4    0.0    -144    0.0            36E5         460    0.0   -535
10 32    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 1 33    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 2 33    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 3 33    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 4 33   18E4   18E4    -150    0.0            36E5         493    493   -515
 5 33   18E4   18E4    -150    0.0            36E5         493    493   -515
 6 33   18E4   18E4    -150    0.0            36E5         493    493   -515
 7 33   18E4   18E4    -150    0.0            36E5         493    493   -515
 8 33   18E4   18E4    -150    0.0            36E5         493    493   -515
 9 33   18E4    0.0    -150    0.0            36E5         493    0.0   -515
10 33    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 1 34    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 2 34    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 3 34    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 4 34   18E4   18E4    -156    0.0            36E5         494    494   -520
 5 34   18E4   18E4    -156    0.0            36E5         494    494   -520
 6 34   18E4   18E4    -156    0.0            36E5         494    494   -520
 7 34   18E4   18E4    -156    0.0            36E5         494    494   -520
 8 34   18E4   18E4    -156    0.0            36E5         494    494   -520
 9 34   18E4    0.0    -156    0.0            36E5         494    0.0   -520
10 34    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 1 35    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 2 35    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 3 35    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 4 35   18E4   18E4    -162    0.0            36E5         483    483   -535
 5 35   18E4   18E4    -162    0.0            36E5         483    483   -535
 6 35   18E4   18E4    -162    0.0            36E5         483    483   -535
 7 35   18E4   18E4    -162    0.0            36E5         483    483   -535
 8 35   18E4   18E4    -162    0.0            36E5         483    483   -535
 9 35   18E4    0.0    -162    0.0            36E5         483    0.0   -535
10 35    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 1 36    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 2 36    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 3 36    0.0    0.0     0.0    0.0            36E3         0.0    0.0     -5
 4 36   18E4   18E4    -168    0.0            36E5         471    471   -550
 5 36   18E4   18E4    -168    0.0            36E5         471    471   -550
 6 36   18E4   18E4    -168    0.0            36E5         471    471   -550
 7 36   18E4   18E4    -168    0.0            36E5         471    471   -550
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 8 36   18E4   18E4     -168    0.0                36E5        471    471    -550
 9 36   18E4    0.0     -168    0.0                36E5        471    0.0    -550
10 36    0.0    0.0      0.0    0.0                36E3        0.0    0.0      -5
 1 37    0.0    0.0      0.0    0.0                36E3        0.0    0.0      -5
 2 37    0.0    0.0      0.0    0.0                36E3        0.0    0.0      -5
 3 37    0.0    0.0      0.0    0.0                36E3        0.0    0.0      -5
 4 37   18E4   18E4     -174    0.0                36E5        466    466    -560
 5 37   18E4   18E4     -174    0.0                36E5        466    466    -560
 6 37   18E4   18E4     -174    0.0                36E5        466    466    -560
 7 37   18E4   18E4     -174    0.0                36E5        466    466    -560
 8 37   18E4   18E4     -174    0.0                36E5        466    466    -560
 9 37   18E4    0.0     -174    0.0                36E5        466    0.0    -560
10 37    0.0    0.0      0.0    0.0                36E3        0.0    0.0      -5
 1 38    0.0    0.0      0.0    0.0                36E3        0.0    0.0      -5
 2 38    0.0    0.0      0.0    0.0                36E3        0.0    0.0      -5
 3 38    0.0    0.0      0.0    0.0                36E3        0.0    0.0      -5
 4 38   18E4   18E4     -180    0.0                36E5        462    462    -570
 5 38   18E4   18E4     -180    0.0                36E5        462    462    -570
 6 38   18E4   18E4     -180    0.0                36E5        462    462    -570
 7 38   18E4   18E4     -180    0.0                36E5        462    462    -570
 8 38   18E4   18E4     -180    0.0                36E5        462    462    -570
 9 38   18E4    0.0     -180    0.0                36E5        462    0.0    -570
10 38    0.0    0.0      0.0    0.0                36E3        0.0    0.0      -5
 1 39    0.0    0.0      0.0    0.0                36E3        0.0    0.0      -5
 2 39    0.0    0.0      0.0    0.0                36E3        0.0    0.0      -5
 3 39   18E4   18E4     -186    0.0                36E5        410    410    -625
 4 39   18E4   18E4     -186    0.0                36E5        410    410    -625
 5 39   18E4   18E4     -186    0.0                36E5        410    410    -625
 6 39   18E4   18E4     -186    0.0                36E5        410    410    -625
 7 39   18E4   18E4     -186    0.0                36E5        410    410    -625
 8 39   18E4   18E4     -186    0.0                36E5        410    410    -625
 9 39   18E4    0.0     -186    0.0                36E5        410    0.0    -625
10 39    0.0    0.0      0.0    0.0                36E3        0.0    0.0      -5
 1 40    0.0    0.0      0.0    0.0                36E3        0.0    0.0      -5
 2 40    0.0    0.0      0.0    0.0                36E3        0.0    0.0      -5
 3 40   18E4   18E4     -192    0.0                36E5        369    369    -680
 4 40    1E5    1E5     -192    0.0                36E5        205    205    -680
 5 40    1E5    1E5     -192    0.0                36E5        205    205    -680
 6 40    1E5    1E5     -192    0.0                36E5        205    205    -680
 7 40    1E5    1E5     -192    0.0                36E5        205    205    -680
 8 40    1E5    1E5     -192    0.0                36E5        205    205    -680
 9 40   18E4    0.0     -192    0.0                36E5        369    0.0    -680
10 40    0.0    0.0      0.0    0.0                36E3        0.0    0.0      -5
 1 41    0.0    0.0      0.0    0.0                36E3        0.0    0.0      -5
 2 41    0.0    0.0      0.0    0.0                36E3        0.0    0.0      -5
 3 41   18E4   18E4     -198    0.0                36E5        332    332    -740
 4 41    1E5    1E5     -198    0.0                36E5        184    184    -740
 5 41    1E5    1E5     -198    0.0                36E5        184    184    -740
 6 41    1E5    1E5     -198    0.0                36E5        184    184    -740
 7 41    1E5    1E5     -198    0.0                36E5        184    184    -740
 8 41    1E5    1E5     -198    0.0                36E5        184    184    -740
 9 41   18E4    0.0     -198    0.0                36E5        332    0.0    -740
10 41    0.0    0.0      0.0    0.0                36E3        0.0    0.0      -5
 1 42    0.0    0.0      0.0    0.0                36E3        0.0    0.0      -5
 2 42    0.0    0.0      0.0    0.0                36E3        0.0    0.0      -5
 3 42   18E4   18E4     -204    0.0                36E5        302    302    -800
 4 42    1E5    1E5     -204    0.0                36E5        168    168    -800
 5 42    1E5    1E5     -204    0.0                36E5        168    168    -800
 6 42    1E5    1E5     -204    0.0                36E5        168    168    -800
 7 42    1E5    1E5     -204    0.0                36E5        168    168    -800
```

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 8 42   1E5   1E5    -204   0.0     36E5   168   168  -800
 9 42  18E4   0.0    -204   0.0     36E5   302   0.0  -800
10 42   0.0   0.0     0.0   0.0     36E3   0.0   0.0    -5
 1 43   0.0   0.0     0.0   0.0     36E3   0.0   0.0    -5
 2 43   0.0   0.0     0.0   0.0     36E3   0.0   0.0    -5
 3 43  18E4  18E4    -210   0.0     36E5   279   279  -855
 4 43   1E5   1E5    -210   0.0     36E5   155   155  -855
 5 43   1E5   1E5    -210   0.0     36E5   155   155  -855
