INTERN EXPERIENCE WITH
WILLIAM F. GUYTON & ASSOCIATES

AN INTERNSHIP REPORT

by

William Scott Stevens

Submitted to the College of Engineering
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in partial fulfillment of the requirement for the degree of

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December 1980

Major Subject: Agricultural Engineering

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ABSTRACT

Intern Experience with William F. Guyton
& Associates (December 1980)

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This report is a review of the author's experience as an intern with William F. Guyton & Associates. William F. Guyton & Associates is a consulting groundwater hydrology firm with offices in Austin and Houston, Texas. The intern worked at the main office in Austin for the duration of the internship.

The author worked on a variety of projects during the internship. These projects encompassed general groundwater studies, computer simulation, technical analyses of aquifer parameters, and inspection of water well construction and testing.

General groundwater studies involved the collection of water well construction and chemical analyses data. The author wrote several computer codes to handle basic computations, and the author used several existing finite difference codes to simulate groundwater movement. The technical analyses of pumping test data were analyzed by the author to determine aquifer parameters. The field work involved on-site inspection of water well construction and involved

quality control of the pumping test after construction.

The author interacted with various agencies of the state and federal government. This interaction was necessary to many of the projects. The collection of water well data and the use of the finite difference codes gave the author the opportunity to obtain knowledge of the daily operations of these agencies.

ACKNOWLEDGEMENTS

The author wishes to express his deepest and most sincere appreciation to Dr. Donald L. Reddell, Professor of Agricultural Engineering, for his leadership and guidance. His untiring dedication was an inspiration to the author. His service as chairman of the author's advisory committee is also greatly appreciated.

Dr. Robert E. Stewart, Distinguished Professor Emeritus of Agricultural Engineering, served as chairman of the author's advisory committee prior to his retirement. His ideals of engineering as a profession had a significant impact on the author. Dr. Stewart was instrumental in the development and growth of the Doctor of Engineering program at Texas A&M University. The author sincerely appreciates his efforts.

Dr. John L. Nieber, Assistant Professor of Agricultural Engineering, and Dr. Marshall J. McFarland, Associate Professor of Agricultural Engineering, provided valuable assistance in the preparation of this report. Their efforts are appreciated.

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The author is indebted to William F. Guyton & Associates and Dr. William L. Guyton, P.E., for providing this internship.

The financial support from Mr. Mills Cox as sponsor of the W.G. Mills Memorial Fellowship in Hydrology is especially appreciated.

The author expresses his appreciation to his wife, Cindy, for her support and encouragement during the course of the author's graduate studies.

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INTRODUCTION

The required internship is an integral aspect of the Doctor of Engineering program. The main goal of the internship is to provide an insight into all phases of an engineering project. Thus, an awareness of the organizational approach to the problem is made as well as the technical design or analysis (Unpublished Guidelines for Industry Participation in the Doctor of Engineering Internship, College of Engineering, Texas A&M University, September 1976).

In an effort to fulfill the goals of the Doctor of Engineering internship, the following objectives were established to provide direction for this internship:

LONG TERM OBJECTIVES

1. To obtain a thorough and in-depth knowledge of the fundamentals of groundwater hydrology.
2. To become an engineer with confidence in my abilities to complete an engineering assignment.

SHORT TERM OBJECTIVES

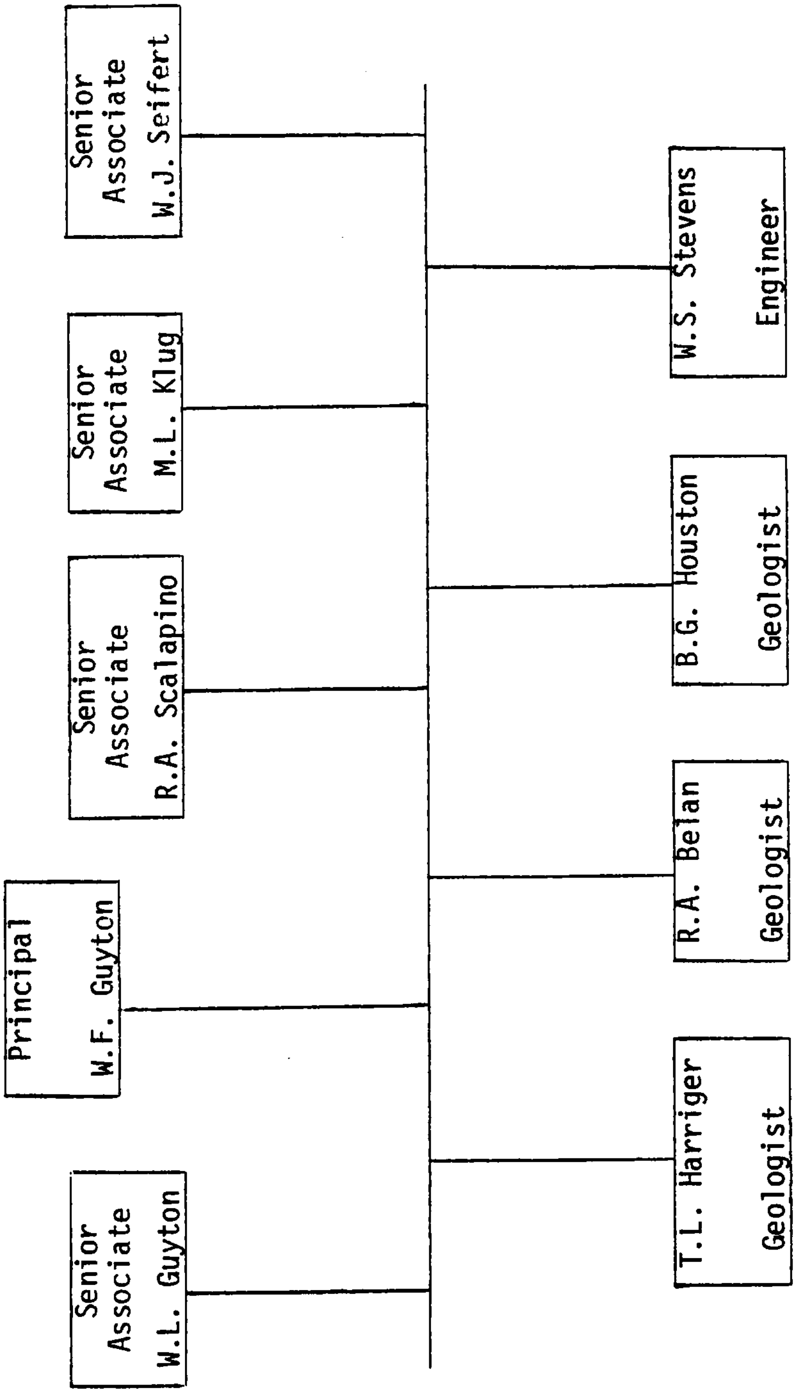
1. To be involved in the design and construction of a connector well field and observation system from the early concept to evaluation of the system and the writing of the final report.
2. To obtain a knowledge of geology, well construction and field evaluations with as much field exposure as possible.

3. To provide assistance in groundwater systems modeling and computer analysis of these models.

William F. Guyton & Associates, hereinafter known as the firm, is a consulting engineering firm specializing in groundwater hydrology. The technical staff consists of engineers and geologists using an interdisciplinary approach for each project. The hierarchial structure of the firm is informal with leadership on all projects provided by the senior staff. This informal hierarchial structure, illustrated in Figure 1, shows the ease of both upward and downward communication allowing any of the junior consultants to have rather easy access to any of the senior associates or the principal.

I was involved in numerous projects during the internship all under the direction of a senior associate or the principal. The project and the project supervisor are shown in Table 1 for all of my projects. Each project is discussed in detail later in this report.

The majority of the technical aspects of this internship involved the computer analysis of groundwater systems. I was also involved in several administrative tasks. Generally, I maintained the records for the computer tapes and files that were necessary by the firm for future documentation. I was also responsible for contacting personnel of the various state and federal agencies that provided information for my projects. Overall, I was responsible for the effective use of all resources required for the completion of the project.



Organizational Chart for William F. Guyton & Associates

Figure 1

Table 1

Internship Projects and Supervisors

Project	Supervisor
Baseline Water Quality and Groundwater Hydrology Study	Dr. W.L. Guyton, P.E. Intern Supervisor
Field Work	R.A. Scalapino
Leach Mine Gradients	M.L. Klug, P.E.
Refinement of Existing Computer Code Utilizing the Nonequilibrium Equation	Dr. W.L. Guyton, P.E.
Well Field Drawdown Analysis Using the Nonequilibrium Computer Code	W.F. Guyton, P.E.
Pumping Test Analysis	Dr. W.L. Guyton, P.E.
Three-Dimensional Groundwater Modeling	Dr. W.L. Guyton, P.E.
Salt Water/Fresh Water Interface Model	Dr. W.L. Guyton, P.E.

BASELINE WATER QUALITY AND GROUNDWATER HYDROLOGY STUDY

A study was conducted by the firm to determine generalized groundwater movement and baseline water quality beneath an industrial plant site. The study involved several aspects of engineering and geology including a field geological survey, water well data collection, and data interpretation.

As a first project, I was responsible for gathering data pertaining to all water wells within a two mile radius of the client's property. The data included information on the size, depth, screened or open interval and static water level of each well. Pertinent information on chemical quality and on the types of logs, such as drillers' and electric logs of the wells, was obtained.

In order to obtain the aforementioned data, interaction with two state agencies was required. These agencies were the Texas Department of Water Resources (TDWR) and the Texas Department of Health (TDH). The TDWR collects as much information as possible on production water wells from all the licensed water well drillers in the state. The TDWR personnel locate the well in the field assigning each a permanent state well number. I was responsible for locating and recording all available information on each well in the study area from these records at the TDWR.

The TDH requires water samples to be taken from most public water supply systems and sent to their laboratory for analysis. A large amount of water for public supply is derived from groundwater;

thus, the TDH was a source for obtaining information on the chemical quality of water from wells.

The records of chemical analysis at the TDH are filed by owner for each county. For this study, the records for two counties covering the area of concern were collected. Complete chemical analyses showing major and minor constituents, organics, and radioactive properties were desired. However, no wells in or near the area had been analyzed to this degree, so as much information as possible was collected.

Because the TDH filed the chemical analysis by owner, the additional problem of correlating these data with the TDWR data was encountered. After several searches through the data files of both agencies, several of the owners were contacted to obtain information on the location and construction of the water well for which only a chemical analysis from the TDH existed.

After exhausting the sources of information, the raw data were compiled and analyzed. The water well information was separated to reflect the water-bearing zone of well completion. From these data Table 2 was prepared describing each well, and Table 3 was prepared showing the chemical analyses.

Static water levels and certain major constituents of the chemical analyses for each aquifer were contoured as an aid in understanding the water quality conditions of the area at the present time. For selected wells in the area, hydrographs were plotted to illustrate the long-term trend of the water levels in the aquifers, as shown in Figure 2.

Table 2

Water Well Construction Data for the Baseline Water Quality and Groundwater Hydrology Study

Well Number	Well Owner	Driller	Year Completed	Altitude of Land Surface (feet)	Depth of Well (feet)	Construction Data			Static Water Level		Use of Water 1/	Logs Available 2/	Water Quality				Remarks
						Casing or Open Hole	Diameter (in)	Depth (feet)	Depth (feet)	Date			Date Sampled	Sulfate (ppm)	Chloride (ppm)	Dissolved Solids (ppm)	
Austin Chalk																	
58-35-703	Travis County	-	-	700	22	C OH	24	0-14 14-22	9.13	3-27-78	D	N	6-7-40	57	11	388	Dug well. 3/
Edwards Limestone																	
58-34-902	S. D. Williams	-	-	902	53	-	-	-	32.09	3-28-46	S	N	11-15-39	22	52	474	3/
58-35-413	W. F. Morrow	L. Daniels	1929	855	336	-	-	0-3	68.96	3-1-78	D,S	N	9-17-70	26	18	458	-
58-35-419	Daniel Gibson	-	-	815	spring	-	-	-	flow	-	U	N	11-13-73	23	25	424	Estimated flow 10 gpm on 11-13-73.
58-35-701	University of Texas	Texas Water Wells, Inc.	1942	790	571	C OH	4	0-320 320-571	163.0	10-14-70	Ind, Irr	D	9-19-49	38	50	479	Originally drilled for magnesium plant. Pumping level 236 ft at 185 gpm on 10-29-42; specific capacity ~3.05. Cemented 228 ft to surface. Caved to 571 ft before 1970. Well originally 610 ft. 4/
58-35-702	Tom Williams	Martin	1935	870	49	C	6	0-22	12.76	10-17-68	D,S	N	6-13-40	17	16	467	3/
58-35-704	G. H. Shafer	C. Shultz	-	740	400	-	-	-	142.88	5-15-59	U	N	12-9-50	188	400	1,177	Abandoned. Water contaminated in 1943 from magnesium plant nearby. 3/
58-35-705	A. C. Roberts	S. W. Glass	1961	720	328	C OH	8	0-178 178-328	109.41	1-18-62	D	N	1-17-62	29	24	335	-
58-35-707	IBM (E. H. Cault)	-	-	760	304	C	5	-	92.67	5-25-45	D,S	N	11-14-39	312	28	760	3/
58-35-708	Robinson Brothers	-	-	801	400	C	4-1/2	-	192.7	1-8-52	D,S	N	10-11-40	310	34	795	3/
58-35-711	J. C. DeGress	-	-	870	63	-	-	-	27.0	11-15-39	U	N	11-15-39	-	19	427	Abandoned.
58-35-714	George Shafer	-	-	755	65	-	-	-	54.10	11-14-39	U	N	7-17-43	160	545	1,452	Abandoned. Contaminated by magnesium plant in 1943.
58-35-716	IBM (J. R. Cault)	Emmett Danley	1904	725	307	C	6	0-170	-	-	U	N	11-14-40	27	22	345	Show of oil at 190 ft
58-35-718	University of Texas	-	-	785	spring	-	-	-	-	-	U	N	12-14-73	24	30	412	Estimated flow 4 gpm on 10-14-40 and 25 gpm on 12-14-73. Rogers Spring.
58-35-719	Beal Stone	-	-	840	spring	-	-	-	-	-	U	N	12-14-73	16	16	350	Estimated flow 5 gpm on 12-14-73.
58-35-804	G. E. Roberts	Robert Crouch	1970	735	416	OH	4-1/2	0-416	-	-	D	E	-	-	-	-	5/
58-35-807	Wallingsford	-	-	700	spring	-	-	-	-	-	S	N	3-22-73	49	38	392	Estimated yield of 50 gpm. Issues through fault in Austin Chalk.
58-35-808	Mrs. Richard Gracy	A. R. Roggenkamp	1976	762	460	C OH	5	0-300 300-460	189.81	6-23-78	D	D	-	-	-	-	Casing cemented 0-40 ft.
58-35-7E	Gene Harmick	W. H. Glass	1974	757	404	C	6-1/4	-	200	11-14-74	D	D	-	-	-	-	-
Glen Rose Limestone																	
58-35-416	Theo Zimmerman	Central Texas Drilling Co.	1968	805	412	-	7	-	38	4-24-68	D	N	9-28-70	16	34	566	-
58-35-706	J. W. Pruett	S. W. Glass	1938	873	126	C	4	-	61.25	4-14-42	D,S	N	6-11-40	-	16	246	3/
58-35-710	M. H. Pruett	-	-	875	272	C	6	-	39.0	8-12-48	D,S	N	9-17-70	17	80	472	100 ft deep before 1949.
58-35-712	J. E. Hill	Ted Norred	1951	868	315	-	7	0-50	170.0	5-51	D,S	N	6-2-51	38	12	378	Glen Rose-Edwards. Reported yield 10 gpm.

