STUDY AND ANALYSIS OF REGIONAL AND SITE GEOLOGY RELATED TO SUBSURFACE SALT DISSOLUTION SOURCE OF BRINE CONTAMINATION IN CANADIAN RIVER AND LAKE MEREDITH, NEW MEXICO - TEXAS

AND FEASIBILITY OF ALLEVIATION OR CONTROL

Final Report

HYDRO GEO CHEM, INC.

Groundwater Consultants

ERRATA SHEET
FOR
FINAL REPORT
ENTITLED
STUDY AND ANALYSIS OF REGIONAL AND SITE GEOLOGY RELATED TO SUBSURFACE SALT DISSOLUTION SOURCE OF BRINE CONTAMINATION IN CANADIAN RIVER AND LAKE MEREDITH, NEW MEXICO-TEXAS AND FEASIBILITY OF ALLEVIATION OR CONTROL

CONTRACT NO. 3-CS-50-01580

Upon examination of the final report submitted to the Bureau of Reclamation (Reclamation) by Hydro-Chem, Inc., Reclamation lists the following changes:

Page 18 — In the eighth line of the last paragraph, change "50" to "60."

Page 52 — In the fourth line of the last paragraph, change "80" to "100-150."

In the fifth line of the last paragraph, change "3650 feet" to "3674 feet elevation."

Page 53 — In the fifth line of the second paragraph, change "1000" to "2500."

STUDY AND ANALYSIS OF REGIONAL AND SITE GEOLOGY RELATED TO SUBSURFACE SALT DISSOLUTION SOURCE OF BRINE CONTAMINATION IN CANADIAN RIVER AND LAKE MEREDITH, NEW MEXICO - TEXAS

AND FEASIBILITY OF ALLEVIATION OR CONTROL

Final Report

Contract No. 3-CS-50-01580

Submitted to

U.S. Bureau of Reclamation
714 South Tyler
Amarillo, Texas 79101

Submitted by

Hydro Geo Chem, Inc.
1430 North Sixth Avenue
Tucson, Arizona 85705

1 May 1984

LAKE MEREDITH SALINITY STUDY

<u>CONTENTS</u> Page

EXECUTIVE SUMMARY. i

Conclusions ii
Recommendations vi

1. INTRODUCTION 1

Purpose and Scope of Investigation 1
Review of Previous Investigations 3
Exploration Studies 4
Reconnaissance Studies 5
Dam-Site Investigations 6
Waste Repository Studies 6
Salinity Studies 7

2. GEOLOGY OF THE STUDY AREA 9

Introduction 9
Stratigraphy 13
Paleozoic Section 13
Triassic and Younger Sediments 17
Geologic History 19
Subsurface Analysis 21
Salt Occurrence 23
Salt Dissolution 30
Surficial Expression of Subsidence Features 35
Structure Mapping in Detailed Study Area 38
Fracture Mapping 40

3. HYDROLOGY AND GEOCHEMISTRY OF THE STUDY AREA 44

Permian-Triassic Groundwater System 44
Permian Groundwater Flow. 44
Triassic Groundwater Flow 49
Shallow Brine Aquifer 52
Canadian River Hydrology. 54
Channel Deposits. 54
Surface-Water Flow. 56
Chemistry of Groundwater - Surface Water System . . . 65
Chemistry of Permian Water. 65
Chemistry of Triassic Water 69
Shallow Brine Aquifer Chemistry 72

Contents - Continued

Page

Chemistry of Water in the Channel Deposits. . . . 72
Surface-Water Chemistry 78
Ute Reservoir. 78
River Water. 78
Lake Meredith. 85
Chemical and Isotopic Determination of Salinity Sources 87
Salinity Sources. 87
Groundwater Mixing. 92
Lake Meredith Water and Salt Budget 95
Water Budget. 96
Salt Budget 98
Prediction of Long-Term Salinity Levels in Lake Meredith. 102

4. FEASIBILITY OF SALINITY CONTROL 104

Methods of Salinity Control 104
Depressurization Wells. 105
Channel Wells 106
Time Effects of Salinity Reduction. 107
Model Description 108
Model Inputs and Calibration. 112
Model Prediction. 114
Model Sensitivity 120
Conclusions Based on Model Simulations. 121
Feasibility of Deep-Well Injection. 124
Hydraulic Characteristics 124
Conflicts With Other Economic Uses. 126
Recommendations 127

REFERENCES 129

APPENDIX A. Water Level Measurements 133

APPENDIX B. Water Quality Analyses 142

APPENDIX C. Water Budget Tables. 173

FIGURES

FIGURES		Page
1.	Location of detailed and general study areas	2
2.	Location of wells listed in Table I.	11
3.	Structural elements in the vicinity of the study area	12
4.	Stratigraphic column	14
5.	Limits of salt dissolution in the vicinity of the study area	24
6.	Isopach map of combined Abo-Sangre de Cristo Formations	25
7.	Structure contour map of Pre-cambrian surface.	27
8.	Isopach map of San Andres	28
9.	Isopach map of the Artesia Formation	29
10.	Structure contour map of San Andres Formation	31
11.	Structure contour map of Artesia Formation	32
12.	Map showing locations of cross-sections	33
13.	East-West geologic section	34
14.	North-South geologic section through Ute Reservoir	36
15.	North-South geologic section through Canadian River	37
16.	Map showing structural features in the detailed study area	39
17	Aerial view of collapse structure (section 2 of T.13N., R.34E)	41
18.	Rotated blocks of Triassic sediment in collapse structure of Figure 17	41
19.	Aerial view of a strongly defined fracture pattern located south of the Canadian River.	41
20.	Location map of wells and measuring points in detailed study area	45

Figures-Continued

		Page
21.	Location map of wells and measuring points in general study area	46
22.	Triassic water-level surface within detailed study area	50
23.	Average yearly flow in Canadian River at Logan, 1927-1981	57
24.	Flow-duration curve for Canadian River at Logan	58
25.	Flow-duration curve for Revuelto Creek	58
26.	Flow-duration curve for Canadian River at state line . .	58
27.	Flow-duration curve for Canadian River at Tascosa . . .	61
28.	Flow-duration curve for Canadian River at Amarillo . . .	61
29.	Average yearly flow in Canadian River at Amarillo, 1939-1981	62
30.	Stiff diagrams of Permian water near recharge area . . .	66
31.	Stiff diagrams of Permian water near study area	68
32.	Stiff diagrams of Triassic water	71
33.	Stiff diagrams of shallow brine aquifer water.	73
34.	Stiff diagrams of water from wells in channel deposits	74
35.	Ranges of chloride concentrations in water from wells in channel deposits	76
36.	Ranges of chloride concentrations in CRMWA piezometers	77
37.	TDS and chloride in river water, October, 1983	79
38.	TDS, chlorides and specific conductance in river water, January, 1984	79
39.	TDS, chlorides and specific conductance in river water, February, 1984.	79
40.	Chloride load and mean flow for Canadian River at Tascosa	83

Figures-Continued

		Page
41.	Chloride load and mean flow for Canadian River at Amarillo	84
42.	Chloride measurements in Lake Meredith	86
43.	Bromide/chloride ratios of surface and groundwater	88
44.	Sodium/chloride ratios of surface and grounwater	90
45.	Stable isotopic distributions	91
46.	Calculated chloride concentration in Lake Meredith	100
47.	Mixing cell model structure	110
48.	Steady state model results	115
49.	Predicted salinity reduction for 100 percent brine reduction	116
50.	Predicted salinity reduction for 50 percent brine reduction	118
51.	Predicted reduction in salinity from channel pumping wells	119
52.	Results of sensitivity to transfer coefficients	122

TABLES Page

1. Log availability from exploration wells in New Mexico. . 10

2. Formation tops from logs of exploration wells in New Mexico. 22

3. Flow-measurement stations in study area. 59

4. Summary of Correlations between Canadian River flow at Amarillo and at various upstream stations. 64

5. Summary of gains in Canadian River flow between Ute Dam and Lake Meredith. 64

6. Summary of chemical characteristics of 23 samples of Triassic groundwater in the study area 70

7. Average chemical characteristics of Canadian River water. 81

8. Average (1969 to 1982) monthly water and salt budget parameters used to predict long-term chloride concentrations 103

A.1. Water levels in wells within New Mexico portion of study area 134

B.1. Selected water-quality analyses of Canadian River and groundwater within and near study area. 143

B.2. Results of water quality determinations, Canadian River water between Ute Dam and Revuelto Creek, Oct. 19 and 20, 1983 151

B.3. Results of water quality determinations, Canadian River water between Ute Dam and Dunes damsite, Jan. 4 and 5, 1984 152

B.4. Results of water quality determinations, Canadian River water between Ute Dam and Revuelto Creek, Jan. 31 and Feb. 1, 1984 155

B.5. Results of water-quality and isotopic analyses from samples collected this study 156

C.1. Monthly water-budget results for Lake Meredith 174

STUDY AND ANALYSIS OF REGIONAL AND SITE GEOLOGY RELATED TO SUBSURFACE SALT DISSOLUTION SOURCE OF BRINE CONTAMINATION IN CANADIAN RIVER AND LAKE MEREDITH AND FEASIBILITY OF ALLEVIATION OR CONTROL NEW MEXICO - TEXAS

EXECUTIVE SUMMARY

The purpose of this study is to identify the geologic and hydrologic controls on the occurrence of brine inflow to the Canadian River below Ute Dam. In addition, the feasibility of brine control, and the long-term effects on Lake Meredith had to be determined.

The occurrence of salt in the subsurface was determined through analysis of well logs and other published information. Isopach and structure-contour maps were drawn for the area, and geologic cross-sections identifying known salt layers were prepared. Field geologic studies concentrated on structure mapping to determine whether surface features could be correlated both with subsurface dissolution and the occurrence of brine.

Hydrologic studies concentrated on the Permian and Triassic formations and the Canadian River. All available flow, chemistry and hydraulic data were collected and analyzed. In addition, several water-quality surveys were conducted within the areas of suspected brine inflow. Water and salt-budgets for Lake Meredith were computed, and this analysis was extended into the future to predict long-term chloride, TDS, and sulfate concentrations in Lake Meredith.

Methods for controlling the brine at its source were evaluated. The feasi-

bility and degree of success of each method was tested using a mathematical model that combines the flow of water and the transport of salt in both the channel sediments and in the Canadian River. Two control measures were assessed. The first considered the direct extraction of brine rrom the river channel sediments. The second considered the effect of depressurizing the brine aquifer. A comparison of the control measures was then done based upon the numerical model.

Finally, the suitability of the region for deep well disposal of the brines was assessed. Locations for geophysical surveys were suggested, as well as requirements for deep-well testing.

CONCLUSIONS

The course of the Canadian River downstream of Ute Dam is coincident with, and probably controlled by, the northern (updip) edge of Permian salt dissolution. The dissolution zones are seen on the surface as subtle trends of flexures and collapse features. Subsurface mapping revealed the presence of large quantities of naturally occurring salt beneath the study area. The Permian units were deposited over a local structural high beneath Ute Reservoir. Localized salt dissolution underneath the reservoir has occurred and appears to have been strongly influenced by the structural high that exists in the Precambrian basement rock. The section beneath the reservoir has been especially prone to salt dissolution and related collapse as shown from isopach and structure mapping of the Paleozoic units.

Detailed structure mapping did not reveal displacive faulting of the Triassic sediments; however, evidence of collapse was found along the course of the river. A very strong northeast trending fracture set was found throughout the area and appears to have influenced the direction of the river. Most of the flexures also trend northeast, suggesting that the folding is associated with subsurface dissolution along the updip limits of the salt-bearing formations. The subparallel nature of the dissolution front, regional fracture patterns, and flexures suggests that the dissolution of salt has been the major control upon the geologic structure in this region.

A shallow brine aquifer identified in previous studies leaks upward into the channel sediments below Ute Dam. The source of the brines is natural, and has existed prior to the construct..on of Ute Dam. The Dam has apparently had little effect on brine flow. The brine enters the channel in two and possibly three areas. These are 1) about one-half mile below Ute Dam, 2) about 3 miles below the dam at the railroad bridge, and 3) possibly in an area one-half mile upstream of the Revuelto Creek confluence. Based on salt-load calculations in the river, and supported by other geochemical and isotopic arguments, approximately 0.6 cfs of deep Permian brine leaks upward into the shallow brine aquifer. Water in this aquifer is a mixture of Permian brines and fresh Triassic water. Approximately 0.9 cfs of this saline water leaks upward into the channel sediment.

River water salt loads, as measured at four locations, indicate that about 70 percent of the salt entering Lake Meredith comes from the New Mexico side of the Canadian River. Most of this salt originates from brine inflow to the channel below Ute Dam. An additional 10 to 15 percent of the salt enters the channel between the Tascosa and Amarillo gages, which may account for the observation of saline water in a deep channel piezometer at the Amarillo gage. The movement of salt down the Canadian River channel is a dynamic process, mostly occurring during high flows when the channel sediments are flushed. At low flows the channel sediments store and retain the salt inflow because the rate of groundwater salt transport is extremely slow in comparison to transport by the river water.

A water budget constructed for Lake Meredith shows that flow in the Canadian River is strongly affected by groundwater losses and bank storage. This was determined by considering flows measured at the Amarillo gage, reservoir diversions, and changes in the reservoir storage, evaporation and precipitation. The reservoir salt budget confirmed that these flow terms were mostly accurate and complete. The salt budget also showed that the chemistry as measured at the Amarillo gage and at the Sanford Dam intake resulted in a correct prediction of Lake Meredith water quality. When the salt and water balances were extended into the future, using average flow and quality parameters and assuming that the lake was maintained at its present volume, the steady-state chloride level in the lake would be 400 milligrams per liter, about 1,500 milligrams per liter for TDS, and 350 milligrams per liter for sulfate.

Two methods of salinity control were considered: the first utilizes a shallow artesian aquifer depressurization well, and the second utilizes dewatering wells in the stream channel sediments placed close to suspected areas of brine inflow. The principle advantage of the first method may be that only one well need be drilled to effectively drop the hydraulic head below river level. Its disadvantages are high initial cost, possibly very high required pumping rates, and a slow depletion of salt in the river channel sediments. The advantages of dewatering wells in the channel deposits are low cost per well, low pumping rates and a more rapid depletion of salt. Disadvantages are that several wells and special flood protection may be required, and piping costs would be greater.

Currently, brine disposal is envisioned to be into a deep disposal well, completed in the Sangre de Cristo, Abo, or equivalent formation, near the Canadian River channel. The actual disposal of the brine appears to be the greatest problem facing any sort of alleviation program. Information on these deep formations in the area is insufficient to judge whether a suitable disposal horizon exists. Further geophysical and hydrologic studies planned by the Bureau of Reclamation should help determine if a suitable injection horizon exists.

RECOMMENDATIONS

The determination of whether aquifer depressurization or channel pumping is the most efficient method for removing brines from the Canadian River is not clear. Simulations of both methods showed results that were similar. However, because the depressurization pumping rate could not be determined, there is much uncertainty in evaluating the results.

Because of the uncertainty in location, number of wells, and pumping rates that must be maintained, the direct removal of brines by pumping in the channel deposits offers more advantages than shallow artesian aquifer depressurization. The question of the number and type of wells required must be studied more thoroughly. The hydraulic characteristics of the channel deposits, especially hydraulic conductivity and specific yield, must be better determined. We recommend that several drive-point wells be installed in the channel below Ute Dam, and that pumping or injection interference tests be run. Several sediment cores should be taken and used for column permeability tests. With this information a simple numerical model of the channel aquifer could be calibrated and the number, spacing, and pumping rates determined.

The evaluation of the shallow brine aquifer should continue. However, we do not believe that another aquifer test should be conducted at TW-1 because of the uncertain well construction. Instead, another well should be drilled, perhaps in concert with a deep test well, and tested in the shallow brine aquifer.

The amount of piping required for brine disposal would depend on the number of wells, the method of disposal, and location of the disposal area. We recommend that the suitability of deep-well disposal in the Logan area be investigated. Surface geophysics run in the area are the logical first steps in the investigation. If promising zones are identified, then a deep test hole should be drilled. The purpose of the drilling is to obtain as much lithologic and hydrologic information as possible. Therefore adequate provision for coring, hole development, monitoring of hydraulic head with depth, fluid sampling, and hydraulic testing must be made.

STUDY AND ANALYSIS OF REGIONAL AND SITE GEOLOGY RELATED TO SUBSURFACE SALT DISSOLUTION SOURCE OF BRINE CONTAMINATION IN CANADIAN RIVER AND LAKE MEREDITH AND FEASIBILITY OF ALLEVIATION OR CONTROL NEW MEXICO - TEXAS

CHAPTER I
INTRODUCTION

This report contains the results of our study on salt pollution in the Canadian River channel upstream of Lake Meredith, Texas. It has been prepared by the staff of Hydro Geo Chem, Inc., Tucson, Arizona for the Bureau of Reclamation, Southwest Region, under Contract No. 3-CS-50-01580. This report summarizes available information, and presents results of additional data collected during this study with our interpretations, conclusions, and recommendations for pollution abatement and for further study.

The location of the study area, as shown in Figure 1, is in northeastern New Mexico and in the west-Texas Panhandle, along the course of the Canadian River. It has been divided into areas of detailed and general study. The detailed study centers around Logan, New Mexico, and encompasses the region of suspected brine inflow to the Canadian River; the area of general study includes the river reach between Ute Dam and Lake Meredith.

PURPOSE AND SCOPE OF INVESTIGATION

Salt concentrations in Lake Meredith, a water-supply reservoir on the Canadian River north of Amarillo, Texas, have increased steadily since the

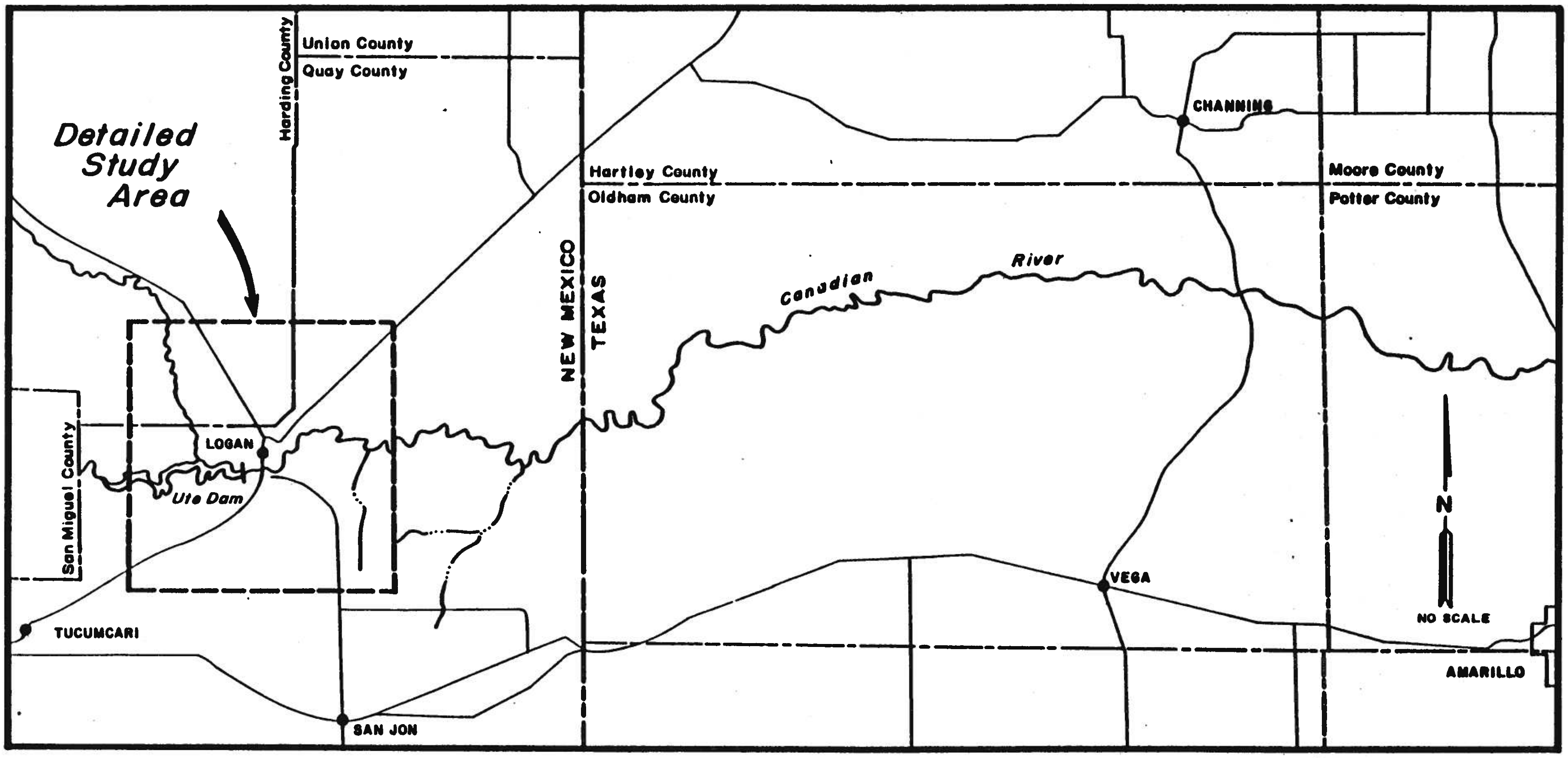


Figure 1. Location of detailed and general study areas

late-1960's and are presently approaching undesirable levels. Sources of salt upstream of the reservoir have been identified as brine seeps from within the Canadian River channel, and most of the salt appears to enter the channel in a several-mile reach downstream of Ute Dam (U.S. Bureau of Reclamation, 1979).

In August, 1983, the Bureau of Reclamation contracted with Hydro Geo Chem, Inc. to study the area downstream of Ute Reservoir and to determine the following aspects of the problem:

1. The geologic controls on the occurrence of brine inflow to the channel;
2. The hydrogeology of both brine and fresh-water systems that comprise the flow of the Canadian River;
3. The correlation between the salt flow in the Canadian River and the rise in salinity in Lake Meredith;
4. An evaluation of the feasibility for reducing saline pollution of Lake Meredith.

REVIEW OF PREVIOUS INVESTIGATIONS

Previous investigations to this study were those conducted for petroleum and uranium exploration, hydrologic and geologic reconnaissance studies, dam-site investigations, nuclear waste repository studies, and Canadian River salinity studies.

Exploration Studies.

Almost all subsurface geological information is from interpretation of geophysical and lithologic well logs from petroleum exploration. Few oil or gas wells were drilled within the detailed study area in comparison to the Texas side of the regional study area. Dobrovolny, Summerson and Bates (1946) were among the first to compile subsurface geologic information for Quay County. They drew detailed geologic cross-sections to the Precambrian surface, including one through the Canadian River channel. Their geologic report and structure-contour map (on the Triassic Chinle Formation), however, was for an area south of the Canadian River. Waneck (1962) presented the geology northwest of the study area near Conchas Dam, but had little subsurface data below the top of the Triassic. Foster and others (1972) compiled a regional analysis of northwestern New Mexico that has been the most useful work for the area. We have refined their work in the detailed study area to include additional deep-well data. Most of the deep-well information was collected from the library at New Mexico Institute of Mining and Technology at Socorro.

In the Texas portion of the study area, petroleum exploration has concentrated on pre-Permian formations. Much of the subsurface information has been compiled by Dutton and others (1979), and Ruppel and Ramondetta (1982).

As part of the National Uranium Resources Evaluation (NURE) program, groundwater, surface water and stream sediment was sampled and analyzed for the Amarillo, Texas NTMS quadrangle (Union Carbide, 1979). This area is at the far eastern edge of our general study area. Stream sediments were sampled and analyzed for uranium in the Tucumcari NTMS quadrangle (Bendix, 1981) but no groundwater sampling program was conducted.

Reconnaissance Studies.

Early geologic studies were not extensively used for this work because all have been incorporated into later works. Four hydrogeologic reports were very useful in the evaluation of the hydraulics and geochemisty of both the Triassic and Permian rocks. Griggs and Hendrickson (1951) compiled well inventories and water-quality data for San Miguel County, which is west of the study area. They reported the water chemistry and depths to water from which an estimate of hydraulic head in of the Permian system in the recharge areas could be made.

Berkstresser and Mourant (1966) reported on the geology and water resources of Quay County. They showed that groundwater flow in the Triassic system was toward the Canadian River, and compiled the only extensive water-level and water-quality tables for the county.

Trauger and Bushman (1964) made a quantitative study of the water resources of the Tucumcari area, concentrating on the Jurassic aquifers. Little information was given about the deeper Triassic rocks in the Tucumcari Basin.

Bassett and Bentley (1983) presented a hydrogeochemical analysis of the deep brine aquifer in Texas. They made use of extensive drill-stem tests to identify an upper-Pennsylvanian - lower-Permian aquifer, estimated its hydraulic potential, and showed it to be continuous with the Permian system in New Mexico.

Dam-Site Investigations.

In accordance with the Canadian River Compact of 1950, which allowed the State of New Mexico to impound up to 200,000 acre-feet of conservation storage below Conchas Dam, the State Engineer's Office conducted several investigations on the suitability of certain parts of the Canadian River channel for an impoundment (Walker and Irwin, 1958). At the Dunes dam site in section 2, T.13 N., R.35 E., a hole was drilled into the Permian Quartermaster Formation. No mention was made of artesian conditions. Triassic collapse features upstream from the hole were identified, and the first published mention was made (to our knowledge) of upstream brine inflow to the channel (Spiegel, 1957a, 1957b).

The impoundment, called Ute Reservoir, was finally built in 1962 upstream of the Dunes site. The Triassic geology of the Ute Reservoir site has been described in a New Mexico State Engineers Report (1961). The Permian was not encountered in shallow drilling at the site. The flow hydraulics in the vicinity of the dam were described by Spiegel (1969). Spiegel (1972b) estimated that about 5 cfs leaks from the dam into the channel.

Waste Repository Studies.

Numerous reports concerned with the evaluation of salt deposits for the storage of nuclear wastes in the Texas Panhandle have been published by the Texas Bureau of Economic Geology (BEG) since 1977. These provide detailed information on the stratigraphy and structure of the Palo Duro, Anadarko and

Dalhart Basins. Estimates of salt-dissolution zones in New Mexico and dissolution rates based on salt loads in rivers, are given in these reports. Much of this work can be extended into our study area because most of the sediments described are the updip extensions of those found in these basins.

Salinity Studies.

In addition to Spiegel's observations of salt in the Canadian River channel, a detailed water-quality survey of the Canadian River made by the Texas Water Quality Board (1970) concluded that much of the salt in the river was entering the stream below Ute Dam near Logan. In 1972, the Bureau of Reclamation began investigating the problem, drilled several groups of piezometers in the channel deposits between Ute Dam and Lake Meredith, and collected and analyzed water samples (U.S. Bureau of Reclamation, 1975). They determined that the poor water quality was primarily from movement of brines upward through the stratigraphic section and not from surface evaporation. In 1975, several deep wells were drilled near the river south of Logan, that encountered an artesian brine aquifer near the Triassic-Permian contact (U.S. Bureau of Reclamation, 1979).

Electrical resistivity and seismic refraction studies were also conducted in the vicinity in order to delineate the occurrence of salt water at depth (U.S. Bureau of Reclamation, 1976). The conclusions were that a section of very conductive rock (interpreted to be a brine aquifer) could be detected that dips to the west at approximately 4 degrees and is from 150 to 300 feet thick.

The brine aquifer was interpreted to be laterally discontinuous, however the assumptions inherent to the electrical soundings were violated because of the existence of near-surface inhomogeneities. At the time of the report, more soundings were recommended; however, none have been done. Additional data are needed to fully assess whether the brine is laterally discontinuous.

CHAPTER II

GEOLOGY OF THE STUDY AREA

INTRODUCTION

This chapter examines the physical setting of the study area in terms of the geologic occurrence of salt and the structural controls upon brine movement. The following stratigraphic descriptions explain formations present in the study area and sets the framework for the following section which describes the occurrence of salt within the detailed study area. Information used in this chapter comes from the published literature, field structure mapping conducted for this study, and analysis of geophysical and geologic well logs. Table 1 list the logs that were used in this analysis. Figure 2 is a location map for the wells listed in the table.

The study area is part of an intracratonic basin along the North American Plate that formed as a result of Paleozoic basement-involved movement (Nicholson, 1960). It lies east of the Sierra Grande Uplift of northeast New Mexico and just south of (and includes parts of) the west-northwest trending Oldham Nose and the Amarillo-Wichita Uplift. These features are shown in Figure 3. Analysis of sedimentation rates by McGookey and Goldstein (1982) shows that the uplift system was periodically active during Mississippian, Pennsylvanian, and Permian times. Major sedimentary basins, such as the Palo Duro Basin and the Tucumcari and Cuervo sub-basins, formed in response to the uplift and its assoc-

Table 1: Log Availability from Exploration Wells in New Mexico

Map No.	Location	Well Name	Operator	New Mexico Well ID No.	Availabile Logs
1	9.36.12	Chapman No 1	C.T. Shook	-	Drillers (no 2951)
2	10.31.23	N. Pueblo No 1	Shell Oil	14513	Acoustic, Gamma Caliper
3	10.31.25	N. Pueblo No 2	Shell Oil	14616	Neutron-porosity Gamma, Caliper
4	11.36. 7	Endee No 1	L.B. Newby	-	Drillers (no 855)
5	12.28.14	Hoover R. No 1	Miami Pet. Co.	15849	SP, Induction
6	12.29.13	Chapell No 1	Puretex Oil Co.	19324	Induction, Neutron-Porosity, Gamma, Caliper
7	12.29.18	Hoover R. No 1	Miami Pet. Co.	15850	Gamma, Laterolog
8	12.30. 7	Chapell No 2	Puretex Oil Co.	14890	Neutron-porosity, Gamma, Caliper
9	12.32.11	Ute Anticline 1	National Oil Co.	25563	Dual-Laterolog, Gamma, Acoustic, Neutron
10	12.32.11	Kimes No 1	O.L. Ledgerwood	15851	Neutron, Gamma
11	12.32.11	Ulmer No 1	S.T. Silverstein	6249	Drillers (no 6249)
12	12.32.35	Tippen No 1	N.G. Penrose	15483	Gamma, Neutron, Drillers (no 6876)
13	13.29. 3	No 1 Ranch	Marland	-	Drillers,
14	13.31.24	State No 1	Nucorp Energy	26194	Dual-Laterolog, Micro-Laterolog, Gamma
15	13.31.25	Dripping Spgs 1	Standard Pet. Co.	-	Drillers (no 858)
16	13.32.32	Columbine St. 1	National Oil Co.	26092	Gamma, Acoustic
17	13.33.15	USBR DH-3	U.S. Bureau Rec.	-	Drillers, Gamma
18	13.34. 9	Olean No 1 Woods	Olean Pet. Co.	-	Drillers
19	13.35. 2	N.M. Eng. DH-10	New Mex. St. Eng.	-	Drillers
20	14.32.16	State No 1	Sunray Mid-Cont.	2565	Mud-Log, Gamma, Neutron
21	14.33.21	Underwood No 1	Cornett	1000	Drillers
22	15.33.10	Arthur Cain No 1	J.A. Talley	6618	SP, Laterolog, Dual-Induction
23	15.33.17	Federal 1-17	Paul Haskins	21644	Gamma, Neutron
24	15.33.21	Conley Cain No 1	Conley Assoc.	21643	Neutron-Porosity, Gamma, Caliper, Density
25	15.33.22	Arthur Cain No 2	Edmonds, Peters	6619	Gamma, Caliper, Interval-Acoustic
26	15.34.28	State No 1	Powers Wire	23774	Gamma-Gamma Gamma, Caliper
27	16.33.27	1-X Olympic St.	Astro-Tex	19016	Caliper, Neutron-Porosity, Density, Gamma
28	16.36.36	State "CP" No 1	Humble Oil	13957	Gamma, Gamma-Gamma, SP, Laterolog, Dual-Laterolog

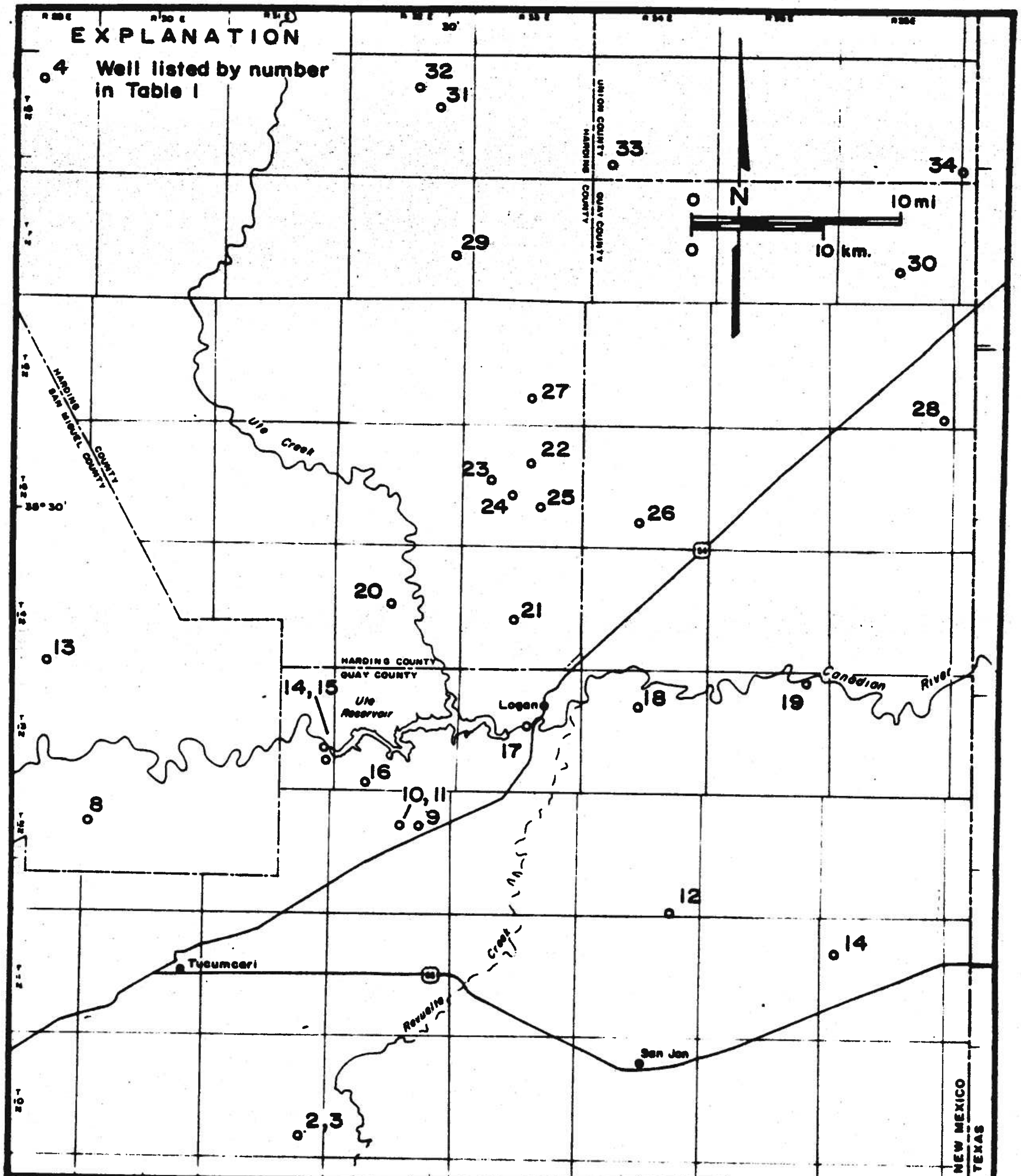
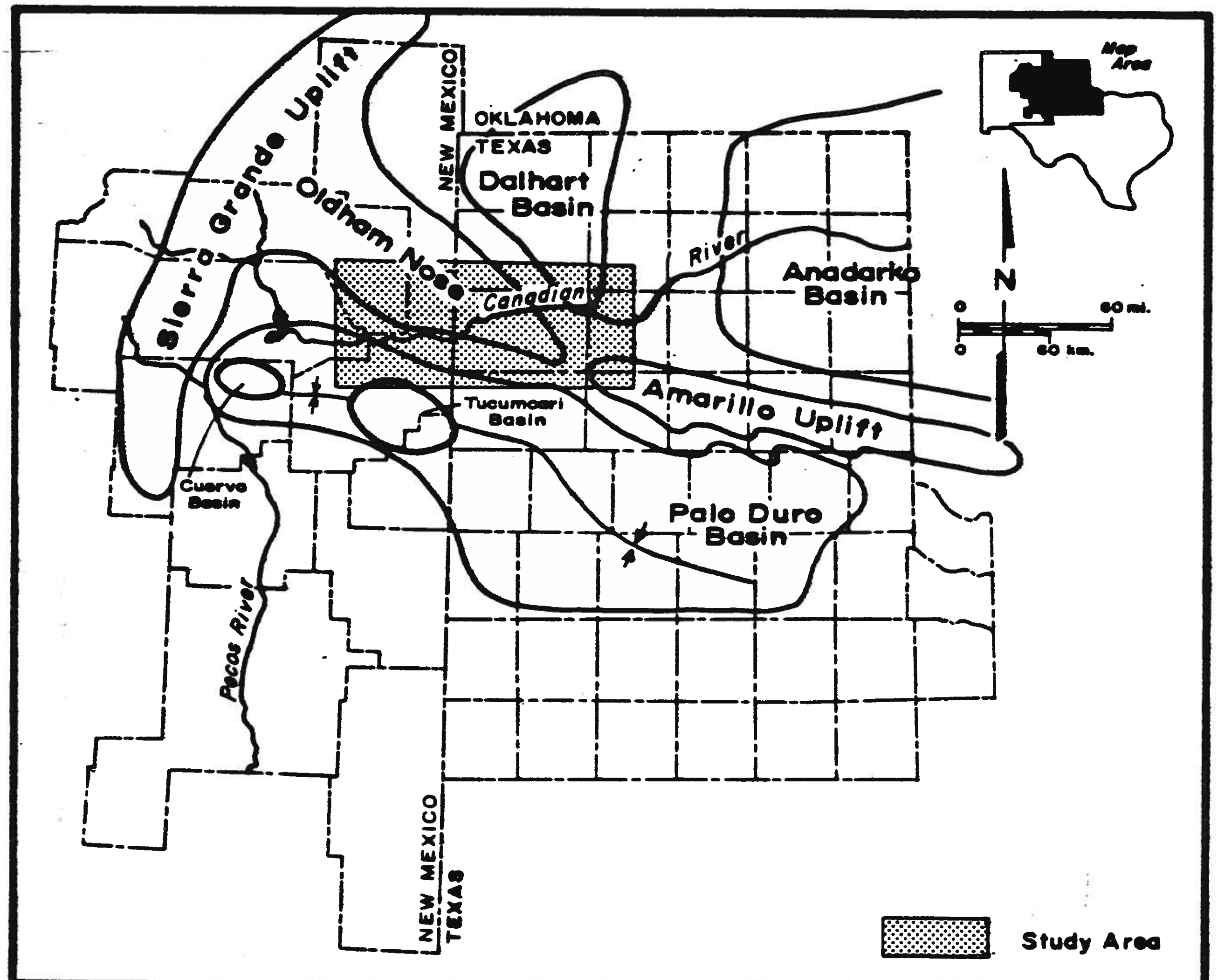


Figure 2. Location of wells listed in Table 1



Adapted from Nicholson, 1960; Gustavson and others, 1982

Figure 3. Structural elements in the vicinity of the study area

HYDRO GEO CHEM, INC.

