COMPARISON OF SEQUENTIAL ANALYSES GENERATED FROM AN ENLARGING DATA BASE. A CASE STUDY IN GROUND WATER CONTAMINATION

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PREFACE

During my studies of hydrogeology, the question of how much information is truly needed for a dependable analysis of a ground water situation was often brought up. The saying "90% of the information comes from 10% of the data," was presented several times in an almost axiomatical sense. This quote, offered by Dr. Wayne Pettyjohn, served as the basic topic of this thesis. Special thanks go to Dr. Pettyjohn, who served as chairman for my thesis committee. His advice and the data obtained from him made this thesis possible.

Gratitude is also extended to Dr. Gary Stewart and Dr. Arthur Hounslow, who were also members of my thesis committee. Each of these individuals offered advice and direction at important stages of my thesis work.

Cathy Southwick played an instrumental part in the final preparation of this work. Special thanks to Cathy for her help and her patience. My thanks also go out to all of the individuals who played a part in completion of this thesis. While there are far to many to mention, they know who they are. Last, but by no means least, my love and deepest gratitude go to my father and mother, Monroe and Netha Powell, for their full and unquestioning support.

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CHAPTER I

INTRODUCTION

Hydrogeologic investigations, particularly as they relate to the study of contaminated areas, range broadly in scope, time, detail, and cost. In order to develop a rapid, general understanding of a particular situation, well known hydrogeologic concepts and principles can be applied to a limited data base. An analysis of this type might be completed on the back of an envelope in a few minutes, and, despite the simple nature of the analysis, it can serve as a guide for additional investigations. At the other extreme, an investigator might depend on test drilling, construction of monitoring wells, lithologic and chemical analyses of rock and water, as well as an almost endless variety of other techniques. Once collected, the information may be used as input for any number of sophisticated computer models for predictive analyses.

Obviously, a large data base will allow a more accurate understanding of the situation. On the other hand, the objectives of the investigation should dictate the degree of detail required. In addition, a considerable understanding of a contaminated site may be developed through the use of limited data. The increase in knowledge derived through addition of an extensive, and, no doubt expensive, data array may not significantly improve the interpretations of the general ground-water system.

In order to test this hypothesis, an actual contaminated site was evaluated by means of increasingly larger data bases. The region contains a number of municipal wells (town of Cyril), all now abandoned, that lie within an area of extensive oil and gas development. Throughout a period of several decades, selected municipal wells became contaminated by chloride. Presently all of Cyril wells are contaminated and abandoned.

General Setting

The town of Cyril is located in the southeastern corner of Caddo County, Oklahoma (fig. 1). Approximately four miles to the north lies the east-west trending West Cement Oil and Gas Field. West Cement Field, which as been in operation since 1917, has been owned and operated by several companies. As is usual in the production of oil, a considerable volume of salt water is produced during operation of the field.

Chloride contamination of Cyril's drinking-water supply has been recognized since 1947, and in 1948 the first municipal well was abandoned. The town, with a population of approximately 1500, was ordered by the Oklahoma Department of Health to cease pumping their remaining (3) municipal water supply wells in late 1990, and by 1991 all wells are abandoned. Several other municipal wells to the north and west had been abandoned in earlier years, as a result of chloride contamination. The last three wells used by the town of

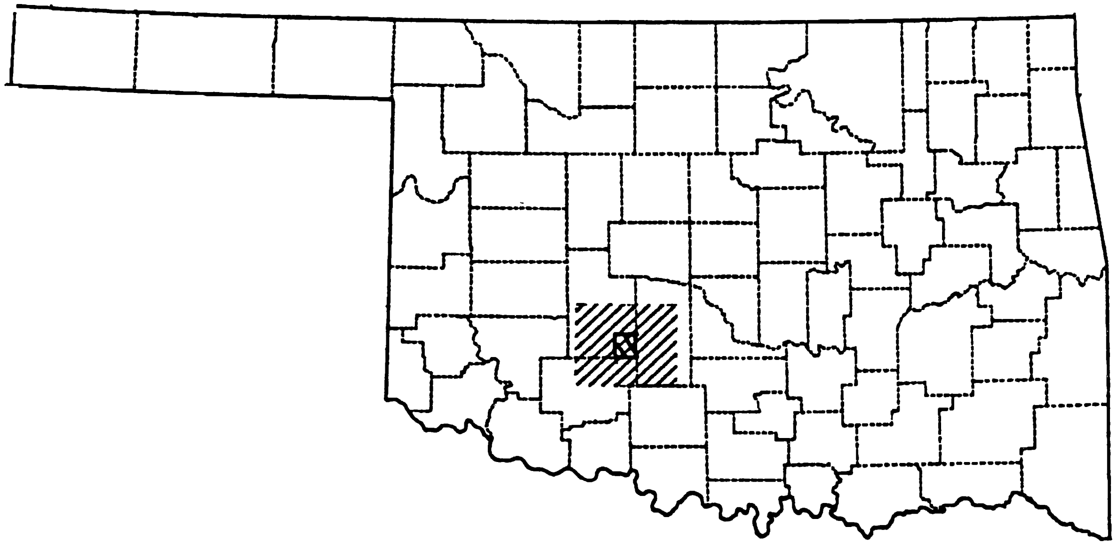


Figure 1. Study Area, Caddo County, Oklahoma

Cyril are designated C-1, C-2, and C-3. These wells tap the Rush Springs aquifer. Owing to the Department of Health order to abandon their wells, the town of Cyril connected to a Rural Water District line in 1991.

As a result of surface mapping, the Cement Field was discovered in 1916. The first well drilled produced gas from the Permian Fortuna Sandstone. In 1917, oil was discovered in the same formation, and by 1920, the field contained 26 completed wells and 36 wells that were in the process of being completed.

The field has been active since that time, including secondary recovery operations and exploration of deeper formations. Approximately 1900 wells have been drilled in the Cement Field to date, and at least 26 reservoirs have been discovered in Permian, Pennsylvanian, and Mississippian formations. More than 150 million barrels of oil and an undetermined amount of gas has been produced from the field.

From 1917 to about 1950, the salt water derived from the production of oil and gas in the Cement Field was discharged into disposal pits. In 1950 salt-water injection wells began to replace disposal pits. This was the direct result of contamination of the surficial aquifer, the sole source of supply for municipal, domestic, and agricultural use. In 1971, some older production wells were converted for injection of oil-field brine for secondary recovery operations. Reportedly, some injection wells and nearby oil wells flowed salt water around the outside of the surface casing during injection, and others appeared to be under very high surface pressure.

The West Cement Oil Field is hydrologically up-gradient from the Cyril water well field. It is probable that the source of contamination of Cyril water wells is located within the West Cement Field.

Geology of the Cement Field Area

Permian red beds in southern Oklahoma overlie several anticlinal structures that are the site of extensive hydrocarbon accumulations. These accumulations generally trend along northwest-southeast lines.

Coloration and cementation changes occur in the red beds above the anticlines of southern Oklahoma. These changes were first reported by Reeves in 1922. He reported that the Whitehorse Sandstone had been altered from it's normal reddish-brown color to pink, yellow, and white on the flanks of the Cement anticline. Reeves (1922) also recorded changes in the cementation of the Rush Springs Sandstone and the Cloud Chief Gypsum in areas above the crest of the anticline. Similar patterns of alteration, including bleached zones above the anticlinal crests, were later recorded at other nearby anticlines. Studies of these altered red beds indicate that such alterations are related to hydrocarbon leakage from underlying reservoirs.

Areas of distinct alteration have been termed "hydrocarbon-induced diagenetic aurole" or HIDA (Al-Shaieb and others, 1988). Such HIDA's are the result of vertical migration of hydrocarbons from deeper, pressurized, compartmentalized basins. Three primary results arise from such migrations: 1) sandstone color alteration, resulting from the reducing environment caused by H^2S gas, 2) oxidation of hydrocarbons causing cementation of sandstones with carbonate and gypsum as well as with calcite over the anticline crests, and 3) reduction of iron oxide by H^2S, leading to formation of pyrite in the altered sandstones.

Stratigraphy

Rush Springs Formation reportedly is 130 to 300 feet thick, and conformably overlies the Marlow Formation, which is 90 to 130 feet thick. The

Rush Springs and Marlow Formations make up the Permian Whitehorse Group (Guadalupian Age). Outcrops of the Rush Springs are restricted to the area of the Cement-Chickasha anticline (Chickasha anticline is the southeast extension of the structure). Weatherford Gypsum occurs locally in the upper part of the Rush Springs. Conformably overlying the Rush Springs is the Cloud Chief Formation.

Lithology

The Rush Springs is commonly "medium to light red or (less commonly) orange-brown to light brown, very fine to medium-grained, predominantly medium- to large-scale trough cross-bedded, weakly indurated subarkosic sandstones." Commonly, the lower part of the formation contains "very coarse, frosted, spherical quartz grains." The Rush Springs exhibits great lithologic homogeneity locally, yet contains silty shale phases and gypsum beds in some locations. Weatherford Gypsum occurs locally in upper portions of the Rush Springs as massive, thick beds (Al-Shaieb, 1988).

Overlying the Rush Springs are 10 to 15 feet of the Cloud Chief Formation. The Cloud Chief Formation is primarily composed of red clay shale and red silty or sandy shale. The first few feet, however, consists of dolomitic sandstones and siltstones, separating the Rush Springs from the overlying Moccasin Creek Gypsum Member of the Cloud Chief.

The Rush Springs Sandstone is underlain by the Marlow Formation, these two formations composing the Whitehorse Group. The Marlow Formation consists primarily of "even-bedded brick-red sandy shale, generally gypsiferous, with some very fine sand and silt loosely cemented with iron oxide and calcite" (Tanaka and Davis, 1963).

The Verden Sandstone Member occurs within the Marlow Formation. The Verden Member is generally about 10 feet thick and is composed of medium- to course-grained sandstone. This sandstone contains rounded quartz grains and subangular chert grains held together by calcium carbonate and interbedded fine-grained sandy shale.

Two dolomite beds occur near the top of the Marlow Formation. An interval ranging from 16 to 20 feet separates the upper Emanuel Dolomite, from the lower, Relay Creek Dolomite. Each of these beds ranges in thickness from paper-thin laminations to a maximum thickness of about 5 or 6 inches. A thin shale with a distinctive pink color occurs about 10 or 15 inches below the Emanuel Dolomite. This pink shale, with a maximum thickness of about one foot, is most likely an altered volcanic ash.

Structure

The anticlinal structure of the Cement-Chickasha area, which trends west-northwest, is slightly overturned to the north. The Permian strata and overlying Quaternary beds are predominantly unfaulted. These beds unconformably overlie a faulted and tightly folded pre-Permian structure. Parallel to the fold axis and a north-dipping normal-fault system is a major south-dipping reverse fault. The pre-Permian fold axis is offset by several minor normal faults. Structural deformation in post-Cloud Chief times produced a gentle, near-symmetric anticline in Permian Time. The anticline is approximately 11 miles long and 2 miles wide along the top of the Rush Springs Formation. The anticlinal crest represents a topographic high dominated by East Cement and West Cement Domes, which are 4 miles apart. The structure is capped by the Moccasin Creek Gypsum Member of the Cloud Chief Formation.

Purpose and Scope

The purpose of this investigation was to determine the amount of data necessary to generate a reliable analysis of a ground-water contamination situation. Three analyses of a ground water contamination situation, each incorporating an increased data base, were compared. The first analysis was based on fundamental hydrogeologic principles and concepts in order to obtain a general understanding of the site and problem. This analysis was limited to a small amount of data, such as that available in the early stages of an investigation. The analysis included determination of the hydraulic gradient, flow direction, and ground-water velocity, evaluation of chloride content of a few chemical analyses of ground water, and estimates of hydraulic properties based on general knowledge and extrapolation. Where appropriate, these estimations were used in computer models to allow a more comprehensive understanding of the situation. Results of this analysis were used to determine the most probable source area(s) of contamination.

The second analysis was based on information obtained from readily available documents, measurements and published reports. Again, the data base was limited, but a number of computer models were used to obtain a better understanding of the ground-water situation, potential source areas, and rates of flow and recharge. The third analysis was based on a number of actual field measurements, driller's logs of test holes and monitoring wells, aquifer tests, chemical data, and a variety of records obtained from municipal, regulatory agency, and company files. Finally, analytical results were compared on the basis of the amount of data incorporated into the analysis versus the relative confidence that can be placed in that analysis.

The computer models used in this investigation include RECHARGE, T-O-T, THEIS WELL FIELD, JPLUME, and WATEVAL. RECHARGE, developed by Pettyjohn and Henning (1978), calculates effective regional ground-water recharge rates. This model analyzes stream discharge data, available from publications of the U.S. Geological Survey, by means of three hydrograph separation routines. The authors caution that the model is not designed for site specific purposes, but rather it was developed to estimate regional ground-water recharge rates.

The version of T-O-T (time-of-travel) used in this investigation is a model developed by the Oklahoma Water Resources Board (Fabian and Summers, 1991) based on the Theis equation. Requiring limited input data, the program calculates the Z-O-C (zone of contribution) or capture zone of a pumping well, as well as the time of travel. The Z-O-C defines an area that serves as a source of water for a well, that is, all water and contaminants within a Z-O-C could eventually appear at the well site. The time of travel is related to hydraulic properties as well as the hydraulic gradient, which steepens toward a pumping well. Time-of-travel calculations graphically indicate the distance a particle of water will travel to reach a well during the time of pumping. Since dispersion is not incorporated within the model, the actual time of arrival of a contaminant is less, by 25 percent or more, than that calculated by the model.

THEIS WELL FIELD is a simple flow model that assumes homogeneous and isotropic conditions with no hydrologic boundaries. It can be used to determine the shape and size of the cone(s) of depression surrounding a pumping well(s). This program, also based on the Theis equation, has the advantage over T-O-T of being able to calculate the effects of interference between wells, while only a single well can be evaluated in each simulation of T-O-T. The effects of interference can be estimated by means of T-O-T, however, by using superposition.

CHAPTER II

PRELIMINARY ANALYSIS

Introduction

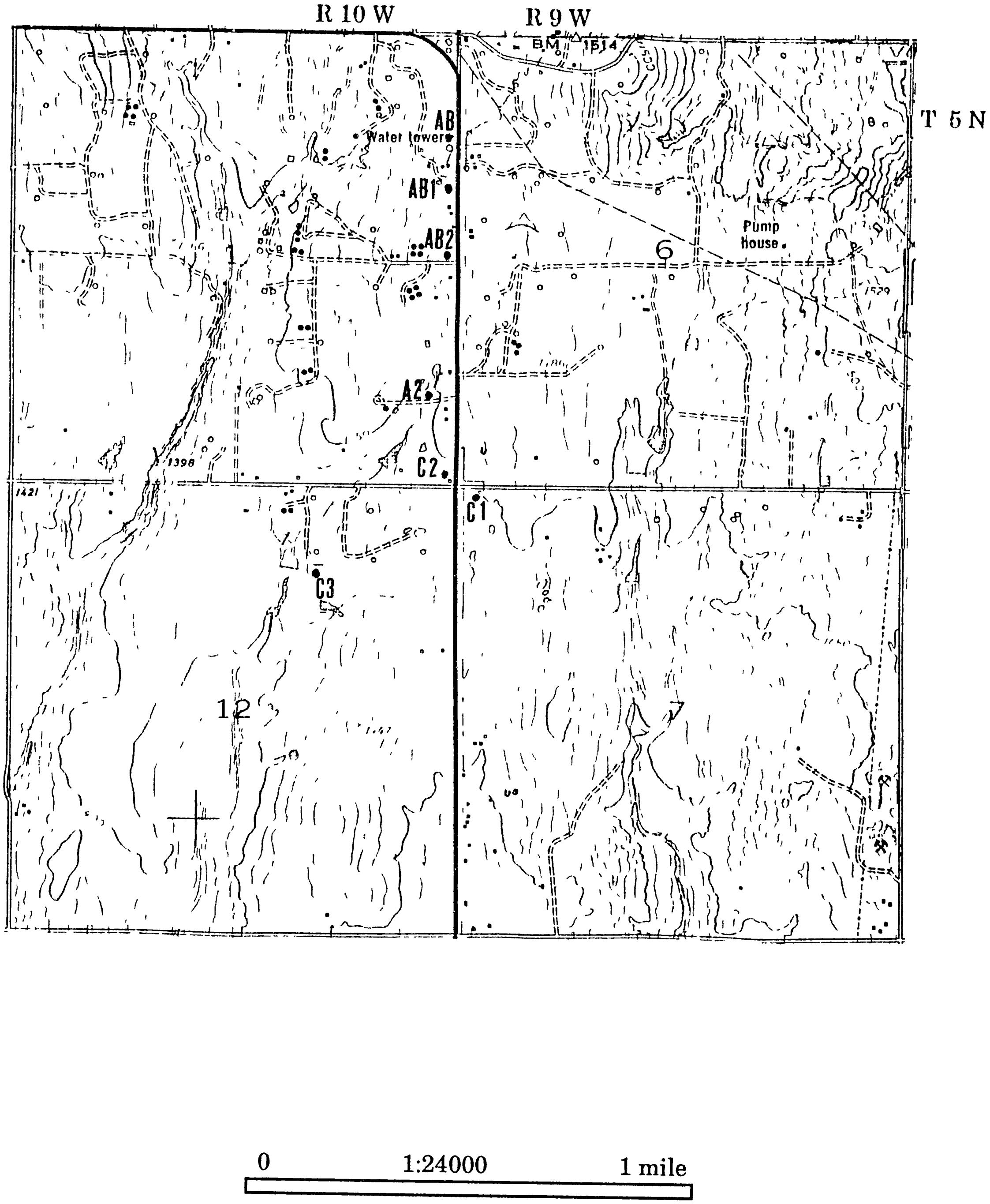
This analysis utilizes only a limited amount of data. The goal is to simulate a situation such as one might encounter in the early stage of an investigation. As a necessity, many hydraulic parameter values are estimations based on application of prior knowledge and/or experience. Such estimations are made so that a worst-case scenario is presented.

Data available for the preliminary analysis consists of; location and limited construction details of three municipal wells (C-1, C-2, and C-3), chemical analyses of water from seven abandoned wells and former pumping rates of the three wells mentioned above. A topographic map was also utilized.

Primary Information

Well Locations and Construction Details

The municipal well field lies approximately two miles north of Cyril (fig. 2). The wells are constructed in the Rush Springs Sandstone, which crops



contour interval: 50 feet

Figure 2. Generalized Topography and Location of Municipal Wells in the vicinity of Cyril

out throughout the area. Reportedly, the Rush Springs consists of fine- to very fine-grained sandstone. The sand is loose in some locations, yet elsewhere it is cemented to a such a degree that wells contain only surface casing.

Well C-1 is located in Sec. 7, T. 5 N., R. 9 W. According to Cyril municipal records, the well, constructed in 1980, is 384 feet deep. The casing, cemented from land surface to a depth of 150 feet, is perforated from 185 to 205 feet and from 350 to 375 feet. The well is gravel packed from 150 to 384 feet. Well C-1 was pumped continuously at a discharge rate ranging from 140 to 166 gallons per minute.

Well C-2, located in the southeast corner of Sec. 1, T. 5 N., R.10 W., was constructed in 1954. It is 170 feet deep, reportedly containing only a few feet of casing. After the construction of C-1, this well was used only during the summers, to supplement the discharge of well C-1. No pumping schedule is available, but the discharge rate is reported to have been 60 gpm.

Well C-3, located in Sec. 12, T. 5 N., R. 10 W., was constructed in 1985. It is 430 feet deep and gravel packed from 200 to 340 feet. Well C-3, a supplemental supply well, reportedly was pumped at a rate of 120 gpm.

Four other abandoned municipal wells lie to the north along the section line road (fig. 2). These wells, assumed to be about 100 feet deep, were abandoned several years previously owing to high chloride concentrations.

Chemical Quality of Water

The U.S. Environmental Protection Agency standard for chloride concentration in public drinking water is 250 mg/L. Concentrations in excess of this standard cause a salty taste. The background concentration of chloride in shallow and surficial aquifers throughout Oklahoma is generally less than about 25 mg/L. The background concentration in the Cyril area should lie in the same general range. Analyses of samples of well water collected in March 12, 1991 from several abandoned municipal wells indicated that the chloride concentration in all cases but one were far above background and, in one case, nearly four times greater than the drinking water standard (Table 1).

The U.S. E.P.A. standard for sulfate concentration in public drinking water supplies is also 250 mg/L. The concentration of sulfate exceeds the drinking water standards in C-1 and is elevated in C-3 and AB. The nitrate concentration in well AB-1 also exceeds the drinking water standard of 10 mg/L for nitrate. This may be related to the manner in which well AB-1 was abandoned. That is, the elevated nitrate could be related to contamination from surface sources if the well is not adequately sealed.

TABLE 1

CYRIL AREA WATER SAMPLES, MARCH 12, 1991

Well	Specific Conductivity	$SO_4^=$	NO_3^--N	Cl^-
	umho	mg/l	mg/l	mg/l
C-1	1700	336	1.9	255
C-2	3260	50	4.9	986
C-3	909	181	2.3	58
AB	1098	139	3.5	158
AB-1	1274	21	20.9	115
AB-2	1440	37	1.4	371
A-2	2570	8	1.7	833

Methodology

Estimation of Parameters

At the time of sampling, water levels were also measured in the abandoned municipal wells. The depth to water is reported in feet below the measuring point of each well. The measuring point is assumed to be six inches above ground surface. Therefore, the water table ranges from 21 to 50 feet below land surface (Table 2).

As shown in Table 3, well depths are known only for C-1, C-2, and C-3. It is assumed that well C-3, which is 430 feet deep, fully penetrates the aquifer, and that the aquifer is constant in thickness. Therefore, saturated thickness is assumed to be 410 feet. Assuming the presence of less permeable materials within the aquifer, a value of 400 feet is a liberal estimate of the total saturated thickness.

As stated earlier, the Rush Springs reportedly consists of fine- to very fine-grained sandstone with degree of cementation varying from none to well-cemented. Hydraulic conductivity is therefore estimated to be between 10 and 100 gpd/sq ft, which is reasonable for a sandstone of this grain size that ranges widely in cementation. Correspondingly, estimates of transmissivity values for the area range from a low of 4000 gpd/ft to a maximum of 40,000 gpd/ft.

Effective porosity (n) of sandstone commonly ranges from about 15 to 30 percent. Owing to the fine-grained nature of the Rush Springs, it is assumed that the effective porosity is 15 percent.

TABLE 2

DEPTH TO WATER AND WATER-TABLE ELEVATIONS
MUNICIPAL WELLS
MARCH 12,1991

Well	Measuring Point Elevation	Depth to Water	Static Level	Approx. Static Level
C-1	1449	31.97	1417.03	1417
C-2	1447	—	—	—
C-3	1431	21.67	1409.33	1409
AB	1492	42.75	1449.25	1449
AB-1	1492	50.00	1442.00	1442
AB-2	1472	36.15	1435.85	1436
A2	1449	28.10	1420.90	1421

TABLE 3

CYRIL WELL DATA

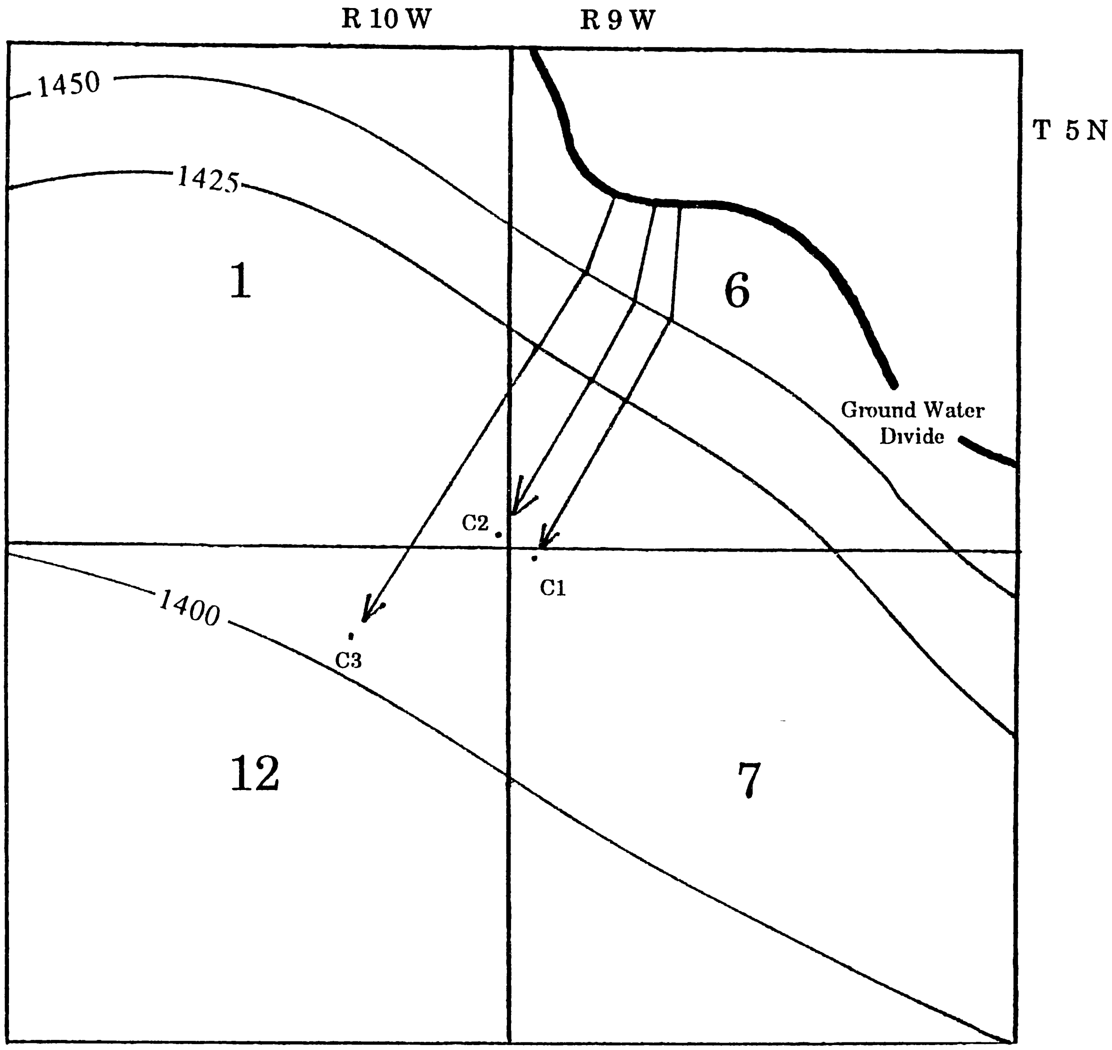
Well	Total Depth (feet)	Depth to Water (feet)	Assumed Screened Interval [1] (feet)
C-1	384	31.97	352
C-2	170	20.00 [2]	150
C-3	430	21.67	400

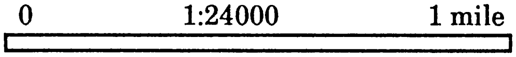
1 - saturated thickness assumed = 400 feet
2 - assumed

In an unconfined aquifer, storativity is equal to specific yield. Since the Rush Springs Sandstone crops out throughout the region, the aquifer should be unconfined, and the specific yield should also average about .15.

It is a generally accepted principle that the water table tends to conform to the surface topography, although it lies at greater depths under hills than it does under valleys. In addition,the hydraulic gradient of the water table decreases with increasing hydraulic conductivity.

Owing to the conformity of the water table to surface relief, a water-table map (fig. 3) was constructed using a topographic map and the water-level measurements listed in Table 2. The map indicates that a ground-water divide, trending northwest-southeast, occurs in Section 6. South of the divide, ground water flows in a southwesterly direction. The hydraulic gradient is approximately 0.01. Assuming that hydraulic conductivity for the area lies within the range of 10 to 100 gpd/ft2, the ground-water velocity should range between 0.089 and 0.893 ft/day.





Contour Interval: 25 feet

Figure 3. Area Water Table, March 12, 1991, showing flow lines of Cyril wells

Ground-Water Flow Direction

The direction of regional ground-water flow was estimated by three different techniques; three-point method, direction of surface stream channels, and a water table map. In the first method, direction of ground-water flow was calculated using the location and water-table elevation in four sets of three wells each, three points being required to define a plane (fig. 4). All measurements indicate flow to the south-southwest (Table 4).

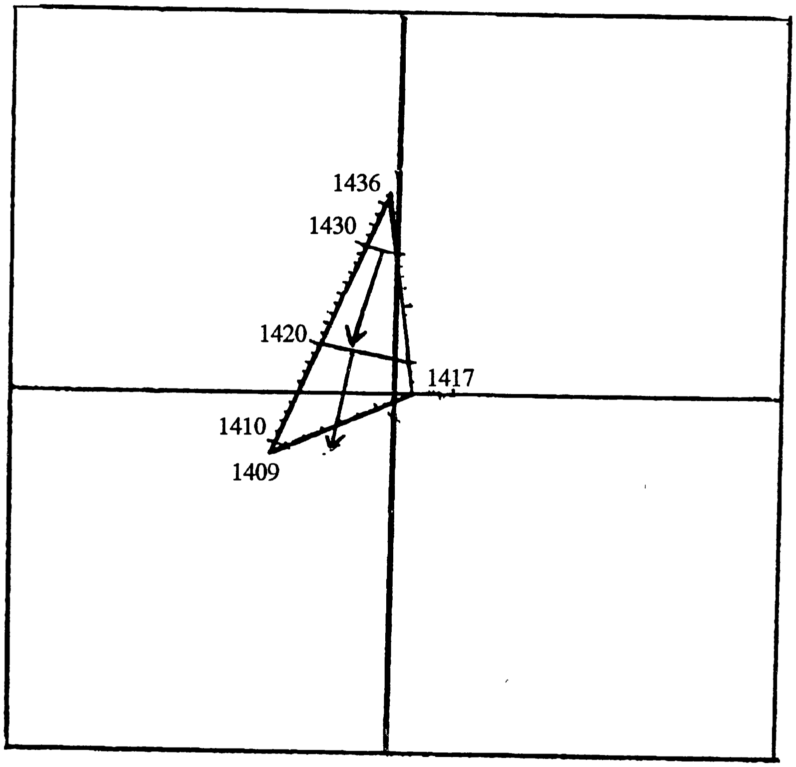


Figure 4. Three-Well Problem, Wells C-1, C-3, and AB-2. Ground Water Flow Direction Equals 75 Degrees (measured counter-clockwise from due East

Ground-water flow direction should mirror the surface gradient. Under this assumption, flow direction of two surface streams was measured (Table 4). These streams generally trend southwestward.

Flow direction also was determined from the water-table map (fig.3). In this case, streams which serve as lines of ground-water discharge exert some control on flow direction. Although flow lines converge on stream channels, the general direction of flow remains southwestward.

Ground-water flow directions determined by the three different methods were averaged. This average was used as the direction for regional flow (Table 4).

TABLE 4

GROUND-WATER FLOW DIRECTION AVERAGES (DIRECTIONS COUNTERCLOCKWISE OF DUE EAST)

Flow Direction	Source
86	Three-Point Problem
80	Three-Point Problem
75	Three-Point Problem
60	Three-Point Problem
70	Surface Stream
61	Surface Stream
75	Water Table Map
55	Water Table Map

Average = assumed regional ground-water flow direction
= 70

Summary of Hydrogeologic Assumptions and Interpretations

In summary, the preliminary analysis and assumptions indicate that the saturated thickness of the Rush Springs aquifer in the study area is about 400 feet thick. Effective porosity and specific yield is assumed to be 0.15. The hydraulic gradient is 0.01, sloping to the southwest. Since hydraulic conductivity should range between 10 and 100 gpd/ft^2, the transmissivity will range between 400 and 40,000 gpd/ft. Interstitial ground-water velocity ranges between 0.089 and 0.89 feet per day. Background concentration of chloride in the Rush Springs is about 25 mg/l, and all Cyril municipal wells have been contaminated.

Modeling

Three computer modeling programs were utilized in this analysis in order to determine probable locations of contamination sources, regardless of the particular type of source. As stated earlier, input to the models included a number of assumed values. Hydraulic conductivity is expected to range from 10 to 100 gpd/ft^2, effective porosity assumed to average 0.15, the hydraulic gradient is 0.01, with saturated thickness assumed to be 400 feet.

T-O-T

Using the T-O-T program, the Z-O-C (Zone of Contribution) and the T-O-T (Time of Travel) for wells C-1, C-2, and C-3 was determined. As previously stated, the Z-O-C defines the area of an aquifer that will contribute water to a pumped well, while the T-O-T is the distance traveled by ground water over a given period of time.

Hydraulic conductivity values of 10 gpd/ft2 and 100 gpd/ft^2 were chosen as lower and upper limits for the analysis. Other parameters also were set at assumed values described earlier. The assumed screened interval (Table 3) was used as the saturated thickness of each of the corresponding wells, resulting in the range of transmissivity values listed in Table 5.

It is assumed that each well was pumped continuously from the time of installation until 1991, when all were abandoned. This establishes a worst-case scenario and provides the maximum possible area for location of contaminant source(s). Pumping periods for C1, C-2, and C-3 were 10, 36, and 5 years, respectively.

TABLE 5

ASSUMED TRANSMISSIVITY VALUES

Well	Minimum (gpd/ft)	Maximum (gpd/ft)
C-1	3520	35,200
C-2	1500	15,000
C-3	4000	40,000

JPLUME

Although not considered in the T-O-T program, dispersion can greatly affect size, distribution, and velocity of a plume of contaminated ground water. The model JPLUME was employed to evaluate the effects of dispersion on the contaminant plume(s) at Cyril, using the following scenario. Assuming a single source of contamination, a single salt-water disposal pit, 100 feet long, began operation in 1940 and continued for 10 years. Leakage from the pit occurred at a constant rate during this time. In 1950 the pit was abandoned and filled. In 1990, Cyril water wells were closed due to high chloride content. Time of consideration for contaminant plume movement is therefore 50 years (1940 -1990). The source was allowed to inject continuously for 3650 days (10 years), representing the time from 1940 to 1950. Initial concentration of chloride at the source was set at 100,000 mg/L, with a recharge rate of 100 gpd. This rate is equal to 2.4 barrels per day or a 10 year total of nearly 8700 barrels.

A second source, placed at the same coordinates (0,0) with a negative injection rate equal to the initial injection rate, was began at time 3650 days. Thus, in effect, the first source was shut off after 10 years. Location and concentration distribution of the resultant plume was modeled for a time equal to 18,250 days (50 years).

Two such simulations were conducted. As in the T-O-T analyses, hydraulic conductivities of 10 and 100 gpd/ft^2 were used. The different hydraulic conductivities manifest themselves in JPLUME as differing groundwater velocities. Grids were varied as necessary to represent plume behavior, longitudinal distance of dispersion being measured from these grid systems. Distance measured was from plume center of mass (highest concentration) to leading edge of the plume.

THEIS WELL FIELD

The program THEIS WELL FIELD was used to assess drawdowns caused by the Cyril wells. In the approach used, the three Cyril wells were pumped in a manner simulating the actual chronological pumping sequence. C-2 was pumped for 26 years, at which time C-1 was placed on line. Both wells then were pumped for five additional years. Finally, C-3 was brought on line and all three wells were pumped for 5 more years.

The heads generated by the program represent the cumulative affect on the water table brought about by pumping of C-1 for 10 years, C-2 for 36 years, and C-3 for 5 years. While in reality, all three wells were not pumped continuously, the simulation presents a worst-case approach similar to that used in the T-O-T program. Again, simulations were run at transmissivity values representing upper and lower extremes.

Results Of Modeling

While a definite location of contamination source(s) was not indicated by this analysis, the examination of available data and use of computer programs did indicate a probable area for such source(s). The T-O-T program was used to determine a Z-O-C and T-O-T for each of the Cyril wells. This process was repeated using both maximum and minimum values of hydraulic conductivity for each well in order to determine the area that could contribute ground water to each well at each value of transmissivity. Superposition of the sequence of maps illustrates the total area that contributed water to the Cyril well field. Superposition was necessary because the program is not designed to incorporate cumulative drawdowns. The distance that ground water contributing to the Cyril well field could travel is limited by the length of time the wells were in existence and the ground-water divide to the northeast. JPLUME was then used to calculate the additional distance traveled by water resulting from dispersion. This dispersion distance was then added to the ground water travel distance calculated by T-O-T to provide a maximum distance which ground water contributing to the Cyril well field would travel. Repetition of this procedure for each of the values calculated by T-O-T allows delineation of the maximum extent of area supplying ground water to the Cyril well field at the assumed maximum and minimum hydraulic conductivity values for the area (fig. 5 and 6).