 6 43   1E5   1E5    -210   0.0     36E5   155   155  -855
 7 43   1E5   1E5    -210   0.0     36E5   155   155  -855
 8 43   1E5   1E5    -210   0.0     36E5   155   155  -855
 9 43  18E4   0.0    -210   0.0     36E5   279   0.0  -855
10 43   0.0   0.0     0.0   0.0     36E3   0.0   0.0    -5
 1 44   0.0   0.0     0.0   0.0     36E3   0.0   0.0    -5
 2 44   0.0   0.0     0.0   0.0     36E3   0.0   0.0    -5
 3 44  18E4  18E4    -216   0.0     36E5   258   258  -915
 4 44   1E5   1E5    -216   0.0     36E5   143   143  -915
 5 44   1E5   1E5    -216   0.0     36E5   143   143  -915
 6 44   1E5   1E5    -216   0.0     36E5   143   143  -915
 7 44   1E5   1E5    -216   0.0     36E5   143   143  -915
 8 44   1E5   1E5    -216   0.0     36E5   143   143  -915
 9 44  18E4   0.0    -216   0.0     36E5   258   0.0  -915
10 44   0.0   0.0     0.0   0.0     36E3   0.0   0.0    -5
 1 45   0.0   0.0     0.0   0.0     36E3   0.0   0.0    -5
 2 45   0.0   0.0     0.0   0.0     36E3   0.0   0.0    -5
 3 45  18E4  18E4    -220   0.0     36E5   237   237  -980
 4 45   1E5   1E5    -220   0.0     36E5   132   132  -980
 5 45   1E5   1E5    -220   0.0     36E5   132   132  -980
 6 45   1E5   1E5    -220   0.0     36E5   132   132  -980
 7 45   1E5   1E5    -220   0.0     36E5   132   132  -980
 8 45   1E5   1E5    -220   0.0     36E5   132   132  -980
 9 45  18E4   0.0    -220   0.0     36E5   237   0.0  -980
10 45   0.0   0.0     0.0   0.0     36E3   0.0   0.0    -5
 1 46   0.0   0.0     0.0   0.0     36E3   0.0   0.0    -5
 2 46   0.0   0.0     0.0   0.0     36E3   0.0   0.0    -5
 3 46  18E4  18E4    -224   0.0     36E5   221   221 -1040
 4 46   1E5   1E5    -224   0.0     36E5   122   122 -1040
 5 46   1E5   1E5    -224   0.0     36E5   122   122 -1040
 6 46   1E5   1E5    -224   0.0     36E5   122   122 -1040
 7 46   1E5   1E5    -224   0.0     36E5   122   122 -1040
 8 46   1E5   1E5    -224   0.0     36E5   122   122 -1040
 9 46  18E4   0.0    -224   0.0     36E5   221   0.0 -1040
10 46   0.0   0.0     0.0   0.0     36E3   0.0   0.0    -5
 1 47   0.0   0.0     0.0   0.0     36E3   0.0   0.0    -5
 2 47   0.0   0.0     0.0   0.0     36E3   0.0   0.0    -5
 3 47  18E4  18E4    -226   0.0     36E5   205   205 -1105
 4 47   1E5   1E5    -226   0.0     36E5   114   114 -1105
 5 47   1E5   1E5    -226   0.0     36E5   114   114 -1105
 6 47   1E5   1E5    -226   0.0     36E5   114   114 -1105
 7 47   1E5   1E5    -226   0.0     36E5   114   114 -1105
 8 47   1E5   1E5    -226   0.0     36E5   114   114 -1105
 9 47  18E4   0.0    -226   0.0     36E5   205   0.0 -1105
10 47   0.0   0.0     0.0   0.0     36E3   0.0   0.0    -5
 1 48   0.0   0.0     0.0   0.0     36E3   0.0   0.0    -5
 2 48   0.0   0.0     0.0   0.0     36E3   0.0   0.0    -5
 3 48  18E4  18E4    -228   0.0     36E5   208   208 -1095
 4 48   1E5   1E5    -228   0.0     36E5   115   115 -1095
 5 48   1E5   1E5    -228   0.0     36E5   115   115 -1095
 6 48   1E5   1E5    -228   0.0     36E5   115   115 -1095
 7 48   1E5   1E5    -228   0.0     36E5   115   115 -1095
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 8 48    1E5    1E5    -228    0.0              36E5     115    115  -1095
 9 48   18E4    0.0    -228    0.0              36E5     208    0.0  -1095
10 48    0.0    0.0     0.0    0.0              36E3     0.0    0.0     -5
 1 49    0.0    0.0     0.0    0.0              36E3     0.0    0.0     -5
 2 49    0.0    0.0     0.0    0.0              36E3     0.0    0.0     -5
 3 49   18E4   18E4    -230    0.0              36E5     210    210  -1085
 4 49    1E5    1E5    -230    0.0              36E5     117    117  -1085
 5 49    1E5    1E5    -230    0.0              36E5     117    117  -1085
 6 49    1E5    1E5    -230    0.0              36E5     117    117  -1085
 7 49    1E5    1E5    -230    0.0              36E5     117    117  -1085
 8 49    1E5    1E5    -230    0.0              36E5     117    117  -1085
 9 49   18E4    0.0    -230    0.0              36E5     210    0.0  -1085
10 49    0.0    0.0     0.0    0.0              36E3     0.0    0.0     -5
 1 50    0.0    0.0     0.0    0.0              36E3     0.0    0.0     -5
 2 50    0.0    0.0     0.0    0.0              36E3     0.0    0.0     -5
 3 50   18E4   18E4    -232    0.0              36E5     215    215  -1070
 4 50    1E5    1E5    -232    0.0              36E5     119    119  -1070
 5 50    1E5    1E5    -232    0.0              36E5     119    119  -1070
 6 50    1E5    1E5    -232    0.0              36E5     119    119  -1070
 7 50    1E5    1E5    -232    0.0              36E5     119    119  -1070
 8 50    1E5    1E5    -232    0.0              36E5     119    119  -1070
 9 50   18E4    0.0    -232    0.0              36E5     215    0.0  -1070
10 50    0.0    0.0     0.0    0.0              36E3     0.0    0.0     -5
 1 51    0.0    0.0     0.0    0.0              36E3     0.0    0.0     -5
 2 51    0.0    0.0     0.0    0.0              36E3     0.0    0.0     -5
 3 51   18E4   18E4    -234    0.0              36E5     217    217  -1065
 4 51    1E5    1E5    -234    0.0              36E5     120    120  -1065
 5 51    1E5    1E5    -234    0.0              36E5     120    120  -1065
 6 51    1E5    1E5    -234    0.0              36E5     120    120  -1065
 7 51    1E5    1E5    -234    0.0              36E5     120    120  -1065
 8 51    1E5    1E5    -234    0.0              36E5     120    120  -1065
 9 51   18E4    0.0    -234    0.0              36E5     217    0.0  -1065
10 51    0.0    0.0     0.0    0.0              36E3     0.0    0.0     -5
 1 52    0.0    0.0     0.0    0.0              36E3     0.0    0.0     -5
 2 52    0.0    0.0     0.0    0.0              36E3     0.0    0.0     -5
 3 52   18E4   18E4    -236    0.0              36E5     234    234  -1005
 4 52    1E5    1E5    -236    0.0              36E5     130    130  -1005
 5 52    1E5    1E5    -236    0.0              36E5     130    130  -1005
 6 52    1E5    1E5    -236    0.0              36E5     130    130  -1005
 7 52    1E5    1E5    -236    0.0              36E5     130    130  -1005
 8 52    1E5    1E5    -236    0.0              36E5     130    130  -1005
 9 52   18E4    0.0    -236    0.0              36E5     234    0.0  -1005
10 52    0.0    0.0     0.0    0.0              36E3     0.0    0.0     -5
 1 53    0.0    0.0     0.0    0.0              36E3     0.0    0.0     -5
 2 53    0.0    0.0     0.0    0.0              36E3     0.0    0.0     -5
 3 53   18E4   18E4    -238    0.0              36E5     253    253   -950
 4 53    1E5    1E5    -238    0.0              36E5     140    140   -950
 5 53    1E5    1E5    -238    0.0              36E5     140    140   -950
 6 53    1E5    1E5    -238    0.0              36E5     140    140   -950
 7 53    1E5    1E5    -238    0.0              36E5     140    140   -950
 8 53    1E5    1E5    -238    0.0              36E5     140    140   -950
 9 53   18E4    0.0    -238    0.0              36E5     253    0.0   -950
10 53    0.0    0.0     0.0    0.0              36E3     0.0    0.0     -5
 1 54    0.0    0.0     0.0    0.0              36E3     0.0    0.0     -5
 2 54    0.0    0.0     0.0    0.0              36E3     0.0    0.0     -5
 3 54   18E4   18E4    -240    0.0              36E5     279    279   -890
 4 54    1E5    1E5    -240    0.0              36E5     154    154   -890
 5 54    1E5    1E5    -240    0.0              36E5     154    154   -890
 6 54    1E5    1E5    -240    0.0              36E5     154    154   -890
 7 54    1E5    1E5    -240    0.0              36E5     154    154   -890
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 8 54   1E5   1E5    -240  0.0        36E5    154   154  -890
 9 54  18E4   0.0    -240  0.0        36E5    279   0.0  -890
10 54   0.0   0.0     0.0  0.0        36E3    0.0   0.0    -5
 1 55   0.0   0.0     0.0  0.0        36E3    0.0   0.0    -5
 2 55   0.0   0.0     0.0  0.0        36E3    0.0   0.0    -5
 3 55  18E4  18E4    -242  0.0        36E5    289   289  -865
 4 55   1E5   1E5    -242  0.0        36E5    161   161  -865
 5 55   1E5   1E5    -242  0.0        36E5    161   161  -865
 6 55   1E5   1E5    -242  0.0        36E5    161   161  -865
 7 55   1E5   1E5    -242  0.0        36E5    161   161  -865