Table 1: Continued

Map No.	Location	Well Name	Operator	New Mexico Well ID No.	Availabile Logs
29	17.32.24	State "FK" No 1	Amoco Oil	24178	Gamma, Neutron
30	17.36.28	State "CO" No 1	Humble Oil	14899	Gamma, Gamma-Gamma SP, Laterolog, Dual-Laterolog
31	18.32.14	"CM" State No 1	Humble Oil	14900	Gamma, Acoustic SP, Laterolog, Dual-Laterolog
32	18.34.31	"CK" State No 1	Humble Oil	14901	Gamma, Acoustic, Caliper
33	18.36.36	BDCDGU1836361K	Amoco Oil	23259	Gamma
34	19.34.16	State "EL" 1	Amoco Oil	24126	Gamma, Caliper, Bulk-Density

iated northwest trending block faulting. Regional isopach maps constructed for the region by Foster and others (1972) and Gustavson and others (1982) indicate that many of the sedimentary systems of the Palo Duro basin can be extended into New Mexico along a synclinal trough defined by the Tucumcari and Cuervo basins.

STRATIGRAPHY

1. Paleozoic Section

The Paleozoic section in Quay and Oldham counties, shown in the stratigraphic column (Figure 4), is comprised of the Sangre de Cristo Formation and the Abo, Yeso, San Andres, and Bernal formations. These units lie unconformably upon the Precambrian surface. The unconformity is marked by arkosic sandstones often referred to as the granite wash, and it reflects tectonic uplift and ero-

SYSTEM	SERIES	NE NEW MEXICO STUDY AREA: GROUP	NE NEW MEXICO STUDY AREA: FORMATION	PALO DURO BASIN: GROUP	PALO DURO BASIN: FORMATION	PALO DURO BASIN: General Lithology & Depositional setting
QUATERNARY	HOLOCENE				*alluvium, dune sand Playa*	
	PLEISTOCENE				*Tahoka cover sands Tule/"Playa" Blanco*	Lacustrine clastics & windblown deposits
TERTIARY	NEOGENE		*Ogallala*		*Ogallala*	Fluvial & lacustrine clastics
CRETACEOUS					*undiferentiated*	Marine shales & limestones
TRIASSIC		DOCKUM		DOCKUM		Fluvial-deltaic & lacustrine clastics
PERMIAN	OCHOA				*Dewey Lake (Quartermaster)*	Sabkha salt, anhydrite, red beds, & peritidal dolomite
			Alibates?		*Alibates*	
	GUADALUPE	ARTESIA	*Bernal* *	ARTESIA	*Salado/Tansill* *	
					Yates	
					Seven Rivers *	
					Queen/Grayburg	
			San Andres *		*San Andres* *	
	LEONARD		*Yeso* *	CLEAR FORK	*Glorieta* *	
					Upper Clear Fork *	
					Tubb	
					Lower Clear Fork *	
					Red Cave	
				WICHITA		
	WOLFCAMP		*Abo*			Shelf & shelf-margin carbonate, basinal shale, & deltaic, sandstone
PENNSYLVANIAN	VIRGIL	MAGDALENA	*Sangre de Cristo "granite wash"*	CISCO	?	
	MISSOURI			CANYON		
	DES MOINES		*Madera*	STRAWN		
	ATOKA			BEND		
	MORROW					
MISSISSIPPIAN	CHESTER					Shelf carbonate & chert
	MERAMEC					
	OSAGE					
ORDOVICIAN				ELLEN-BURGER		Shelf dolomite
CAMBRIAN						Shallow marine (?) sandstone
PRECAMBRIAN						Igneous & metamorphic

*SALT PRESENT

Figure 4. Stratigraphic column

HYDRO GEO CHEM, INC.

sion of the granitic Precambrian basement. Most, if not all, of the Cambrian to Late Mississippian carbonates thought to be deposited in the region were removed by erosion. Some of these are preserved as carbonates in deeper parts of the Palo Duro Basin (Gustavson and others, 1982).

The Sangre de Cristo and Abo Formations are arkosic sandstones derived from granitic sources located to the north and west of Logan, New Mexico. The sands of the Sangre de Cristo are poorly sorted, angular to subangular, and arkosic. The Abo Formation is more well-sorted than the Sangre de Cristo. Both formations include shale; the shales of the Sangre de Cristo Formation being more silty and sandy than those of the Abo Formation. A combined thickness of 400 to 2000 feet is found in the detailed study area. The thicker sequences are associated with the fault-bounded Tucumcari basin. The distinction between the two formations is not always clear because they grade into each other and are both laterally discontinuous.

The Yeso Formation conformably overlies the Abo and Sangre de Cristo Formations and contains lithologies that range from glauconitic yellowish sandstone to pale red shale with varying amounts of interbedded evaporites such as halite and anhydrite. The sandstone units of the formation are fine-grained, moderately to well-sorted, and often contain evaporites. Texas and New Mexico have developed separate nomenclature for the sandstone units within the Yeso; however, we make no distinction between the units for this report. The total thickness of the Yeso varies between 600 and 1300 feet in the detailed study area, thinning to the north and west.

The conformably overlying San Andres Formation contains fine grained sands, evaporites, dolomite, and limestone. The sand content of the formation increases to the north and west of Logan. Because varying quantities of evaporites appear to have been dissolved from the San Andres in the area of detailed study, many of the salt units within the San Andres pinch out or vary considerably in thickness. The formation is between 250 and 1000 feet thick in the detailed study area, the thinner sequences being away from the sedimentary basin.

Overlying the San Andres is the Bernal Formation of the Artesia Group, which we call the Artesia in this report. The dominant lithology is pale salmon pink to yellowish shale and siltstone with traces of halite. Gypsum is also common and is one characteristic of the Artesia Group sediments. The sands are fine grained, well-sorted, and quartzose. Between 175 and 800 feet of Artesia sediments were conformably deposited upon the San Andres Formation in the detailed study area. The formation is thinnest in the area around Logan and thickens toward the Tucumcari and Palo Duro Basins and southward into southeastern New Mexico.

The Alibates dolomite lentil of the Quartermaster Formation overlies the Artesia and is present east of the detailed study area in Texas. It has been described as a very tight limestone that grades to dolomite where it was found in well DH-10 at the Dunes damsite in section 2, T.13 N., R.35 E. (Spiegel, 1972a), but has not been detected on any logs in the area of detailed study.

2. Triassic and Younger Sediments

Exposed throughout the detailed study area are the Triassic age fluvio-deltaic sands and shales of the Dockum Group. In New Mexico, the Dockum Group has been subdivided in ascending order into the Santa Rosa Sandstone, the Chinle Formation, and the Redonda Formation. In Texas correlative units are called the Tecovas and Trujillo formations. The distinction between the Triassic units is difficult because the sediments are laterally and vertically discontinuous. The best exposures occur along the Canadian River and its tributaries. Presently, between 400 and 1600 feet of Triassic sediments are preserved in the study area. Between 1200 and 1600 feet of sediments were originally deposited in the detailed study area (Foster and others, 1972).

Locally, the lithology of the Triassic rocks consists of discontinuous arkosic sandstones, siltstones, and shales. Conglomeratic units are also found. Large cross-bedded sandstone units are exposed throughout the area and form sedimentary troughs (paleo-channel deposits) that are between 50 and 500 feet in length. These units grade laterally into siltstones and shales. Our analysis of geophysical and lithologic logs show that the entire Triassic section is similar to the exposed sections. Portions of the lower Triassic section appear to have been silicified and are of a higher bulk density than overlying units. Our analysis of gamma logs show that between 15 and 40 percent of the section is comprised of relatively continuous, thick bedded shales, but attempts at correlation of Triassic sands and shales at a regional scale using the well logs and other drill-hole information were speculative at best. Kottlowski (1969) observed that the Triassic section becomes more shale rich to the south and east.

Between 600 and 800 feet of Jurassic and Cretaceous rocks were deposited in the area but have since been removed by erosion (Foster and others,1972). They are present to the west of the area of investigation in San Miguel County. These sediments were a continuation of the sedimentary systems that began in the Triassic.

The Tertiary system is represented north of the study area by the Ogallala Formation of Neogene age. These clastic sediments were eroded from the Rocky Mountains, transported to the Panhandle region by fluvial processes, and deposited in large alluvial fans. Post Ogallala erosion has isolated these fans from their source areas. No Ogallala sediments remain in the vicinity of the Canadian River.

Quaternary deposits in the study area consist of alluvial sands and gravels in the river channels and a few localized active sand dunes. The channel sediments are predominantly fine sands, clays, and gravel lenses. The channel sediments apparently increase in thickness downstream from Ute Dam. Spiegel (1972b) states that they are 100 feet thick at the state line and continue to thicken to the east. However, a series of piezometers drilled by the Bureau of Reclamation and by the Texas Canadian River Municipal Water Authority (CRMWA) were reported to be in river sediments that are 50 feet thick or less. It is possible that the wells encountered large blocks of rock derived from the cliffs adjacent to the river. A veneer of gravels and irregularly preserved caliches can be found in the highlands and terraces above the river channel.

GEOLOGIC HISTORY

The Texas Panhandle region was the site of shallow marine shelf deposition between Cambrian and Late Mississippian time. By early Permian time, tectonic activity created rapidly subsiding marine basins and numerous fault-bounded highlands (Handford and others, 1981). The Sierra Grande Uplift and the Bravo Dome were major sediment sources at various times (Budnik and Smith, 1982) in the area of investigation.

Shelf and shelf margin carbonate depositional systems existed throughout the region by Late Pennsylvanian and persisted through Early and Middle Permian (Wolfcampian to Early Leonardian) time over most of the Panhandle region (Handford and others, 1981). By the end of the Wolfcamp, the uplifts that supplied sediment were submerged by the Permian sea, and the Texas Panhandle was again part of a broad shelf that extended north into the mid-continent. During Leonardian time, evaporitic environments migrated southward into the Texas Panhandle as the marine shelf systems shifted southward (Handford and others, 1981). The study area was then behind the shelf margin for the remainder of the Permian (Budnik and Smith, 1982). A long period of relative stability and arid climatic conditions allowed the accumulation of thick, onlapping evaporitic sediments in the study area. Thus, the evaporite facies are typical of a sabkha environment and contain a mixture of carbonates, halite, gypsum, anhydrite, and very fine grained clastics.

Relatively rapid carbonate deposition in shallow water then led to the formation of carbonate shoals that expanded and coalesced to form broad tidal flats. Wave action during storm tides carried more carbonate sediment onto the tidal flats, eventually building them above normal tidal ranges. Brine pans and evaporite deposits formed on this supratidal surface, intermittently flooded by tidal action or in some cases by groundwater seepage. The salt plain deposits generally grade laterally into continentally derived redbeds. These sediments appear in multiple cycles and are a record of shorter term fluctuations in the sedimentation pattern superimposed on the broad cycle of Permian regression. The Yeso Formation is a record of cyclic sedimentation patterns which were controlled by a delicate dynamic balance among competing processes of basin subsidence, eustatic sea-level variation, clastic sediment supply, and aggradation/progradation of intertidal and supratidal sediments (Presley and McGillis, 1982).

At the end of the Permian, climatic changes and renewed subsidence of the sedimentary basin, both perhaps related to the opening of the Gulf of Mexico, (McGowen and others, 1979), dramatically changed the nature of sediments. Erosion of some of the Permian section prior to deposition of Triassic rocks has occurred regionally. The arid sabkha environment of the Permian gave way to relatively humid, continental environments of the Triassic, and extensive fluvio-deltaic sediments were deposited throughout the region.

The Mesozoic history of the study area is best shown by the Triassic section because the Jurassic and Cretaceous rocks are poorly preserved in the region. The depositional environments were predominantly humid, continental fluvial and deltaic systems that created abrupt lateral and vertical facies changes. During this time, the meteoric circulation of groundwater began to dissolve underlying evaporites. The Canadian and Pecos river systems formed along the updip edge of the sedimentary basin and were most likely captured by dissolution-caused collapse structures (Gustavson and others, 1982). These patterns of structural deformation remain as the major features in the region today.

SUBSURFACE ANALYSIS

The occurrence of salt in the Yeso, San Andres, and Artesia Formations is controlled by the depositional and diagenetic history of the sedimentary basin. This analysis of the subsurface is designed to illustrate the history of the formations within the detailed study area through the construction of isopach and structure contour maps. It is based upon the well logs listed in Table 1. The formation tops determined from the logs and used for map construction are included in Table 2.

Our lithologic analysis of the available well logs shows that 20 to 40 percent of the three Permian units may contain salt. The updip limits of salt-bearing units have undergone dissolution in the vicinity of Ute Reservoir and rapid lateral thinning of the formations occurs across a Precambrian basement structural high. Within the Artesia, the salt-bearing facies grade updip into undifferentiated sandstones and shales. The underlying San Andres grades from halite to anhydrite and dolomite updip from the Tucumcari basin. The Artesia shows marked thinning associated with collapse. The area of thinning also lies just north of an east-west trending fault zone that has been active

Table 2: Formation Tops from Logs of Exploration Wells in New Mexico

Map No.	Location	Well Name	Elev. (MSL)	Depth (ft)	Formation Tops (ft below Elev. datum) Arte-sia	San Andres	Yeso	Abo	Sangre Cristo	Pre-Camb
1	9.36.12	Chapman No 1	4060	1050	-	-	-	-	-	-
2	10.31.23	N. Pueblo No 1	4116	5058	650	1380	2225	3540	-	-
3	10.31.25	N. Pueblo No 2	4126	2769	823	1558	2530	-	-	-
4	11.36. 7	Endee No 1	4070	3503	757	1605	2360	-	-	-
5	12.28.14	Hoover R. No 1	4084	6655	1540	1754	2130	3310	-	7530
6	12.29.13	Chapell No 1	4094	4930	-	1805	2090	3200	-	4510
7	12.29.18	Hoover R. No 2	4119	7077	1642	1846	2710	3480	-	7060
8	12.30. 7	Chapell No 2	4167	5009	1040	1750	2210	2840	3400	4130
9	12.32.11	Ute Anticline 1	4073	3647	890	1078	1813	2755	-	3350
10	12.32.11	Kimes No 1	4052	6505	850	1130	1830	2785	-	3645
11	12.32.11	Ulmer No 1	4060	2035	860	1165	1764	-	-	-
12	12.32.35	Tippen No 1	4120	6128	740	1170	1910	3230	4100	5285
13	13.29. 3	No 1 Ranch	4092	4990	1640	1925	2595	-	3602	-
14	13.31.24	State No 1	3829	3136	574	894	1620	2312	2810	3020
15	13.31.25	Dripping Spgs 1	3790	3011	635	905	1573	2875	-	2985
16	13.32.32	Columbine St. 1	3970	3404	890	1088	1800	2574	3070	3208
17	13.33.15	USBR DH-3	3810	596	514	-	-	-	-	-
18	13.34. 9	Olean No 1 Woods	3915	3930	560	864	1490	2910	3370	3930
19	13.35. 2	N.M. Eng. DH-10	3585	240	150	-	-	-	-	-
20	14.32.16	State No 1	3926	2853	652	842	1325	2195	2540	2716
21	14.33.21	Underwood No 1	3940	1370	920	945	-	-	-	-
22	15.33.10	Arthur Cain No 1	4257	2891	820	1110	1600	2359	2688	2851
23	15.33.17	Federal 1-17	4220	1450	752	1058	-	-	-	-
24	15.33.21	Conley Cain No 1	4210	1452	723	1050	1420	-	-	-
25	15.33.22	Arthur Cain No 2	4147	1430	725	998	-	-	-	-
26	15.34.28	State No 1	4075	2459	608	925	1390	2240	-	-
27	16.33.27	1-X Olympic St.	4225	2908	800	1160	1600	2420	2755	2870
28	16.36.36	State "CP" No 1	4086	1159	398	692	-	-	-	-
29	17.32.24	State "FK" No 1	4762	2693	1462	1758	2012	2115	-	2600
30	17.36.28	State "CO" No 1	4299	1395	676	966	-	-	-	-
31	18.32.14	"CM" State No 1	4700	2100	1290	1577	1955	-	-	-
32	18.34.31	"CK" State No 1	4765	1914	1345	1598	-	-	-	-
33	18.36.36	BDCDGU1836361K	4408	2900	920	1220	1645	2240	-	-
34	19.34.16	State "EL" 1	4872	2526	1206	1404	1772	-	-	-

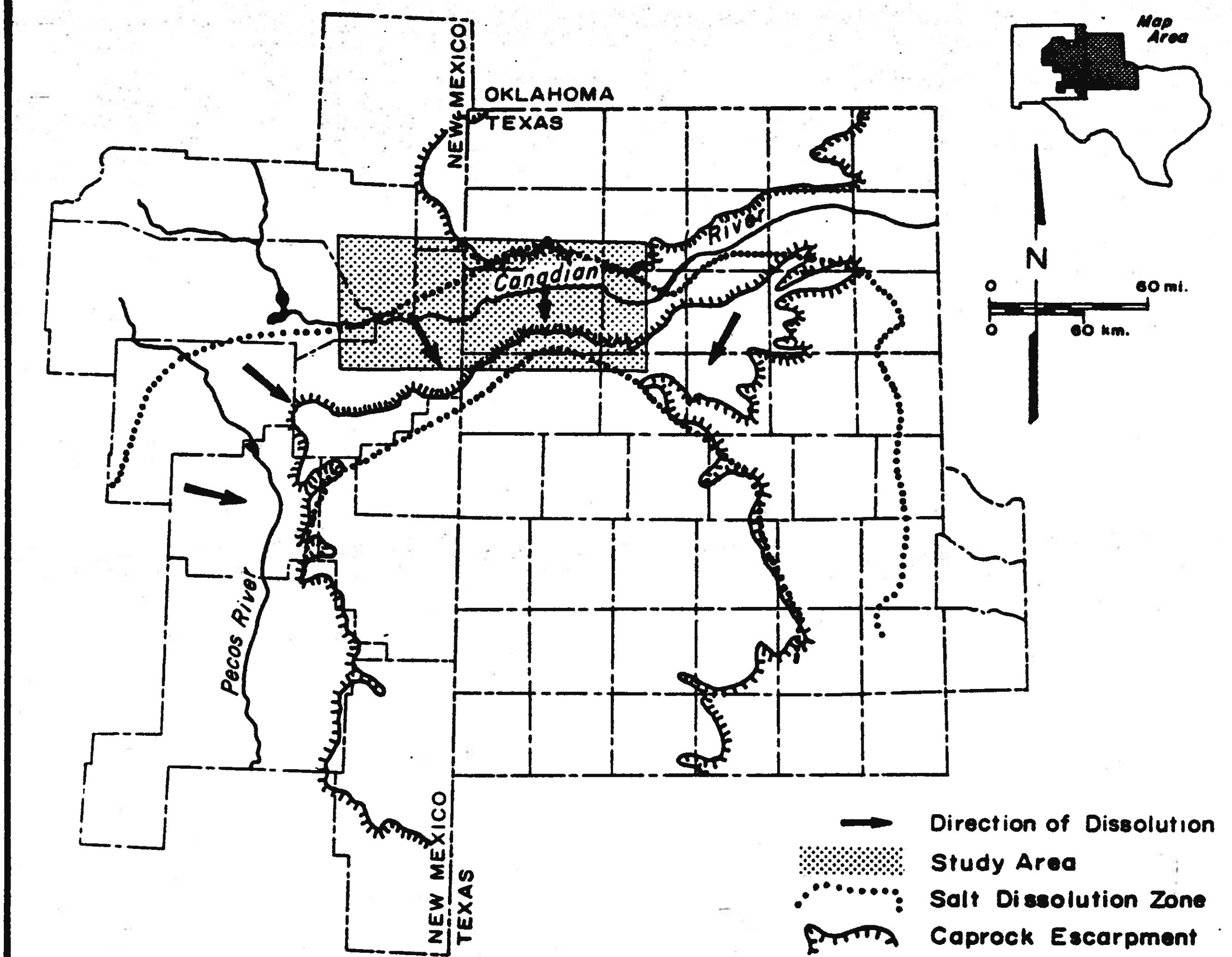
since at least Pennsylvanian time.

Gravity and magnetic potential field maps are often useful in the analysis of sedimentary basins. We examined the available coverage for the Logan area but found the data not to be useful for the specific area so the data have not been included in this report.

1. Salt Occurrence

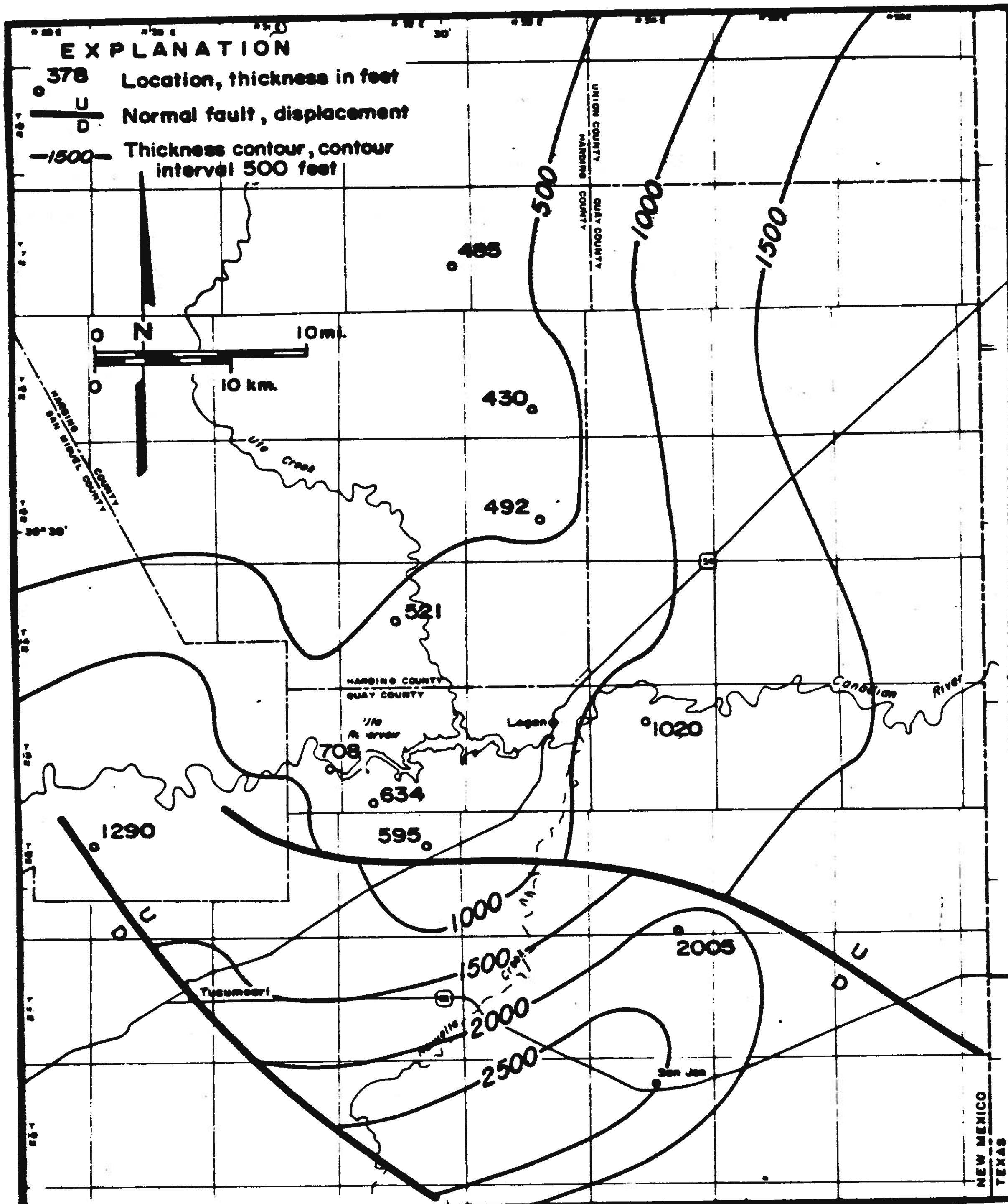
The present-day limits of salt dissolution have been mapped by Gustavson and others (1982) and are shown in Figure 5. Although the original extent of salt deposition was near the Texas/Oklahoma border, dissolution along the updip edge of the salt-bearing units has been extensive and now occurs in a broad zone that runs sub-parallel to the Precambrian basement highs that delineate the updip edge of the sedimentary basin. The Canadian River flows across the dissolution zones between Ute Reservoir and Lake Meredith. The dissolution front passes to the south across the western part of the study area (refer to Figure 5).

Construction of an isopach map (Figure 6) of the Sangre de Cristo and Abo Formations is used to show the sedimentary systems that operated during the first stage of the development of the basin. The units are thinner in the vicinity of Ute Reservoir as shown by the North-South zone of thinning that crosses vicinity of Ute Reservoir in Figure 6. We interpret this to be the effect of a Precambrian basement structure that influenced the the sedimentary systems that formed on the Precambrian because they appear to have partially



Adapted from Simpkins and others, 1981

Figure 5. Limits of salt dissolution in the vicinity of the study area



Adapted from Foster and others, 1972

Figure 6. Isopach map of combined Abo-Sangre de Cristo Formations

HYDRO GEO CHEM, INC.

bypassed the area as they filled the developing basin. Faulting south of the reservoir appears to have been influential during the development of the formations as the units greatly thicken across the fault shown in Figure 6. The basin geometry has not drastically changed since late Pennsylvanian to early Permian time.

The geometry of the sedimentary basin is defined by the present-day Precambrian basement surface illustrated in Figure 7. Regionally, it can be observed that the Oldham nose is part of a series of uplifts that limit the depth to the basement rock to the north and west of Logan. The well control for the map is sparse, but the area of thinning that is observed in the Sangre de Cristo and Abo Formations correlates to a similarly trending structure in the basement rocks.

Subsequent deposition of the San Andres and Artesia Formations is the last stage of Paleozoic sedimentation, marked by significant quantities of bedded salt, gypsum, and anhydrite. The thickness of the units in the study area is roughly proportional to the amount of salts present in the formations. Both units appear to have been influenced by the presence of the Precambrian structure. The San Andres isopach map (Figure 8) illustrates the effect of the basement structure in an area north of the reservoir. Immediately south of the reservoir there is a northwest trending accumulation of sediments which contain thicker sections of bedded salt than those sediments on the Precambrian basement high. This trend, lying above a fault zone that has been mapped in the basement, may be fault controlled. The Artesia isopach map (Figure 9) shows that thinning is quite pronounced over the area of the reservoir. The southern end

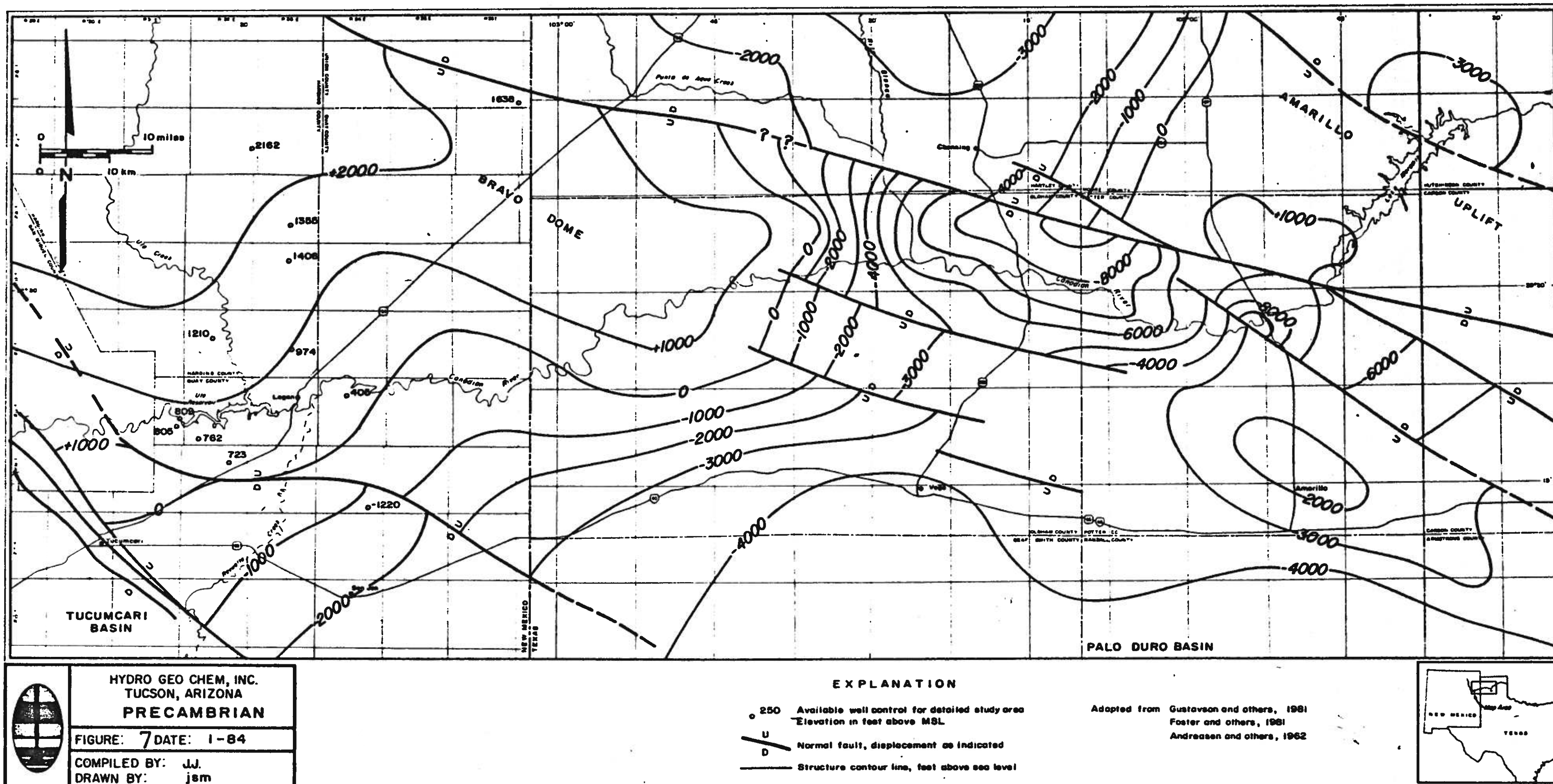


Figure 7. Structure contour map of Pre-cambrian surface

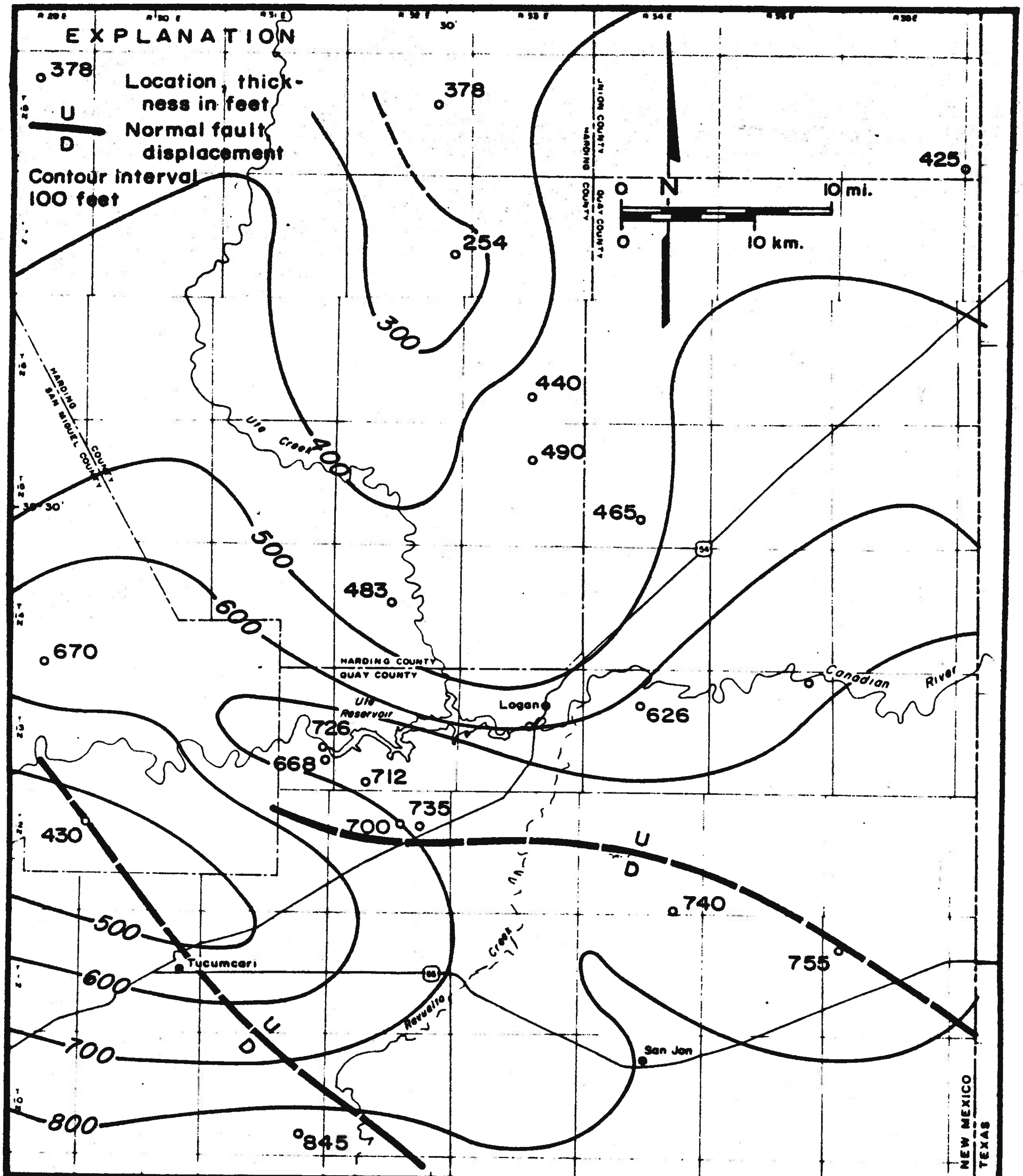
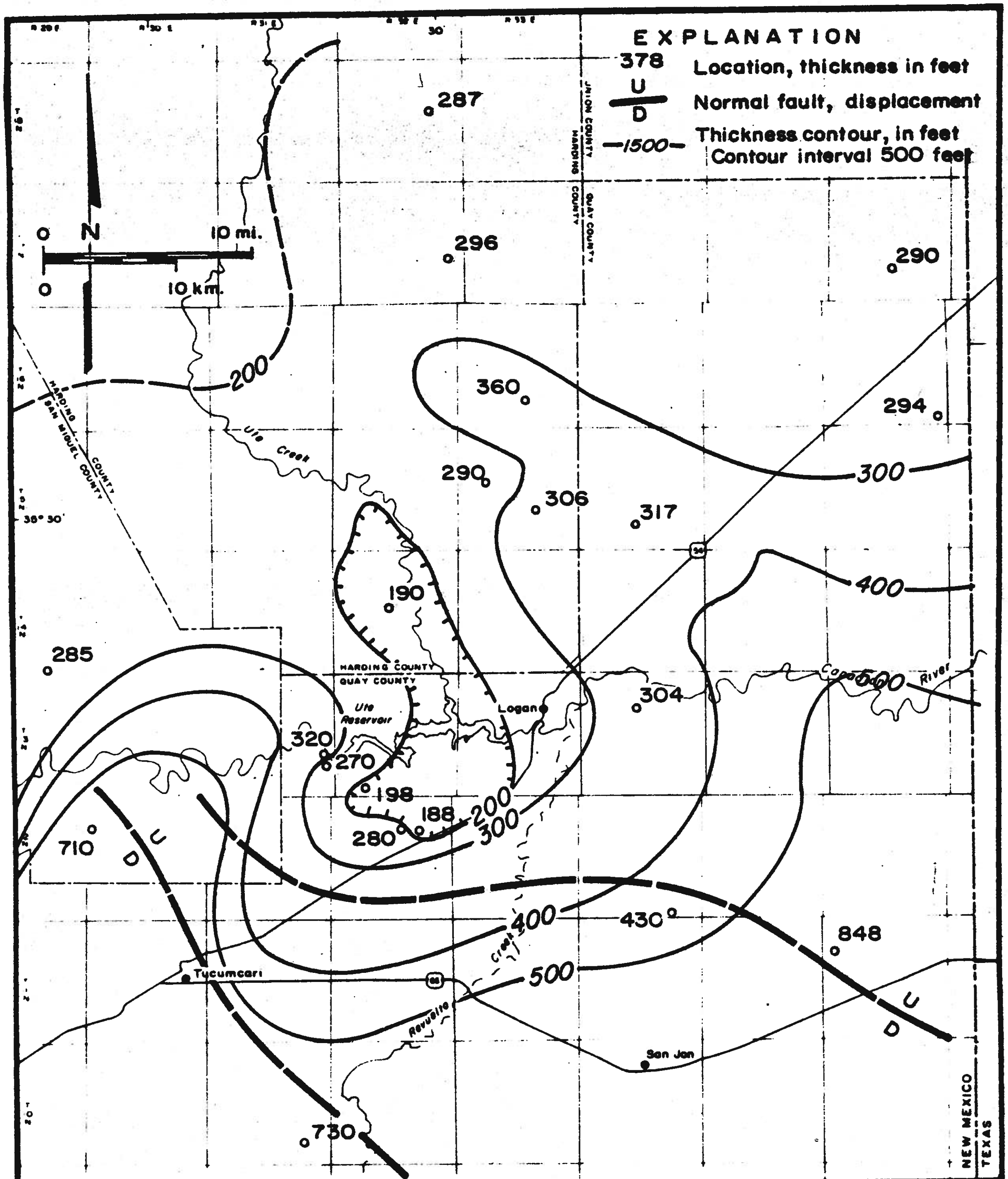


Figure 8. Isopach map of San Andres



Adapted from Foster and others, 1972

Figure 9. Isopach map of the Artesia Formation

of the thinning area lies above the northwest trending accumulation within the San Andres Formation. Structure contour maps of the top of both the San Andres (Figure 10) and the Artesia (Figure 11) Formations show a depression in the area of thinning of the Artesia. We believe that this depression is a result of dissolution induced collapse of a large region around Ute Reservoir. This area lies above both a basement fault and Artesia Formation thinning and down-warping.

2. Salt Dissolution

In order to further illustrate the patterns of salt dissolution, three geologic cross-sections were constructed for the study area. The locations of these sections are shown in Figure 12. The identification of salt in the well logs requires that a combination of logs be interpreted. Because bedded salt is soluble and hole enlargement occurs during drilling, caliper logs are often useful. Acoustic logs help differentiate between the evaporites because gypsum and halite have different acoustic wave velocities. Density and neutron logging can also be effective indicators of bedded salt. Neutrons are strongly attenuated and densities are anomalously low in the presence of halite. Gamma logs are generally available for most wells and can be used to identify sedimentary facies as well as salt distibution in a formation. Accurate lithologic logs obtained during the drilling of the wells are generally not available.