Table 2 (continued)

Well Number	Well Owner	Driller	Year Completed	Altitude of Land Surface (feet)	Depth of Well (feet)	Construction Date: Casing or Open Hole	Construction Date: Diameter (in)	Construction Date: Depth (feet)	Static Water Level: Depth (feet)	Static Water Level: Date	Use of Water 1/	Logs Available 2/	Water Quality: Date Sampled	Water Quality: Sulfate (ppm)	Water Quality: Chloride (ppm)	Water Quality: Dissolved Solids (ppm)	Remarks
Glen Rose Limestone (Continued)																	
58-35-713	Harold Strickland	Dick Sanders Drilling Co.	1967	880	314	C OH	7 6-1/4	0-63 63-314	106.5	9-28-70	D	D	9-28-70	36	20	452	Glen Rose-Edwards. Cement from surface to 63 ft.
58-35-715	Spray Subdivision	Hugh Glass	1968	880	316	C OH	-	0-22 22-316	75.0	5-3-68	P	D	6-72	18	24	640	Yield reported 12 gpm.
58-35-717	Capitol Aggregates	W. H. Glass and Son	1963	880	280	C	8	0-60	84.40	8-8-73	Ind	N	8-8-73	42	40	510	Glen Rose-Edwards. Estimated yield of 33 gpm.
58-35-7F	James Fry	Tom Arnold	1975	800	280	C OH	4	0-190 190-280	60	7-29-75	D	D	-	-	-	-	-
Hosston Sand																	
58-35-709	Balcones Research Center, University of Texas	Texas Water Wells, Inc.	1942	785	-	-	-	-	-	-	U	D	-	-	-	-	Abandoned during construction. 4/

FOOTNOTES:

1/ D - domestic Ind - industrial
S - stock Irr - irrigation
U - unused P - public supply

2/ N - none available
D - drillers' log
E - electric log

3/ Historical water-level measurements

4/ Drillers' logs in files of Texas Department of Water Resources.

5/ Electric or radioactivity logs in files of Texas Department of Water Resources.

Table 3

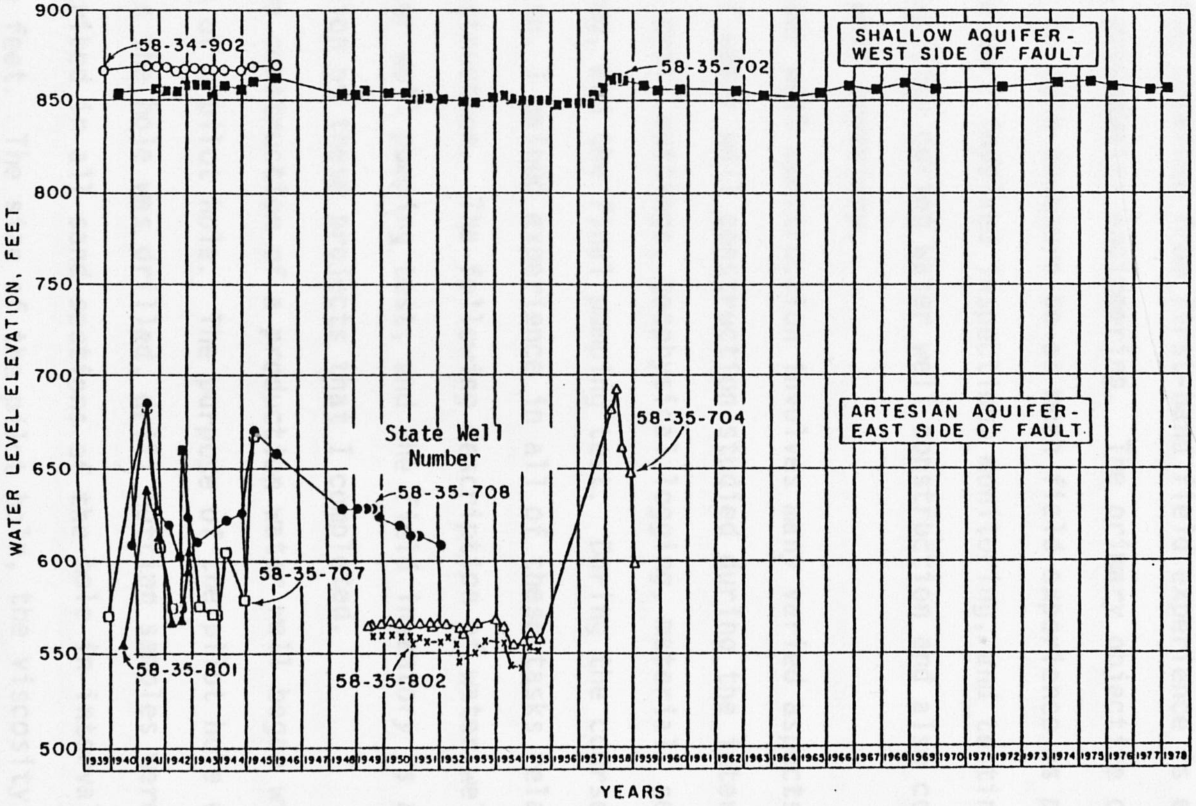
Chemical Analysis of Water Wells for the Baseline Water Quality and Groundwater Hydrology Study

Well Number	Date of Collection	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved Solids	Total Hardness as $CaCO_3$	Specific Conductance (micromhos/cm)	pH	Percent Sodium	SAR 1/
Austin Chalk																			
58-35-703	11-14-39	-	-	-	-	-	-	342	66	11	-	-	-	245	-	-	-	-	-
	6-7-40	-	-	110	10	15	-	336	57	11	-	20.0	-	388	316	-	-	9.36	0.3
Edwards Limestone																			
58-34-902	11-15-39	-	-	101	52	13	-	476	22	52	-	-	-	474	467	-	-	5.72	0.2
58-35-413	9-17-70	12	-	95	44	9	-	439	26	18	1.2	37.0	-	458	420	751	7.3	4.47	0.1
58-35-419	11-13-73	16	-	118	19	13	<1.0	406	23	25	0.2	9.0	0.1	424	376	698	7.8	7.03	00.2
58-35-701	11-4-42	14	0.2	71	17	46	-	329	33	30	0.6	0.0	-	375	247	-	7.5	28.82	1.2
	9-19-49	12	7.4	73	32	34	-	338	38	50	0.0	0.0	-	479	314	-	7.5	19.07	00.8
58-35-702	6-13-40	-	-	141	22	2	-	451	17	16	-	48.0	-	467	444	-	-	0.97	0.0
58-35-704	11-14-39	-	-	86	26	28	-	378	31	37	-	-	-	393	333	-	-	15.92	0.6
	7-17-43	-	-	478	222	152	-	310	311	1,318	-	-	-	2,633	2,106	-	-	13.57	1.4
	5-9-49	12	-	170	90	77	-	333	130	392	-	0.2	-	1,034	794	1,910	7.2	17.41	1.1
	9-9-49	-	-	-	-	-	-	312	190	452	-	-	-	795	-	2,140	8.1	-	-
	10-9-49	8	13.0	140	94	115	-	292	93	458	-	2.8	-	1,184	736	1,990	7.4	25.36	1.0
	12-9-50	12	-	153	80	162	-	370	188	400	-	0.8	-	1,177	710	2,130	7.4	33.14	2.6
58-35-707	11-14-39	-	-	116	57	66	-	366	312	28	1.3	-	-	760	525	-	-	21.51	1.2
58-35-708	10-11-40	-	-	78	76	96	-	403	310	34	3.5	-	-	795	507	-	-	29.16	1.8
58-35-711	11-15-39	-	-	100	49	-	-	470	-	19	-	28.0	-	427	450	-	-	-	-
58-35-714	11-14-39	-	-	164	11	2	-	451	48	30	-	-	-	476	457	-	-	0.94	0.0
	7-17-43	-	-	372	80	44	-	511	160	545	-	-	-	1,452	1,258	-	-	7.07	0.5
58-35-716	10-14-40	-	-	54	31	30	-	329	27	22	-	20.0	-	345	264	-	-	19.92	0.8
58-35-718	10-11-40	-	-	124	34	22	-	525	15	27	-	20.0	-	497	449	-	-	9.62	0.4
	7-17-43	-	-	138	32	3	-	538	14	20	-	-	-	472	476	-	-	1.35	0.0
	9-30-49	-	-	-	-	-	-	389	12	31	-	-	-	-	-	-	7.8	-	-
	12-14-73	13	-	92	34	14	<1.0	398	24	30	0.2	8.0	0.2	412	370	687	7.7	7.59	0.3
58-35-719	6-10-40	-	-	117	23	3	-	439	-	14	-	20.0	-	389	389	-	-	1.66	0.0
	7-20-43	-	-	124	22	1	-	455	12	12	-	-	-	395	400	-	-	0.54	0.0
	5-4-49	12	-	122	22	6	-	438	13	17	-	6.3	-	413	395	724	-	3.19	0.1
	12-18-50	10	-	116	29	5	-	462	13	16	-	6.0	-	422	408	738	7.6	2.59	0.1
	12-14-73	11	-	98	19	8	<1.0	355	16	16	0.2	5.7	0.6	350	323	595	7.6	5.09	0.1
58-35-807	3-22-73	8	-	110	8	26	-	311	49	38	0.4	<0.4	0.2	392	306	664	7.8	15.54	0.6
Glen Rose Limestone																			
58-35-416	9-28-70	12	-	126	43	15	-	473	16	34	0.1	88.0	-	566	492	890	7.4	6.22	0.2
58-35-706	6-11-40	-	-	7	32	6	-	378	-	16	-	-	-	246	325	-	-	8.05	0.2
58-35-710	9-17-70	12	-	137	25	9	-	510	17	18	0.2	3.5	-	472	450	781	7.2	4.21	0.1
58-35-712	6-2-51	14	-	58	51	11	-	391	38	12	-	2.0	-	378	354	716	7.7	6.32	0.2
58-35-713	9-28-70	15	-	97	45	9	-	465	36	20	1.2	<0.4	-	452	425	733	7.5	4.38	0.1
58-35-715	6-1-72	-	-	87	44	13	-	-	18	24	1.2	8.0	-	640	401	-	7.4	6.63	0.2
58-35-717	8-8-73	11	-	119	37	17	3.0	433	42	40	0.3	28.0	0.1	510	449	819	7.8	7.54	0.3

FOOTNOTE:

1/ Sodium adsorption ratio

All of the above are in units of milligrams per liter except specific conductance, pH, percent sodium, and SAR.



Hydrographs of Selected Wells for the Baseline
Water Quality and Groundwater Hydrology Study

Figure 2

FIELD WORK

A thorough knowledge of the techniques of water well construction and testing obtained from first-hand field experience is essential for good groundwater engineering. The primary objective of this internship was to gain exposure to as much field experience as possible. The field work involved inspection, monitoring, and testing production capability during water well construction and also conducting a water well inventory.

Water well construction involves many varied aspects. The phases of water well construction studied during the internship were sampling drill cuttings, geophysical logging, materials setting, gravelling, and the final pumping test. During the course of the internship, I gained experience in all of these tasks related to water well construction. The following description of water well construcion, water well pumping test, and the field inventory is a general description of these projects that I completed.

The construction of a production water well began with the drilling of a pilot hole. The purpose of the pilot hole was two-fold. First, as the hole was drilled, drill cutting samples were collected and described in all sand sections of the hole in intervals of no more than ten feet. The size of the pilot hole, the viscosity and pumping rate of the drilling fluid, and the rate of drilling affect the time for the drill cuttings to reach the surface as well as the spatial distribution of the drill cuttings at the surface. Thus, by limiting the drilling in a sand formation to ten feet, a representative sample of the formation can be collected. Samples from the other sections were observed and described but not collected. Secondly, after the pilot hole was drilled, an electric induction log was made in the pilot hole. Using the sample drill cuttings and the electric log, estimates of the locations of the sand sections in the hole were made. Also, the amount of sand determined using both of these techniques may be estimated and used to predict if the well will meet specified production guarantees. The selection of the well screen was based on the particle size distribution from a sieve analysis of the drill cuttings and the length of the sand sections from the drillers' log and the electric log. The construction of a pilot hole is a key element in the decision process of the success or failure of a production gravel-walled water well. All decisions about the construction of the well were placed on the contractor. The firm would provide technical advice in the analysis of the well data to the contractor. Any deviations from the specifications contract had to be approved by the owner. Generally, the owner, the contractor, and the firm were three separate entities. Thus, the contractor assumed all financial risk in the success or failure and he gained or suffered financially because of the risk.