 8 55   1E5   1E5    -242  0.0        36E5    161   161  -865
 9 55  18E4   0.0    -242  0.0        36E5    289   0.0  -865
10 55   0.0   0.0     0.0  0.0        36E3    0.0   0.0    -5
 1 56   0.0   0.0     0.0  0.0        36E3    0.0   0.0    -5
 2 56   0.0   0.0     0.0  0.0        36E3    0.0   0.0    -5
 3 56  18E4  18E4    -243  0.0        36E5    278   278  -890
 4 56   1E5   1E5    -243  0.0        36E5    155   155  -890
 5 56   1E5   1E5    -243  0.0        36E5    155   155  -890
 6 56   1E5   1E5    -243  0.0        36E5    155   155  -890
 7 56   1E5   1E5    -243  0.0        36E5    155   155  -890
 8 56   1E5   1E5    -243  0.0        36E5    155   155  -890
 9 56  18E4   0.0    -243  0.0        36E5    278   0.0  -890
10 56   0.0   0.0     0.0  0.0        36E3    0.0   0.0    -5
 1 57   0.0   0.0     0.0  0.0        36E3    0.0   0.0    -5
 2 57   0.0   0.0     0.0  0.0        36E3    0.0   0.0    -5
 3 57  18E4  18E4    -244  0.0        36E5    268   268  -915
 4 57   1E5   1E5    -244  0.0        36E5    149   149  -915
 5 57   1E5   1E5    -244  0.0        36E5    149   149  -915
 6 57   1E5   1E5    -244  0.0        36E5    149   149  -915
 7 57   1E5   1E5    -244  0.0        36E5    149   149  -915
 8 57   1E5   1E5    -244  0.0        36E5    149   149  -915
 9 57  18E4   0.0    -244  0.0        36E5    268   0.0  -915
10 57   0.0   0.0     0.0  0.0        36E3    0.0   0.0    -5
 1 58   0.0   0.0     0.0  0.0        36E3    0.0   0.0    -5
 2 58   0.0   0.0     0.0  0.0        36E3    0.0   0.0    -5
 3 58  18E4  18E4    -245  0.0        36E5    259   259  -940
 4 58   1E5   1E5    -245  0.0        36E5    144   144  -940
 5 58   1E5   1E5    -245  0.0        36E5    144   144  -940
 6 58   1E5   1E5    -245  0.0        36E5    144   144  -940
 7 58   1E5   1E5    -245  0.0        36E5    144   144  -940
 8 58   1E5   1E5    -245  0.0        36E5    144   144  -940
 9 58  18E4   0.0    -245  0.0        36E5    259   0.0  -940
10 58   0.0   0.0     0.0  0.0        36E3    0.0   0.0    -5
 1 59   0.0   0.0     0.0  0.0        36E3    0.0   0.0    -5
 2 59   0.0   0.0     0.0  0.0        36E3    0.0   0.0    -5
 3 59  18E4  18E4    -246  0.0        36E5    250   250  -965
 4 59   1E5   1E5    -246  0.0        36E5    139   139  -965
 5 59   1E5   1E5    -246  0.0        36E5    139   139  -965
 6 59   1E5   1E5    -246  0.0        36E5    139   139  -965
 7 59   1E5   1E5    -246  0.0        36E5    139   139  -965
 8 59   1E5   1E5    -246  0.0        36E5    139   139  -965
 9 59  18E4   0.0    -246  0.0        36E5    250   0.0  -965
10 59   0.0   0.0     0.0  0.0        36E3    0.0   0.0    -5
 1 60   0.0   0.0     0.0  0.0        36E3    0.0   0.0    -5
 2 60   0.0   0.0     0.0  0.0        36E3    0.0   0.0    -5
 3 60  18E4  18E4    -247  0.0        36E5    242   242  -990
 4 60   1E5   1E5    -247  0.0        36E5    135   135  -990
 5 60   1E5   1E5    -247  0.0        36E5    135   135  -990
 6 60   1E5   1E5    -247  0.0        36E5    135   135  -990
 7 60   1E5   1E5    -247  0.0        36E5    135   135  -990
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 8 60   1E5    1E5     -247    0.0        36E5     135    135   -990
 9 60  18E4    0.0     -247    0.0        36E5     242    0.0   -990
10 60   0.0    0.0      0.0    0.0        36E3     0.0    0.0     -5
 1 61   0.0    0.0      0.0    0.0        36E3     0.0    0.0     -5
 2 61   0.0    0.0      0.0    0.0        36E3     0.0    0.0     -5
 3 61  18E4   18E4     -248    0.0        36E5     235    235  -1015
 4 61  18E4   18E4     -248    0.0        36E5     235    235  -1015
 5 61  18E4   18E4     -248    0.0        36E5     235    235  -1015
 6 61  18E4   18E4     -248    0.0        36E5     235    235  -1015
 7 61  18E4   18E4     -248    0.0        36E5     235    235  -1015
 8 61  18E4   18E4     -248    0.0        36E5     235    235  -1015
 9 61  18E4    0.0     -248    0.0        36E5     235    0.0  -1015
10 61   0.0    0.0      0.0    0.0        36E3     0.0    0.0     -5
 1 62   0.0    0.0      0.0    0.0        36E3     0.0    0.0     -5
 2 62   0.0    0.0      0.0    0.0        36E3     0.0    0.0     -5
 3 62  18E4   18E4     -249    0.0        36E5     228    228  -1040
 4 62  18E4   18E4     -249    0.0        36E5     228    228  -1040
 5 62  18E4   18E4     -249    0.0        36E5     228    228  -1040
 6 62  18E4   18E4     -249    0.0        36E5     228    228  -1040
 7 62  18E4   18E4     -249    0.0        36E5     228    228  -1040
 8 62  18E4   18E4     -249    0.0        36E5     228    228  -1040
 9 62  18E4    0.0     -249    0.0        36E5     228    0.0  -1040
10 62   0.0    0.0      0.0    0.0        36E3     0.0    0.0     -5
 1 63   0.0    0.0      0.0    0.0        36E3     0.0    0.0     -5
 2 63   0.0    0.0      0.0    0.0        36E3     0.0    0.0     -5
 3 63  18E4   18E4     -250    0.0        36E5     221    221  -1065
 4 63  18E4   18E4     -250    0.0        36E5     221    221  -1065
 5 63  18E4   18E4     -250    0.0        36E5     221    221  -1065
 6 63  18E4   18E4     -250    0.0        36E5     221    221  -1065
 7 63  18E4   18E4     -250    0.0        36E5     221    221  -1065
 8 63  18E4   18E4     -250    0.0        36E5     221    221  -1065
 9 63  18E4    0.0     -250    0.0        36E5     221    0.0  -1065
10 63   0.0    0.0      0.0    0.0        36E3     0.0    0.0     -5
 1 64   0.0    0.0      0.0    0.0        36E3     0.0    0.0     -5
 2 64   0.0    0.0      0.0    0.0        36E3     0.0    0.0     -5
 3 64  18E4   18E4     -250    0.0        36E5     214    214  -1090
 4 64  18E4   18E4     -250    0.0        36E5     214    214  -1090
 5 64  18E4   18E4     -250    0.0        36E5     214    214  -1090
 6 64  18E4   18E4     -250    0.0        36E5     214    214  -1090
 7 64  18E4   18E4     -250    0.0        36E5     214    214  -1090
 8 64  18E4   18E4     -250    0.0        36E5     214    214  -1090
 9 64  18E4    0.0     -250    0.0        36E5     214    0.0  -1090
10 64   0.0    0.0      0.0    0.0        36E3     0.0    0.0     -5
 1 65   0.0    0.0      0.0    0.0        36E3     0.0    0.0     -5
 2 65   0.0    0.0      0.0    0.0        36E3     0.0    0.0     -5
 3 65  18E4   18E4     -250    0.0        36E5     208    208  -1115
 4 65  18E4   18E4     -250    0.0        36E5     208    208  -1115
 5 65  18E4   18E4     -250    0.0        36E5     208    208  -1115
 6 65  18E4   18E4     -250    0.0        36E5     208    208  -1115
 7 65  18E4   18E4     -250    0.0        36E5     208    208  -1115
 8 65  18E4   18E4     -250    0.0        36E5     208    208  -1115
 9 65  18E4    0.0     -250    0.0        36E5     208    0.0  -1115
10 65   0.0    0.0      0.0    0.0        36E3     0.0    0.0     -5
 1 66   0.0    0.0      0.0    0.0        36E3     0.0    0.0     -5
 2 66   0.0    0.0      0.0    0.0        36E3     0.0    0.0     -5
 3 66  18E4   18E4     -251    0.0        36E5     202    202  -1140
 4 66  18E4   18E4     -251    0.0        36E5     202    202  -1140
 5 66  18E4   18E4     -251    0.0        36E5     202    202  -1140
 6 66  18E4   18E4     -251    0.0        36E5     202    202  -1140
 7 66  18E4   18E4     -251    0.0        36E5     202    202  -1140
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 8 66  18E4  18E4    -251   0.0                       36E5        202   202 -1140
 9 66  18E4   0.0    -251   0.0                       36E5        202   0.0 -1140
10 66   0.0   0.0     0.0   0.0                       36E3        0.0   0.0    -5
 1 67   0.0   0.0     0.0   0.0                       36E3        0.0   0.0    -5
 2 67   0.0   0.0     0.0   0.0                       36E3        0.0   0.0    -5
 3 67  18E4  18E4    -251   0.0                       36E5        200   200 -1150
 4 67  18E4  18E4    -251   0.0                       36E5        200   200 -1150
 5 67  18E4  18E4    -251   0.0                       36E5        200   200 -1150
 6 67  18E4  18E4    -251   0.0                       36E5        200   200 -1150
 7 67  18E4  18E4    -251   0.0                       36E5        200   200 -1150
 8 67  18E4  18E4    -251   0.0                       36E5        200   200 -1150