The east-west cross-section A-A' (Figure 13) shows that the Artesia decreases in thickness underneath the area between Revuelto Creek and Ute Reservoir. Well number 26092 also shows that part of the section may be down-dropped

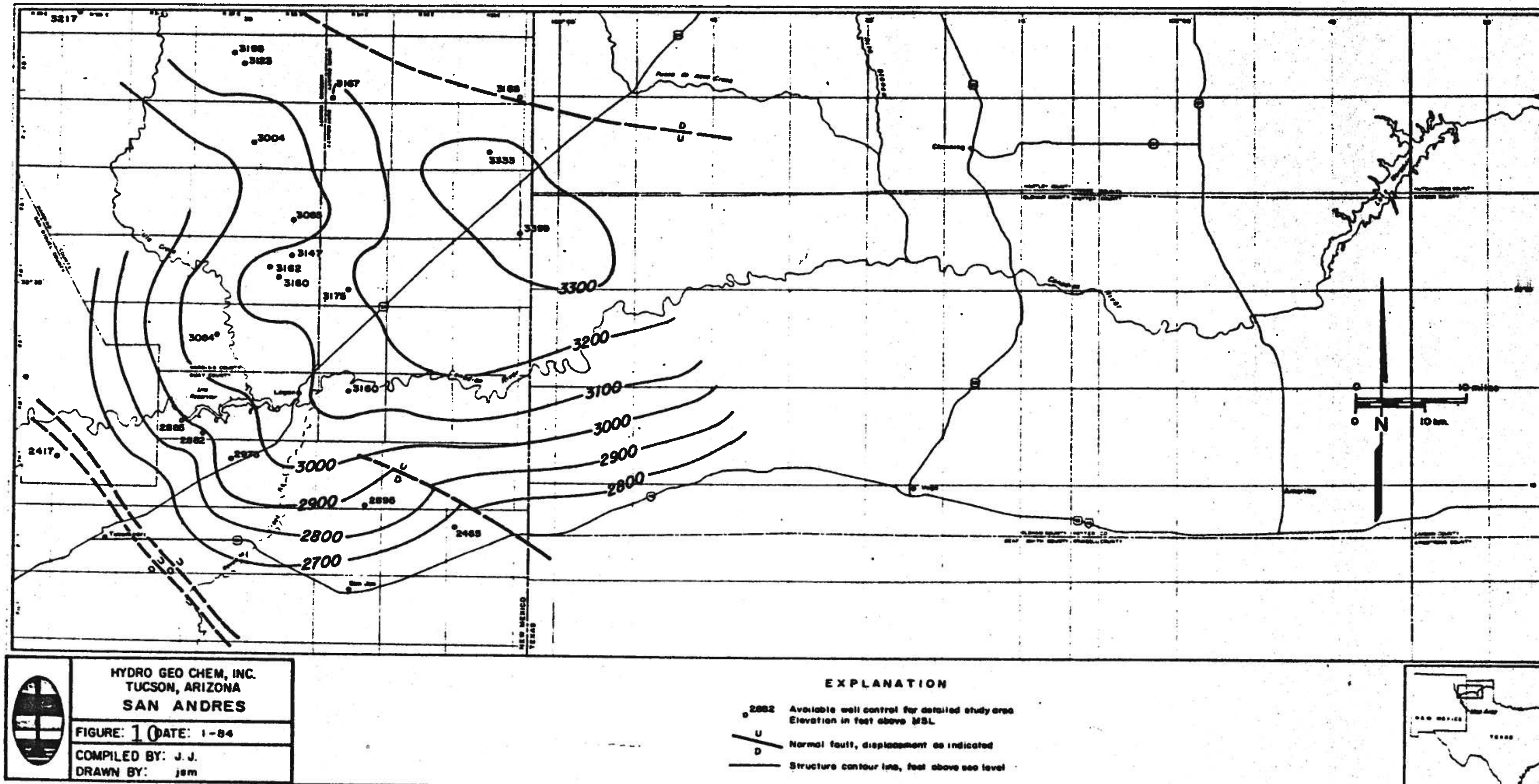


Figure 10. Structure contour map of San Andres Formation

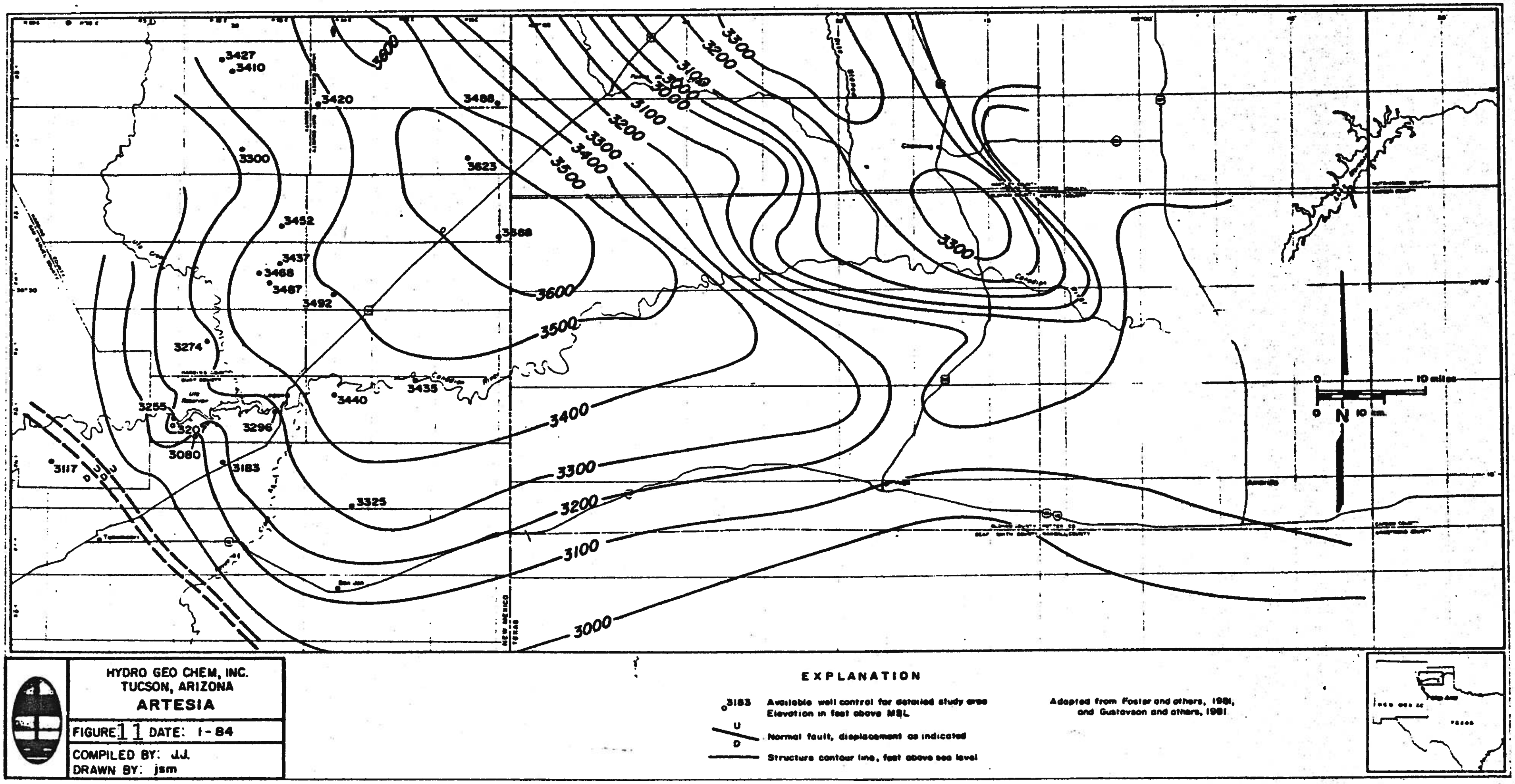


Figure 11. Structure contour map of Artesia Formation

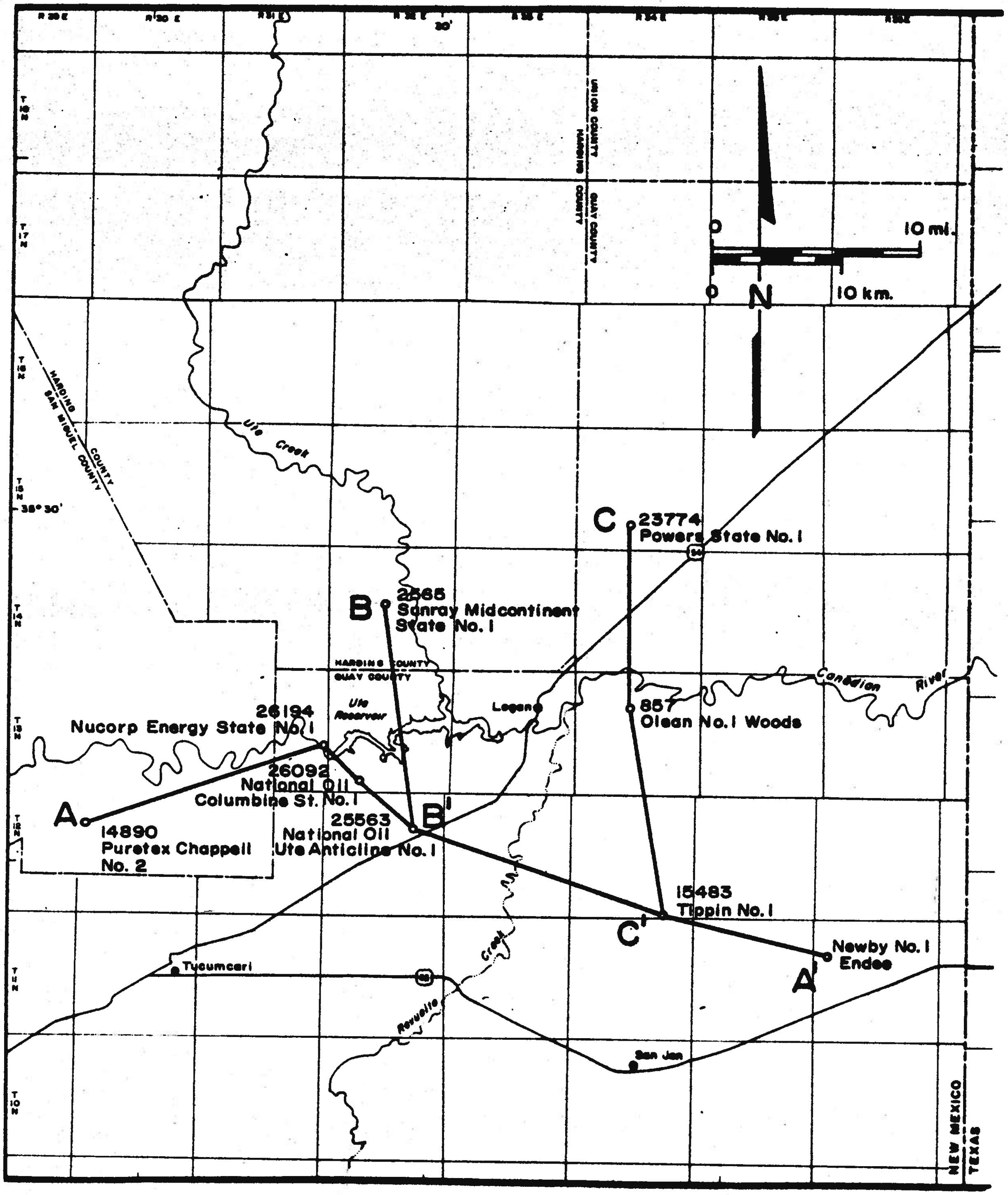


Figure 12. Map showing locations of cross-sections

EXPLANATION

o 14890	Well number
Puretex Chappell No. 2	Operator, name

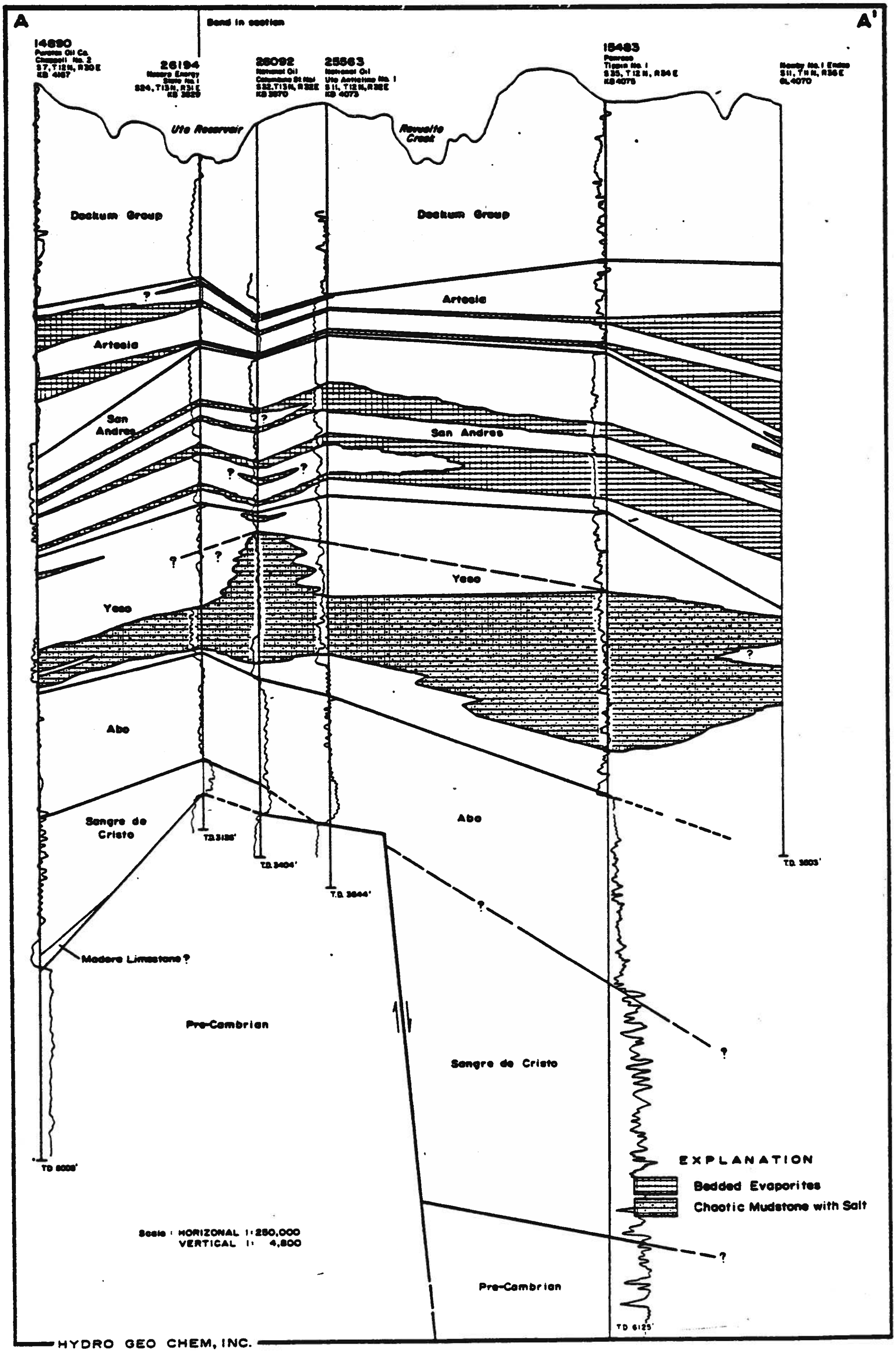


Figure 13. East-West geologic section

due to increased dissolution of salt. A Precambrian fault, found south of Revuelto Creek (Figure 7), appears to have influenced the Sangre de Cristo and Abo Formation thicknesses and possibly the San Andres. Two types of salt are illustrated which may be either massive salt or chaotic mudstone with salt. The chaotic mudstone facies may represent dissolution residue in some areas. Sections B-B' and C-C' (Figures 14 and 15) are north-south cross-sections that show the updip thinning and decreased salt thicknesses noted for the region. The cross-sections further illustrate the effect of the basement structure upon salt deposition and dissolution.

The area around Ute Reservoir appears to be especially prone to salt dissolution because of a structural high in the Precambrian basement that has influenced all of the Paleozoic sedimentary systems. Thinning is due to both salt dissolution and to the normal variation in stratigraphic thickness over a structural high.

SURFICIAL EXPRESSION OF SUBSIDENCE FEATURES

Within the detailed study area we attempted to identify faults, sinkholes, fracture zones or other features of the exposed Dockum Group that may be evidence of subsidence or collapse and may also act as conduits for the upward leakage of brine. The visible geologic structure in the area shows that the regional tectonic history has been quiet. Flexures rarely exhibit dips greater than 5 to 10 degrees, and no faults were found. An east-west trending anticline was mapped along the Canadian River in the area of Ute Reservoir that runs sub-

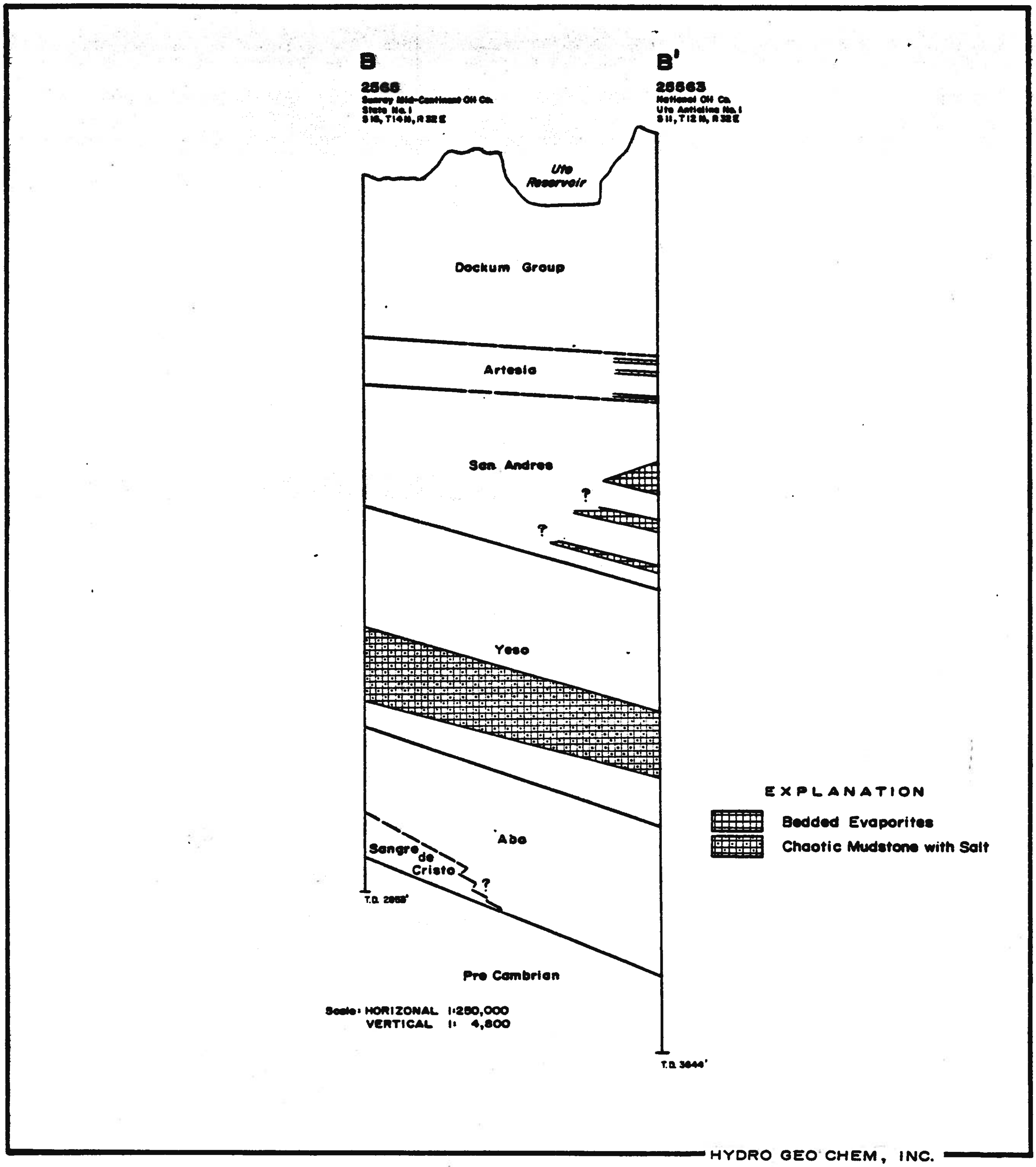


Figure 14. North-South geologic section through Ute Reservoir

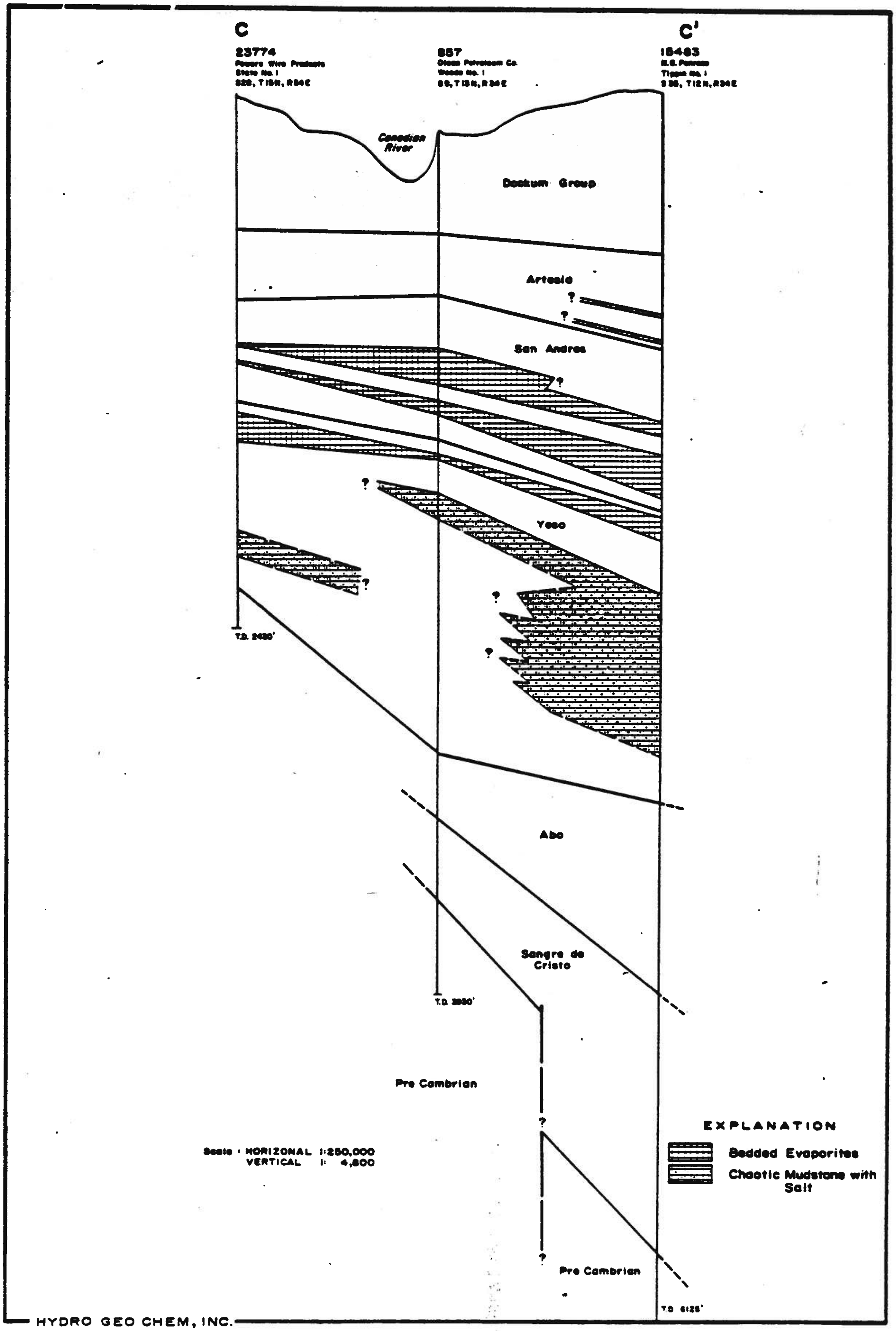


Figure 15. North-South geologic section through Canadian River

parallel to the dissolution fronts mapped in the subsurface. Northeast trending flexures and fracture zones have been mapped that may also have formed in response to dissolution. The observable structures are believed to be primarily controlled by the dissolution of salt units in the underlying Artesia and San Andres formations.

We have used two lines of evidence to identify the subsurface features from surface expressions. Structure mapping and air photo analysis show the patterns of folds and depressions. Then, in order to examine the subtle structures in greater detail, fracture orientation data were collected at numerous locations over the detailed study area. Analysis of the fracture data shows that a regional fracture pattern exists in the area. Localized variations and general trends of individual fracture sets have been found and can be related to dissolution.

1. Structure Mapping in Detailed Study Area

Two major structural trends were observed during mapping of the detailed study area. Broad, northeast trending flexures that plunge 5-10 degrees southwest occur south of the Canadian River (Figure 16). North of the river, the flexures appear to plunge northeast. The best exposures are found to the south where the flexures plunge southwest. Revuelto and Tuscocoillo creeks run subparallel to the axial trends of the flexures. An east-west trending flexure has also been mapped along the Canadian River that defines the reversal of the plunge of the flexures. Both trends are evident from analysis of 1:24000 scale aerial photos.

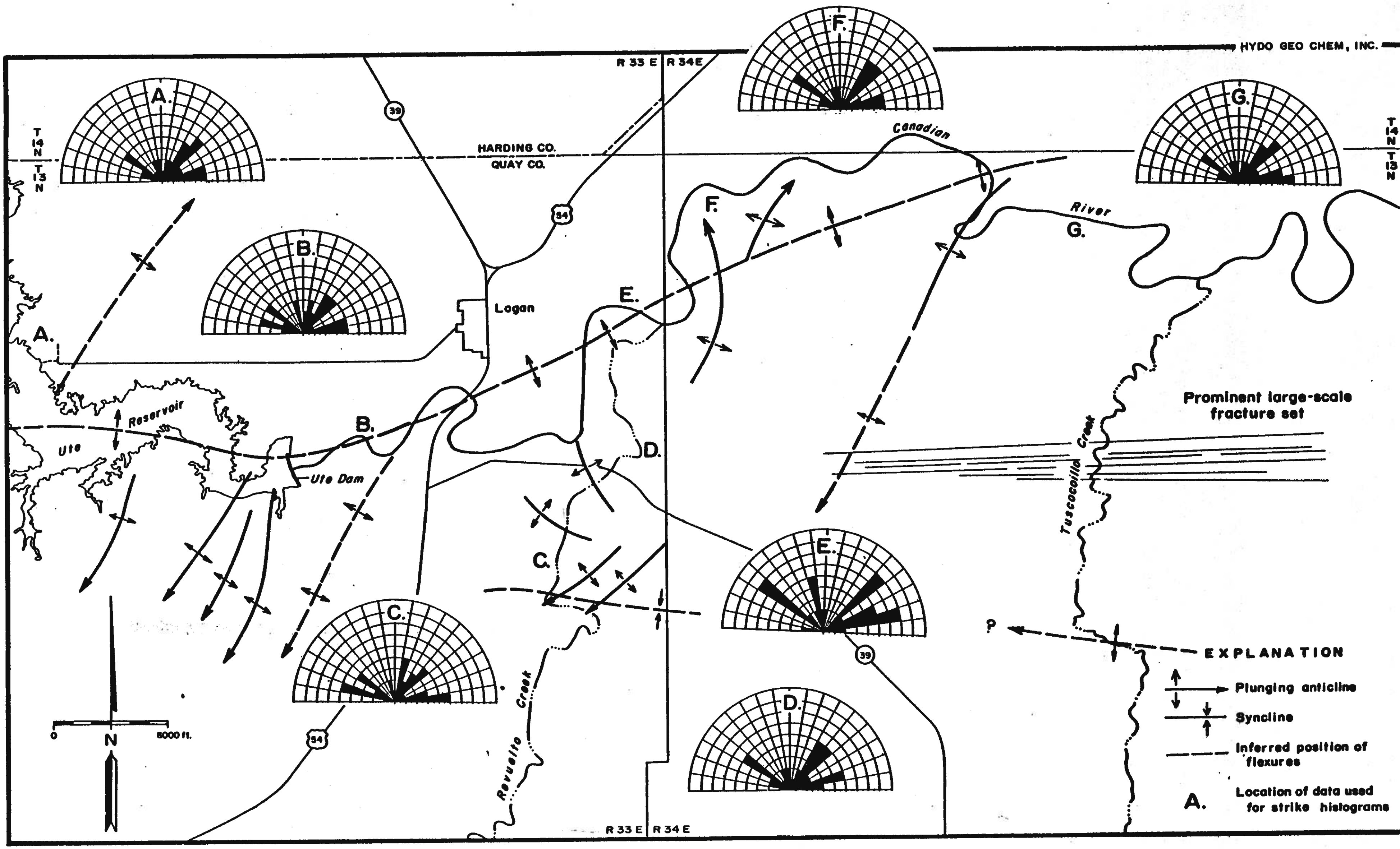


Figure 16. Map showing structural features in the detailed study area

From aerial photographs and low-level aerial observations, we have identified a general grouping of depressions that runs east-west through Logan and along the Canadian River. The trend of the depressions and the mapped flexure are parallel to the subsurface dissolution fronts that have been identified in the area. Follow-up field investigation has confirmed the existence of collapse structures along the river. Rotated blocks of Triassic sandstone were found in a circular collapse structure (section 2, T.13 N., R.34 E.) that is bisected by a northeast trending fracture zone traceable on the surface for 1-2 miles (photographs, Figures 17 and 18). Another collapse feature is suspected in section 6, T.13 N., R.34 E., that lies along the trend of depressions noted in the detailed study area; a large unit of conglomerate appears to be downdropped (without rotation) approximately 50 to 100 feet, and the density of fractures exposed along the river increases significantly in the vicinity. Between Ute Reservoir and the Highway 54 bridge, salt dissolution controlled collapse features are not as evident. However, the fracture patterns there become more chaotic.

2. Fracture Mapping

Fracture orientation data were collected throughout the detailed study area in order to examine the regional fracture patterns and to provide further structural information. The majority of the fractures were near-vertical, spaced between 6 inches and 3 feet apart, and showed little evidence of displacement. Dilatant fractures, filled with a fine-grained sand and often with a calcareous cement, were found throughout the detailed study area. No preferred orientation was observed for the filled cracks.

Figure 17: Photo showing aerial view of collapse structure located in section 2 of T.13N., R.34E.

Figure 18: Photo showing rotated blocks of Triassic sediment in collapse structure of Figure 17.

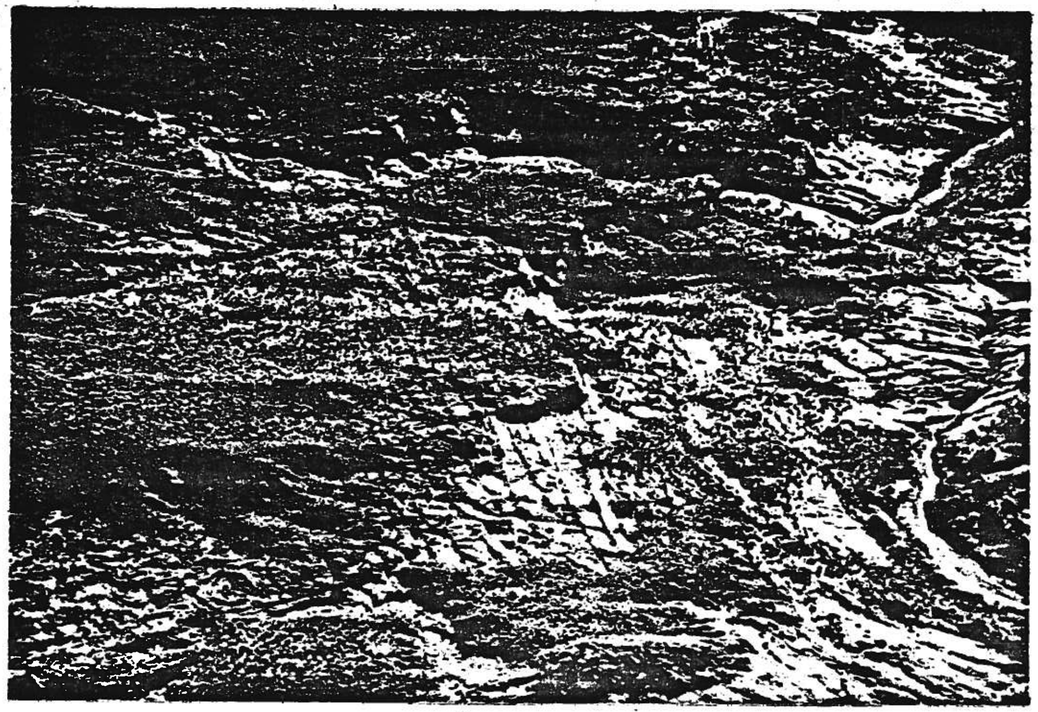


Figure 19: Photo showing aerial view of strongly defined fracture located south of the Canadian River.

Regionally, the fracture patterns are relatively consistent throughout the area. Four major sets can be identified that trend N50W-N70W, N30W-N10W, N30E-N50E, and N70E-N90E. Rose diagrams of fracture orientation have been constructed for subregions of the map area (Figure 16) to demonstrate the spatial variation of orientations. The northeast set is oriented along the same direction as the dominant trend of the flexures mapped on the surface, while the east-west set corresponds to the general trend of the salt dissolution fronts mapped in the subsurface. The N50W-N70W and the N30E-N50E fracture sets appear to control the orientation of the Canadian River; the river often takes turns in these two directions. The N30W-N10W set controls a few minor drainages along the axis of the anticline that runs along the river.

Within the detailed study area, folding is developed in northeast and eastwest directions. The eastwest trend appears to have developed in response to the broad salt dissolution fronts in the subsurface. The observed folding is relatively minor, and most of the associated fractures run subparallel to the front. These observations imply that the regional dissolution is a primary force in the structural development of the area. Comparison of the rosettes of fracture strike direction shows the east-west fractures to shift slightly in orientation with the direction of the river.

The best developed fracture sets are oriented parallel and perpendicular to the northeast trending flexures. They have been observed regionally (Stearns, 1972) and may be tectonic in origin. These fracture sets appear to have influenced the salt dissolution front which has led to localized dissolution and collapse, especially along the northeast direction. The course of Revuelto

Creek and part of the Canadian River appear to be controlled by a northeast trending fracture system in the area just downriver of Ute Reservoir. No displacement of Triassic sandstones could be found. South of the river, an extremely well-pronounced set of east-west trending fractures were found (photograph, Figure 19). These occur between the river and a linear east-west trend defined by upper Rana Canyon and flexures mapped in the upper sections of Revuelto and Tuscocoillo creeks.

Dilational fractures found throughout the area are now filled with a calcite cement. These are widespread, found in many orientations, and are often seen along anticlinal axes. The origin of the calcareous cement has not been established, but the existence of the open cracks indicates that dilatant stresses have been an influence in the area and are likely to have enhanced vertical fluid movement.

CHAPTER III

HYDROLOGY AND GEOCHEMISTRY OF THE STUDY AREA

This chapter is divided into discussions of the hydraulics of flow in the Permian - Triassic groundwater system, the hydrology of the channel deposits, the Canadian River flow, and the chemistry of these flow components. The degree of mixing is determined using geochemical and isotopic data. Lastly, a water and salt balance for Lake Meredith is presented.

Most data used in this chapter are tabulated in the appendices. Locations of measuring points, piezometers, and wells in the detailed study area are shown in Figure 20. Locations of the measuring points in the general study area are shown in Figure 21

PERMIAN-TRIASSIC GROUNDWATER SYSTEM

1. Permian Groundwater Flow

Because of depth, poor water yield and quality, no water wells tap Permian formations within the study area. The Permian recharge area is about 100 miles west of Logan, along the Sangre de Cristo Uplift (see Figure 3). Wells in this region are at elevations of 6500 to 7000 feet, and water levels are mostly greater than 300 feet below land surface (Griggs and Hendrickson, 1951). The wells are mainly in the San Andres and Yeso formations and yields are generally small.

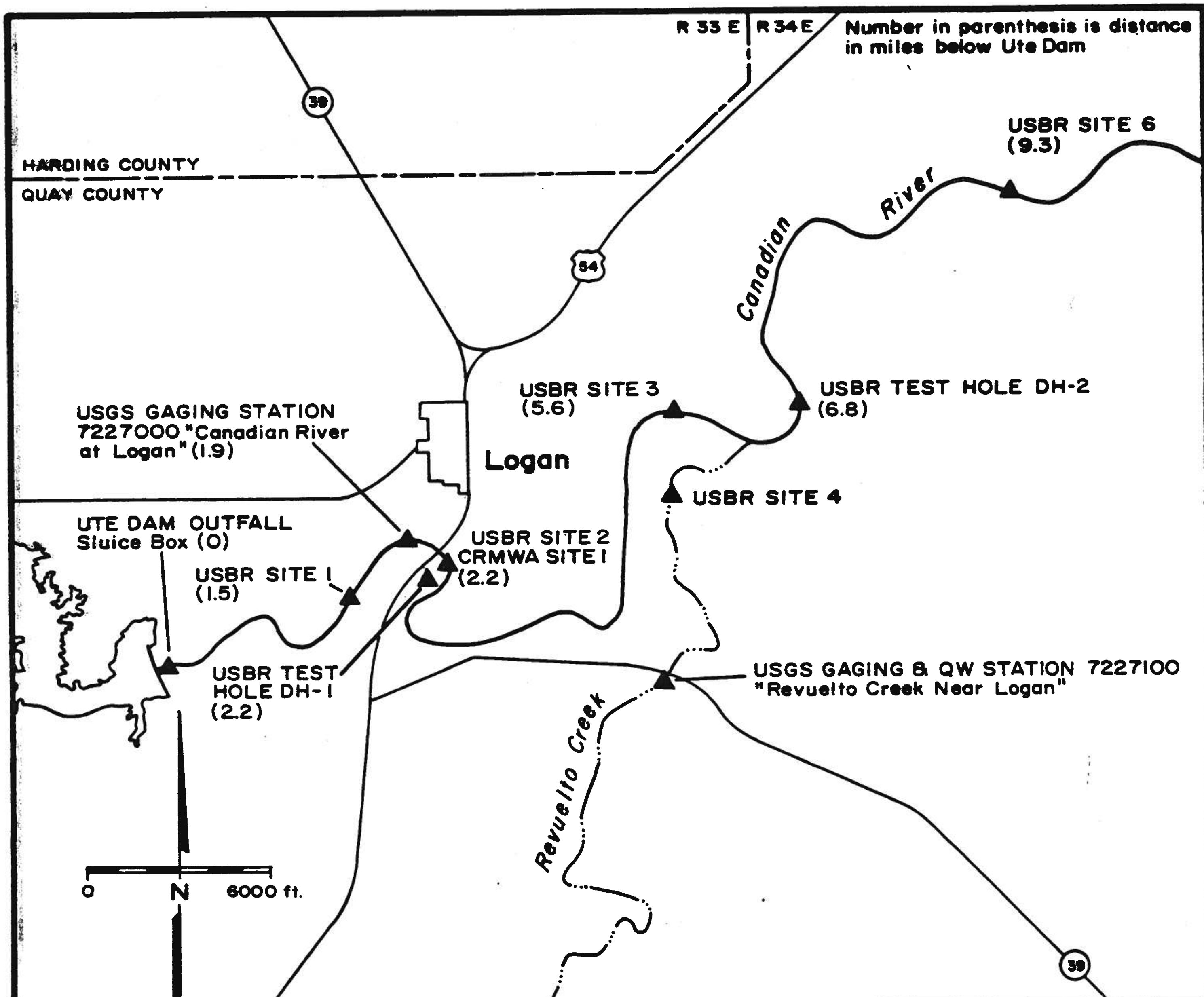


Figure 20. Location map of wells and measuring points in detailed study area

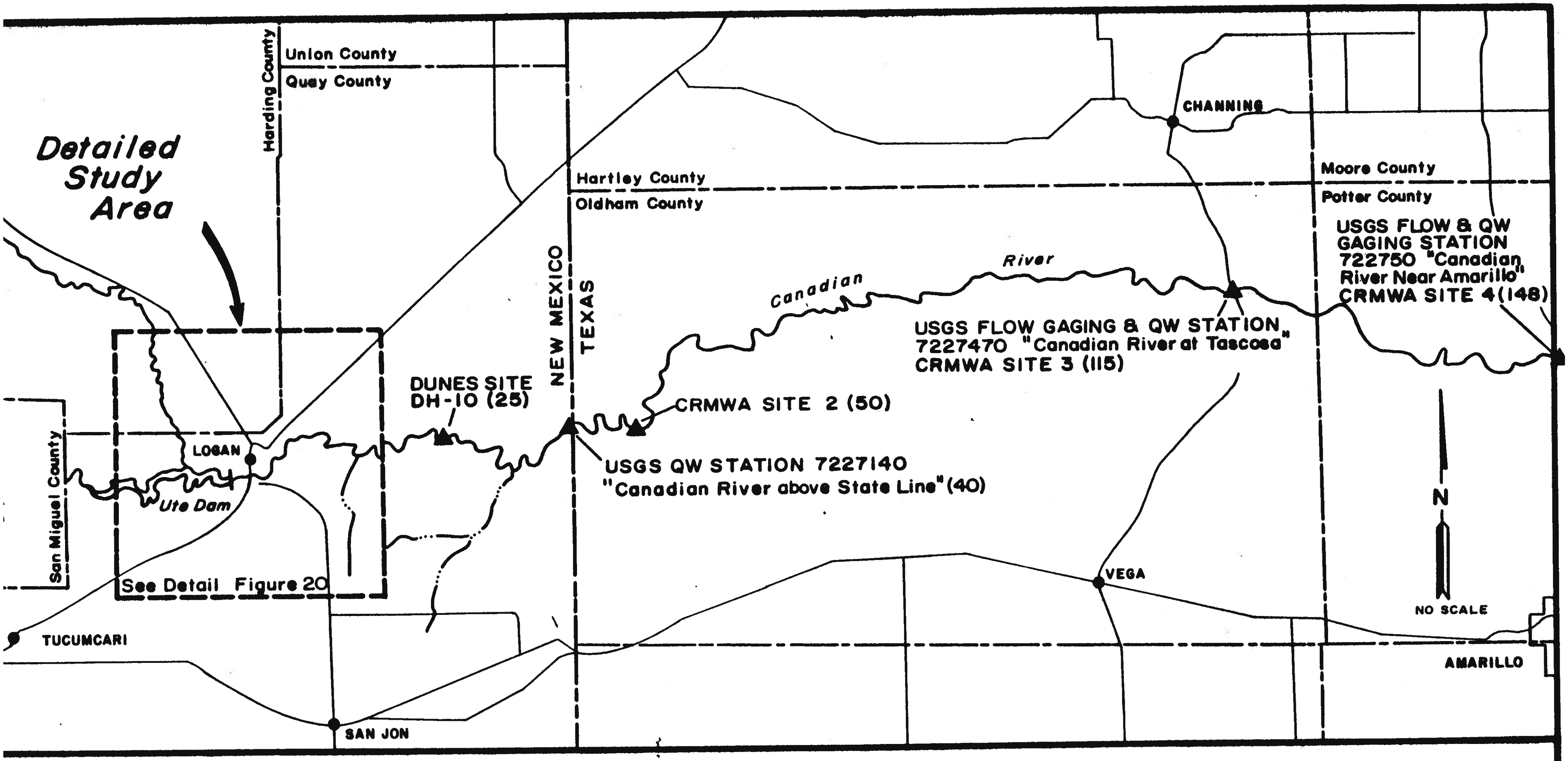


Figure 21. Location map of wells and measuring points in general study area

HYDRO GEO CHEM, INC.