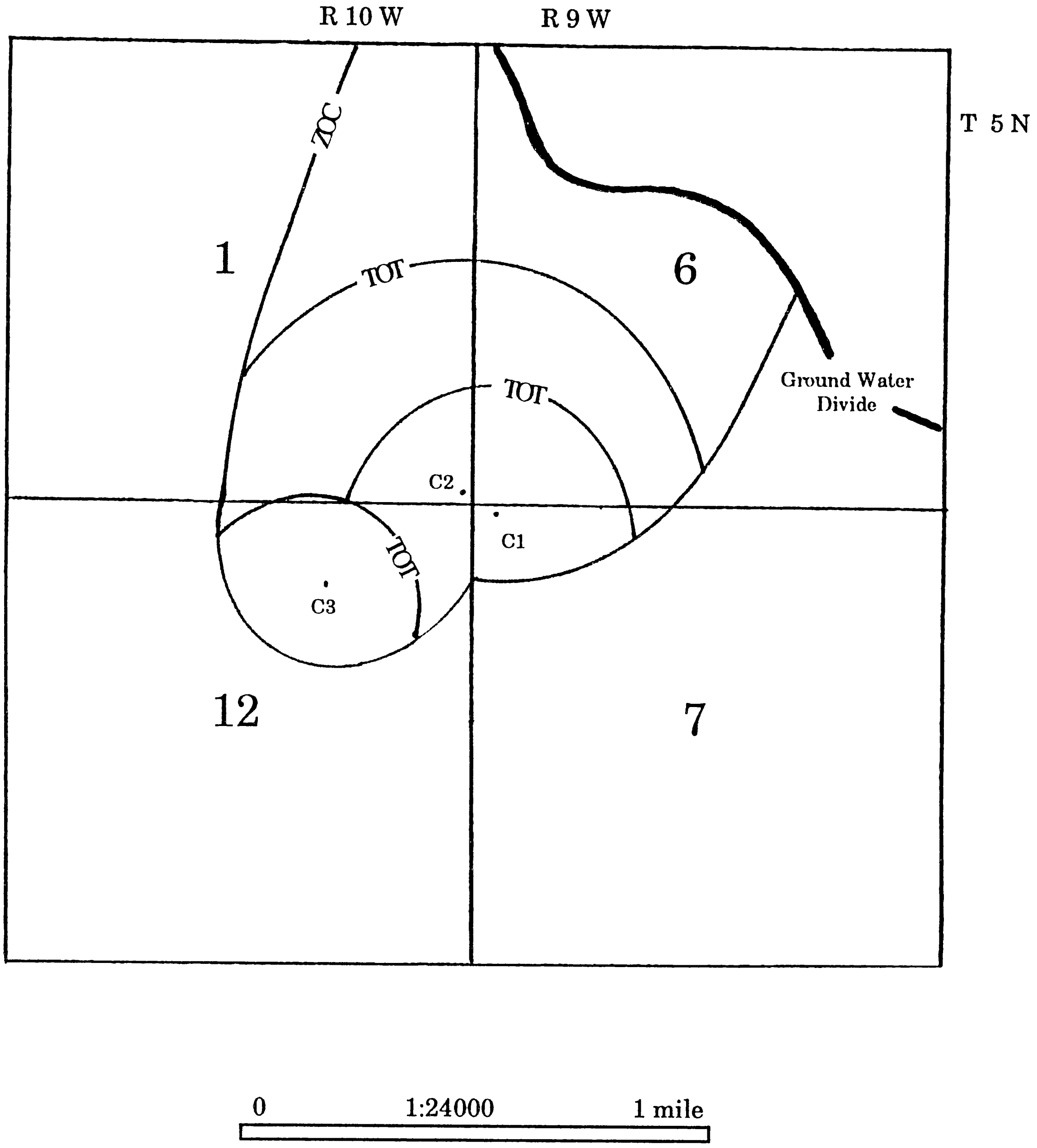


Figure 5. Area Supplying Ground Water to Cyril Well Field
Hydraulic Conductivity = 10 gpd/ft^2

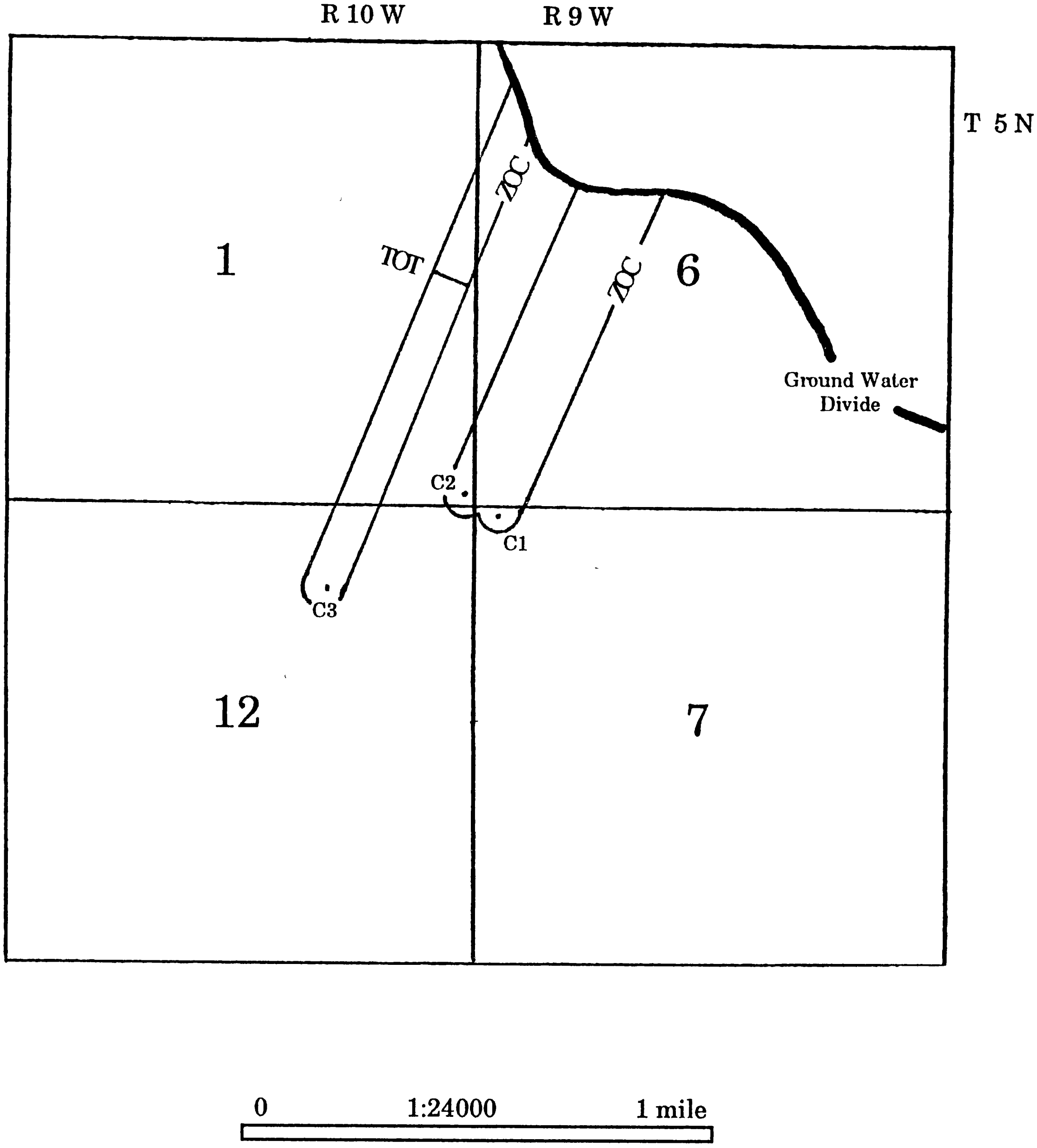


Figure 6. Area Supplying Ground Water to Cyril Well Field
Hydraulic Conductivity = 100 gpd/ft

Any source which would result in contamination of the ground water found in the Cyril wells would be located within the area supplying ground water to these wells. The combination of the two areas mentioned above would indicate the total areal extent of possible source locations (fig. 7). This combined area is centered around the junction of sections 6 and 7 of T. 5 N., R. 9 W. and sections 1 and 12 of T. 5 N., R. 10 W. The area extends approximately 800 feet southeast of Cyril 3 into the northeast 1/4 of section 12. The area extends approximately 2800 feet northeast of Cyril 2 into the southeastern 1/4, of section 1, with a strip about 800 feet wide in the northwestern corner of section 7. The majority of the southwest corner of section 6 is included with a 1200 feet wide strip extending to the ground water divide that cuts diagonally across section 6.

As show by THEIS WELL FIELD, continous pumping of the wells in the Cyril well field would result in a drawdown which would alter the water table locally. Resulting drawdown over the four sections concerned (assuming no recharge) is shown in figures 8 and 9. Development of a cone of depression would cause an increased hydraulic gradient in the vicinity of the well, resulting in an increased interstitual ground velocity. The greater velocity would, in turn, result in a greater Z-O-C, increasing the area in which contaminant sources might be located. This possibility was not considered in this analysis due to the prsence of the ground water divide discussed earlier which would limit the area which would contribute ground water to the Cyril well field.

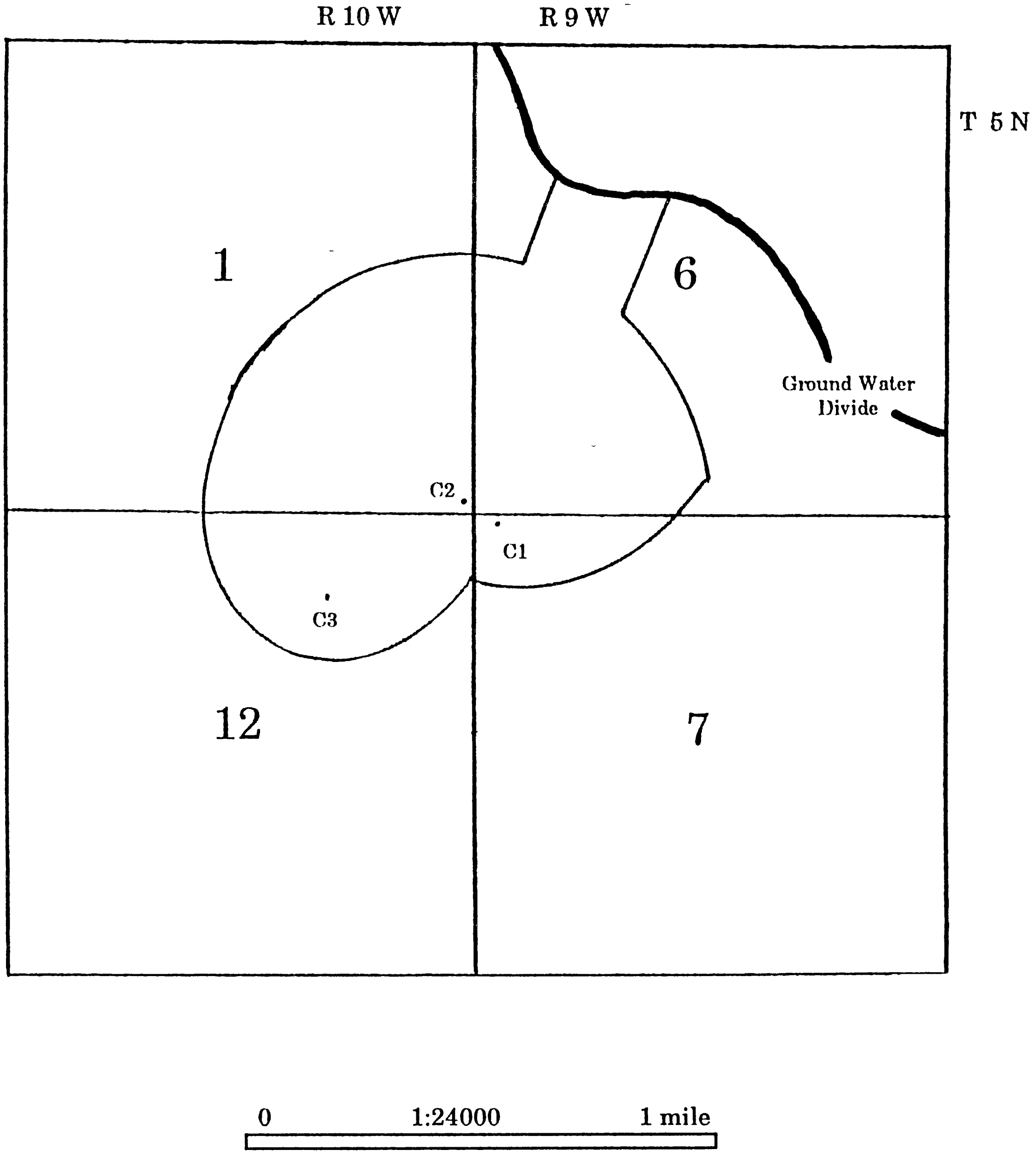
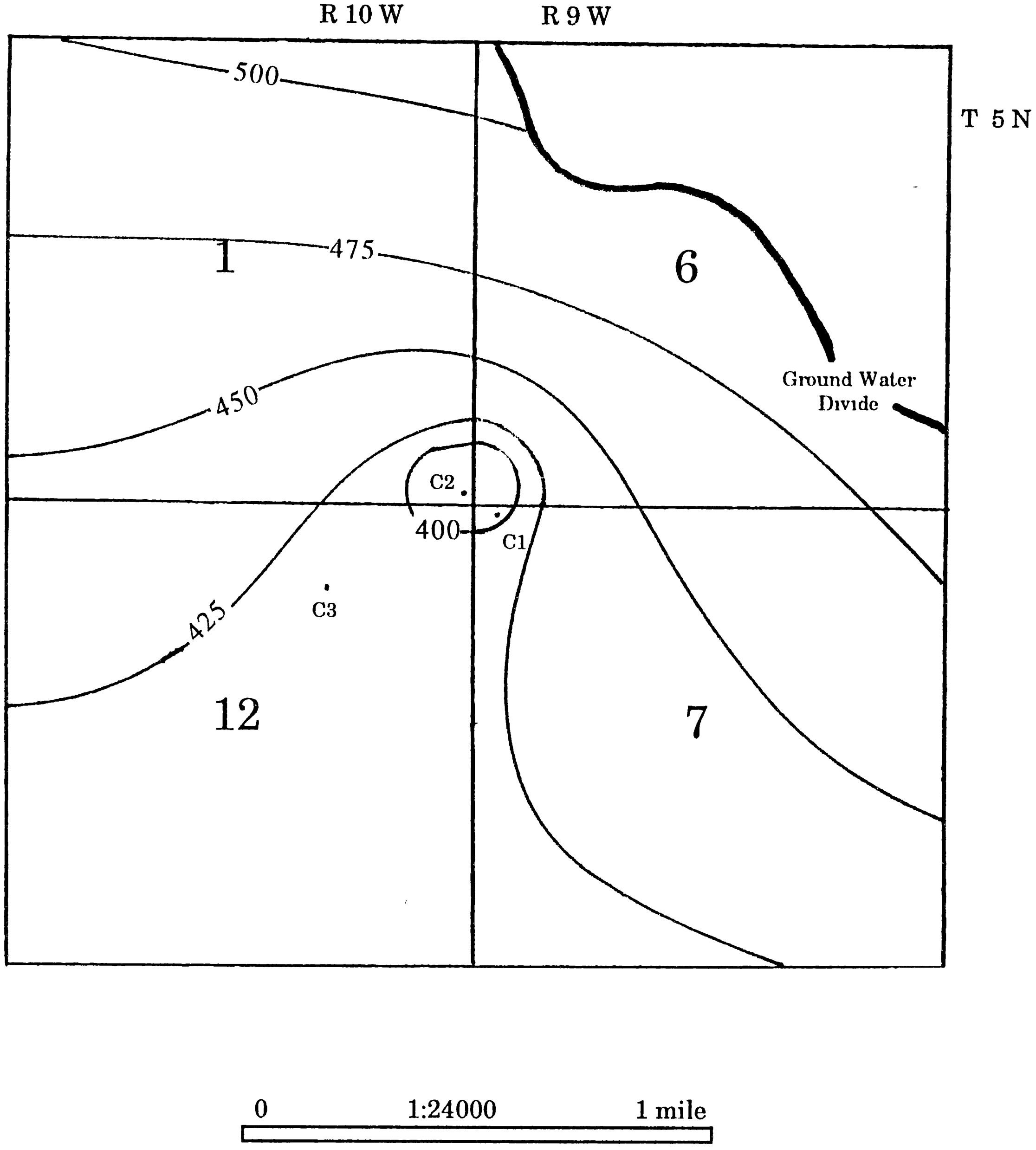
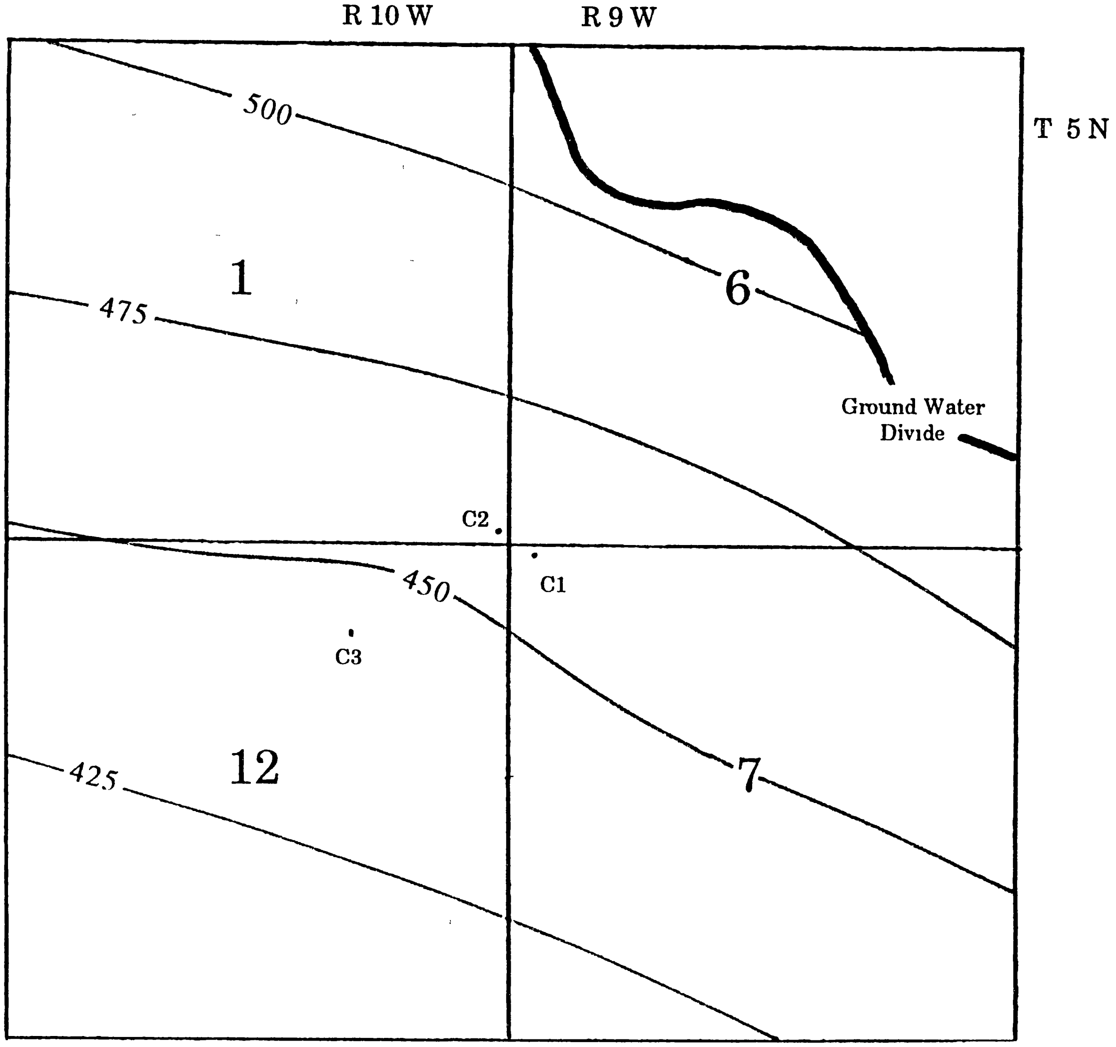


Figure 7. Area of Possible Source Location(s), First Analysis



Contour Interval: 25 feet

Figure 8. Area Water Table after pumping of Cyril Well Field
Hydraulic Conductivity = 10 gpd/ft^2



0 1:24000 1 mile

Contour Interval: 25 feet

Figure 9. Area Water Table after pumping of Cyril Well Field Hydraulic Conductivity = 100 gpd/ft^2

CHAPTER III

USE OF PUBLISHED PARAMETERS

Introduction

The second analysis of the study area involved a larger data base consisting of the information available for the first analysis plus published information, reports, records, and areal photographs. The initial analysis delineated an area of probable contamination source(s), even though a definite site was not identified.

Potential Sources of Chloride

Chloride, the major contaminant in this investigation, can result from several sources. Disregarding improbable sources, such as water-softener regeneration brine and calcium chloride deicing salts, two remain. These two, natural salt sources and oil-field related activities, appear to provide reasonable potential origins for chloride at the site.

Several salt plains occur in western Oklahoma, all of which are several miles northwest of Cyril. In addition to the considerable distance of any known natural salt occurrences, the possibility of any of these salt plains serving as contamination source in the vicinity of Cyril is eliminated by presence of the Cement anticline. This structure, which appears as a topographic ridge, serves as both a surface water and ground-water divide. The anticlinal crest is located several hundred yards north of the municipal well field. This structure and the associated ground-water divide eliminates the possibility of chloride contamination from any source that lies north of the anticline.

The West Cement Oil and Gas Field was developed along the flanks of the Cement anticline, after drilling of the first well production in 1917. Oil-field brine was discharged into surface disposal pits until about 1950 when the Oklahoma Corporation Commission required that pits no longer be used owing to numerous examples of ground-water contamination. After 1950 disposal was accomplished by means of saltwater injection wells. In the early 1970's, secondary recovery operations were initiated.

Brine derived from activities in this field is the probable source of chloride contamination. Several oil-field activities could result in ground-water contamination. Among these are:

1) brine spills and pipeline leaks
2) spills at or near brine disposal pits
3) infiltration from brine disposal pit(s)
4) spills related to injection well operation
5) leaking injection well(s)
6) fluid migration along the annular space of inadequately cemented well casing(s) and abandoned wells

It is assumed that activities 1, 2, and 4 listed above, would not contribute a sufficient quantity of brine to result in such widespread contamination as is present in the Cyril area. Available information suggests that possibility 6 may have some merit, however, no details are available. It is assumed that contamination of the well field is largely the result of the infiltration of brine from disposal pits and injection well operations.

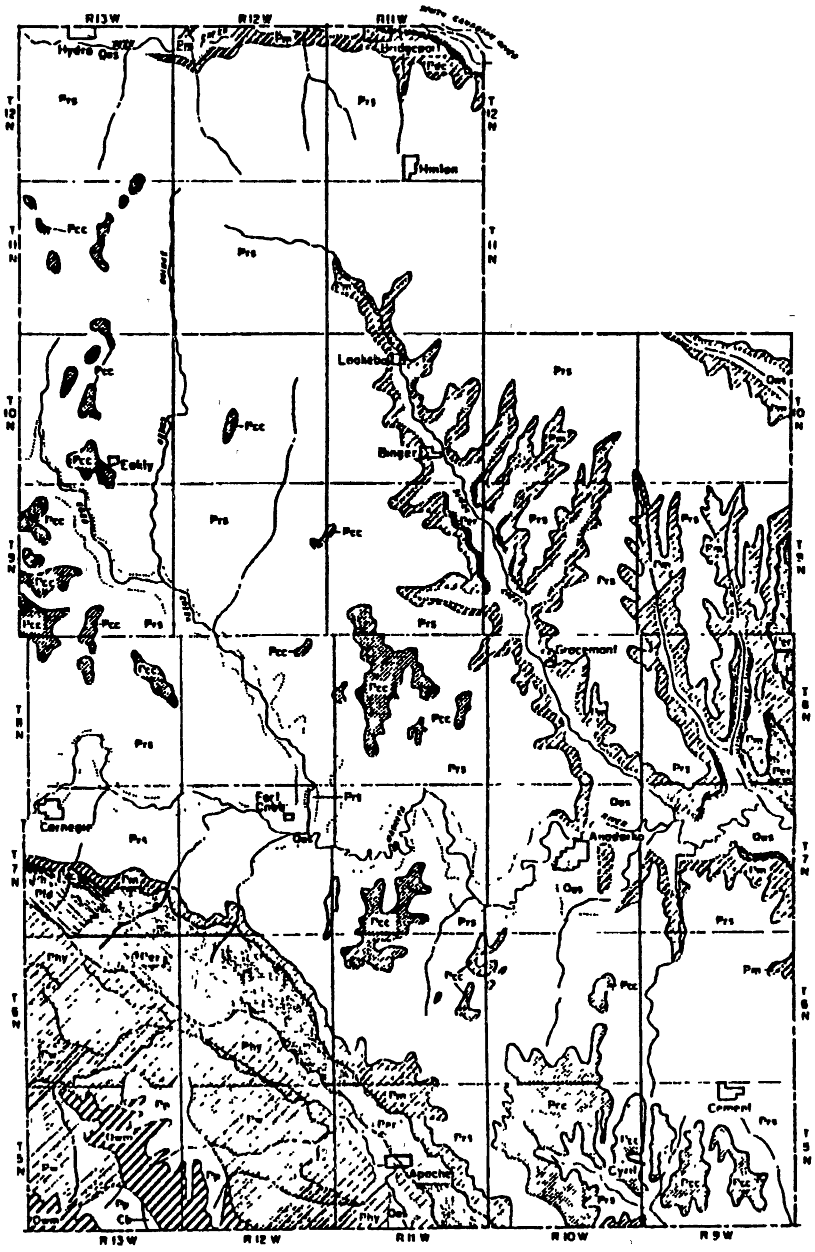
Literature Review

Geology

A geologic map and generalized stratigraphic section of Caddo County are shown in figures 10 and 11, respectively. Major stratigraphic units of concern in the study area, in descending order, are the Cloud Chief Formation and the Whitehorse Group, the latter of which consists of the Rush Springs Sandstone and the Marlow Formation.

A large outlier of the Cloud Chief Formation occurs in the vicinity of Cyril. The Cloud Chief consists of red clay-shale and red silty or sandy shale. Locally the formation contains large quantities of gypsum. In some places, the Cloud Chief is similar to the underlying Rush Springs Sandstone (Tanaka and Davis, 1963).

The Rush Springs Sandstone, which crops out throughout the study area, forms the upper unit of the Whitehorse Group. The Rush Springs



Quaternary:
- Qas Alluvium on first and second bottoms and low terraces

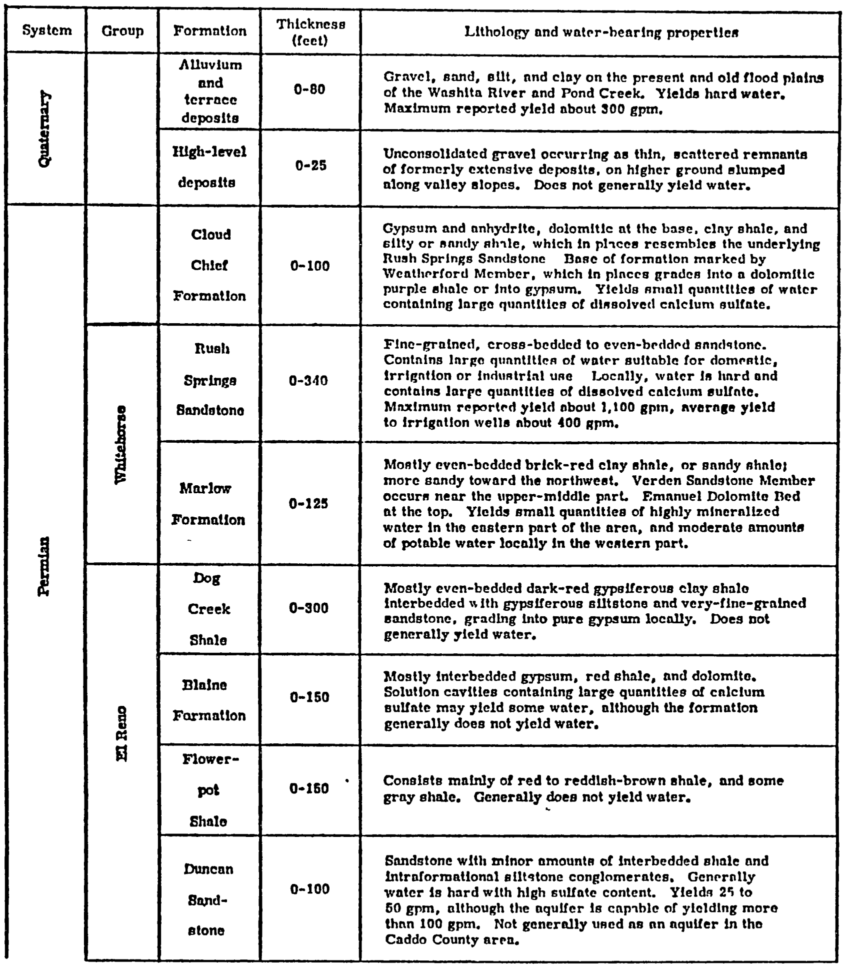
Permian:
- Pcc Cloud Chief formation
- Prs Rush Springs Sandstone (Whitehorse group)
- Pm Marlow formation (Whitehorse group
- Per El Reno group
- Pde Dog Creek Shale
- Pb Blaine Gypsum

Permian - Continued
- Pfd Flowerpot Shale and Duncan Sandstone
- Phy Hennessey Shale
- Pw Wichita formation
- Pp Post Oak Conglomerate member of Wichita formation

Ordovician.
- OwmUpper part of Arbuckle group

Cambrian
- Cb Lower part of Arbuckle group

Figure 10. Geology of Caddo County, Oklahoma (excerpted from Soil Survey of Caddo County, Oklahoma, 1973)



System	Group	Formation	Thickness (feet)	Lithology and water-bearing properties
Quaternary		Alluvium and terrace deposits	0-80	Gravel, sand, silt, and clay on the present and old flood plains of the Washita River and Pond Creek. Yields hard water. Maximum reported yield about 300 gpm.
		High-level deposits	0-25	Unconsolidated gravel occurring as thin, scattered remnants of formerly extensive deposits, on higher ground slumped along valley slopes. Does not generally yield water.
Permian		Cloud Chief Formation	0-100	Gypsum and anhydrite, dolomitic at the base, clay shale, and silty or sandy shale, which in places resembles the underlying Rush Springs Sandstone Base of formation marked by Weatherford Member, which in places grades into a dolomitic purple shale or into gypsum. Yields small quantities of water containing large quantities of dissolved calcium sulfate.
	Whitehorse	Rush Springs Sandstone	0-340	Fine-grained, cross-bedded to even-bedded sandstone. Contains large quantities of water suitable for domestic, irrigation or industrial use Locally, water is hard and contains large quantities of dissolved calcium sulfate. Maximum reported yield about 1,100 gpm, average yield to irrigation wells about 400 gpm.
		Marlow Formation	0-125	Mostly even-bedded brick-red clay shale, or sandy shale; more sandy toward the northwest. Verden Sandstone Member occurs near the upper-middle part. Emanuel Dolomite Bed at the top. Yields small quantities of highly mineralized water in the eastern part of the area, and moderate amounts of potable water locally in the western part.
	El Reno	Dog Creek Shale	0-300	Mostly even-bedded dark-red gypsiferous clay shale interbedded with gypsiferous siltstone and very-fine-grained sandstone, grading into pure gypsum locally. Does not generally yield water.
		Blaine Formation	0-150	Mostly interbedded gypsum, red shale, and dolomite. Solution cavities containing large quantities of calcium sulfate may yield some water, although the formation generally does not yield water.
		Flower-pot Shale	0-150	Consists mainly of red to reddish-brown shale, and some gray shale. Generally does not yield water.
		Duncan Sand-stone	0-100	Sandstone with minor amounts of interbedded shale and intraformational siltstone conglomerates. Generally water is hard with high sulfate content. Yields 25 to 50 gpm, although the aquifer is capable of yielding more than 100 gpm. Not generally used as an aquifer in the Caddo County area.

Figure 11. Generalized Stratigraphic Column, Caddo County (excerpted from Ground Water; Rush Springs Sandstone, 1963)

consists chiefly of reddish brown, very-fine grained, silty sandstone. Calcareous sandy beds, 6 to 12 inches thick, occur randomly throughout the unit, although such units are more common in the lower parts. Solution of calcite by ground water has resulted in "soft streaks" of loose sand (Davis. 1950). In the Cement area, the sandstone is reported to be bleached gray, containing approximately 40 percent dolomite (Soil Survey, Caddo County, 1973).

The thickness of the Rush Springs ranges from 140 to 330 feet, thickening to the north and west. Even-bedded to highly cross-bedded, the formation shows characteristics of shallow marine deposition. Sand grains are subangular to sub-round, homogeneous in lithologic nature, and loosely cemented with iron oxide and calcite (Tanaka and Davis, 1963). Coarse, almost perfectly spherical grains are common; the formation is noted it's homogeneity.

The Marlow Formation forms the lower part of the Whitehorse Group. According to Tanaka and Davis (1963), the Marlow consists largely of even-bedded, brick-red, sandy shale, generally gypsiferous, with some very fine sand and silt that is loosely cemented with iron oxide and calcite. Formation thickness ranges from 90 to 128 feet, with an average of about 100 feet in the Caddo County area.

Although not distinguished in this study, the Marlow has been divided into several smaller units, which include the Verden Sandstone Member, the Emanual Dolomite Bed, and the Relay Creek Dolomite Bed (Tanaka and Davis, 1963). The Verden Sandstone, approximately 10 feet thick, consists of medium to coarse, rounded quartz and subangular chert grains cemented with calcium carbonate. This unit also contains interbedded fine-grained sandy shale. The Emanual Dolomite Bed and the Relay Creek Dolomite Bed occur near the top of the Marlow Formation. In Caddo County, the two dolomites range in thickness from paper-thin lamination to a maximum of about 5 to 6 inches with a vertical separation of the two ranging from 16 to 20 feet.

Hydrogeologic Characteristics of
the Rush Springs and Marlow

Hydrologic Characteristics of the Rush Springs

Although generally considered to be unconfined, the Rush Springs aquifer exhibits both confined and unconfined conditions. The water level in some wells, for example, appears to fluctuate in response to changes in barometric pressure, as would a confined aquifer. This is not surprising, however, since most bedrock units contain individual zones that are well-cemented or consist of fine-grained material. Each unit of this type, regardless of thickness or areal extent, would tend to confine the ground water below it so that the aquifer would respond as though it were confined or semi-confined.

Storativity of an unconfined system is equal to the specific yield of the aquifer material. Therefore, a storativity value in the range of 20 to 30 percent would be expected for the Rush Springs aquifer. Storativity values calculated from some aquifer tests of the Rush Springs, however, are considerably smaller than the specific yield. It is likely, in these cases, that the period of pumping was too short for gravity drainage of the very fine-grained material to become complete, and, as a result, calculated storativity values would be in the range of 0.001 to 0.01.

In 1948, an aquifer test was conducted on the Rush Springs by Davis using a water well owned by Magnolia Petroleum Company (Sec. 3, T. 4 N.,

R. 7 W., Grady County). Drilled to a depth of 500 feet and plugged back to 122 feet below ground surface, the Magnolia well penetrated the full thickness of the Rush Springs sandstone. At this location, the formation consisted of a homogeneous, fine-grained, massive sandstone. The well was pumped for 24 hours with an average discharge of 163 gallons per minute. Storativity was set at 0.1, due to assumption of water table conditions, with an approximate transmissivity of 13,000 gpd/ft reported (Davis, 1955).

A second aquifer test was conducted by Davis in April, 1949, in Pond Creek Basin. Pond Creek Basin lies primarily in the west-central part of Caddo County, with slight extensions into northeastern Washita and southeastern Custer Counties. Pond Creek (known locally as Cobb Creek) is a perennial stream whose baseflow is maintained by seepage from the Rush Springs (Davis, 1950). Pond Creek Basin is an area of fairly extensive irrigation.

The aquifer test was conducted using the Shoop well, one of several irrigation wells in the basin. Geologic conditions at the test site were considered representative of the area, with the Rush Springs Sandstone lying immediately below a light, sandy, highly permeable soil. Saturated thickness of the Rush Springs at this site was estimated to be 265 feet, and the calculated transmissivity was 5000 gpd/ft. Therefore, hydraulic conductivity is approximately 19 gpd/ft^2. Davis suggested that the calculated aquifer test values were indicative of the hydrogeologic parameters within the Pond Creek

Basin area, but that they were conservative relative to the Rush Springs in other areas.

Tanaka and Davis (1963) described two Rush Springs aquifer tests that were conducted in Caddo County. A test in 1956 (northwest corner of Sec. 23, T.10 N. R.12 W.), resulted in transmissivity values ranging from 11,000 to 14,000 gpd/ft, and storativity values ranging from 0.01 to 0.03, and averaging 0.02. A second test, conducted in 1959, yielded a transmissivity of 13,000 gpd/ft. Recovery data only were used to evaluate this test, due to variations in the discharge rate during the test.

Based on these tests, Tanaka and Davis (1963) assumed an average transmissivity for the Rush Springs of 10,000 gpd/ft, and a mean hydraulic conductivity of 35 gpd/ft^2. Since irrigation wells, with discharge rates (175 to 730 gpm) substantially larger than those provided by Cyril municipal wells, were used for these tests, the calculated values of both transmissivity and hydraulic conductivity may be higher than those in the vicinity of Cyril.

Church and others (1965) reported that the hydraulic conductivity of the Rush Springs in the Caddo Creek area was approximately 30 gpd/ft^2, but no other details were given.

Hydrologic Characteristics of the Marlow Formation

The Marlow Formation in the Pond Creek Basin area was described by Davis (1955) as "too impermeable to yield more than enough water for stock use". In Grady and Stephens Counties, the Marlow was reported to yield no more than 1 or 2 gallons per minute (Davis, 1955).

Tanaka and Davis (1963) reported that the Marlow Formation contains permeable sandy zones, 0.5 to 5 feet in thickness, in parts of Caddo County. An electric log of a test hole in Sec. 23, T.10 N., R. 12 W. indicates that the Marlow consists of a series of shale and sandstone units that range in thickness from about 6 inches to 3 feet. From this log, Tanaka and Davis calculated that permeable beds form an aggregate thickness of about 20 feet in the formation. Using the thickness of 20 feet and an average hydraulic conductivity value of 12 gpd/ft^2 (from U.S. Geologic Survey Hydrologic Laboratory analyses), the authors calculate a transmissivity of about 240 gpd/ft for the the Marlow. Tanaka and Davis state that this figure does not reflect potential yield of the formation due to the completion without casing of the irrigation wells used in this study. The washing out of silt and very-fine sand would increase the effective diameter of the well bore, which would increase the quantity of water that could be released from the formation into the well.

Ground-Water Quality

Ground-Water Quality of the Rush Springs Sandstone

The earliest report concerning ground-water quality in the Cyril area is by Gould (1905), who stated that the water in Caddo County is 'good' and usually soft. Analyses of twelve 1948 samples representing the Rush Springs in the Pond Creek Basin (Table 6) indicated the water to be of good quality with few elevated concentrations of any constituent. The majority of chloride concentrations are below 15 mg/l, with the greatest concentration being only 49 mg/l. Sulfate concentrations are also low, the greatest being 21 mg/l. Several nitrate concentrations are elevated to the extent that they exceed U.S. Environmental Protection Agency standards for drinking water. This is most likely due to contamination from fertilizers and/or pesticides since the area is one of high irrigation and agricultural use. (Davis, 1950).

Thirty-nine ground water samples (1946-1950) from the Rush Springs aquifer in Grady and northern Stephens counties (Table 7) also indicated, for the most part, a good water quality. While five of the samples exhibit chloride concentrations in excess of 100 mg/l, none are above the U.S. E.P.A. standards. However, nine samples do exhibit sulfate concentrations in excess of U.S. E.P.A. standards, possibly due to location and well depth. As was the

TABLE 6

RUSH SPRINGS IN THE POND CREEK BASIN

Location Sec.	T.N.	R.W.	sample date	Water Temparature degrees F.	Parts Per Million Calcium	Magnesium	Sodium and Potassium	Carbonate	Bicarbonate	Sulfate	Chloride	Fluoride	Nitrate	Total Hardness as CaCo3	Dissolved Solids	Specific Conductance micromhos @ 25 F.
5	8	12	3/24/48	63	24	12	2.4	0	99	9.9	14	ND	4	109	192	192
1	8	13	3/17/48	62	27	13	29	0	110	16	11	ND	75	121	273	273
1	9	12	3/18/48	61	17	7.6	16	0	72	12	12	0.2	25	74	144	144
16	9	12	3/18/48	59.5	47	18	16	12	206	8.7	10	0.4	15	191	202	389
19	9	12	3/17/48	60	20	10	13	0	99	9.7	14	ND	10	91	145	217
24	9	12	3/24/48	61	36	16	108	0	316	21	49	ND	50	157	448	742
3	9	13	3/24/48	59.5	47	8.7	47	0	239	12	9	0.4	40	153	296	455
28	9	13	8/18/48	60	54	13	15	0	188	20	9	ND	40	188	282	407
31	10	12	3/19/48	60	57	19	21	0	260	16	25	0.1	1	221	280	477
4	10	13	3/17/48	59.5	37	5.2	16	0	145	7.8	14	ND	3	114	156	268
3	11	12	3/19/48	61	73	9.2	22	18	210	5.7	14	ND	50	220	290	465
33	12	13	3/18/48	60.5	70	8	39	0	326	5.8	11	ND	5	208	339	554

TABLE 7

RUSH SPRINGS IN GRADY AND STEPHENS COUNTIES

Location				Parts Per Million											
SEC.	T.N.	R.W.	sample date	Calcium	Magnesium	Sodium and Potassium	Bicarbonate	Sulfate	Chloride	Fluoride	Nitrate	Hardness as CaCO3 Calcium-Magnesium	Hardness as CaCO3 Noncarbonate	Dissolved Solids (*)	Specific Conductactance micromhos @ 25 F
16	3	7	4/3/46	66	24	24	360	3	9		5	263		335	
17	3	7	4/3/46	55	19	57	344	13	17		25	216		378	
26	3	7	7/28/48	62	27	40	155	14	109	0.2	70	266	138	429	706
26	3	7	7/28/48				148	15	114	0.6	70	263			674
2	3	8	1/23/46	68	44	44	192	21	43		255	350		704	
3	3	8	1/23/46	78	78	28	326	68	61		189	515		748	
4	3	8	4/5/46	68	37	49	163	13	64		236	322		694	
9	3	8	4/5/46	83	15	17	160	60	32		84	268		487	
15	3	8	4/5/46				114	68	102		352	596			
3	4	7	12/23/48	87	14	12	257	53	23		4	274	64	365	560
5	4	5	1/24/46	90	10	6.2	278	24	12		11	266		344	
9	4	7	2/4/46	61	7.5	34	250	15	8		30	183		329	
16	4	7	2/4/46	29	14	21	74	14	53		33	130		305	
29	4	7	4/5/46	100	46	3.2	207	176	54		21	438		603	
29	4	7	7/7/50	88	19	17	229	95	26		14	298	110	463	625
10	4	8	4/5/46	48	12	70	196	14	12		223	170		476	
14	4	8	4/6/46	68	16	20	276	12	18		19	236		342	
15	4	8	4/4/46	57	29	29	248	95	10		9	262		420	
17	4	8	4/5/46	299	57	78	192	449	183		330	980		1490	
20	4	8	4/5/46	279	13	110	118	591	183		24	750		1260	
23	4	8	2/6/46	364	33	22	198	876	9		5.5	1040		1400	
23-24		8	2/7/46	100	17	1.6	199	140	5		9.6	320		436	
23-34		8	2/7/46	37	22	59	312	31	7		17	183		327	
23-44		8	4/4/46	144	20	163	137	532	43		86	442		1060	
25	4	8	2/6/46	10	8.1	18	96	10	4		2	58		115	

* = Residue on Evaporation @ 180 degrees.