 9 67  18E4   0.0    -251   0.0                       36E5        200   0.0 -1150
10 67   0.0   0.0     0.0   0.0                       36E3        0.0   0.0    -5
 1 68   0.0   0.0     0.0   0.0                       36E3        0.0   0.0    -5
 2 68   0.0   0.0     0.0   0.0                       36E3        0.0   0.0    -5
 3 68  18E4  18E4    -251   0.0                       36E5        194   194 -1180
 4 68  18E4  18E4    -251   0.0                       36E5        194   194 -1180
 5 68  18E4  18E4    -251   0.0                       36E5        194   194 -1180
 6 68  18E4  18E4    -251   0.0                       36E5        194   194 -1180
 7 68  18E4  18E4    -251   0.0                       36E5        194   194 -1180
 8 68  18E4  18E4    -251   0.0                       36E5        194   194 -1180
 9 68  18E4   0.0    -251   0.0                       36E5        194   0.0 -1180
10 68   0.0   0.0     0.0   0.0                       36E3        0.0   0.0    -5
 1 69   0.0   0.0     0.0   0.0                       36E3        0.0   0.0    -5
 2 69   0.0   0.0     0.0   0.0                       36E3        0.0   0.0    -5
 3 69  18E4  18E4    -252   0.0                       36E5        189   189 -1205
 4 69  18E4  18E4    -252   0.0                       36E5        189   189 -1205
 5 69  18E4  18E4    -252   0.0                       36E5        189   189 -1205
 6 69  18E4  18E4    -252  72E4                       36E5        187   187 -1215
 7 69  18E4  18E4    -252  72E4                       36E5        187   187 -1215
 8 69  18E4  18E4    -252   0.0                       36E5        189   189 -1205
 9 69  18E4   0.0    -251   0.0                       36E5        189   0.0 -1205
10 69   0.0   0.0     0.0   0.0                       36E3        0.0   0.0    -5
 1 70   0.0   0.0     0.0   0.0                       36E3        0.0   0.0    -5
 2 70  18E4  18E4    -252   0.0                       36E5        187   187 -1215
 3 70  18E4  18E4    -252   0.0                       36E5        187   187 -1215
 4 70  18E4  18E4    -252   0.0                       36E5        187   187 -1215
 5 70  18E4  18E4    -252   0.0                       36E5        187   187 -1215
 6 70  18E4  18E4    -252  72E4                       36E5        187   187 -1215
 7 70  18E4  18E4    -252  72E4                       36E5        187   187 -1215
 8 70  18E4  18E4    -252   0.0                       36E5        187   187 -1215
 9 70  18E4   0.0    -252   0.0                       36E5        187   0.0 -1215
10 70   0.0   0.0     0.0   0.0                       36E3        0.0   0.0    -5
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 2 71  18E4  18E4    -252   0.0                       36E5        187   187 -1215
 3 71  18E4  18E4    -252   0.0                       36E5        187   187 -1215
 4 71  18E4  18E4    -252   0.0                       36E5        187   187 -1215
 5 71  18E4  18E4    -252   0.0                       36E5        187   187 -1215
 6 71  18E4  18E4    -252  72E4                       36E5        187   187 -1215
 7 71  18E4  18E4    -252  72E4                       36E5        187   187 -1215
 8 71  18E4  18E4    -252   0.0                       36E5        187   187 -1215
 9 71  18E4   0.0    -252   0.0                       36E5        187   0.0 -1215
10 71   0.0   0.0     0.0   0.0                       36E3        0.0   0.0    -5
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 5 72  18E4  18E4    -252   0.0                       36E5        187   187 -1215
 6 72  18E4  18E4    -252  72E4                       36E5        187   187 -1215
 7 72  18E4  18E4    -252  72E4                       36E5        187   187 -1215
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 9 72   18E4   18E4     -252    0.0                          36E5          187     187 -1215
10 72   18E4    0.0     -252    0.0                          36E5          187     0.0 -1215
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 2 73   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 3 73   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 4 73   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 5 73   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 6 73   18E4   18E4     -252   72E4                          36E5          187     187 -1215
 7 73   18E4   18E4     -252   72E4                          36E5          187     187 -1215
 8 73   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 9 73   18E4   18E4     -252    0.0                          36E5          187     187 -1215
10 73   18E4    0.0     -252    0.0                          36E5          187     0.0 -1215
 1 74    0.0    0.0      0.0    0.0                          36E3          0.0     0.0    -5
 2 74   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 3 74   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 4 74   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 5 74   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 6 74   18E4   18E4     -252   72E4                          36E5          187     187 -1215
 7 74   18E4   18E4     -252   72E4                          36E5          187     187 -1215
 8 74   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 9 74   18E4   18E4     -252    0.0                          36E5          187     187 -1215
10 74   18E4    0.0     -252    0.0                          36E5          187     0.0 -1215
 1 75    0.0    0.0      0.0    0.0                          36E3          0.0     0.0    -5
 2 75   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 3 75   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 4 75   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 5 75   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 6 75   18E4   18E4     -252   72E4                          36E5          187     187 -1215
 7 75   18E4   18E4     -252   72E4                          36E5          187     187 -1215
 8 75   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 9 75   18E4   18E4     -252    0.0                          36E5          187     187 -1215
10 75   18E4    0.0     -252    0.0                          36E5          187     0.0 -1215
 1 76    0.0    0.0      0.0    0.0                          36E3          0.0     0.0    -5
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 3 76   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 4 76   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 5 76   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 6 76   18E4   18E4     -252   72E4                          36E5          187     187 -1215
 7 76   18E4   18E4     -252   72E4                          36E5          187     187 -1215
 8 76   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 9 76   18E4   18E4     -252    0.0                          36E5          187     187 -1215
10 76   18E4    0.0     -252    0.0                          36E5          187     0.0 -1215
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 2 77   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 3 77   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 4 77   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 5 77   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 6 77   18E4   18E4     -252   72E4                          36E5          187     187 -1215
 7 77   18E4   18E4     -252   72E4                          36E5          187     187 -1215
 8 77   18E4   18E4     -252    0.0                          36E5          187     187 -1215
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10 77   18E4    0.0     -252    0.0                          36E5          187     0.0 -1215
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 5 78   18E4   18E4     -252    0.0                          36E5          187     187 -1215
 6 78   18E4   18E4     -252   72E4                          36E5          187     187 -1215
 7 78   18E4   18E4     -252   72E4                          36E5          187     187 -1215
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10 78  18E4   0.0   -252  0.0        36E5   187   0.0 -1215
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 5 79  18E4  18E4   -252  0.0        36E5   187   187 -1215
 6 79  18E4  18E4   -252  72E4       36E5   187   187 -1215