After the decision to construct the production well was made, the pilot hole was reamed to specified depth and surface casing was cemented into place. The surface casing provided protection from pollutants which could otherwise enter the well from the surface. It also provided protection from undesirable groundwater zones which may be near the surface. The remainder of the pilot hole was then drilled to the total depth. The screen and blank liner selected from the pilot hole phase were set in place. The blank liner provided protection from clays and fine-grained sand that a gravel pack could not restrict from entering the well. Finally, the gravel pack was pumped into the annulus between the screen or blank liner and the wall of the well. These last two activities were extremely important to ensure that the well was constructed properly and to provide the best well possible.

During the construction process, I was responsible for the accurate collection of the drill cutting samples; for determining the validity of the log based on prior knowledge from the drill cutting samples; for monitoring and recording data associated with the setting and cementing of the surface casing; for setting the screen and blank liner; and for gravelling the water well.

A final pumping test of the well was made before approval by the firm and acceptance by the client. Usually the pumping test consisted of four three-hour steps, in which pumping was conducted at a constant rate for three hours with a three-hour recovery period following each pumping step. The recovery steps made analysis of the pumping test simpler and more accurate by eliminating the compounding of drawdown trends which occur when pumping steps are continuous. In addition to the step tests, a forty-eight hour continuous test, followed by twenty-four hours of recovery measurements, was conducted to establish the long-term drawdown trend of the well. Water level measurements were taken during the twenty-four hour recovery period prior to the long continuous test. Generally, most of the drawdown trend from the step tests had diminished and were not apparent during this recovery period.

Analysis of the pumping test data yields an indication of the present condition of the well. The pumping test provided insight into the production capabilities of the well. Since final acceptance of the well depended on the outcome of this test, accurate data collection and analysis were extremely important. From the results of both the step tests and the continuous test, transmissivities and specific capacities for the well were calculated. Specific capacity is a measure of the well's ability to produce a specified flowrate over a period of time with a certain drawdown.

Another important aspect of groundwater evaluation is the water well inventory. As previously described, water well data from various sources such as state agencies were collected. A water well inventory encompasses the physical location of the well in the field, and provides a check of the accuracy of the data for the well. In addition, information can be gathered on any wells for which no records existed which were missed during earlier data collection. Two procuedures were used to gain information on wells for the field inventory. The first was to physically travel over the study area and observing the location and condition of as many water wells as possible. Second, personal contact was made with local residents to gain their knowledge of water wells in the area.

Water well inventories are varied in nature. Some require detailed data on location, water level measurements, chemical analysis, and short-term pumping tests. However, other inventories are made to confirm well locations and to gather water samples. The type of inventory was dependent on the clients' needs and on the amount and quality of information that was available in an area from historical records.

I was involved in one water well inventory covering three counties near the Texas Gulf Coast. The objective of the inventory was to verify the location of all large production wells previously recorded, collect water samples, and to locate and gather well information on large production wells not on record.

LEACH MINE GRADIENTS

In the southwestern United States, uranium mining has been undertaken by many companies. Energy related mining companies use various mining techniques, some of which involve the use of groundwater.

The firm became involved with one such energy related mining company. The client was beginning mining operations using deep vertical shaft mining, and was planning a pilot leach mine. The deep shaft mining involved dewatering a massive confined aquifer in the region. The pilot leach mine, chemical mining of uranium, was located within five miles of the dewatering wells for the deep shaft mine. Because of this close proximity of the leach mine to the dewatering sites the client was interested in the effects that a combination of three dewatering wells would have on the rate and direction of groundwater movement, and thus the movement of the leaching chemical.

The leaching material was to be injected at the pilot leach mine while four surrounding wells would remove the leaching material with the uranium in solution. Three existing dewatering sites from the deep shaft mine were selected to provide the driving force in order to observe the resultant groundwater movement. Prior to my internship, a computer code was developed to compute pumping rates at each dewatering well. Constant drawdown was imposed at each well to dewater the deep shaft mine. The resulting pumping rates generated by the code were used to predict drawdown at four observation points surrounding the leach mine.

Using the drawdown observed from the four surrounding observation points as the driving force, a computer code was developed by me to compute the magnitude and the angle of the gradient of groundwater movement at the leach mine. The derivation of the gradient vector is given in Appendix III-1.

To determine the movement of the leaching chemical, it was necessary to know the direction of the gradient and the rate of the groundwater movement. The direction of the gradient was found by the following:

$$D = \arctan (G_i / G_j) \qquad \text{............} \quad (1)$$

where,

G_i = magnitude of the gradient vector in the i-direction, LL^{-1},
G_j = magnitude of the gradient vector in the j-direction, LL^{-1},
i and j = mutually prependicular coordinate axes, and
D = angle of the gradient vector from the horizontal axis.

The rate of the groundwater movement was found by using the following form of Darcy's Law:

$$\bar{V} = \frac{KG}{\theta} \qquad \text{............} \quad (2)$$

where,

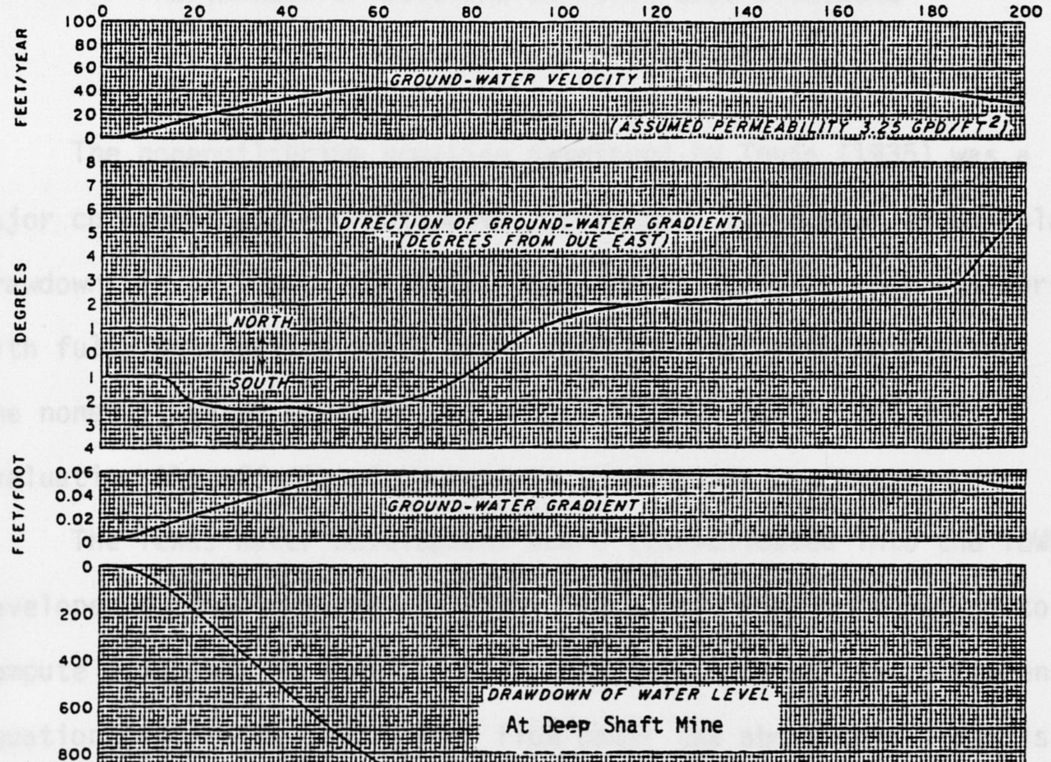
$\bar{G}$ = gradient vector at the leach mine, LL^{-1},

$\bar{V}$ = velocity vector of groundwater movement, LT^{-1},

θ = porosity of the aquifer, and

K = hydraulic conductivity of the aquifer, LT^{-1}.

The rate and direction of groundwater movement at the leach mine are shown in Figure 3 for the assumed conditions.



Effects at Leach Mine Due to Pumping Three
Dewatering Wells 5 Miles from Leach Mine

Figure 3

REFINEMENT OF EXISTING COMPUTER CODE UTILIZING THE NON-EQUILIBRIUM EQUATION

The nonequilibrium equation developed by Theis (1935) was a major contribution in groundwater hydrology. It is used to calculate drawdowns in confined, nonleaky, homogeneous and isotropic aquifers with fully penetrating wells under constant discharge conditions. The nonequilibrium equation has become an invaluable tool for evaluating the effects of pumpage on groundwater systems.

The Texas Water Development Board (consolidated into the TDWR) developed a computer code utilizing the nonequilibrium equation to compute drawdowns in a well field. The governing partial differential equation describing groundwater flow under the above conditions is:

$$\frac{\delta^2 h}{\delta r^2} + \frac{1}{r}\frac{\delta h}{\delta r} = \frac{S}{T}\frac{\delta h}{\delta t} \quad \text{............} \quad (3)$$

where,

h = hydraulic head in the aquifer, L,

S = coefficient of storage, and

T = coefficient of transmissivity, L^2T^{-1}.

The boundary conditions for Equation 3 are given as follows:

$$h\ (\infty, t) = h_0 \quad \text{............} \quad (3a)$$

$$\lim_{r \to 0} r \frac{\delta h}{\delta r} \doteq \frac{Q}{2\pi T} \quad \text{............} \quad (3b)$$

Where,

h_0 = initial hydraulic head in the

aquifer, L.

The initial condition for Equation 3 is given as :

$$h\ (r,o) = h_o \qquad \ldots\ldots\ldots\ldots \qquad (3c)$$

The solution of Equation 3 given by Theis (1935) is:

$$s = \frac{Q}{4\pi T}\left(-0.5772 - \ln u + \sum_{n=1}^{\infty} \frac{u^n}{n \cdot n!}\right) \ldots\ldots\ldots \qquad (4)$$

where,

$s = h_o - h$ = drawdown, L,

Q = well discharge, L^3T^{-1}.

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

r = distance from pumped well to observation point, L,

S = coefficient of storage, and

t = time, T.

Thus, Equation 4 represents the nonequilibrium equation.

The computer code was modified to read data, initialize arrays, assign the flowrate and length for each pumping period, and print results. The flowchart for the code is given in Appendix IV-1.

The solution to the nonequilibrium equation was compiled into a subroutine. In the subroutine, the drawdown was calculated at each observation point for each time period of constant well discharge. The logical sequence of the subroutine is illustrated in the flowchart in Appendix IV-2.

The code repeats the above calculations for each pumping well. The combined effect from several wells was obtained by summing the drawdowns from each well at a point. This procedure is based upon the principle of superposition, and results from the linearity of Equation 3.

To give the code more flexibility, a subroutine to compute drawdowns for anisotropic conditions was also created by me and my intern supervisor. To facilitate this computation, the coordinate system axes has to be oriented to correspond to the direction of maximum and minimum transmissivity. The following equations represent the solution by Theis (1935) under anisotropic conditions:

$$s = \frac{Q}{4\pi T} \left(-0.5772 - \ln u_r + \sum_{n=1}^{\infty} \frac{u_r^{\,n}}{n \cdot n!} \right) \text{.........} \quad (5)$$

where,

$$T_e = (T_{max} \cdot T_{min})^{\frac{1}{2}} \text{ , } L^2T^{-1}\text{, and}$$

where,

T_{max} and T_{min} represent values of transmissivity along the principle axis of the transmissivity tensor (see Figure 4) L^2T^{-1}, and

T_e = effective transmissivity, L^2T^{-1}.

$$U_r = \frac{r^2S}{4T_rt} \quad \text{............} \quad (5b)$$

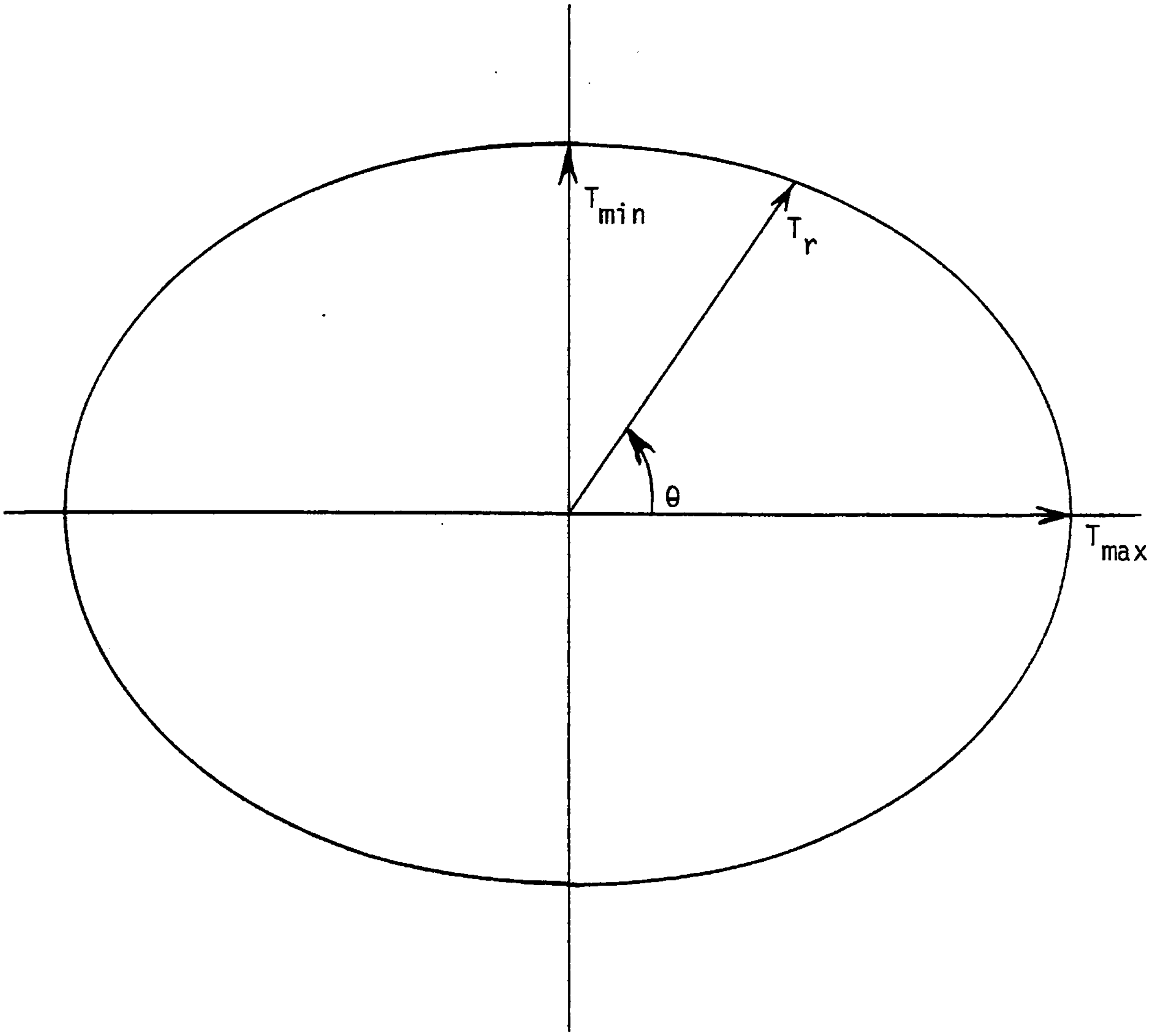
where,

$$T_r = \frac{T_{max}}{\cos^2\theta} + \frac{T_{min}}{\sin^2\theta} = \text{directional ...} \quad (5c)$$

transmissivity, L^2T^{-1},

where,

θ = angle from the major principle axis.