TABLE 7 (Continued)

Location SEC.	T N.	R.W.	sample date	Calcium	Magnesium	Sodium and Potassium	Bicarbonate	Sulfate	Chloride	Fluoride	Nitrate	Hardness Calcium-Magnesium	as CaCO3 Noncarbonate	Dissolved Solids (*)	Specific Conductactance micromhos @ 25 F
				Parts Per Million											
26	4	8	2/6/46	68	28	94	288	221	8		1	274		558	
27	4	8	4/4/46	64	17	15	203	46	9		43	230		367	
28	4	8	4/4/46	274	20	9.7	238	536	8		28	766		993	
33-1	4	8	8/3/46	304	20	46	90	777	40	0.4	1	840	767	1640	1660
33-1	4	8	8/3/46	541	31	144	99	1570	52	0.4	0.2	1480	1400		2200
36	4	8	2/6/46	58	22	19	278	12	6		33	235		306	
33	5	7	1/24/46	77	6.6	6.2	220	14	8			219		332	
18	6	8	1/17/50	36	15	17	113	64	13			152	59	264	375
9	9	8	6/6/47	122	37	6	49	393	18	0.4	2	456	402	796	1060
34	10	8	6/6/47	34	13	11	105	26	14	0.2	20	138	39	215	422

* = Residue on Evaporation @ 180 degrees.

case in the Pond Creek Basin, several nitrate values are in excess of recommended levels, probably related to agricultural practices in the area. Ground Water: Rush Springs Sandstone listed forty-two analyses (Table 8) of Rush Springs ground water samples taken from 1945 to 1957 (Tanaka and Davis 1963). Again, these samples indicate good quality water with few isolated concentrations of chloride, sulfate, and/or nitrate in excess of U.S. E.P.A. standards. The authors report an average chloride concentration in the area of their investigation of 14 mg/L.

Ground-Water Quality of the Marlow Formation

In the Pond Creek basin, Davis (1950) described the water of the Marlow Formation as very hard, and high in calcium, magnesium, and sodium sulfates. In Grady and northern Stephens Counties, water from the Marlow also is reported to be very hard and high in sulfate. Davis (1950) stated that water from the Marlow is commonly reported to be unsuitable for human consumption, with some so highly mineralized that cattle refuse to drink it. Tanaka and Davis (1963) reported that, although one sample of water from the Marlow (well Sec. 24, T.10N., R.9W.) resembles water from the Rush Springs, water from the Marlow is usually harder and has higher sulfate and dissolved solids concentrations than that from the Rush Springs.

TABLE 8

RUSH SPRINGS IN CADDO COUNTY

Parts Per Million

Location			sample date	Silica	Calcium	Magnesium	Sodium and Potassium	Bicarbonate	Sulfate	Chloride	Fluoride	Nitrate	Hardness as CaCO3		Dissolved Solids	Specific Conductance Micromhos 25 F	pH
Sec.	T.N.	R.W.											Calcium-Magnesium	Noncarbonate			
3	5	9	8/16/56	22	62	6.2	4	122	28	28	0	20	180	80	236	388	8
3	5	9	8/3/51	22	385	80	396	264	201	1160	0	65	1290	1070	3160	4920	7
35	5	9	8/12/48		54	12	212	212	41	20		30	184	10	310	490	
• 1	5	10	8/23/51	22	92	17	272	272	78	11	0.3	16	800	76	407	610	8
• 1	5	10	8/16/56	24	100	12	274	274	7	37	0	60	298	74	399	640	7
• 2	5	10	12/11/46	16	141	33	258	258	261	15	0	7.2	488		646	890	7
10	7	10	3/23/48		605	83	159	159	1690	14	0.4	2	1850	1720	2700	2630	
30	7	11	8/22/49		246	6.6	216	216	476	8	0.3	50	64	464	986	1200	
2	7	12	2/7/57		37	7.7	16	132	10	3		50	124	16	186	310	8
2	7	12	8/23/51	24	74	8.5	14	189	79	7	0.3	7	220	64	318	477	8
5	7	12	3/17/48		12	4.4	38	107	16	6		20	48	0	174	237	
34	7	12	3/17/48		21	0.3	49	158	12	10	0	4	54	0	154	222	
4	8	12	3/23/48		57	51	17	218	190	7	0.6	0.5	352	0	555	849	
5	6	12	3/24/48		24	12	2	99	10	14	0	4	109		192	296	
11	8	12	6/18/46		66	9.2	8	236	7	16			203				8
12	8	12	12/5/45		35	15		216	15	11							7
13	8	12	12/5/45		36	15		216	12	11							7
14	8	12	12/5/45		86	12		418	32	11		0					8
1	8	12	3/17/48		27	13	29	110	16	11	0	75	121	31	273	393	
1	8	13	11/8/49		448	45	29		1270	36		0	1310	1310	2020	2110	
34	12	11	8/29/47					240	17	35		20				580	
4	12	13	9/26/51	24	54	13	26	266	9	8	0	1.9	188	0	259	476	8
33	12	13	3/18/48		70	8	39	325	6	11		5	200	0	339	554	

• - Background Analyses - Chapter V

TABLE 8 (Continued)

Location Sec.	T.N.	R.W.	sample date	Silica	Calcium	Magnesium	Sodium an Potassium	Bicarbonate	Sulfate	Chloride	Fluoride	Nitrate	Hardnes as CaCO3 Calcium-Magnesium	Noncarbonate	Dissolved Solids	Conductance Micromhos 25 F	pH
				Parts Per Million													
4	9	10	3/23/48		40	19	25	196	23	10	0.2	20	170	1	287	515	
16	9	10	3/23/48		66	27	32	280	9	8	0.2	90	276	25	343	626	
1	9	12	3/18/48		17	7.6	16	72	12	12	0.2	25	74	15	144	204	
12	9	12	3/18/48		47	18	16	206	9	10	0.4	15	191	2	202	389	
19	9	12	3/17/48		20	10	13	99	10	14	0	10	91	10	145	217	
24	9	12	3/24/48		36	16	108	316	21	49	0	50	157	0	448	742	
3	9	13	3/24/48		47	8.7	47	239	12	9	0.4	40	153	0	296	455	
28	9	13	8/18/48		54	13	15	188	20	9		40	188	34	282	407	
5	10	11	3/24/48		12	7.3	8	75	10	3	0.4	0	60	0	79	149	
32	10	11	5/23/56		47	9.4	14	210	4	8		1.3	156	0	220	356	7
33	10	11	5/24/56		53	2.9	21	170	38	6		8.5	144	4	270	414	8
23	10	12	4/13/56	30	48	7.3	11	185	13	5	0	1.2	150	0	204	325	7
31	1	12	3/19/48		57	19	21	260	16	25	0.1	1	221	7	280	477	
4	10	13	3/17/48		37	5.2	16	145	8	14	0	3	114	0	156	268	
3	11	11	3/23/48		59	13	31	249	8	14	0.2	3	200	0	262	455	
22	11	11	8/29/47		48	13	20	172	11	16		30	173	16	244	383	
22	11	11	4/5/49		64	18	16	304	6	7		4.5	234	0	286	489	
3	11	13	3/19/48		73	9.2	22	210	6	14	0	50	220	179	290	465	
31	12	11	3/19/48		45	9	50	289	4	12	0	0	149	0	252	447	

Ground water Recharge

Ground-water recharge to the Rush Springs aquifer was estimated by two different techniques. For the regional perspective the computer model RECHARGE, discussed in Chapter I, was used. An attempt was also made to evaluate site specific ground-water recharge by means of Darcy's Law

Using RECHARGE, regional recharge rates were calculated using stream flow data for the Little Washita River. Except for water year 1983, these data are available for the period 1952 through 1985. Regional ground-water recharge rates range from a low of 11,000 gpd/sq. mile (0.23 inches/yr) in 1971 to a high of 120,000 gpd/sq. mile (2.5 inches/yr) in 1960. Annual statistics for 1961 and 1971 are shown in Table 9, and annual recharge rates for the region are shown in figure 12. The mean regional recharge rate for the entire period of record was approximately 49,300 gpd/sq. mile (1.1 inch/yr).

Recharge rates for the Cyril area were calculated by means of Darcy's Law. Using a topographic map of the area, and a map showing the ground-water divide, an area was delineated for the calculation of recharge (fig. 13). The Cement anticline, which forms a ground-water divide, borders the north side of the area, and streams to the east and west also serve as ground-water divides. These divides define a theoretical flow tube. The flow tube is approximately 2200 feet wide, and it is assumed that the saturated thickness of the aquifer is 70 feet. Cross-sectional area of ground-water flow, therefore, is

TABLE 9

DISCHARGE STATISTICS, 1960 AND 1971

1960	
Minimum Discharge	3.9 cfs
Mean Discharge	75.388 cfs
Maximum Discharge	2180 cfs
Total Discharge for the Year	2.377443 (10^{9}) cubic feet 4.508132 inches
Total Discharge/Year/Basin Area	1.047332 (10^{7}) cf/sq. mi. .3756785 cf/sq. ft.
Total Ground Water Discharge/Year/Basin Area	1.330388 (10^{9}) cubic feet 2.522696 inches
Percent of Total Discharge due to Ground Water Runoff	55.9588
Recharge Rate	120,000 gpd/sq. ft. 4.304408 (10^{-3}) gpd/sq.ft.

1971	
Minimum Discharge	0 cfs
Mean Discharge	10.02 cfs
Maximum Discharge	531 cfs
Total Discharge for the Year	3.160169 (10^{8}) cubic feet .6539723 inches
Total Discharge/Year/Basin Area	1519312 cf/sq. mi. 5.449782 (10^{-2}) cf/sq.ft.
Total Ground Water Discharge/Year/Basin Area	1.199232 (10^{8}) cubic feet .2481717 inches
Percent of Total Discharge due to Ground Water Runoff	37.94835
Recharge Rate	11,000 gpd/sq.mi. 3.945707 (10^{-4}) gpd/sq.ft.

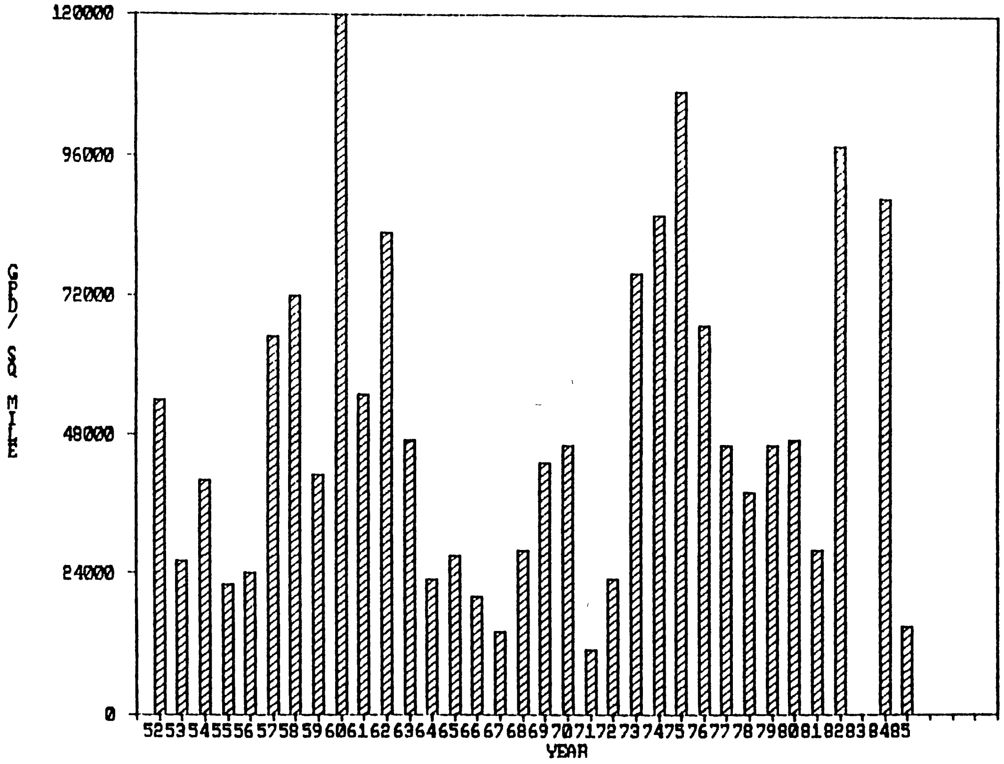
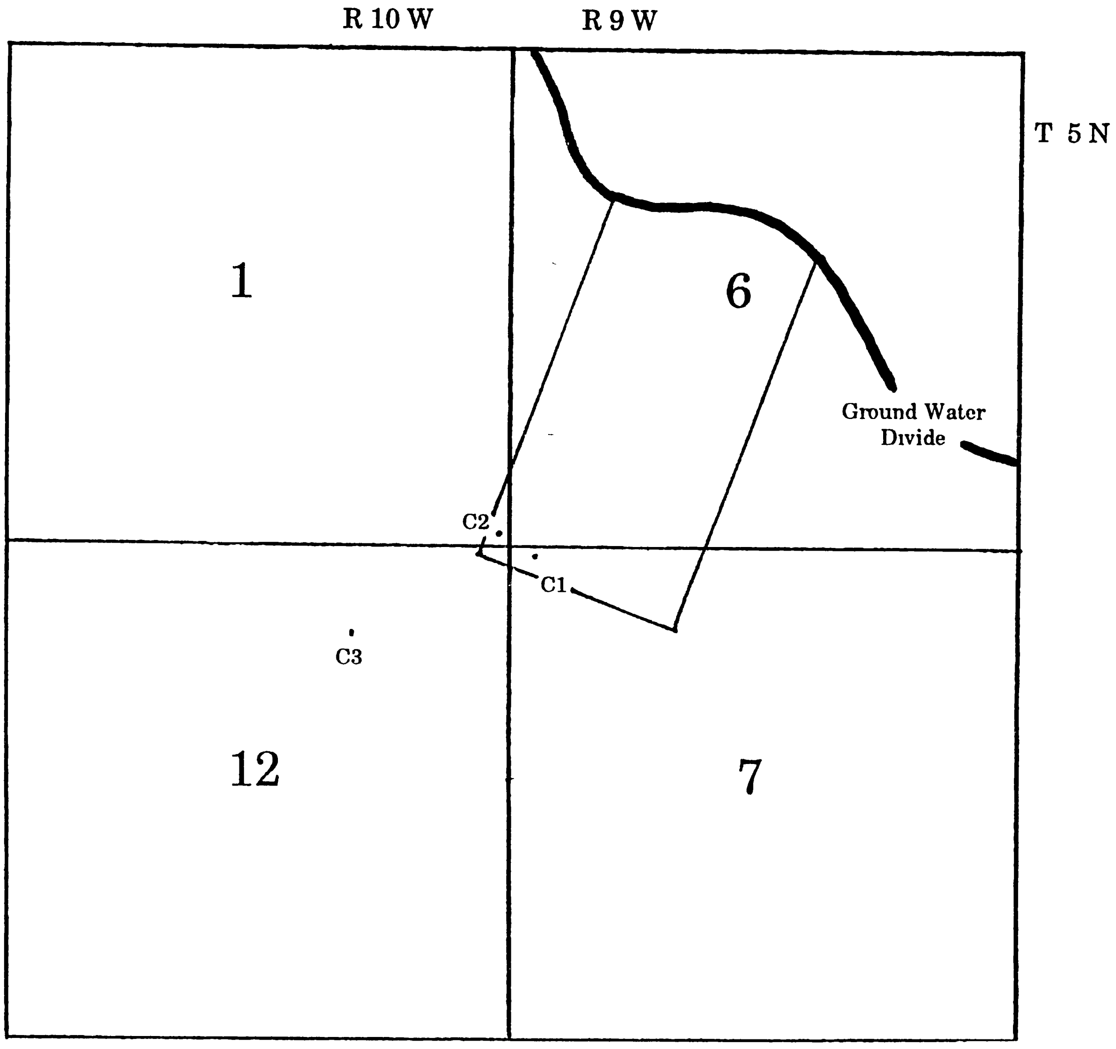


Figure 12. Annual Recharge Rates for the Region

154,000 square feet. Hydraulic conductivities values of 19 and 35 gpd/ft^2 were used for upper and lower limits.

A water-table map was constructed (fig. 14) using water level data collected February 13-21, 1991. While this data was collected at an earlier time than data used in the previous analysis, it was not available at that time. It was incorporated into this analysis since it covers a larger area, allowing preparation of a more accurate map. Hydraulic gradient, measured along flow lines of the Cyril wells, averages 0.01. Assuming hydraulic conductivity values of 19 and 35 gpd/ft^2, an effective porosity of 0.15, and a hydraulic gradient of .01, ground-water velocity should range between 0.16 and 0.31 feet/day.



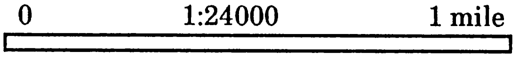
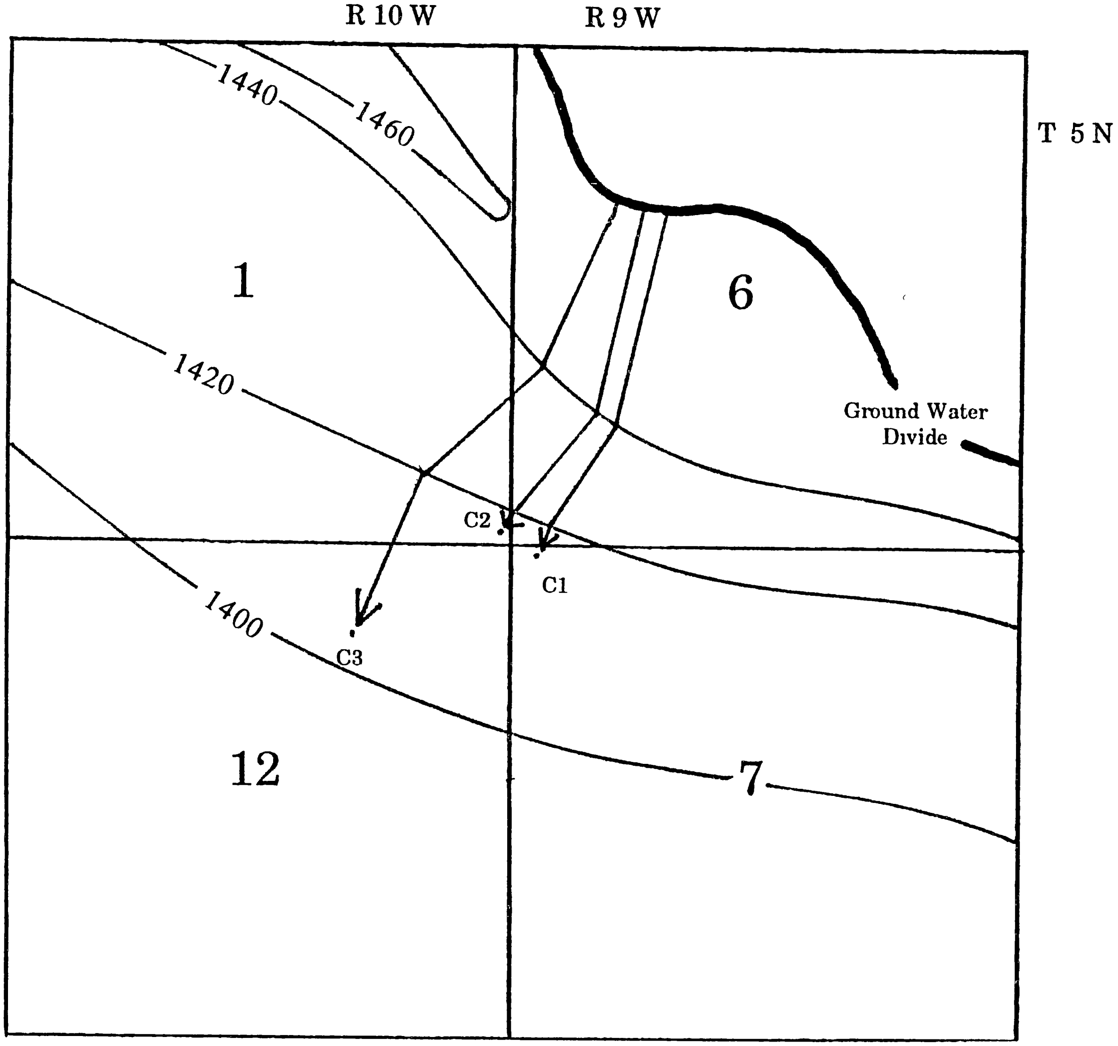
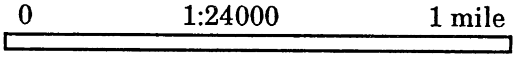


Figure 13. Flow Tube Delineated for Area Recharge





Contour Interval: 20 feet

Figure 14. Area Water Table, February 13-21, 1991, showing flow lines of Cyril wells

Since it is assumed that the water table remains nearly constant within the area, the volume of water that flows through a cross section of the flow tube should be equal to the volume of water that infiltrates to the saturated zone. By means of Darcy's Law, underflow was calculated to range between 29,260 and 53,900 gpd in the area of the flow tube. This volume is equivalent to 92,696 gpd/sq. mile(1.9 inches/yr) and 170,755 gpd/sq. mile(3.6 inches/yr), which falls within the the same order of magnitude of rates determined by the RECHARGE program.

Modeling

T-O-T

T-O-T was used to determine a zone of contribution and a time of travel for each of the three Cyril wells. The largest value for hydraulic conductivity and the smallest transmissivity value were used in modeling in order to establish a worst-case scenario. Simulations were based on a transmissivity of 5,000 gpd/ft, a hydraulic conductivity of 35 gpd/ft^2, and a saturated thickness of 143 feet.

JPLUME

JPLUME was again employed to determine the effects of dispersion on contaminant movement, with the same parameters input into the model as those used in T-O-T. Locations of contaminant plumes resulting from purging wells and/or leaking brine pits were also estimated.

Purging Wells. According to records of the operating company, several injection and production wells were known to have a history of purging either fresh or salty water around the outside of the surface casing. Other wells were reported to have unusually high pressures at the well head. In this analysis, wells that were reported to have purged were treated as contamination sources. The assumption was made that wells purging at ground surface also were contaminating the aquifer.

A scenario was established with leakage set at 2 barrels per day for 30 days (1 month). An exception was well No. 21-2 (SW 1/4, NE 1/4, Sec. 1, T 5 N, R 10 W,), which reportedly purged at least two different times. The second purge continued for approximately 150 days (5 months). Well No. 62-1 (NE 1/4, NE 1/4, Sec. 7, T 5 N, R 9 W,) and Darlington No. 2 (NE 1/4, NE 1/4, Sec. 12, T 5 N, R 10 W.) were not incorporated into the model because they are outside of the ZOC. Nine wells were modeled, well No. 21-2 was input twice to account for the two purging events: the total number of sources was 10.

Brine Pits. Estimation of the number and sizes of brine pits in the area were made from aerial photographs. Photographs were available for 1937, 1948, 1955, 1961, 1966, and 1974. Visual inspection of the areal photographs showed a wide range in the number of pits from one time to the next (Table 10). In the 1937 photograph, only 6 pits were evident in sections 1 and 6.

By 1948, however, this number had increased to 40. In the years after 1948, the number of pits decreased, with only 15, 12, and 12 evident in 1955, 1961, and 1966, respectively. No active pits are evident on an aerial photograph taken in 1974

TABLE 10

ACTIVE BRINE PITS ON AERIAL PHOTOGRAPHS

YEAR	NUMBER OF ACTIVE PITS
1937	6
1948	40
1955	15
1961	12
1966	12
1974	0

JPLUME simulations of pits within the ZOC of the Cyril wells were made for each year an areal photograph was available. Each pit was treated as a separate source with the period of leakage set to represent a time from the date of the photograph to the year before the next photograph. The time of interest was for the entire simulation was 19,345 days (53 years), representing the interval 1937 to 1990.

Infiltration From Brine Pits. Estimation of sizes of brine pits were obtained from examination of the aerial photographs as well as determination of the number of pits. From this, the average size of a disposal pit was determined. The number of pits within the ZOC, the average size of the pits, and the infiltration rate, based on an assumed vertical hydraulic conductivity of 19 gpd/ft^2, were combined to estimate the volume of seepage from pits for each photograph year. Annual seepage was multiplied by number of years the pits were assumed to be in operation. Results of these calculations are shown in Table 11.

Results of Modeling

Oil-field activities within the West Cement Oil and Gas Field are assumed to be the source of contamination of the Cyril municipal well field. Of these activities, leakage of brine pits and/or injection wells is the most probable source of contamination.

Analysis by T-O-T allowed delineation of a zone of contribution and a time of travel distance for ground water contributing to the Cyril Municipal Well Field. Again, the zone of contribution illustrates the area which would contribute ground water to a well field, while the time of travel is the distance ground water contributing to the well field will travel during the time of operation. The T-O-T program does not consider affects of dispersion, yet dispersion can add a considerable distance to the time of travel distance. Addition of a dispersion distance calculated by JPLUME provided the maximum area which would contribute ground water to the Cyril well field during it's time of operation (fig.15). Input parameters for both models were set to establish a worst-case scenario. Since any source contaminating the Cyril

TABLE 11

SEEPAGE VOLUMES OF PITS DELINEATED ON AERIAL PHOTOGRAPHS (VERTICAL HYDRAULIC CONDUCTIVITY: 19 gpd/ft^2)

YEAR	NUMBER OF PITS	SEEPAGE PER YEAR (gal)	ASSUMED OPERATION TIME (years)	TOTAL SEEPAGE (gal)
1937	3	36,500	10	365,000
1948	23	226,665	6	1,359,000
1955	6	78,840	5	394,200
1961	5	43,800	4	175,200
1066	6	63,510	4	254,040
1974	0	0	0	0

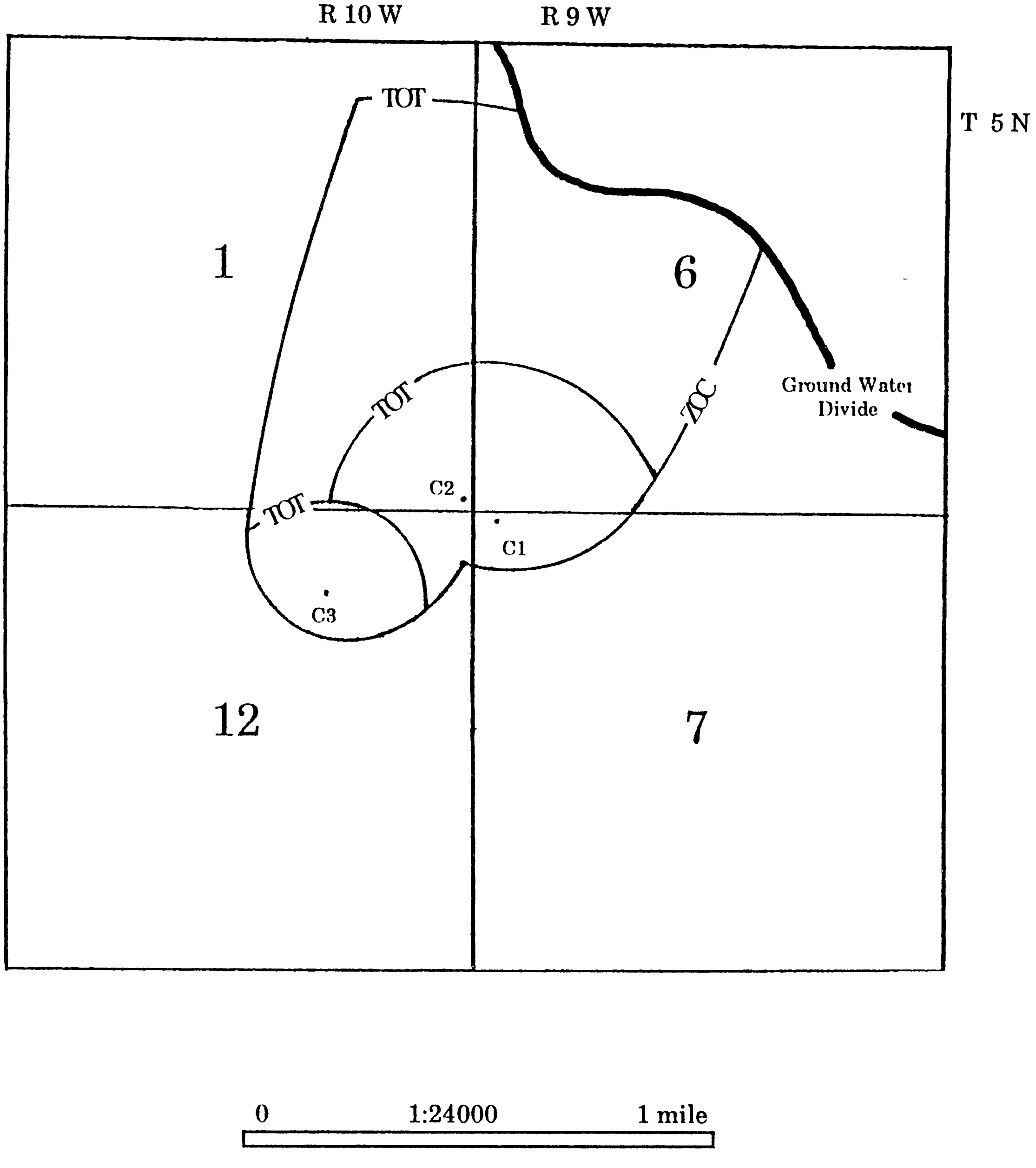


Figure 15. Maximum Area Contributing Ground Water to the Cyril Well Field - Area of Possible Source Location(s), Second Analysis

wells would necessarily be located in the area contributing ground water to the well field, figure 15 also serves to delineate an area of probable source location(s). This area is similar to the area outlined in the first analysis, covering portions of sections 6 and 7 of T. 5 N., R. 9 W. and sections 1 and 12 of T. 5 N., R. 10 W. From a point approximately 400 feet southeast of Cyril 3 (NE 1/4, section 12) , the area covered extends about 6000 feet northeast to the ground water divide in section 6, with an approximate width of 4600 feet.

JPLUME was also used to estimate the theoretical extent of contaminant plumes originating from leakage of brine pits and purging wells as of 1990. Plumes resulting from purging wells and brine pits were then superimposed to show the theoretical extent of contamination originating from these sources (fig.16).

Calculation of theoretical recharge of the area gives an idea of the possible quantity of contaminated water, which could aid in remediation plans. As was the case in the preliminary analysis, the area delineated as probable location of contamination sources would contain only sources that directly affect the municipal well field. Other sources are likely beyond this area. Many of these other possible sources, such as grass covered pits, may not be readily visible or discussed in available records. Other historical information, such as aerial photographs and well records, may supply useful information on potential sources, but they were not available in this analysis.

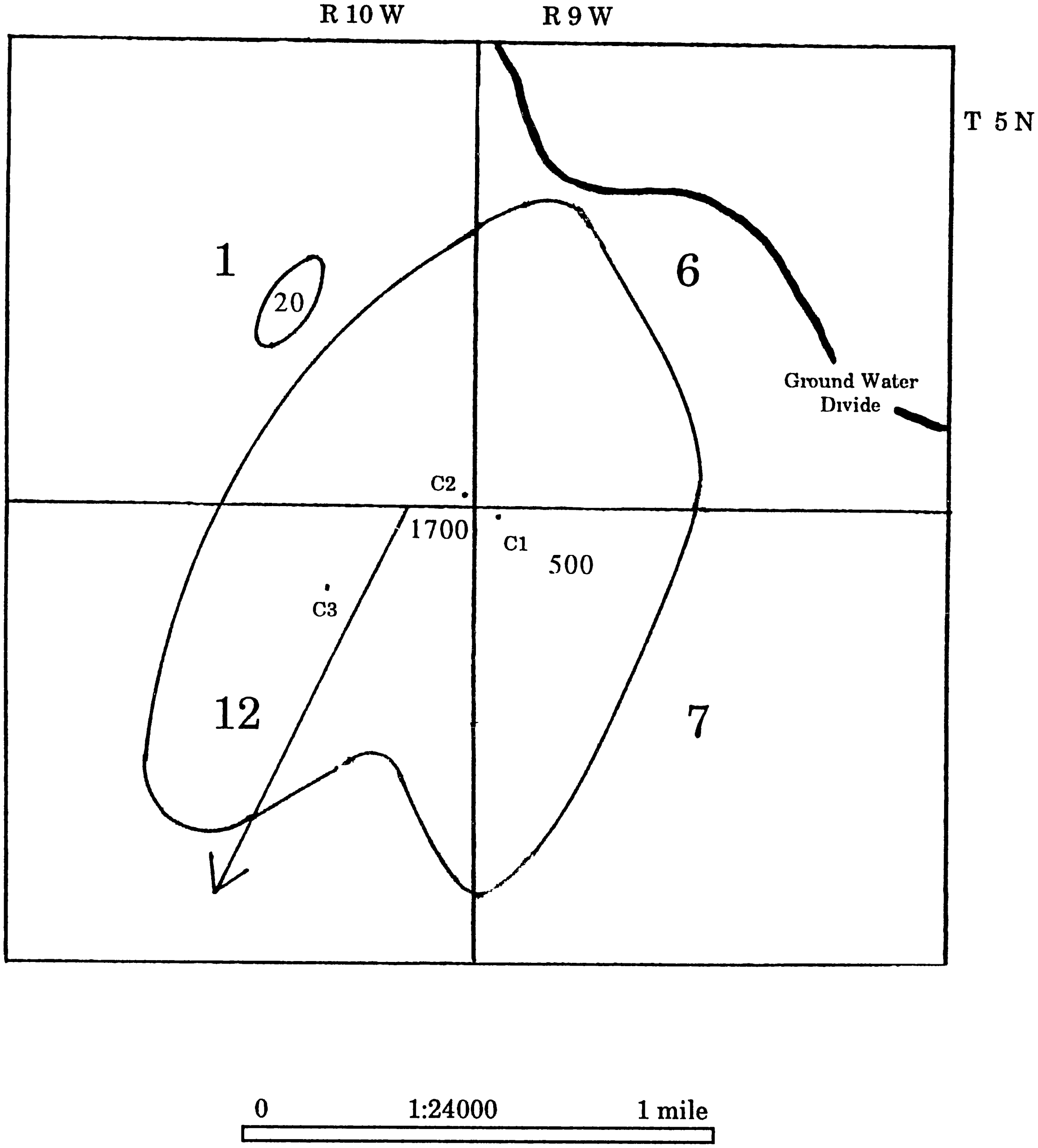


Figure 16. Theoretical Extent of Contamination (concentrations in mg/l)

CHAPTER IV.

SITE-SPECIFIC ANALYSIS

Introduction

In this analysis, site-specific data were used, and most of the actual tests were conducted specifically to assess the Cyril situation. Additional information incorporated into this analysis was obtained from the logs of test holes and monitoring wells, aquifer tests, water-level measurements, and pertinent historic information. In addition, chemical analyses of ground-water samples and measurements of the chloride concentration and electrical conductivity were available from cuttings obtained from drilled test holes.

This final analysis is divided into three parts. This chapter uses hydrologic characteristics to delineate an area of probable contaminant source location(s). Evaluation of the chemical data is contained in Chapter V, and the core data are discussed in Chapter VI.

History of Contamination

In September 1947, the town of Cyril requested the Division of Water

Resources of the Oklahoma Planning and Resources Board to investigate the cause of chloride contamination of their municipal wells. An investigation by the Oklahoma Geological Survey, Oklahoma Ground Water Engineers, and the Oklahoma Corporation Commission concluded that shallow surficial saltwater disposal pits in the West Cement Field were the source of chloride. The Corporation Commission requested that disposal pits no longer be used in Section 1or 6.

In 1951, Magnolia Petroleum Company (Mobil Corporation) concluded that brine pits were inadequate for disposal of the approximate 900 barrels per day of saltwater that was being produced in the field. They also noted that saltwater seeped from many of the disposal pits, discharged along hill sides, and eventually flowed into nearby streams. In June 1951, it was reported that livestock refused to drink from a local stream because of the excessive salt content. In addition, another complaint from a local rancher stated that approximately three acres of vegetation had been killed by saltwater in the vicinity of a disposal pit. A subsequent investigation by the Division of Water Resources of the Oklahoma Planning and Resources Board concluded that saltwater from disposal pits was entering fresh water strata tapped by Cyril municipal wells.

Attempts by Magnolia to increase the rate of evaporation by burning oil floating on the pits were unsuccessful. Trucking of saltwater to an alternate disposal site was considered to be economically unfeasible. Failure of the attempts to dispose of the brine on site gave rise to the concept of saltwater injection through wells. Selected low yield production wells were converted to injection to supplement the disposal pits. Although some pits were maintained for emergency use, disposal pits diminished after saltwater injection began in 1951.

The chloride content of the town wells continued to steadily increase until the early 1970's. The steady increase in chloride suggests that disposal pits and the plumes originating from their earlier use continued to serve as contaminant sources.

In 1971 a full scale operation for secondary recovery was initiated in the Cement Field. A number of injection wells were completed, largely in the eastern half of Section 1. Apparently all of the injection wells were modified production wells. Some injection and near-by production wells are known to have purged saltwater to the surface around the outside of the surface casing during injection, while others were reported to have, at times, unusually high surface pressures. All of these wells are located within and up-gradient of the municipal well field.