 7 79  18E4  18E4   -252  72E4       36E5   187   187 -1215
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 5 80  18E4  18E4   -252  0.0        36E5   187   187 -1215
 6 80  18E4  18E4   -252  72E4       36E5   187   187 -1215
 7 80  18E4  18E4   -252  72E4       36E5   187   187 -1215
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 4 82  18E4  18E4   -252  0.0        36E5   187   187 -1215
 5 82  18E4  18E4   -252  0.0        36E5   187   187 -1215
 6 82  18E4  18E4   -252  0.0        36E5   187   187 -1215
 7 82  18E4  18E4   -252  0.0        36E5   187   187 -1215
 8 82  18E4  18E4   -252  0.0        36E5   187   187 -1215
 9 82  18E4  18E4   -252  0.0        36E5   187   187 -1215
10 82  18E4   0.0   -252  0.0        36E5   187   0.0 -1215
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 6 83  18E4  18E4   -252  0.0        36E5   187   187 -1215
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10 85   18E4    0.0     -252    0.0                  36E5          187    0.0 -1215
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 6 86   18E4   18E4     -252    0.0                  36E5          187    187 -1215
 7 86   18E4   18E4     -252    0.0                  36E5          187    187 -1215
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 9 86   18E4   18E4     -252    0.0                  36E5          187    187 -1215
10 86   18E4    0.0     -252    0.0                  36E5          187    0.0 -1215
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 6 87   18E4   18E4     -252    0.0                  36E5          187    187 -1215
 7 87   18E4   18E4     -252    0.0                  36E5          187    187 -1215
 8 87   18E4   18E4     -252    0.0                  36E5          187    187 -1215
 9 87   18E4   18E4     -252    0.0                  36E5          187    187 -1215
10 87   18E4    0.0     -252    0.0                  36E5          187    0.0 -1215
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 2 88    0.0    0.0      0.0    0.0                  36E3          0.0    0.0    -5
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 6 88   18E4   18E4     -252   36E4                  36E5          187    187 -1215
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 9 88   18E4   18E4     -252    0.0                  36E5          187    187 -1215
10 88   18E4    0.0     -252    0.0                  36E5          187    0.0 -1215
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 2 89    0.0    0.0      0.0    0.0                  36E3          0.0    0.0    -5
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 6 89   18E4   18E4     -252   36E4                  36E5          187    187 -1215
 7 89   18E4   18E4     -252   36E4                  36E5          187    187 -1215
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10 89   18E4    0.0     -252    0.0                  36E5          187    0.0 -1215
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 2 90    0.0    0.0      0.0    0.0                  36E3          0.0    0.0    -5
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10 90  18E4   0.0    -252   0.0          36E5     187   0.0 -1215
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 5 91  18E4  18E4    -252   0.0          36E5     187   187 -1215
 6 91  18E4  18E4    -252  36E4          36E5     187   187 -1215
 7 91  18E4  18E4    -252  36E4          36E5     187   187 -1215
 8 91  18E4  18E4    -252   0.0          36E5     187   187 -1215
 9 91  18E4  18E4    -252   0.0          36E5     187   187 -1215
10 91  18E4   0.0    -252   0.0          36E5     187   0.0 -1215
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 5 92  18E4  18E4    -252   0.0          36E5     187   187 -1215
 6 92  18E4  18E4    -252  36E4          36E5     187   187 -1215
 7 92  18E4  18E4    -252  36E4          36E5     187   187 -1215
 8 92  18E4  18E4    -252   0.0          36E5     187   187 -1215
 9 92  18E4  18E4    -252   0.0          36E5     187   187 -1215
10 92  18E4   0.0    -252   0.0          36E5     187   0.0 -1215
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 2 93   0.0   0.0     0.0   0.0          36E3     0.0   0.0    -5
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 5 93  18E4  18E4    -252   0.0          36E5     187   187 -1215
 6 93  18E4  18E4    -252  36E4          36E5     187   187 -1215
 7 93  18E4  18E4    -252  36E4          36E5     187   187 -1215
 8 93  18E4  18E4    -252   0.0          36E5     187   187 -1215
 9 93  18E4  18E4    -252   0.0          36E5     187   187 -1215
10 93  18E4   0.0    -252   0.0          36E5     187   0.0 -1215
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 3 94  18E4  18E4    -252   0.0          36E5     187   187 -1215
 4 94  18E4  18E4    -252   0.0          36E5     187   187 -1215
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 7 94  18E4  18E4    -252  36E4          36E5     187   187 -1215
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 5 96  18E4  18E4    -252   0.0          36E5     187   187 -1215
 6 96  18E4  18E4    -252   0.0          36E5     187   187 -1215
 7 96  18E4  18E4    -252   0.0          36E5     187   187 -1215
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 8 96  18E4  18E4    -252   0.0                 36E5       187   187  -1215
 9 96  18E4  18E4    -252   0.0                 36E5       187   187  -1215
10 96  18E4   0.0    -252   0.0                 36E5       187   0.0  -1215
 1 97   0.0   0.0     0.0   0.0                 36E3       0.0   0.0     -5
 2 97   0.0   0.0     0.0   0.0                 36E3       0.0   0.0     -5
 3 97  18E4  18E4    -252   0.0                 36E5       187   187  -1215
 4 97  18E4  18E4    -252   0.0                 36E5       187   187  -1215
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 2 98   0.0   0.0     0.0   0.0                 36E3       0.0   0.0     -5
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 6 98  18E4  18E4    -252   0.0                 36E5       187   187  -1215
 7 98  18E4  18E4    -252   0.0                 36E5       187   187  -1215
 8 98  18E4  18E4    -252   0.0                 36E5       187   187  -1215
 9 98  18E4  18E4    -252   0.0                 36E5       187   187  -1215
10 98  18E4   0.0    -252   0.0                 36E5       187   0.0  -1215
 1 99   0.0   0.0     0.0   0.0                 36E3       0.0   0.0     -5
 2 99   0.0   0.0     0.0   0.0                 36E3       0.0   0.0     -5
 3 99   0.0  18E4    -252   0.0                 36E5       0.0   187  -1215
 4 99   0.0  18E4    -252   0.0                 36E5       0.0   187  -1215
 5 99   0.0  18E4    -252   0.0                 36E5       0.0   187  -1215
 6 99   0.0  18E4    -252   0.0                 36E5       0.0   187  -1215
 7 99   0.0  18E4    -252   0.0                 36E5       0.0   187  -1215
 8 99   0.0  18E4    -252   0.0                 36E5       0.0   187  -1215
 9 99   0.0  18E4    -252   0.0                 36E5       0.0   187  -1215
10 99   0.0   0.0    -252   0.0                 36E5       0.0   0.0  -1215
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APPENDIX C

STEP DRAWDOWN ANALYSIS

The step drawdown test data for the new wells R69, R70, and R71 (Figures C.1-C.6) were analyzed. The new wells are located 3 to 4 miles downstream from the Riyadh well field. The data were collected by the Abunayyen drilling organization during well development. The diameter of each well is about 18 inches and the depth of each is about 656 feet.

The coefficients B and C of the drawdown equation were calculated by both the Jacob and the Rorabaugh methods and an average value was chosen for each well (Figures C.7 and C.8). The efficiency of the well at different pumping rates was also calculated, as shown in Table C.1.

Table C.1 Well Efficiency. -- $WE = \frac{BQ}{BQ + CQ^n}$

Well	Pumping Rate	BQ	CQ^2	WE (%)
R69	280	3.14	0.60	84
	556	6.23	2.30	74
	825	9.24	4.80	66
	1095	12.37	8.24	60
R70	270	8.40	0.50	94
	545	16.90	2.00	89
	825	25.60	4.45	85
	1180	36.60	8.80	81
R71	270	5.40	0.40	92
	645	12.90	20.50	84
	1100	22.00	7.30	75

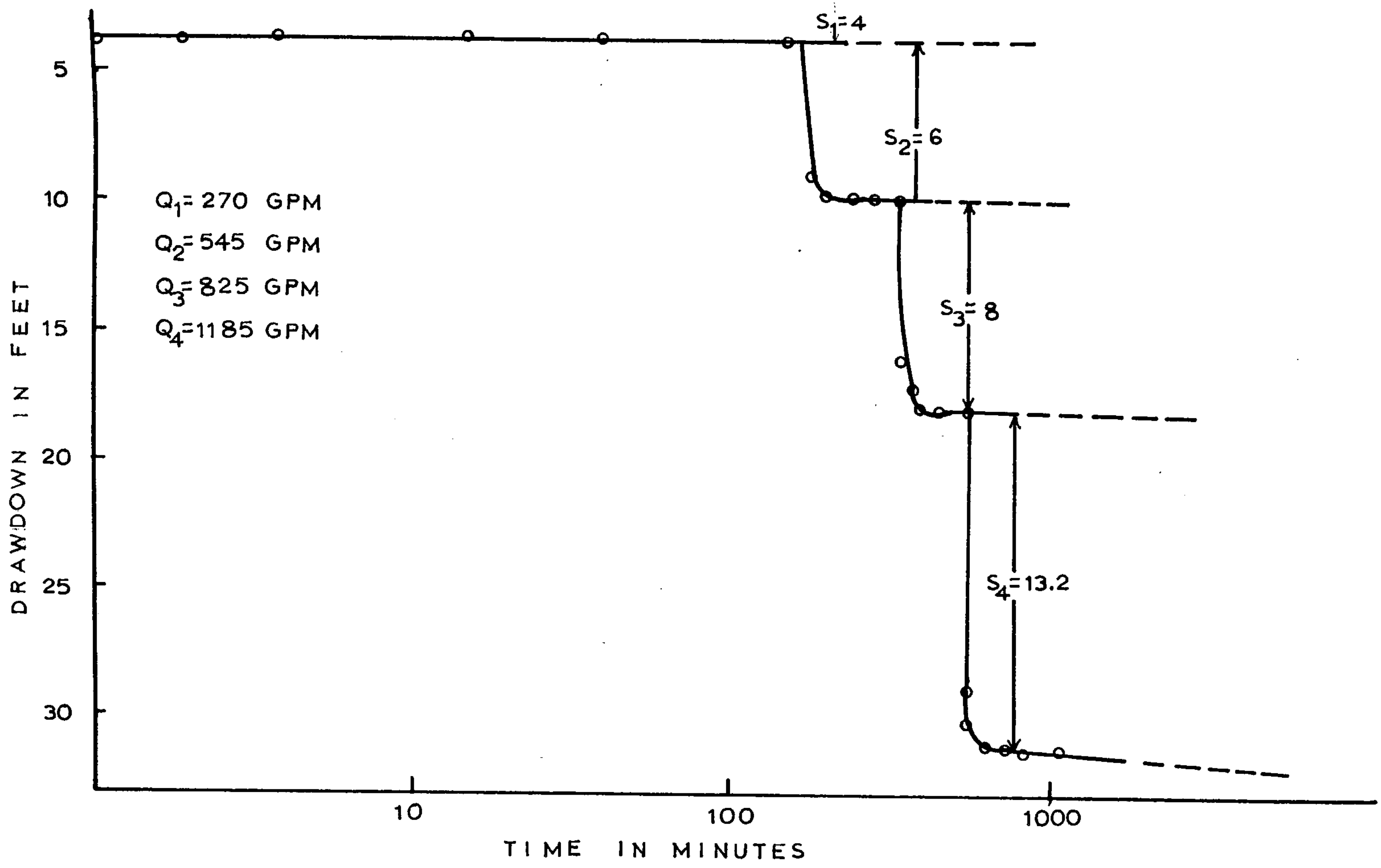

Figure C.1 Time Drawdown Curve during a Step Drawdown Test for Well R69.