Elliptical Cone of Depression
Showing Anisotropy

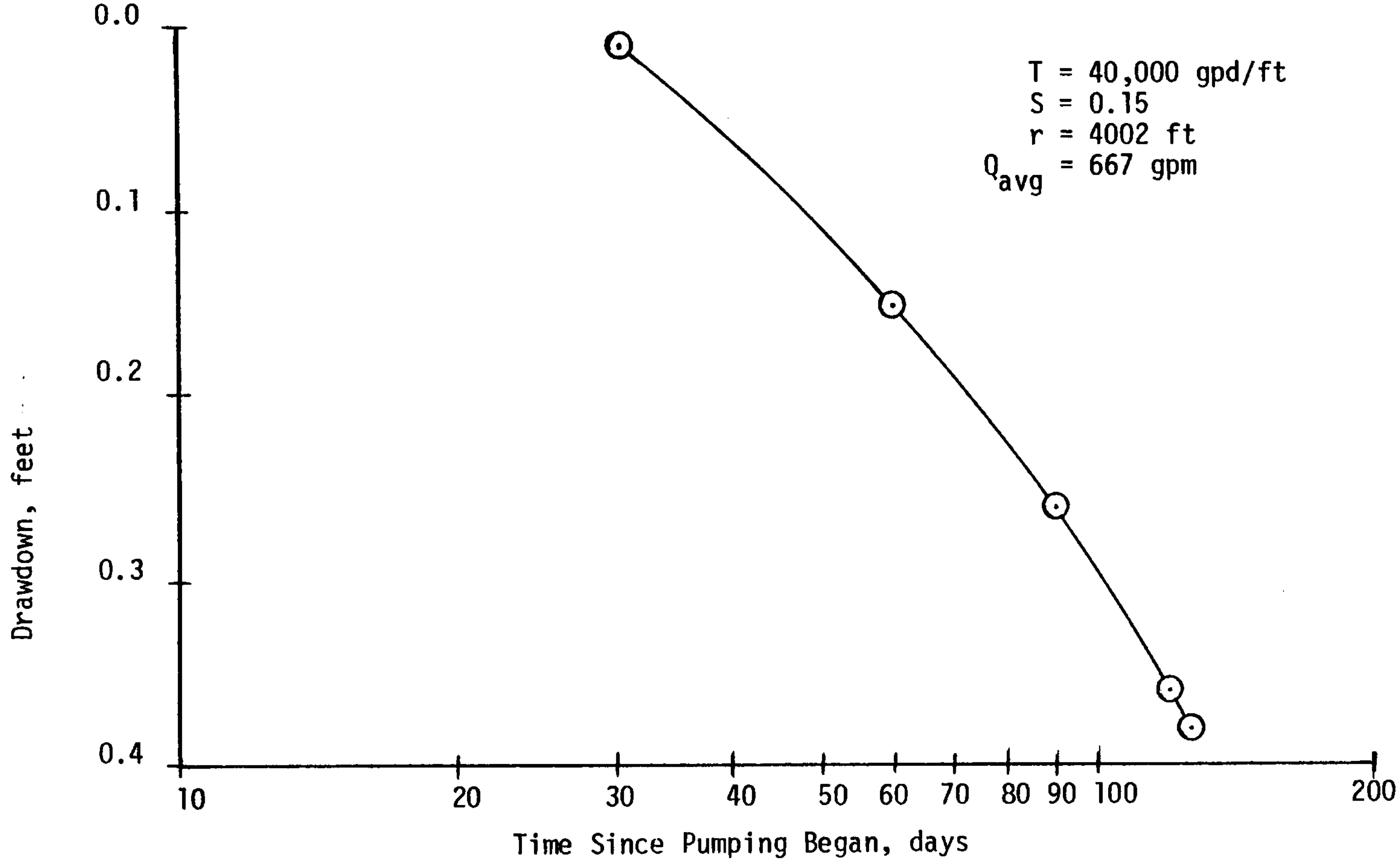
Figure 4

This subroutine is used to solve the nonequilibrium equation for the anisotropic case as shown in the flowchart in Appendix IV-2.

The documentation of the computer code involved the testing of several cases. Two cases are shown in Appendix IV-3a and IV-4. The results for both cases were checked by manual computation of drawdown for each time period caused by each pumping well for all observation points. An example of the check is illustrated in Appendix IV-3b. The shape and trend of the time drawdown curve in Figure 5 illustrate the code computed drawdowns according to the theory of groundwater movement under the previously described conditions and assumptions.

The documentation of the anisotropic subroutine was accomplished by reproducing the results of the isotropic cases above. Due to time limitations, no further documentation was provided.

The computer code utilizing the nonequilibrium equation for groundwater movement is a useful tool for evaluating the drawdowns in a well field under the aforementioned simpifying assumptions. Analysis of well field conditions occurs frequently in a consulting groundwater firm. Thus, the code is not only a time saving tool, but it also provides a greater degree of accuracy than the hand calculations normally used.



Time Drawdown Curve for the Nonequilibrium Equation

Figure 5

WELL FIELD DRAWDOWN ANALYSIS USING THE NONEQUILIBRIUM COMPUTER CODE

A study to locate additional wells in an existing well field was conducted for an electric power company by the firm. As new units of the power plant are installed more wells are needed to provide boiler-feed water with limits on the water quality.

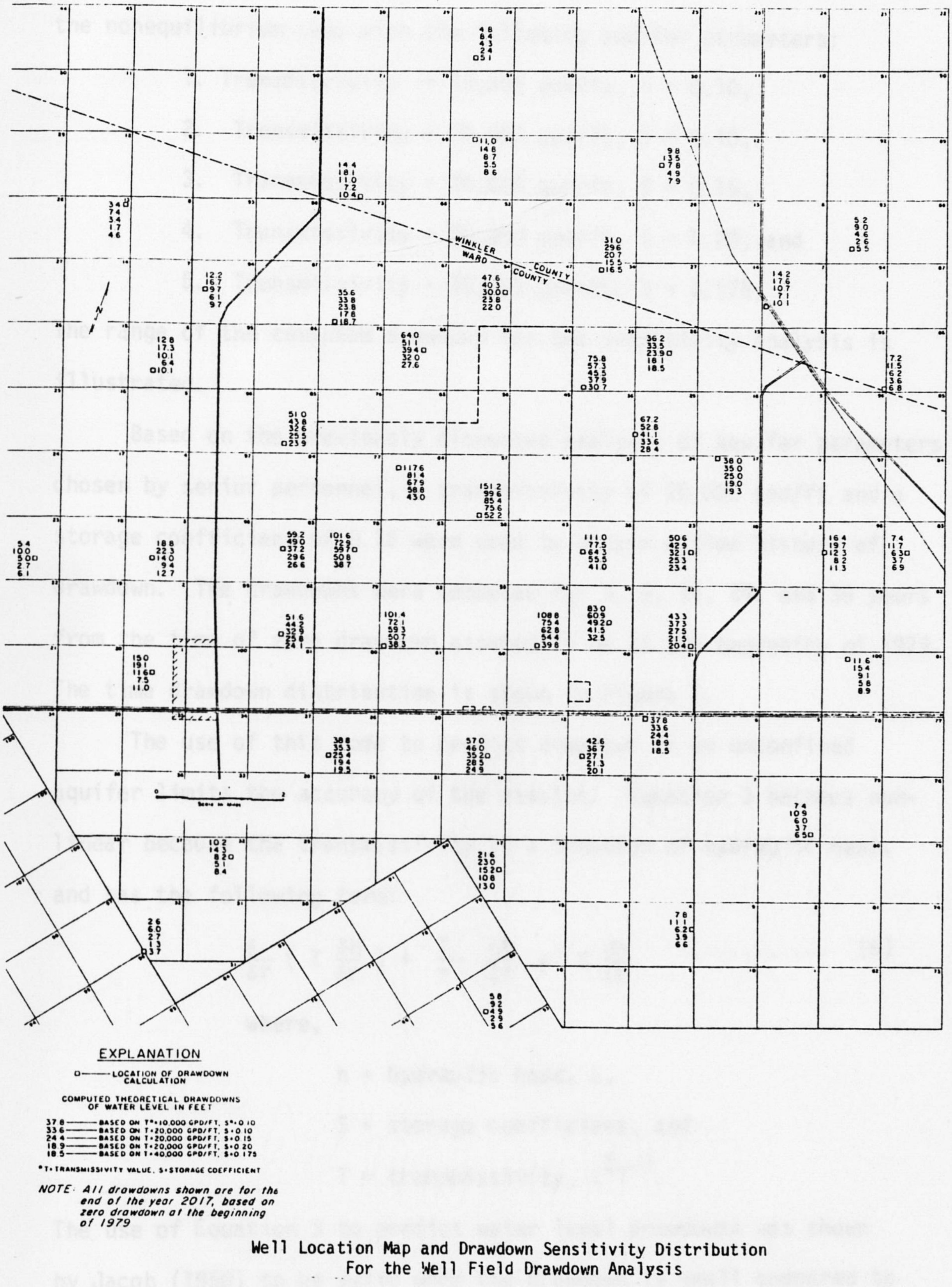
A small but integral part of the study was the prediction of drawdown in and around the well field. The computation of the drawdowns was accomplished using the nonequilibrium computer code described in the previous section. The use of the nonequilibrium equation restricts the accuracy of the drawdown prediction because the assumptions that the water-bearing units were homogeneous, isotropic and infinite in areal extend were not entirely fulfilled. The transmissivity generally appears to increase from east to west through the well field. Also, the water-bearing unit decreases in thickness until it is very thin several miles east of the well field. The water-bearing unit exists under unconfined conditions and the amount of saturated thickness dewatered generally exceeds the range for which the nonequilibrium equation is valid (Jacob, 1950).

The first phase of this project was to determine the accuracy of the code when predicting drawdowns in existing wells, and to determine the applicable range for transmissivity and coefficient of storage. Pumpage data were obtained from the power plant personnel on a daily basis for seven months. This pumpage data was summed on a monthly basis to yield the actual volume of water removed for the first four months. A constant pumping rate was chosen to remove the same volume of water during the computer code simulation. Likewise, a weekly pumpage rate was obtained to simulate the total volume of water removed over the last three months. The geometry of the well field was established and distances between wells for use in the code were established.

Initial runs of the computer code using the nonequilibrium equation were made. The code computed water level drawdowns at several points in the well field where field measurements were available. The results of these runs were presented to senior personnel in the firm. They selected the most reasonable aquifer parameters that reflected the field measurements. They chose a transmissivity of 20,000 gallons per day per foot and a storage coefficient of 0.15.

The second phase of the project involved use of the nonequilibrium code to predict drawdown in and around the well field due to the pumpage from existing and proposed wells. Nineteen wells currently exist in the well field, and 38 additional wells are planned to provide the required water supply for the three units of the power plant. Drawdowns were computed at 46 locations in and around the well field. The locations were selected to provide adequate coverage of the well field and an area covering five miles in all directions from the boundaries of the well field. The location of these observation points are shown in Figure 6.

Drawdowns at the 46 observation points were computed using



NOTE: All drawdowns shown are for the end of the year 2017, based on zero drawdown at the beginning of 1979

Well Location Map and Drawdown Sensitivity Distribution
For the Well Field Drawdown Analysis

Figure 6

the nonequilibrium code with the following aquifer parameters:

1. Transmissivity = 10,000 gpd/ft, S = 0.10,
2. Transmissivity = 20,000 gpd/ft, S = 0.10,
3. Transmissivity = 20,000 gpd/ft, S = 0.15,
4. Transmissivity = 20,000 gpd/ft, S = 0.20, and
5. Transmissivity = 40,000 gpd/ft, S = 0.175.

The range of the computed drawdown for the sensitivity analysis is illustrated.

Based on the previously discussed analysis of aquifer parameters chosen by senior personnel, a transmissivity of 20,000 gpd/ft and a storage coefficient of 0.15 were used to obtain a time history of drawdown. The drawdowns were computed for 4, 9, 14, 24, and 39 years from the time of zero drawdown assumed to be at the beginning of 1979. The time drawdown distribution is shown in Figure 7.