Going eastward, down-dip, toward the study area, the Permian becomes thicker, with a corresponding decline in water yield and quality. Two oil or gas test wells drilled near the study area provide information of the hydrology of the Permian in this area. The Ray No. 1 Hoover well, in section 30, T.11 N., R.28 E., 35 miles southwest of Logan, reportedly had a 1000 gpm artesian flow from the Yeso (Berkstresser and Mourant, 1966). Surface elevation is about 4800 feet. The hydraulic gradient between the Uplift and this well is probably about 15 feet per mile. The permeability of the Permian in this area is very high to cause such a large flow rate, and is probably due to carbonate dissolution, which has been observed in nearby Santa Rosa and along the Pecos River (Kelley, 1972). The Dripping Springs well, located about 12 miles west of Logan in section 25, T.13 N., R.31 E., along the south bank of the Canadian River, was drilled to Precambrian in 1918. We observed in September, 1983, that this well also flows at the surface (about 3800 feet elevation). The unregulated flow rate was less than 100 milliliters per minute of brine; it has probably been flowing for many years. If the original hydraulic head was near land surface, then the hydraulic gradient from the Sangre de Cristo Uplift was about 18 feet per mile.

No further hydraulic information exists on the Permian in the New Mexico portion of the study area. In the Panhandle of Texas, numerous drill-stem tests from oil and gas holes have been analyzed by Bassett and Bentley (1983). The authors identify a hydrologically combined lower Permian and Pennsylvanian system, called the Wolfcamp, separated from shallower aquifers by hundreds of feet of bedded salt. Permian water from New Mexico, described above, is assumed by Bassett and Bentley to be connected to this Wolfcamp aquifer. The hydraulic gradient is eastward at about 17 feet per mile. The highest measured hydraulic head was about 2800 feet elevation in mid-Oldham County, Texas, which was the farthest west that the authors considered. The hydraulic gradient between the Ray No. 1 Hoover well and mid-Oldham County is about 18 feet per mile. The permeability of the system was estimated by the authors to be on the order of 10^{-3} ft/day, which is consistent with its lithology and depth of burial. The eventual discharge area for this Permian aquifer is probably as salt springs along and east of the caprock escarpment in the east Texas Panhandle.

Along the Canadian River downstream from Tascosa, Texas, the Permian Quartermaster Formation is exposed. Several flowing wells near the river are probably completed in these rocks. We have no water quality, geologic, or well construction information for these wells. Because the hydraulic potential of the lower Permian Wolfcamp aquifer is hundreds of feet below land surface in Texas (Bassett and Bentley, 1983), the source of the flowing water from these wells is probably from a fairly shallow circulation system.

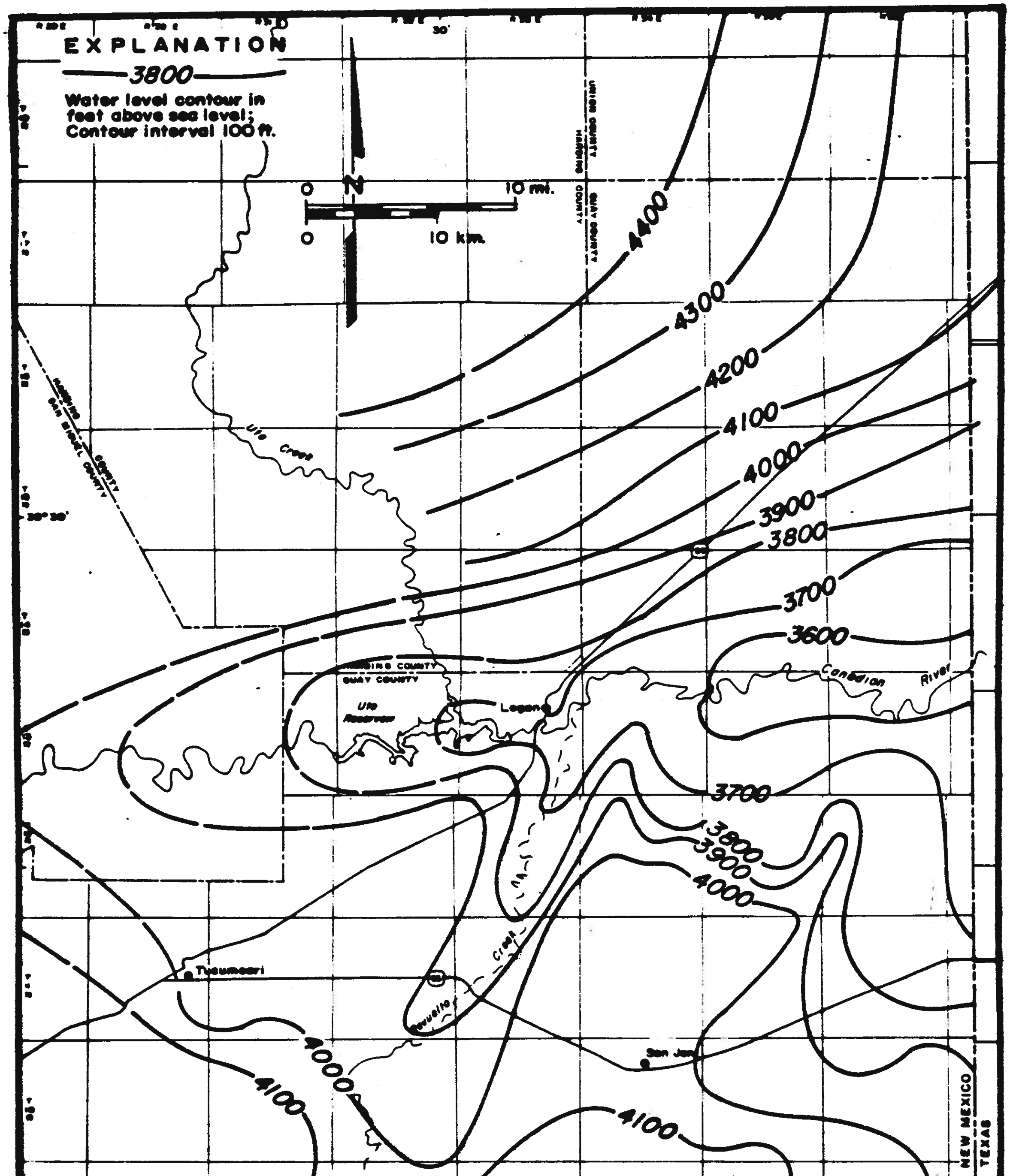
In summary, the Permian groundwater flows eastwardly at a fairly even gradient between 15 and 20 feet per mile from the Sangre de Cristo Uplift to Texas. Heads are above land surface in the New Mexico portion of the study area, but because the hydraulic gradient is much steeper than the land surface gradient, heads are far below land surface in Texas. The permeability of the Permian rocks is generally low but may locally be very high due to fractures and dissolution. This is probably the case in the area of the Ray No. 1 Hoover well, and has even been noted deep in the Palo Duro Basin in Texas.

2. Triassic Groundwater Flow

The Triassic system in the study area is divided into the Santa Rosa Sandstone, Chinle and Redonda formations. It is separated from the salt-prone Permian rocks by the shales and mudstones of the Artesia Group. Most of the available hydrologic information for the Triassic is from Berkstresser and Mourant (1966), who performed the majority of the water-level and water-quality measurements. In Texas few published data are available on Triassic water wells within the general study area because most potable water is utilized from the overlying Ogallala aquifer.

Figure 22 is a map of the Triassic water-level surface within the detailed study area. These water levels are tabulated in Appendix A, Table A.1. Most of the Triassic flow within this area is toward the Canadian River. The topography and surface drainages are seen to strongly influence water levels, especially south of the river. The Canadian River, Revuelto Creek, and Rana Canyon are apparent discharge areas for the Triassic. The shape of the surface shows that much of the recharge to the Triassic is derived locally. Several groundwater mounds are evident between the streams, some of which may be due to irrigation recharge from the Tucumcari Project. Contours are smoother north of the river because data are fewer and because the Triassic becomes buried under dune sand and the Ogallala Formation, thus reducing the influence of surface features.

Transmissivity of the Triassic aquifer has not been measured within the study area. Hydraulic conductivity has been estimated by Bassett and Bentley (1983) to range from 0.25 and 2.5 ft/day. Because the Triassic is usually poor-



Adapted from Berkstresser and Mourant, 1966

Figure 22. Triassic water-level surface within detailed study area

HYDRO GEO CHEM, INC.

ly sorted, well-cemented, shale-rich, and highly fractured, a 10-fold variation in hydraulic conductivity in the area is reasonable and probably conservative. Well records (Griggs and Hendrickson, 1951; Berkstresser and Mourant, 1966) indicate that the Triassic has typically low water yields. Estimates of specific capacity based on these records range from about 0.01 gpm/ft to 0.5 gpm/ft. The saturated thickness of the Triassic aquifer is unknown because both the lower Triassic and upper Permian are shale-rich. Logs of wells DH-10 (Spiegel, 1972b), DH-1, DH-2 and DH-3 (unpublished records from U.S. Bureau of Reclamation) indicate that thickness is from 150 to 300 feet. We estimate that Triassic transmissivity near the Canadian River averages about 300 ft^2/day.

The amount of water flowing into the Canadian River from the Triassic aquifer can be calculated by

$$Q = TIL$$

where Q is flow, T is transmissivity, I is hydraulic gradient, and L is stream length. The average hydraulic gradient north of the river is about 40 feet/mile; south of the river it is extremely variable but probably averages 20 ft/mile. Using a transmissivity of 300 ft^2/day, the calculated discharge from the Triassic into the Canadian River is 0.15 cfs per stream mile, or a total of about 5 cfs between Ute Dam and the state line. The heterogeneity of the rocks, thickness variations, and changes in hydraulic gradient probably cause this inflow to occur unevenly along the channel. For example, because of greater saturated thickness, more discharge to the river would be expected near Logan than at the state line. We observed on several occasions that flow in the river increased about 1 cfs near the Highway 54 bridge. In Texas, as the Triassic thins through erosion and becomes more shale-rich, much less water is conducted to the river. In addition, the water-level gradient appears to decrease eastwardly toward the state line. Therefore, we believe that most groundwater inflow from the Triassic occurs within the New Mexico portion of the study area.

3. Shallow Brine Aquifer

Wells drilled by the Bureau of Reclamation south of Logan along the banks of the Canadian River into lower Triassic and upper Permian rocks encountered a sand - gravel aquifer that flowed saline to brackish water at the surface. These wells were drilled to ascertain the existance of such an artesian reservoir, based on the belief that brine discharge to the river was occurring in the area, and on the results of a surface resistivity survey (U.S. Bureau of Reclamation, 1979). No mention of artesian water or brine is made in other logs from wells in the vicinity. The New Mexico State Engineers office drilled a test hole (DH-10) into the Permian Quartermaster Formation (stratigraphically above the Artesia) about 20 miles downstream from Logan, but no mention was made of encountering either artesian flow or saline water (unpublished drilling records from New Mexico State Engineers office; Walker and Irwin, 1958).

Drilling records and geophysical logs of these wells (furnished by Bureau of Reclamation) indicate that the top of the aquifer is a shale layer in the lower Triassic. It is probably bounded on the bottom by shale near the top of the Artesia Group, with a saturated thickness of about 80 feet. The hydraulic head appears to be a few feet above river level, about 3674 feet (unpublished records from Bureau of Reclamation). This newly-identified aquifer is below and appears to be isolated from the Triassic aquifer previously discussed. Its location in the stratigraphic section above the San Andres and Yeso formations, known artesian brine aquifers, tends to isolate the layer from below. Thus we name it the shallow brine aquifer. The hydraulic head in this aquifer has not been measured but from estimates given by the Bureau of Reclamation it is probably similar to that in the Triassic aquifer in the vicinity. The head is higher than that in the river deposits. It is also possible that the head in the Permian brine aquifer is the same as in this shallow brine aquifer. The two brine aquifers might also be connected by fractures or dissolution channels. Evidence for a deep circulation pattern is given in the chemistry sections later in this chapter.

A test of this aquifer was conducted by the Bureau by pumping one of the wells and monitoring the response in several observation wells. A pumping rate of greater than 400 gallons per minute was obtained, but there were interpretation problems due to well construction and pump difficulties. However, a fair Theis curve match was obtained, giving a transmissivity of, roughly, 2500 ft^2/day. The calculated storage coefficient was in the artesian range. No evidence of leakage, recharge boundaries, or stabilization of the drawdown curve could be seen in the data, which is puzzling considering both the proximity of the wells to the river and brine discharge, and to the overlying or nearby Triassic water-table aquifer. It is probable that either the cone of depression had not expanded enough to intercept an area of upward leakage, or that this effect was masked by test problems.

It has been postulated that brine discharge to the Canadian River below Ute Dam has been caused by pressurization of this shallow brine aquifer by Ute

Reservoir, or that brine flow has increased because of the reservoir. However, Spiegel (1957a) mentioned the existence of brine inflow in this area several years prior to the construction of Ute Dam. Also, geochemical evidence, given later in this chapter, shows that the rate of chloride inflow to the river has not risen significantly since dam construction. Thus, the effect, to date, of Ute Reservoir on the flow of brine to the river has not been large. This does not preclude the possibility of planned higher reservoir stages affecting brine flow in the future.

CANADIAN RIVER HYDROLOGY

1. Channel Deposits

The Canadian River below Ute Dam has cut a channel through nearly 1000 feet of Triassic rocks (difference between the elevation of the stream channel and the elevation of the Triassic under the caprock). Between 50 and 75 feet of fine-grained clastic sediments have been deposited in the channel. The channel is 400 to 600 feet wide for most of the reach between Ute Dam and the New Mexico-Texas state line. Along the 75 river miles between state line and Tascosa, Texas the river widens its flood plain to as much as 2 miles; at Tascosa the channel width is about 0.7 miles. Downstream from Tascosa the channel gradually narrows to about 1000 feet. The stream gradient is fairly uniform, averaging 5.3 feet per mile, from an elevation of about 3680 feet at Ute Dam to 2900 feet at the bridge at Highway 287 north of Amarillo, 148 river miles downstream.

The Canadian River Municipal Water Authority (CRMWA) and the Bureau of Reclamation have each drilled several piezometers into the channel deposits since about 1972. See Figures 20 and 21 for locations of these wells. Each of the sites have several piezometers at depths between 15 and 50 feet. Drilling notes furnished by the Bureau of Reclamation mention that sand, a few 'pea sized' gravel lenses or interbeds, and clay were encountered while drilling. Depths to bedrock under the channel ranged from 20 feet in Revuelto Creek, to 34 feet at USBR Site 1, to 50 feet at USBR Site 6 and CRMWA Sites 2 and 4. At the Dunes damsite, well DH-10 penetrated about 80 feet of channel deposits (Spiegel, 1957a). Water levels in the piezometers are generally within a foot or two of the land surface, and there are no noticable water-level variations between piezometers open at different depths at the same sites. Permeability has not been measured in any of the channel piezometers. Given the predominance of poorly sorted, medium to fine grained sands, and the uncertain continuity of gravel layers, we estimate that the channel's hydraulic conductivity ranges between 5 and 20 feet/day (Davis and DeWiest, 1966). Based on the higher value, flow rates through the alluvium are calculated to vary from about 500 ft^3/day (5.8×10^{-3} cfs) at piezometer Site 1, to about 6600 ft^3/day (7.6×10^{-2} cfs) at Tascosa. These flows are small because of the very low hydraulic gradient. Errors in our estimates of hydraulic conductivity or channel cross-section would cause at most a doubling or tripling of this flow value, still a very small number. The actual fluid velocity within the channel sediments is less than 0.1 feet per day for an assumed effective porosity of 20 percent. This does not imply that the influence of the channel deposits on brine flow is small; however, by these calculations we can see that the largest amount of brine is transported by surface water.

2. Surface-Water Flow

Surface-water flow in the Canadian River between Ute Reservoir and Lake Meredith has been measured by the Bureau of Reclamation and the USGS for locations listed in Table 3. These locations are shown in Figures 20 and 21. Flow data was obtained from Water Resources Data from New Mexico and Texas, various years, from USGS Water-Supply Papers, and from unpublished Bureau of Reclamation data. The discussion of flow begins at Ute Dam and proceeds in a downstream direction.

Flow from Ute Dam is periodically measured through a Parshall flume connected to a long toe drain. During the period of this study, flow averaged about 1 cfs. In addition there is a small amount of leakage from the flood gates. Spiegel (1969) estimated that 5 cfs leaks through or around the dam into the river; however, from our observations, this rate seems too high.

The flow record for the Canadian River at Logan, about 2 miles downstream of the dam, is shown in Figures 23 and 24. The effect of closure of Ute Dam in December, 1963, is obvious; mean monthly flow dropped from 307 cfs before closure to 30 cfs since closure; the median flow from 80 to about 2 cfs. The large difference between mean and median flows is due to the few occasions of flow over the spillway at Ute Dam. The low median flow is about equal to that which seeps through the dam.

Base flow in Revuelto Creek, which enters the Canadian River about 6 miles below Ute Dam, is largely sustained by irrigation return from the Tucumcari Pro-

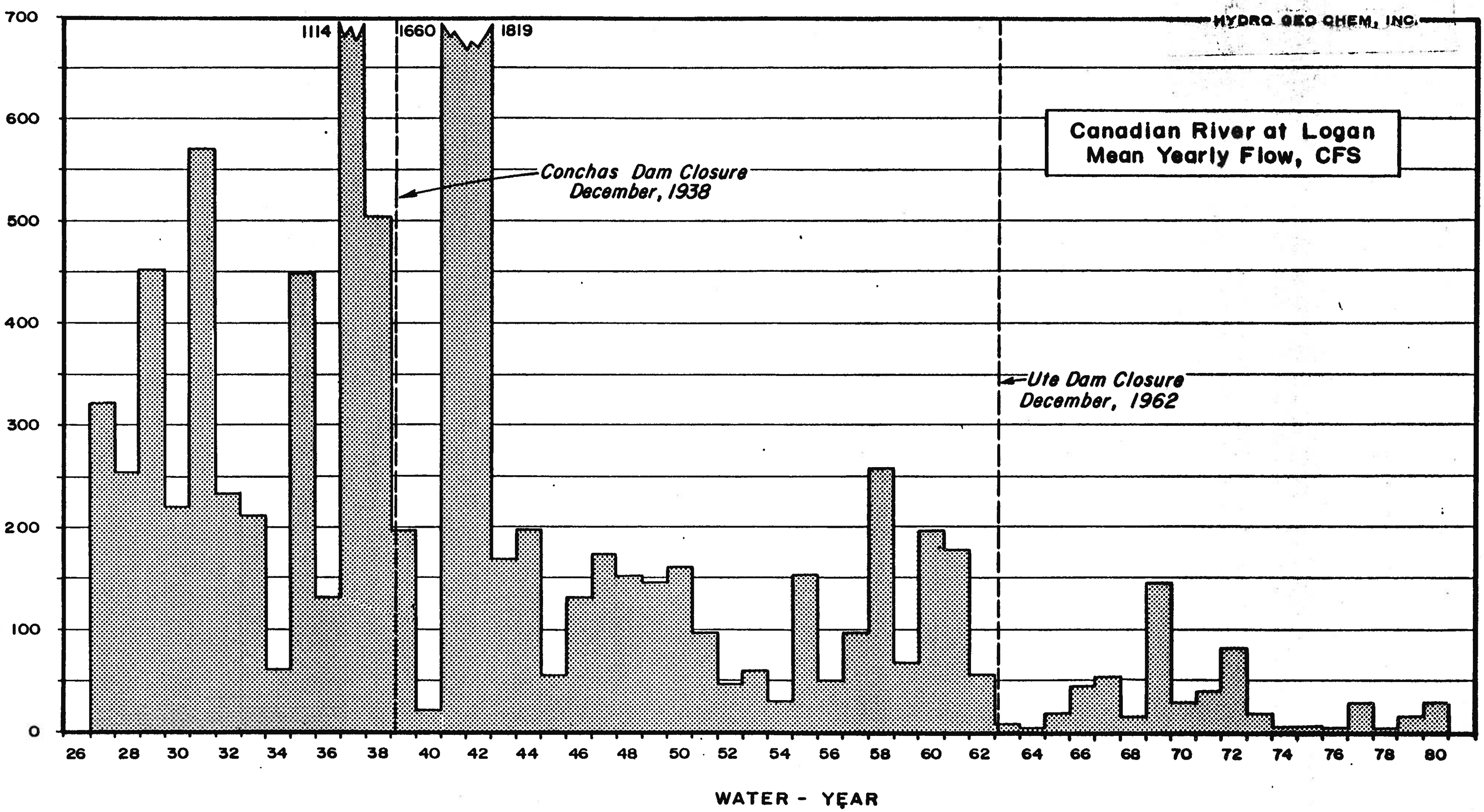


Figure 23. Average yearly flow in Canadian River at Logan, 1927-1981

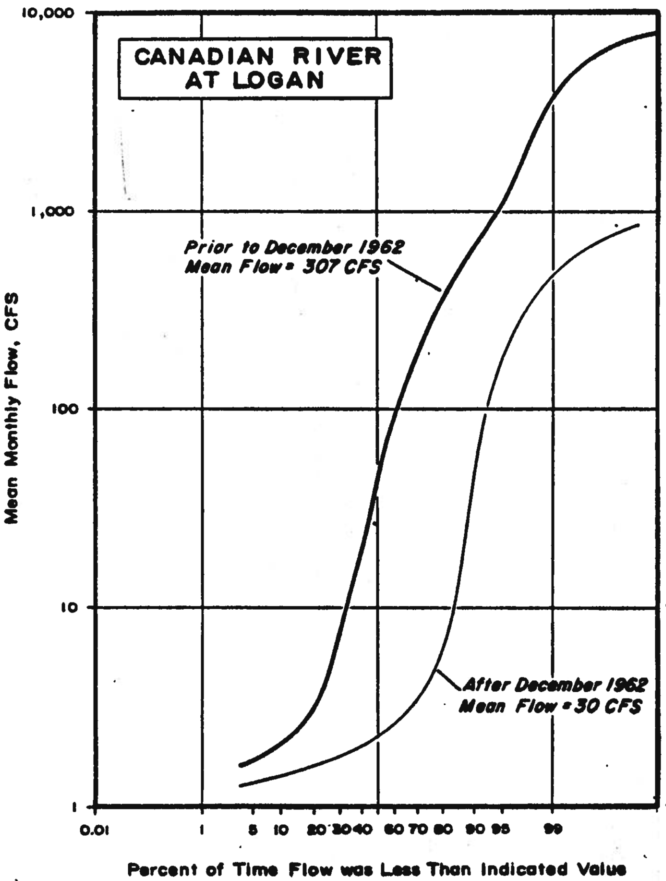


Figure 24

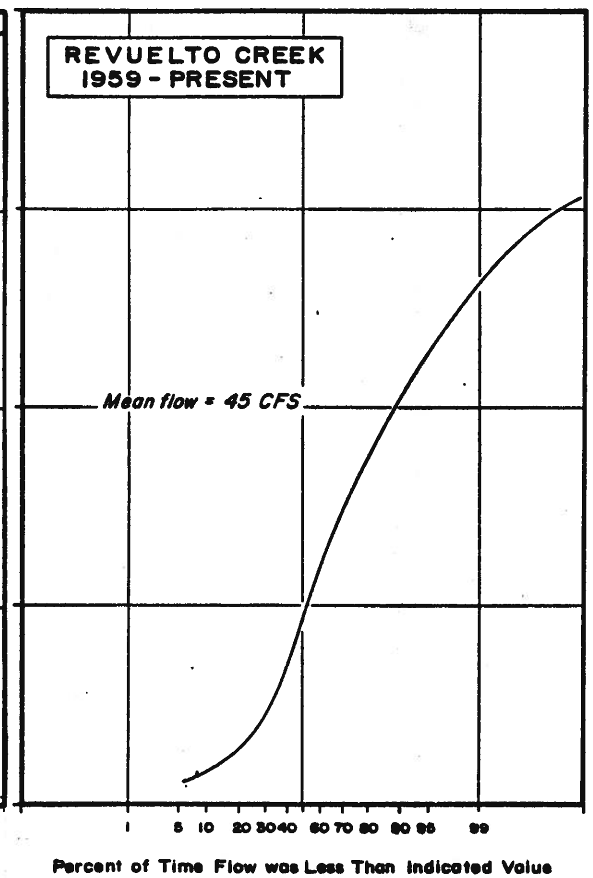


Figure 25

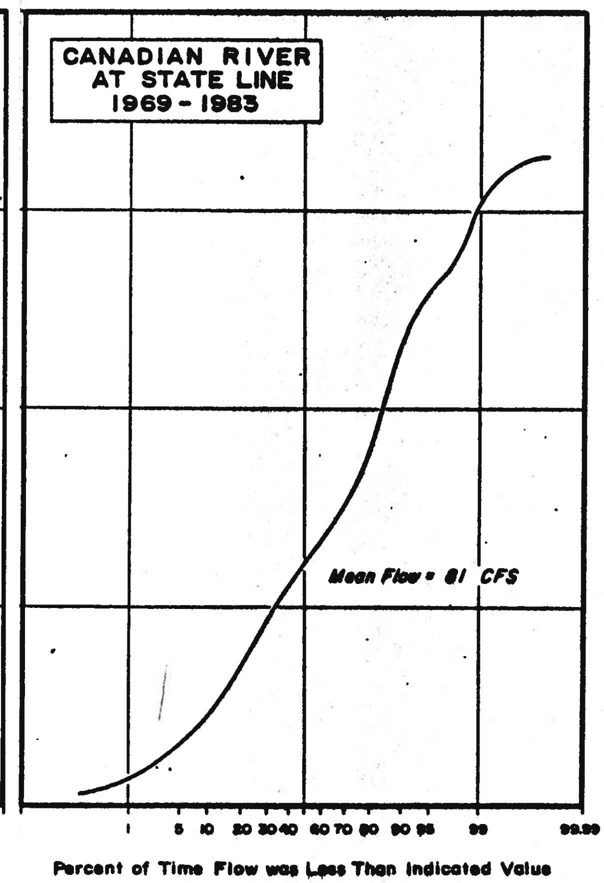


Figure 26

Flow duration curves

HYDRO GEO CHEM, INC.

ject. Figure 25 shows the flow-duration curve for Revuelto Creek. Mean monthly flow is 45 cfs and the median is 8 cfs. As expected, flows in Revuelto Creek and the Canadian River at Logan show no correlation. Their combined mean flow is 75 cfs. The combined median flow for the period since Ute Dam was closed is 10 cfs.

Table 3: Flow-measurement stations in study area

USGS Station	Location	Period of Record (water years)
-	Ute Reservoir Toe Drain	1969?-present (periodic measurements taken, only)
7227000	Canadian River at Logan (near Hwy 54 bridge)	1909-1910; 1912-1915 1924-1925; 1927-present
7227100	Revuelto Creek near Logan (at Hwy 39 bridge)	1959-present
7227140	Canadian River above State Line	1969-present (periodic measurements taken, only)
7227470	Canadian River at Tascosa	1968-1977
7227500	Canadian River nr Amarillo (at Hwy 87-287 bridge)	1924-1926; 1938-present

Flows are periodically measured near the New Mexico - Texas state line, about 40 river miles downstream from Ute Dam; however, no gaging station is maintained there. Figure 26 shows the flow-duration curve for this station, based on 127 flow measurements since 1969. The mean measured flow is 81 cfs and the median is 13 cfs.

The correlation between combined daily flows upstream at the Revuelto and

Logan stations and these state line measurements is good for low flows but poor for high flows. When only low flows since 1969 are considered in the correlation, the average state line flow was 11 cfs, while the average flow at the combined Logan and Revuelto stations was 7 cfs, with a correlation coefficient (using least-squares analysis) of 0.70, which is fairly good. Thus the low flow increases by about 4 cfs between the Revuelto Creek confluence and the state line. This is mostly due to base flow increases, or groundwater inflow. This is in agreement with the previous calculation of Triassic discharge to the river.

The flow-duration curve for the Canadian River at Tascosa, Texas, 115 river miles downstream from Ute Dam, is shown in Figure 27. Mean monthly flow is 168 cfs, and the median is about 30 cfs for the period between 1968 and 1977. The mean monthly flow for the same period at the combined Logan and Revuelto stations was 81 cfs, for a net gain of 87 cfs. During low flows, however, the gain is only 5 to 15 cfs, and some periods show stream losses. (Tascosa recorded three months of zero flow.) When large gains in flow occurred, it was during the summer rainy season, most likely from the perennially flowing Punta de Agua drainage (located about 20 miles upstream of Tascosa). Thus there is probably little groundwater inflow between the state line and Tascosa. This supports the hypothesis that little Triassic groundwater discharges to the river in Texas.

The Canadian River near Amarillo, 148 river miles downstream from Ute Dam, is the last flow measurement station upstream of Lake Meredith. The flow-duration curve is shown in Figure 28 and the total flow record in Figure 29. Mean monthly flow at the Amarillo station dropped from 456 cfs to 190 cfs

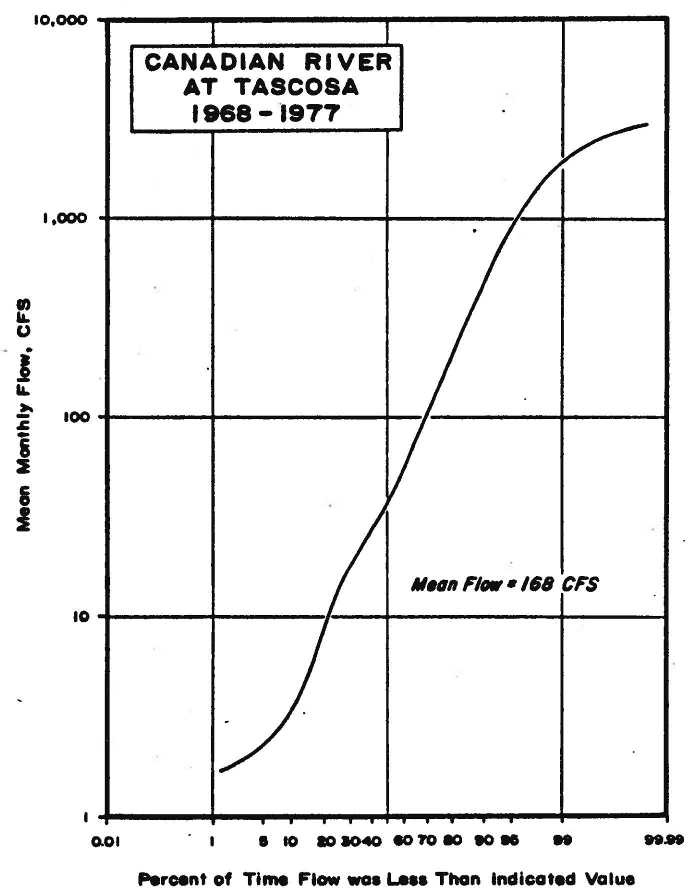


Figure 27

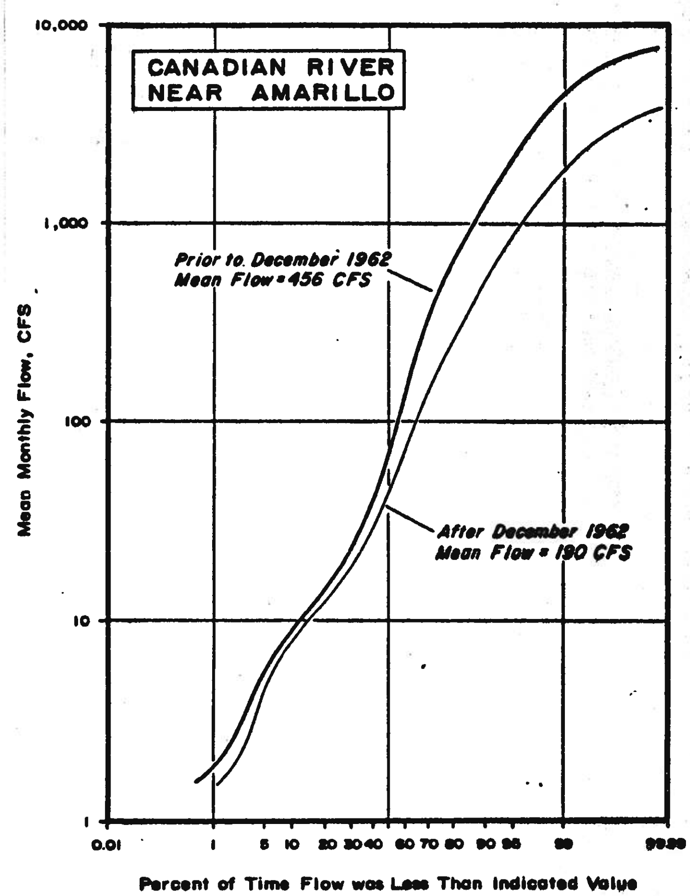


Figure 28

Flow duration curves

HYDRO GEO CHEM, INC.

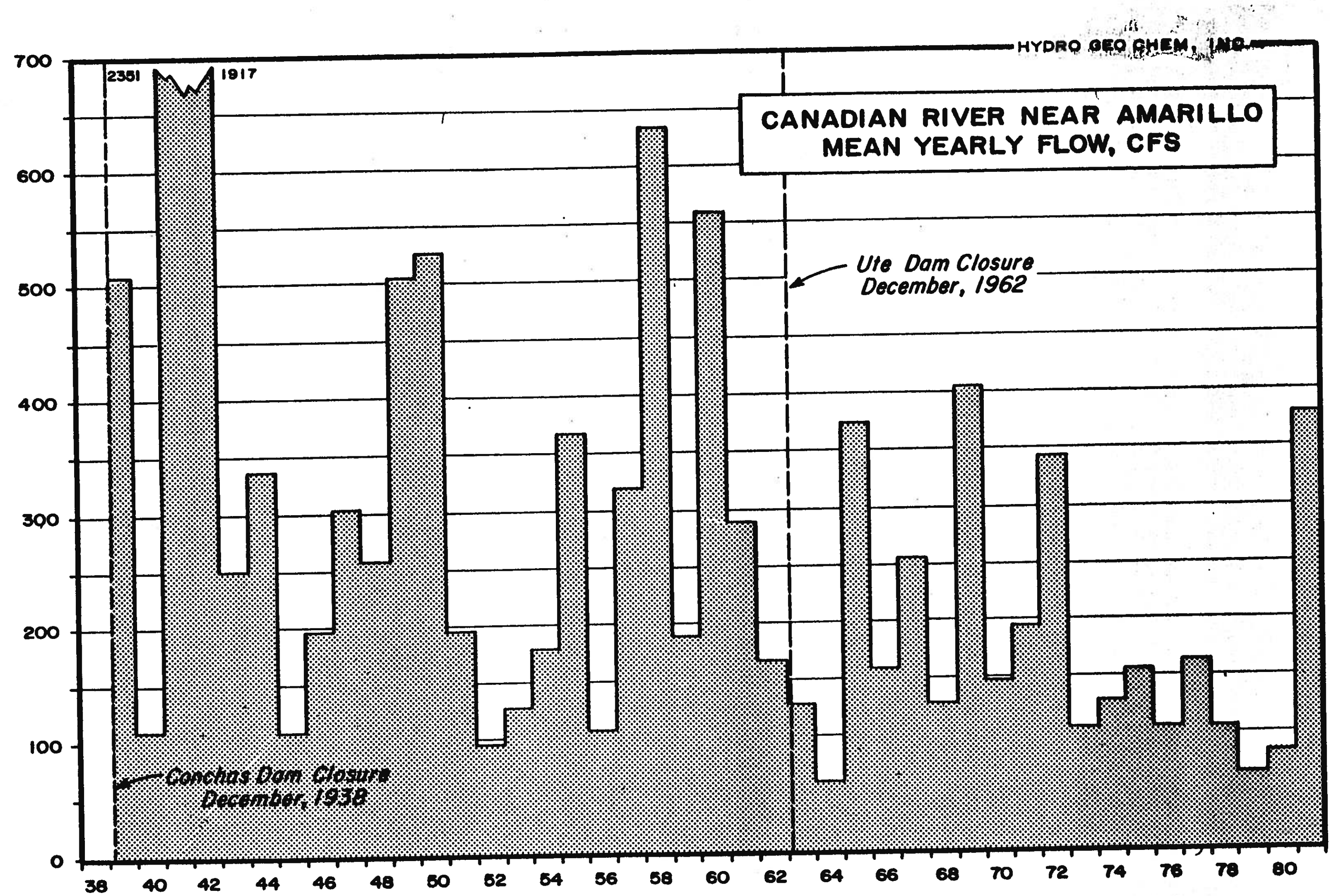


Figure 29. Average yearly flow in Canadian River at Amarillo, 1939-1981

after the closure of Ute Dam, which is nearly the same reduction as at the Logan gage. The median flow at Amarillo dropped from 65 cfs to 50 cfs after dam closure, much less than the drop at Logan. Thus, since Ute Dam closure, much of the flow at Amarillo has come from the drainage area downstream of the Logan gage.