In the mid 1970's, the chloride content of Cyril's wells began to rapidly increase. The rather dramatic rise in chloride content took place after the initiation of the secondary recovery operations. The steady increase in chloride concentration is exemplified by C-2 (fig. 17). The increase in chloride concentration in municipal water wells, coincident with purging of injection

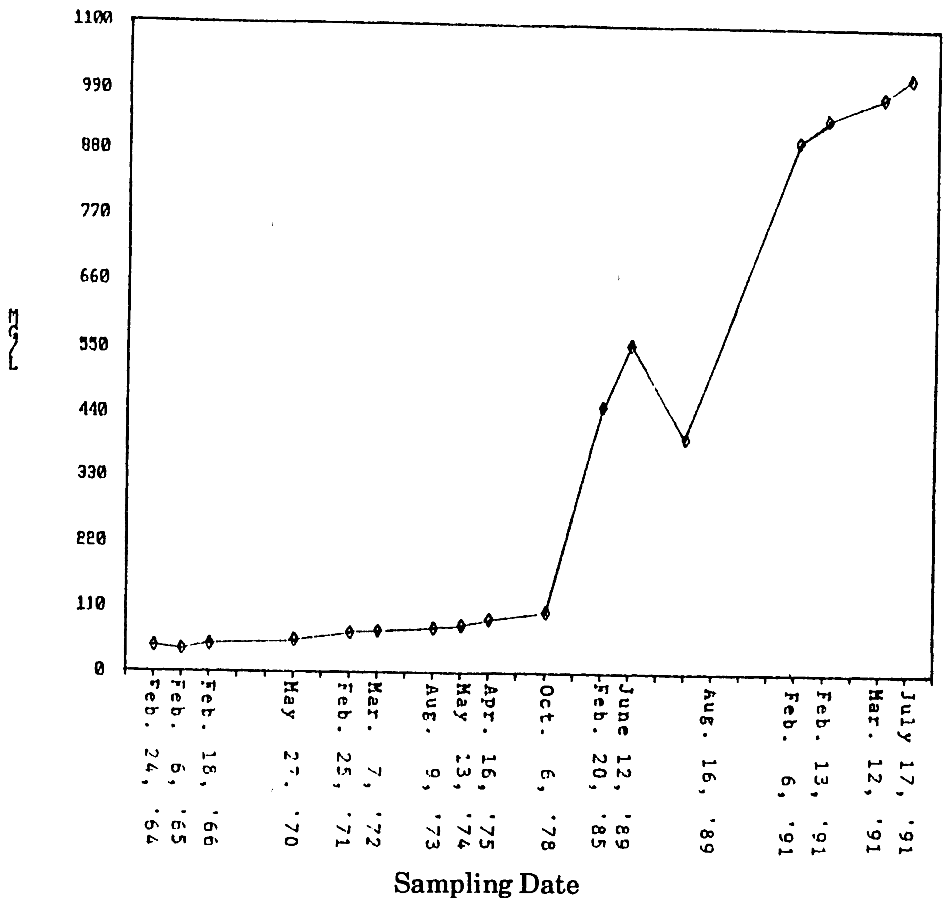


Figure 17. Chloride Concentration, Cyril Well 2

and/or production wells, implies leakage of such wells serves as additional sources of contamination.

Methodology

Hydraulic Characteristics

The water table map constructed earlier using water-table elevations from the period February 13-21, 1991, was again utilized (fig. 18). Estimates of hydraulic conductivity and transmissivity were supplemented by the

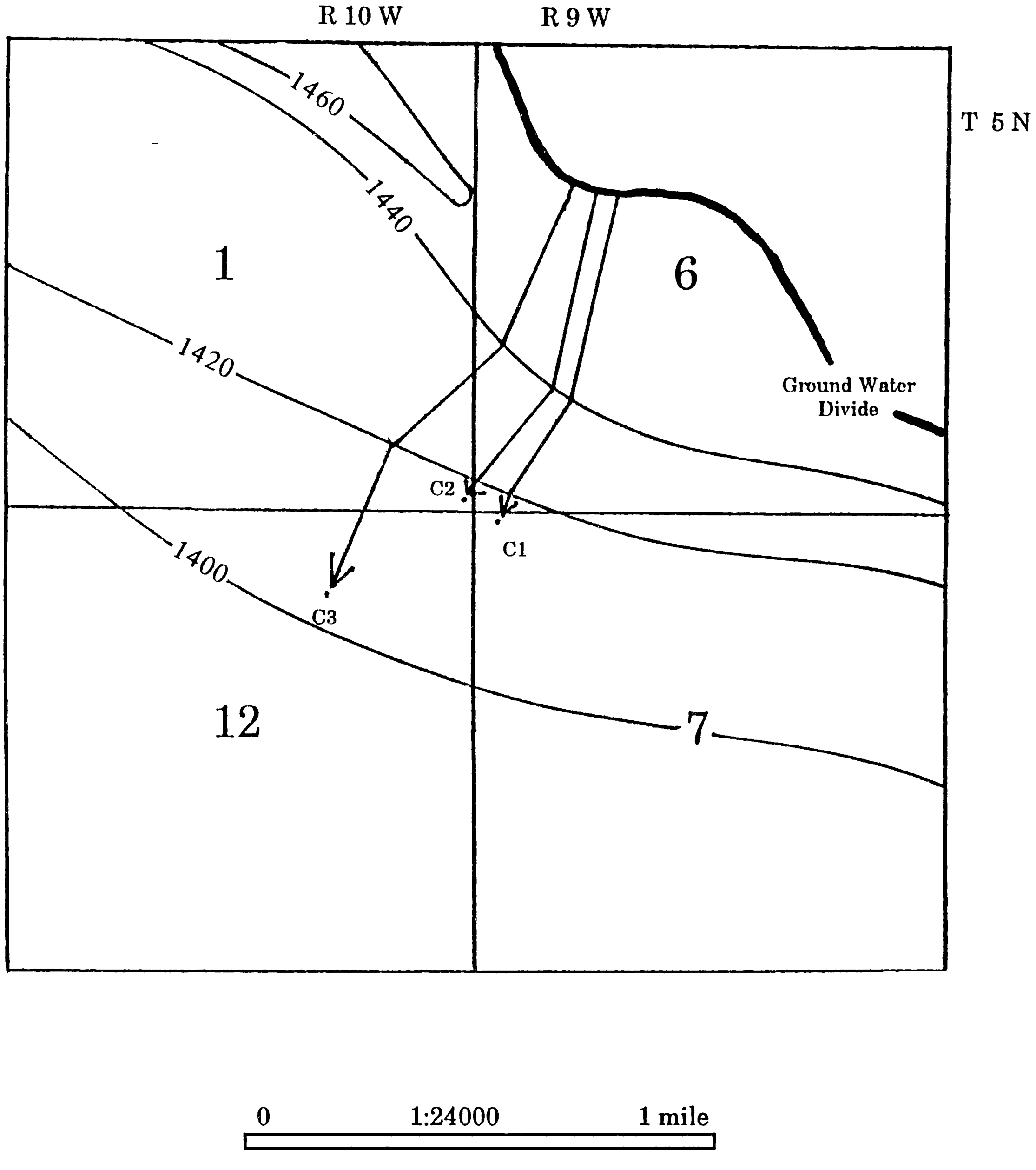


Figure 18. Area Water Table, February 13-21, 1991, showing flow lines of Cyril Wells

analysis of two aquifer tests that were performed on the Rush Springs in the spring of 1991. In the first case, well W-PW (southeast quarter of Section 1), with a saturated thickness of 60 feet, was used as the production well. Well W-PW is 118 feet deep and screened from 88 to 118 feet. A gravel pack extends from a depth of 40 feet to the bottom of the well. Well W-6, 67.4 feet from the production well, was used as an observation well. It is 118 feet deep, is screened from 98 to 118 feet, and is gravel packed from 36 to 118 feet. The saturated thickness was reported to be 60 feet. The production well was pumped at a rate of 13.5 gpm for 240 minutes, and drawdown was measured in the pumped well and in observation well W-6.

At the second site, (NW 1/4, Sec. 6, T. 5 N., R. 9 W.) well D-5PW served as the production well, and well D-2 was used as an observation well. D-5PW is 105 feet deep, screened from 75 to 105 feet, and gravel packed from 34 to 105 feet. Saturated thickness was 61 feet. Well D-2, which is 60.5 feet from the production well, is 98 feet deep, contains 20 feet of screen, and is gravel packed from 32 to 98 feet. A reported saturated thickness of 61 feet was used for well D-2 also. The production well was pumped at a rate of 12 gpm for 240 minutes.

On the basis of these tests the average value of transmissivity is 1013 gpd/ft, hydraulic conductivity is 17 gpd/ft^2, and storativity is 0.24. Calculated storativity values ranged from .00016 to 0.73, but both tests were far too short for an accurate determination. Drawdown data, well logs and calculations are shown in an appendix .

Geologic Cross-Sections

Geophysical logs of test holes and monitoring wells were used to construct geologic cross-sections (fig. 19 and 20). Water table elevations of appropriate wells were placed on the cross-sections allowing measurement of the saturated thickness. As the cross-sections illustrate, the saturated thickness of the Rush Springs tends to increase southwestward from the ground-water divide in Section 6, although the average saturated thickness is about 50 feet. This is substantially less than the assumed thickness used in previous analyses. The base of the Rush Springs Sandstone is assumed to be the top of a shale unit that lies at a depth of 80 to 100. The shale, approximately 20 feet thick, is the upper unit of the Marlow Formation, which appears to be about 300 feet thick.

Geophysical logs indicate significant amounts of sandstone in the sandstone and shale sequence of the Marlow. Both C-1 and C-3 are screened below the shale unit that forms the top of the Marlow. This suggests that individual sandstone units within the Marlow are quite permeable, at least in this area. In addition, wells C-1 and C-3 were pumped at rates of 140 and 120 gpm, respectively, twice the rate of C-2. This also indicates that the Marlow is quite permeable. Unfortunately, the presence of gypsum in the Marlow leads to a water type high in sulfate.

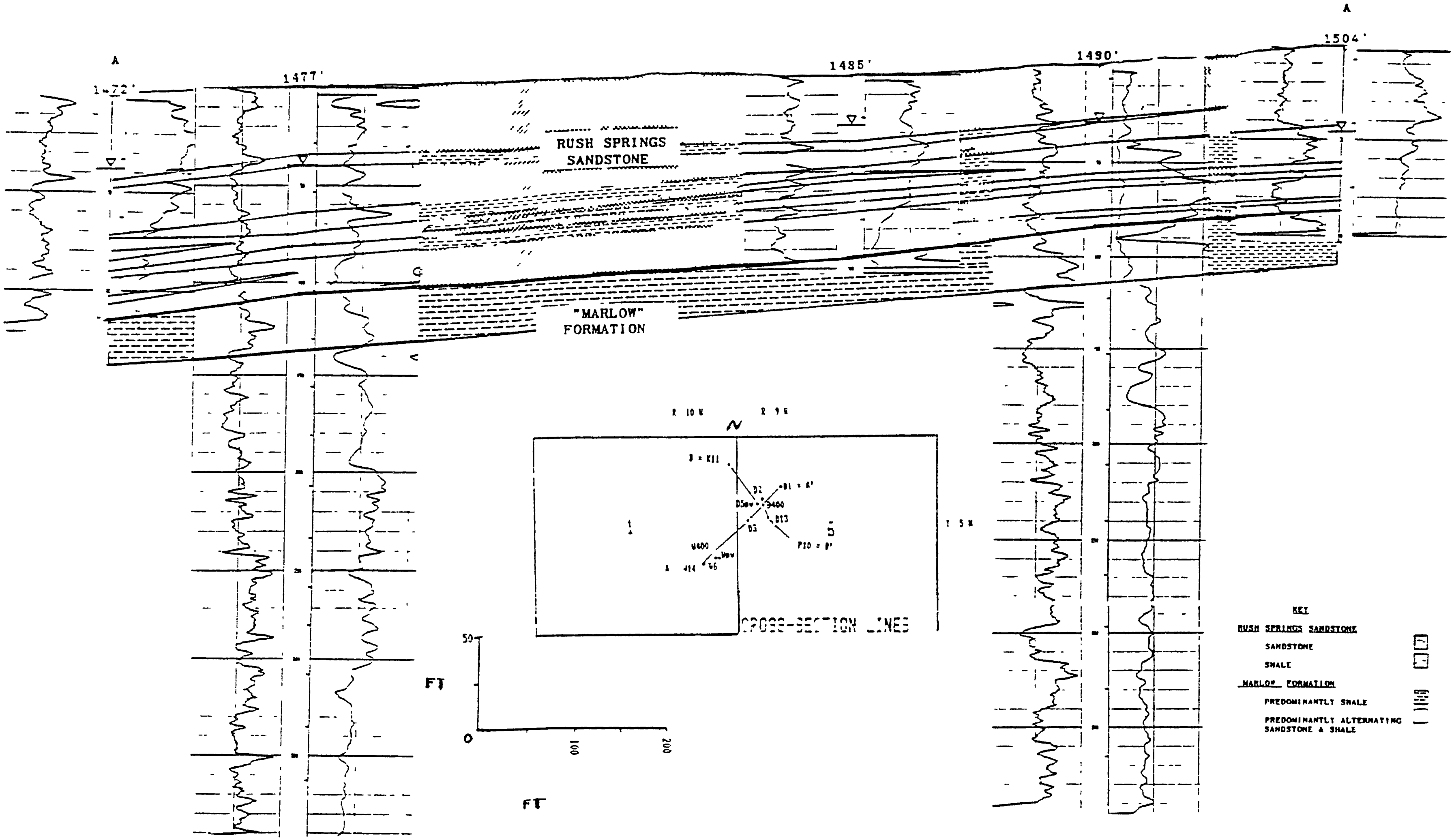


Figure 19. Cross-Section Sub-Parallel Ground Water Flow. Surface Elevation @ top of Center Depth Track. Gamma Ray Log left of Depth Track. Resistivity Log right of Depth Track
Scales: Gamma Ray - 0 to 150 API units; Resistivity - 0 to 50 ohm-meters.
Marlow Formation extends to log bottoms.

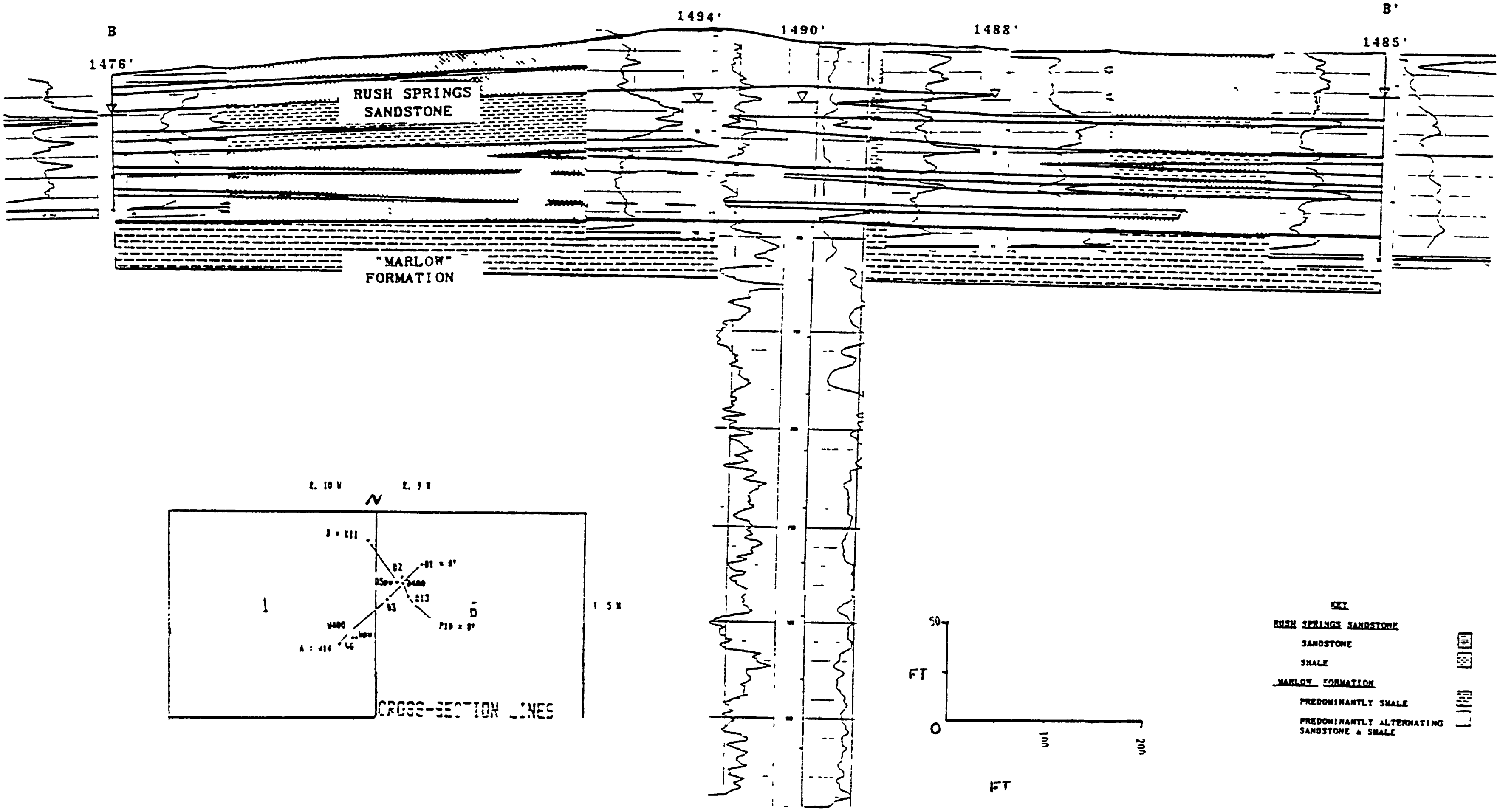


Figure 20. Cross-Section Sub-Perpendicular Ground Water Flow. Surface Elevation @ top of Center Depth Track. Gamma Ray Log left of Depth Track. Resistivity Log right of Depth Track. Scales: Gamma Ray - 0 to 150 API units; Resistivity - 0 to 150 ohm-meters. Marlow Formation extends to log bottoms.

Considering these facts, modeling of the ground-water system was approached in a two-fold manner. First, impact of contamination on the Rush Springs Sandstone was modeled and a second analysis was made for the Marlow Formation.

Modeling

THEIS WELL FIELD

Owing to the extensive areal extent of the shale unit at the top, the Marlow Formation is assumed to form a confined aquifer in which storativity is in the range of 0.00001 to 0.0001. Accordingly, the hydraulic gradient that forms the cone(s) of depression surrounding C-1 and C-3 during pumping will be substantially different from production wells tapping the Rush Springs. The shape and extent of the cone(s) of depression were estimated by use of THEIS WELL FIELD. The potentiometric surface of the Marlow was estimated for 1985 and 1990. This served to model the cone of depression formed after pumping of C-1 and then C-1 and C-3 together. Hydraulic gradients were approximately 0.03 in 1985 and 0.09 in 1990.

TIME OF TRAVEL

TIME OF TRAVEL was used to delineate areas that contribute ground water to the town wells. C-2, 170 feet deep, reportedly was completed as an open borehole that extends through the Rush Springs and into the Marlow. C-1 and C-3 are screened only in the Marlow. Consequently, C-2 is the only well that produced water from the Rush Springs aquifer. Using this information, a ZOC was calculated for well C-2.

C-2 extends approximately 20 feet below the confining bed designated as the upper unit of the Marlow Formation. The pumping history of well C- 2 is unknown, yet the discharge was only 60 gpm. Since C-2, reportedly, was used only as a supplemental source, continual pumping was extremely unlikely. These facts leads to the conclusion that impact of C-2 on the Marlow aquifer was negligible. Therefore, only C-1 and C-3 were assumed to impact the Marlow.

Drawdowns resulting from pumping C-1 and C-3 were calculated with TOT. Drawdown for C-3 was based on the assumption that pumping was continuous, although it is known that C-3 served only in a supplementary role. The drawdowns created by each well were added, and the discharge rate necessary to achieve the total drawdown by means of a single well was calculated. This approach was followed because it is not possible to evaluate multiple wells with T-O-T. Use of the 1990 hydraulic gradient established a worst-case scenario.

JPLUME

Brine Pits. Plumes resulting from saltwater disposal pits were modeled in the same manner described in Chapter 3. Disposal pits were assumed to impact only the Rush Springs aquifer because of the shale unit at the top of the Marlow, as well as other but thinner shaley or cemented zones in the Rush Springs. The period of leakage from pits remained as initially established, while hydrologic parameters were modified to account for the more accurate information obtained during this evaluation. The chloride concentration of the brine that was placed in the disposal pits was 99,875 mg/l, which is an average of analyses described in an unpublished report (NUS, 1989).

Affect of Purging Wells on the Rush Springs. The Rush Springs aquifer was assumed to have been impacted by purging wells, as well as by leakage from disposal pits. In modeling the impact of purging wells, it was assumed that each well purged saltwater, with a chloride concentration of 106,400 mg/l, into the Rush Springs for a period of 30 days.

Affect of Purging Wells on the Marlow. Purging wells were assumed to be the only sources that could contaminate the Marlow aquifer. Although specific values for hydrologic parameters are unknown for the Marlow, the geologic cross-sections described earlier indicate the Marlow is about 300 feet thick. The assumption that only a third of this thickness consists of sandstone sufficiently permeable to readily transmit water results in an effective saturated thickness of 100 feet.

Hydraulic conductivity of the Marlow was assumed to be about the same as the Rush Springs (17 gpd/ft^2), resulting in a transmissivity of 1700 gpd/ft. Storativity is estimated to be 0.0001, since the Marlow is confined. Dispersion for the Marlow was set at a ratio of 5 to 2.5.

JPLUME modeling of the Marlow was divided into two portions. As discussed earlier, the cone of depression resulting from pumping the well field would be more extreme than the cone developed in the Rush Springs aquifer. Plume locations were calculated for 1985 and 1990 with hydraulic gradient changes calculated by THEIS WELL FIELD being incorporated at the proper times. As the cone of depression developed, flow direction shifted toward the center of this cone, the location of the imaginary well representing wells C-1 and C-3.

Concentrations in the theoretical plume are well below the levels actually present at depths attributed to the Marlow aquifer in the area. A confining bed above the gravel pack of C-1 and C-3, as well as the discontinued use of disposal pits, discounts the possibility of these pits continuing to serve as source of contamination to the Marlow. Purging wells within the West Cement Oil and Gas Field are therefore assumed to be the only source of contamination in the Marlow. Possible explanations of the inconsistence between the modeled and measured concentrations include; purging of a greater number of wells than modeled, purging of modeled wells for a longer time than modeled, plumes originating at the modeled wells have not, as yet, arrived at wells C-1 and, particularly, C-3, or more probably, a combination of these three.

Results

Historical information indicates that operations in the West Cement Oil and Gas Field are the source of chloride contamination of the Cyril water supply. Saltwater disposal pits and injection wells were treated as contaminant sources. Test results and well logs were used to obtain site-specific hydrologic parameters. Comparison of constructed geologic cross-sections and well data lead to the observation that water production was from the Rush Springs, as well as from underlying formations. In this analysis, underlying formations were treated as a single hydrologic unit, termed the Marlow Formation.

The presence of an aerially continuous confining unit resulted in the Marlow being considered as a confined aquifer in this analysis. As a result, large changes in the hydraulic gradient may occur from pumping of Cyril wells 1 and 3. Hydraulic gradients were estimated, using THEIS WELL FIELD, for 1985 and 1990.

The chemical quality of water production from the two aquifers clearly shows that both are contaminated. A zone of contribution was calculated for

C-2, using TIME OF TRAVEL. This shows the area contributing ground water from the Rush Springs (fig. 21). The ZOC, approximately 3800 feet wide, extends about 600 feet into the northeast corner of section 12, about 600 feet into the northwest corner of section 7, and north to the ground water divide in section 6. Laterally, the ZOC extends approximately 1000 feet into the eastern 1/2 of section 1 and covers most of the western 1/2 of section 6. Compared to areas delineated earlier as contributing to the Cyril wells, this ZOC does not extend as far to the southeast, but does incorporate more of section 1.

Effects of well C-2 on the Marlow would be negligible, but C-1 and C-3 would affect the aquifer. Therefore, the area contributing ground water to an imaginary well representative of the combined effects of C-1 and C-3 also was calculated. Placement of such an imaginary well at a point midway between C-1 and C-3 into the T-O-T model allows determination of the area that contributes ground water to the imaginary well, and thus to C-1 and C-3 (fig. 22). The elliptical area, extends approximately 1000 feet into the southwest corner of section 6 and 1400 feet into the northwest corner of section 7. The area extends approximately 1400 feet into the southeastern corner of section 1 and covers the majority of the northeastern 1/4 of section 12.

As in the previous analyses, location of contaminant sources should closely correspond to those areas contributing ground water to the Cyril well field. Addition of the areas delineated as contributing to the well field supplies a total area that should contain all sources that would impact the well

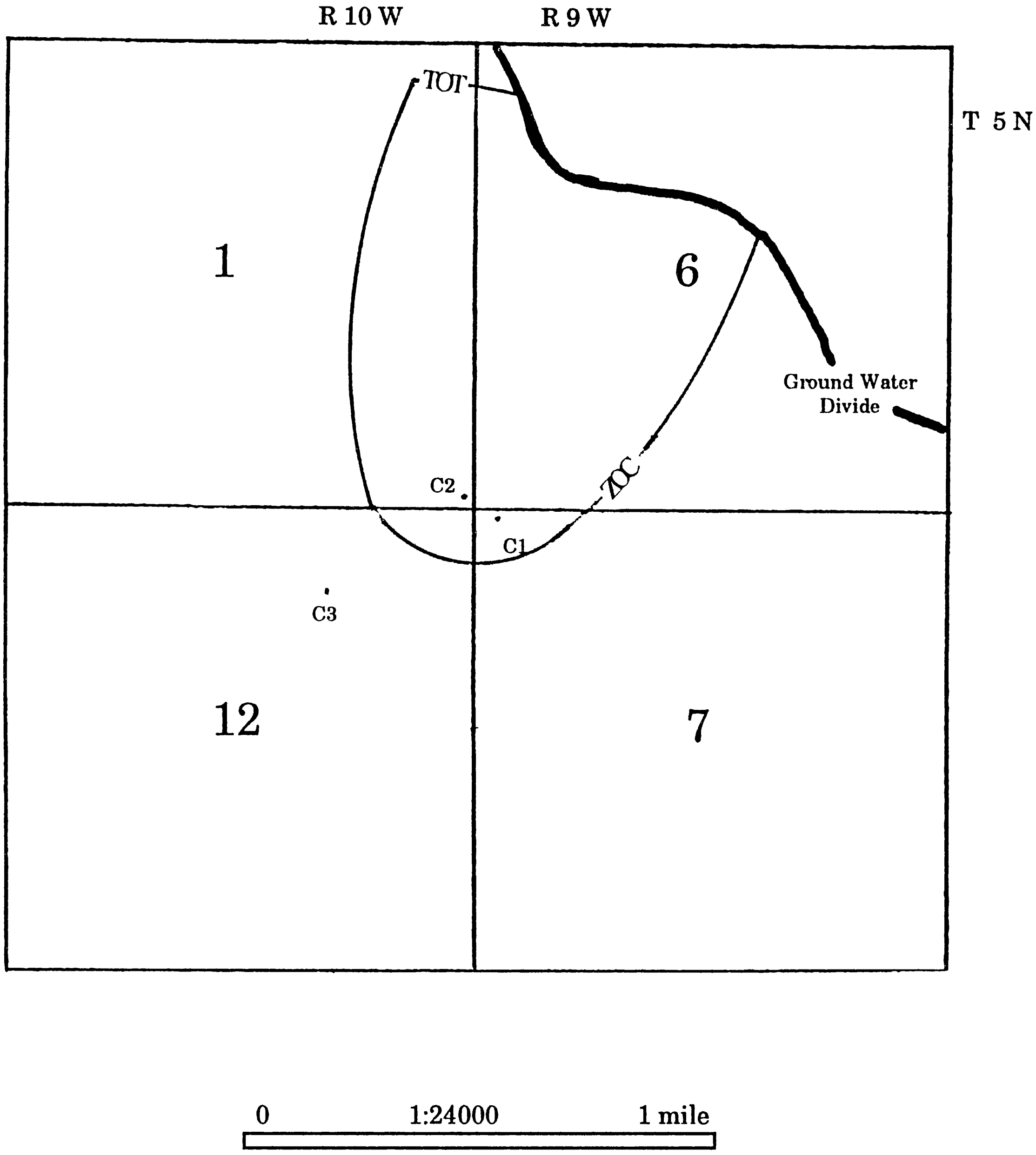


Figure 21. Zone of Contribution, Cyril Well 2

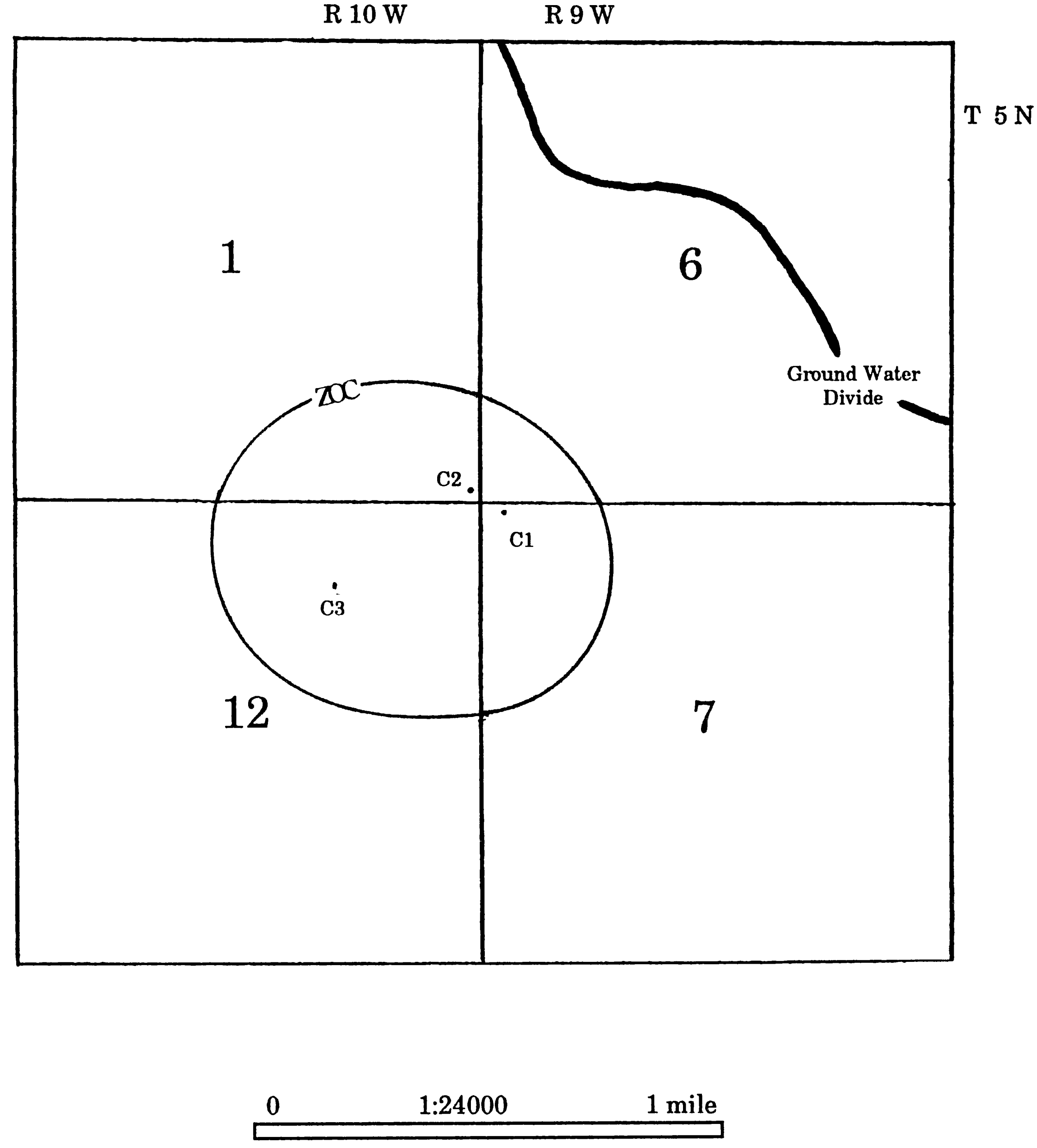


Figure 22. Area Contributing Ground Water to Cyril Well 1 and 3

field (fig. 23). The possibility of other sources outside the delineated area should not be discounted because of the effects of dispersion, radius of influence at purging wells, and differences in pumping rate and duration.

The location and concentration of plumes resulting from leaking evaporation pits and purging wells was estimated by use of JPLUME. It is assumed that the Rush Springs aquifer was contaminated by evaporation pits and purging wells, while the Marlow aquifer received contamination from only purging wells. A large plume results in modeling contamination of the Rush Springs aquifer (fig, 24), since chloride will move with the ground water. However, development of a significant cone of depression in the Marlow will result in concentration of contamination in the area of an imaginary well which represents Cyril wells 1 and 3 (fig. 25).

Concentration of the theoretical plume modeled for the Marlow aquifer is well below levels of contamination found at depths attributed to the Marlow aquifer in the study area. Presence of a confining bed above C-1 and C-3 gravel packs and the discontinued use of disposal pits, discounts the possibility of evaporation pits serving as source of contamination to the Marlow aquifer. Purging of a greater number of wells, purging of modeled wells for longer times, incomplete migration of plumes present or combinations of these are possible explanations of concentration differences found in the Marlow.

Due to necessities of modeling, the Marlow aquifer was treated as a

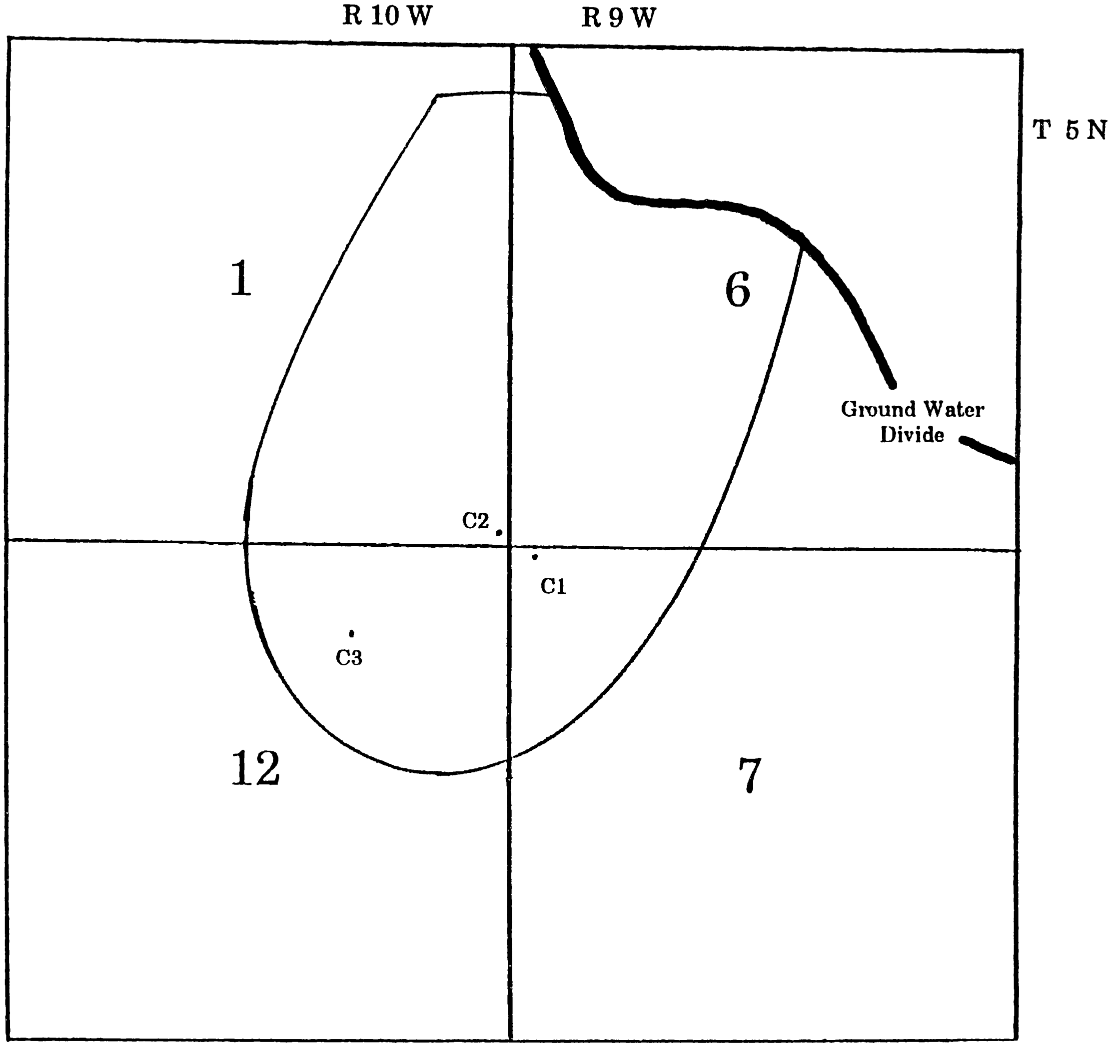


Figure 23. Area of Possible Source Location(s), Third Analysis

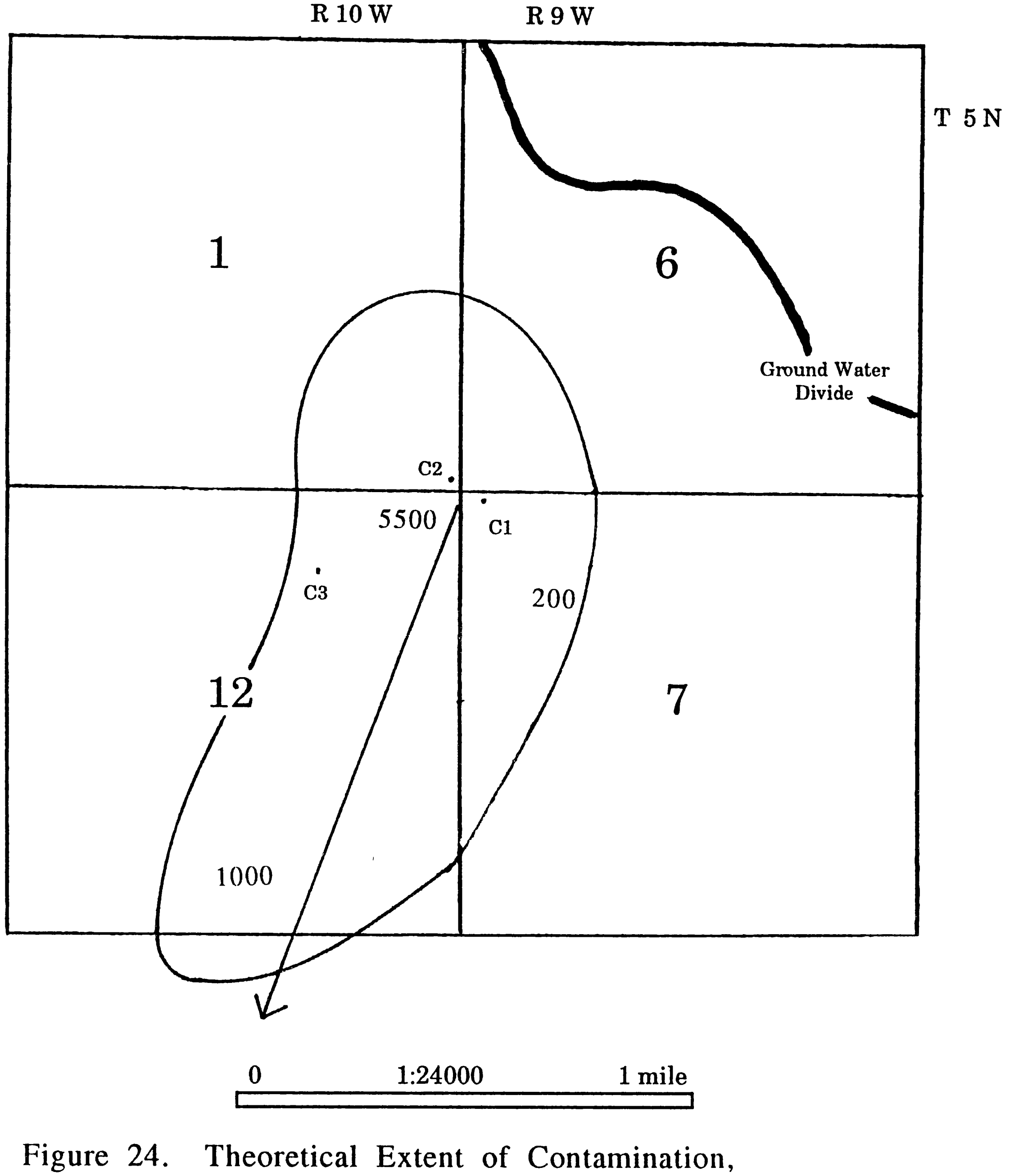


Figure 24. Theoretical Extent of Contamination, Rush Springs Aquifer (concentrations in mg/l)

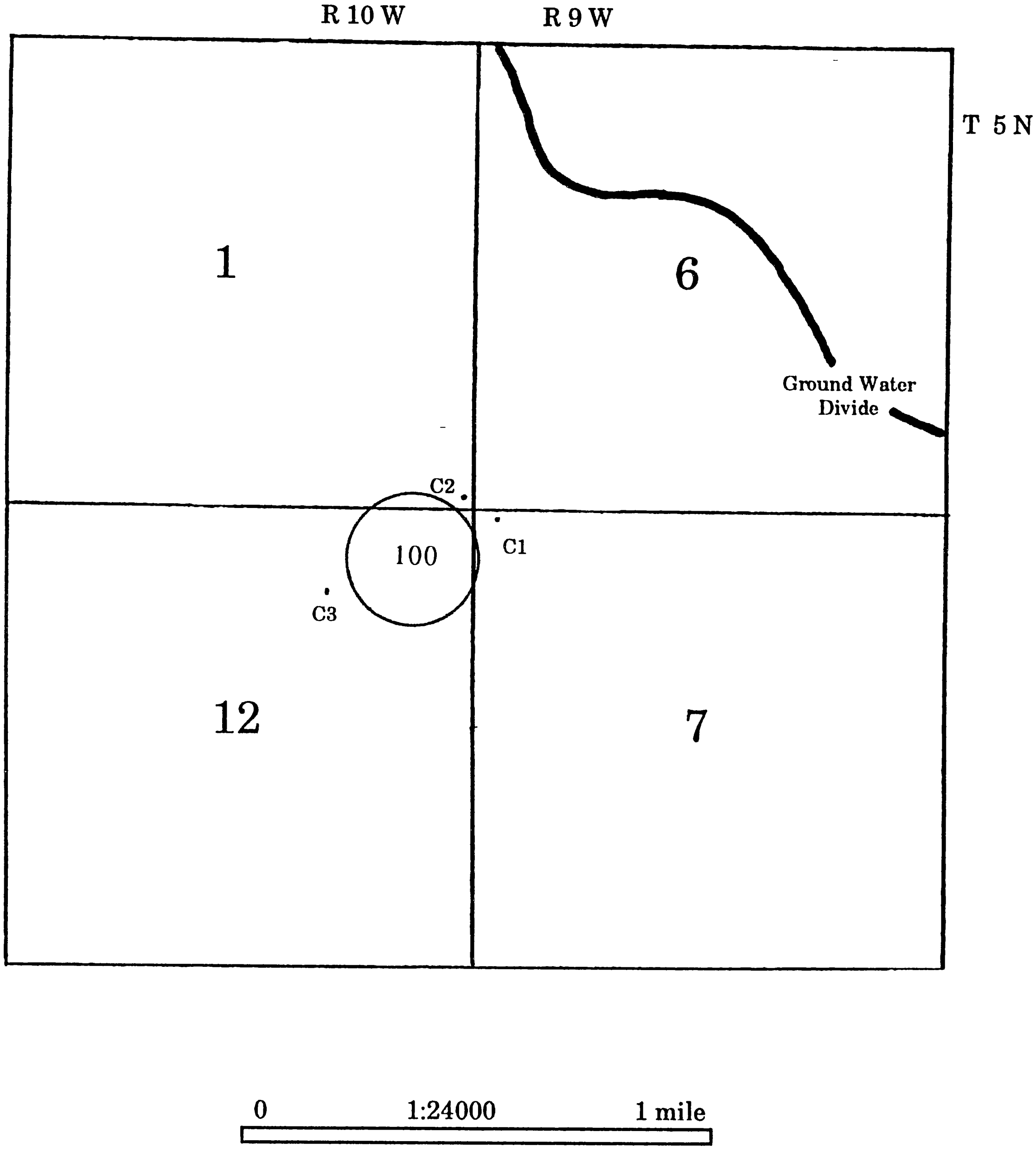


Figure 25. Theoretical Extent of Contamination, Marlow Aquifer (concentrations in mg/l)

single unit, although it actually consists of an alternating sequence of shale and sandstone. Each sandstone unit may contain a plume, and the individual plumes will travel at differing rates, depending upon the hydraulic situation of each individual layer. This will result in a plume "front" that is staggered, rather than a symmetrical plume as suggested by JPLUME. While this may effect distance traveled by the contaminant, it should not greatly affect the delineated area of possible source location.