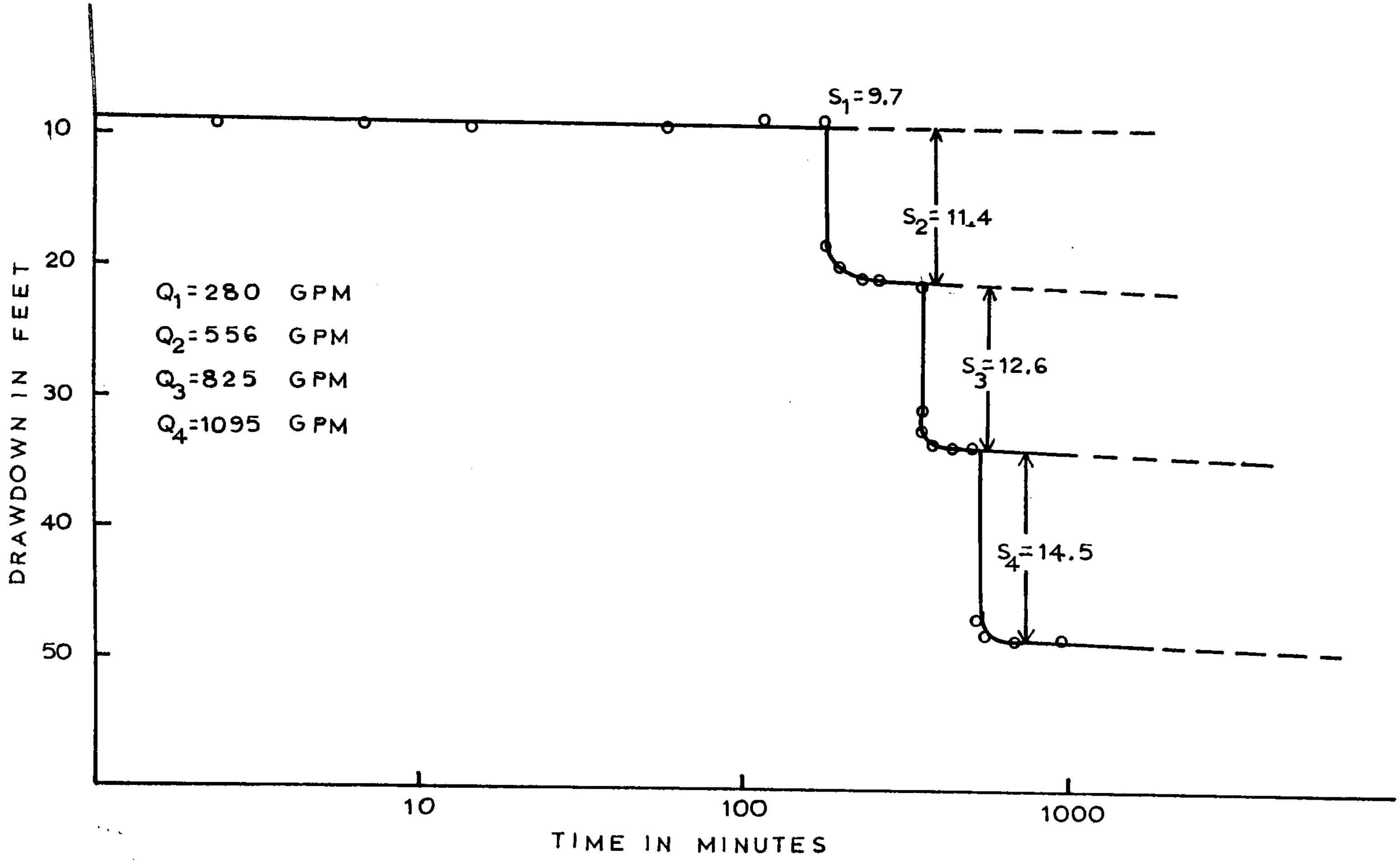

Figure C.2 Time Drawdown Curve during a Step Drawdown Test for Well R70.

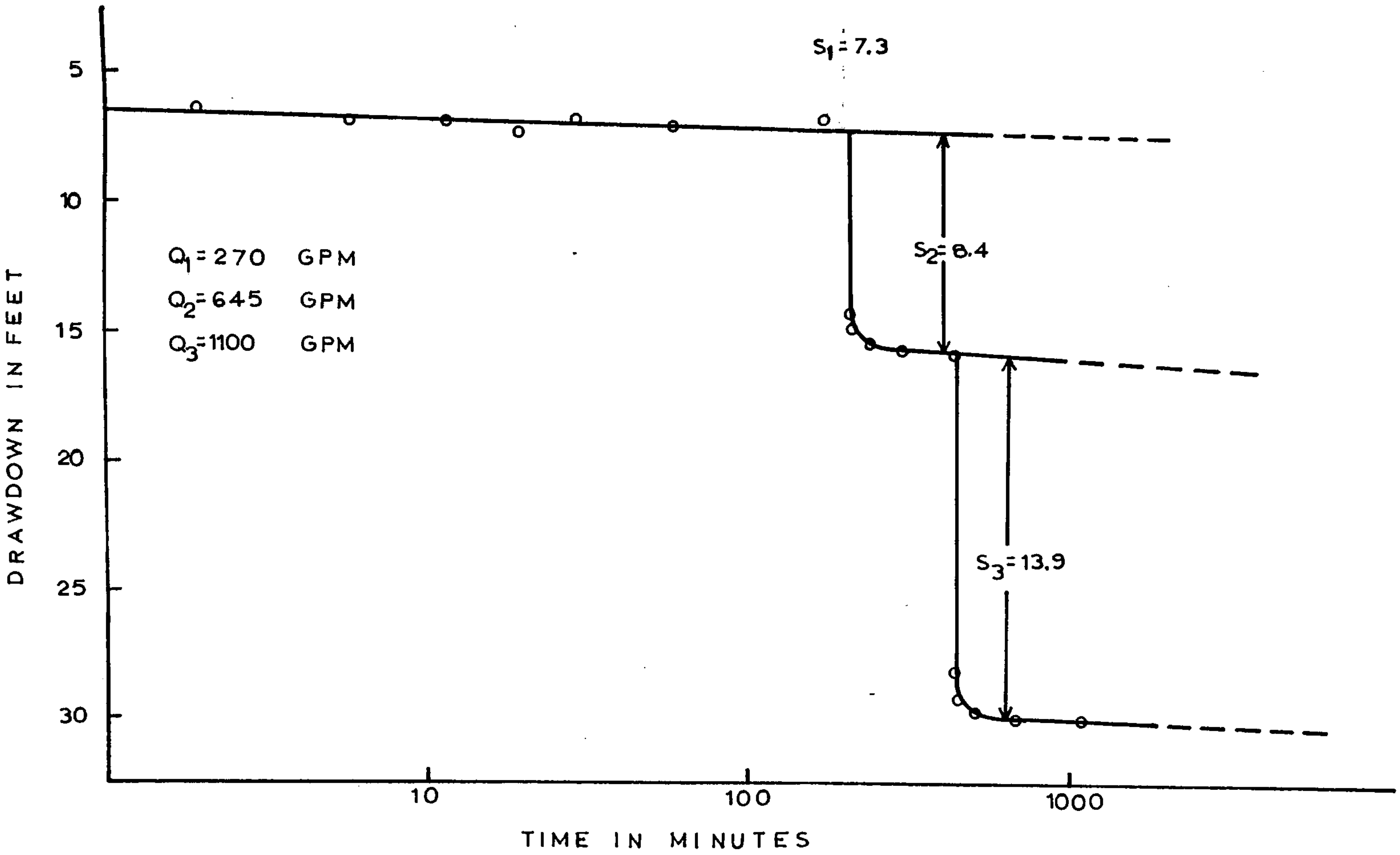

Figure C.3 Time Drawdown Curve during a Step Drawdown Test for Well R71.