The correspondence between flow at the Amarillo gage and the other upstream stations are listed in Table 4. We can see that the correlation between Logan and Amarillo dropped after the completion of Ute Dam. When the flow from Revuelto Creek is added to the Logan record, the correlation improves, but not as much as for the pre-Ute Dam period. The reduced correlation is due to reduction of flow upstream of Logan. Historically, an average of 67% of the flow at Amarillo came from upstream of Logan (307 cfs/456 cfs), but this dropped to 16% (30 cfs/190 cfs) after completion of the dam. The correlation between flows at Tascosa and at Amarillo is high, primarily due to a consistent gain in flow between the gaging stations, much of which comes from sewage effluent and from some groundwater inflow.

On the average, the river gains in flow between Ute Dam and the gage near Amarillo. We estimate that the present-day gains are roughly distributed as discussed above and as summarized in Table 5.

Table 4: Summary of correlations between Canadian River flow at Amarillo and at various upstream stations

Correlation between	Mean Flow at Amarillo (cfs)	Mean Flow at other station (cfs)	Correlation coefficient (r^2)
Amarillo and Logan, prior to 1962	456	307	0.81
Amarillo and Logan, after 1962	190	30	0.39
Amarillo and Tascosa, 1968 to 1977	196	168	0.90
Amarillo and (Logan plus Revuelto), 1959 to 1981	196	92	0.60
Amarillo and State Line, 1969 to 1981	173	81	-

Table 5: Summary of gains in Canadian River flow between Ute Dam and Lake Meredith

	Flow Gain	From
1.	30 cfs	below Ute Dam, of which about 2 cfs is from seepage and groundwater inflow, the rest from the few occasions of flow over the spillway.
2.	45 cfs	from Revuelto Creek, primarily from irrigation return (about 8 cfs) and flood flows.
3.	5 cfs	between Revuelto Creek and State Line, primarily from groundwater inflow.
4.	87 cfs	between State Line and Tascosa, primarily from flood flows, probably from the Punta de Agua drainage.
5.	22 cfs	between Tascosa and Amarillo, mostly from groundwater groundwater inflow, some from irrigation return, little from flood flows.

Total: 190 cfs at Amarillo gage

CHEMISTRY OF GROUNDWATER - SURFACE WATER SYSTEM

Chemical analyses of groundwater and surface water have been obtained from the literature, from unpublished records, or from samples collected during this study. These analyses are tabulated in Appendix B.

1. Chemistry of Permian Water

The chemistry of groundwater generally reflects the composition of the rock types it flows through as well as the distance from its point of recharge and time spent in the aquifer. Water quality in the primary recharge area for the Permian is generally good for the 9 available analyses (Griggs and Hendrickson, 1951). Total dissolved solids average 750 mg/l, and chlorides average less than 10 mg/l. The predominant water types are calcium bicarbonate, calcium sulfate, ana sodium bicarbonate. The first two types are those evolved through dissolution of limestone or dolomite and gypsum, typical rocks comprising the San Andres and Yeso. The third water type is probably due to exchange of calcium for sodium on clay minerals.

A convenient way to compare water quality analyses from several sources is graphically using Stiff diagrams. In this type of graph, ion concentrations (on an equivalence basis) are plotted as points on two scales, one for major cations, the other scale for major anions, and the points are connected, giving the analysis a characteristic shape. Figure 30 shows Stiff diagrams of water analyses from Permian and Pennsylvanian rocks from the recharge area. The characteristic shapes show the dominance of the calcium, sulfate, and bicar-

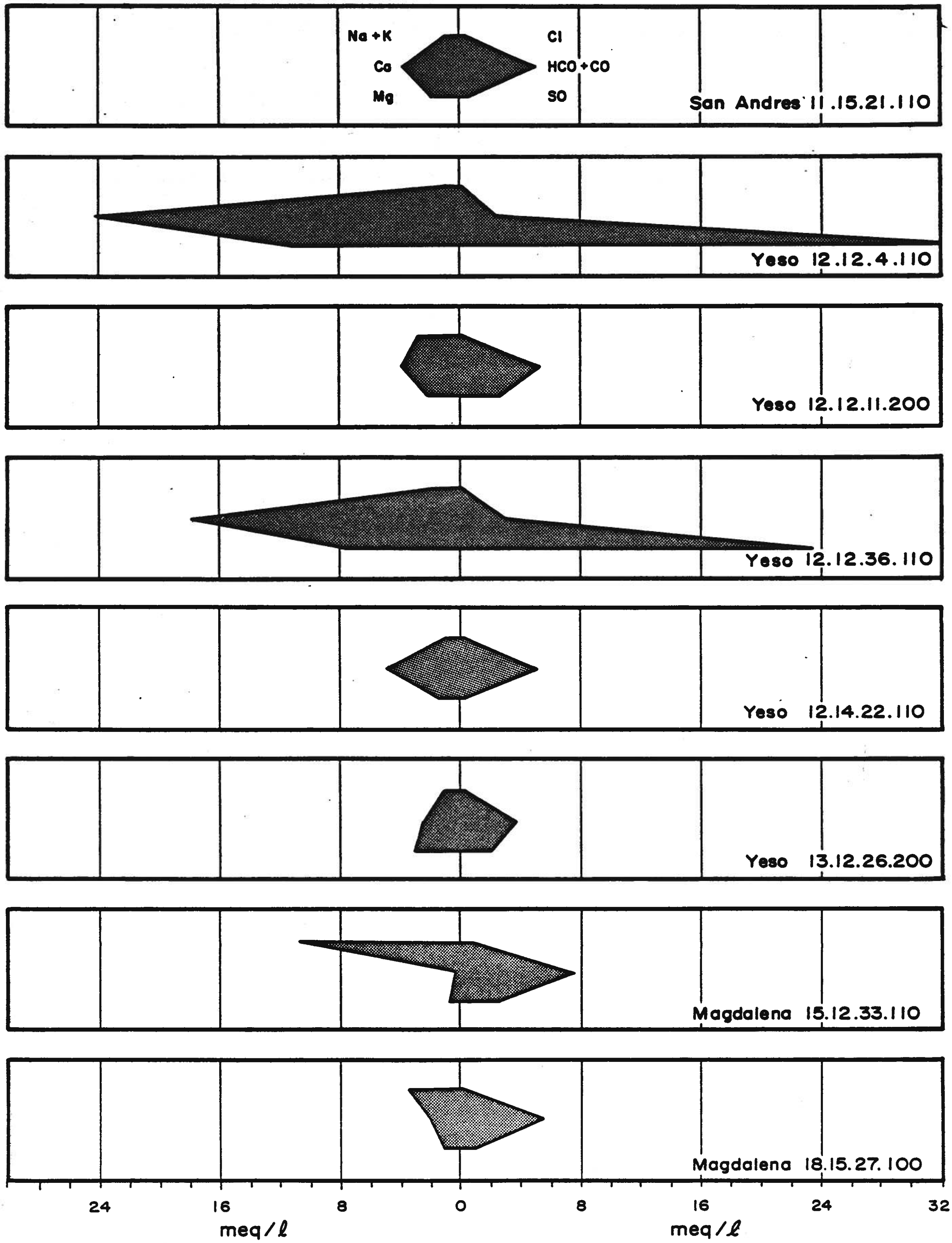


Figure 30. Stiff diagrams of Permian water near recharge area

bonate ions in the water chemistry, and the lack of chloride.

The evolution of Permian water as it flows eastward from its recharge area can be seen in the Stiff diagrams in Figure 31. Halite dissolution is evident in the diagram for the Ray No. 1 Hoover well (11.28.30.232) near Tucumcari. Both sodium and chloride greatly increase, and are nearly equal on an equivalence basis. This strongly implies that the source of the ions is through the dissolution of halite. The increases in calcium, bicarbonate and sulfate from their concentrations in the recharge area are due to the continued contact with Permian carbonates and gypsum. However, the relatively low total dissolved solids (7,100 mg/l) compared to Permian water quality farther to the east, indicates that the location of this well was near, but still to the west of, Permian halite deposits.

The analysis from the Dripping Springs well, from a sample collected in this study, is also shown in Figure 31 and listed in Appendix B. This water is predominantly of sodium-chloride, much more concentrated than the water from Ray No. 1 Hoover. It has low pH (6.02), high TDS (81,000 mg/l), and may evolve CO_2 gas, by a combination of sulfate reduction and hydrocarbon oxidation:

$$SO_4^{-2} + 2CH_2O + 2H^+ \rightarrow H_2S + 2CO_2 + 2H_2O$$

The source of the salt is evidently from halite dissolution. This well is along the boundary of the halite dissolution zone shown in Figure 5.

Stiff diagrams of four wells in Hartley and Potter counties, Texas, are

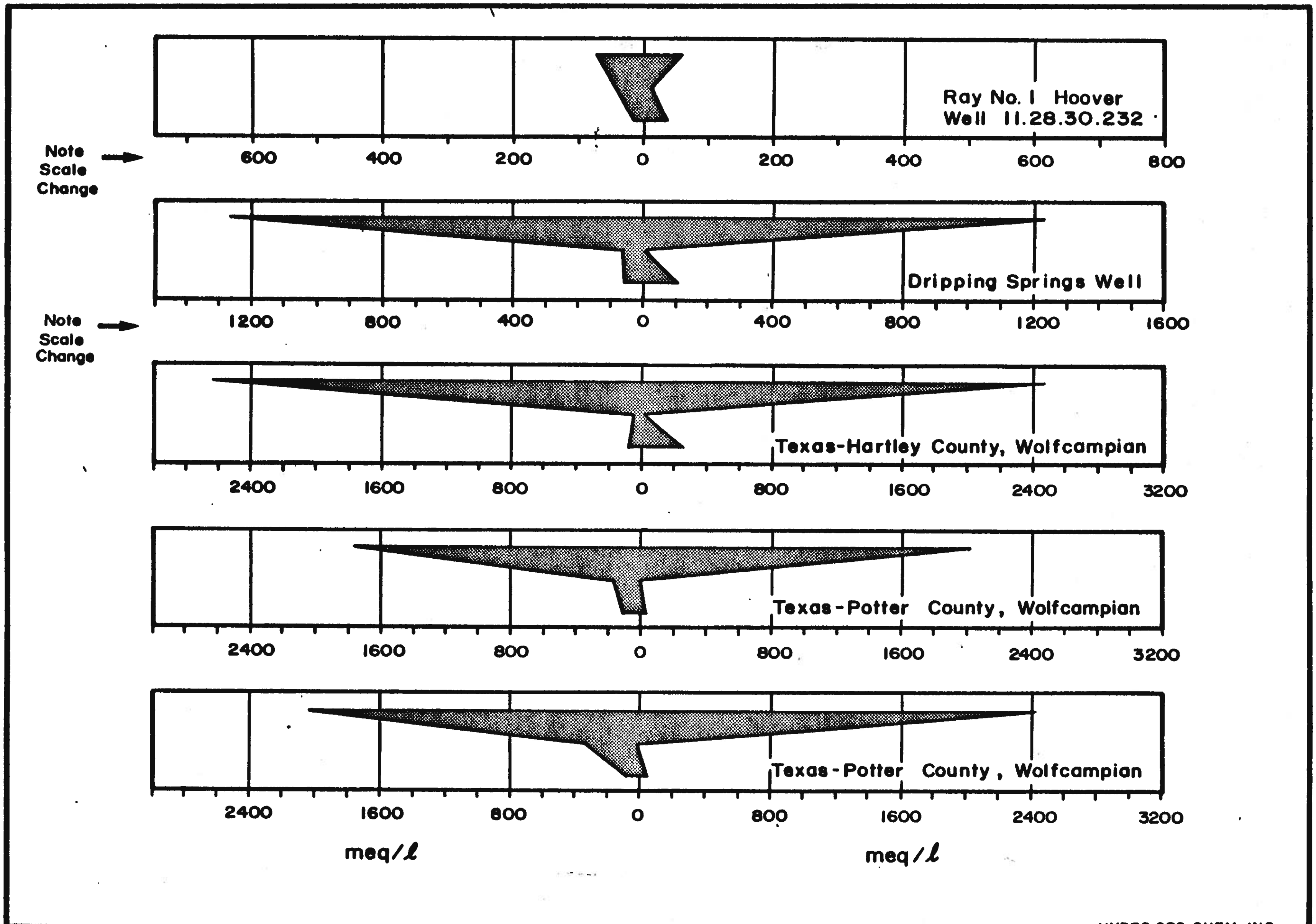


Figure 31. Stiff diagrams of Permian water near study area

shown in Figure 31 to illustrate the evolution of water quality down the flow path. The continued dissolution of halite, raising the average total dissolved solids to an average of 150,000 mg/l, is consistent with eastward thickening salt beds overlying the Wolfcamp. Other important reactions are the nearly complete loss of carbonate species, and probable outgassing of CO_2 from the sample.

The 10-fold increase in calcium between the New Mexico and Texas water samples is probably due to cation exchange by clay minerals. This would also cause a depletion of sodium relative to chloride, which is seen in the analyses.

Thus we see the evolution of Permian waters toward a sodium-chloride brine. Within the area of detailed study there seems to be an abrupt degradation in water quality, with a 10-fold increase or more in total dissolved solids, obviously related to halite dissolution along a zone that passes through the detailed study area.

2. Chemistry of Triassic Water

The chemistry of Triassic groundwater is primarily influenced by residence time, flow-path length, lithology, and ion exchange properties of the rocks. In some areas, the quality of excess irrigation water from the Tucumcari Project is also a factor. Because of the spatial variability of these influences, water quality is expected to show similar variability.

The average characteristics of twenty-three Triassic water analyses in the detailed study area are listed in Table 6.

Table 6: Summary of chemical characteristics of 23 samples of Triassic groundwater in the study area

Ion	Range mg/l	Average mg/l	Average meq/l
Ca	2 - 210	54	2.7
Mg	0 - 190	35	2.9
Na	4 - 1370	366	15.9
K	3.2 - 7.1	4.7	0.12
HCO_3	88 - 852	449	7.4
CO_3	0 - 75	14	0.46
SO_4	56 - 1760	416	8.7
Cl	4 - 1130	152	4.3
Br	0.15 - 0.50	0.29	0.004
pH	6.9 - 9.3	7.7	—
TDS	527 - 5520	1261	—

Stiff diagrams and locations of several water analyses from Triassic wells in the vicinity of Ute Reservoir are shown in Figure 32. The groundwater is predominantly sodium-bicarbonate to sodium-sulfate. Chloride is generally low except in two analyses. Probable chemical reactions producing these water types are dissolution of limestone, gypsum, or calcareous cement in sandstones, and exchange of calcium for sodium on shales and clays. Stiff diagrams of water from Ute Reservoir and water from dam seepage (Ute Outflow) are also shown. Note that the surface water is predominantly sodium-bicarbonate and low in dissolved solids, while the outflow water is more typical of Triassic water, except that chloride is higher than average, which may be due to mixing with deeper waters. Groundwater mixing is discussed later in this chapter.

The amount of chlorides entering the river from Triassic groundwater can be calculated by assuming that the average chloride concentration in groundwater is 152 mg/l and the gain in flow rate is 5 cfs. This amount is equal to 21,500 mg/sec, or about 0.02 Kg/sec.

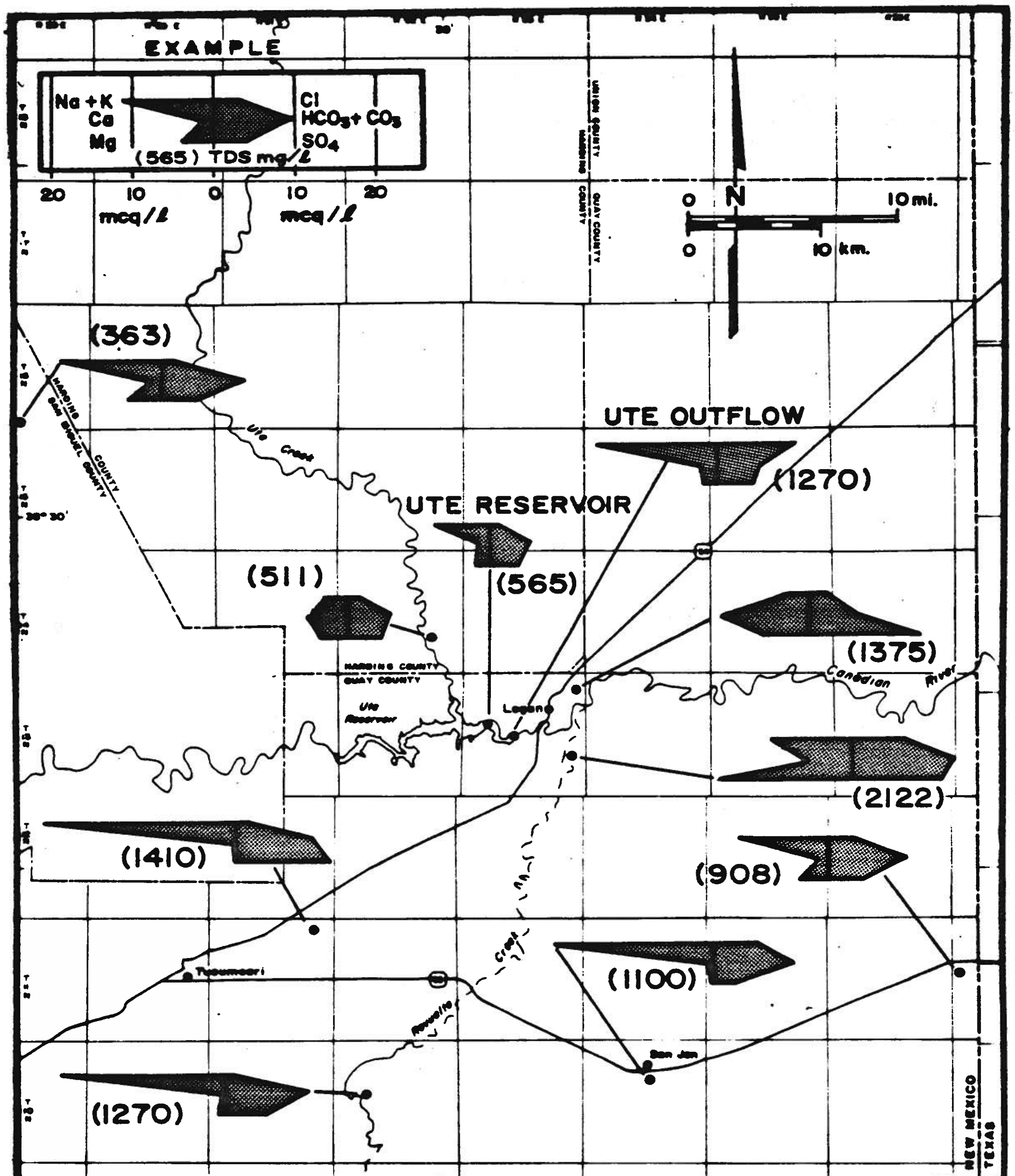


Figure 32. Stiff diagrams of Triassic water

HYDRO GEO CHEM, INC.

3. Shallow Brine Aquifer Chemistry

Analyses of water from wells OW-3 and DH-2, Bureau wells drilled into the shallow brine aquifer, are listed in Appendix B. Stiff diagrams of the analyses are shown in Figure 33. Both are sodium-chloride water types, although DH-2 concentrations are much lower than OW-3, and both are fresher than the Permian brines.

The chemical similarity between OW-3 water and deeper Permian water suggest that the former is a more dilute sample of the deeper water. On the other hand the DH-2 sample indicates that the area of brine in the shallow aquifer is not extensive, even though the aquifer itself appears to be. The quality of the water in DH-2 appears to be better than both the overlying channel deposit water, discussed below, and the underlying Permian water.

Oxygen, hydrogen and carbon-14 isotopes were collected and analyzed from well OW-3 to help define the source of water to the shallow brine aquifer. These analyses are discussed later in this chapter.

4. Chemistry of Water in the Channel Deposits.

Water quality has been measured in several piezometers in the channel deposits since 1974, to delineate and quantify the amount of brine seepage into the river channel. Chemical analyses of this water were furnished by the Bureau of Reclamation or were collected for this study. They are tabulated in Appendix B, Table B.1. Stiff diagrams of these analyses are shown in Figure 34. All sam-

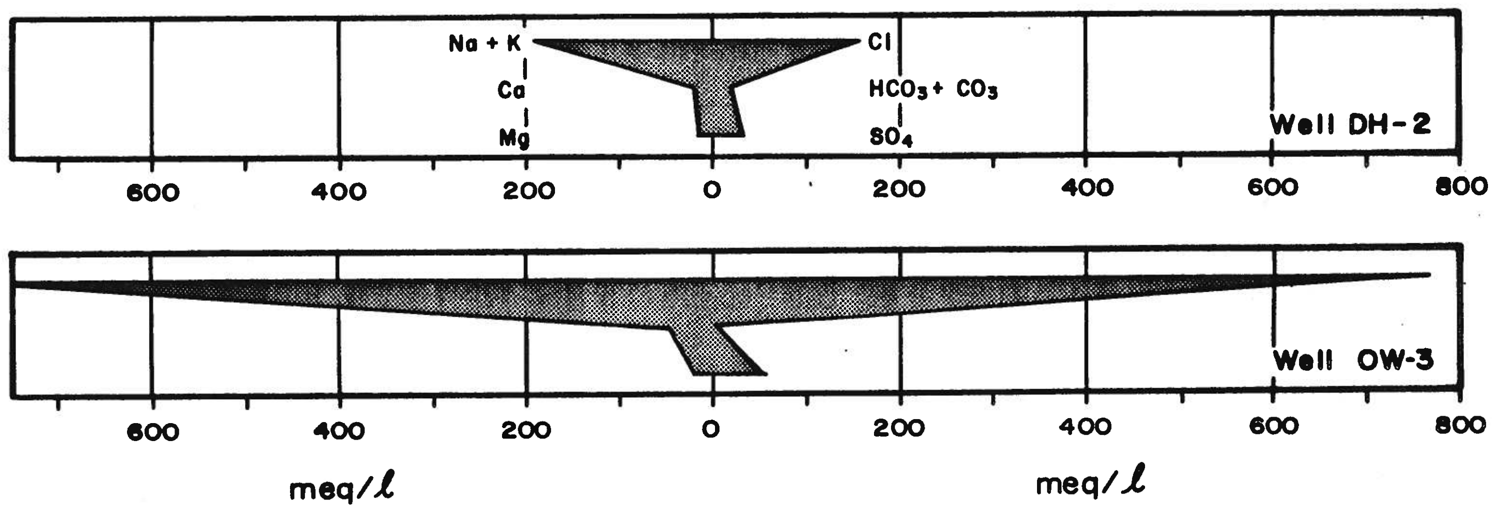


Figure 33. Stiff diagrams of shallow brine aquifer water

HYDRO GEO CHEM, INC.

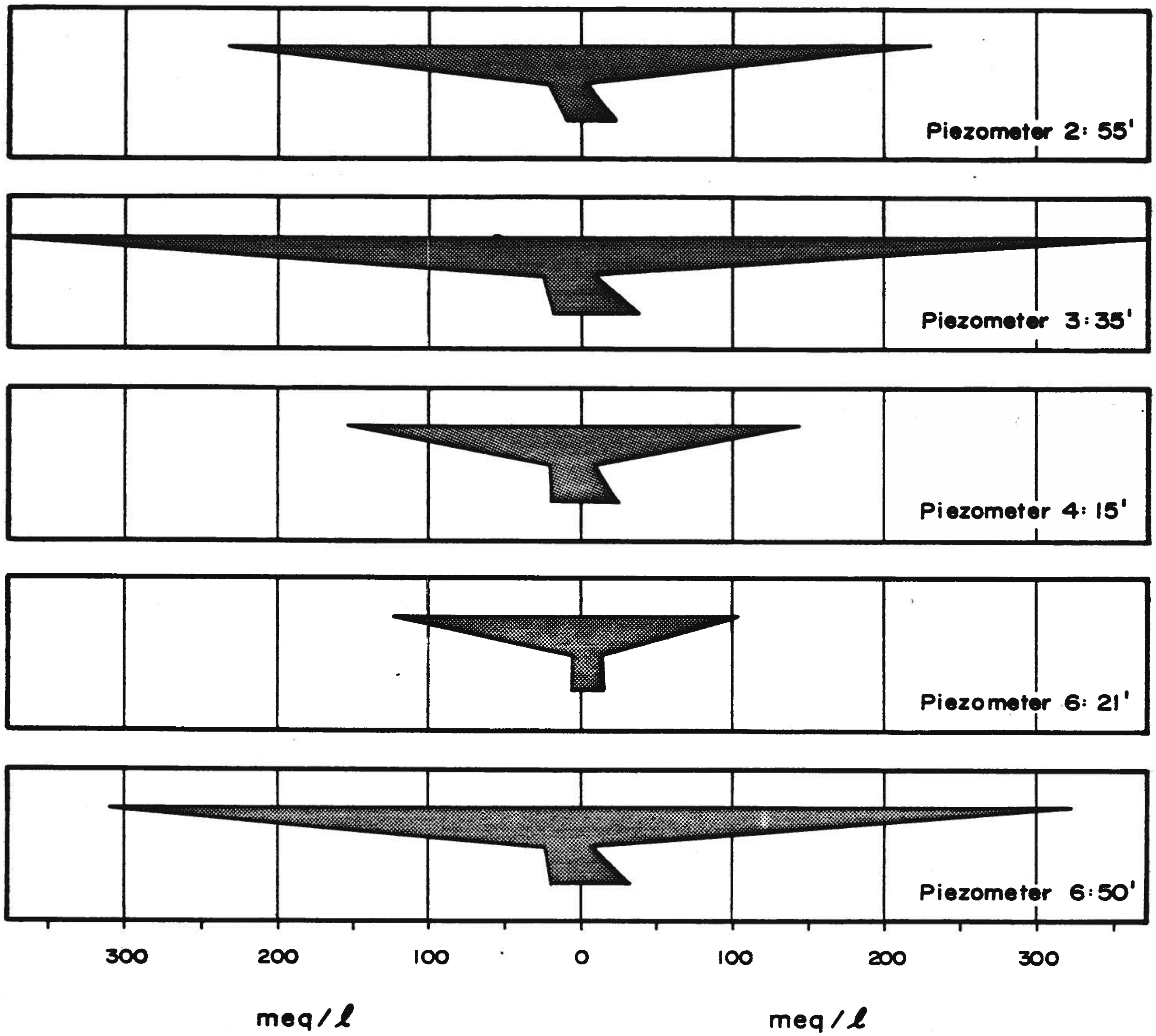


Figure 34. Stiff diagrams of water from wells in channel deposits

ples are easily seen to be a sodium-chloride type. The maximum salt concentration is at Site 3, indicating that salt enters the channel between Sites 2 and 3, as well as upstream of Site 2. A comparison of chloride in the deep and shallow piezometers at Site 6 shows strong evidence for salinity stratification within the channel deposits. This is probably due to density flow of brine along the bottom of the channel deposits. It is not possible to ascertain whether brine enters the channel between Sites 3 and 6. The information does imply that some brine inflow takes place near Site 4 in Revuelto Creek.

The range in chloride concentrations in the deep and shallow USBR piezometers with distance downstream from Ute Dam is shown in Figure 35. It is seen that brine enters the channel upstream of Site 1 and between Sites 2 and 3. The shallow piezometer results correspond with the deep piezometers, but have lower concentrations, caused by river flows periodically flushing the shallow sediments. For comparison, the analyses from well DH-2 are also shown. The large chloride range in the deep piezometer at Site 4 suggests that the Revuelto Creek deposits are a minor source of brines, and that creek water periodically flushes the channel deposits.

Two partial analyses from four CRWMA piezometer sites between Highway 54 bridge and the Amarillo gage are shown in Figure 36. These are plotted against distance from Ute Dam. The chloride distribution in this graph shows there are two sources of brine, that no brine enters the river between the state line and Tascosa, and that salinity stratification, or brine density flow, observed in the piezometers close to Logan, dissipates by the state line. The salinity in the river water and in the groundwater between these two stations becomes simi-

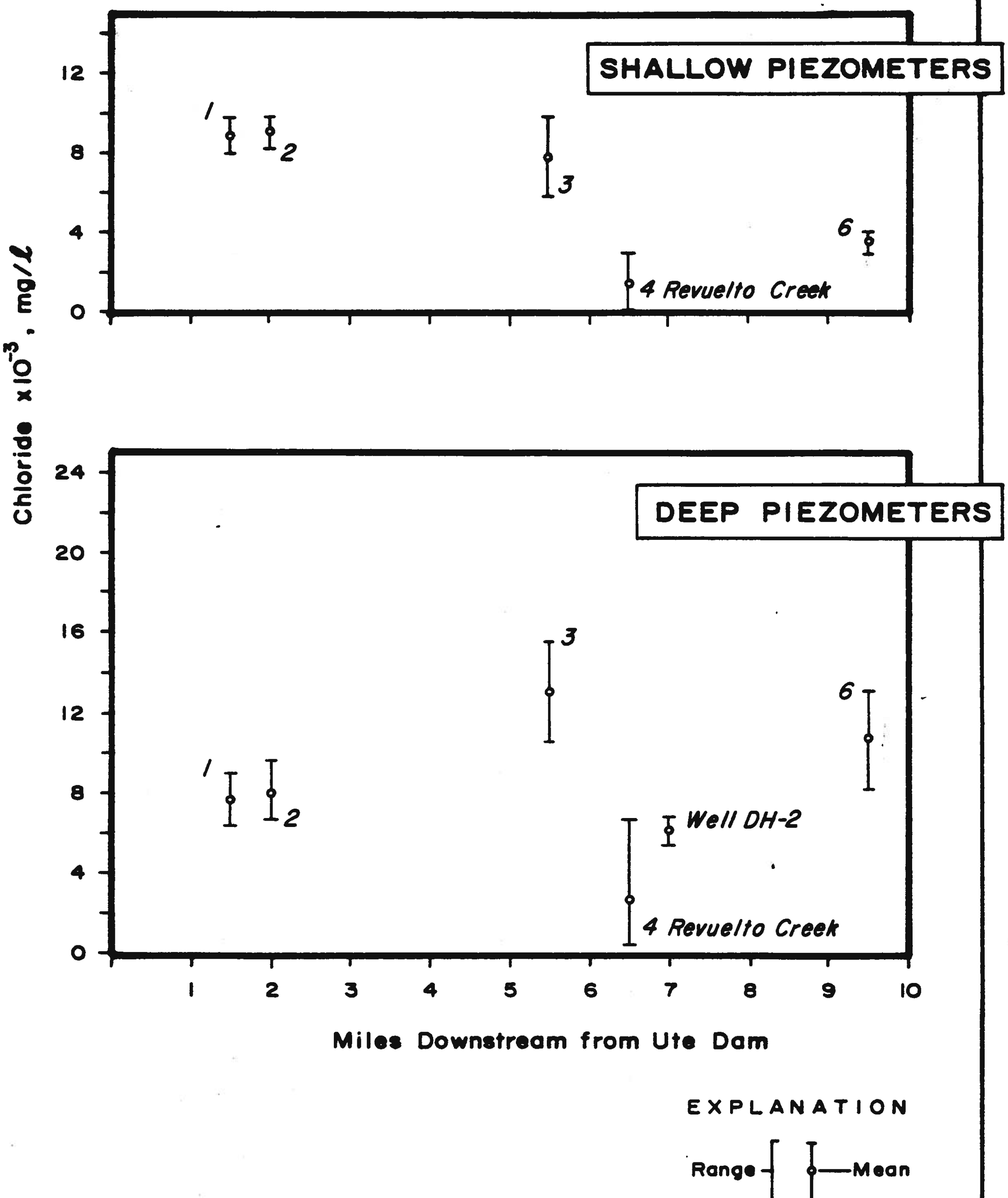


Figure 35. Ranges of chloride concentrations in water from wells in channel deposits

HYDRO GEO CHEM, INC.

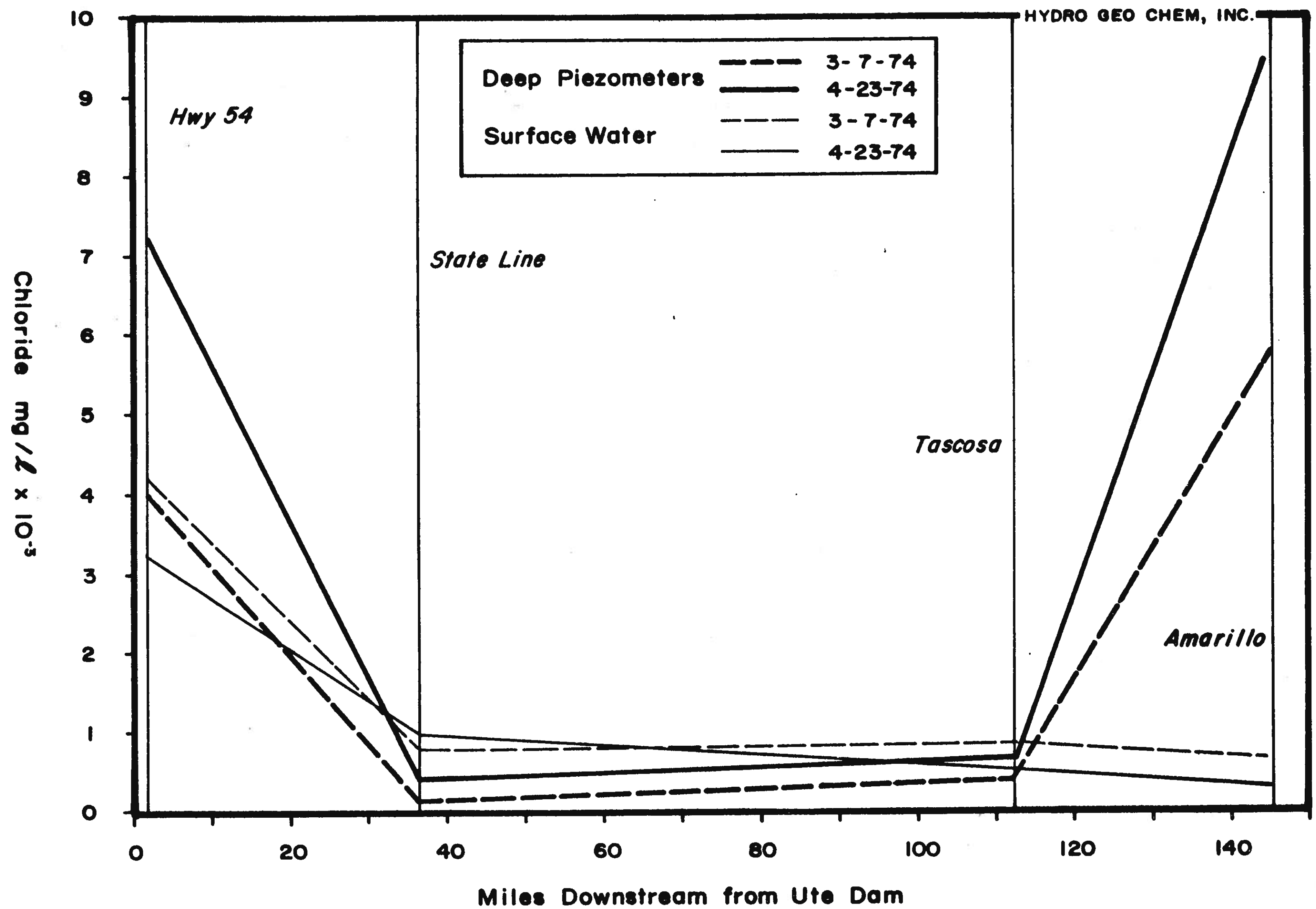


Figure 36. Ranges in chloride concentrations in CRMWA piezometers

lar in concentration.

5. Surface-Water Chemistry

Ute Reservoir

The quality of water in Ute Reservoir has been measured since 1967 (data from USGS WATSTORE files). The average TDS is about 500 mg/l and chloride rarely exceeds 50 mg/l, with no general trends in either parameter over time. It is predominantly a sodium-bicarbonate water type. Depth-quality measurements in the reservoir have revealed no salinity stratification.

River Water

Surface water quality has been routinely measured at the Revuelto, state line, Tascosa, and Amarillo stations for many years. It is not measured at Logan. During this study we measured several water-quality parameters of the stream water between Ute Dam and Revuelto Creek in an effort to isolate the particular brine inflow areas. During one low-flow period we extended this survey downstream almost as far as the Dunes damsite. In addition, a survey of Revuelto Creek was made. The results of these surveys are listed in Appendix B, Tables B.2, B.3, and B.4. Plots of chloride concentration, TDS, and specific conductivity of river water between Ute Dam and the Revuelto Creek confluence are shown in Figures 37, 38, and 39.