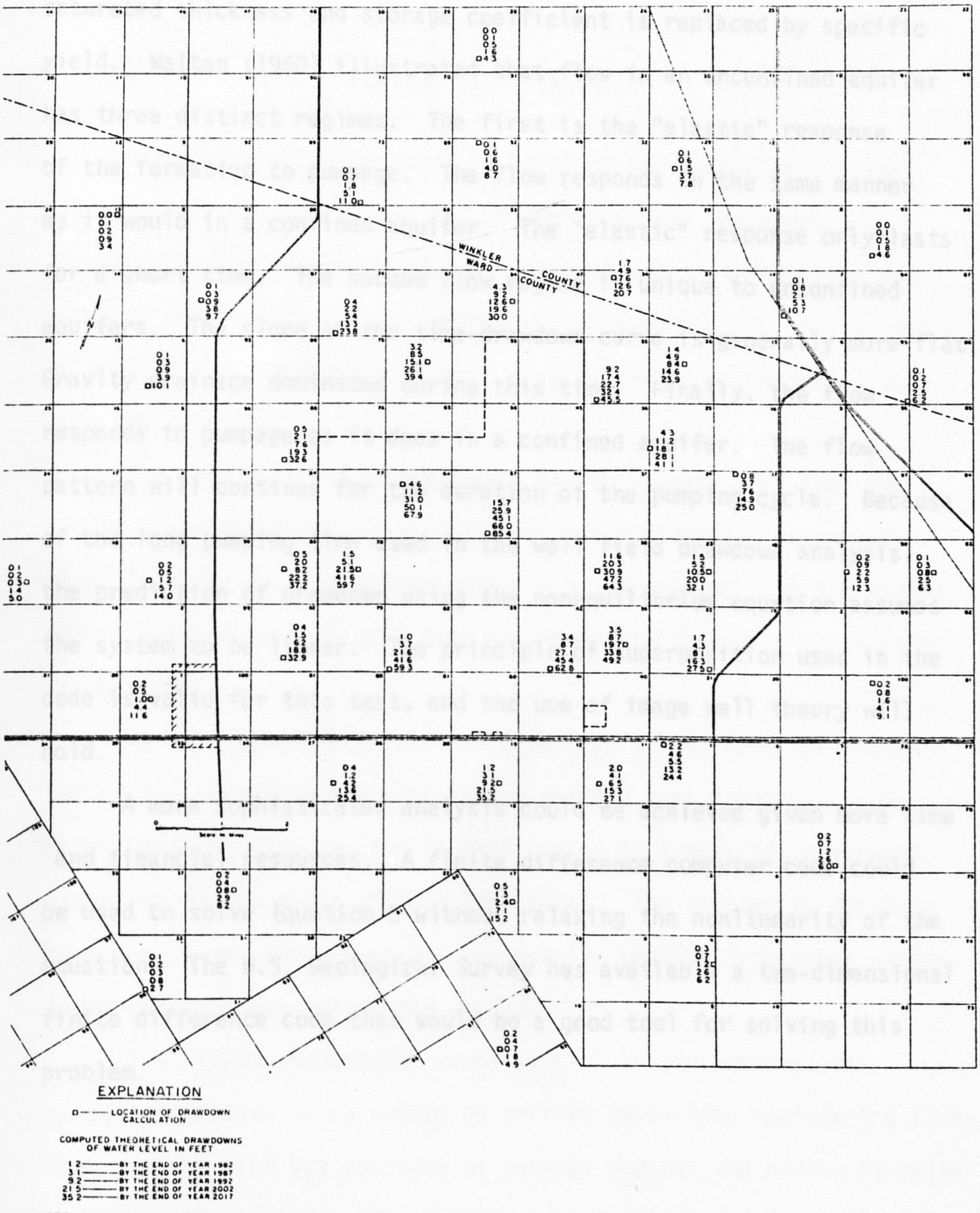
The use of this code to predict drawdown in an unconfined aquifer limits the accuracy of the results. Equation 3 becomes nonlinear because the transmissivity is a function of hydraulic head, and has the following form:

$$\frac{\delta}{\delta r}\left(T \frac{\delta h}{\delta r} \right) + \frac{T}{r}\frac{\delta h}{\delta r} = S \frac{\delta h}{\delta r} \quad \ldots\ldots\ldots\ldots \quad (6)$$

where,

h = hydraulic head, L,
S = storage coefficient, and
T = transmissivity, L^2T^{-1}.

The use of Equation 3 to predict water level drawdowns was shown by Jacob (1950) to be valid when the drawdown is small compared to



NOTE: All drawdowns shown are based on zero drawdown at the beginning of year 1979, transmissivity of 20,000 gpd/ft, and storage coefficient of 0.15.

Time-Drawdown Distribution for the Well Field Drawdown Analysis

Figure 7

saturated thickness and storage coefficient is replaced by specific yield. Walton (1960) illustrated that flow in an unconfined aquifer has three distinct regimes. The first is the "elastic" response of the formation to pumpage. The flow responds in the same manner as it would in a confined aquifer. The "elastic" response only lasts for a short time. The second flow regime is unique to unconfined aquifers. The slope of the time-drawdown curve is generally more flat. Gravity drainage dominates during this time. Finally, the flow responds to pumpage as it does in a confined aquifer. The flow pattern will continue for the duration of the pumping cycle. Because of the long pumping time used in the well field drawdown analysis, the prediction of drawdown using the nonequilibrium equation assumes the system to be linear. The principle of superposition used in the code is valid for this test, and the use of image well theory will hold.

A more sophisticated analysis could be achieved given more time and financial resources. A finite difference computer code could be used to solve Equation 6 without relaxing the nonlinearity of the equation. The U.S. Geological Survey has available a two-dimensional finite difference code that would be a good tool for solving this problem.

PUMPING TEST ANALYSIS

Regulation of groundwater is becoming more prevalent as many states strive to control the use of their natural resources. To accomplish water conservation, one southeastern state requires consumptive use permits for the withdrawal of groundwater. The burden of proving the nondamaging effects of groundwater withdrawal lies with the applicant.

The firm's client, a phosphate mining company, requires the use of groundwater and, thus, the need for consumptive use permits. As an integral part of making application for consumptive use permits, an analysis of pumping test data was needed to determine the aquifer parameters.

An understanding of the basic geology of the area was needed before the technical analysis of any pumping test commenced. The major water-bearing aquifer in this region is a massive, cavernous limestone on the order of 1000 feet thick. The aquifer is overlain by a clay layer that separates the massive aquifer from other water-bearing formations nearer the surface.

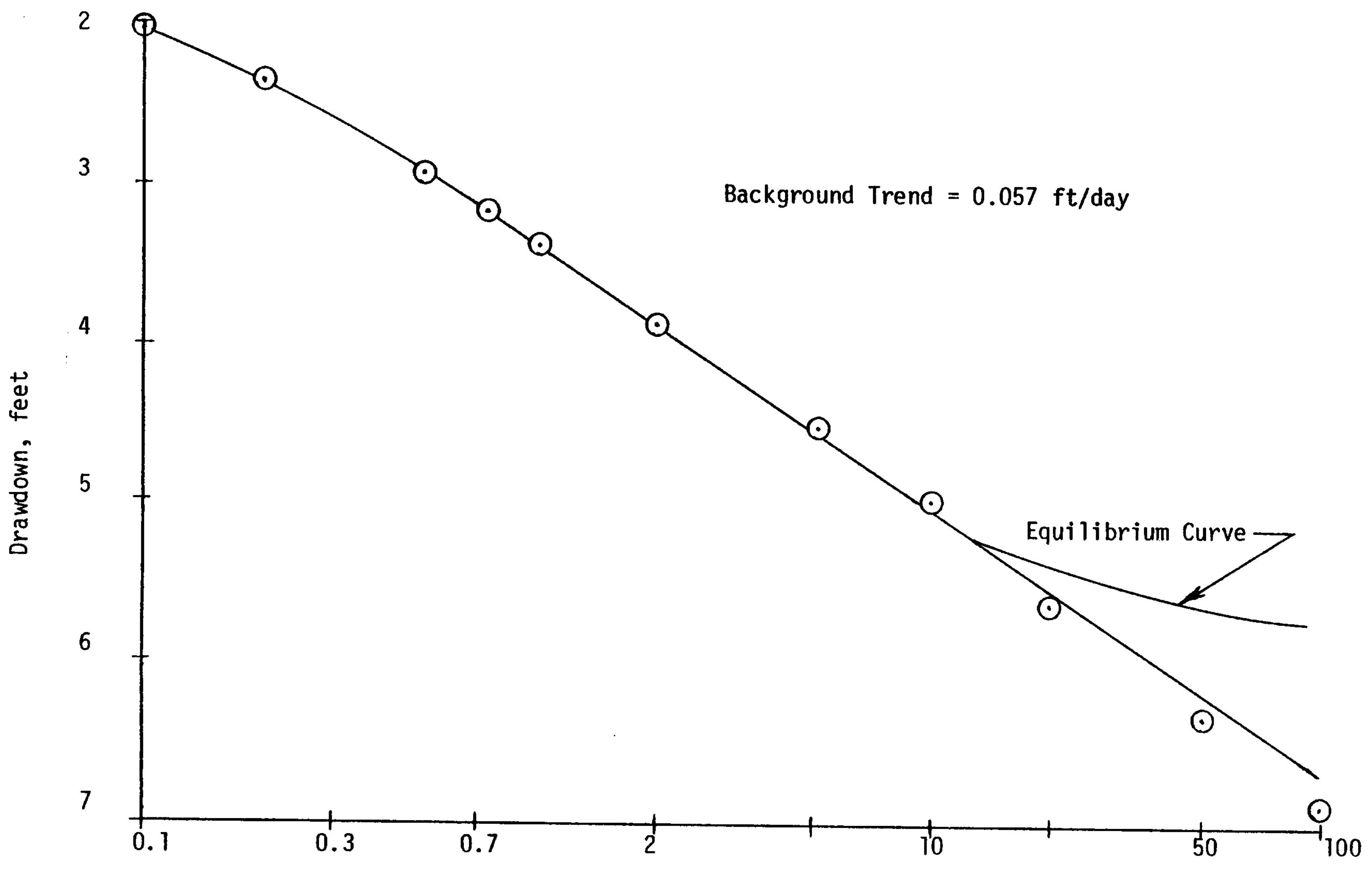
The client requested a reanalysis of an old pumping test conducted several years before by another consulting engineering firm. This pumping test was analyzed by several federal and county agencies and consulting firms. All of these groups computed essentially the same values of transmissivity and storage coefficient. They also computed a value of leakage to the massive aquifer through the clay layer from the other water-bearing formations.

The massive aquifer is confined and extremely prolific. The transmissivity for the aquifer is generally known to be on the order of 500,000 gallons per day per foot with a coefficient of storage of about 0.001. Because of the large transmissivity, the effects of any pumpage several miles from the test site would influence the results of the test. Prior to the beginning of the test, water levels in observation wells located approximately 10 to 20 miles from the test site were measured and recorded. These water levels were measured for several weeks prior to the start of the pumping test, and they were plotted to illustrate any background trend caused by other pumpage in the area. From this analysis, an average background trend of about 0.057 feet per day was estimated.

The actual pumping test was run continuously at a rate of 3,480 gallons per minute for ten days. The resulting drawdown data from two wells located 100 feet and 500 feet from the pumped well were corrected for background trend. A time-drawdown graph of the corrected data was plotted as shown in Figures 8 and 9.

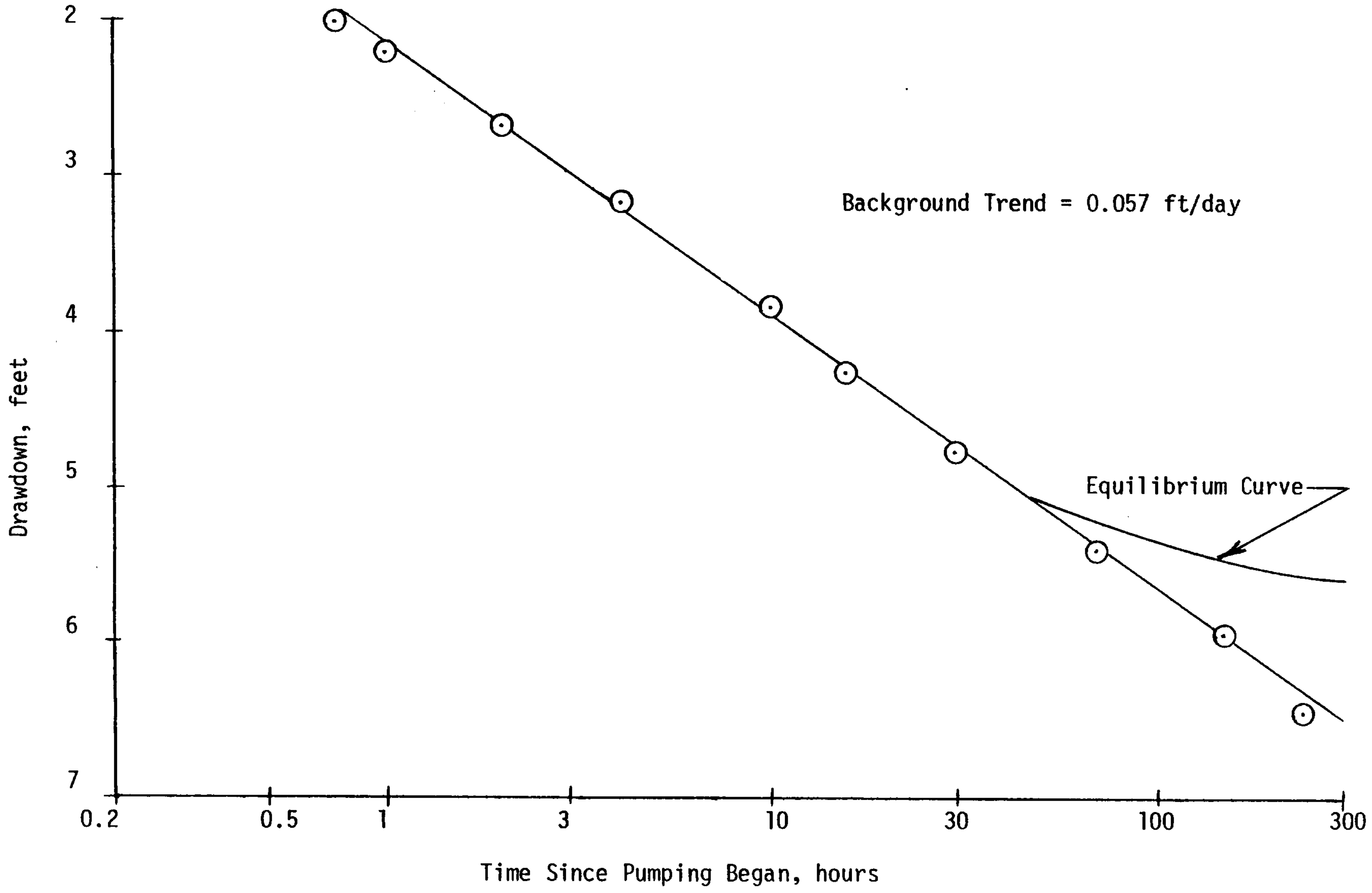
Each of the various agencies and firms that analyzed this pumping test estimated a value for leakage all of which varied only slightly. However, if leakage were present, the time-drawdown graph would tend toward a zero slope eventually reaching equilibrium when the leakage from other zones would supply the water demand. A time-drawdown curve illustrating the equilibrium condition which occurs with leakage is also shown in Figures 8 and 9.