It also was assumed in modeling efforts that the two aquifers are not hydraulically connected. In reality, hydrologic connections do exist. C-2 and purging wells, and perhaps abandoned wells, serve as connecting conduits. Such hydraulic connections, however, should have little affect on size of areas delineated as possible contaminant source sites. Although definite sources within the area of contribution are known, it is probable that others have been or are present. These areas should be examined before any remediation is attempted.

CHAPTER V.

CHEMISTRY OF THE GROUND WATER

Introduction

This part of the site-specific analysis addresses chemical analyses of ground water and oil-field brines. Historical analyses, assumed to be uncontaminated, indicate natural ground-water conditions. Analyses of brines produced locally indicate constituent concentrations in these brines. Recent ground-water analyses represent current conditions. Time-sequential analyses from well C-2 show degradation of water quality over time. C-2, a known "open hole" with surface casing only, was used to determine the percentage of water contributed from Rush Springs and from the Marlow. The presence of unexpected calcium chloride type water present in some wells is discussed, as well as the sodium/chloride ratios and their implications.

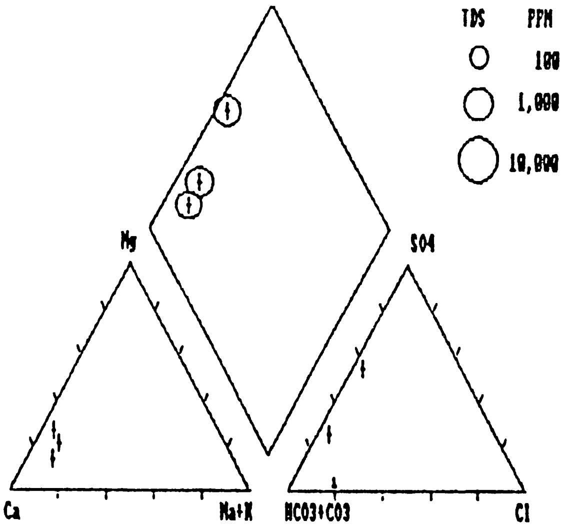
Historic Background

Few historic ground-water analyses are available for the study area. Three chemical analyses from ground water of the Caddo County area

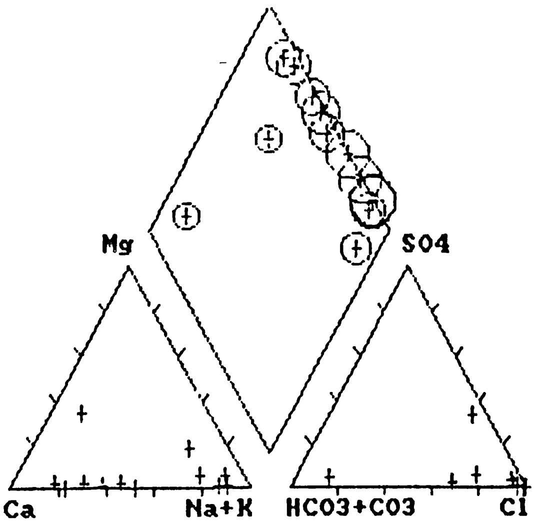
(Table 8) were chosen since the sample location for the three was in or near the study area. These analyses indicate ground water in the Rush Springs is of good quality with low chloride content, high temporary hardness, and some relatively high sulfate concentrations, which probably are dependant on well location. Piper plots and Stiff diagrams of these analyses are shown in figures 26 and 27. Quality of water for the Rush Springs is described as "suitable for irrigation and domestic use", while water from the underlying Marlow "has such high salinity, ... that it is unfit even for stock use" (Tanaka and Davis 1963).

Oil-Field Brines

Two analyses (Table 12) from disposal pits in the West Cement Oil Field were obtained from the NUS report (1989). Sodium content was not reported in the analyses, a sum of differences method being employed to balance the analyses. Three analyses of brine samples collected from waterflood units (Table 12) were described by Preston, 1982. A Piper plot and Stiff diagrams (fig. 26 and 27) show these samples to be exceedingly high in chloride, sodium, and potassium concentrations. Stiff diagrams also show elevated concentrations of calcium and magnesium.



BACKGROUND ANALYSES



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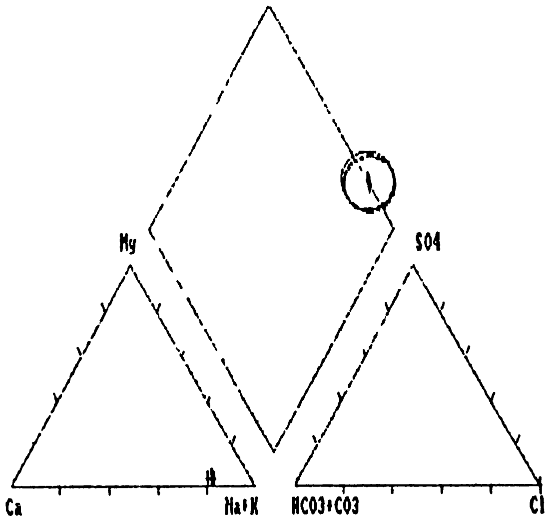
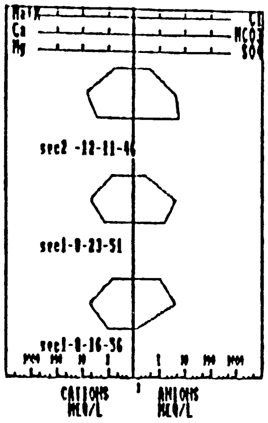
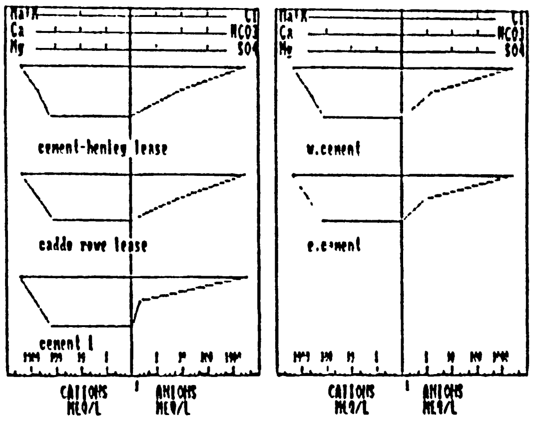


BRINE SAMPLES

Figure 26. Piper Plots



BACKGROUND ANALYSES



BRINE SAMPLES

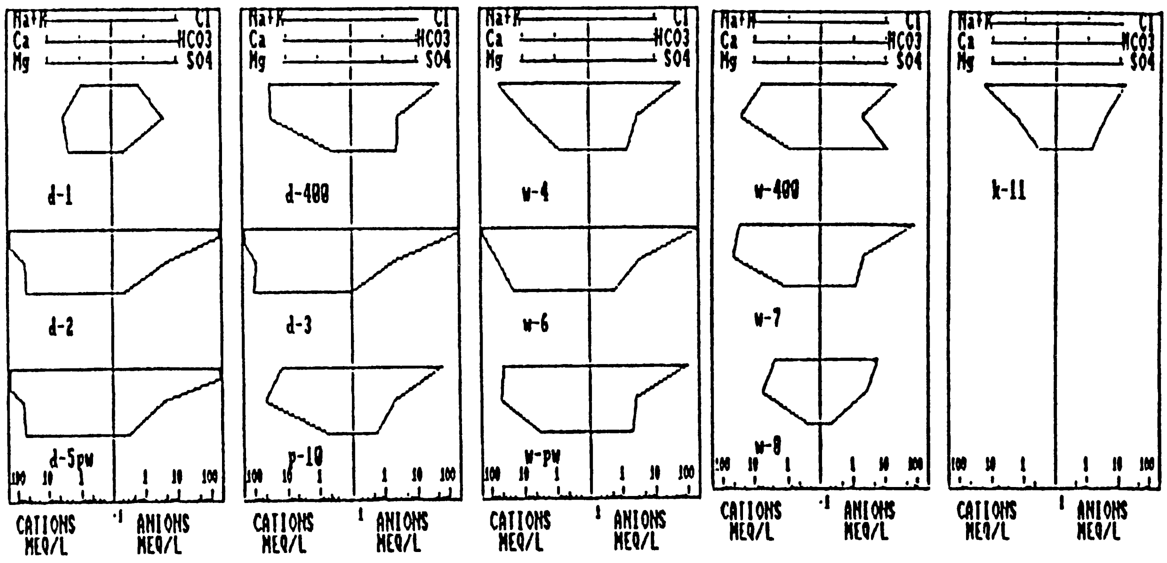


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Figure 27. Stiff Diagrams

TABLE 12

AREA BRINE SAMPLES

SAMPLE	SODIUM	CALCIUM	MAGNESIUM	CHLORIDE	BICARBONATE	DISSOLVED SOLIDS	pH	CONDUCTIVITY	DENSITY
CEMENT-HENLEY LEASE		9657	1914.8	110334	444	165550	6		1.1
CORRECTED CEMENT-HENLEY	57015	9657	1914.8	110334	444	165550	6		1.1
CADDO ROWE LEASE		9612	1576.2	111388	444	168380	6		1.1
CORRECTED CADDO ROWE	58390	9612	1576.2	111388	444	168380	6		1.1
CEMENT 1	68000	13100	1970	134000	12	217464	5.4	227273	1.1
WEST CEMENT	51100	8990	1510	99300	100	161368	6.5	192308	1.1
EAST CEMENT	56399	9620	1720	109000	54	1766990	6.1	204082	1.1

Present Conditions

Analyses of recent samples from area wells offer a view of present ground-water conditions. The most recent samples were taken June 3 - 6, 1991 (Table 13). On a Piper plot, the majority of these analyses plot in areas indicating salinity and/or a permanent hardness (fig. 26). Sodium and calcium are the major cations with chloride being the primary anion present. The predominance of these ions suggests brine contamination of the ground water. This suggestion is supported by the resemblance of the majority of Stiff diagrams of recent analyses to Stiff diagrams of brine analyses (fig.27). An exception is shown in the resemblance of Stiff diagrams of D-1 and W-8 to Stiff diagrams of background analyses.

The elevated magnesium concentrations present may result from brine contamination. A portion, however, may result from dissolution of dolomitic beds in the Cloud Chief Formation and/or dolomites within the Marlow Formation. Dissolution of these materials would bring magnesium into solution, which would resist re-precipitation, tending to move along the ground water (Hem, 1989).

Chronological Degradation of Water Quality

Time-sequential analyses are available for several wells in the study area. These analyses allow appraisal of water quality changes over time, in a

TABLE 13

JUNE 3-6, 1991

WELL	SODIUM	CALCIUM	MAGNESIUM	CHLORIDE	SULFATE	BICARBONATE	DISSOLVED SOLIDS	HARDNESS	pH	CONDUCTIVITY
D-1	19	71	29	25	12	247	409	296	6.8	620
D-2	15734	1155	624	28002	12	294	45821	5444	6.5	70500
D-3	8201	1755	1260	19418	5	135	30774	9552	6.3	47000
D-400	725	568	4	1958	120	165	3541	1442	6.8	5500
D-5PW	17567	1332	678	31339	16	229	51161	6110	6.7	8800
K-11	4300	35	4	559	66	224	1318	104	7.2	2000
P-10	327	956	6.3	2125	28	129	3571	2416	6.6	5500
W-4	1272	162	8.9	2124	68	176	3811	442	7.1	5900
W-6	5874	1199	236	11751	29	206	19295	3966	6.5	29700
W-7	701	982	14	2750	59	124	4754	2511	6.3	7300
W-8	58	118	2.9	207	11	159	556	307	6.8	850
W-PW	1019	1020	37	3337	95	147	5655	2700	6.4	8700
W-400	134	541	10	729	540	118	2072	1394	6.6	3200

single well. C-2, a known "open hole" connecting the Rush Springs and the Marlow, was used for such an appraisal. Analyses from February 18, 1966, February 20, 1985, and August 17, 1991 were examined (Table 14). Comparison of the dissolved solids and chloride content from these analyses show concentrations of both have undergone drastic increases over the 25-year span (fig. 28). Increases from acceptable constituent levels to concentrations well in excess of federal recommended drinking water standards (500 mg/l for dissolved Solids and 250 mg/l for chloride) illustrates a continued degradation of water quality at this site.

Water-quality degradation continues currently, in parts of the study area. Samples collected from area wells on April 1, 1991 were compared with samples taken from the same wells on June 3, 1991 (Table 15). Upon comparison, some, but not all, samples indicate a further decline in water quality. Examples of improving and declining water quality are represented by samples from D-2 and P-10, respectively (fig. 29 and 30).

Although incorrect analytical results may give false impressions of improving water quality, it is assumed all analyses are correct. More plausible explanations are the depletion of residual wastes in closed disposal pits and/or the relocation or discontinued use of injection wells. Contaminant input would thus decrease or end, improving water quality. Migration of a contaminant plume center past a well could also result in an apparent decrease in contaminant concentrations. In addition, it is well known that

TABLE 14

WELL C-2

SAMPLE DATE	SODIUM	POTASSIUM	CALCIUM	MAGNESIUM	CHLORIDE	SULFATE	BICARBONATE	SILICA	DISSOLVED SOLIDS	HARDNESS	pH	CONDUCTIVITY
2/18/66	40	1.1	141	28	46	310	271	1	630	468	7.4	
2/20/85	57				454	62			971	819	7.4	1832
2-20-85 CORRECT	57		232.8		454	62			971	819	7.4	1832
7/17/91	90		531	16	1019	42	135		1803	1393	7	2700

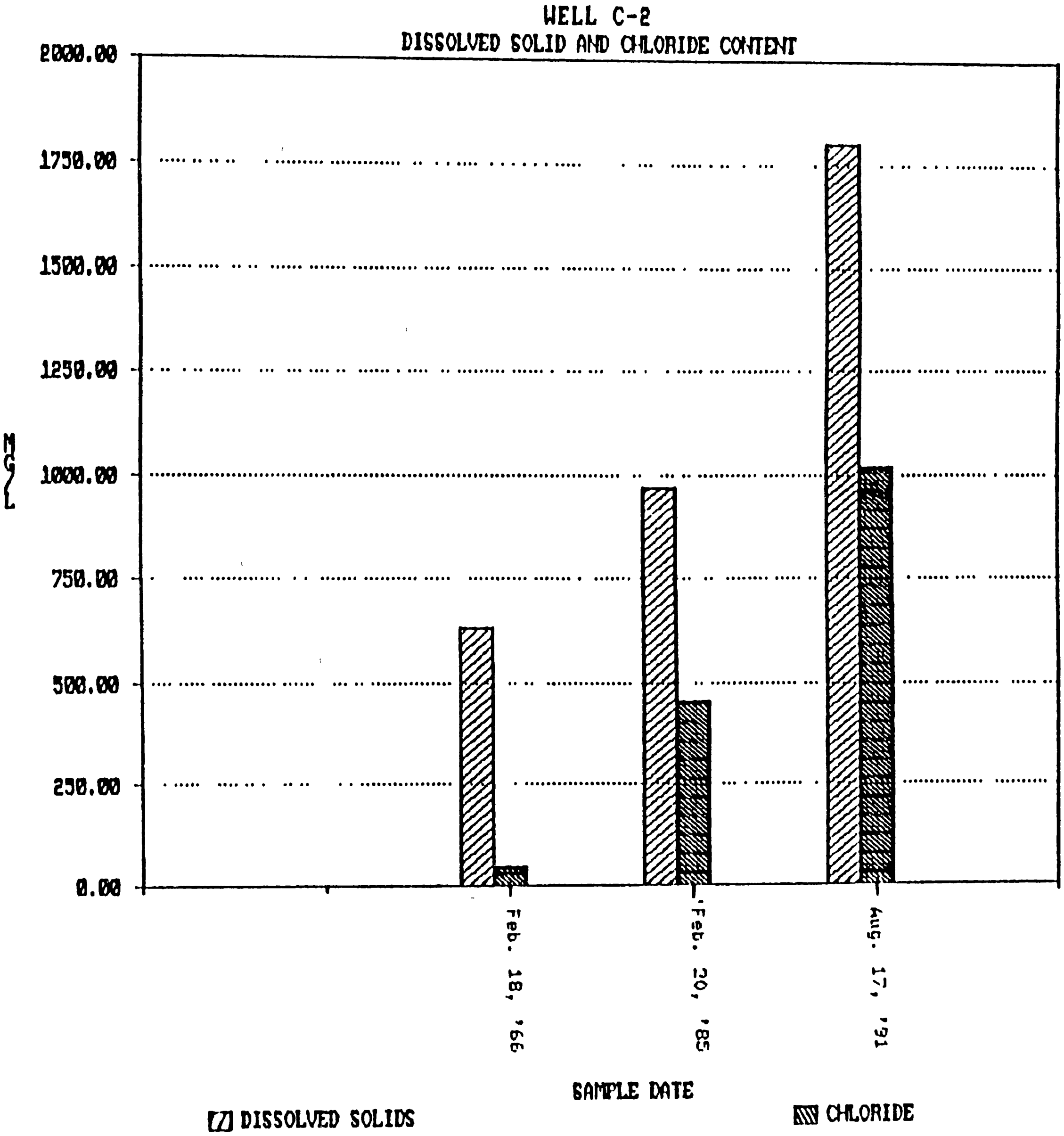


Figure 28. Dissolved Solids and Chloride Content, Well C-2

TABLE 15

SPRING 1991

APRIL SAMPLES

WELL	SODIUM	CALCIUM	MAGNESIUM	CHLORIDE	SULFATE	BICARBONATE	DISSOLVED SOLIDS	HARDNESS	pH	CONDUCTIVITY
D-2	19570	3676	364	37670	6	229	61515	10681	6.2	94600
P-10	4.4	701	6.2	1159	32	148	2051	1778	6.6	3200
JUNE SAMPLES										
WELL										
D-2	15734	1155	624	28002	12	294	45821	5444	6.5	70500
P-10	327	956	6.3	2125	28	129	3571	2416	6.6	5500

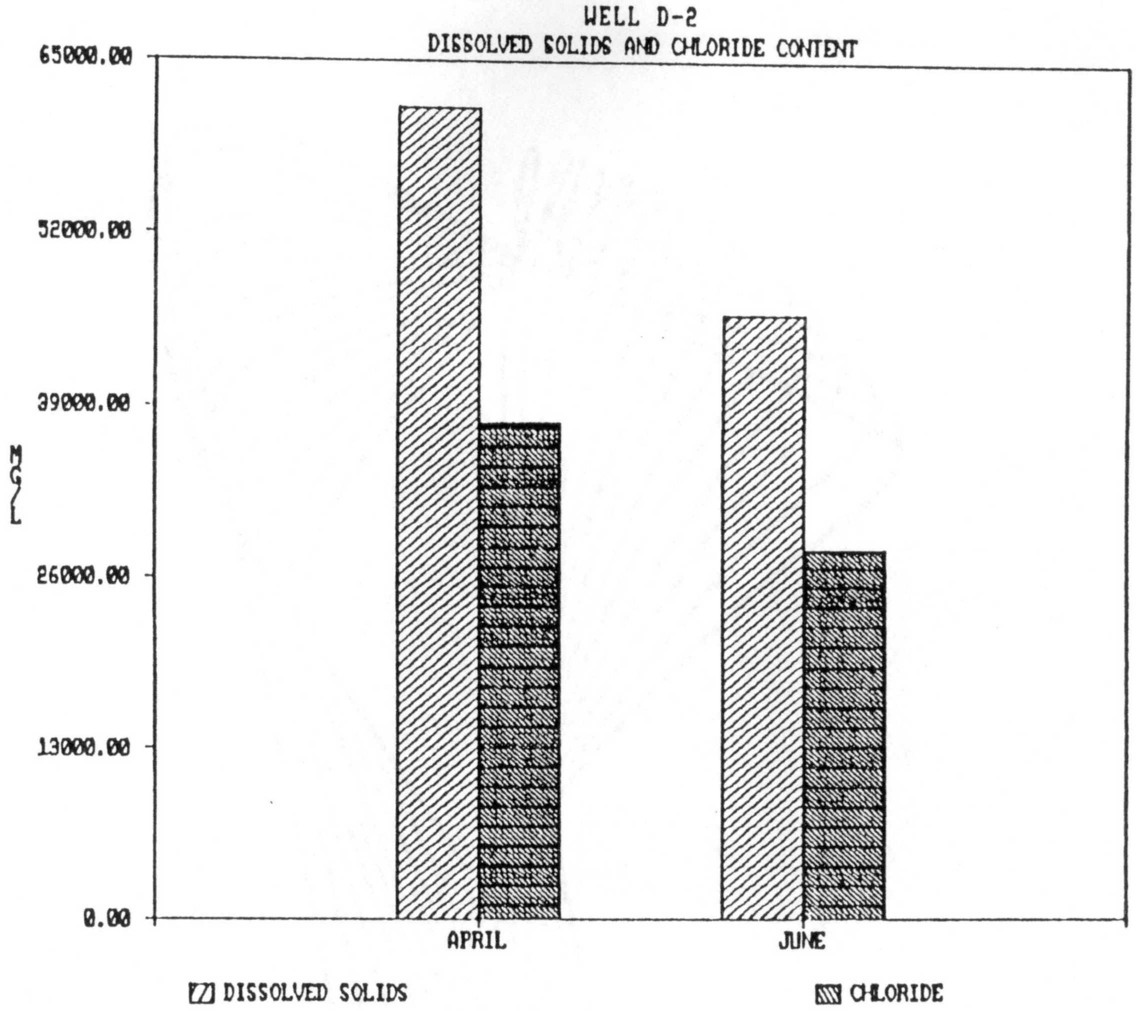


Figure 29. Dissolved Solids and Chloride Content, Well D-2

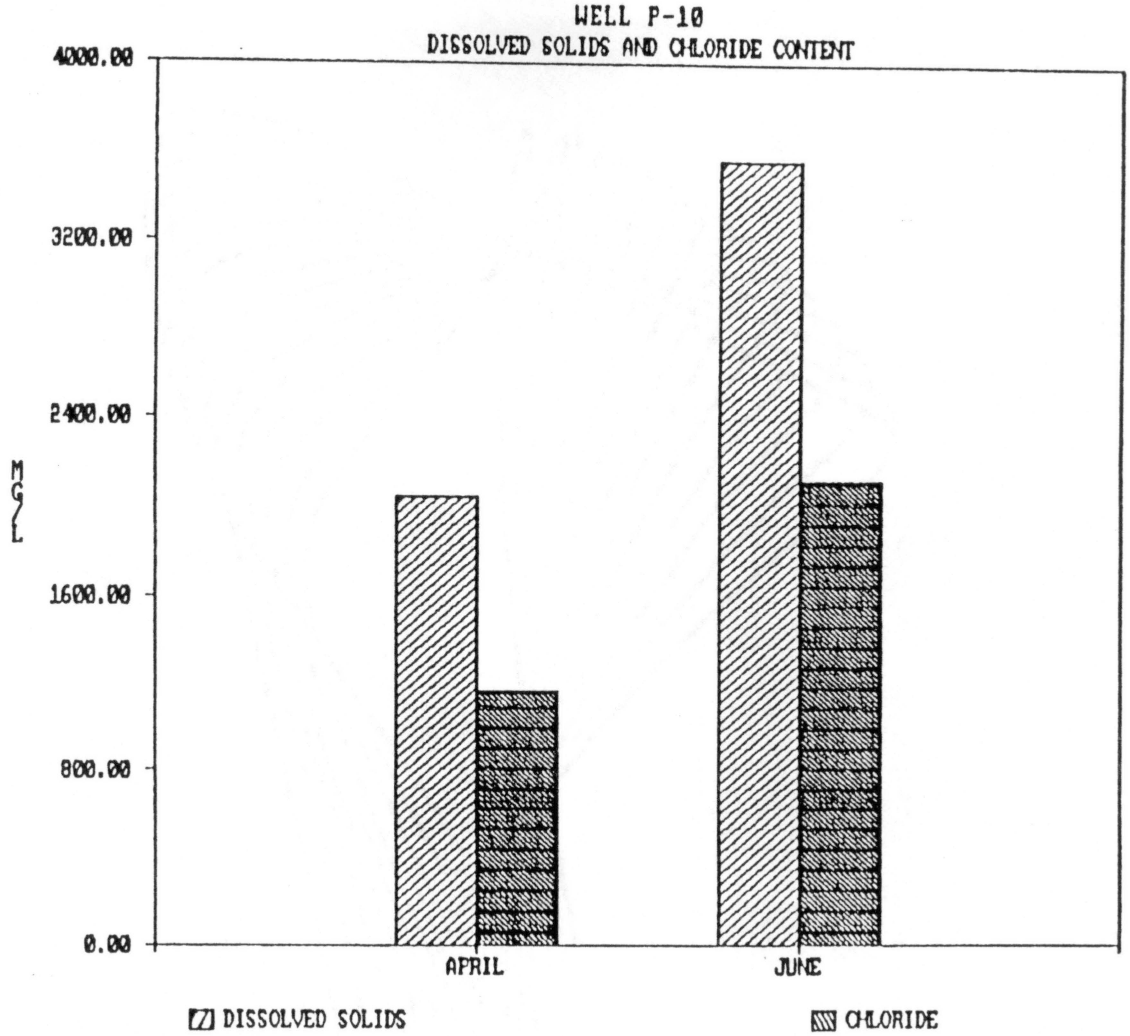


Figure 30. Dissolved Solids and Chloride Content, Well P-10

chemical quality can range within rather broad limits from one time to the next due to ground-water recharge and the leaching of contaminants.

Percentage of Ground-Water Contribution

Well C-2 is known to penetrate both the Rush Springs and the Marlow aquifers. Using the assumption that sulfate concentrations tend to be elevated in the Marlow due to higher gypsum content, and the fact that the confining bed separating the two lies 100 to 125 feet below ground surface, analyses can be grouped according to the aquifer of origin. Theoretical mixtures, using concentrations of wells tapping individual aquifers, were compared with the sulfate concentration of C-2, allowing estimation of the percentage of water being contributed to C-2 by each aquifer. Ground-water samples collected in June 1991 from D-3 and W-6 were chosen as representative of the Rush Springs, and D-400 and W-400 were used to represent the Marlow. These two sets of data indicate that the Rush Springs aquifer contributes from 68 to 97 percent of water produced from C-2, with the Marlow contributing the remaining 3 to 32 percent. This supports the exclusion of C-2 when determining the area contributing ground water to the Cyril well field from the Marlow aquifer.

Presence of Calcium-Chloride Waters

As pointed out by Dr. Arthur Hounslow, some of the June analyses show anomously elevated concentrations of calcium as well chloride (i.e. well D-3). Natural brines in which calcium and chloride are the primary dissolved ions are fairly common (Hem, 1989). A natural salt spring is present in Sec. 36, T. 6 N., R. 10 W. A calcium-chloride water type originating from this source, however, would be unexpected due to presence of the ground-water divide described previously. Some possible explanations for the elevated calcium concentrations include contamination from brines with elevated calcium concentrations, well acidization, formation-fracing techniques, disposal of wastes from these procedures, and/or dissolution of gypsum.

Examination of brine samples shows elevated calcium concentrations. However, in some samples, sodium concentrations are much higher. Elevated ion concentrations from brine leakage, therefore, would register as NaCl type waters, not the calcium chloride type encountered.

Both Cloud Chief and Marlow Formations contain significant amounts of gypsum in the area. Addition of calcium ions from the dissolution of gypsum to brines could supply high enough calcium concentrations to overshadow sodium concentrations, resulting in a Ca^{++}-Cl^{-} water type. Dissolution of gypsum would also result in elevated sulfate concentrations.

Acidization is usually performed on oil wells soon after the casing is placed. The acid is introduced into the well, remains in the formation for a selected interval, and then is removed and sent to a disposal site. Disposal methods are unknown. Acids used in this procedure, normally hydrochloric, would introduce chloride ions into the system. Fracing also is commonly performed soon after completion of a well. Acid involved in fracing procedures also could serve to introduce chloride. Elevation of calcium concentrations due to these procedures could result from breakdown of calcite cement and/or calcium-bearing minerals.

Fluids used in acidization and/or fracing procedures are removed after completion of the procedure. Even though all fluids are not always removed completely, the volume required to escape and produce such elevated concentrations as are present, would be prohibitive. Elapsed time between acidization/fracing procedures and sampling would also be prohibitive of elevated concentrations resulting from these procedures.

Methods of disposal of wastes from acidization and fracing procedures in the Cement Field are not clear, but mixture and disposal of these wastes with brines and salt waters would be probable. Leakage from disposal pits and, later, of injection wells, could result in release of these wastes, as well as salt water. The percentage of salt water would overshadow that of acidization waste water. Therefore, sodium would be the major cation present in most cases. However, at points where acidization waste waters predominated, calcium could assume the position of major cation present.

Dissolution of gypsum could supply additional calcium ions in locations of higher gypsum content, while adsorption/precipitation could retard calcium migration in other locations.

Unless neutralized, waste fluids from acidization and/or fracing procedures would be acidic. While it is unlikely these fluids would be extremely acidic, it is also unlikely they would undergo neutralization before disposal. Current analyses show that the pH of the ground water ranges from 5.7 to 7.8, averaging 6.8. Historical analyses of area waters indicate an average pH above 7.0. It is uncertain whether this indicates a lowering of the pH, or is simply the result of a small sample size. Regardless of this, lower pH values would seem to indicate a source of lower pH fluid and would warrant farther investigation.

Sodium/Chloride Ratios

Methods using sodium to chloride ratios have been reported as useful to determine the origin of a contaminated sample. While some research shows "... no given ratio for which ranges can be used to distinguish clean water from any of the brines" (Novak, 1986, p.—), use of Na^+/Cl^- ratios does continue.

Leonard and Ward (1962) used Na^+/Cl^- ratios to distinguish oil-field brines from salt-spring brines in western Oklahoma. Naturally-occurring salt-spring brines consistently yielded a ratio near 0.64. A ratio greater than 0.60 was considered indicative of a natural halite source, while a ratio near or less than 0.50 was considered indicative of a brine source.

Similar work by Leonard (1964) showed that Na^+/Cl^- ratios in Kansas oil-field brines to be very constant. Ratios of sodium to chloride in natural waters were greater than 0.60, and usually greater than 1, while Na^+/Cl^- ratios of oil-field brines were usually less than 0.60. Using these ratios, Leonard (1972) attributed chloride concentrations greater than 100 mg/l in ground water to contamination by oil-field brine in cases where Na^+/Cl^- was less than 0.60.

With one exception, samples in the study area with chloride concentrations greater than 100 mg/l, exhibit Na^+/Cl^- ratios that are less than 0.50 (NUS Corporation, 1989), suggesting contamination by oil-field brines. Several samples exhibit ratios well above 0.64, which indicate natural halite is an unlikely source of sodium (Leonard and Ward, 1962). Comparison of chloride concentrations and Na^+/Cl^- ratios in samples taken May 21, 1991 and June 3-6, 1991 (Table 16) supports this conclusion. With few exceptions, Na^+/Cl^- ratios of samples with a chloride concentration over 100 mg/l are below 0.60 (fig. 31), indicating oil-field brine as the probable contaminant source. However, the Na^+/Cl^- ratio may give incorrect indications in those locations where elevated chloride is associated with elevated calcium concentrations and low sodium concentrations, as discussed earlier. Contamination

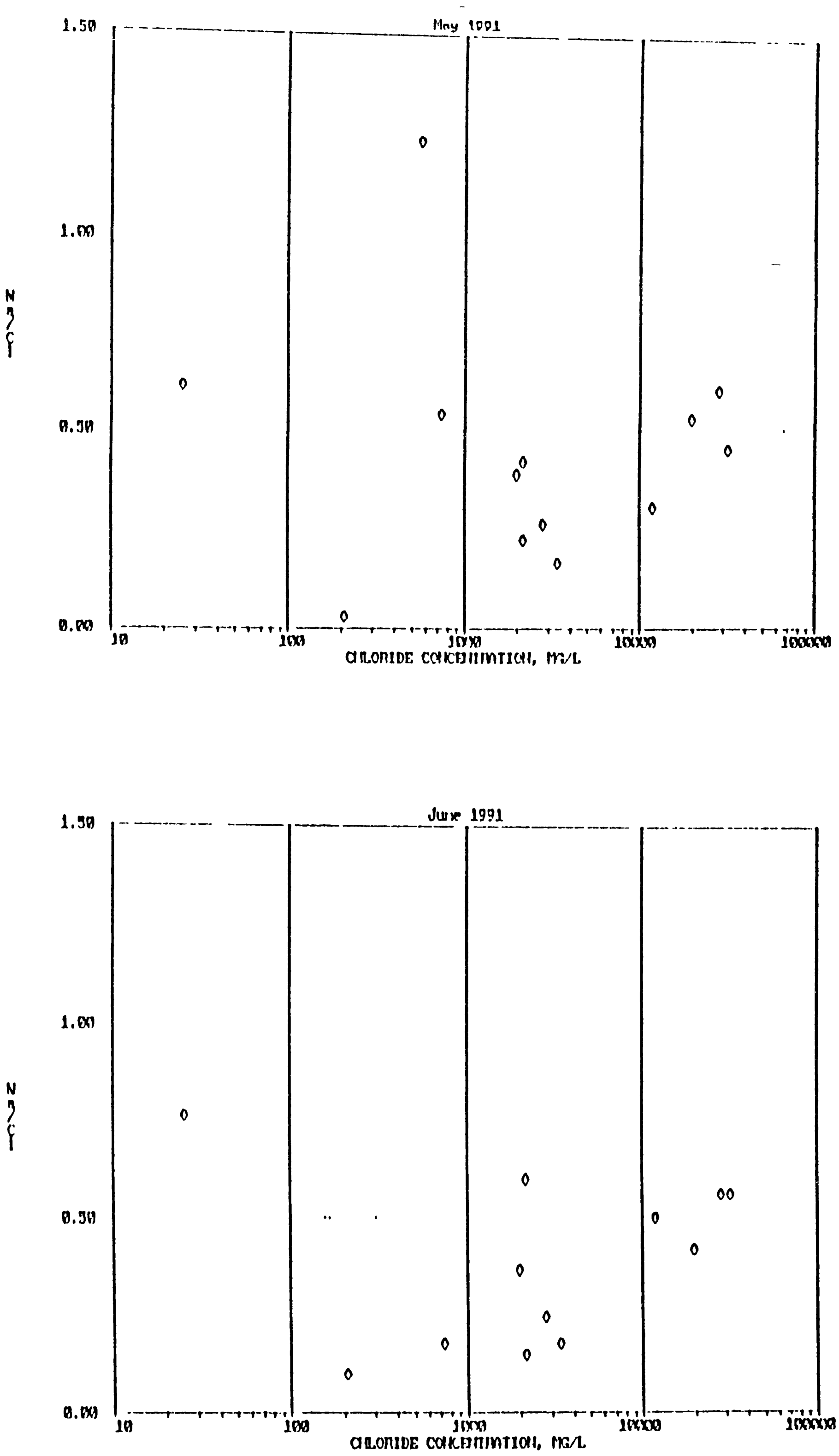


Figure 31. Na+/Cl- versus Chloride Concentration May and June, 1991

from natural sources, i.e. the natural salt-spring in Sec. 36, T. 6 N., R. 10 W., would be prohibited by the ground-water divide formed by the Cement Anticline.