During the first survey in October, 1983, the sampling interval was about every quarter mile. Two areas where salinity increased rapidly downstream were found (Figure 37). The first was about 0.5 miles downstream from Ute Dam, just

Figure 37

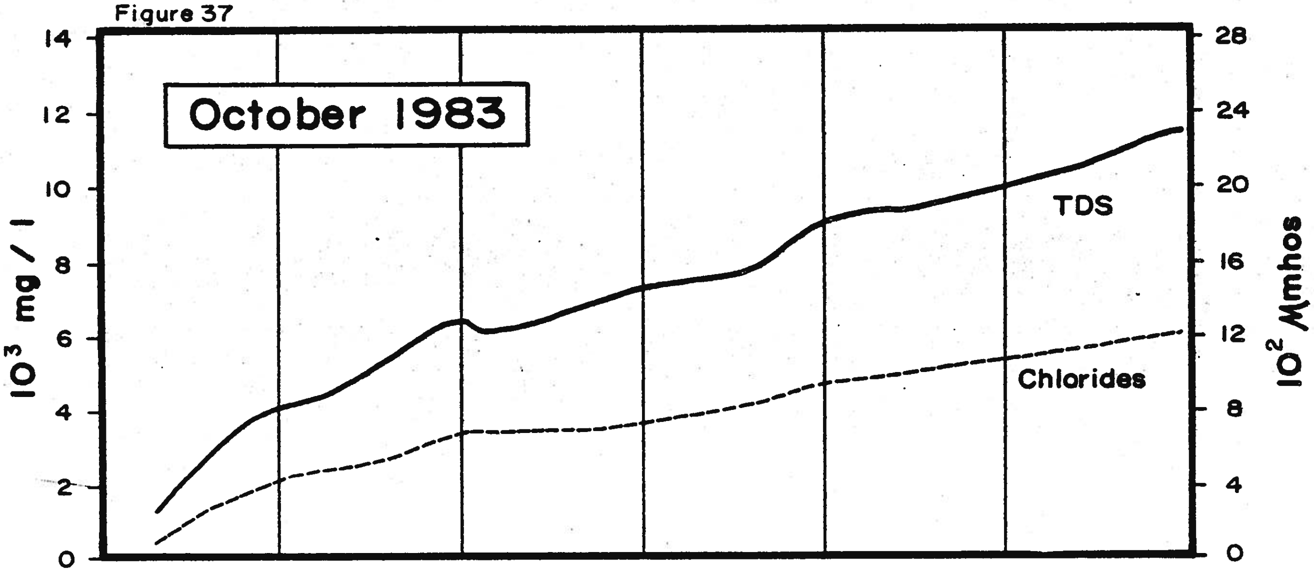


Figure 38

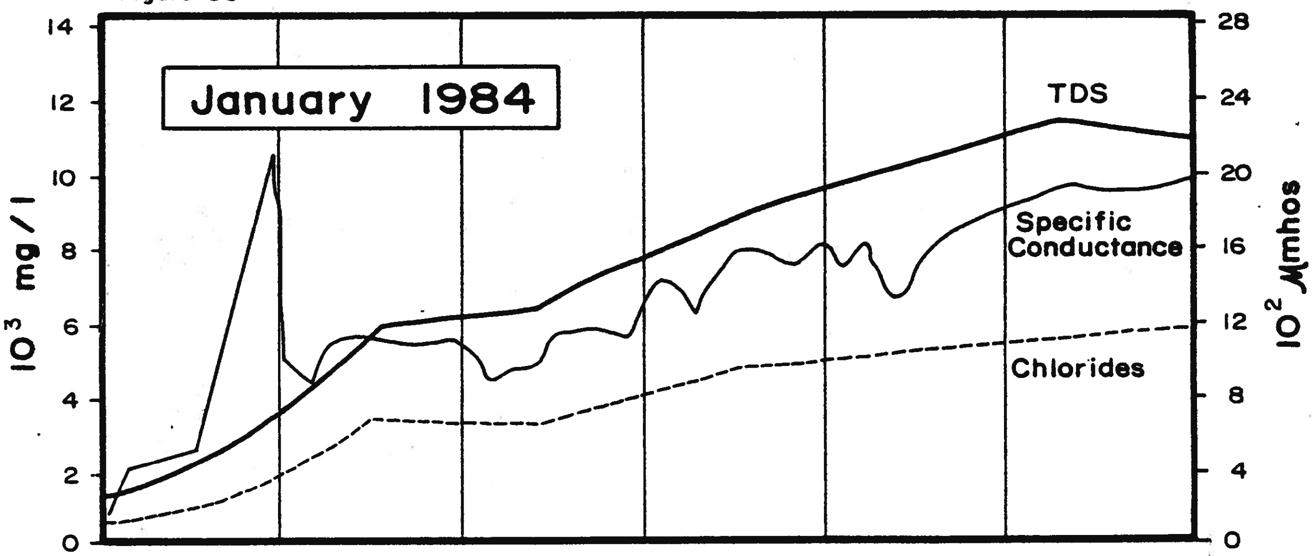
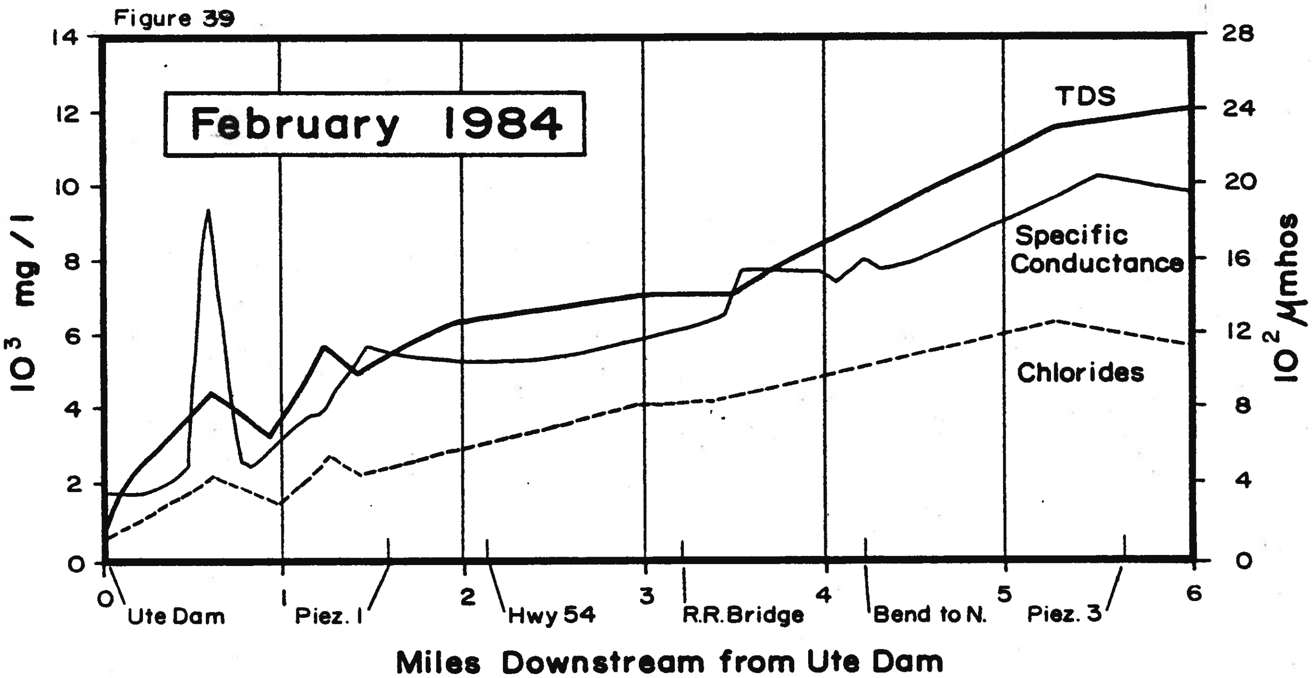


Figure 39



below some beaver dams; the other was about 3 miles downstream, beginning at the railroad bridge. The salinity in the river gradually increased to Revuelto Creek.

In January, 1984 we used a specific conductivity meter to further refine salinity increases in the channel. Figure 38 shows a spike at 0.9 miles, which was a saline pool, not noticed during the first survey. No further increase occurred until about mile 3, near the railroad bridge. An additional salinity increase was found about 0.5 miles upstream of piezometer Site 3. This survey was continued an additional 18 miles downstream, and also nearly 9 miles up Revuelto Creek. Results are listed in Table B.3. No additional highly-saline areas along either reach were found.

A final survey was made on January 31 and February 1, 1984 to determine whether the continuing low-flow conditions in the river would result in higher salinities. Table B.4 lists results of that survey. Plots are shown in Figure 39. This figure generally mimics the previous two graphs, differing little in TDS or chloride concentration. However, numerous pools of brine were seen that were not noticed on previous trips. Table B.4 lists several, all having nearly identical conductivities of about 60,000 micromhos. These pools were concentrated in three areas: the first beginning about 0.8 miles downstream of Ute Dam and continuing for about 0.3 miles; the second immediately downstream of the railroad bridge; the third about 0.8 miles downstream of the railroad bridge, where the river begins its sharp turn to the north. River flows were nearly the same during these three periods, estimated at about 3 cfs near the confluence with Revuelto Creek.

It should be noted that during each of these surveys no brine seeps or springs were seen. The increase in salinity in the river water comes from brine which seeps into the bottom of the channel deposits, as the water chemistry from the piezometers verifies. Assuming that areas of brine inflow to the channel deposits result in degradation of the river water immediately downstream, then the three areas of stream quality degradation probably correspond to three areas of brine inflow. It may also be possible that at the railroad bridge, excavation due to bridge construction and to a buried cable nearby have disturbed the channel sediments such that the brine is forced to the surface in the area.

Some of the important water quality characteristics measured at Ute Dam and at the Revuelto Creek, State Line, Tascosa, and Amarillo stations are listed in Table 7. Chloride loads were computed using weighted average chloride concentrations and average flows, both on a monthly basis. Selected analyses are listed in Appendix B, Table B.1.

Table 7: Average chemical characteristics of Canadian River water

Station	No. Samples	Averages (mg/l) Cl	Na	SO_4	Avg Cl Load (kg/sec)		Water Type
Ute Dam	2	330	340	190		0.009	Na-Cl
Revuelto	325	218	96	410	Entire Record (59-83):	0.08	Na-SO_4
State Line	121	1728	1000	373	Entire Record (69-83):	0.80	Na-Cl
					During overlap w/Tascosa:	0.95	
Tascosa	113	530	413	290	Entire Record (68-77):	0.96	Na-Cl
Amarillo	384	320	442	268	During overlap w/Tascosa:	1.15	Na-Cl-SO_4
					Prior to Ute Dam (1962):	1.02	
					After Ute Dam (1962):	1.07	
					Entire Record (50-82):	1.05	

The chloride loads show that brine inflow dominates water quality by the state line, with little contribution from Ute water or Revuelto Creek. When the Revuelto Creek and Ute chloride loads are subtracted, about 0.72 Kg/sec of chloride comes from the Canadian River. We showed earlier that the predominant inflow area is between Ute Dam and Revuelto Creek.

The drop in concentration between state line and Tascosa is due to the influx of fresher water to the system. This influx is consistent with the flow patterns in the stream, discussed earlier. However we see that the chloride load remains virtually the same between state line and Tascosa.

We can see that the period of overlapping record among the water-quality stations was also the period of highest average chloride load, indicating that over time the chloride load in the river has increased. There has been a slight upward trend in average chloride load at Amarillo over the years, although we suspect that it may partially be due to changes in sampling frequency. There is an increase in chloride load between Tascosa and Amarillo of 0.19 Kg/sec. The source of this chloride is not known, although sewage effluent or a shallow source of chloride in the Permian rocks which the river cuts through are plausible sources. Evidence supporting the latter was presented earlier, as shown in Figure 36. Thus, of the average chloride load of 1.05 Kg/sec at Amarillo, about 70 percent comes from upstream of the state line.

The transport of salt down the river is not constant, but varies with flow rate. Figures 40 and 41 show the chloride load plotted against mean annual flow for the Tascosa and Amarillo stations. Flow and salt load show good correlation

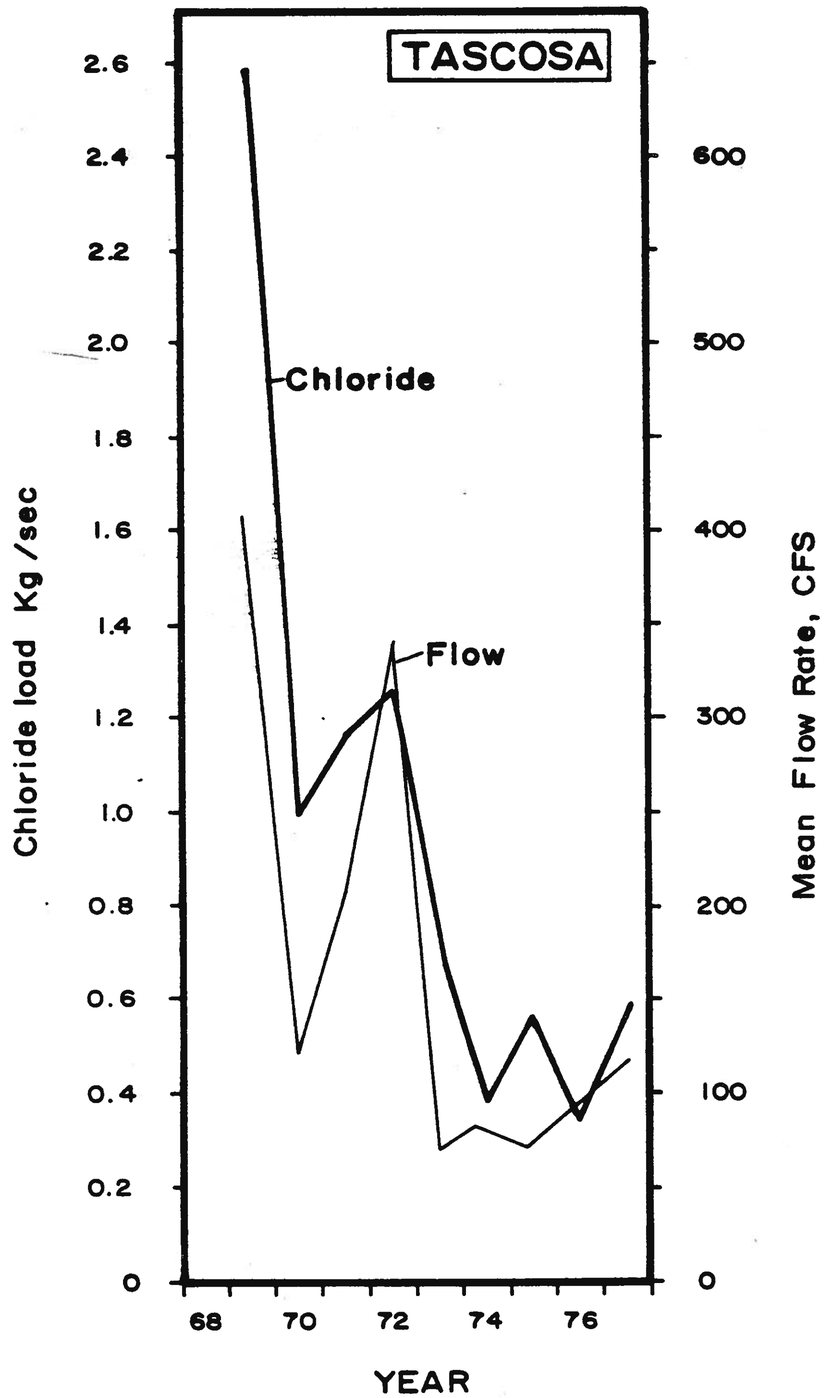


Figure 40. Chloride load and mean flow for Canadian River at Tascosa

HYDRO GEO CHEM, INC.

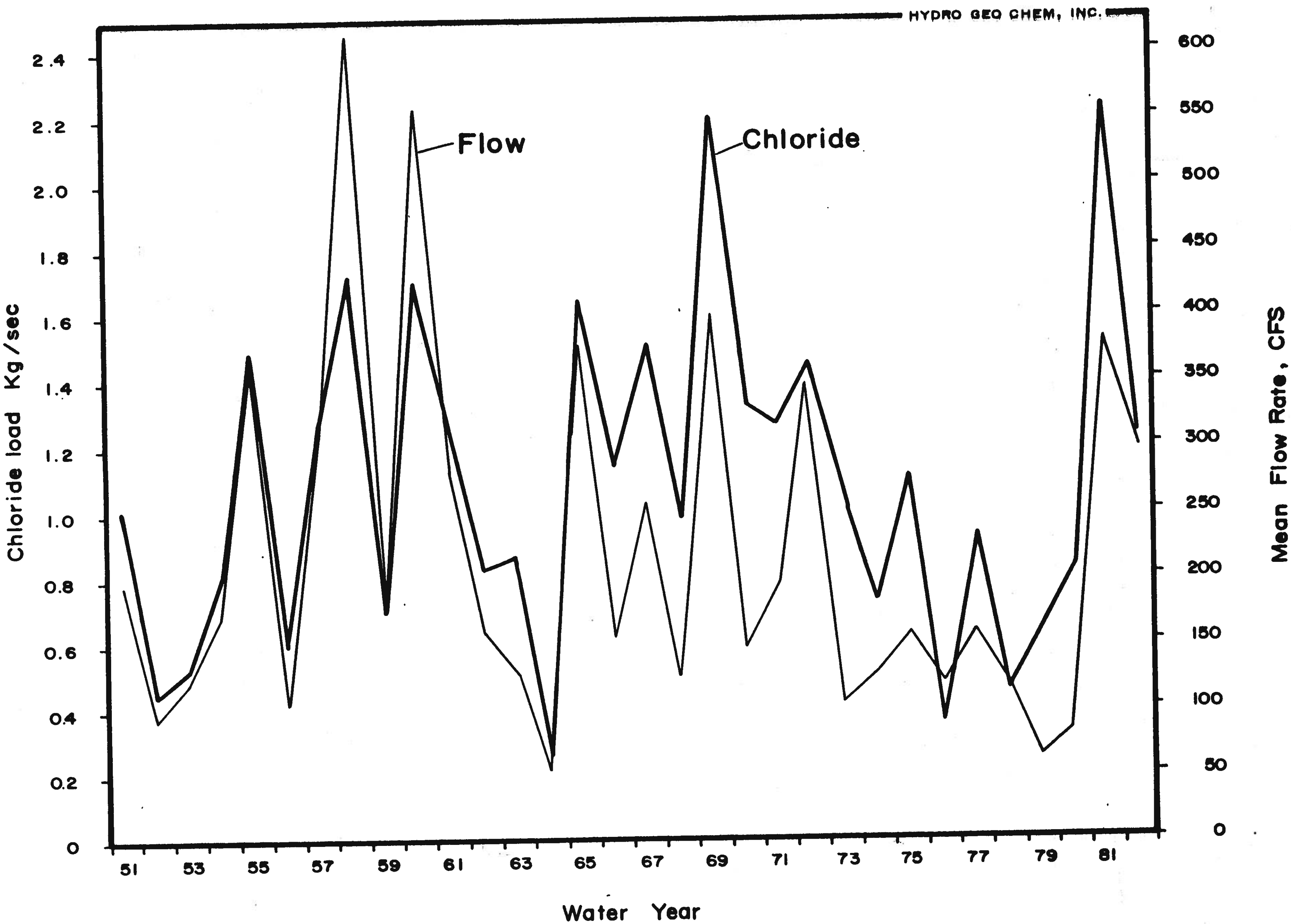


Figure 41. Chloride load and mean flow for Canadian River at Amarillo

at both stations. However, this information seems to violate our simple conceptual model of a constant salt input from brine seeps. To reconcile this apparent conflict, we must understand the role of the alluvial channel deposits in the storage and transport of salt. During low river flows, the salt concentrates in the channel because of upward brine movement, coupled with the inability of the narrow stream (only a small fraction of the canyon width) to come in contact with the brine. Evaporation also concentrates the salt, much of which occurs along the banks of the stream. (Evaporation within the channel between Ute Dam and Lake Meredith may account for a loss of about 45,000 acre-feet annually, or about one-third of the average flow at Amarillo. This adds, roughly, 70 mg/l of chloride to the average concentration.) Thus as the flow decreases, the salt load also decreases, the difference going to increased salt storage in the channel deposits. During high flows, this salt is flushed from storage, resulting in the higher salt loads. Evidence for this interpretation is in the periodic freshening of the water sampled from shallow piezometers at Sites 1 through 6.

Lake Meredith

Table B.1 in Appendix B lists water quality analyses from Lake Meredith collected from Sanford Dam. Figure 42 shows chloride concentration in the lake over time from samples collected at the dam and at mid-lake. The mid-lake values tend to oscillate around the others showing the same trends. Thus, these values are probably representative of the entire lake. The correlation between water quality in the lake and that in the Canadian River is discussed later in the water and salt budgets section.

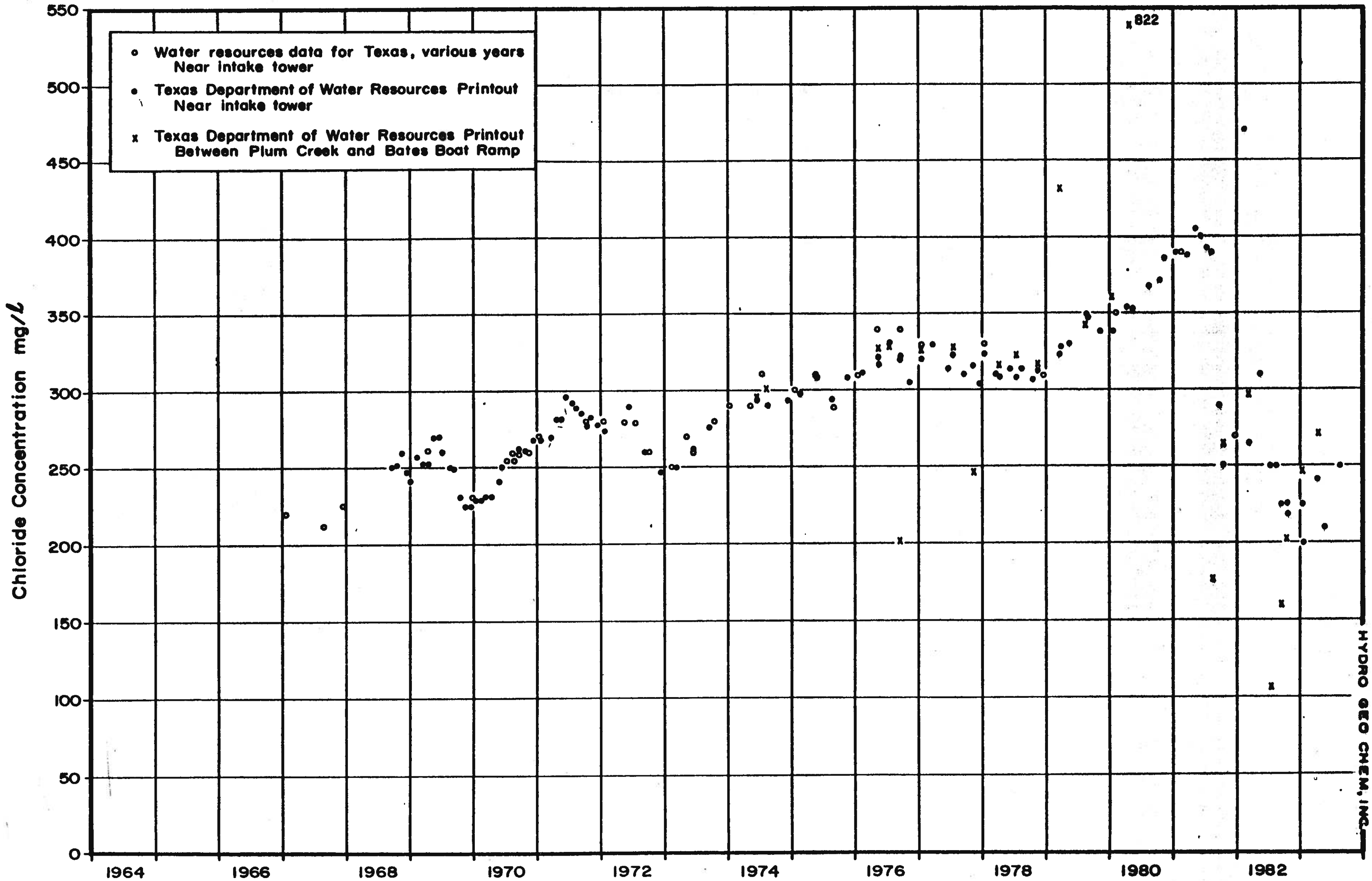


Figure 42. Chloride measurements in Lake Meredith

GEOCHEMICAL AND ISOTOPIC DETERMINATION OF SALINITY SOURCES

There are several components of flow which comprise Canadian River water. Water from Ute Reservoir, from tributary flow such as Revuelto Creek, from Triassic groundwater inflow, and from brine springs are the components most important to this study. It is also desirable to quantify the components which comprise the water of shallow brine aquifer. The information presented in the previous sections, together with isotopic analyses from some of the water samples, allow for estimates of mixing to be made.

1. Salinity Sources

Increased salinity can result from natural dissolution of halite, man caused pollution, mostly due to poor oil-field brine disposal practices, or evaporation. It was calculated above that evaporation within the Canadian River channel could not account for much of the increased salt concentration. However there are many cases of oil-field brine contamination. Whittemore (see Appendix B) has found that the ratios of bromide to chloride in water are much higher in fresh water and in oil-field brines than in halite solution brines. We collected several samples for bromide and chloride determination. Figure 43 is a plot of bromide/chloride ratios against chloride concentration for these samples. All fall in the range of halite dissolution, indicating that oil field brines do not contribute to salinity in the river. The progression from fresh water on the left to brine on the right shows that these waters become more saline through continuing halite dissolution. The Ute outflow sample (from toe drain) is seen to be a mixture of reservoir water and Triassic water. However the Tri-

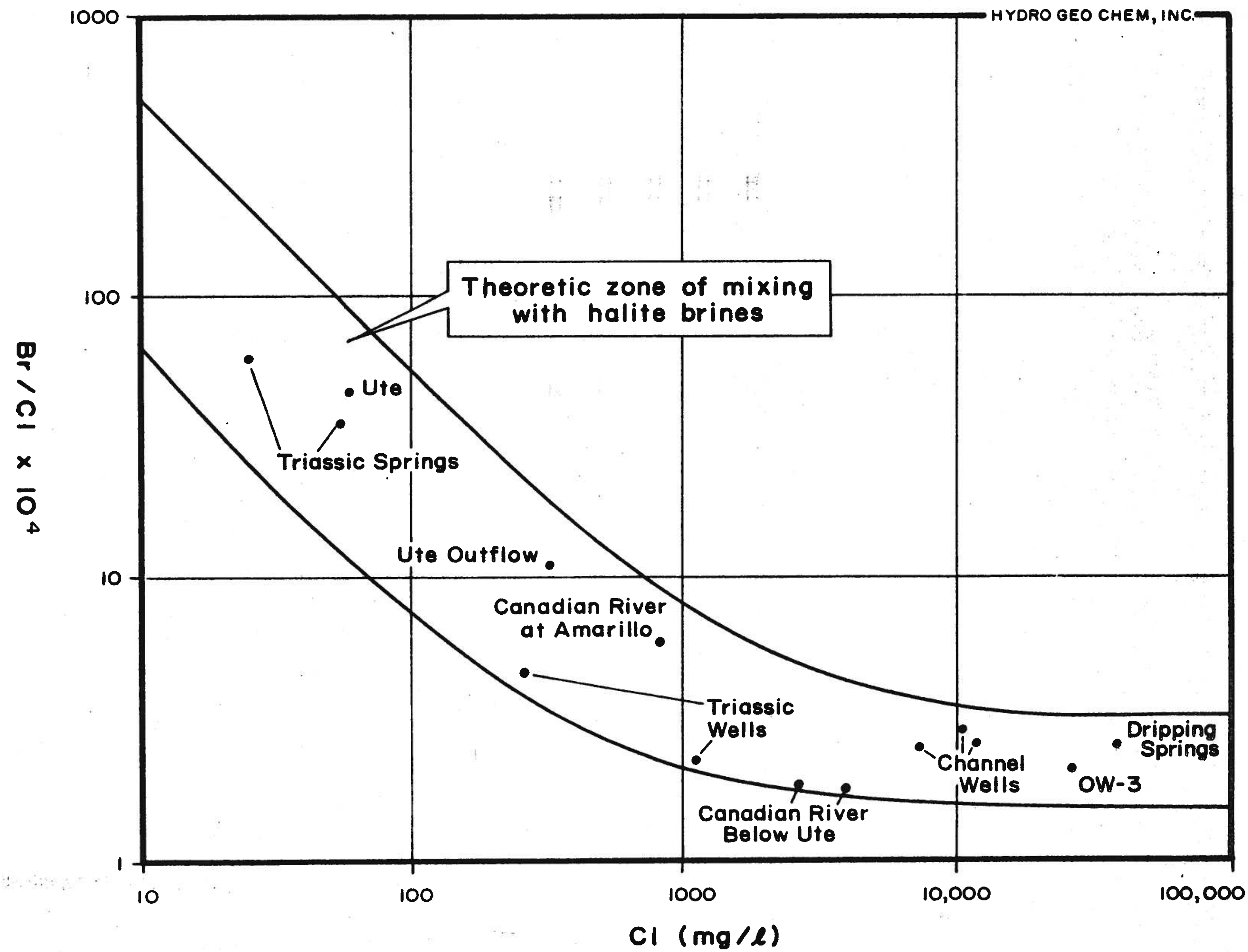


Figure 43. Bromide/chloride ratios of surface and groundwater

assic water itself may be slightly mixed with brines themselves. The differences between the OW-3 and Dripping Springs well samples are the result of dilution of OW-3 with, possibly, Triassic water. However the OW-3 analysis is much more similar to Permian water than to Triassic water.

Other ion ratios are useful in differentiating salinity sources or degrees of mixing. Figure 44 is a plot of sodium/chloride ratios (on an equivalence basis) against chloride concentration for Triassic and Permian groundwater and Canadian River water. The dotted line is one of best fit for those samples obviously influenced by brine. A sodium/chloride ratio of unity indicates a pure halite solution. For comparison the ratio for rainfall is included. The progression of Canadian River water toward a Permian brine is shown, as well as the degradation of water quality in the river after the construction of Ute Dam. The Revuelto Creek and Triassic samples plot far to the right of the mixing line, indicating that these are not greatly influenced by brine.

Two of the most useful indicators of chemically differentiating water are stable oxygen and hydrogen (deuterium) isotopes. Results of isotopic analyses for Ute Reservoir, Ute outflow, Triassic well water, and shallow brine aquifer water are shown in Figure 45. The axes represent the ratios of oxygen-18 to oxygen-16, and hydrogen-2 to hydrogen-1. The meteoric line is the line of best fit established by Craig (1961) for many precipitation samples in the northern hemisphere. Analyses that plot to the right of the line, as ours do, indicate enrichment through evaporation. The analysis for OW-3 is distinctly different from the others. Furthermore, its isotopic values are nearly identical to those in precipitation collected at the same latitude and elevation as our

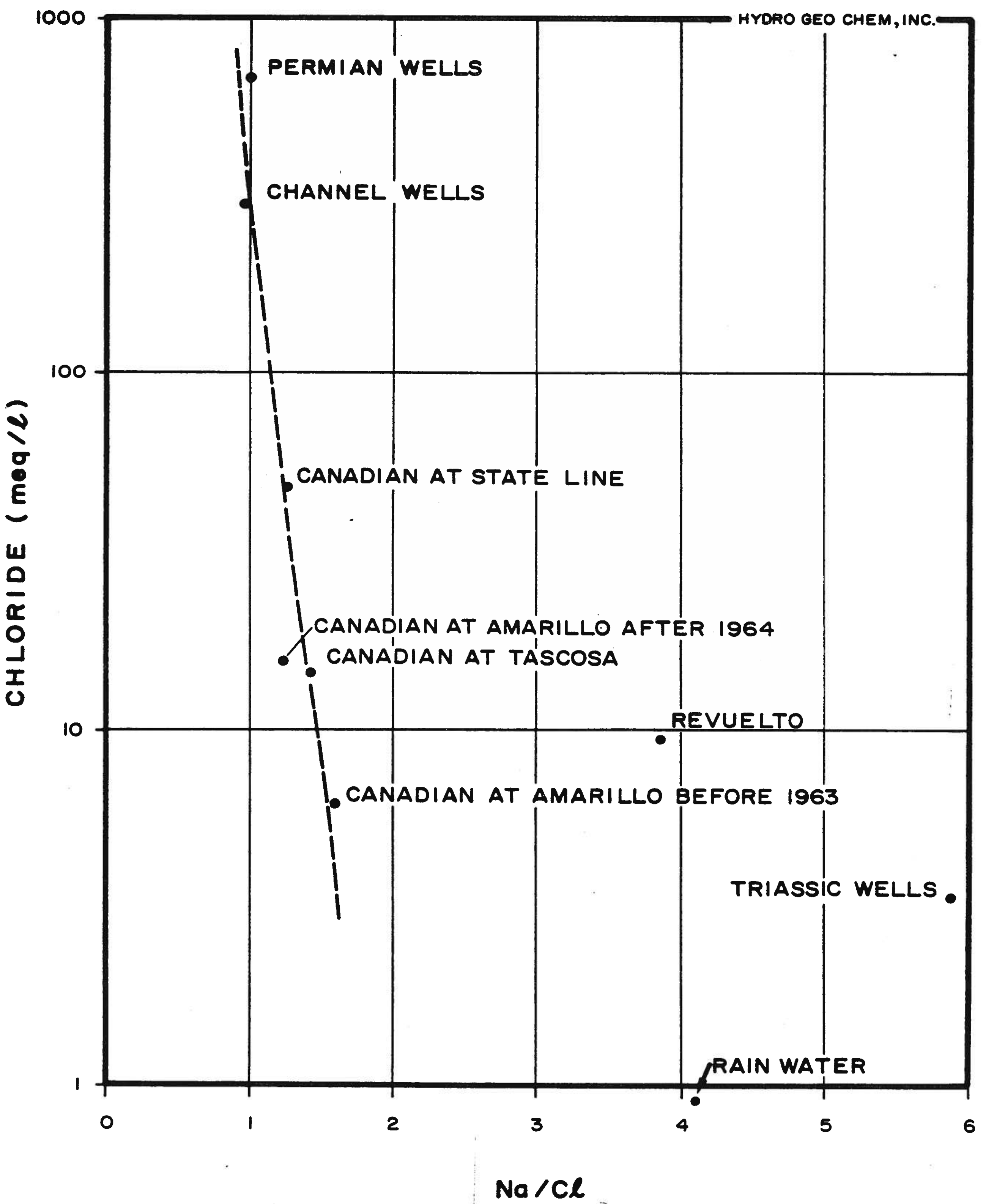


Figure 44. Sodium/chloride ratios of surface and groundwater

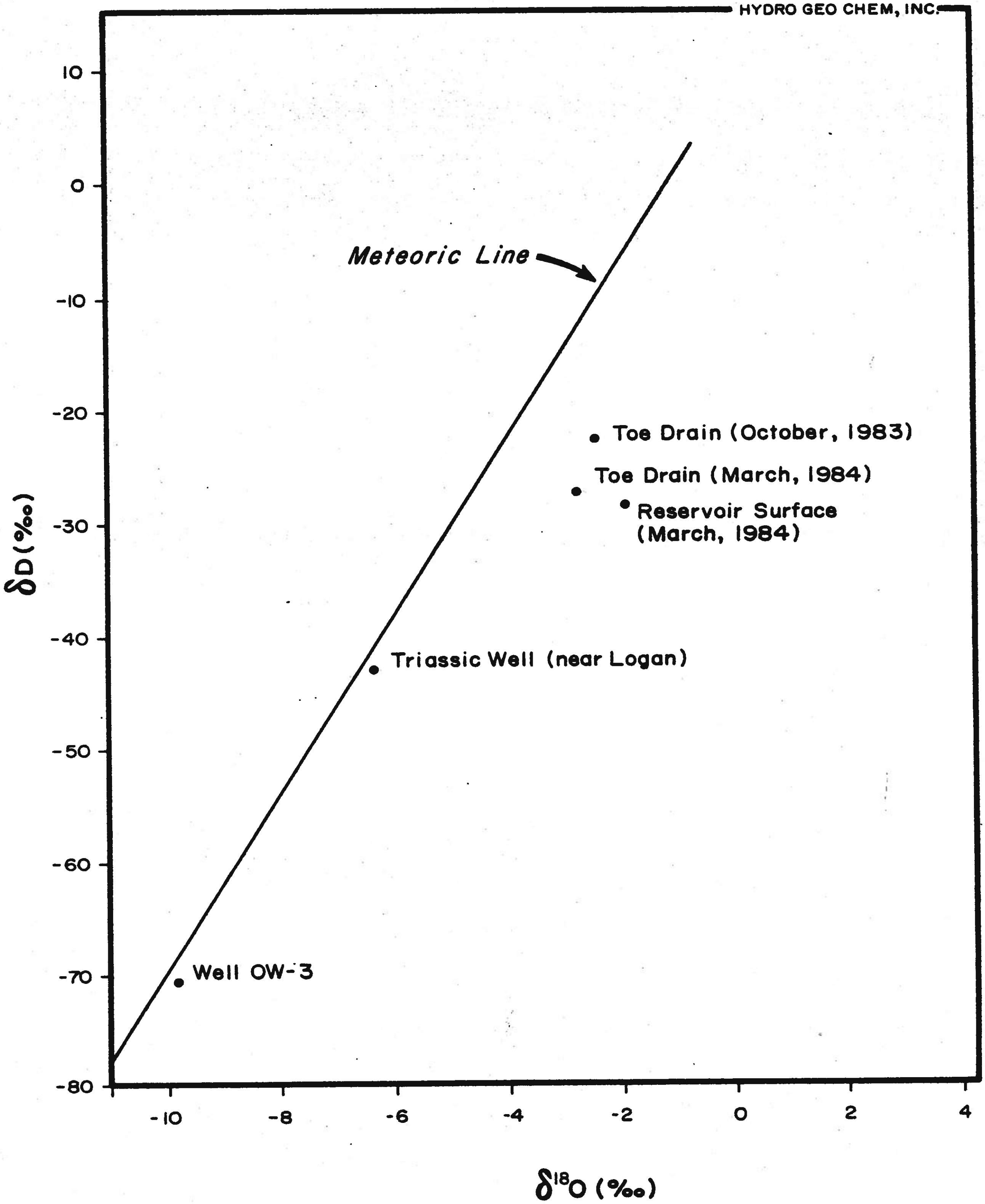


Figure 45. Stable isotopic distributions

hypothesized Permian recharge area in the Sangre de Cristo uplift. Its closeness to the meteoric line suggests that the sample has not been enriched through evaporation. The Triassic well analysis is that which would be expected in rainfall at the latitude and elevation of the Logan area, thus supporting the idea of local recharge to the Triassic. The isotopic separation between OW-3 and Triassic samples indicates that the shallow brine aquifer is connected to the deeper Permian aquifer, and may be isolated from the Triassic.

Samples collected from the reservoir and drain show enrichment typical of evaporation. This enrichment is expected from surface-water impoundments, especially in the southwest where evaporation is high. Samples from the toe drain show slightly less enrichment in oxygen, but more enrichment in hydrogen. If the outflow water is a mixture of reservoir and Triassic water, then these samples should plot on a mixing line between the Triassic and reservoir points. All three points plot closely, however, so this discrepancy may only be due to the sensitivity of the analysis. The large isotopic difference between water from the toe drain and Triassic well water, despite their chemical similarity (see section on Triassic chemistry), suggests that much of the dissolved solids in the toe drain water is derived from dam materials themselves.

2. Groundwater Mixing

A sample of OW-3 water was also analyzed for carbon-14 content to estimate the "age" of the water, or how long it has been isolated from the biosphere. Water has an atmospheric equilibrium value of carbon-14 when it enters the ground, but the value decays at a known rate once water is removed from the atmospheric source. An apparent age, in percent of modern carbon-14, is determined; however accurate age dating requires that all sources of carbon in a water sample be known.

The total carbon in a sample can be calculated using pH and alkalinity measurements. For well OW-3, with a pH of 6.36 and an alkalinity of 836 mg/l (see Appendix B), the total carbon is 1670 mg/l. Assuming that the Dripping Springs well is representative of deep Permian water, with a pH of 6.02 and an alkalinity of 765 mg/l, total carbon is 2400 mg/l. For Triassic water, we use the analysis from the Revuelto Creek windmill; with a pH of 6.93 and alkalinity of 580 mg/l, the total carbon is 730 mg/l. If, as we propose, the shallow brine aquifer is a mixture of Permian and Triassic water, then by the ratios of total carbon, it is composed of 57 percent Permian and 43 percent Triassic water.

The measured "age" of the OW-3 sample is 5.72 ± .58 PMC. The deep Permian water would have essentially no carbon-14 because of its long residence time in the aquifer. Therefore the carbon-14 must represent some input of recent water. The percentage of modern carbon is given by

$$\text{PMC (shallow brine)} = \frac{\text{PMC (Triassic)} \cdot \text{Triassic carbon} \cdot \text{Triassic fraction}}{\text{Shallow brine carbon}}$$

Solving for PMC Triassic, we get 0.33, or about one-third modern carbon. This is reasonable considering the exceptionally high carbon content of the water (most groundwater contains about 250 mg/l), and the del carbon-13 of -4.65 per mill, which is high, indicating more calcite dissolution than normal.

The age of a sample is given by the carbon-14 decay equation:

$$t = -8266 \cdot \ln (A_s/A_{std})$$

where the ratio is equal to PMC of the sample. The carbon-14 age is 23,600 years. This, of course, represents a mixture of waters of different ages, and is not absolute.