The pumping test was conducted in an area where the aquifer



Time Drawdown Curve for the Massive Aquifer 100 Feet from the Pumped Well

Figure 8



Time-Drawdown Curve for the Massive Aquifer 500 Feet from the Pumped Well
Figure 9

parameters such as transmissivity, storage coefficient, and leakage were generally known to the correct order of magnitude. The several groups that analyzed these tests appeared to fit the parameters to the data disregarding the physical response that the data illustrated as shown by the time-drawdown curve. The importance of a complete analysis rather than a "cookbook" approach was illustrated during this project. However, in defense of these groups, their method of solution was not known to me, and the only means by which criticism is justified is on the basis of the above analysis.

THREE-DIMENSIONAL GROUNDWATER MODELING

In a few localized parts of the country, withdrawal of large amounts of groundwater has caused the land surface to subside. In Texas, extensive removal of groundwater has created such subsidence problems along the Gulf Coast near Houston. The Texas Legislature has created the Harris-Galveston Counties Subsidence District to control subsidence by regulating groundwater withdrawal in Harris and Galveston counties.

The U.S. Geological Survey has developed a model of the groundwater system for the entire Gulf Coast region of Texas. The model along with a three-dimenisonal finite difference computer code was used to predict land surface subsidence by computing water level drawdowns due to groundwater withdrawal. The results would assist them in issuing permits and limiting pumpage in the region. Ideally, permitted pumpage will control the amount of land surface subsidence in a given area.

The model developed by the U.S. Geological Survey consisted of five layers representing three aquifers and two clay zones in the Houston area. The first layer, the deepest, is the Evangeline aquifer composed of very fine to medium quartz sand. The next layer, in ascending order of depth, is a clay bed that is semipermeable. The third layer is the Chicot aquifer composed of fine to course sand. The fourth layer is another semipermeable clay layer. The last layer is a water table aquifer composed of sand. The subsurface geology in the Houston area is comprised of quartz sand with interbedded clays.

The schematic shown in Figure 10 illustrates the thickness selected for each layer by the U.S. Geological Survey.

The initial aspect of this project was to evaluate the aquifer parameters for each of the layers. The basis for accomplishing this task was to contour the data by use of a digital computer. Transmissivity and storage coefficient of the two aquifers, hydraulic conductivity and specific storage of the two clay layers, thickness of all layers, and the effective leakage between each layer were contoured. Because the system was modeled using a finite difference grid of nonuniform grid spacing, special problems existed for using the computer contouring program. The contouring routine required that the grid spacing be uniform. A computer code to interpolate data from a nonuniform grid system was used. The interpolated data were used to establish the proper format and descriptive parameters for use in the contouring code.

The effective leakage used in the code to predict the leakance between layers required more detailed analysis for understanding the model data. From Figure 11 and Darcy's Law, flow from the center of the grid to the boundary is as follows:

$$Q_1 = K_1 A \frac{h_1 - h}{\Delta z_1/2} \qquad \text{............} \quad (7)$$

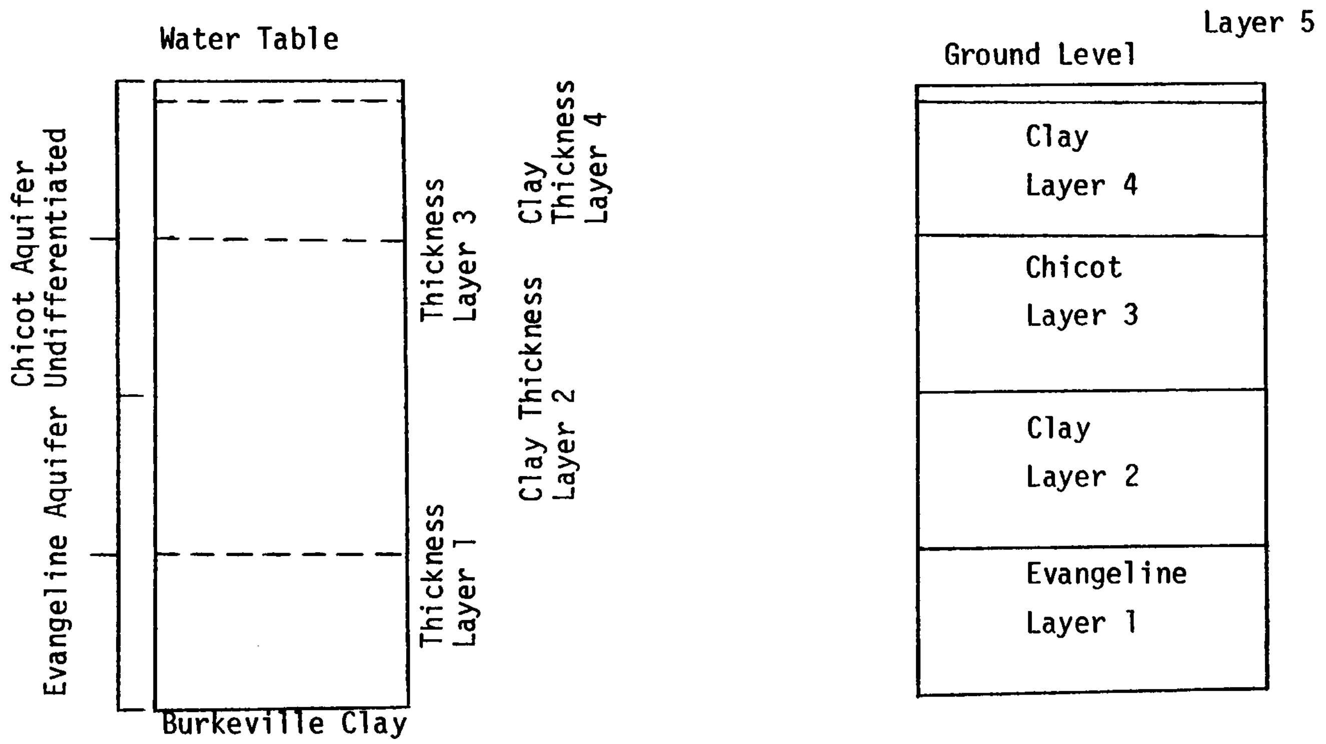
where,

Q_1 = flow rate, L^3T^{-1},

K_1 = hydraulic conductivity, LT^{-1},

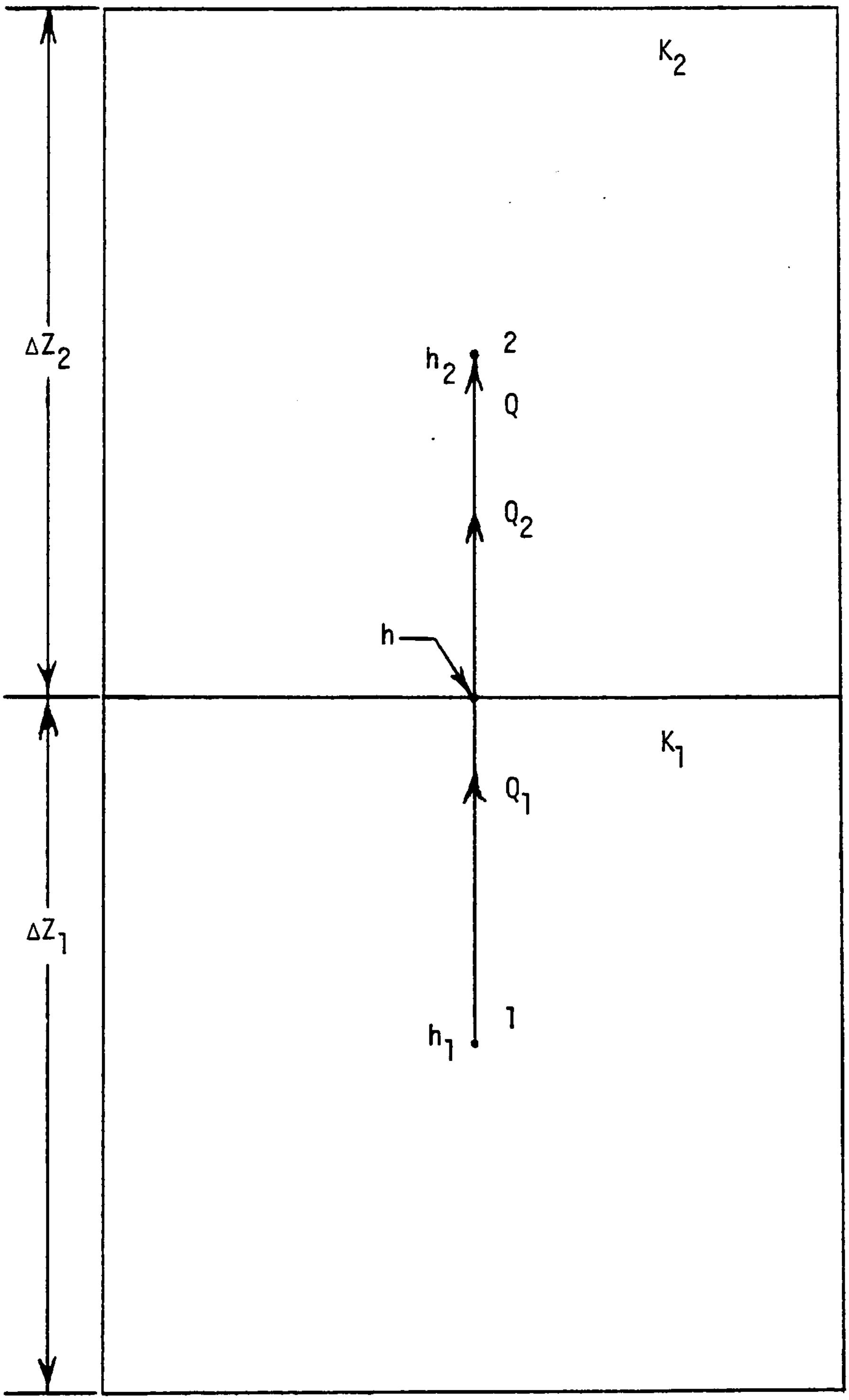
A = cross sectional area, L^2,

h_1 = hydraulic head at the center



Schematic of the Gulf Coast Layered Aquifer System

Figure 10



Schematic of Flow Between Finite Difference Grids

Figure 11

grid, L,

Δz_1 = thickness of grid 1, L, and

h = hydraulic head at the boundary, L.

Likewise, the flow from the boundary to the center of an adjoining grid is as follows:

$$Q_2 = K_2 A \frac{h - h_2}{(\Delta z_2/2)} \qquad \text{............} \quad (8)$$

The flow from the center of one grid to the center of the adjoining grid follows as:

$$Q = K_e A \frac{h_1 - h_2}{\frac{\Delta z_1}{2} + \frac{z_2}{2}} \qquad \text{............} \quad (9)$$

where,

K_e = equivalent hydraulic conductivity of the two layers, LT^{-1}.