TABLE 16

CHLORIDE CONCENTRATION AND NA^+/CL^- RATIOS
AREA WELLS

	MAY, 1991		JUNE,1991	
WELL	Cl^- (mg/l)	Na^+/Cl^-	Cl^- (mg/l)	Na^+/Cl^-
D-1	51	0.61	25	0.76
D-2	16918	0.60	28002	0.56
D-3	10359	0.53	19418	0.42
D-400	1182	0.39	1958	0.37
D-5PW	17789	0.45	31339	0.56
K-11	114	1.24	559	7.70
P-10	213	0.23	2125	0.15
W-4	6251	0.42	2124	0.60
W-6	5348	0.31	11751	0.50
W-7	2460	0.27	2750	0.25
W-8	325	0.03	207	0.10
W-400	220	0.54	729	0.18
W-PW	4607	0.17	3337	0.18

Results of Chemical Analysis

Chemical quality of ground water in the area of the Cyril well field was examined in this part of the site-specific analysis. Historic analyses from the study area indicate good water quality with low chloride content, but relatively high temporary hardness. Isolated high sulfate concentrations are probably due to well location. Brine analyses show high concentrations of chloride, sodium, potassium, calcium, and magnesium. Samples taken June 3 - 6, 1991 illustrate current conditions, the majority of these analyses indicating saline and/or permanently hard waters.

Sequential analyses from C-2, an "open" hole, show a continuing degradation of water quality over a span of 25 years. Degradation continues in some locations of the study area, while water quality in other locations appears to be improving. Possible explanations of improvement include depletion of disposal pit wastes, re-location of injection wells, and migration of a plume center past a monitoring well.

Sulfate concentrations from wells tapping the Rush Springs and Marlow aquifers were compared with the sulfate concentration of a July, 1991 analysis of C-2, in order to calculate percentages of contribution from each aquifer. Such calculations show the Rush Springs aquifer contributing 68 to 97 percent of the water obtained from C-2, with the Marlow contributing 3 to 32 percent.

Occurrence of unexpected calcium-chloride type water in some wells in the study area is possibly the result of a combination of several possibilities. This combination, which includes disposal of acidization and/or formation-fracing wastes in disposal pits and/or injection wells, high calcium concentrations in brines, dissolution of gypsum, and calcium ion adsorption/precipitation, could result in calcium chloride waters at isolated places.

In the study area, the majority of ground-water samples with chloride concentration in excess of 100 mg/l exhibit Na^+/Cl^- ratios approximately equal to or less than 0.60. Such relationships indicate oil-field brines as probable contamination sources. Presence of the Cement Anticline eliminates the possibility of contamination from known salt springs, supporting conclusions that contamination results from oil-field brines.

CHAPTER VI

CORE INFORMATION

Introduction

The final part of the site-specific analysis involves an evaluation of a number of cores taken during the drilling of wells for investigation of Cyril ground-water problem. Cores were collected from sites in abandoned disposal pits with specific conductance and chloride concentration measured.

Residual hydrocarbons in pits at the location of wells D-2, P-10, K-11, W-4, and W-6 cause a dark appearance on aerial photographs. Saturation of the soil with oil and a strong petroleum odor was noted at these sites, with oily soil and/or mottles noted in D-400 and W-PW.

Background levels of chloride were obtained from measurements taken at D-1, although specific conductance was not measured. However, correlation of chloride content and specific conductance in other cores suggests specific conductance would be low in D-1 also.

Locations of cored wells are shown in figure 32. Tables 17 and 18 list chloride and specific conductance measurements, respectively, from the soil profile of cored wells.

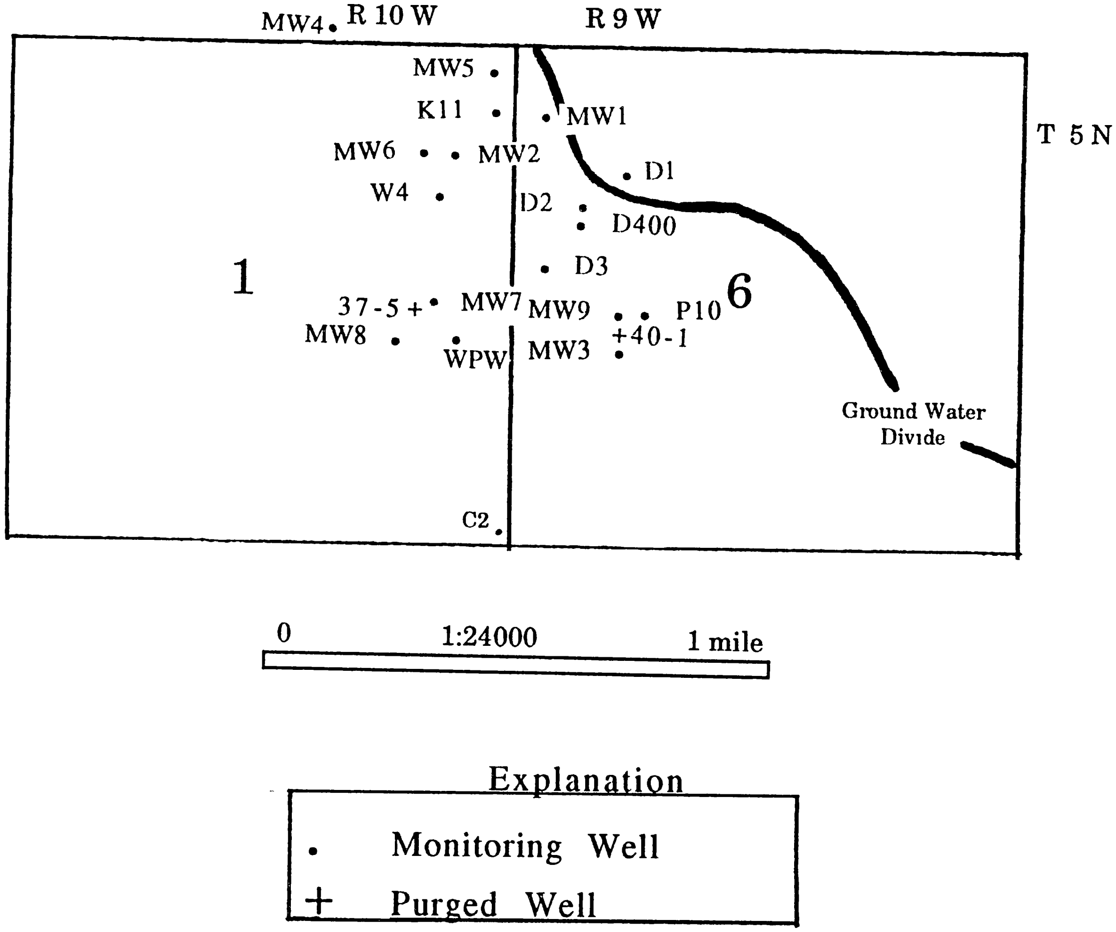


Figure 32. Location of Select Monitoring and Purged Wells

TABLE 17

CHLORIDE CONCENTRATION IN SOIL PROFILE

	Chloride, mg/kg					
WELL depth, in feet	D-1	D-2	D-3	D-400	P-10	W-4
0-10	51	360-347	105-35	428-1349	7570-6332	86-70
10-20	45	372-648	83	3364	4777	74
20-30	44	660-1945	111	3126	1143	175
30-40	44	1412	111	3936	243	175
40-50	38	2662	60	4967	192	889
50-60	38	4700	60	4005	192	
60-70	43	5811				
70-80	43					

WELL depth, in feet	W-PW	W-7	W-8
0-10	1111-4380	1913-566	40-108
10-20		242	80-35
20-30		245	42
30-40		245	4

Methodology

Chloride concentrations were reported for intervals of 10 feet. It was assumed that end values of this range coincide with upper and lower ends of the measured interval. In those instances where one value was reported for an interval, this value was assigned to both end members. The chloride concentrations of select cores were plotted to show the changes in concentration which occur with depth (fig.33). Well D-1 illustrated background conditions, well D-2 represented an area with a high residual hydrocarbon concentration, and D-3 served to illustrate an area where the chloride concentration was above background levels but there was no evidence of hydrocarbons in the disposal pit visible on aerial photographs (fig. 33). Scale changes

TABLE 18

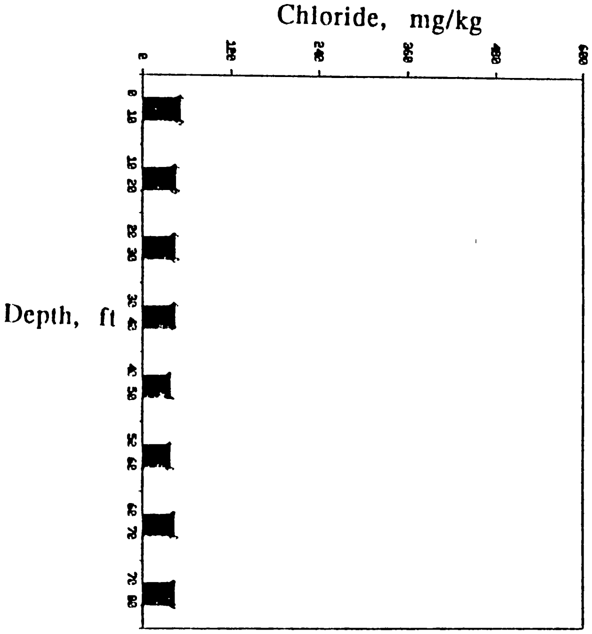
SPECIFIC CONDUCTANCE WITH DEPTH

Specific Conductance, micromhos/cm

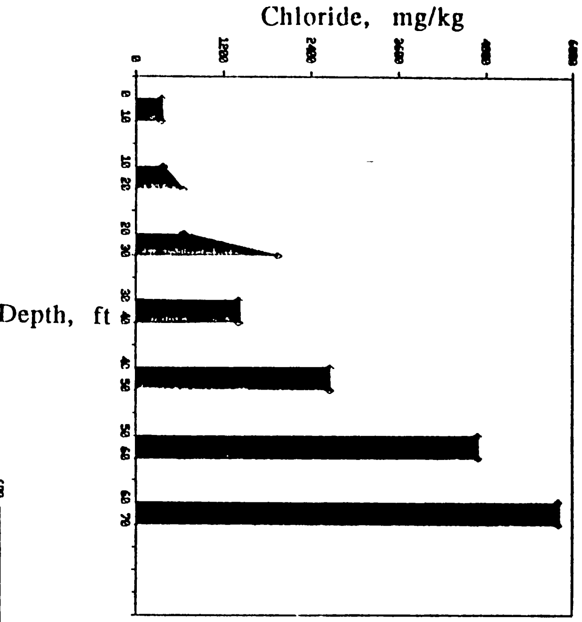
Well Depth, ft	D-2	D-3	D-400	P-10	K-11	W-4	MW-7	MW-8
1	1450	460	100	8200	1100	1820	3490	7000
2	5400	670	550	11000	1400	2700	3580	9000
3	4000	330	2700	9200	1130	3500	3800	10100
4	4500	320	2700	5700	1100	2200	4500	10500
5	1400	250		4900	1250	1700	5900	10600
6							11100	10800
7							13100	10900
8							13800	11000
9							14000	11000

Specific Conductance, micromhos/cm

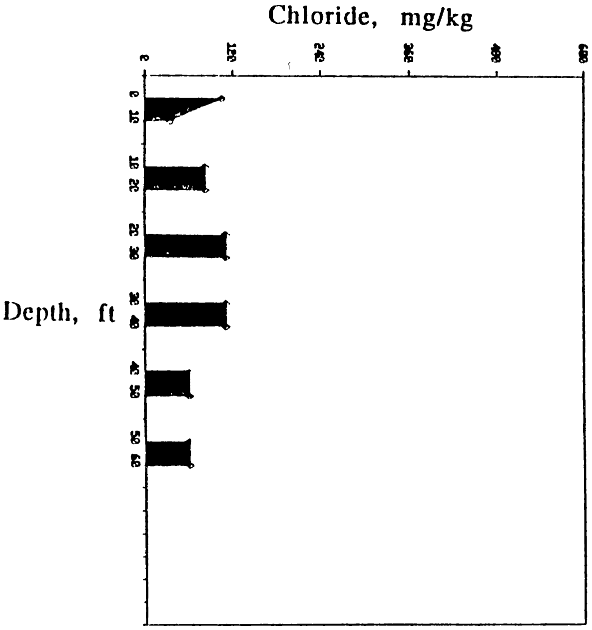
Well Depth, ft	MW-1	MW-2	MW-4	MW-5	MW-6	MW-7	MW-8
0	720	2580	680	590	5200	3090	5800
10	810	7500	680	690	15600	14500	11200
20	900	7600	690	700	16100	14300	11200
30				850	16200	14100	11200
40				8000		14000	11200
50						13900	11200
60						10100	11200
70						8200	11200
80						6900	11000
90						5500	11000
100						5000	10100
110						4200	7400
120						3300	5900



Well D-1



Well D-2



Well D-3

Figure 33. Chloride Concentrations of Soil profiles

were incorporated in order to best illustrate concentration contrasts between the sites.

Changes in specific conductance with depth also were noted. Specific conductance is related to dissolved solid content by a factor of approximately .67. Thus, an elevated specific conductance would imply the a high dissolved solid content. Specific conductance measurements were not made for D-1, so only D-2 and D-3 were compared (fig.34).

Specific conductance measurements at MW-7 were taken at intervals of one foot over the first nine feet. At greater depths measurements were taken at intervals of 10 feet, to a total depth of 120 feet (Table 18). Specific conductance peaks within the first 10 feet (fig. 35). These values decrease only slightly to a depth of 50 feet, where they begin to taper sharply. Such behavior is mirrored in other wells where specific conductance measurements were taken in the upper 10 feet.

Contamination by Purging Wells

As shown earlier, a major confining unit lies at a depth of approximately 100 feet. Several minor confining units, while not aerially extensive, are present at shallower depths. These confining units would tend to prohibit migration of contaminants from surface sources to depths below approximately 100 feet. Yet, elevated concentrations of chloride are found at depths

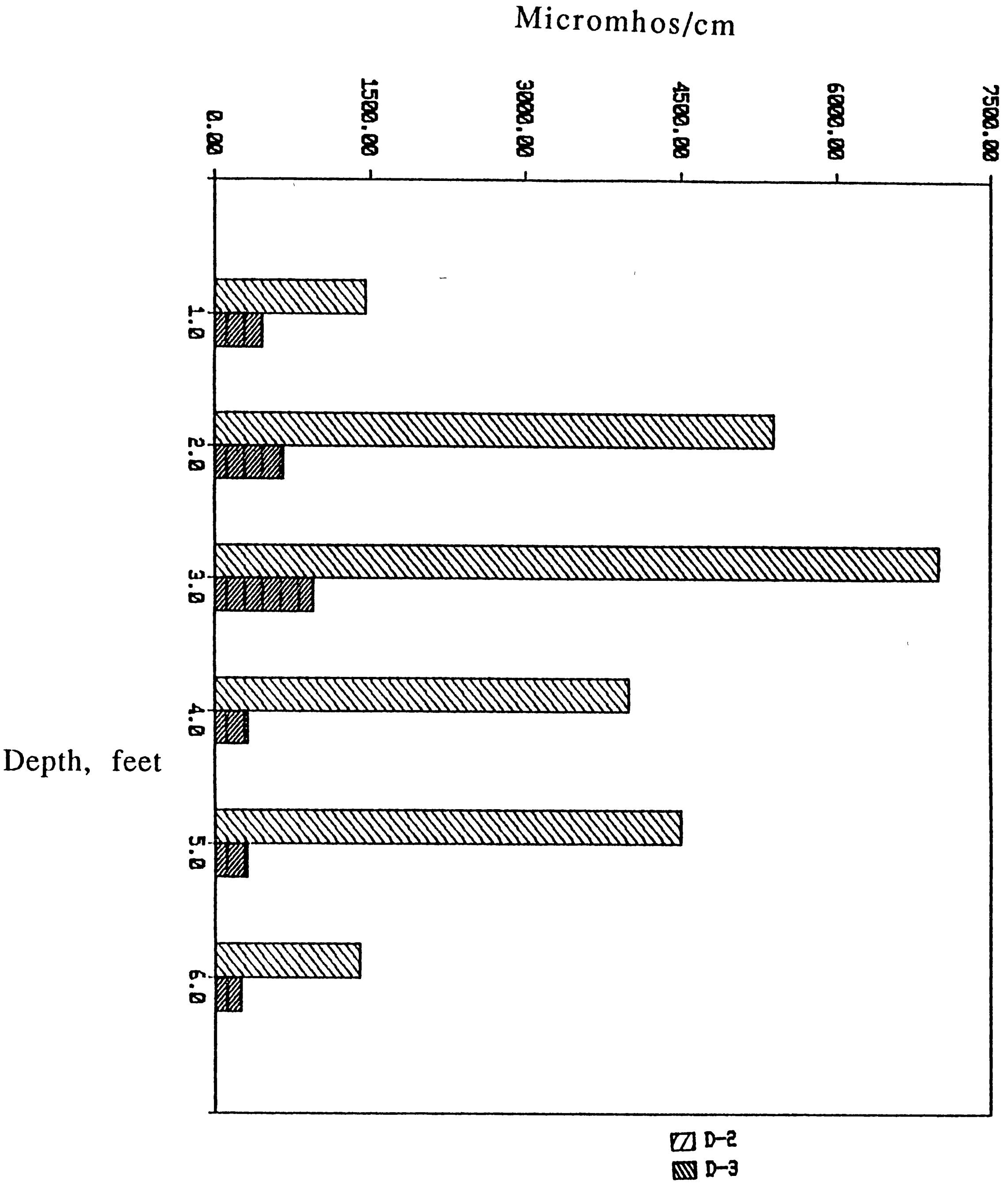


Figure 34. Specific Conductance with Depth
Well D-2 versus Well D-3

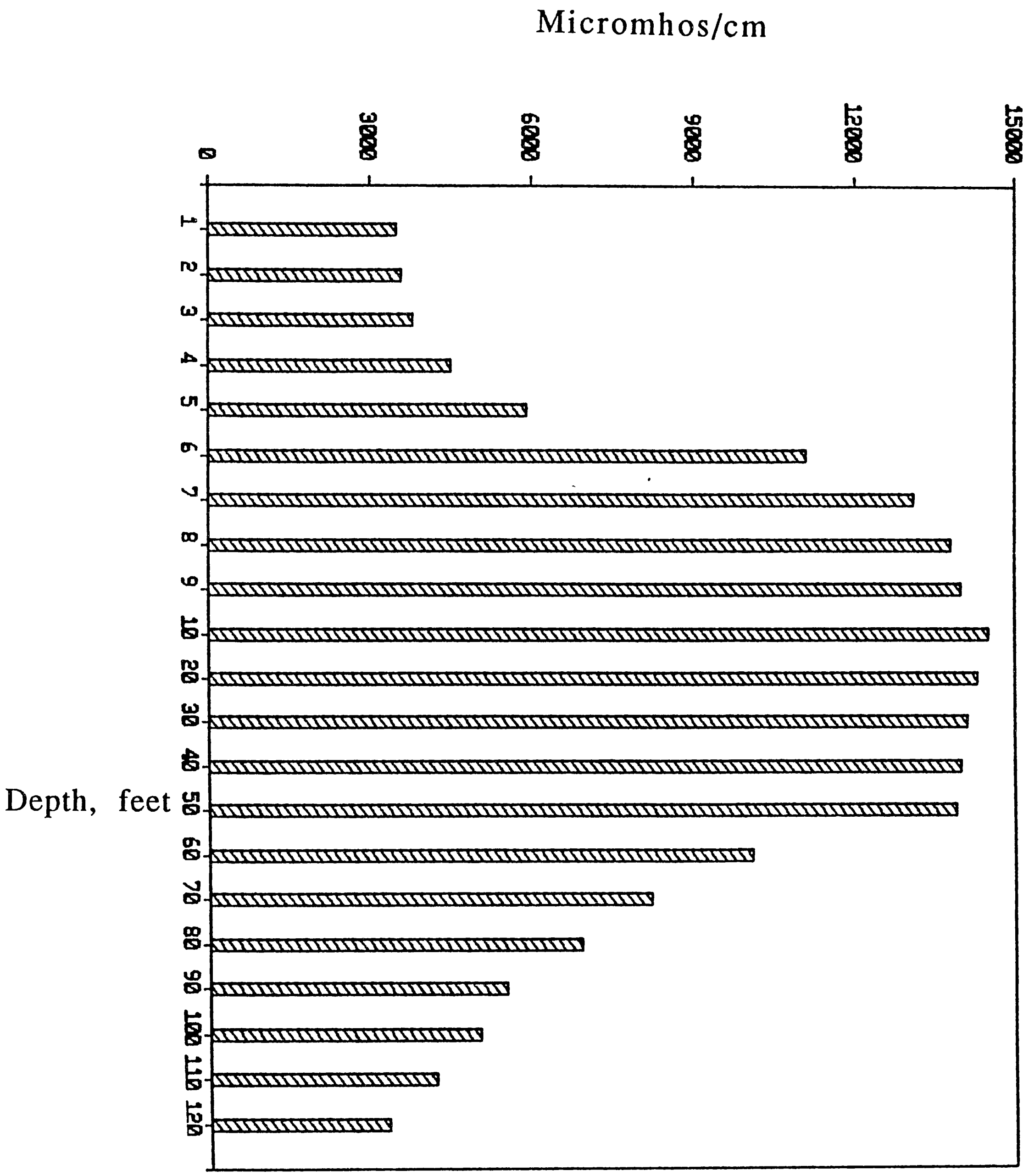


Figure 35. Specific Conductance with Depth
Well MW-7

at least as great as 400 feet. Presence of elevated chloride concentrations below the major confining unit implies a source of contamination other than disposal pits.

Several wells are known to have purged to the surface during injection. Known purging at the surface and the highly corrosive nature of oil-field brine (average life of steel casing is approximately 12 years; Leonard, 1972), suggest the likelihood of other wells having incompetent casing. Such wells could continue to purge at depth, even though such purges would not necessarily be evident at the ground surface.

Chloride concentrations of ground water were determined in monitoring wells located up-gradient of wells known to have purged. These concentrations were compared with chloride concentrations taken at similar depths down-gradient of these wells.

Ground-water chloride concentration were measured up- and down-gradient of injection well 40-1 using MW-9 and MW-3, respectively (fig. 36). Well 40-1 purged to the surface in August 1982. A similar approach was used at well 37-5, which purged in August 1977, using up-gradient measurements from MW-7 and down-gradient chloride measurements from MW-8 (fig,37).

Results of Core Data Evaluation

Specific conductance and chloride concentration were measured in cores taken from abandoned disposal pits. Observations made at the time of

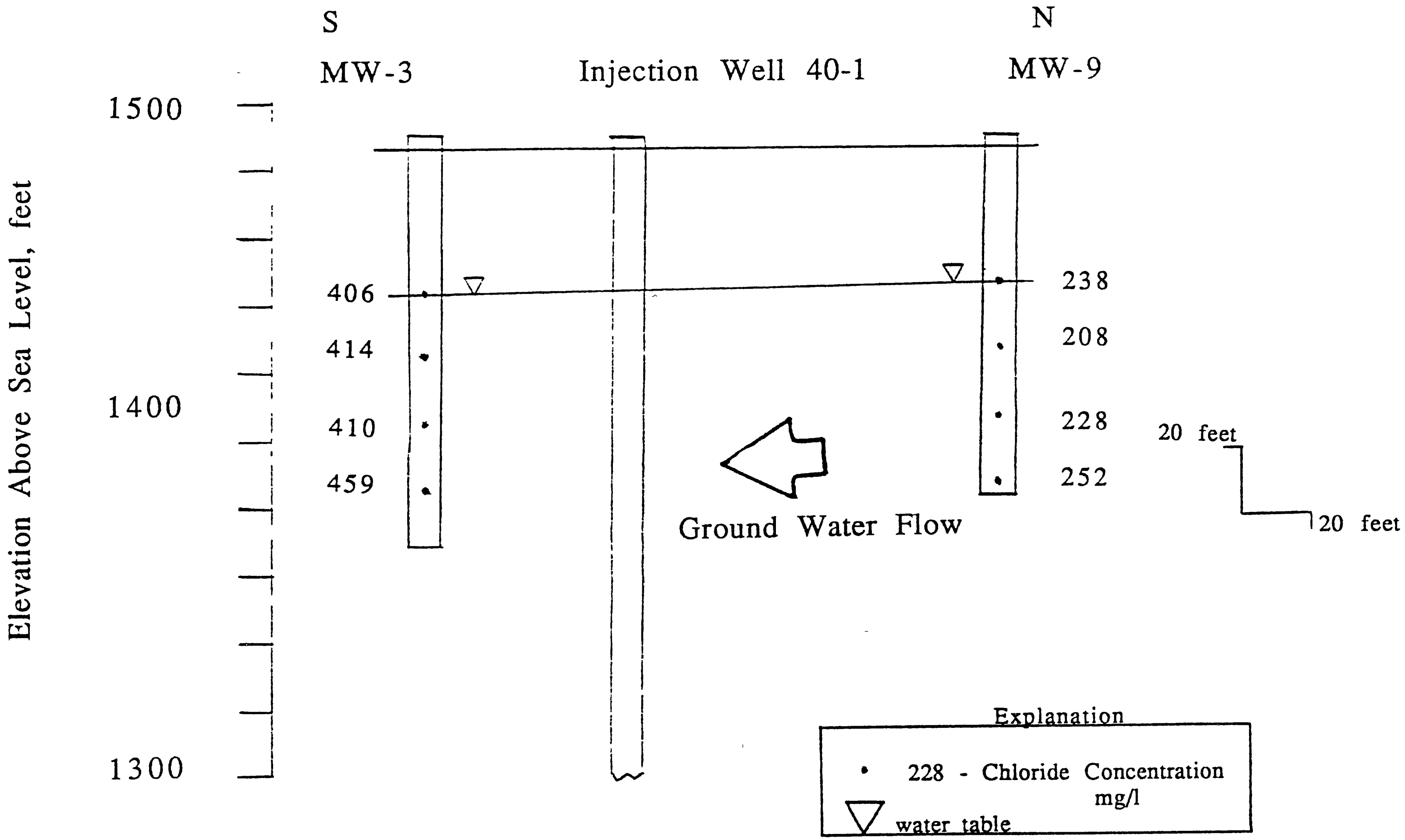


Figure 36. Ground Water Cross-Section showing Chloride Concentration, Wells MW-3 and MW-9

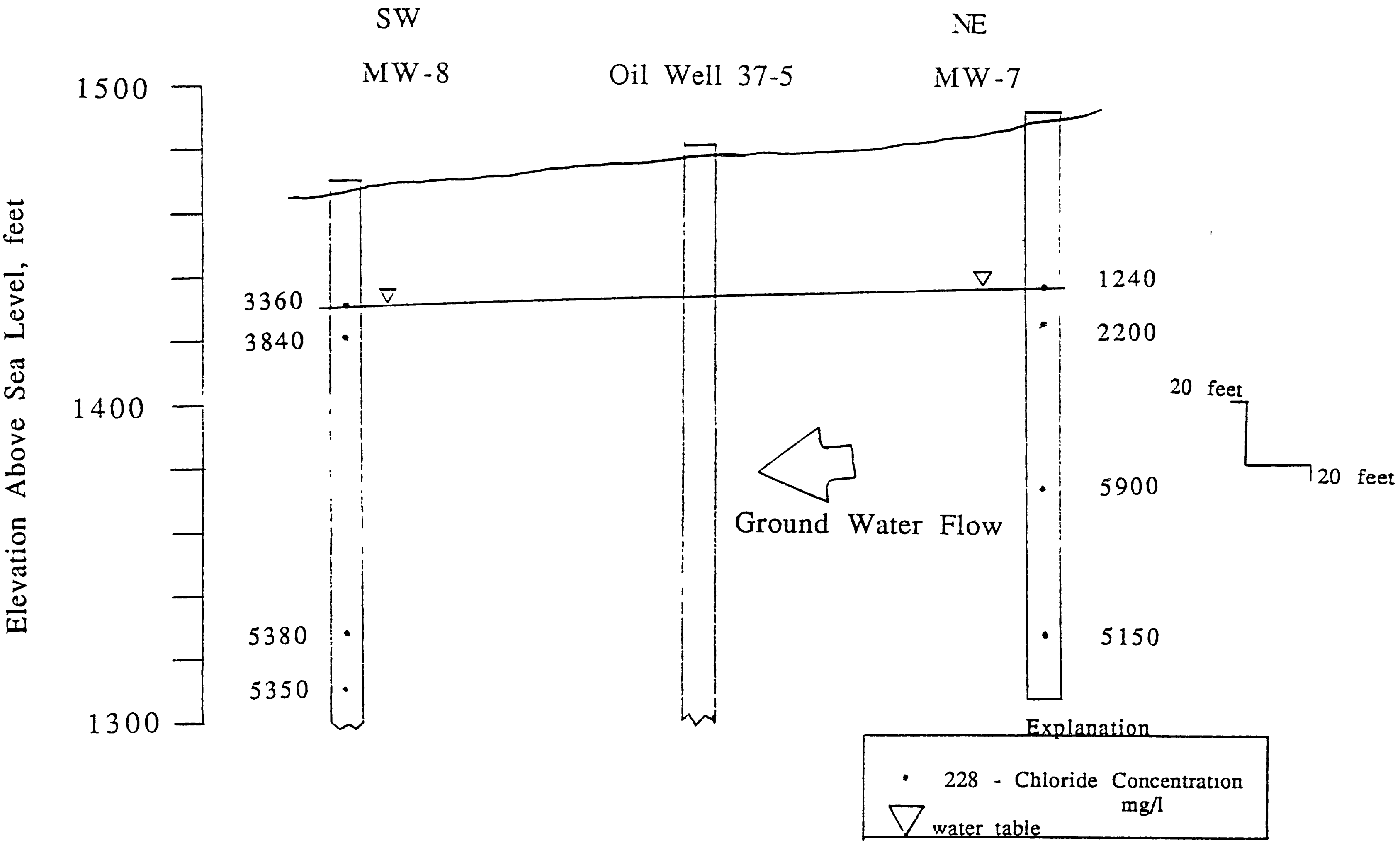


Figure 37. Ground Water Cross-Section showing Chloride Concentration, Wells MW-7 and MW-8

collection note saturation of the soil with oil and a strong petroleum odor at sites that exhibited dark discoloration on aerial photographs. Comparison of plots of the chloride concentrations at D-2 and D-3 indicate elevated measurements coincide with the presence of residual hydrocarbons. Both cores were taken at abandoned pit sites, yet a high concentration of residual hydrocarbons present in D-2 is not present in D-3. Apparently, low concentration of residual hydrocarbons at the D-3 site has allowed reduction of chloride by leaching processes, while such processes are hindered by high residual hydrocarbons at D-2. This would suggest that leaching and subsequent migration of contaminants is retarded by the presence of residual hydrocarbons within abandoned pits.

Measurements of specific conductance exhibit similar results when plotted over depth. This suggests dissolved solids content is elevated at sites where residual hydrocarbons are high.

Elevated concentrations measured in these locations indicate isolated areas of unreleased contaminants. Removal of low permeability materials that cover the pits would allow increased leaching of chloride ions into ground water and subsequent migration. This suggests that additional contamination would be likely if the residual hydrocarbons were removed.

Core data also suggest that abandoned disposal pits are unlikely sources of contamination at this time, although they certainly were in the and later until leaching removed most of the chloride. As shown by these data, chloride ions and other contaminants are either leached from pit areas or retarded by residual hydrocarbons, yet ground-water contamination in the area continues. This implies leakage from injection/production wells. Elevated chloride concentrations in ground water down-gradient from 40-1 and 37-5, each known to have purged in the past, support the idea of past leaking injection or production wells. An exception to this is apparent in chloride concentrations of MW-7. The elevated chloride concentrations up-gradient of the purging well at this depth (1370 feet) is a possible result of addition of chloride by a contaminant plume originating up-gradient of monitoring well MW-7.

CHAPTER VII

SUMMARY AND CONCLUSIONS

Introduction

Ground-water contamination at Cyril, Oklahoma was analyzed three times, an increasing amount of data being incorporated into each sequential analysis. In the primary analysis of the situation, very limited amounts of data were available, and hydraulic parameters had to be estimated. In the second analysis hydraulic parameters, as well as additional pertinent information, were obtained from published data. Final analysis of the situation incorporated site-specific information based on actual tests, drilled holes, and chemical analyses. Accuracy and reliability of the analyses were then compared on the basis of the amount of data incorporated into each.

Summary of Analyses

Analysis 1: Use of Limited Data.

In the initial analysis, the location, construction details, and pumping history were known for a few of the Cyril municipal water supply wells.

Limited water-quality analyses were available. These analyses, which listed sulfate, nitrate, and chloride concentrations and specific conductivity, indicated that some constituent concentrations exceeded federal drinking water standards. Reported water levels in wells, combined with a topographic map, were used to generate a water-table map of the area. Hydrologic gradient and ground-water velocity were approximated from this map.

Three computer models were used to aid in the analysis. Hydrologic parameters necessary were estimated or extrapolated from known data. All parameters were set to provide a worst-case scenario. TIME OF TRAVEL was utilized to establish the area contributing ground water to the Cyril municipal well field during the period in which it was in operation. The distance traveled by ground water contributing to the well field also was calculated. JPLUME was used to estimate affects of dispersion. The addition of dispersion distances to TIME OF TRAVEL results provides a maximum distance ground water might travel from an up-gradient source. Drawdowns resulting from pumping of the Cyril municipal wells were assessed by THEIS WELL FIELD.

A ground-water divide northeast of the municipal well field limits the area up-gradient of the well field that contributes ground water to the well field. Use of a range of hydrologic parameters in modeling limits the lateral extent of the zone of contribution. Neither a definite contaminant source nor a specific source location was indicated by this analysis, but combination of results from all of the procedures serves to delineate an area in which contamination source(s) are most probably located (fig. 38).

Analysis 2: Use of Published Data

In the second analysis, oil-field related activities in the West Cement Oil and Gas Field appeared to be the most probable source of contamination. Activities, which are the most probable contamination sources, include leakage from disposal pits and/or leakage of injection wells.

Published parameters, including information on general geology, area stratigraphy, water quality, and hydrologic characteristics, were used in a variety of analytical procedures. A new water table map was constructed using additional site data. Gradient and ground-water velocities were calculated from this map. TIME OF TRAVEL was employed to calculate the area contributing ground water to the Cyril well field by means of a worst-case situation. JPLUME was used to establish the location and concentration distribution of contaminant plumes. Disposal pits were treated as individual sources, with the number, size, and time of activity estimated from aerial photographs. Wells known to have purged were treated as separate sources, with parameters set to establish a worst-case scenario.

A regional view of ground-water recharge rates was determined by use of RECHARGE. Stream flow records of the Little Washita River were used

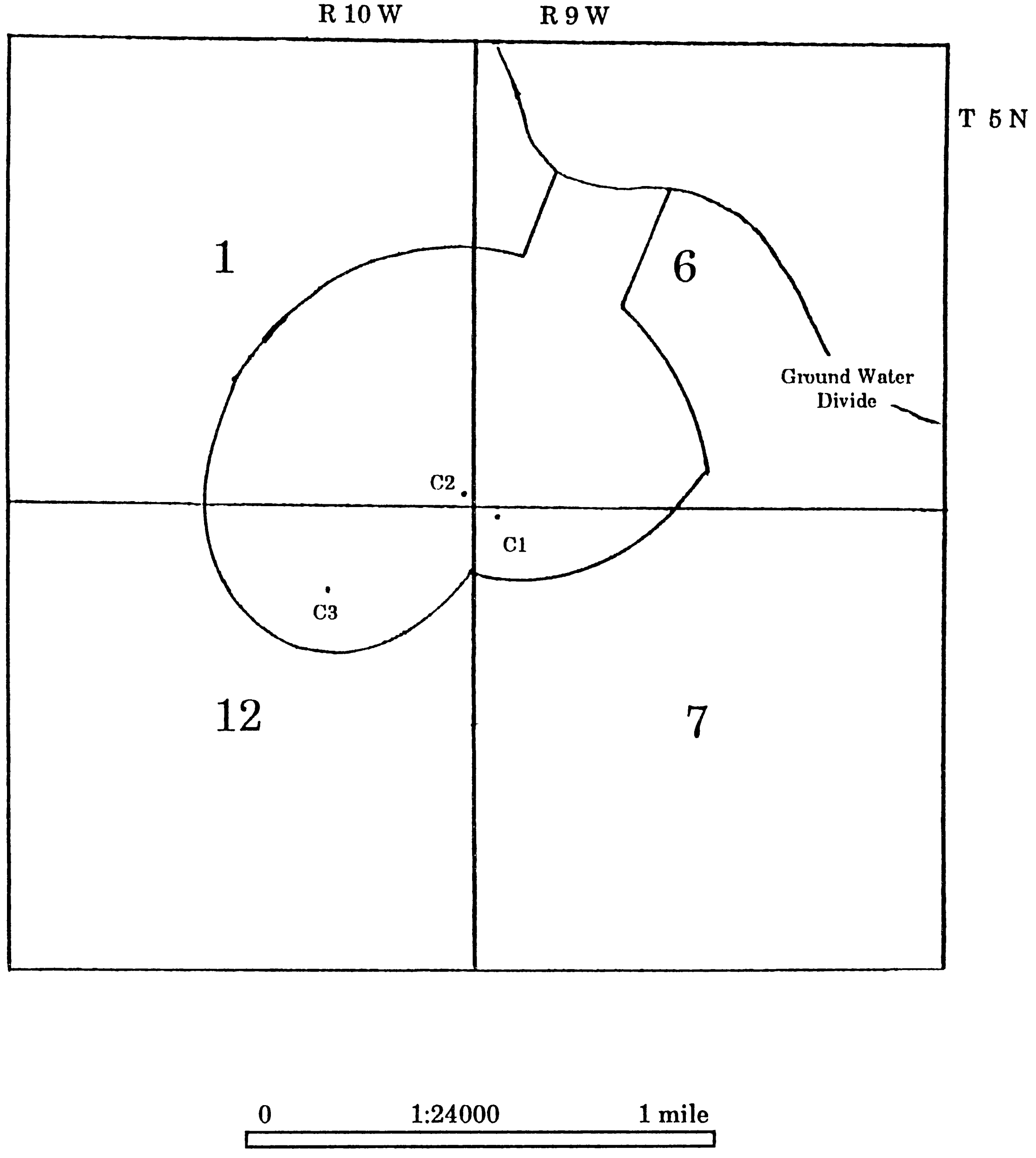


Figure 38. Area of Possible Source Location(s), First Analysis

as input values. Recharge rates for the Cyril area were calculated by means of Darcy's law. These site specific rates were used to estimate amounts of seepage from disposal pits. Modeling results, combined with generated maps, were used to delineate an area of probable source location (fig. 39).

Analysis 3: Use of Site-Specific Data

In final analysis of the Cyril situation, data gathered specifically from several field investigations of the area were utilized. Historic information indicated past occurrences of local stream and ground-water contamination that were related to the production of oil and gas in the West Cement Oil and Gas Field.

The water table map from the second analysis was again utilized. Aquifer tests indicate an average transmissivity of 1013 gpd/ft and a hydraulic conductivity of 17 gpd/ft2 in the area. Subsurface cross-sections generated from test hole well logs were used to determine the saturated thickness. The cross-sections also indicate that the uppermost unit of the Marlow Formation, which consists of shale, serves as a confining unit. Pumping rates of wells screened below the confining unit suggest high water-producing capabilities for these lower aquifers.