Now that the various sources making up the groundwater and surface water have been identified, simple mass-balance techniques can be used to quantify these sources. The conservative chloride and bromide ions are used in the calculations, and are checked for reasonableness using TDS, sodium, and sulfate.

The amount of chloride entering the Canadian River below Ute Dam was estimated to be 0.70 Kg/sec. If the entire amount of chloride is from the deep Permian system, then the upward flow rate from the deep Permian is

$$0.70 \text{ Kg/sec} \div 0.0437 \text{ Kg/l} = 16.2 \text{ l/sec} = 0.57 \text{ cfs}$$

Using the same formula, substituting the chloride concentration in well OW-3, 27,400 mg/l (0.0274 Kg/l), we obtain 0.90 cfs flow from the shallow brine aquifer into the river.

This rate can be verified using another calculation. We assume that the shallow brine aquifer is a mixture of Triassic and deep Permian water, and that 0.57 cfs of Permian water flows into the shallow brine aquifer. The addition of Triassic water, at an average of 250 mg/l chlorides, needed to arrive at a mixture containing 27,400 mg/l chlorides (concentration in OW-3) is given by

$$(43{,}700 \text{ mg/l}) \cdot (0.57 \text{ cfs}) + 250 \text{ mg/l} \cdot X = 27{,}400 \text{ mg/l} \cdot (0.57 + X)$$

where X = Triassic flow rate

$$X = 0.34 \text{ cfs}$$

Combining the 0.34 cfs Triassic water with the 0.57 cfs deep Permian water gives 0.91 cfs, an excellent agreement with the previous calculation.

By mixing these proportions of Triassic (37 percent) and deep Permian (63 percent) water, we should be able to derive an analysis of the shallow brine aquifer that is close to the OW-3 analysis. Using the Dripping Springs well and the Revuelto Creek windmill analyses (see Appendix 2), the calculated shallow brine aquifer analysis for is listed below on the left and the OW-3 analysis on the right.

	Calculated	OW-3
TDS:	51,500 mg/l	49,000 mg/l
SO_4:	3,460 mg/l	2,880 mg/l
Na:	18,500 mg/l	17,500 mg/l
Ca:	890 mg/l	800 mg/l
Mg:	430 mg/l	220 mg/l
Br:	6.3 mg/l	5.5 mg/l

The average difference, except for magnesium, is about 15 percent. Given the uncertainty in the chemistry of both the Permian water below the brine aquifer, and the Triassic water, this difference is fairly small and lends validation to the mixing percentages calculated above.

LAKE MEREDITH WATER AND SALT BUDGET

Sanford Dam is about 27 river miles downstream from the Amarillo gage. The dam was closed in October, 1964 and Lake Meredith began filling. We calculated a water budget for the lake to see how river flow and salt load in the Canadian River correlated with changes in storage and salt concentration in the reservoir.

1. Water Budget

The form of the water budget equation is

$$I - O = \Delta S$$

where I is the inflow, O is the outflow, and ΔS is the change in lake storage. The various components of the water budget for Lake Meredith may be written as

1. Inflow terms:
   - I_c = from Canadian River at Amarillo gage
   - I_s = from surface water runoff downstream of Amarillo gage
   - I_r = from rain on reservoir surface
   - I_g = from groundwater

2. Outflow terms:
   - O_d = from diversions
   - O_e = evaporation from reservoir surface
   - O_{ec} = evaporation from Canadian River between the Amarillo gage and the reservoir
   - O_s = from seepage through dam
   - O_g = to groundwater

3. Change in reservoir storage: ΔS

The water budget equation can now be written:

$$I_c + I_s + I_r + I_g - O_d - O_e - O_{ec} - O_s + O_g = \Delta S$$

Grouping terms that have been measured or estimated on the right, and terms that are unknown on the left:

$$I_s + I_g - O_g - O_{ec} = (O_d + O_e + O_s) - (I_c + I_r) + \Delta S$$

We call the left side of the equation the residual, and is what is solved for in the water budget. It can be seen that the residual also contains the total error in all of the terms on the right side of the equation. Data used to solve this equation were from 1) pan evaporation and rainfall measurements collected at Sanford Dam or from nearby Borger, Texas; 2) diversions, Canadian River flow, and changes in reservoir storage from U.S. Geological Survey Water Supply Papers (various years); 3) seepage from the dam from information given by Mr. John Williams of CRMWA and from an empirical formula relating seepage to volume in the reservoir using a maximum of 6.5 cfs, the maximum observed flow; 4) and area-capacity data from the Bureau of Reclamation. Pan evaporation was multiplied by a lake/pan coefficient of 0.7. The data were compiled on a monthly basis since October, 1964, and are given with the water-budget results in Appendix C, Table C.1.

The results show an average residual of -2100 acre-feet per month, although its distribution is very uneven, only occurring about 38% of the months and only when there are large flows at Amarillo. The correlation between large Amarillo flows and large negative residuals indicates that bank storage (equivalent to the term O_g) accounts for a substantial quantity of water. Because of the net gain in reservoir storage, a negative residual is expected. During small Amarillo flows and when reservoir levels decline, small positive residuals occur. The lack of large positive residuals indicate that groundwater inflow, I_g, and not surface water below the Amarillo gage, I_S, accounts for much of the difference.

Whether these residuals are an actual measure of the groundwater component or only represent a large component of error in some of the other terms cannot be answered with this information. The pattern of residuals indicate that the error terms are not large. The salt budget for the reservoir provides additional information supporting the results obtained in the water budget.

2. Salt Budget

As was determined in the water budget, the source of water to Lake Meredith is overwhelmingly from the Canadian River. Thus, it is reasonable to expect that the source of salinity in the lake is also from the river. The salt budget is analogous to the water budget and can be used to test the hypothesis that salinity in the Canadian River accounts for salinity in Lake Meredith. The salt-budget equation may be written with the following notation:

V_r^k = volume in Lake Meredith during month k

C_r^k = salinity concentration in Lake Meredith during month k

Then,

$V_r^k \cdot C_r^k$ = the mass of salt during month k, and

$V_r^{k-1} \cdot C_r^{k-1}$ = the mass of salt during month k - 1.

Q_a^k = Canadian River flow at the Amarillo gage during month k

C_a^k = salinity concentration in the Canadian River at the Amarillo gage during month k

Then,

$Q_a^k \cdot C_a^k$ = mass of salt inflow during month k

O_d^k = diversions from the lake

O_s^k = seepage through the dam

R_r^k = residual, as calculated in the water budget

$\frac{(C_r^k + C_r^{k-1})}{2}$ = average salinity concentration in the lake

The mass of salt corresponding to the diversions, seepage, and residual

terms

is the average salinity term.

The equation for the change in the mass of salt between month k-1 and k is:

$$V_r^k \cdot C_r^k - V_r^{k-1} \cdot C_r^{k-1} = I_a^k \cdot C_a^k + R_r^k \cdot \frac{(C_r^k + C_r^{k-1})}{2} - (O_d^k + O_s^k) \cdot \frac{(C_r^k + C_r^{k-1})}{2}$$

The values of lake volume, Amarillo flow, seepage, diversions, and residuals were those used in the water budget. The values for salinity input, C_a^k, were the weighted mean monthly chloride, total disolved solids, and sulfate concentrations at the Amarillo gage. The equation was programmed along with the water-budget, solving for lake concentration, C_r^k. The results are shown for chloride on Figure 46. The comparison between measured and calculated values

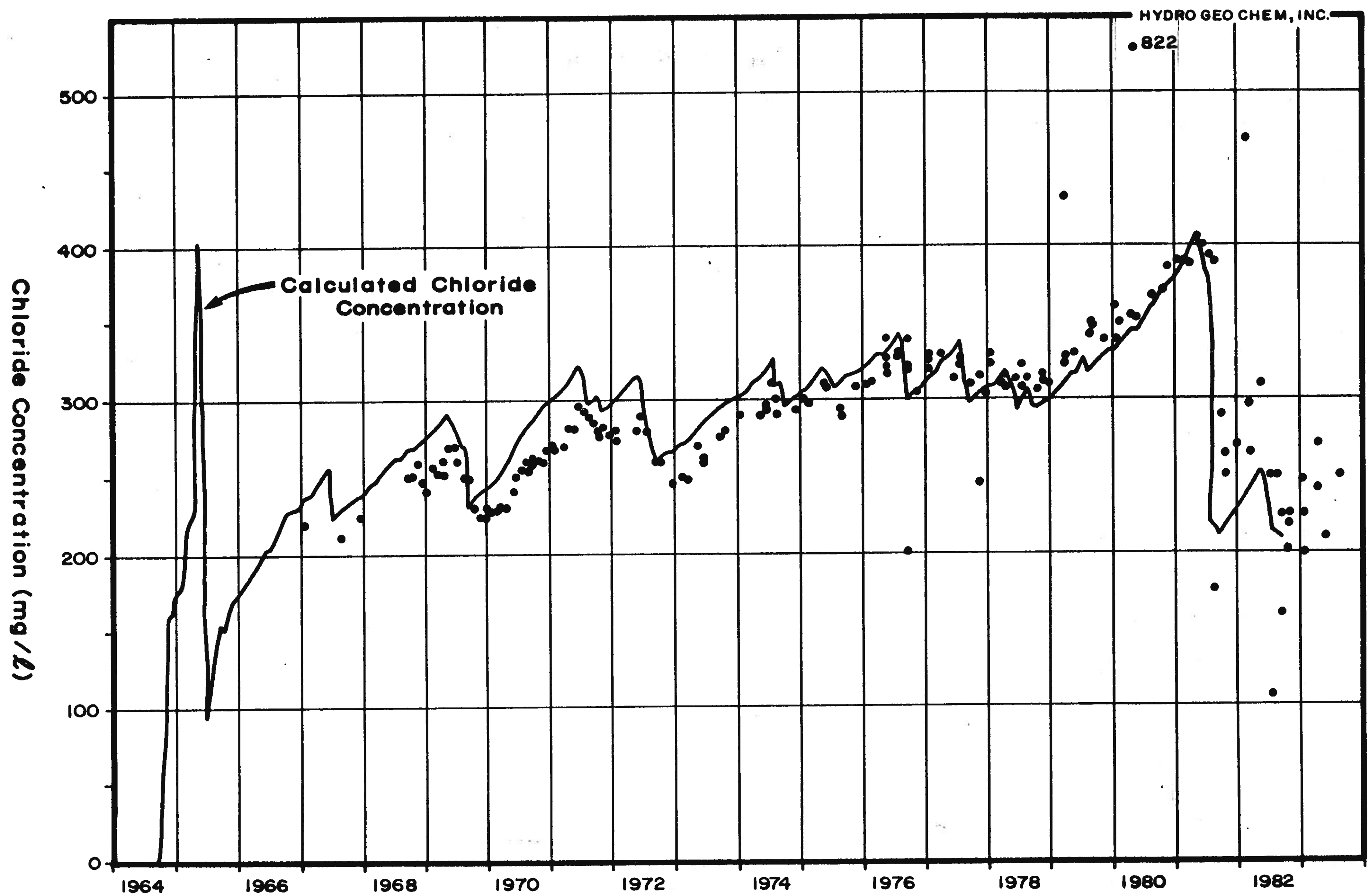


Figure 46. Calculated chloride concentration in Lake Meredith

is, in general, excellent, rarely differing by more than 5 percent from the measured values. Prior to 1972, the calculated values were systematically slightly high, while after 1972 they were slightly low, although at all times the chloride trends were correctly simulated. This agreement in general validates the assumptions made in both the water and salt budgets, as well as showing that the data used are accurate.

Salt-budget calculations were also made using total dissolved solids and with sulfate, though the results are not plotted. The behavior of both calculated parameters was nearly identical; however they differed substantially from the chloride calculations. During the first few years calculated TDS and sulfates were much lower than measured values, as low as 40 percent of measured. During later years calculated and measured were nearly identical. The probable reason for the low calculated values during early years is that when the lake was first filling, much gypsum was dissolved from the surrounding Quartermaster Formation. Thus measured lake concentrations would be higher than those calculated using Canadian River concentrations.

Based on the salt and water budgets the following conclusions can be made:

1. The large calculated residuals in the water budget represent, for the most part, actual groundwater inflows and outflows. The total error embedded in the residual term is relatively small.

2. The total salt load in the reservoir is that which passes in the surface water at the Amarillo gage. If there is an additional source of

salt near the Amarillo gage, little enters the surface water below the gage.

3. Periods of increasing salt concentration in the reservoir are those when inflows are small. This is because the salt concentration of the inflow is comparatively much higher during these periods. Periods of decreasing salt concentration coincide with periods of large inflows, increases in reservoir storage, and large negative water-budget residuals.

3. Prediction of Long-Term Salinity Levels in Lake Meredith

With this salt budget it is possible to predict the long term salinity concentration in Lake Meredith, providing we make several simplifying assumptions. First we must assume that the reservoir has reached a dynamic steady state. Since 1969 reservoir volume has averaged roughly 400,000 acre-feet, although it has ranged between 150,000 and 550,000. Therefore we take the period from 1969 to 1982 to represent a steady state. Second, we assume that diversions, inflow, evaporation, and rainfall follow the same averages as those determined during this steady-state period. Third, we assume that the salt input from the Canadian River follows the same patterns as in the past. This means that no change in the shallow brine aquifer occurs.

These averages, for each month, are given in Table 8. The reservoir chloride prediction was made by continuing the water-budget program past the last calculated month (September, 1982) by inputing these monthly averages and running the calculation until a steady-state chloride was reached. After 40 years the concentration was 400 mg/l. After an additional 20 years the maximum concentration increased by only an additional 2 mg/l. Thus we can say that the steady state chloride concentration will be about 400 mg/l given the above conditions.

The same calculations were made with TDS and sulfate. The calculated steady state concentrations are 1,550 mg/l for TDS and 360 mg/l for sulfates. These values may be low because of continuing dissolution of some minerals within the reservoir.

Table 8: Average (1969 to 1982) monthly water and salt budget parameters used to predict long-term chloride concentration

Month	Change in Storage	Diversions	Amarillo Flow	Amarillo Chloride	Pan Evap. (in.)	Precip. (in.)
January	-4015	-4380	1993	647	3.044	0.26
February	-3115	-4273	2259	618	3.954	0.46
March	-4315	-4972	1880	589	6.815	1.00
April	-4231	-5724	4469	455	9.947	0.96
May	-2500	-6134	8777	314	11.387	2.64
June	3194	-6860	29514	208	13.546	3.25
July	2624	-7726	24562	273	14.405	2.29
August	19871	-7151	34580	172	12.554	2.93
September	5579	-6135	23716	214	9.206	1.83
October	-4961	-5470	9660	311	7.692	1.16
November	-2677	-4379	3696	468	4.184	0.64
December	-5454	-4763	1520	620	2.812	0.26

This calculation, of course, ignores exceptional flow conditions, such as those which produced the high salinities from 1978 to 1981. Such events would temporarily cause salinities to rise above the long-term average. Also not accounted for is long-term climatic changes which would cause the average values listed in Table 8 to become invalid.

CHAPTER IV

FEASIBILITY OF SALINITY CONTROL

In this chapter we present and evaluate two methods to control the flow of brine into the Canadian River. The first method considers depressurization of the shallow brine aquifer beneath the river. The second method considers several dewatering wells in the channel sediments near the sources of brine inflow. These control measures are evaluted using a numerical model of the flow of salt and water in the groundwater-surface water system. The model allows for the interaction between the river channel sediments and the river as the major transport mechanism that operates to move subsurface salts into Lake Meredith is the flushing of the sediments by the river. Finally, we discuss the feasibility of deep-well injection for brine disposal.

METHODS OF SALINITY CONTROL

If no actions are taken to reduce the brine inflow to the Canadian River, long-term Lake Meredith chloride concentrations may approach 400 mg/l, or even higher during sustained low-flow periods. Total dissolved solids may exceed 1,500 mg/l. Whether this is acceptable to the municipal and industrial users of the reservoir water is not be addressed in this study. However, the salinity reduction which might be achieved through various positive control measures can be evaluated. The methods, advantages, and disadvantages of each system are discussed below.

1. Depressurization Wells

The rationale behind aquifer depressurization is to reduce the upflow of brine by lowering the hydraulic head of the shallow brine aquifer by means of a pumping well. In such a depressurization program, advantage is taken of the high aquifer diffusivity (T/S) to establish a large radius of pumping influence and thereby lower the hydraulic head over a large area. By decreasing the hydraulic potential, the flow should also decrease. Such a well (or wells) would be drilled into the shallow brine aquifer to a depth of about 400 to 500 feet. The pumping rate would have to exceed the upward leakage rate, because water would be removed from storage in the aquifer as well as being derived from captured leakage.

Depressurization wells have two main disadvantages. First, the hydraulic head of the aquifer is probably about 60 feet above the bottom of the river channel deposits, and flow to the surface takes place through a poorly defined fracture network. Therefore, reducing the head to an effective level may require high pumping rates. Also, the TW-1 test drawdown curve did not show any evidence of leakage, suggesting that the aquifer is extensive and that proper placement of depressurization wells may be difficult. This may mean that although one well may be capable of pumping a rate equal to the total natural upward leakage rate, several wells may be required to reduce the head over a large enough area.

The second disadvantage of depressurization wells to control the upward movement of brines is that the source of brines to the Canadian River is from the river-channel deposits. If the shallow brine aquifer is depressurized, the storage of brines in the channel deposits may only be slightly affected for long time periods. Thus there may be a long-term in the effectiveness of the depressurization program, because the only mechanism for removing brine from the channel deposits is through the slow process of upward diffusion to the river water, aided by occasional flushing from spillage over Ute Dam.

2. Channel Wells.

The storage of salt in the river-channel deposits between Ute Dam and Revuelto Creek is on the order of 10^8 kilograms (based on a 500 foot wide, 50 foot deep, 6.5 mile channel, with 25 percent porosity, and an average of 13,000 mg/l chloride). This amount is equal to that contributed to the river from about 7 years of upward leakage into the channel. Removal of salt directly from the channel deposits should have a rapid effect on the salinity of the river water, an effect that should be measureable in the river water soon after implementation. Such removal can be accomplished by pumping from several shallow (50 feet deep or less) wells completed in the river-channel deposits in the 6-mile reach between Ute Dam and Revuelto Creek. Wells could be drilled within the channel itself and pumped with suction or with windmill-powered piston pumps. They could also be completed as large-diameter collector wells along the channel bank, with horizontal drive-points into the channel, similar to the so-called "Ranney Well". (See Chow, 1964, page 13-32, for an illustration of this type of construction.)

Establishment of a shallow well field in the channel holds two advantages.

First, as mentioned above, the effects should be rapid and measureable. River water and groundwater quality could be monitored regularly to assess the efficiency of the program. Second, the wells could be efficiently located in the areas of high salt concentration. Because the per well cost is low, the cost of making a drilling location mistake would also be small. In addition, should water quality in one well improve, it could be temporarily shut down to reduce the disposal rate.

We anticipate that there are three disadvantages in using shallow channel wells. First, because we suspect several wells would be required, surface piping costs would be high. The variable rate of pumping (if windmills are used or if wells are shut down for various reasons) may necessitate some temporary surface storage of the brines if disposal capacities are exceeded. Second, higher total pumping rates may be required than those from depressurization wells. This is because of the large storage in the channel deposits and the relatively small radius of influence of a pumping well. Storage of salts downstream of the confluence with Revuelto Creek would not be affected. Third, because the wells would be in or adjacent to the river channel, some sort of flood protection would be required, especially in the channel below Revuelto Creek.

TIME EFFECTS OF SALINITY REDUCTION

The characteristics of the brine aquifer, channel aquifer and the surface water must be accurately assessed to predict the effects of any salinity alleviation scheme. This is a difficult problem because, as we have shown in the previous chapters, the brine stored in the channel sediments is partially isolated from the surface water by density differences, and is primarily transported to the surface water by periodic flushing. The transport of most of the salt down the river channel occurs sporadically during these periods of flushing. Because of the complexity of the modes of salt transport, predictions require that several simplifications to the above-described conceptual model of the system be made.

1. Model Description

No computer codes are available which describe both solute transport and flow in a combined groundwater - surface water system. We have formulated a mathematical solution, called a mixing-cell model, which considers, in a very simplified manner, coupled water flow and solute transport. In the model we consider only the river-channel sediments and the river itself. The shaloow brine aquifer is considered as a constant flux term to the sediment cells. Thus the hydraulic connection between the two aquifers and any corresponding lag time for flow is neglected in the model. The mixing-cell model uses blocks, or cells, to represent discrete volumes of the aquifer and river reaches. Within each cell the amount of salt that enters and leaves is acounted for (mass balance). The mechanisms of brine movement are both by diffusion and by convection: diffusion processes which control movement of brine from the sediment cells to the river cells, and convection which controls the movement of brine within the sediment cells. In this model, the flow of brine due to density contrasts is neglected.

Two mass-balance equations are used in the model. The meaning of each of the terms used in the equations is shown in the block diagram representing the cells in the model, Figure 47. For river cells the mass balance equation is

$$\frac{C_i^K - C_i^{k-1}}{\Delta t} =$$

$$\frac{Q_{i,i+1}^k \cdot C_{i+1}^k}{V_i} + \frac{Q_{in} \cdot C_{in}}{V_i} - \frac{Q_{i,i-1}^k \cdot C_i^k}{V_i}$$

$$- \frac{\alpha_{i,i+m} \cdot A_{i,i+m}}{V_i} \cdot \frac{(C_i^k - C_{i+m}^k) + (C_i^{k-1} - C_{i+m}^{k-1})}{2}$$

where C_i^k is the concentration for cell i at time k

$Q_{i,i+1}^k$ is the flow between cells i and i+1 at time k

V_i is the flow volume

$\alpha_{i,i+m}$ is the transfer coefficient between river and sediment cells

$A_{i,i+m}$ is the area of transfer between river and sediment cells

Q_{in} is the volume of sources (e.g. Revuelto Creek)

C_{in} is the salt concentration of sources

For the cells representing the river sediments the mass-balance equation is written

$$\frac{C_{m+i}^k - C_{m+i}^{k-1}}{\Delta t} =$$

$$\frac{A_{m+i,m+i+1} \cdot K \cdot I}{V_{m+i}} \cdot \frac{(C_{m+i+1}^k - C_{m+i+1}^{k-1})}{2} - \frac{A_{m+i,m+i-1} \cdot K \cdot I}{V_{m+i}} \cdot \frac{(C_{m+i}^k - C_{m+i}^{k-1})}{2}$$

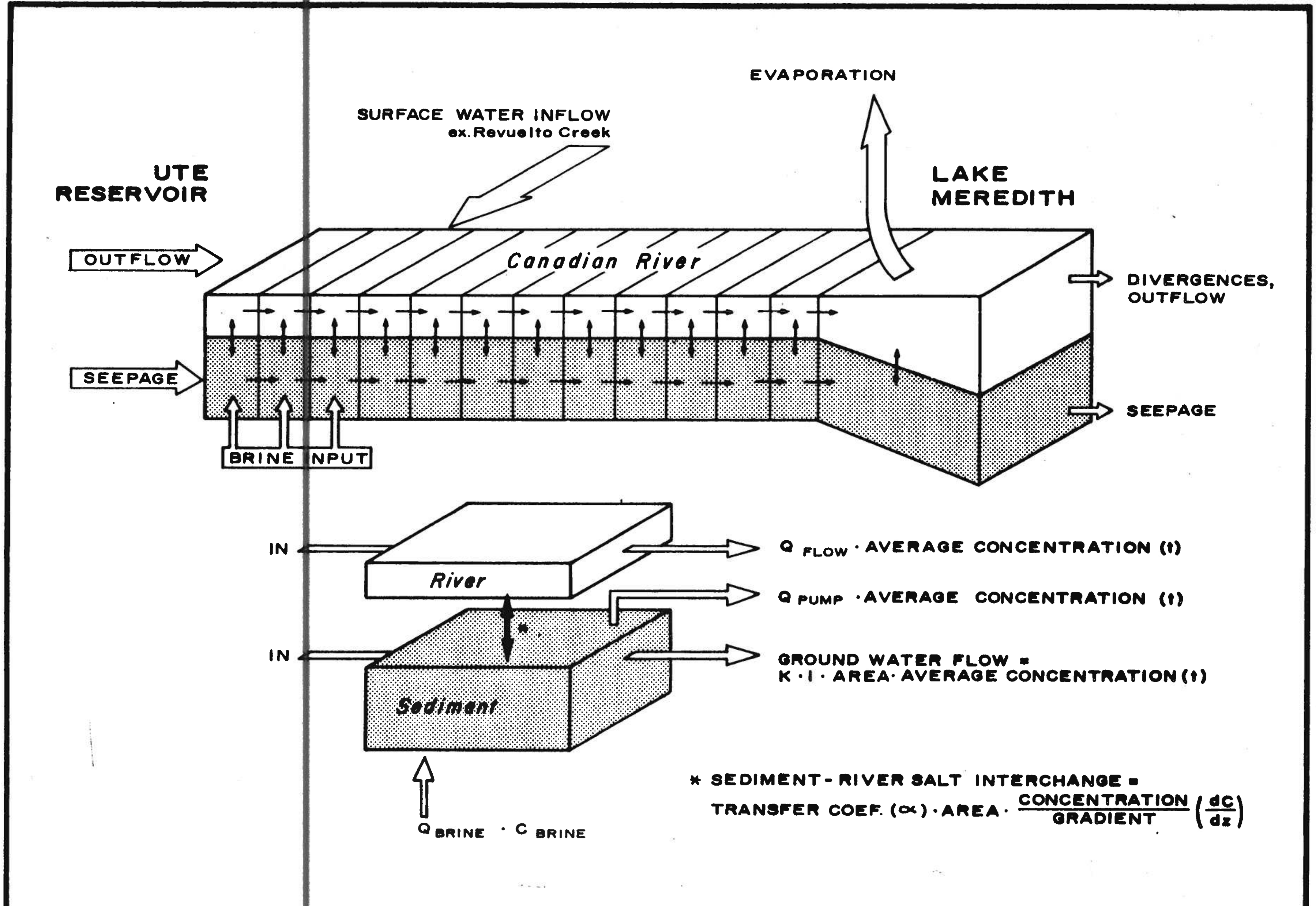


Figure 47. Mixing cell model structure

$$+ \frac{{}_{m+i,i} \cdot A_{m+i,i}}{V_{m+i}} \cdot \frac{(C_i^k - C_{i+m}^k) + (C_i^{k-1} - C_{i+m}^{k-1})}{2}$$

$$+ \frac{Q_{brine} \cdot C_{brine}}{V_{m+i}} - \frac{Q_{pump}}{V_{m+i}} \cdot \frac{(C_{m+i}^k + C_{i+m}^{k-1})}{2}$$

where C_{m+i}^k is the concentration in sediment cell m+i

C_i^k is the concentration in the overlying river cell

$A_{m+i,m+i+1}$ is the cross-sectional area between adjacent cells

K is hydraulic conductivity

I is hydraulic gradient

V_{m+i} is the volume of the sediment cell m+i

Q_{brine} is the flow rate of brine into the sediment cell

C_{brine} is the brine concentration.

We simulated the river reach between Ute Dam and Lake Meredith. The model was divided into twenty river cells and twenty corresponding sediment cells, and initial estimates of hydraulic conductivities, gradients, transfer coefficients, and concentrations were assigned to each cell. To allow for greater detail, 10 cells are used to represent the river between Ute Dam and Revuelto Creek, 6 additional cells are used above the state line, and 4 cells are used between state line and Lake Meredith.

The model has been designed to simulate the low-flow characteristics of the system, not the periodic high-flow salt transport. Thus we neglect an important mode of transport; however, by this the model predictions may be more conservative. The predictions are simulated in two ways. To simulate the effects of depressurization wells, the brine inflow is cut off from those cells receiving it, and the freshening of water in downstream cells is monitored. To simulate the effects of dewatering from shallow channel wells, the brine inflow continues at its steady-state rate, while certain sediment cells are pumped, and downstream cells monitored for freshening.

2. Model Inputs and Calibration

Once salt reaches the surface water, transport is fairly rapid. Therefore, the slow movement of brines within the channel sediment and into the surface water is all that we are concerned about in this model. This upward movement is proportional to the concentration (diffusion) gradient between the sediment cells and the surface water cells, the constant of proportionality being the transfer coefficient. This coefficient has no direct physical meaning, because the maintenance of the diffusion gradient in the model neglects other transport processes such as density flow and convection.

The following conditions were input to the model:

1. A hydraulic conductivity of the cells representing the channel deposits of 30 ft/day and a hydraulic gradient of 0.001 ft/ft.

2. Two cfs flow at 1,300 mg/l TDS at the upstream boundary to represent flow from Ute Dam and Triassic groundwater.

3. Nine-tenths cfs flow at 49,000 mg/l TDS shallow brine inflow, evenly distributed among the 10 cells representing the channel sediments between Ute Dam and Revuelto Creek.

4. Seven cfs flow at 1,200 mg/l at cell number 10, representing input from Revuelto Creek.

5. Three cfs at 1,250 mg/l distributed evenly between the cells representing

Revuelto Creek and state line, representing groundwater inflow from the Triassic rocks.

During the calibration process the transfer coefficient was adjusted until the differences between modeled and observed concentrations and gradients were small. The criteria used for calibration were:

1. TDS concentration in the cells representing the channel deposits upstream of Revuelto Creek average 27,000 mg/l (as per the analysis from Piezometer Site 3).

2. TDS in the cell representing the Canadian River above Revuelto Creek average 11,000 mg/l.

3. TDS in cell 8, approximately where Piezometer site 6 is located, average 20,000 mg/l (as per the analysis from Piezometer Site 6).

4. The downstream concentration gradient in both surface-water cells and sediment cells decreases until the concentrations are equal at cell 4, which is the approximate location of the state line.

It was found that one value for the transfer coefficient would not allow all of the above criteria to be met. Calibration required that one high value be used for cells above Revuelto Creek and a low value for cells below Revuelto Creek. This is consistant with the movement of brine in the channel deposits. Upstream of the Revuelto Creek confluence brine may enter the surface water convectively as well as through dispersion. A high transfer coefficient accounts for this convective term. Below the confluence brine becomes more isolated from the surface water by density differences, which is simulated by decreasing the transfer coefficient in these cells.

A satisfactory calibration was obtained using transfer coefficients of 0.44 and 0.0014 ft/day, for cells above and below Revuelto Creek, respectively. The

TDS concentrations in the sediment and river cells are shown in Figure 48. The river concentration is slightly lower than that measured in the cells receiving brine, while the sediment cells are slightly higher. This should result in conservative predictions of the effects of salinity reductions. Because the water was not diluted with further fresh water inflow below the state line cell, simulated concentrations are higher than measured in the downstream cells. This will not affect the predictions.

3. Model Prediction

The time effects on salinity from aquifer depressurization was tested in two ways. First, to simulate the effects of shallow brine aquifer depressurization a simulation was run using the initial steady-state conditions described above, but shutting off all the brine input to the sediment cells. Then, to simulate the effects of less than total depressurization efficiency, a simulation was run with only half of the brine stopped. Simulations were run for 10 years in all cases, becauses differences between various simulations would be apparent by that time. Figure 49 shows the reduction in salinity over time at cells representing the Canadian River (cell 11) above the confluence with Revuelto and at state line (cell 4) for a simulation of 100 percent brine flow reduction. The effect after 10 years depressurization is about 24 percent reduction in salinity in the river. The salinity in cell 4 was nearly equal to that in cell 2, adjacent to Lake Meredith. Within the river cells upstream, salinity was reduced 41 percent after 10 years. There is no depressurization pumping rate used or inferred in the model.

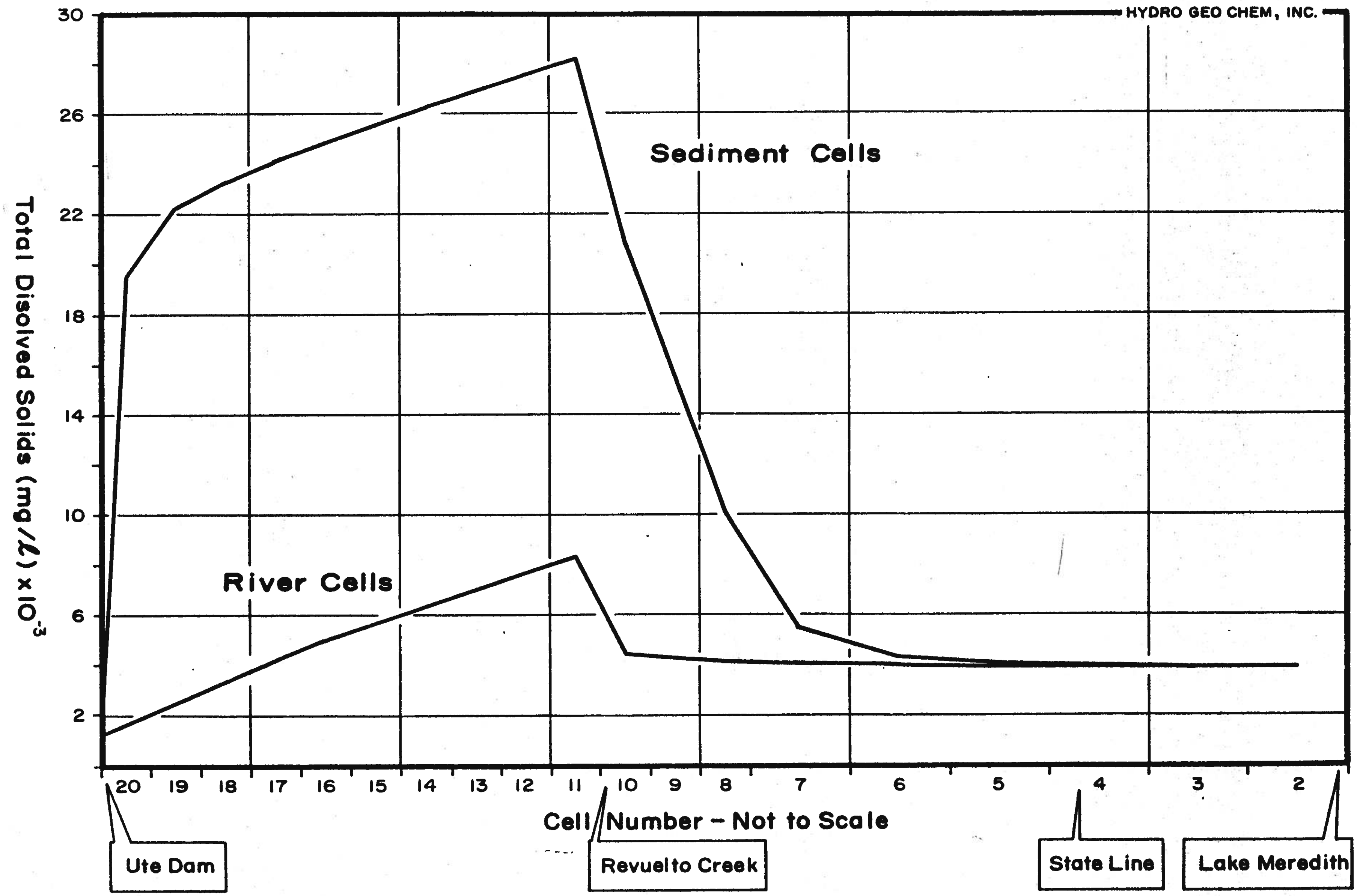


Figure 48. Steady state model results

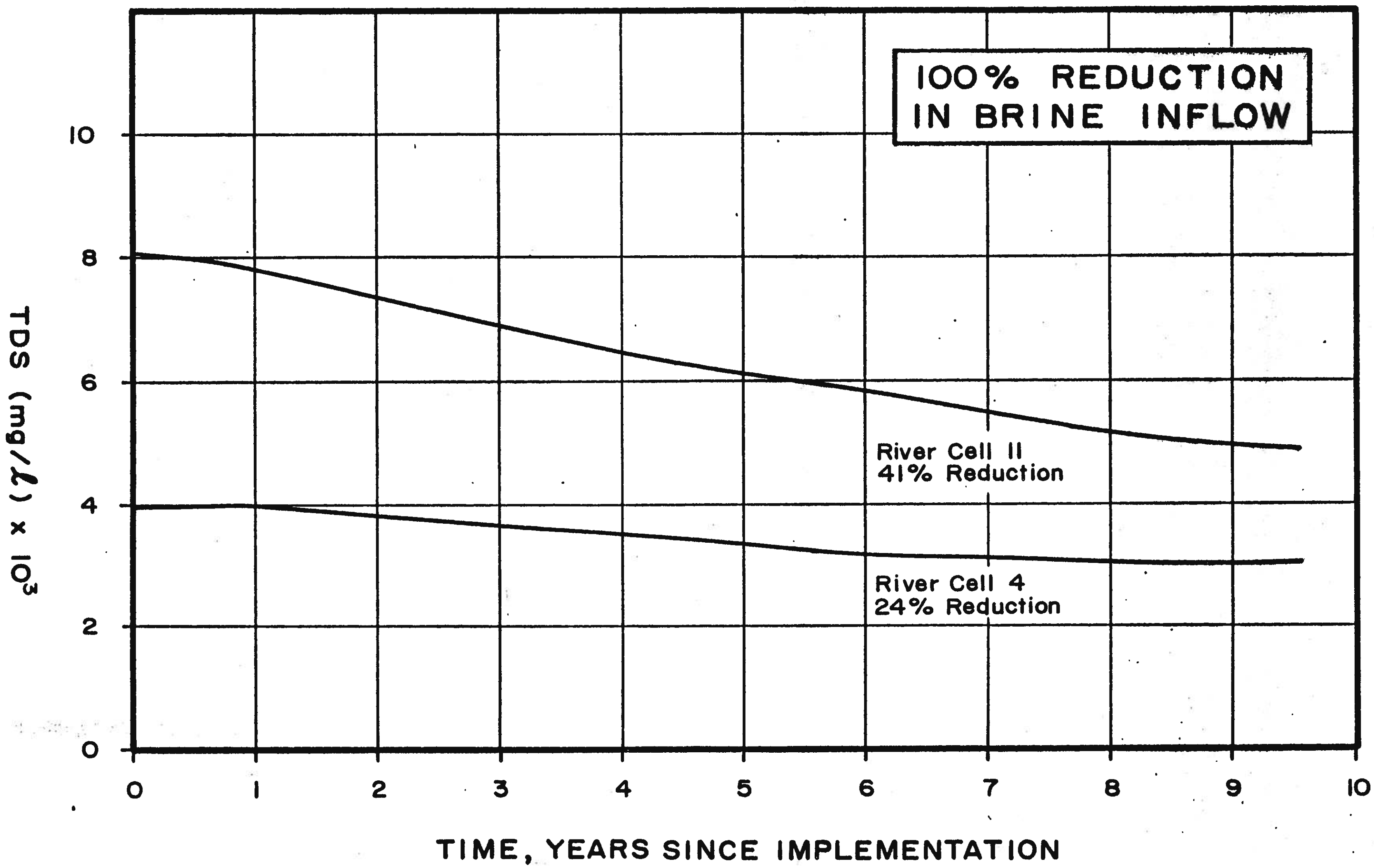


Figure 49. Predicted salinity reduction for 100 percent brine reduction

HYDRO GEO CHEM, INC.

Figure 50 shows the salinity reduction over time when the brine inflow is reduced by only 50 percent. We can see that the time for the system to respond is nearly the same, however the amount of salinity reduction is about half of that from the previous simulation.