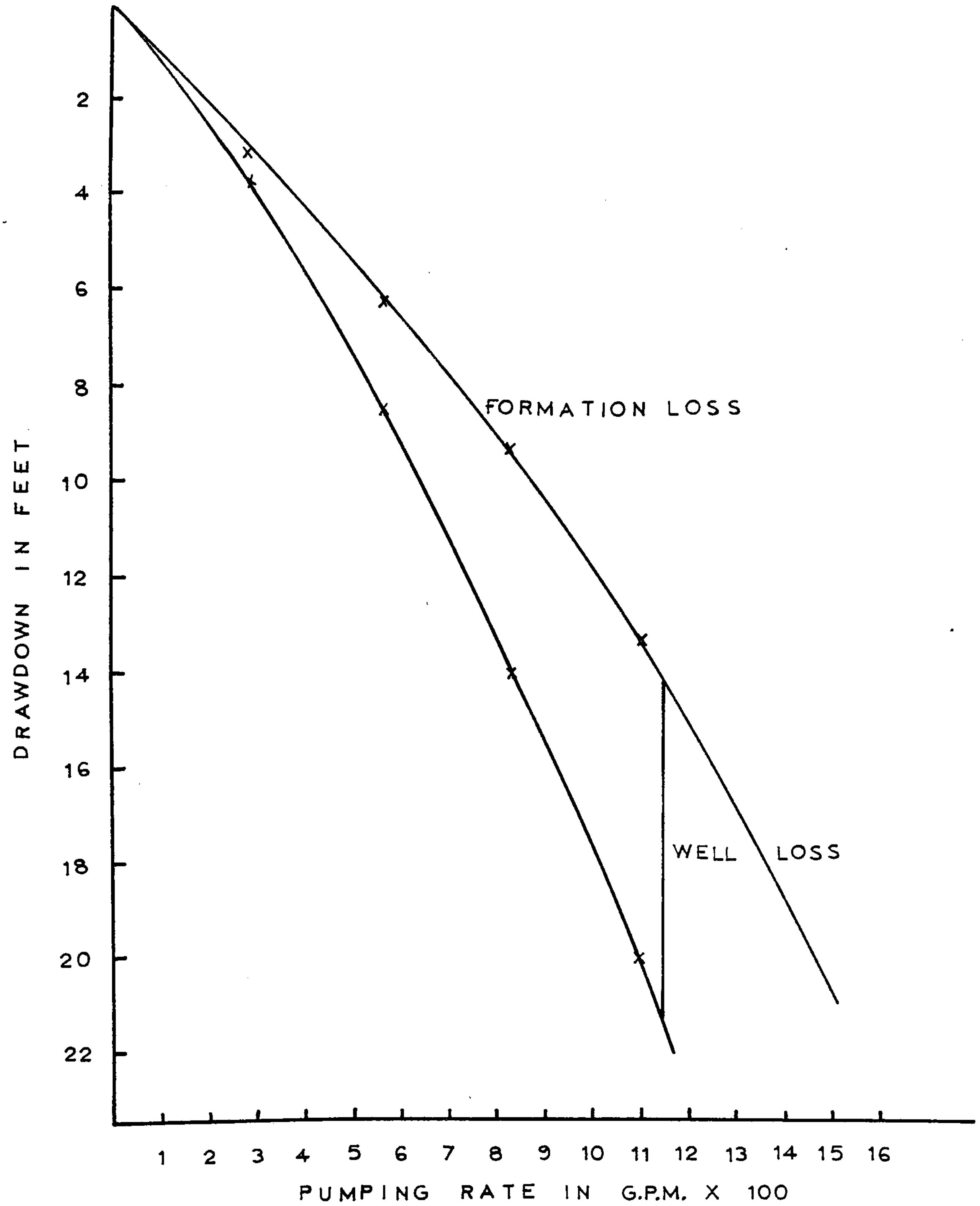

Figure C.4 Total Drawdown in Well R69.

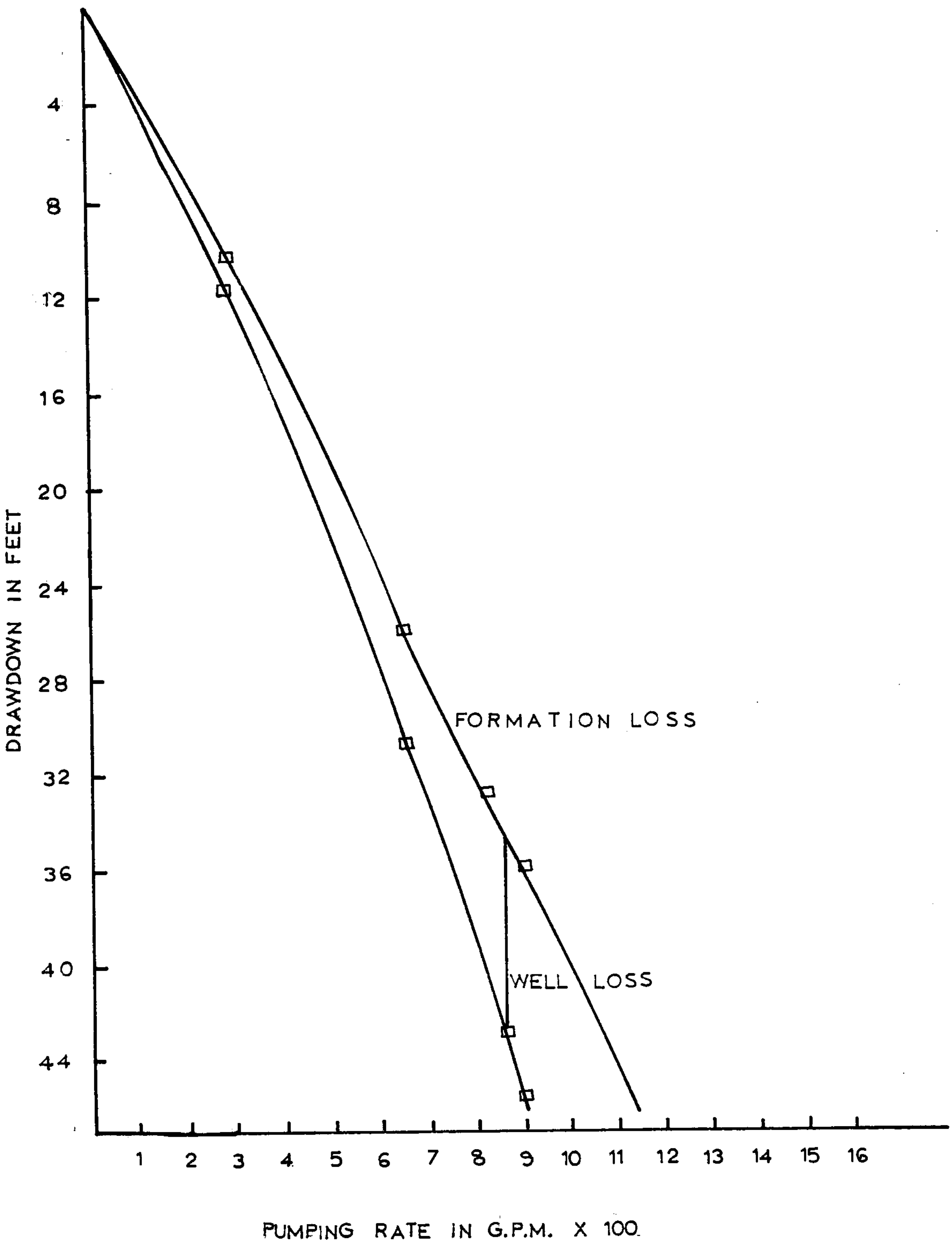

Figure C.5 Total Drawdown in Well R70.

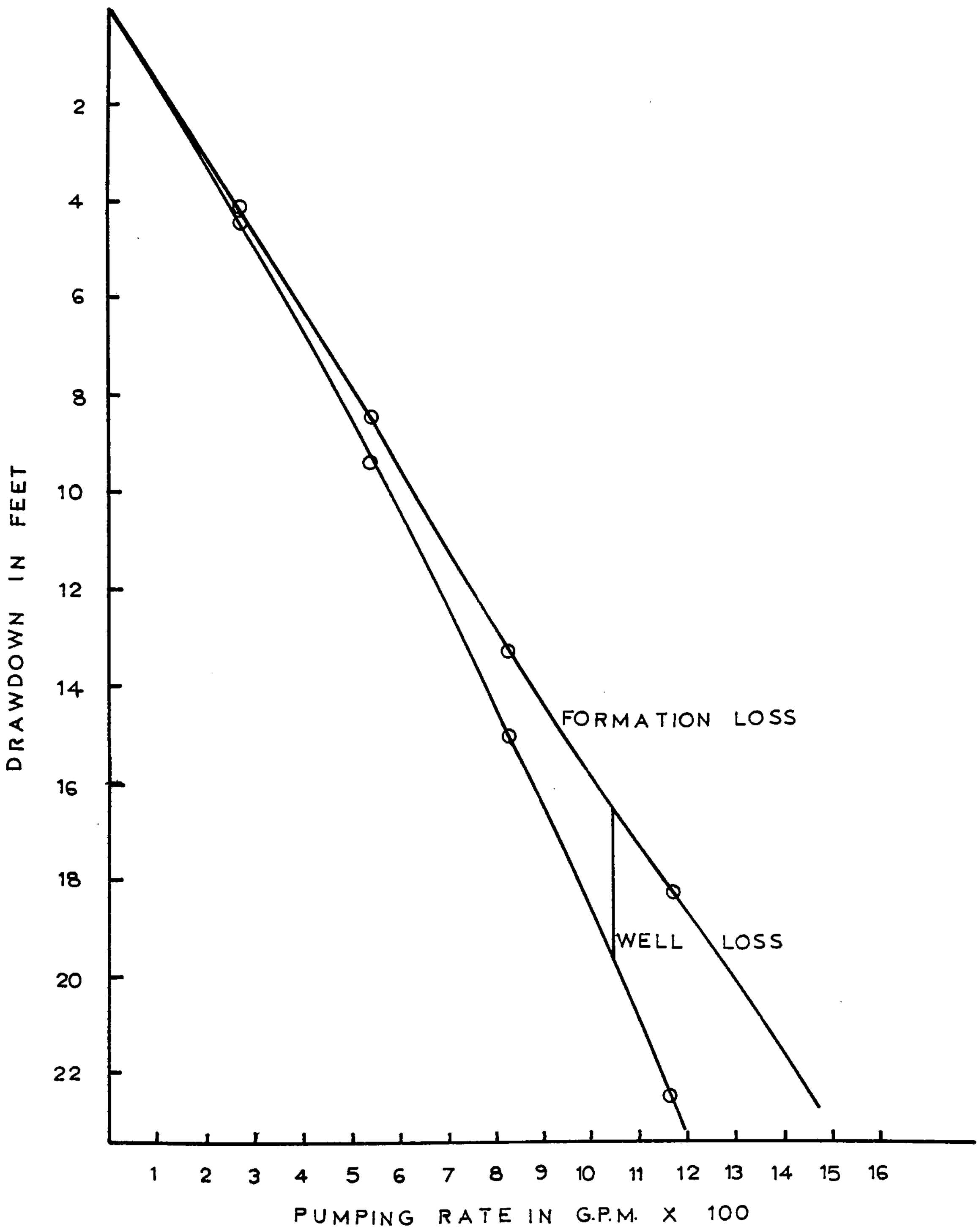

Figure C.6 Total Drawdown in Well R71.