Assuming steady state uniform flow across the boundary so that $Q_1 = Q_2 = Q$ and combining Equations 6 and 7 yields:

$$K_e = \frac{K_1K_2\ (\Delta z_1 + \Delta z_2)}{K_1\Delta z_2 + K_2\Delta z_1} \qquad \text{............} \quad (10)$$

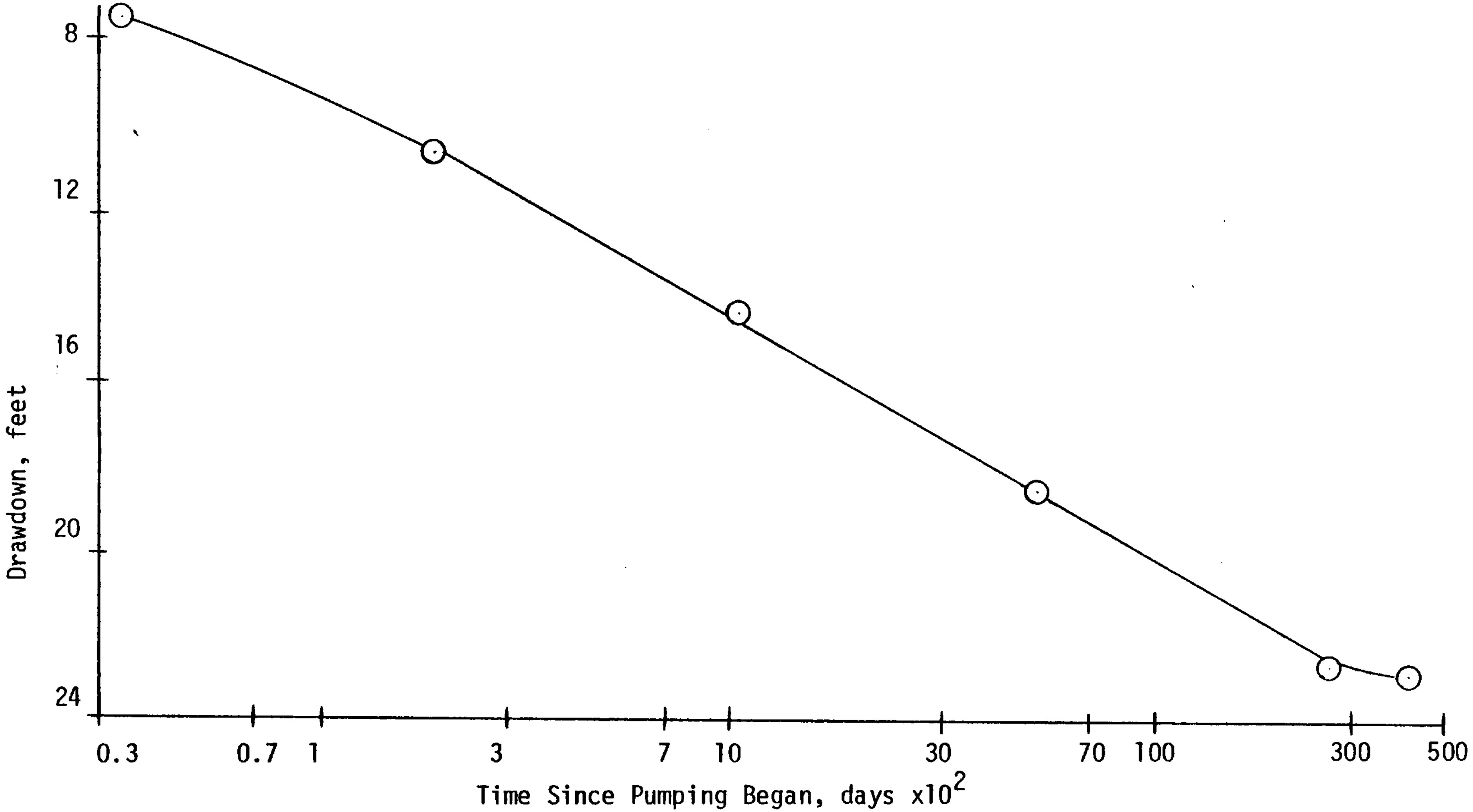
Substituting K_e in Equation 8 yields:

$$Q = \frac{2\ K_1K_2}{K_1\Delta z_2 + K_2\Delta z_1}\ A\ (h_1 - h_2) \qquad \text{............} \quad (11)$$

The term $\frac{2K_1K_2}{K_1\Delta z_2+K_2\Delta z_1}$ is known as the harmonic mean of the hydraulic conductivity. This term is read into the code to model leakage and it is known as the TK Matrix in the code. Thus, the TK Matrix represents a form of effective leakage that was contoured.

After the contouring of the aquifer parameters was completed and a better understanding of the model was gained, the code was run using these model data and included proposed pumpage in the grids for the new well fields. Each proposed well field and pumpage were run separately to ascertain the effects of each independently. A time-drawdown curve illustrating one of the runs is shown in Figure 12. These runs were made to obtain the effects of each proposed well field and to check the validity of the model.

The project provided valuable experience in the use of computerized data contouring and manipulation. Insight into the process of evaluating complex computer codes for productive use was gained. More importantly, however, was the experience gained from the interactions with the U.S. Geological Survey and the political ramifications involved with that interaction. During the course of the evaluation and contouring of the data, several errors between the data and the published report describing the model and data were found. Because of the potential socio-economic impact of this governmental project, the immediate correction of these errors was imperative.



Time-Drawdown Curve Five Miles From the Pumped Well
Simulated by the Three-dimensional Groundwater Model

Figure 12

SALT WATER/FRESH WATER INTERFACE MODEL

Salt water intrusion into the fresh water supply of coastal areas is a problem of growing concern. As fresh groundwater is withdrawn, salt water replaces the withdrawn fresh water. Various governmental agencies are analyzing the problem. To control salt water intrusion, they are limiting the amount of water to be pumped from an area over time. In addition to government interest, private industries, which rely heavily on the use of groundwater, are concerned with the potential threat to a valuable natural resource. Because of these concerns about salt water encroachment, both industry and government are studying ways to alleviate the problem and there by meet future water demands.

The client, a phosphate mining company, required large amounts of groundwater in the phosphate extraction process. They were interested in an evaluation of the regional effects of all major sources of pumpage on the movement of the salt water/fresh water interface.

The salt water and fresh water will mix together forming a broad interface of varying salt concentrations throughout the interface. To simplify the problem, the interface was assumed to be sharp with no mixing. Thus, the salt water and fresh water were assumed to be immiscible.

As with any groundwater model, results are only as good as the aquifer parameters that describe the system. The model and the code used to simulate the system were obtained from the U.S. Geological Survey. Thus, analysis of the model parameters was imperative to the project.

The model parameters were contoured to better visualize and understand the formulation of the model. As with the previously described groundwater movement model, the model data were contoured from a nonuniform finite difference grid. The nonuniform grid containing the model data was transformed into a uniform grid by computer interpolation of the data. The interpolated data were then arranged into the proper sequence with the appropiate descriptors for input into the contouring code.

After the data were contoured and analyzed, the code and model were ready for use. The code, using the model data and historical pumpage, was run until the model reached steady state. The resulting potentiometric surface and the location of the salt water/fresh water interface were saved for the final runs.

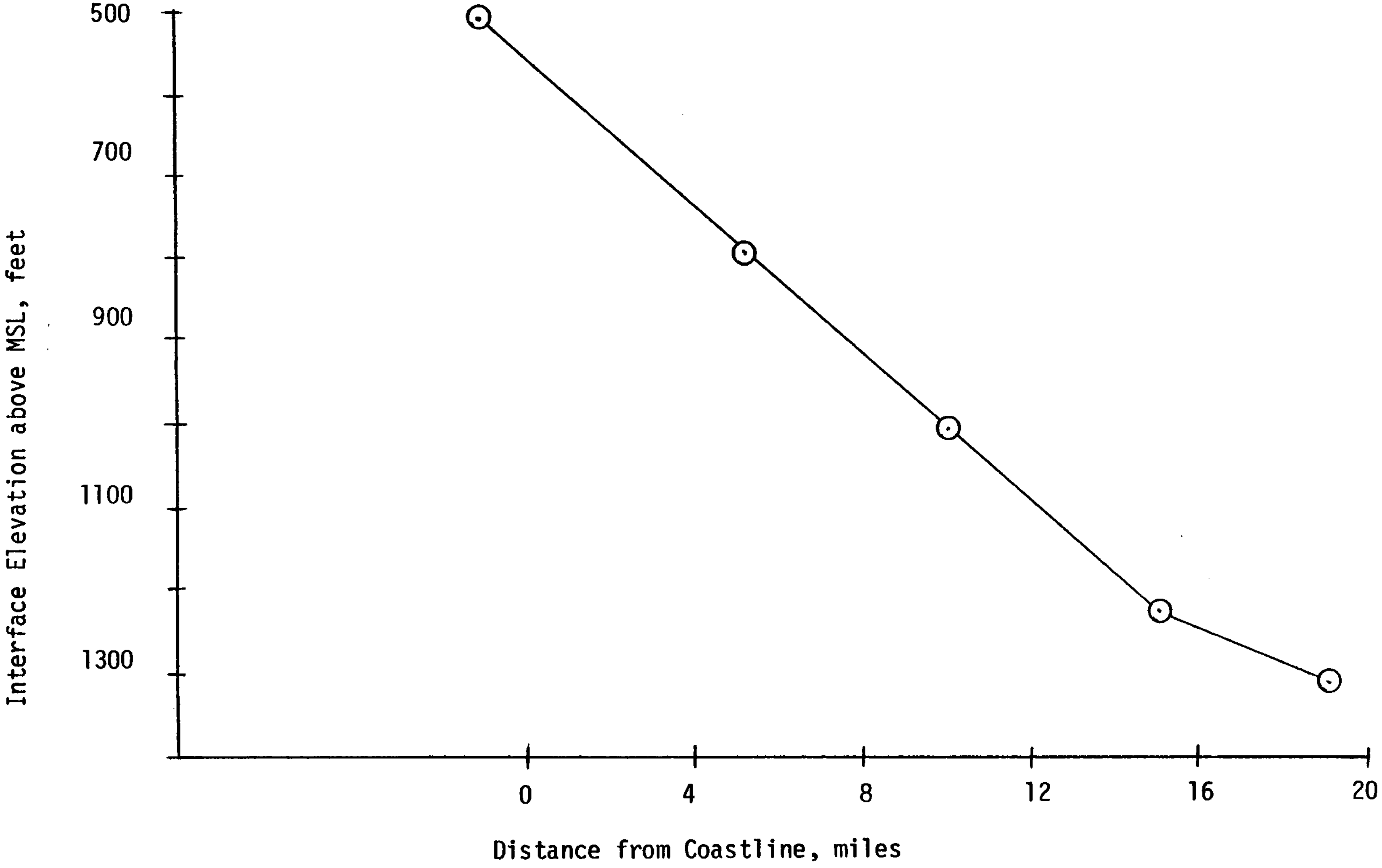
To predict the movement of the salt water/fresh water interface, the total regional pumpage was divided into irrigation, municipal, existing mine, and proposed mine pumpage groups. The proposed mine pumpage included all the phosphate mine pumpage that is not currently being used but is permitted. The four cases included the following combinations of the above pumpage as follows:

1. Existing mine pumpage,
2. Existing and proposed mine pumpage,
3. Existing mine, irrigation, and municipal pumpage, and

4. Existing and proposed mine, irrigation and municipal pumpage.

The main objective of this assignment was to establish the data for the four cases of pumpage for use in the code. The pumpage data were divided into several groups consisting of several years of pumpage for each of the four cases mentioned above. The pumping rates assigned were based on an equivalent volume of annual water withdrawn. Each group, therefore, contained several years of approximately the same amount of pumpage, thus eliminating the need to use yearly pumpage. Without this feature, the cost of using the code with the yearly pumpage data would have been prohibitive to the project.

A consultant, the author of the salt water/fresh water interface code, was retained to assist in using the code and interpreting the results. The above four cases were run by the consultant with assistance from me. An example from one of the runs shows the toe of the salt water interface progressing inland (Figure 13).



Location of the Salt Water/Fresh Water Interface after 34 Years of Pumpage

Figure 13

SUMMARY AND CONCLUSIONS

The Doctor of Engineering internship provided a challenging and enlightening experience. The internship was an avenue for me to gain experience as a graduate engineer for the first time outside academia. If nothing else was gained, the "real world" experience was well worth the time and effort expended.

The internship was with a small consulting engineering firm specializing in groundwater hydrology. The consulting engineer faces many problems that are not covered nor protected by the shields of government or large corporate business. The consulting engineer must always strive for excellence by going that "extra mile" to obtain and present solutions for all problems that he undertakes. Time and money constraints were of utmost importance, and they had to be dealt with efficiently. I faced these constraints daily gaining a broader appreciation for the limits imposed in the business community. Problems of interest arose several times that were not within the scope of the project. These problems were left unanswered because of these limiting constraints.

The interaction between me and the many different people of governmental agencies and private enterprises provided interesting, troublesome, and at times comic problems in the quest for an engineering solution. This exposure in dealing with people from broad and various backgrounds gave me a better understanding of the complexities of obtaining a sound engineering solution.

The size of the firm did not allow me to be involved in the management, economic, and financial analysis of the projects in the firm. The ideal internship would include at least an exposure to this side of engineering management. However, I gained experience in the economic and financial aspects of a portion of the projects.

Generally, the internship experience provided a firm foundation on which to build a successful career as a professional engineer. Even though many skills were tapped, I learned the value of utilizing my current skills and developing new ones in order to accomplish the goals of the firm.