The impact of contamination was modeled for both the surficial Rush Springs and the deeper Marlow aquifers. THEIS WELL FIELD was utilized

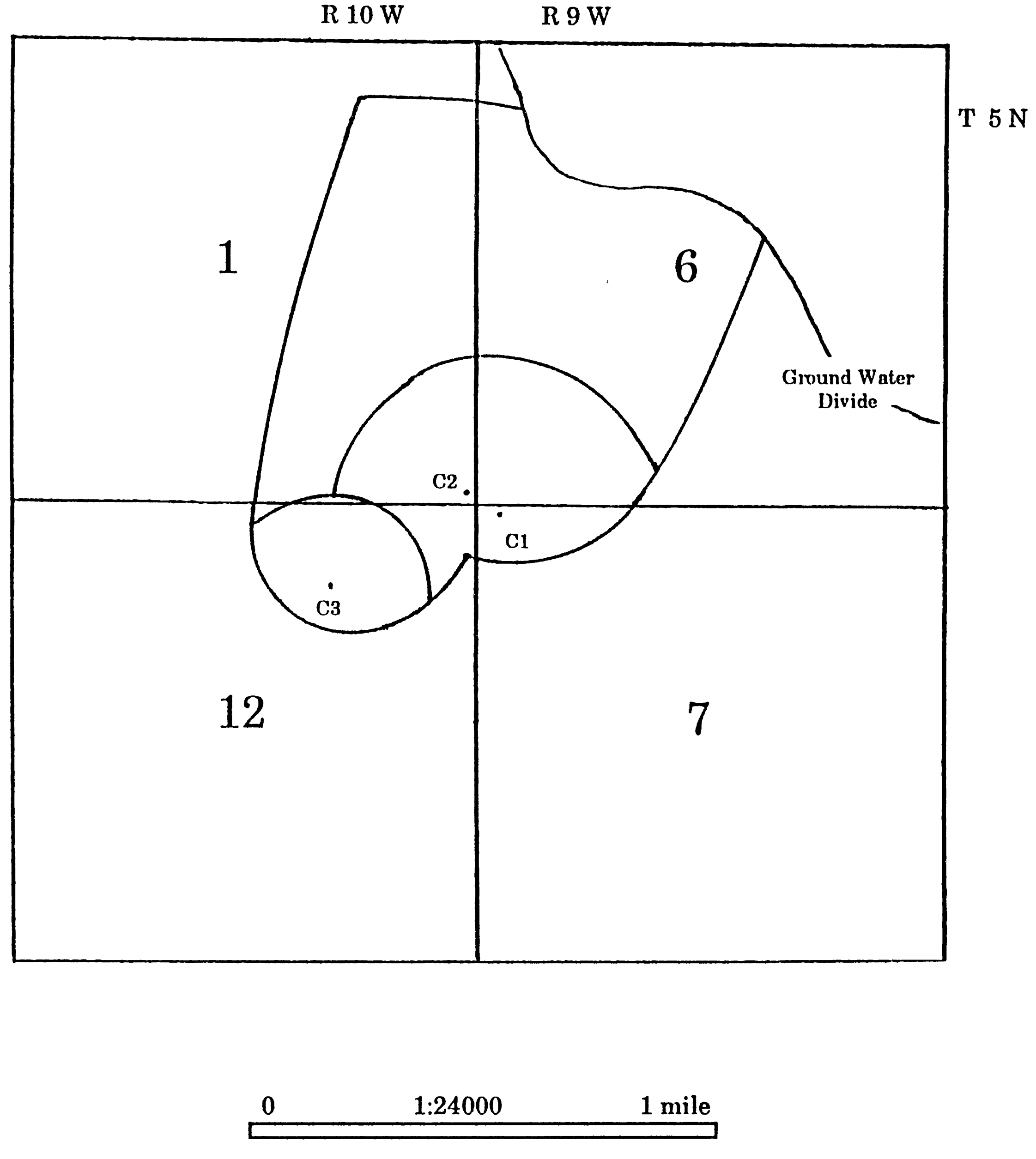


Figure 39. Area of Possible Source Location(s), Second Analysis

to estimate changes in the hydraulic gradient resulting from pumping of the confined Marlow. JPLUME was used to estimate plume location and concentration distribution. Modeling of disposal pits was performed in a similar manner to previous analyses, with pertinent parameters altered to site-specific values. While it was assumed that disposal pits would impact only the Rush Springs, purging wells were assumed to impact both the Rush Springs and the Marlow. The impact of purging wells was, therefore, modeled for both aquifers. Calculated hydraulic parameters were used in modeling of the upper Rush Springs. Since specific parameters are not available for the Marlow aquifer, the effective thickness of the Marlow was estimated from cross-sections, dispersion was set at 5:2.5, and other hydraulic parameters were assigned the same values used in the Rush Springs model.

The chemical quality of water pumped from the Rush Springs and Marlow indicates that both aquifer are contaminated. The use of site-specific hydraulic parameters in modeling allowed calculation of the zone of contribution to the Cyril well field and delineation of an area of probable source location (fig. 40).

The final analysis included an examination of area ground-water chemistry. Time-sequential analyses from C-2 show that water-quality degradation has occurred at least throughout the past 25 years, but water quality in isolated locales appears to be improving. Possible explanations of improving water quality are: depletion of residual wastes in closed disposal

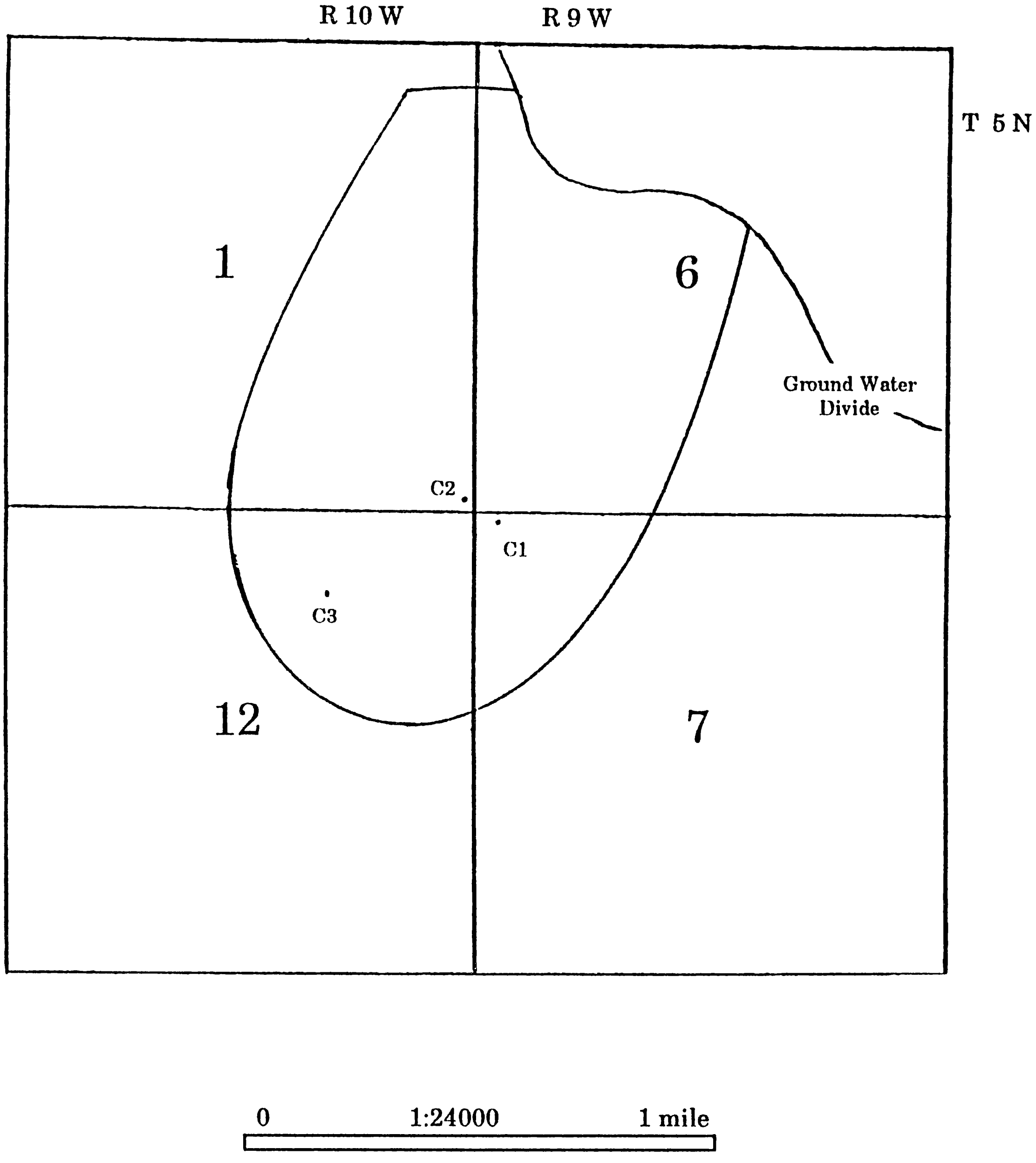


Figure 40. Area of Possible Source Location(s), Third Analysis

pits, depletion of chloride within the unsaturated zone in the vicinity of disposal pits, relocation or discontinued use of injection wells and/or passage of a plume center.

Sulfate concentrations indicate that the Rush Springs contributes 68 to 97 percent of the water produced by C-2, with the Marlow contributing 3 to 32 percent. Isolated occurrences of calcium chloride type water are most likely the result of well acidization and formation-fracing techniques, leakage of acidization waste fluids from disposal pits or saltwater injection wells, and/or gypsum dissolution. Sodium/chloride ratios from area samples tend to be less than 0.50, again indicating oil-field brine as the probable source of contamination.

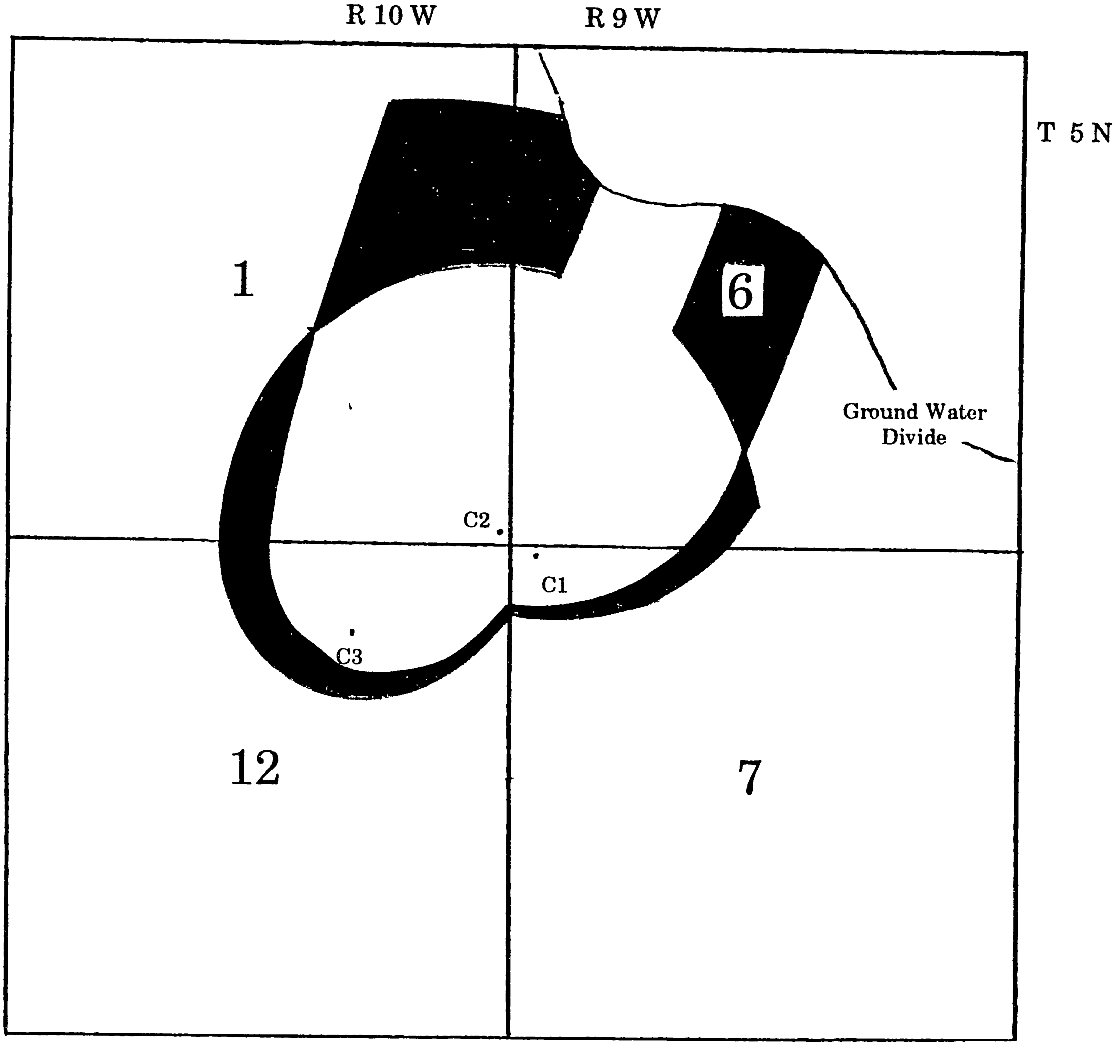
Chloride concentration and specific conductance of cores drilled through abandoned disposal pits also were examined in the final analysis. Comparison of measurements in pits with residual hydrocarbons present and pits where hydrocarbons are absent, suggest that, where present, residual hydrocarbons substantially reduce the rate of leaching of chloride in the unsaturated zone. Residual hydrocarbons tend to form a layer of very low permeability that hinders infiltration. Removal of the hydrocarbon lining would likely result in an increased rate of leaching, which would lead to additional groundwater contamination.

Since contaminants have already been largely leached from the unsaturated zone or are largely immobile because of the residual hydrocarbon layer, abandoned pits are not major sources of contamination at this time. Yet, ground water contamination continues in the area. Chloride concentrations down-gradient of wells known to have purged in the past, are elevated in comparison to chloride concentrations at similar depths up-gradient of the purged wells. This may be a result of plume centers of mass which have not migrated past the monitoring wells. It may also indicate that purging continues at depth, the purging well serving as an ongoing source of contamination. Such measurements would need to be repeated periodically in order to fully support one of these hypotheses.

Comparison Of Results

Results of the first two analyses indicate a potential source area that is similar in size and general shape. Figure 41 shows the areal difference between areas delineated by the two analyses. Although no definite contamination source was established by the initial analysis, operations in the West Cement Oil and Gas Field were suggested. In the second analysis, information provided by literature review strengthens the suggestion sufficiently to warrant the assumption that, indeed, activities within the Cement Oil and Gas Field served as the source of ground-water contamination.

The close resemblance between the predicted areas of probable source location(s) suggests that estimations based on general principles and experience can lead to an understanding of the ground-water situation that is very



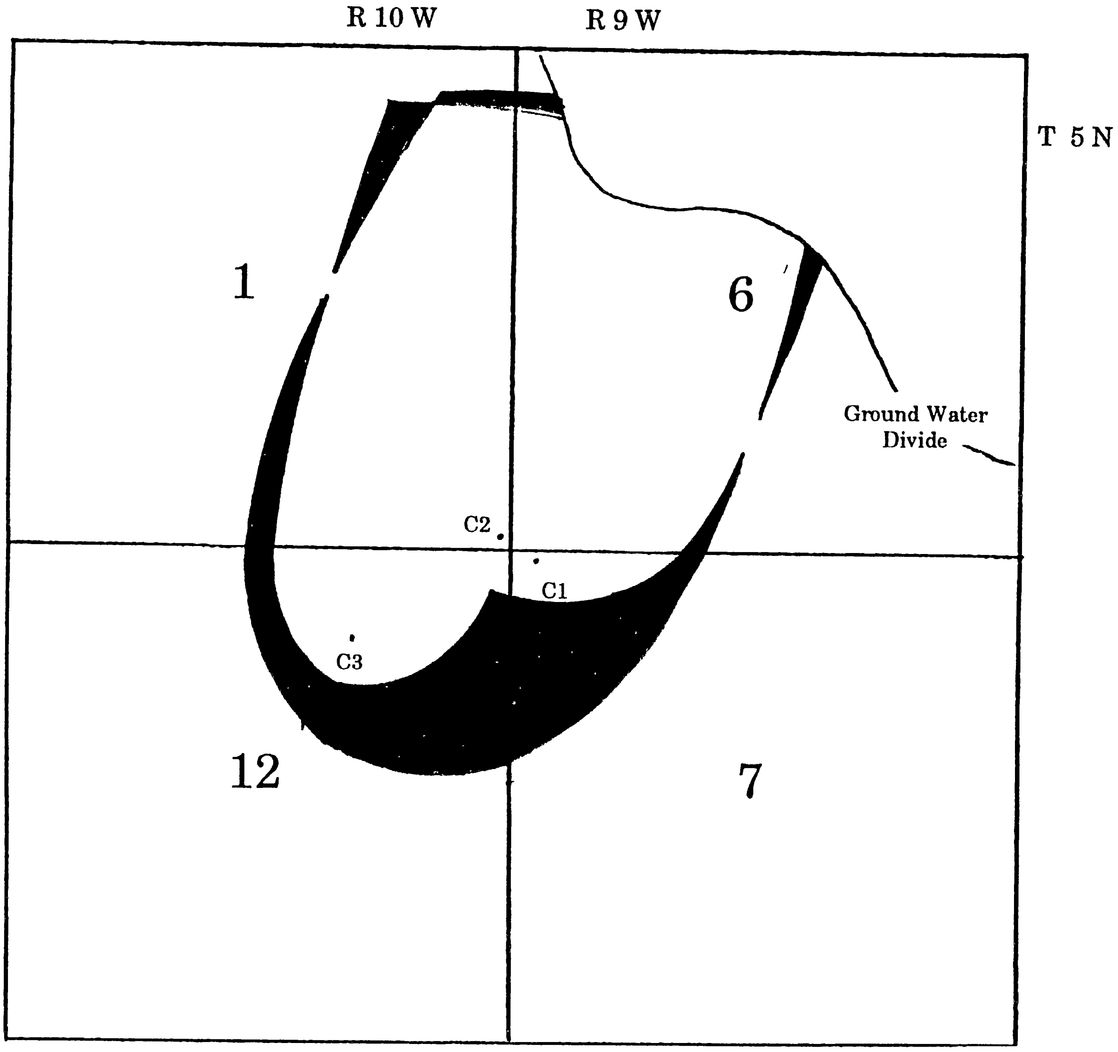
0 1:24000 1 mile

Figure 41. Areal Difference between Analysis 1 and 2 Results

similar to an analysis based on published information, although the time element is vastly reduced in the general approach. While it was not possible to locate a definite contaminant source by either approach, subsequent examination of a potential source area should allow a more precise identification.

In the final analysis, site-specific information indicated water production from two distinct aquifers, the lower being confined. The surficial Rush Springs aquifer was affected only by C-2, while the deeper Marlow aquifer supplied water to C-1 and C-3. A more definite and smaller hydraulic conductivity for the Rush Springs, based on two aquifer tests, indicates the area contributing ground water to C-2 is larger than that calculated by earlier analyses. Similar calculations indicate a large area contributing ground water to C-1 and C-3. The West Cement Oil and Gas Field was treated as the definite source of contamination in this analysis.

The potential area for location of contaminant source(s) indicated by the final analysis is larger than areas indicated by the two prior analyses (fig. 40). The larger size results from the smaller hydraulic conductivity of the Rush Springs aquifer, and water production from two aquifers in the area. Yet the earlier analyses implied areas of possible source locations that are not greatly different, areally, from that indicated by the final, more detailed analysis (fig. 42). The largest difference results from the greater area contributing ground water to the deeper, confined aquifer.



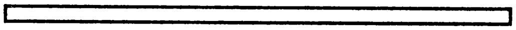


Figure 42. Areal Difference between Analysis 2 and 3 Results

Conclusions

Comparison of results from a series of analyses conducted on the same ground-water contamination situation, each using an increased data base, shows that the amount of information needed is dependant upon the degree of accuracy required. Yet, an analysis based on a very limited data base can provide results that are comparable to an analysis based on detailed information. A basic understanding of area geology and hydrogeology allows an analysis based on estimates derived from only general principles, although experience is certainly an aid. Indeed, an analysis based only on such estimations and limited data provides results which are comparable to the results of an analysis based on published data.

The reason for similar interpretations may be related to the fact that data published in geologic and hydrogeologic reports often are based on limited data from few sites. In the case of hydrogeologic reports, hydraulic characteristics are routinely gathered using available sites, often involving irrigation, municipal, or industrial wells which have a higher than normal yield. Such wells provide values that, in many cases, are the exception rather than the rule, and do not represent widespread conditions. Use of site-specific data for a large area, such as a county, can result in an assessment that is incorrect.

Comparisons indicate that results of a quick and simple analysis may be very similar to the results obtained from a much more complex and expensive analysis which is based on site-specific data. Differences do exist between such analyses, but, at least in the example used in this report, the differences are minor, primarily resulting from the incorporation of data which indicated water production at the site was from two aquifers instead of one. The small differences in interpretation suggest that a fair amount of confidence can be placed in analyses generated from limited amounts of information.

Many situations may demand the collection and use of detailed data. Incongruent data, which cannot be sufficiently explained, may be an indication of a need for more detailed information. Analytical results which are not explainable by basic geologic or hydrogeologic reasoning may also indicate the need for farther testing. While published data may supply some of the explanations in such situations, site-specific data may be necessary for a complete understanding.

The conclusions stated above suggests that, in some cases, a ground water investigation might best be approached in an incremental sense, incorporating additional information sources as required. An investigation of this type would start with an analysis using limited amounts of data and proceed with analysis until the required accuracy of results was achieved. Thus, time-consuming and expensive research and site-specific testing might be avoided. In some situations, a limited data base such as estimations or published information could provide the necessary results. In other cases, a higher degree of accuracy will be required. In such a case, aquifer tests, geochemical analyses, placement and monitoring of additional wells, analysis of well logs, area history and/or other pertinent information may be necessary. Which of these, if any, are needed or desired, must be dictated by the purpose and scope of the project.

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APPENDIX

AQUIFER TEST DATA

AQUIFER TEST DATA

Pumped Well: Wise
Saturated Thickness: 60 feet
Observation Well: W-6
Saturated Thickness: 60 feet
Discharge: 13.5 gpm
Distance: 67.4 feet

	Wise		W-6	
Time (minutes)	drawdown (feet)	corrected drawdown	drawdown (feet)	corrected drawdown
0				
1	0.27	0.27	0.05	0.05
1.5			0.25	0.25
2	9.10	8.41	0.40	0.40
3	9.96	9.88	0.70	0.70
4	10.29	0.20	0.90	0.89
5	11.46	10.37	1.10	1.09
6	11.31	10.24	1.25	1.24
7	11.23	10.17	1.35	1.33
8	11.13	10.10	1.43	1.41
9	11.10	10.07	1.50	1.48
10	10.98	9.98	1.75	1.72
20	10.98	9.98	1.80	1.77
30	11.25	10.24	1.90	1.87
50	11.31	10.24	1.95	1.92
60	11.06	10.04	2.00	1.96
80	11.06	10.04	2.00	1.96
90	11.06	10.04	2.03	2.00
100	11.08	10.06	2.05	2.01
120	11.13	10.09	2.05	2.01
150	11.17	10.13	2.05	2.01
180	11.19	10.15	2.10	2.06
210	11.19	10.15	2.10	2.06
240	11.23	10.18	2.10	2.06

Pumped Well:

Specific Capacity:
T = 1989 gpd/ft
K = 33.2 gpd/ft^2

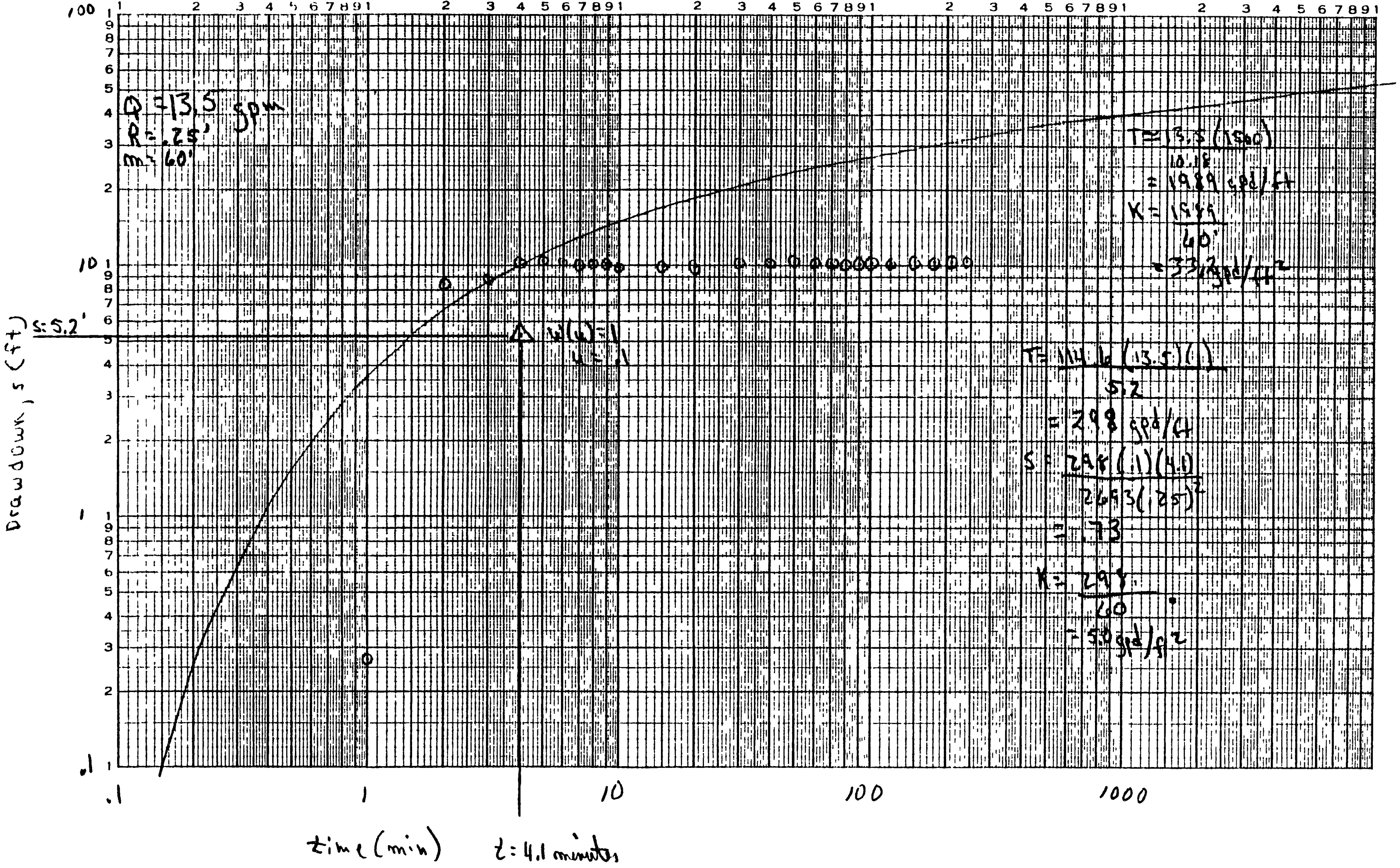
Theis graph
T= 298 gpd/ft
K = 5.0 gpd/ft^2

W-6:

Theis graph:
T = 1758 gpd/ft
K = 29.3 gpd/ft2

Full Logarithmic, 3 x 5

Time v Drawdown (corrected for Water Table) Well: Wise pumped well



Q = 13.5 gpm
R = .25'
m = 60'

T = 13.5 (1500) / 10.18
= 1989 gpd/ft
K = 1989 / 60'
= 33.2 gpd/ft²

T = 114.6 (13.5)(1) / 5.2
= 298 gpd/ft
S = 298 (.1)(4.1) / 2693 (.25)²
= .73
K = 298 / 60
= 5.0 gpd/ft²

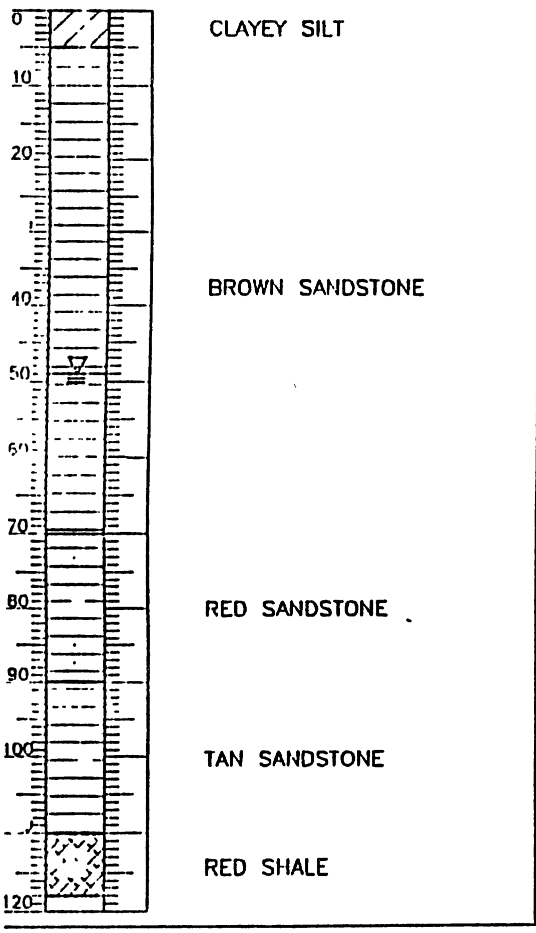
WELL W-PW

PROJECT MOBIL - CYRIL

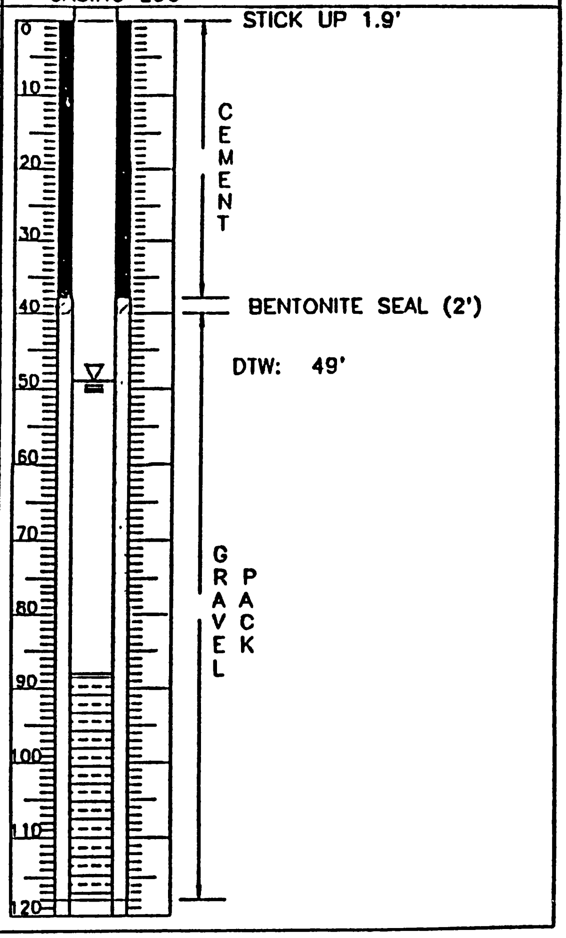
TOP OF CASING ELEVATION 1479.93
BOTTOM OF CASING ELEVATION 1360.3
TOTAL DEPTH 119.6
GROUND ELEVATION 1477.9
TOP OF SCREEN ELEVATION 1390.3
TOTAL LENGTH OF SCREEN 30'

COORDINATES: NORTH 6842.05
EAST 9486.32
CASING DIAMETER 6"
DATE DRILLED APRIL 16, 1991
DRILLED BY EUBANK DRILLING CO.
FAIRVIEW, OK.
LOGGED BY: STREIT

WELL LOG



CASING LOG



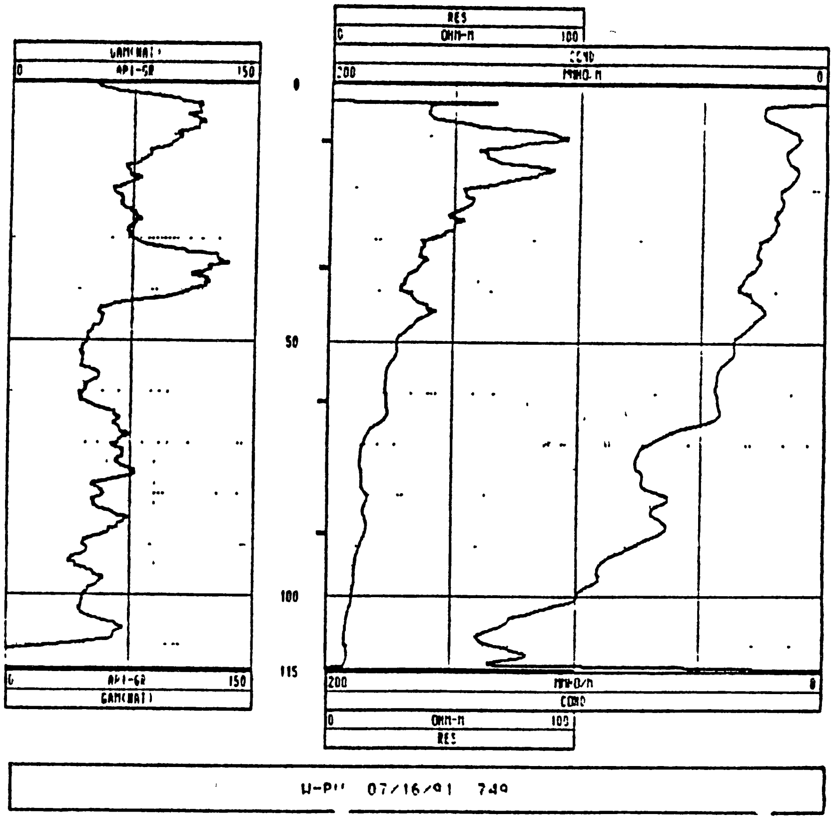
Century

CGC

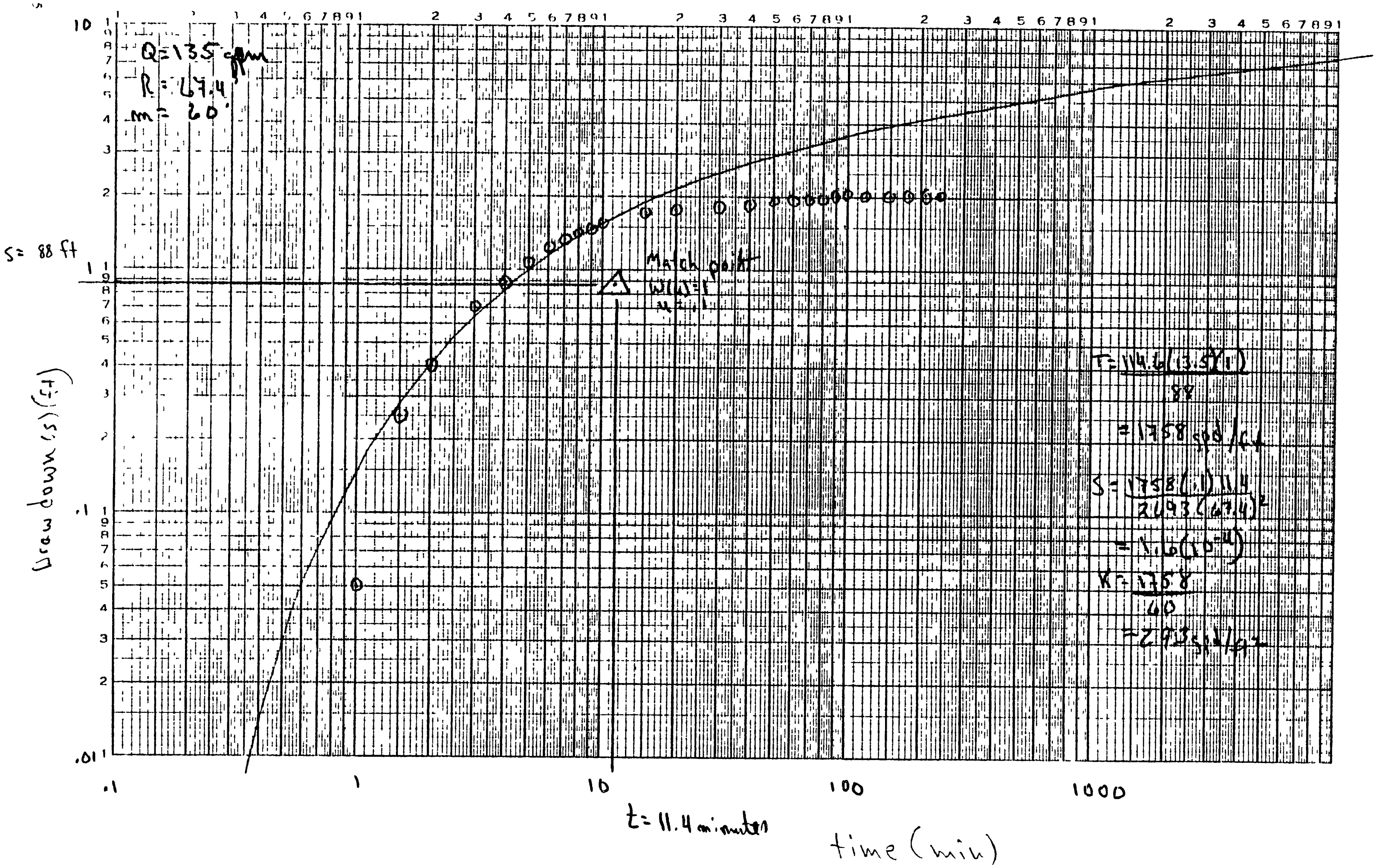
W-PW

COMPANY	: MOBIL OIL - CYRIL			OTHER SERVICES: NONE	
WELL	: W-PW				
LOCATION/FIELD	: CYRIL				
COUNTY	: CADDO				
STATE	: OKLAHOMA				
SECTION	: NA	TOWNSHIP	: NA	RANGE	: NA
DATE	: 07/16/91	PERMANENT DATUM	: GL	ELEVATIONS	
DEPTH DRILLER	: 115	ELEV. PERM. DATUM	: NA	KB	: NA
LOG BOTTOM	: 115.20	LOG MEASURED FROM	: TOC	DF	: NA
LOG TOP	: -1.50	DRL MEASURED FROM	: GL	GL	: NA
CASING DRILLER	: 115	LOGGING UNIT	: 9103		
CASING TYPE	: PVC	FIELD OFFICE	: TULSA		
CASING THICKNESS	: .25	RECORDED BY	: SPOHR		
BIT SIZE	: 2.75	BOREHOLE FLUID	: WATER	FILE	: ORIGINAL
MAGNETIC DECL.	: 8	RM	: 0	TYPE	: 9510A
MATRIX DENSITY	: 2.68	RM TEMPERATURE	: 0	LOG	: 2
FLUID DENSITY	: 1.0	MATRIX DELTA T	: 0	PLOT	: 9510A 0
NEUTRON MATRIX	: SANDSTONE	FLUID DELTA T	: 0	THRESH	: 7500
REMARKS	:				

ALL SERVICES PROVIDED SUBJECT TO STANDARD TERMS AND CONDITIONS


GAM(NAT)
API-GR
0
150
RES
OHM-M
0
100
COND
MMHO/M
200
0
0
50
100
115
W-PII 07/16/91 749

Well: W-6


Ful Logarithmic 3 x 5
Q=135 gpm
R = 67.4'
m = 60'
s= 88 ft
Match point
W(u)=1
1/u=1
t=11.4 minutes
T=114.6(13.5)(1) / 88
=1758 gpd/ft
S=1758(.1)11.4 / 2693(67.4)²
=1.6(10⁻⁴)
K=1758 / 60
=29.3 gpd/ft²
Drawdown (s) (ft)
time (min)
10
1
.1
.01
.1
1
10
100
1000