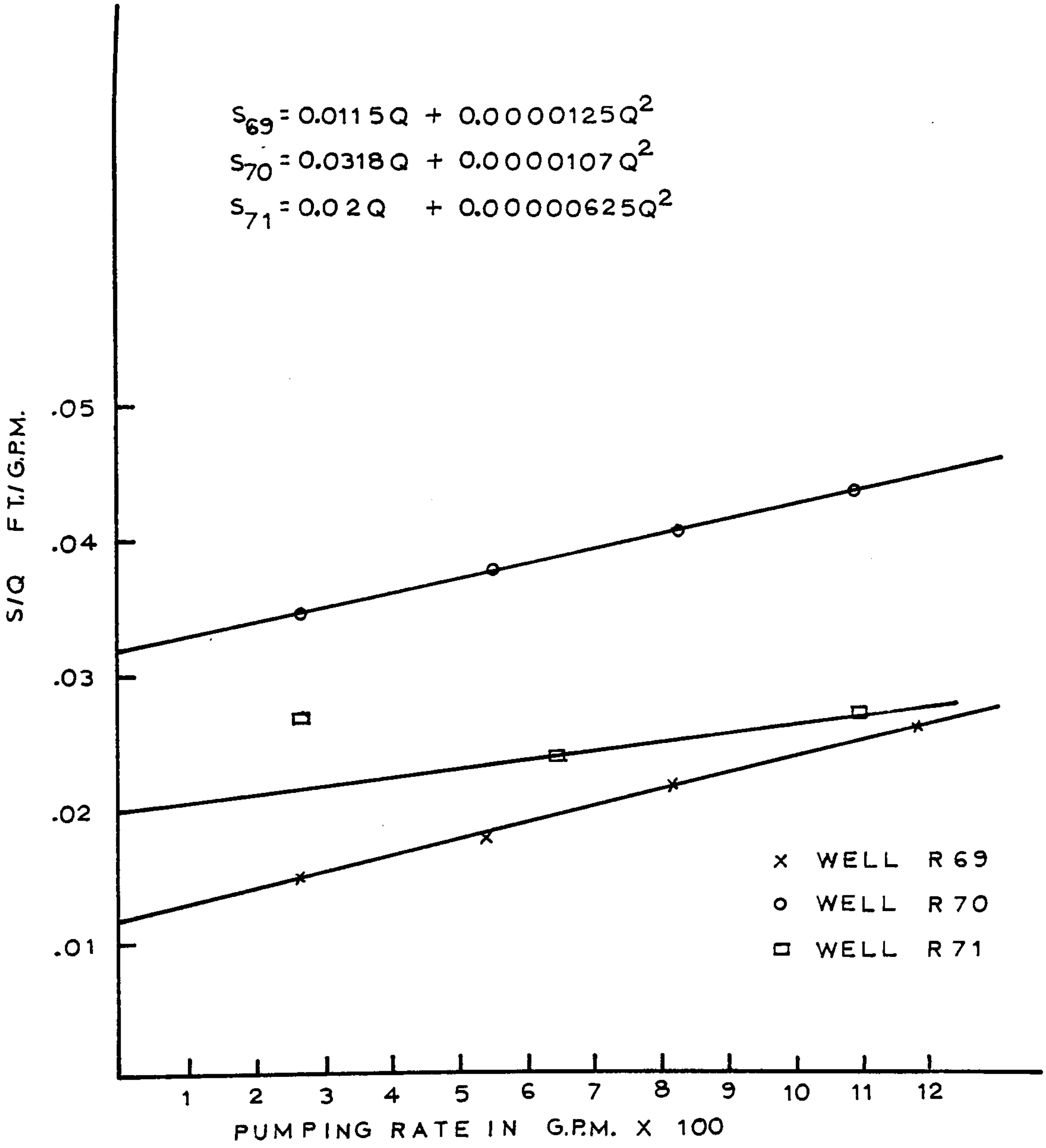

Figure C.7 Graphical Determination of B and C for Jacob Equation.

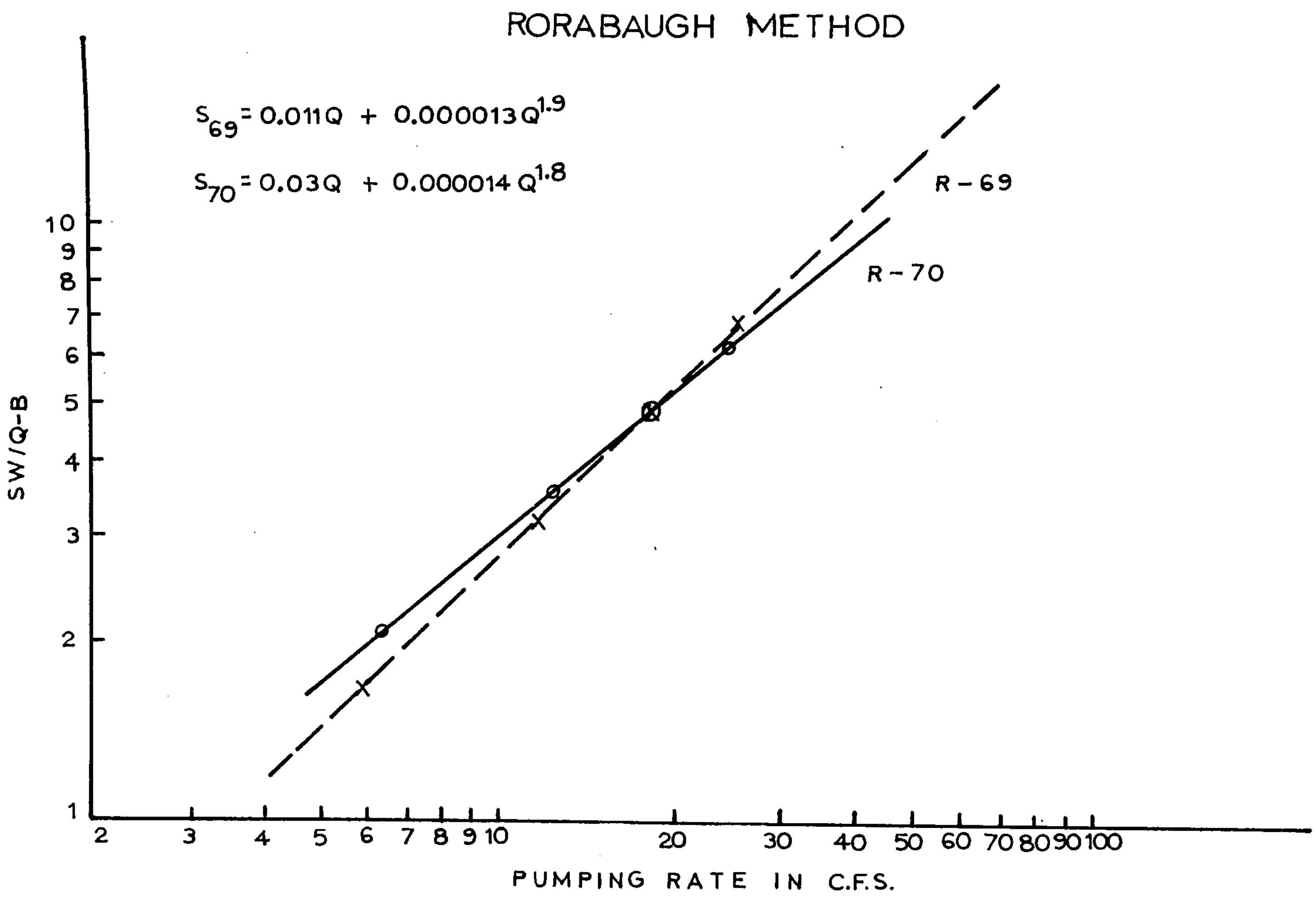

Figure C.8 Rorabaugh Graphical Determination of B and C.

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