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APPENDICES

APPENDIX III-1

Derivation of the Gradient Vector

The gradient vector comprises the magnitude and direction of the gradient at the leach mine. The schematic of the leach mine and the observation points used to evaluate the gradient vector are illustrated in Figure 14. Using the physical layout of the leach mine system the gradient vector was derived as follows:

$$h_a = \frac{h_1 + h_2}{2} \quad \ldots\ldots \quad \text{III-1}$$

$$h_b = \frac{h_2 + h_4}{2} \quad \ldots\ldots \quad \text{III-2}$$

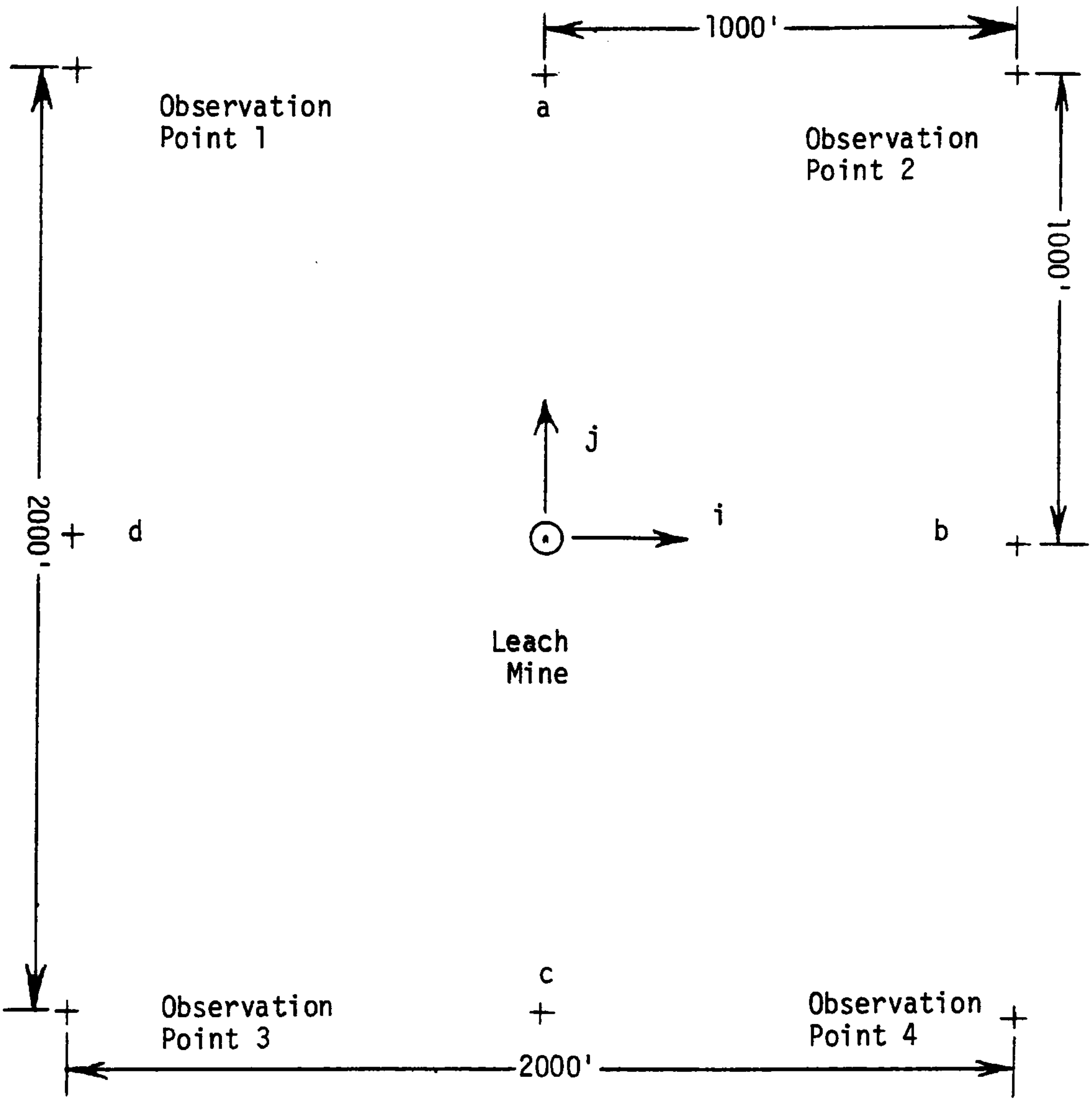
$$h_c = \frac{h_3 + h_4}{2} \quad \ldots\ldots \quad \text{III-3}$$

$$h_d = \frac{h_1 + h_3}{2} \quad \ldots\ldots \quad \text{III-4}$$

where,

h_a = average hydraulic head at point a, L,
h_b = average hydraulic head at point b, L,
h_c = average hydraulic head at point c, L,
h_d = average hydraulic head at point d, L,
h_1 = hydraulic head at point 1, L,
h_2 = hydraulic head at point 2, L,
h_3 = hydraulic head at point 3, L,
h_4 = hydraulic head at point 4, L.

The i-component and j-component of the velocity vector was computed using the average hydraulic heads as follows:



Schematic of Leach Mining System

Figure 14

$$G_i = \frac{h_b - h_d}{x_{bd}} \qquad \text{............ III-5}$$

$$G_j = \frac{h_a - h_c}{x_{ac}} \qquad \text{............ III-6}$$

where,

G_i = magnitude of the gradient vector in the i-direction, LL^{-1},

G_j = magnitude of the gradient vector in the j-direction, LL^{-1},

i and j = mutually prependicular coordinate axes,

x_{bd} = distance between points b and d, L, and

x_{ac} = distance between points a and c, L.

The resulting gradient vector is as follows:

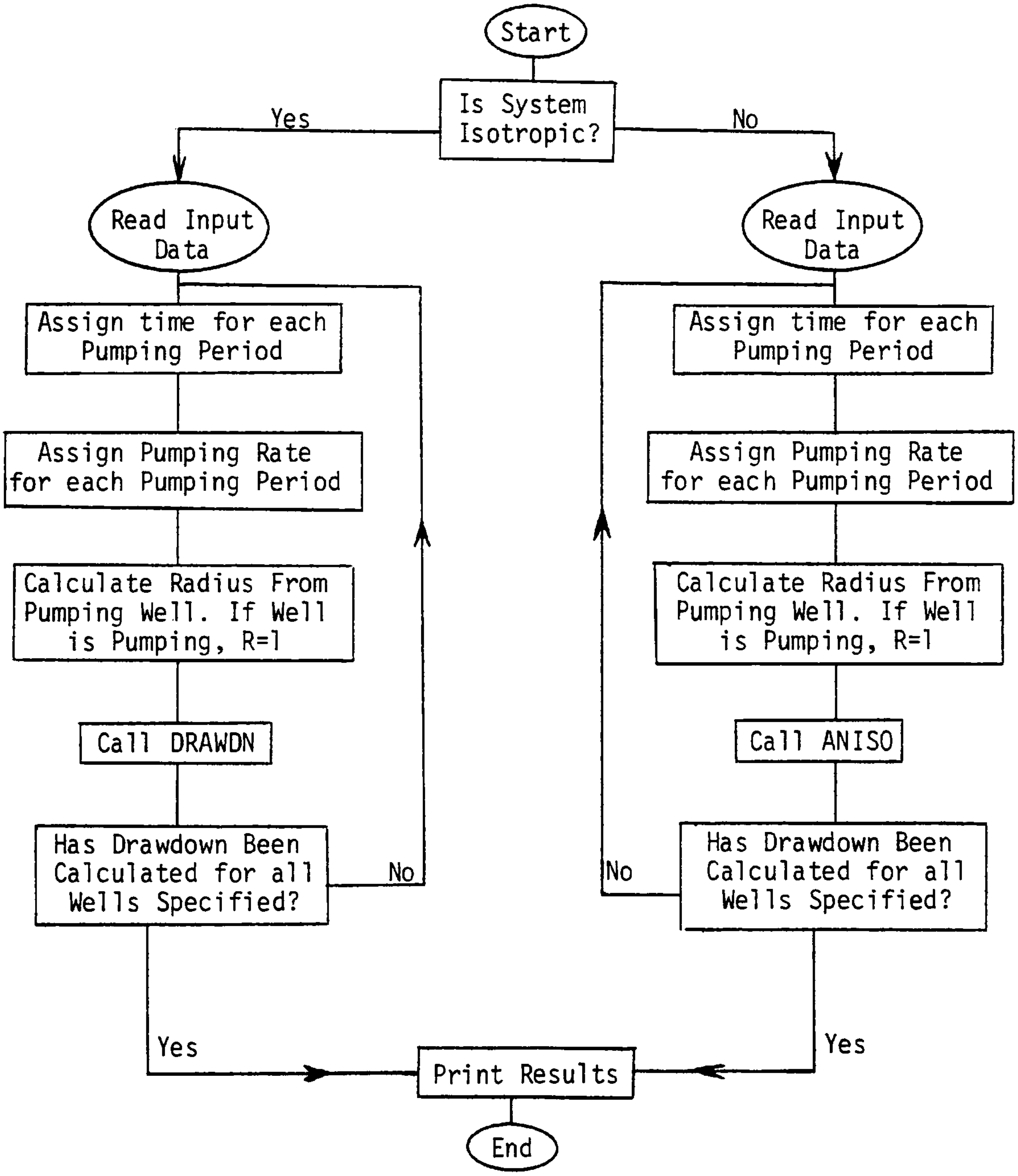
$$\bar{G} = (G_i^{\,2} + G_j^{\,2})\ 1/2 \qquad \text{............ III-7}$$

where,

$\bar{G}$ = gradient vector at leach mine, LL^{-1}.

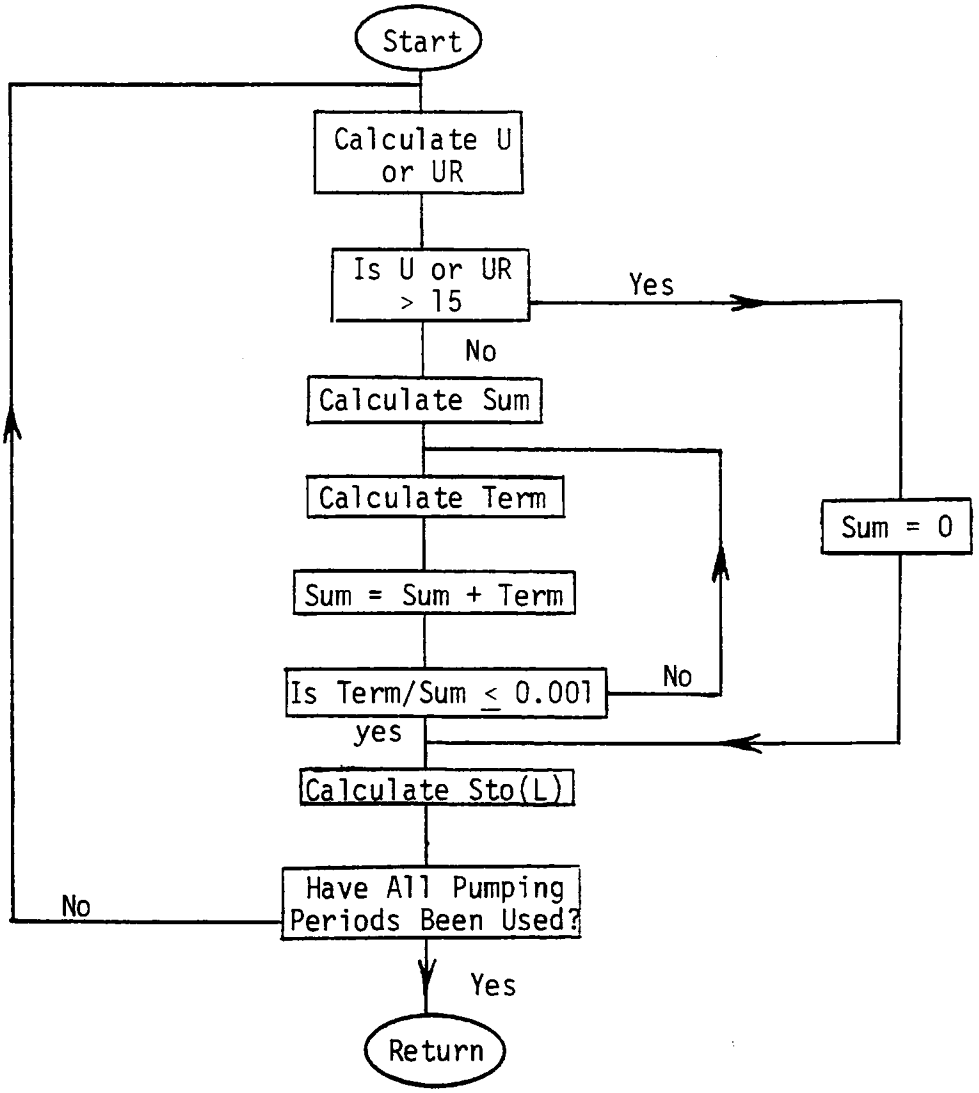
APPENDIX IV-1

Flow Chart for the Nonequilibrium Equation



APPENDIX IV-2

Flow Chart to Compute Drawdown Under Isotropic (U) and Anisotropic (UR) Conditions



APPENDIX IV-3a

Water Level Drawdown In a Homogeneous Confined Aquifer

Start of Pumping = December 1979
Total Number of Pumping Periods = 6
Transmissivity (gpd/ft) = 40000.
Storage Coefficient = 0.15000
Total Number of Pumping Wells = 1

Pumping Wells Average Pumping

Well	Coordinates	(ft)			Elapsed Time	(days)		
No.	X	Y	30.	60.	90.	120.	127.	134.
1	0.	0.	1000	0	500	250	750	1500

Computed Water Level Drawdowns On Observations Wells (ft)

Well	Coordinates	(ft)			Elapsed Time	(days)		
No.	X	Y	30.	60.	90.	120.	127.	134.
2	2830.	2830.	0.01	0.15	0.26	0.36	0.38	0.40

APPENDIX IV-3b

Check Computations for Results in Appendix IV-3a

Time, days	30	60	90	120	127	134
Drawdown, Feet	0.015	0.167	0.420	0.701	0.766	0.831
		-0.015	-0.167	-0.420	-0.485	-0.550
		0.152	0.007	0.084	0.111	0.140
			0.260	-0.004	-0.009	-0.017
				0.361	0.000	0.000
					0.383	0.000
						0.404

APPENDIX IV-4

Water Level Drawdown
In A Homogeneous Confined Aquifer

Start of Pumping = 21 June 1979
Total Number of Pumping Periods = 3
X-Transmissivity (gpd/ft) = 50000.
Y-Transmissivity (gpd/ft) = 50000.
Storage Coefficient = 0.00100
Total Number of Pumping Wells = 1

Pumping Wells — Average Pumping

Well	Coordinates (ft)		Elapsed Time (days)		
No.	X	Y	10	30	45
1	1000.	2000.	1000.	0	500.

Computed Water Level Drawdowns On Observation Wells (ft)

Well	Coordinates (ft)		Elapsed Time (days)		
No.	X	Y	10	30	45
1	1000.	2000.	43.15	0.92	22.61
2	600.	2250.	14.93	0.92	8.50
3	100.	1300.	10.89	0.92	6.48
4	1050.	1000.	11.48	0.92	6.78
5	1500.	2300.	13.96	0.92	8.02
6	900.	3200.	10.64	0.92	6.36

VITA

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