WELL W-6

PROJECT MOBIL - CYRIL

TOP OF CASING ELEVATION 1479.41

BOTTOM OF CASING ELEVATION 1360.3

TOTAL DEPTH 119.1

GROUND ELEVATION 1477.7

TOP OF SCREEN ELEVATION 1380.3

TOTAL LENGTH OF SCREEN 20'

COORDINATES: NORTH 6845.33

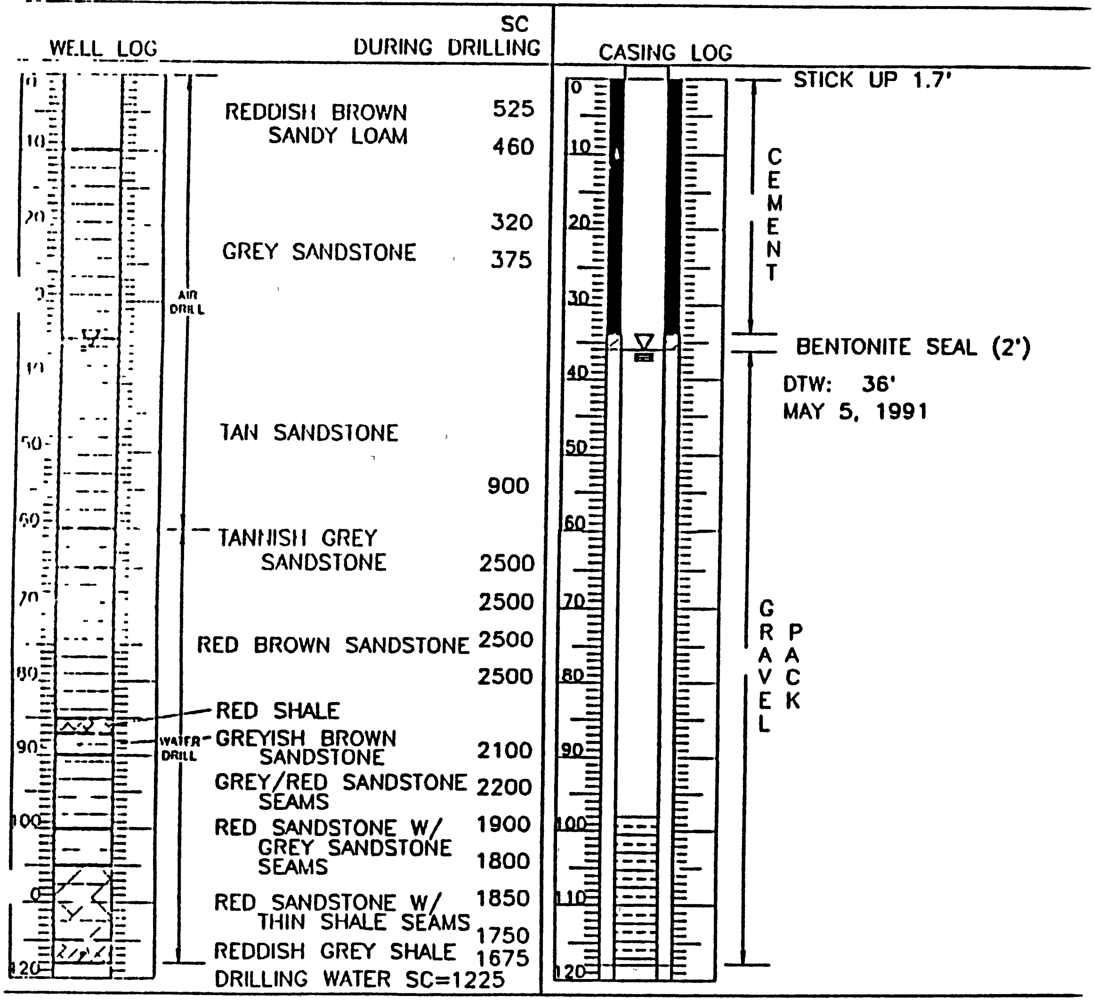
EAST 9425.75

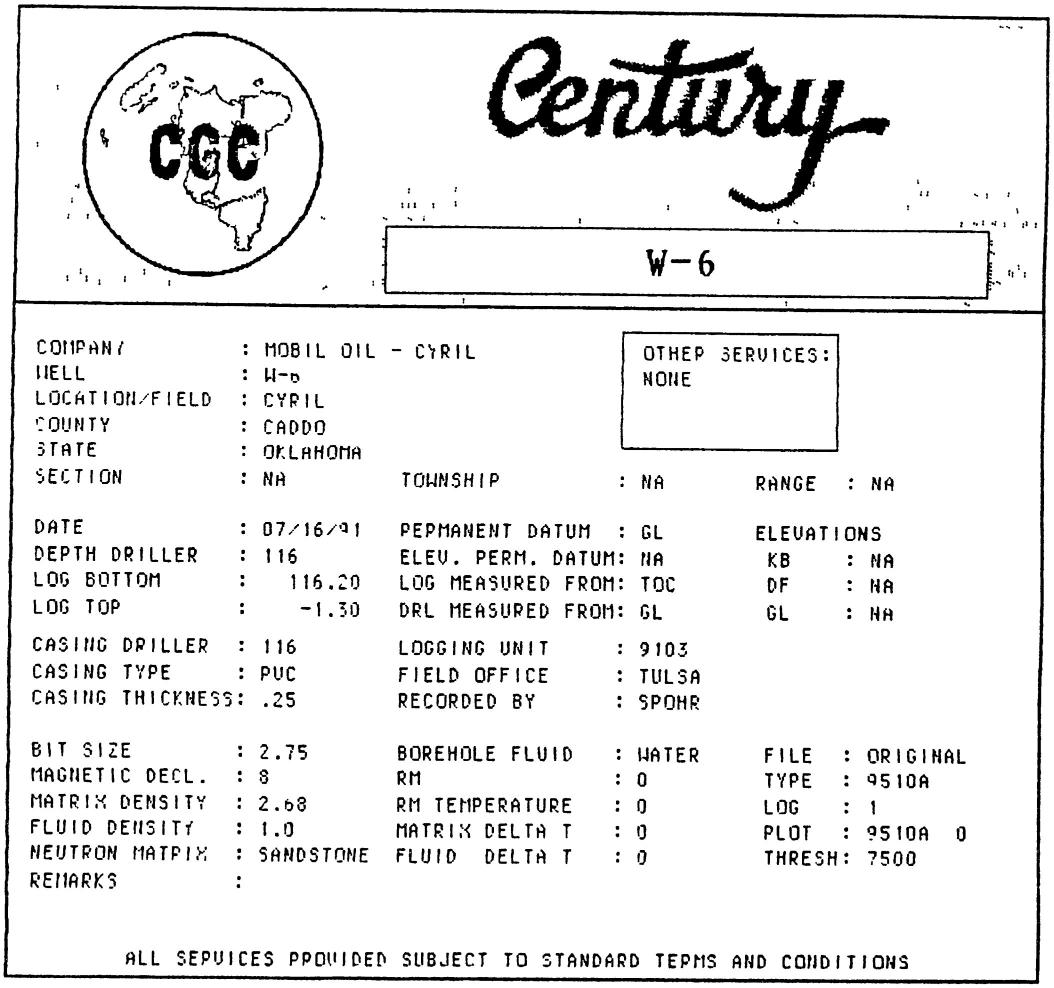
CASING DIAMETER 2"

DATE DRILLED APRIL 2, 1991 (0'-60')
MAY 5, 1991 (60'-113')

DRILLED BY EUBANK DRILLING CO.
FAIRVIEW, OK.

LOGGED BY: STREIT/MAST





CGC

Century

W-6

COMPANY : MOBIL OIL - CYRIL
WELL : W-6
LOCATION/FIELD : CYRIL
COUNTY : CADDO
STATE : OKLAHOMA
SECTION : NA
TOWNSHIP : NA
RANGE : NA

OTHER SERVICES:
NONE

DATE : 07/16/91
DEPTH DRILLER : 116
LOG BOTTOM : 116.20
LOG TOP : -1.30

PERMANENT DATUM : GL
ELEV. PERM. DATUM: NA
LOG MEASURED FROM: TOC
DRL MEASURED FROM: GL

ELEVATIONS
KB : NA
DF : NA
GL : NA

CASING DRILLER : 116
CASING TYPE : PVC
CASING THICKNESS: .25

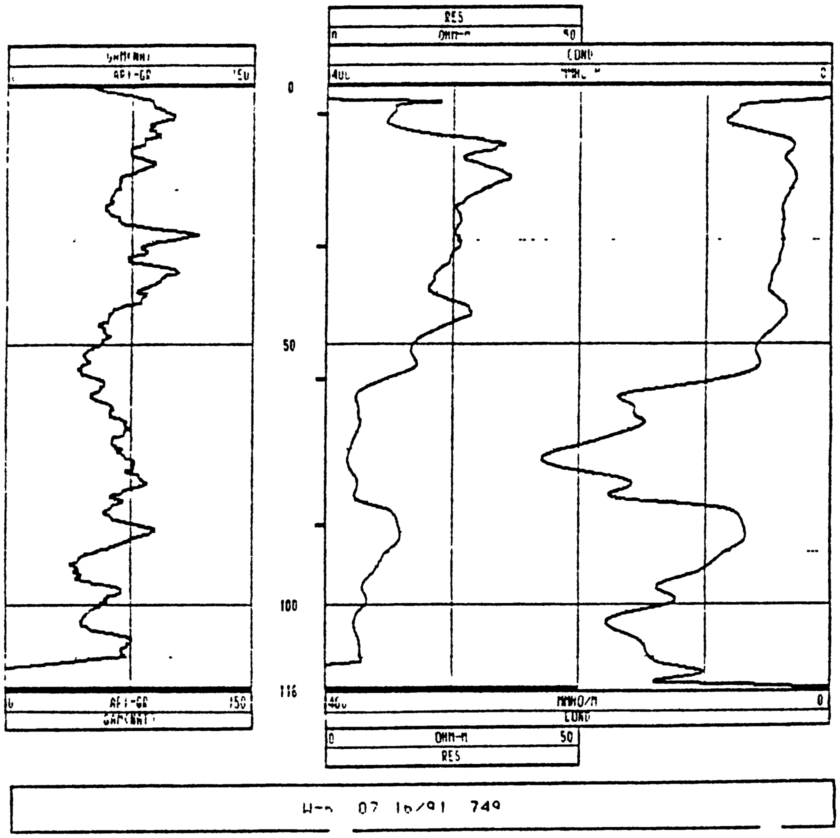
LOGGING UNIT : 9103
FIELD OFFICE : TULSA
RECORDED BY : SPOHR

BIT SIZE : 2.75
MAGNETIC DECL. : 8
MATRIX DENSITY : 2.68
FLUID DENSITY : 1.0
NEUTRON MATRIX : SANDSTONE
REMARKS :

BOREHOLE FLUID : WATER
RM : 0
RM TEMPERATURE : 0
MATRIX DELTA T : 0
FLUID DELTA T : 0

FILE : ORIGINAL
TYPE : 9510A
LOG : 1
PLOT : 9510A 0
THRESH: 7500

ALL SERVICES PROVIDED SUBJECT TO STANDARD TERMS AND CONDITIONS


RES
0 OHM-M 50
GAMMA(NAT)
0 API-GR 150
COND
400 MMHO/M 0
0
50
100
116
0 API-GR 150
GAMMA(NAT)
400 MMHO/M 0
COND
0 OHM-M 50
RES
W-6 07 16/91 749

Pumped Well: Davis 5
Saturated Thickness: 61 feet
Observation Well: D-2
Saturated Thickness: 61 feet
Discharge: 12 gpm
Distance: 60.5 feet

	Davis		D-2	
Time (minutes)	drawdown (feet)	corrected drawdown	drawdown (feet)	corrected drawdown
0				
1	10.98	9.99		
2	15.33	13.40	0.01	0.01
3	8.08	15.40	0.02	0.02
4	19.92	16.67	0.05	0.05
5	21.25	17.55	0.10	0.10
6	22.21	18.17	0.10	0.10
7	23.17	18.77	0.10	0.10
8	23.71	19.10	0.15	0.15
9	24.31	19.47	0.15	0.15
10	24.81	19.76	0.17	0.17
15	27.63	21.37	0.20	0.20
20	30.38	22.81	0.25	0.25
30	34.50	24.74	0.35	0.35
40	39.44	26.69	0.55	0.55
60	40.96	27.21	0.65	0.65
70	42.33	28.04	0.80	0.79
90	44.42	28.25	0.95	0.94
100	45.23	27.46	1.00	0.99
120	46.76	28.84	1.20	1.19
150	50.04	29.52	1.40	1.38
180	52.90	29.96	1.65	1.63
210	54.29	30.13	1.80	1.77
240	54.46	30.15	1.95	1.92

Pumped Well:

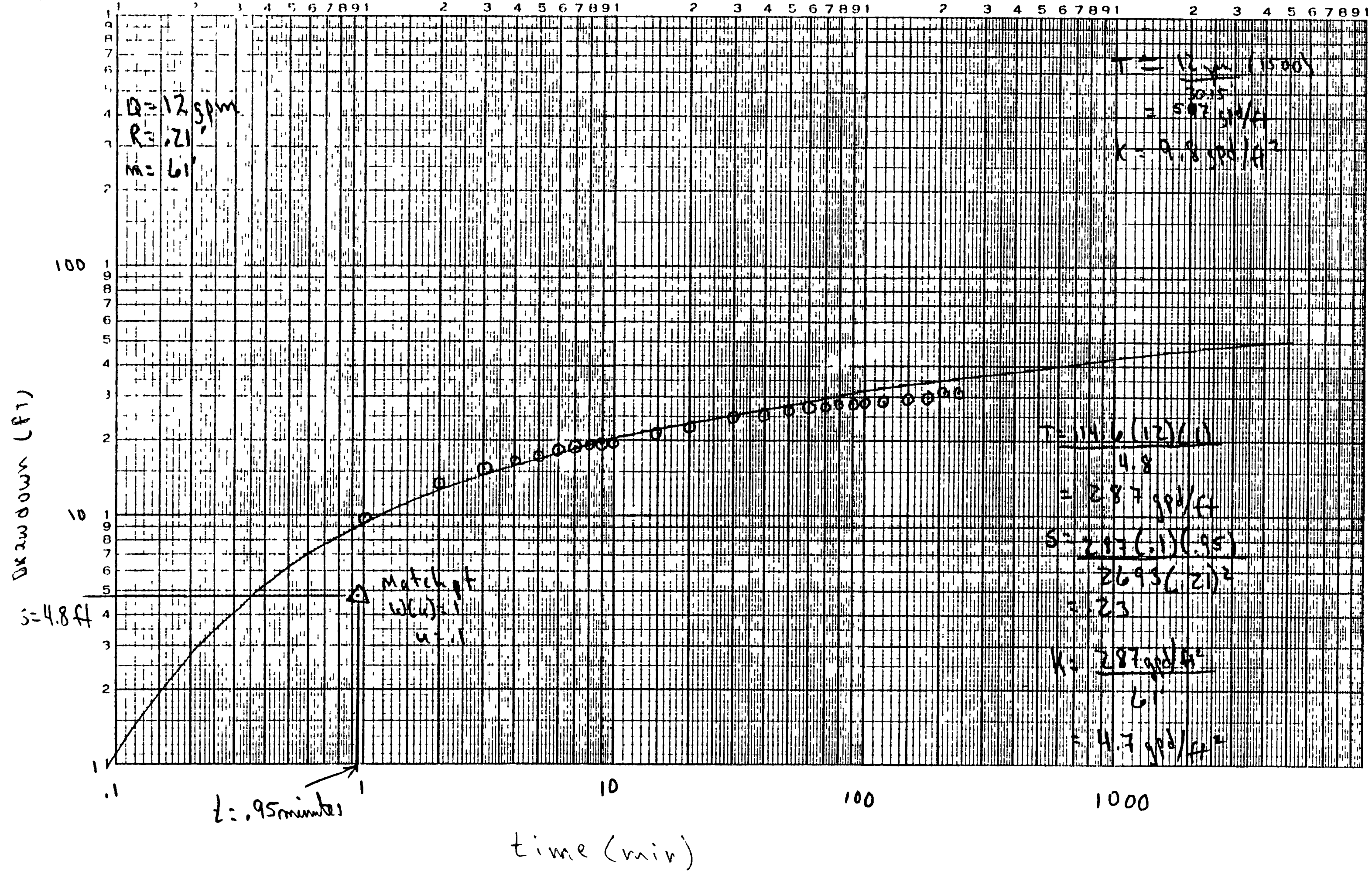
Specific Capacity:
T = 597 gpd/ft
K = 9.8 gpd/ft2

Theis graph:
T = 287 gpd/ft
K = 4.7 gpd/ft2

D-2

Theis graph:
T = 1146 gpd/ft
K = 18.8 gpd/ft2

Time v Draw down
Well: Davis Pumped Well (DSPW)

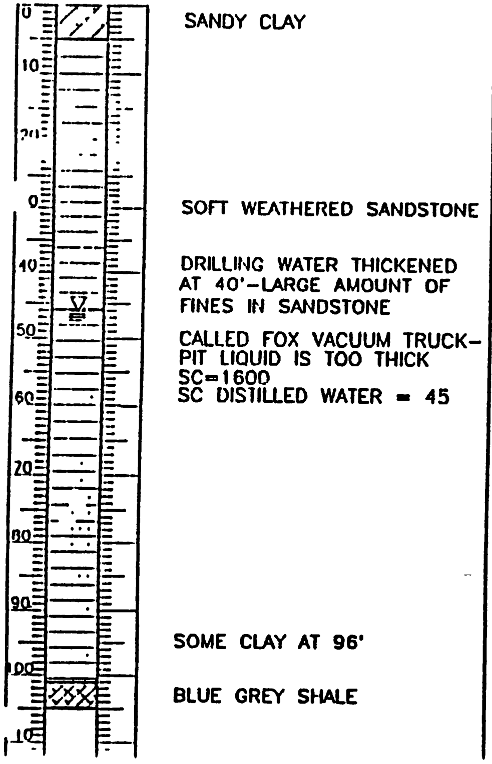


WELL D-5PW

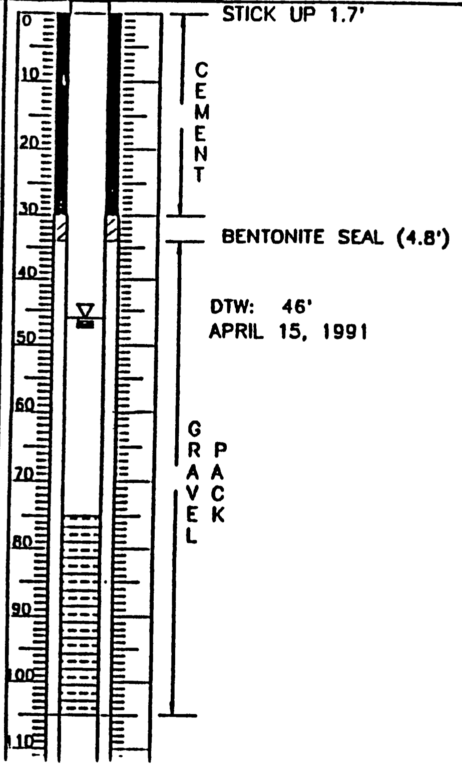
PROJECT MOBIL - CYRIL

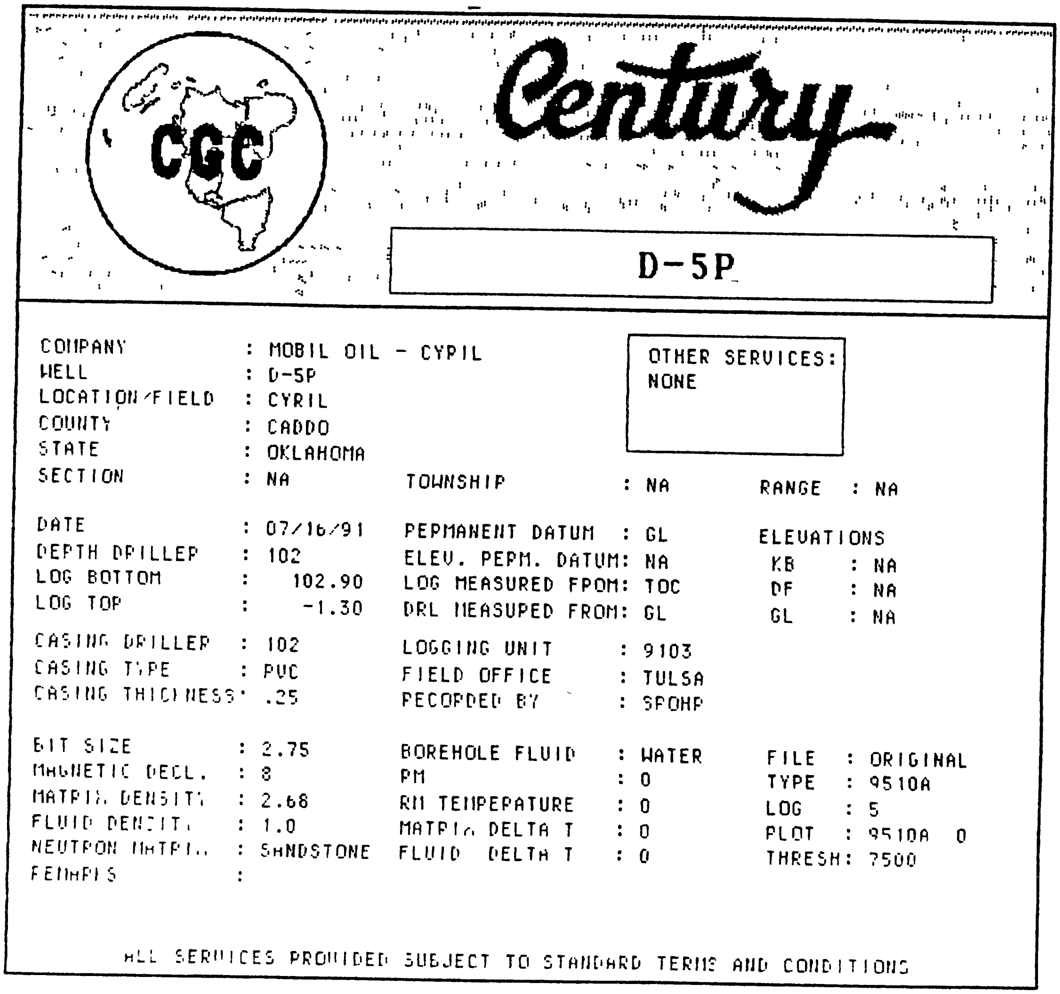
TOP OF CASING ELEVATION	1495.99	COORDINATES: NORTH	8170.40
BOTTOM OF CASING ELEVATION	1389.9	EAST	10,603.74
TOTAL DEPTH	106.1	CASING DIAMETER	5"
GROUND ELEVATION	1494.3	DATE DRILLED	APRIL 15, 1991
TOP OF SCREEN ELEVATION	1419.9	DRILLED BY	EUBANK DRILLING CO. FAIRVIEW, OK.
TOTAL LENGTH OF SCREEN	30'	LOGGED BY:	STREIT

WELL LOG



CASING LOG





Century

D-5P

COMPANY : MOBIL OIL - CYRIL
WELL : D-5P
LOCATION/FIELD : CYRIL
COUNTY : CADDO
STATE : OKLAHOMA
SECTION : NA
TOWNSHIP : NA
RANGE : NA

OTHER SERVICES:
NONE

DATE : 07/16/91
DEPTH DRILLER : 102
LOG BOTTOM : 102.90
LOG TOP : -1.30
PERMANENT DATUM : GL
ELEV. PERM. DATUM: NA
LOG MEASURED FROM: TOC
DRL MEASURED FROM: GL

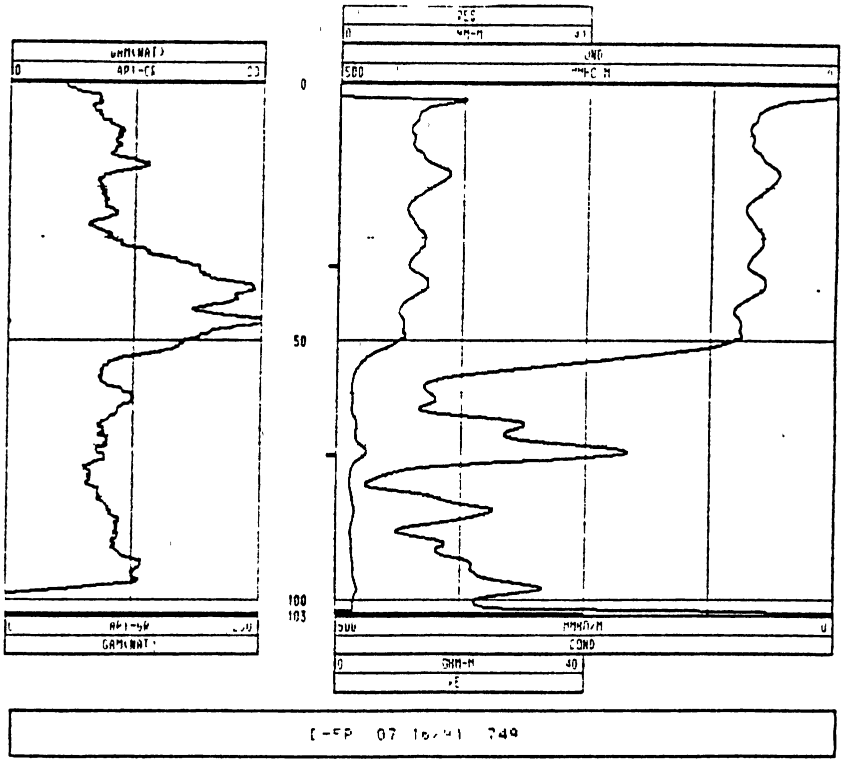
ELEVATIONS
KB : NA
DF : NA
GL : NA

CASING DRILLER : 102
CASING TYPE : PVC
CASING THICKNESS: .25
LOGGING UNIT : 9103
FIELD OFFICE : TULSA
RECORDED BY : SPOHR

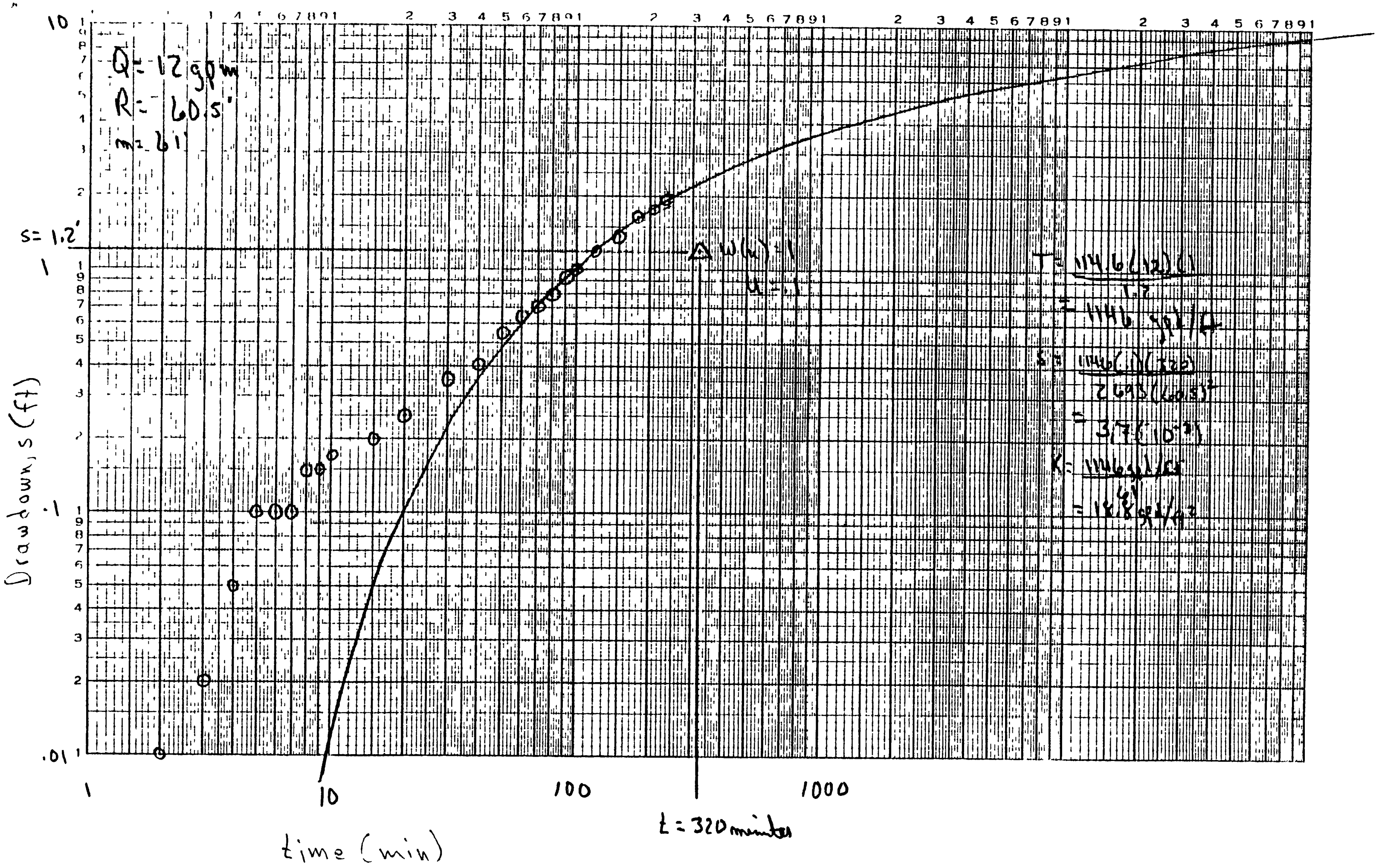
BIT SIZE : 2.75
MAGNETIC DECL. : 8
MATRIX DENSITY : 2.68
FLUID DENSITY : 1.0
NEUTRON MATRIX : SANDSTONE
REMARKS :
BOREHOLE FLUID : WATER
RM : 0
RM TEMPERATURE : 0
MATRIX DELTA T : 0
FLUID DELTA T : 0

FILE : ORIGINAL
TYPE : 9510A
LOG : 5
PLOT : 9510A 0
THRESH: 7500

ALL SERVICES PROVIDED SUBJECT TO STANDARD TERMS AND CONDITIONS


GAM(NAT)
0
API-GR
RES
0
OHM-M
40
COND
500
MMHO/M
0
0
50
100
103
API-GR
GAM(NAT)
500
MMHO/M
0
COND
0
OHM-M
40
RE
E-FP 07 16/91 749

Well D-2



$T = \frac{114.6(12)(1)}{1.2}$

$= 1146 \text{ gpd/ft}$

$S = \frac{1146(.1)(320)}{2693(60.5)^2}$

$= 3.7(10^{-3})$

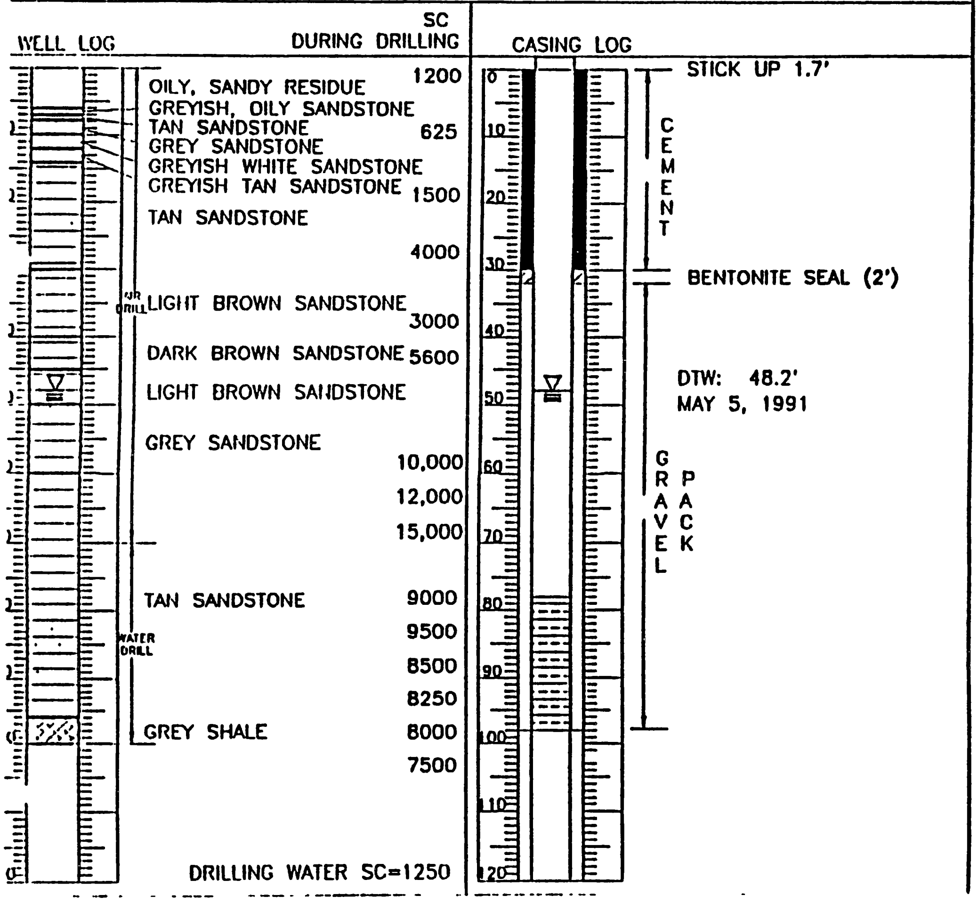
$K = \frac{1146 \text{ gpd/ft}}{61'}$

$= 18.8 \text{ gpd/ft}^2$

WELL D-2

PROJECT MOBIL – CYRIL

TOP OF CASING ELEVATION	1497.78	COORDINATES: NORTH	8824.08
BOTTOM OF CASING ELEVATION	1398.0	EAST	10,632.13
TOTAL DEPTH	99.8	CASING DIAMETER	2"
GROUND ELEVATION	1496.1	DATE DRILLED	APRIL 1, 1991 (0'-70') APRIL 4, 1991 (70'-98')
TOP OF SCREEN ELEVATION	1418.0	DRILLED BY	EUBANK DRILLING CO. FAIRVIEW, OK.
TOTAL LENGTH OF SCREEN	20'	LOGGED BY:	STREIT/MAST

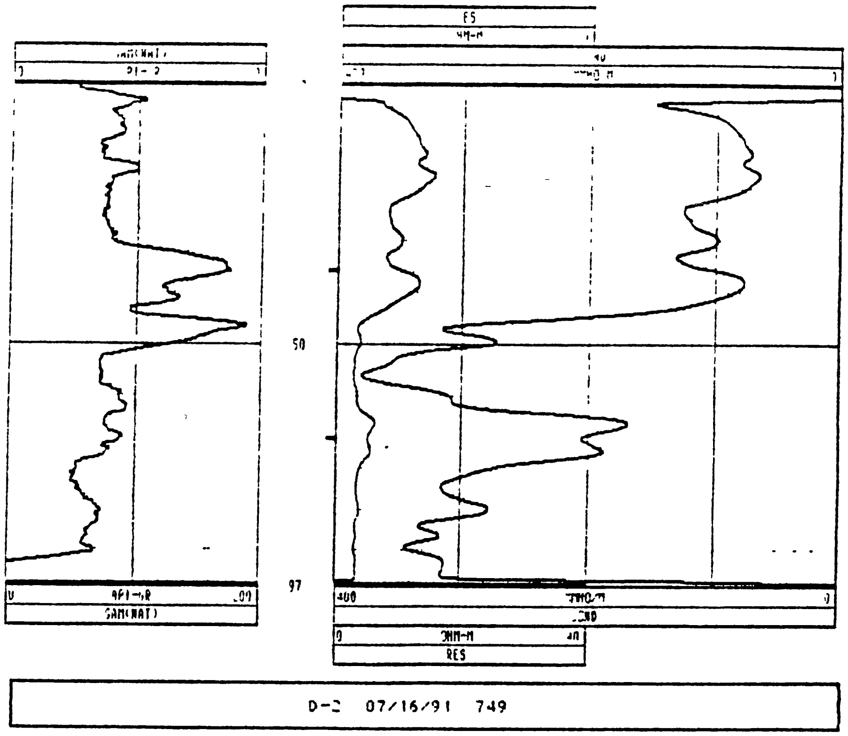


Century

D-2

COMPANY	: MOBIL OIL - CYRIL			OTHER SERVICES: NONE	
WELL	: D-2				
LOCATION/FIELD	: CYRIL				
COUNTY	: CADDO				
STATE	: OKLAHOMA				
SECTION	: NA	TOWNSHIP	: NA	RANGE	: NA
DATE	: 07/16/91	PERMANENT DATUM	: GL	ELEVATIONS	
DEPTH DRILLER	: 96	ELEV. PERM. DATUM	: NA	KB	: NA
LOG BOTTOM	: 96.70	LOG MEASURED FROM	: TOC	DF	: NA
LOG TOP	: -1.30	DRL MEASURED FROM	: GL	GL	: NA
CASING DRILLER	: 96	LOGGING UNIT	: 9103		
CASING TYPE	: PVC	FIELD OFFICE	: TULSA		
CASING THICKNESS	: .25	RECORDED BY	: SPOHR		
BIT SIZE	: 2.75	BOREHOLE FLUID	: WATER	FILE	: ORIGINAL
MAGNETIC DECL.	: 8	RM	: 0	TYPE	: 9510A
MATRIX DENSITY	: 2.68	RM TEMPERATURE	: 0	LOG	: 4
FLUID DENSITY	: 1.0	MATRIX DELTA T	: 0	PLOT	: 9510A 0
NEUTRON MATRIX	: SANDSTONE	FLUID DELTA T	: 0	THRESH	: 7500
REMARKS	:				

ALL SERVICES PROVIDED SUBJECT TO STANDARD TERMS AND CONDITIONS


ES
50
97
0
API-GR
200
GAM(NAT)
400
MMHO/M
0
COND
0
OHM-M
40
RES
D-2 07/16/91 749

AVERAGE VALUES

Transmissivity, gpd/fT

597
287
1146
1989 mean T = 1012.5 = 1013 gpd/ft
298
1758

total= 6075

Hydraulic Conductivity, gpd/ft2

9.8
4.7
18.8
33.2 mean K = 16.8 = 17 gpd/ft2
5.0
29.3

total= 100.8

Storativity

0.73
0.00016
0.23 mean S = 0.240965 = 0.24
0.0037

total= 0.96386

VITA

Leonard A. Powell

Candidate for the Degree of

Master of Science

Thesis: COMPARISON OF SEQUENTIAL ANALYSES GENERATED FROM AN ENLARGING DATA BASE. A CASE STUDY IN GROUND WATER CONTAMINATION.

Major Field: Geology

Biographical:

Personal Data: Born in Many, Louisiana, December 28, 1962 son of Monroe and Netha Powell.

Education: Graduated from Florien High School, Florien Louisiana, in May 1980; received Associate Degree in Chemical Technology from Northwestern State University, Natchitoches, Louisiana in May 1983; received Bachelor of Arts Degree in Anthropology from Northwestern State University, Natchitiches, Louisana in May 1987; received Bachelor of Science Degree in Geology from Northwestern State University, Natchitoches, Louisana in July 1987; completed requirements for Master of Science Degree in Geology at Oklahoma State University, Stillwater, Oklahoma in May, 1992.

Professional Experience: Teaching Assistant, “Practical Approaches to Ground-Water Hydrology and Contamination,” 1990-1991; Teaching Assistant, School of Geology 1989-1991.

Professional Affiliations: National Ground Water Association; Association of Groundwater Scientists and Engineers