The salinity reduction expected from pumping shallow channel wells was simulated by removing 0.9 cfs, a rate equal to the simulated brine inflow, distributed in 5 cells. This is equivalent to 5 wells pumping a rate of about 80 gpm each. The salinity reduction in two cells is shown in Figure 51. We can see that at this rate the salinity reduction is not quite equal to the reduction obtained from a 100 percent brine inflow (depressurization) reduction. This is because of the large volume brine storage in the channel deposits. Over a longer time period than 10 years, however, as sediment storage is depleted, the salinity reduction would be as great as for the 100 percent depressurization case.

Long-term salinity reductions, beyond 10 years, from a 100 percent brine inflow reduction program, would approach 70 percent of the total, which is our estimate of the amount of salt contributed by the shallow brine aquifer. If the long-term chloride concentration is 400 mg/l without any control measure, then the ultimate salinity level with control will be at a chloride concentration of about 120 mg/l.

The time necessary to achieve such a reduction can be estimated through extrapolation of the salinity reduction curve in Figure 49 to 100 percent reduction. At an average reduction rate of 2.4 percent per year, it would take 42 years for the Canadian River to completely reduce its salinity to 30 percent of

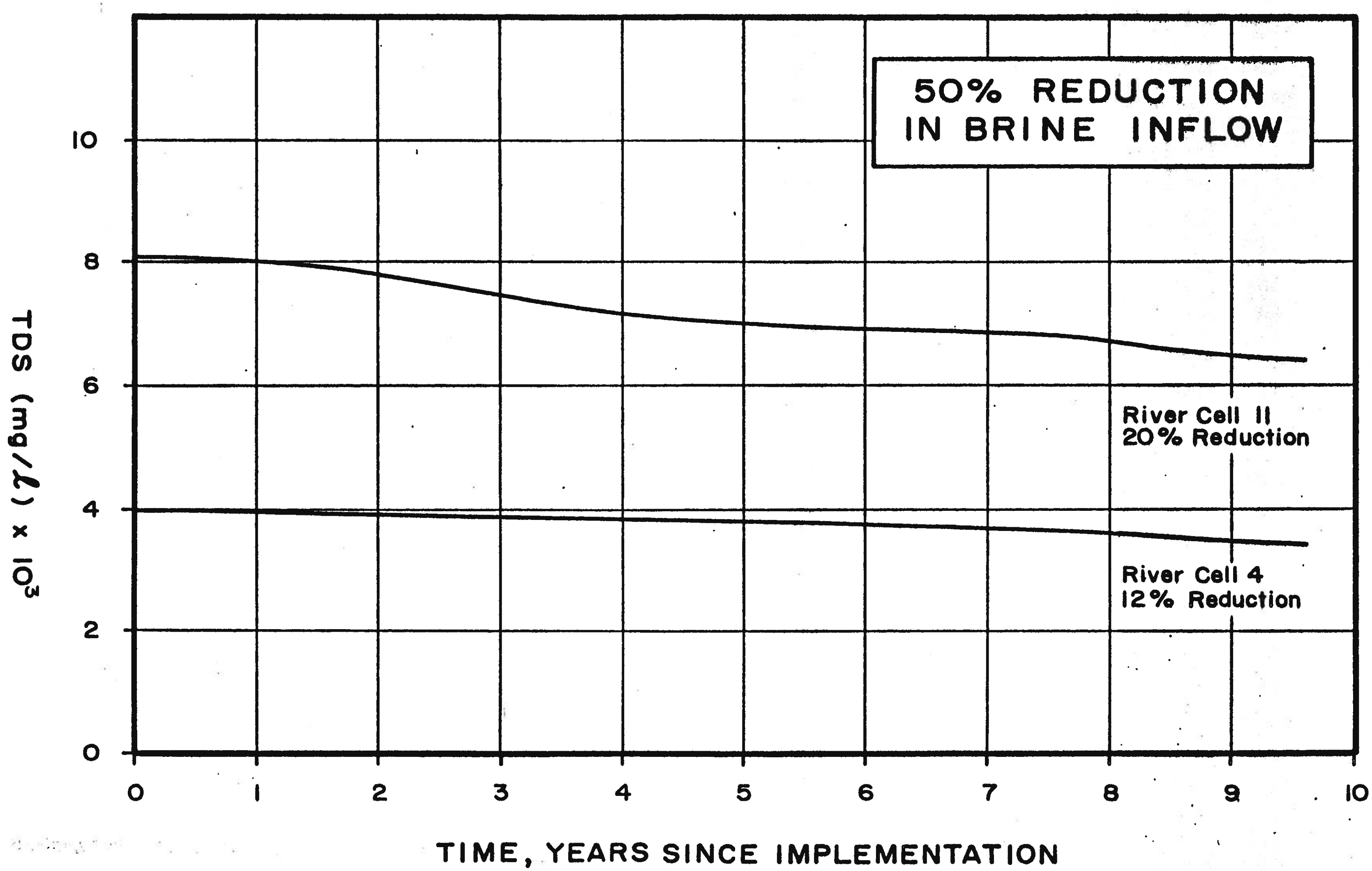


Figure 50. Predicted salinity reduction for 50 percent brine reduction

HYDRO GEO CHEM, INC.

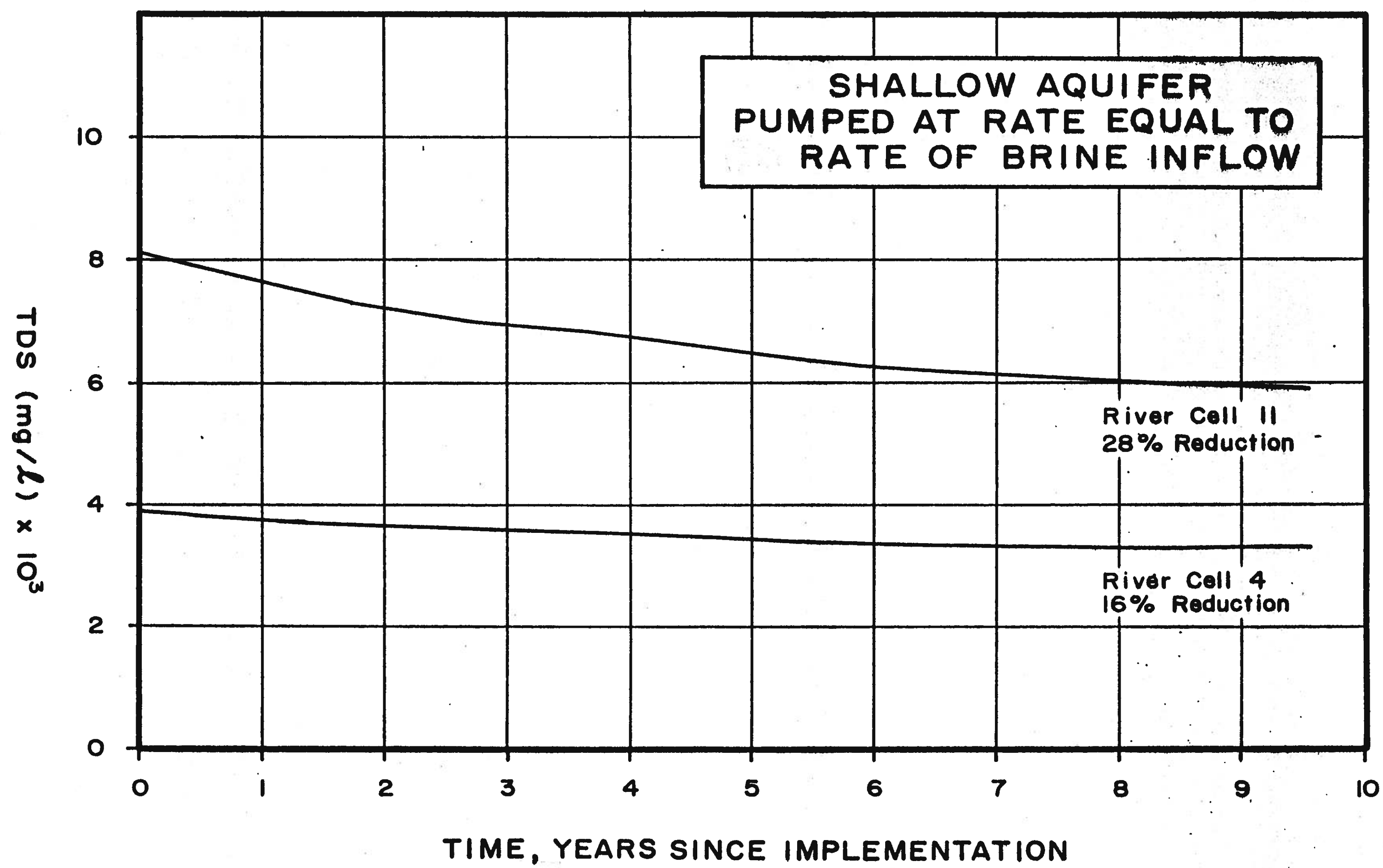


Figure 51. Predicted reduction in salinity from channel pumping wells

HYDRO GEO CHEM, INC.

its former value. The effect on Lake Meredith would be similar, although at a slightly slower rate.

This calculation, of course, is conservative because the the important mechanism of flood-flow transport of salt is neglected. However, with the planned increase in Ute Reservoir storage, these flows will probably less frequent in the future. We cannot estimate the flushing rate if flood flows are considered.

4. Model Sensitivity

Uncertainties in our estimation of hydrologic parameters give rise to errors in the prediction. A test of the effects of uncertainty in the parameters is to vary each parameter individually within its plausible range and run model simulations with each of these variations. The change in the prediction resulting from a change in a particular parameter is a measure of the sensitivity of the prediction to that parameter. If the sensitivity is small, when we can conclude that even if the parameter is poorly estimated, the prediction will not be badly affected by errors. On the other hand, if the sensitivity is large, then an error in the parameter will lead to large errors in the prediction. This procedure is called a sensitivity analysis.

In the sensitivity analysis we have considered possible errors in the hydraulic conductivity of the channel sediments and in the transfer coefficient. The effect of varying the hydraulic conductivity between 10 and 60 ft/day on the prediction from aquifer depressurization was very small. This is partly because of actual insensitivity and partly because of the model formulation, which has a low fixed hydraulic gradient that corresponds to the physical setting of the river. Nearly the same insensitivity held true for cases in which the sediment cells were pumped.

Because the steady-state simulations were relatively insensitive to the values of the transfer coefficient, we consider this parameter poorly estimated. Therefore we varied it two times larger and two times smaller than the steady-state values, and re-ran the simulation for 100 percent brine inflow reduction. The results were plotted as percent salinity reduction over time for all three simulations at river cell number 11, and are shown in Figure 52. We can see that the sensitivity of the prediction to this parameter is high, with a variation in salinity reduction of from 26 percent to 57 percent. It should be noted that these transfer coefficients are slightly beyond the plausible range, because each resulted in worse steady state salinity distributions than was obtained with the standard transfer coefficents.

5. Conclusions Based on Model Simulations

Because the shallow brine aquifer was not implicit to the model, we could not simulate brine aquifer pumping rates. Therefore a comparison between the two proposed salinity reduction methods based on required pumping rates was not possible. However, the salinity reduction results from either aquifer depressurization or channel sediment pumping are similar if the brine flow rate can be completely stopped. Shallow channel wells would probably yield more rapid results because confining units between the brine aquifer and the channel sediments would result in time lags, not considered in the model. However, over several years, this

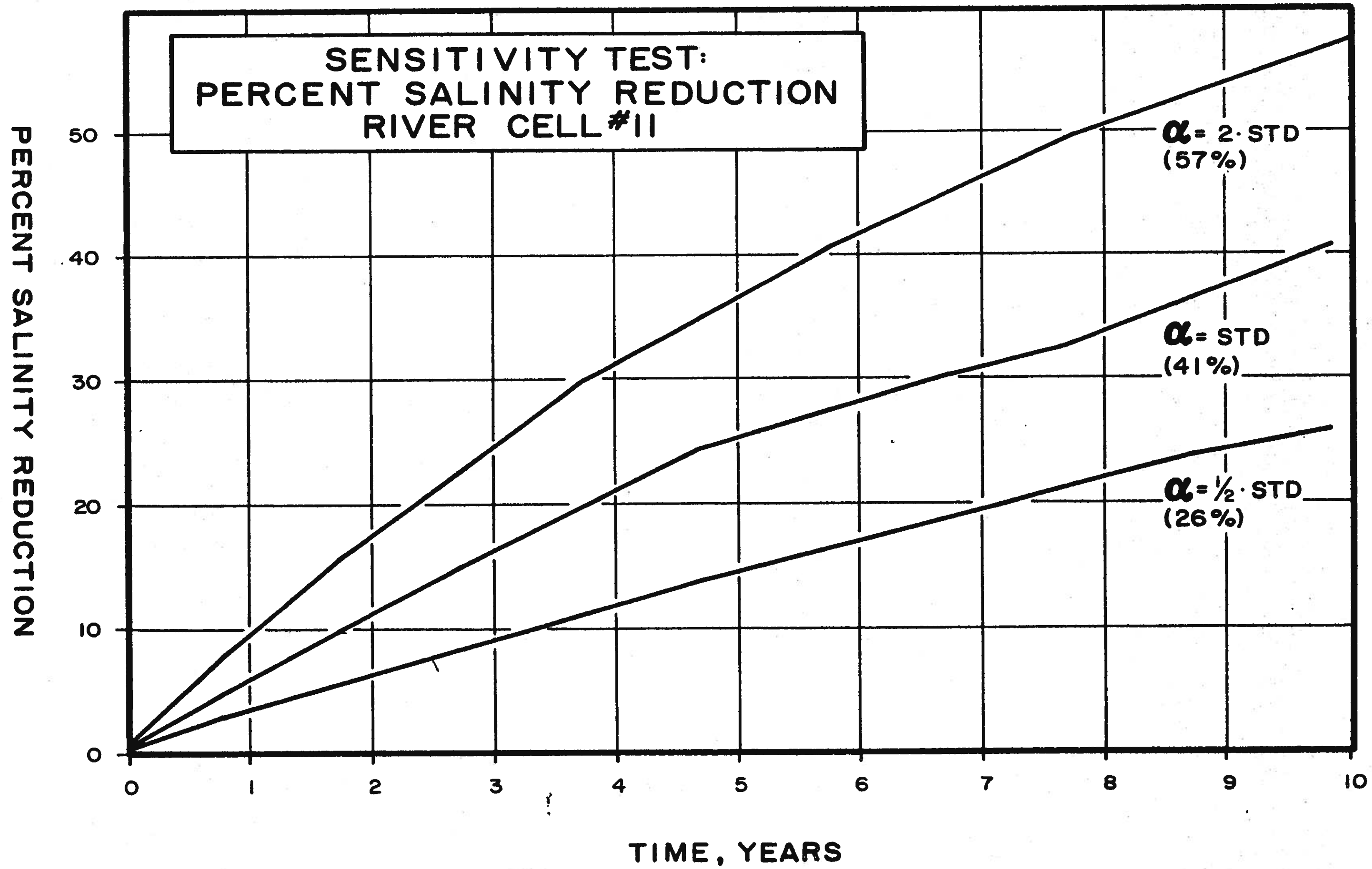


Figure 52. Results of sensitivity to transfer coefficients

HYDRO GEO CHEM, INC.

effect would diminish. Also, the rate of pumping from channel wells would have to be slightly more than the brine inflow rate to achieve the same results as complete aquifer depressurization. In either case, there would be no short-term rapid reduction in salinity.

Whether channel wells or depressurization wells would yield superior salinity-reduction results cannot be unequivocally determined by these simulations. Their relative efficiencies in reducing river salinity was shown. We can conclude that, if the brine aquifer can be depressurized to a level below the bottom of the channel sediments, it will result in a salinity reduction as shown in Figure 49. Furthermore, if pumping from the channel sediments exceeds the brine inflow rate, similar long-term salinity reductions could be achieved.

The number of wells that would be required in either salinity reduction scheme cannot now be calculated with the available information. However, we estimate that at least two shallow brine aquifer depressurization wells would be necessary to cover an area which would extend from Ute Dam to Revuelto Creek. The locations of shallow channel wells should be adjacent to and downstream of the three high salinity zones identified in the channel. Thus about six wells may be required. The necessary pumping rate from any of the wells would depend on the hydraulic characteristics encountered; thus several aquifer tests would need to be conducted.

FEASIBILITY OF DEEP-WELL INJECTION

In the Bureau of Reclamation (1979) report the feasibility of surface disposal of brines was evaluated. Since that report, there has been increased interest in deep-well disposal in the area because of piping and land costs and long-term environmental effects from a surface disposal site.

The general criteria for evaluating the feasibility of deep-well disposal of brines are: first, that a horizon of suitable hydraulic characteristics can be found at an economical distance and depth; second, that the horizon is adequately isolated such that other aquifers are protected; third, that other economic uses are not jeopardized. To our knowledge there are no deep injection wells within the detailed study area, but there are many in the Panhandle portion of the study area that are used for oil-field brine injection and for water-flood operations. It is recognized that additional data collection, in the form of surface geophysical surveys and, probably, test drilling, is necessary in this area to assess its suitability for injection. However, enough information is available to comment on its potential in the Logan area.

1. Hydraulic Characteristics

Potable water exists throughout the Triassic Formation in the detailed study area, as well as in Ute Reservoir, and, marginally, in Revuelto Creek and the Canadian River. The lower Triassic as well as all deeper formations contain brackish to briny water. The disposal horizon must be isolated from any unit in contact with these sources of potable water, as well as from the brine aquifer.

Therefore we can exclude Triassic and the Permian Artesia or laterally-equivalent formations. The Permian San Andres offers a potential horizon because of its permeability. Drillers logs of the Ute Anticline No 1 well (see Table 1) mention lost-circulation zones within the formation. However, because of its shallowness, (see Table 2) the San Andres may not offer sufficient separation from potable water sources. In addition, the fracture systems or faults which allow the brine to move into the Canadian River channel may be related to salt dissolution in the San Andres, thus permitting upward leakage of the injected brines. The Glorieta appears to be discontinuous in the area, or becomes dolomitic and salt-prone, so it is not anticipated that it would be a good horizon. The Yeso represents about 1500 feet of generally low permeability shales, siltstones, sulfate and carbonate rocks. If a higher permeability zone, such as equivalents of the Tubb or Fullerton sands, is found in the middle- to lower- Yeso, it may represent a suitable injection horizon. However the zone may be too thin (probably between 35 and 170 feet) to provide sufficient transmissivity.

The lower Permian- Pennsylvanian section is about 2500 to 3000 feet below land surface in the detailed study area. The Abo and "granite wash" potentially offer a good disposal horizon for brines. Examination of drillers and geophysical logs from several wells in the vicinity of Logan show that there is between 500 and 1000 feet of combined Abo-Sangre de Cristo thickness. It is predominantly a poorly-sorted, clay-rich, arkosic sandstone, with interbedded shale and siltstone. Because of its thickness and depth, its confinement by the overlying Yeso, and potentially high transmissivity, this sequence is the most promising horizon for brine disposal.

Drill-stem tests (DST), not available to us, may have been run on many of the deep wells in the area. The Ute Anticline No I well was tested in the San Andres and Yeso (Nat. Oil Co., Denver, pers. com.). No tests of the Abo or Sangre de Cristo were run. In the absence of such information, we should assume that pressures are lithostatic, the above-mentioned lost circulation zones notwithstanding, and fluids may flow at the surface from wells drilled in the Permian or Pennsylvanian formations.

2. Conflicts with Other Economic Uses

Most of the subsurface information in the study area came from unsuccessful oil or gas holes. To our knowledge no active or capped oil or gas wells are located in the detailed study area. Because the area has a history of unprofitable drilling there is probably little potential for any significant hydrocarbon discoveries or extensive drilling activity.

Drilling for carbon dioxide is a potential economic activity in the area. Foster and Jensen (1972) show existing CO_2 fields north of the Canadian River in Harding and Union counties, but none within the study area. Producing zones range from Precambrian to Triassic. Two wells within the study area were seen to evolve gas. The Dripping Springs well bubbles slightly with an odorless gas; we noticed during sampling of well OW-3 that it was somewhat charged with gas, confirmed by the lab to contain CO_2.

Uranium has been found within the study area, but only within the Chinle or Morrison formations (Finch, 1972). There are a number of prospects but currently no active mining. There seems little potential for conflict with any proposed deep well disposal.

Capturing brine flow by depressurization or channel pumping may cause flow in the Canadian River to be reduced, or even eliminated during low flow periods in the Logan area. Despite the poor quality, cattle drink from this source. It may be possible to augment flow by releasing an amount from Ute Dam equal to the amount being pumped, probably 1 to 2 cfs.

3. Recommendations

Further effort should be made to locate DST and fluid pressure data obtained during test-well drilling. With these data possible injection zones, indications of required injection pressures, and zone correlations can be determined. Also, more work needs to be done on geophysical log interpretation and correlation, particularly for units below the San Andres. Surface geophysics have not been run in the vicinity of Logan (except for the resistivity and seismic refraction surveys conducted by the Bureau), but have been run south of and to the Ute Anticline well. The data from these surveys are available for inspection from Permian Exploration Co. of Roswell, New Mexico and from other seismic operators in the region. If these data prove useful, they should be purchased and used for subsurface analysis.

In concert with this work, we recommend that surface geophysical surveys be conducted in the vicinity of Logan. Seismic reflection surveys are recommended because this type of geophysics can determine lateral discontinuities of the units, a very important consideration in subsurface injection studies. The line locations should be south of the Canadian River because the Abo and Sangre de Cristo thicken in that direction. The survey can be tied into the Ute Anticline well either directly or through the use of synthetic seismic profiles generated from the geophysical logs obtained for the test well.

If promising zones are identified in the survey, one or two test holes should be drilled to intercept the zones. Such drilling must be designed carefully so that the maximum hydrogeologic information can be obtained. Potential injection intervals should be cored so that fractures, bedding, and solution openings can be identified, and so that lab measurements of porosity and permeability can be made. In the Abo or Sangre de Cristo, sidewall cores should be considered. Geophysical well logs (acoustic, caliper, temperature, neutron, resistivity, gamma, density), sample logs and drillers logs should be obtained and analyzed from these test wells.

The design of drill stem tests (DST) is the most important consideration. The DST configuration and implementation must allow for accurate measurement of permeability and fluid pressure, as well as allow for uncontaminated fluid samples. These tests will be a rather time-consuming operation, so sufficient testing and stand-by time must be allocated. Computations of injection rates and pressures should be made with these values, as well as the compatibility of injection and formation fluids. The feasibility of drilling one or more injection wells or the rejection of the option of deep-well disposal will depend on these computations in concert with the formation evaluations done using the log data.

REFERENCES

Bassett, R.L., M.E. Bentley. 1983. Deep brine aquifers in the Palo Duro Basin: regional flow and geochemical constraints. Report of Investigations No. 130, Texas Bureau of Economic Geology, University of Texas at Austin. 59 p.

Bendix Field Engineering Co. 1981. Uranium hydrogeochemical and stream sediment reconnaiassance of the Tucumcari NTMS quadrangle, New Mexico/Texas. Report GJBX-183(81). Grand Junction, Colorado.

Berkstresser, Charles F. and Walter A. Mourant. 1966. Ground-water resources and geology of Quay County, New Mexico. Ground-Water Report No. 9, State Bureau of Mines and Mineral Resources, New Mexico Institute of Mining and Technology, Socorro.

Budnik, R. and D. Smith. 1982. Regional stratigraphic framework of the Texas panhandle. In Geology and Geohydrology of the Palo Duro Basin, Texas Panhandle. Texas Bureau of Economic Geology, University of Texas at Austin. 38 p.

Chow, Ven Te. 1964. Handbook of applied hydrology. McGraw- Hill, New York.

Craig, H. 1961. Isotopic variations in meteoric waters. Science. vol 133.

Davis, S.N. and R.J.M DeWeist. 1966. Hydrogeology. John Wiley and Sons. New York.

Dobrovolny, Ernest, C.H. Sumerson and R.L Bates. 1946. Geology of northwestern Quay County, New Mexico. U.S.G.S. Oil and Gas Investigations Map OM-62.

Dutton, S.P., Robert J. Finley, W.E. Galloway, Thomas C. Gustavson, C. Robertson Handford, Mark W. Presley. 1979. Geology and geohydrology of the Palo Duro Basin, Texas Panhandle. A Report on the Progress of the Nuclear Waste Isolation Feasibility Studies (1978). Geologic Circular 79-1, Bureau of Economic Geology, University of Texas at Austin. 99 p.

Finch, Warren. 1972. Uranium in eastern New Mexico. New Mexico Geological Society Twenty-Third Field Conference Guidebook.

Foster, R.W. and J.G. Jensen. 1972. Carbon dioxide in northeastern New Mexico. New Mexico Geological Society Twenty-Third Field Conference Guidebook.

Foster, R.W., R.M. Fentress and W.C. Riese. 1972. Subsurface geology of eastcentral New Mexico. New Mexico Geological Survey Spec. Pub. No. 4

Griggs, R.L. and G.E. Hendrickson. 1951. Geology and ground-water resources of San Miguel County, New Mexico. Ground-Water Report No. 2 State Bureau of Mines and Mineral Resources, New Mexico Institute of

Gustavson, T.C., R.L. Bassett, R. Budnik, R.J. Finley, A.G. Goldstein, J.H. McGowen, E. Roedder, S.C. Ruppel, R.W. Baumgardner, Jr., M.E. Bentley, S.P. Dutton, G.E. Fogg, S.D. Hovorka, D.A. McGookey, P.J. Ramondetta, W.W. Simpkins, D. Smith, D.A. Smith, E.A. Duncan, J.A. Griffin, R.M. Merritt, and E.R. Naiman. 1982. Geology and geohydrology of the Palo Duro Basin, Texas Panhandle. A Report on the Progress of Nuclear Waste Isolation Feasibility Studies (1981), Texas Bureau of Economic Geology, University of Texas at Austin. 211 p. p.s 1

Handford, C. Robertson, Shirley P. Dutton, and Paul E. Fredericks. 1981. Regional cross sections of the Texas Panhandle: Precambrian to Mid-Permian. Texas Bureau of Economic Geology, University of Texas at Austin. 8 p.

Kelley. V.C. 1972. Geology of the Santa Rosa area. New Mexico Geological Society Twenty-Third Field Conference Guidebook.

Kottlowski, F.E. 1969. State Bureau of Mines and Mineral Resources, Socorro, New Mexico. Letter to Mssrs. W. Mourant, Z. Spiegel, and C.B. Read.

McGookey, D.A. and A. G. Goldstein. 1982. Structural influence on deposition and deformation at the northwest margin of the Palo Duro Basin. In Geology and Geohydrology of the Palo Duro Basin, Texas Panhandle. Texas Bureau of Economic Geology, University of Texas at Austin.

McGowen, J.H., G.E. Granata, and S.J. Seni. 1979. Depositional framework of the Lower Dockum Group (Triassic) Texas Panhandle. Report of Investigations No. 97, Texas Bureau of Economic Geology, University of Texas at Austin.

New Mexico State Engineer's Office. 1961. Preliminary report on the geology of the Ute Damsite, Quay County, New Mexico. Canadian River Storage Sites Investigation, Ute Reservoir, Quay County, New Mexico.

Presley, Mark W. and Kathy A. McGillis. 1982. Coastal evaporite and tidal-flat sediments of the Upper Clear Fork and Glorieta Formations, Texas Panhandle. Report of Investigations No. 115, Texas Bureau of Economic Geology, University of Texas at Austin.

Spiegel, Zane. 1957a. Preliminary evaluation of geology and hydrology of the Dunes Dam and reservoir site on the Canadian River, Quay County, New Mexico. New Mexico State Engineer's Office. Memorandum dated March 25.

Spiegel, Zane. 1957b. Geologic map of the Dunes reservoir site, Canadian River, Quay County, New Mexico. Office of the State Engineer, Santa Fe, New Mexico. 2 sheets, scale 1:16500.

Spiegel, Zane. 1969. Reservoir leakage under the spillway of Ute Dam, Quay County. Memorandum to Peter Shoenfeld, Attorney, Office of the State Engineer, Santa Fe, New Mexico. Dated January 16.

Spiegel, Zane. 1972a. Problems of the Triassic stratigraphy in the Canadian River Basin, Quay, San Miguel, and Guadalupe Counties, New Mexico. New Mexico Geological Society Twenty-third Field Conference Guidebook.

Spiegel, Zane. 1972b. Cenozoic geology of the Canadian River Valley, New Mexico. New Mexico Geological Society Twenty-third Field Conference Guidebook.

Stearns, D.W. 1972. Structural interpretation of fractures associated with the Bonita Fault. New Mexico Geological Twenty-third Field Conference Guidebook.

Texas Water Quality Board. 1970. Canadian River water quality survey, Logan, New Mexico to Tascosa, Texas. Canadian River Project Preliminary report 527. Austin.

Trauger, F.D. and F.X. Bushman. 1964. Geology and ground water in the vicinity of Tucumcari, Quay County, New Mexico. New Mexico State Engineer. Sanmta Fe.

Union Carbide Corp. 1979. Hydrogeochemical and stream sediment reconnaissance basic data for Amarillo NTMS quadrangle, Texas. Report K/UR-125. Oak Ridge, Tennessee.

U.S. Bureau of Reclamation. 1975. Interim progress report of investigations, Lake Meredith Salinity Study. Southwest Region, Amarillo, Texas.

U.S. Bureau of Reclamation. 1976. Report on electrical resistivity and seismic refraction surveys, Canadian River, Lake Meredith Salinity Study. Engineering and research center.

U.S. Bureau of Reclamation. 1979. Lake Meredith salinity study. Appraisal level investigation of the Canadian River, Texas-New Mexico. Southwest Region, Amarillo Texas.

Walker, F.C., and W.H. Irwin. 1958. Report concerning geologic and engineering feasibility, Dunes Dam site, Canadian River Project, New Mexico. State Engineers Office, Santa Fe.

Wanek, A.A. 1962. Reconaissance geologic map of parts of Harding, San Miguel, and Mora counties, New Mexico. U.S. Geological Survey OM Map-208.

APPENDIX A

WATER LEVEL MEASUREMENTS

Table A.1: Water levels in wells within New Mexico portion of study area
Depths and elevations rounded to nearest foot.
Formation symbols and data sources explained at end of table.

Well No. Location	Formation	Land-Surf. Elev.	Well Depth	Water-Level Elev.	Date (mo/yr)	Source
10.33. 7.234	Trc	3950	114	3895	3/55	1
10.33.12.222	Qc?	4027	30	4004	2/55	1
10.33.12.422	Trc	4045	188	3969	2/55	1
10.33.23.441	Qc?	4100	51	4079	2/55	1
10.33.25.131	Qc	4050	35	4017	2/55	1
10.33.36.333	Qc?	4225	84	4182	2/55	1
10.34. 6.444	Trc	4045	124	3998	3/55	1
10.34.10.233	Trc	4030	270	3990	48	1
10.34.10.233a	Trc/Trsr	4030	500	3990	48	1
10.34.17.222	Trc	4060	124	4003	2/55	1
10.34.17.441	Trc	4100	220	3997	2/55	1
10.34.19.221	Trc	4102	232	3958	2/55	1
10.34.21.113	Trc	4080	231	3980	-	1
10.34.22.132	Trc	4085	200	3983	2/55	1
10.34.28.412	Qc?	4090	72	4044	12/54	1
10.34.30.332	Qc?	4200	53	4169	2/55	1
10.34.33.333	Qc	4130	44	4089	2/55	1
10.34.35.111	Qc	4100	27	4074	12/54	1
10.34.36.433	Qc	4118	33	4086	12/54	1
10.35. 1.333	Trc	3985	69	3946	11/54	1
10.35. 4.333	Trc?	3970	71	3948	11/54	1
10.35. 5.222	Trc	4013	24	3993	11/54	1
10.35. 5.222a	Trc	4013	89	3998	54	1
10.35. 6.111	Qal	4050	40	4020	2/55	1
10.35. 9.424	Qal	3945	45	3933	11/54	1
10.35.13.221	Qal	3940	37	3905	11/54	1
10.35.14.334	Trc	3975	220	3872	11/54	1
10.35.22.121	Trc	4000	153	3970	-	1
10.35.28.211	Trc		200		-	1
10.35.29.222	Trc	3990	123	3939	5/56	1
10.35.29.222a	Trc	3995	225	3960	-	1
10.35.34.220	Qal		22		-	1
10.36. 1.224	Qal	3850	28	3832	11/54	1
10.36. 3.224	Trc	3901	57	3884	1/53	1
10.36. 3.442	Trc	3939	59	3952	8/53	1
10.36.13.211	Trc		72		-	1
10.36.14.211	Trc	3910	17	3896	11/54	1
10.36.14.311	Trc	3909	77	3889	8/53	1
10.36.21.223	Trc	3930	71	3889	11/54	1
10.36.26.222	Trc	3930	72	3897	12/54	1
10.36.26.332	Qal	3920	21	3901	8/53	1
10.37. 7.412	Qal	3880	49	3854	12/54	1
10.37.18.122	Trc	3975	154	3897	12/54	1
10.37.19.343	Trc	4010	95	3964	8/53	1
10.37.30.110	Trc	4040	200	3900	-	1
11.32. 3.424	Trc	4023	144	3926	51	1

Table A.1: Continued

Well No. Location	Formation	Land-Surf. Elev.	Well Depth	Water-Level Elev.	Date (mo/yr)	Source
11.32. 4.420	Trc	4028	-	3923	7/48	1
11.32. 5.220	Trc	4000	140	3878	7/48	1
11.32. 7.135	Trc	4065	180	3843	7/48	1
11.32. 7.244	Trc	4015	200	3875	-	1
11.32.10.333	Trc	4013	136	3901	3/55	1
11.32.11.111	Trc	4025	300	4011	3/55	1
11.32.11.113	Trc	4030	125	3990	7/48	1
				4005	55	1
11.32.11.430	Trc	4016	145	3871	2/46	1
11.32.12.333	Trc	4004	160	3878	7/48	1
11.32.13.130	Trc	4002	-	3924	9/44	1
11.32.13.333	Trc	3969	124	3858	11/54	1
11.32.14.444	Trc	3970	112	3877	11/54	1
11.32.15.444	Trc	3965	105	3903	7/48	1
11.32.17.343	Trc	4002	160	3857	-	1
11.32.17.343a	Trc	402	204	3882	-	1
11.32.19.424	Trc	3993	400	3914	3/55	1
11.32.19.424a	Trc	3992	185	3912	3/55	1
11.32.19.442	Trc	3991	165	3926	-	1
11.32.20.121	Trc	3995	164	3926	7/48	1
11.32.21.112	Trc	3974	200	3916	1/54	1
11.32.21.311	Trc	3972	-	3914	7/48	1
11.32.23.443	Trc	3930	120	3870	-	1
11.32.24.211	Trc	3893	165	3781	2/46	1
11.32.24.323	Trc	3925	107	3847	3/55	1
11.32.25.333	Trc	3920	150	3880	-	1
11.32.28.434	Trc	3972	145	3907	-	1
11.32.28.434a	Trc	3972	180	3907	-	1
11.32.30.422	Trc	3994	188	3918	3/55	1
11.32.32.433	Trc	3987	83	3979	4/55	1
11.32.34.442	Trc	3950	76	3896	4/45	1
				3937	3/55	1
11.32.34.444	Trc	3956	200	3816	-	1
11.33. 3.124	Qal	3850	20	3838	2/55	1
11.33.13.424	Trc	4105	40	4078	2/55	1
11.33.23.242	Trc	4087	44	4068	2/55	1
11.33.25.443	Trc	4000	125	3880	2/55	1
11.33.28.232	Trc	4040	47	4024	2/55	1
11.33.28.334	Trc	3980	78	3954	2/55	1
11.33.28.341	Trc	4025	54	3987	2/55	1
11.33.35.242	Trc	4000	31	3976	2/55	1
11.34. 2.333	Trc	4195	109	4126	11/54	1
11.34. 5.433	Trc	4205	111	4124	3/55	1
11.34. 6.314	Trc	4127	50	4087	2/55	1
11.34.11.224	Trc	4195	84	4147	11/54	1
11.34.12.112	Trc	4195	78	4149	11/54	1
11.34.15.111	Trc	4175	73	4157	11/54	1
11.34.15.224	Trc	4220	133	4128	2/55	1

Table A.1: Continued

Well No.	Location	Formation	Land-Surf. Elev.	Well Depth	Water-Level Elev.	Date (mo/yr)	Source
	11.34.18.211	Trc	4080	68	4002	46	1
	11.34.26.113	Qc/Trc	4080	60	4053	2/55	1
	11.34.31.442	Trc	4035	56	4018	3/55	1
	11.34.33.143	Trc	4060	108	4097	2/55	1
	11.34.33.144	-	4060	135	4035	-	1
	11.35. 1.114	Trc	4050	16	4038	11/54	1
	11.35.13.133	Trc	4095	44	4060	11/54	1
	11.35.14.224	Trc	4115	82	4058	11/54	1
	11.35.23.222	Trc	4076	54	4050	11/54	1
	11.35.25.333	Qal	4000	-	3985	5/53	1
	11.35.26.133	Trc	4135	122	4038	11/54	1
	11.35.28.433	Trc	4015	70	3987	11/54	1
	11.35.29.121	Qc/Trc	4100	66	4054	-	1
	11.36.15.424	Trc/Trsr	3895	270	3695	51	1
	11.36.16.320	Trc/Trsr	3900	238	3704	11/54	1
	11.37.17.320	Trsr	3847	800	3647	-	1
	11.37.17.321	Trsr	3860	264	3660	53	1
	11.37.18.421	Trsr	3850	250	3830	53	1
	11.29.26.212	Je	4090	40	4063	6/55	1
	12.31. 2.444	Trc	4049	206	3989	-	1
	12.31.31.122	Trc	4070	75	4027	6/55	1
	12.31.34.212	Trc	4140	135	4065	-	1
	12.32. 1.422b	Trsr	3983	278	3799	9/53	1
	12.32. 1.433	Qc?	3990	60	3934	9/53	1
	12.32. 4.444	Trc	4090	195	3937	-	1
	12.32. 6.421	Trc	3914	112	3809	3/55	1
	12.32. 7.334	Trc	4058	200	3878	-	1
	12.32. 8.313	Trc	4020	200	3917	3/55	1
	12.32. 9.224	Trc	4110	249	4010	-	1
	12.32.11.444	Trc	4040	220	3911	8/55	1
	12.32.12.221	Trc	3993	60	3952	9/44	1
	12.32.13.111	Trc	4016	150	3936	-	1
	12.32.15.412	Trc	4050	198	3900	-	1
	12.32.19.111	Trc/Trsr	4105	265	3880	-	1
	12.32.20.422	Trc	4072	213	3879	3/55	1
					3880	4/57	1
	12.32.21.244	Trc	4050	192	4018	-	1
	12.32.23.111	Trc	4021	177	3907	3/55	1
	12.32.24.211	Trc	4038	215	3911	3/55	1
	12.32.25.213	Trc	4062	173	3964	3/55	1
	12.32.30.333	Trc	4151	380	3901	-	1
	12.32.33.224	Trc	4055	395	3880	-	1
	12.32.35.224	Trc	4049	183	3995	-	1
	12.33. 4.411	Trc	3907	95	3900	3/55	1
	12.33. 4.411a	Trc	3905	85	3880	9/44	1
	12.33. 5.333	Trc	3976	80	3921	1/47	1
	12.33. 5.434	Trc	3945	72	3922	1/47	1
					3935	3/55	1

Table A.1: Continued

Well No.	Location	Formation	Land-Surf. Elev.	Well Depth	Water-Level Elev.	Date (mo/yr)	Source
	12.33. 6.421	Trc	3967	67	3923	9/44	1
					3936	3/55	1
	12.33. 7.124	Trc	3975	218	3904	10/54	1
	12.33. 9.224	Trc	3850	69	3788	-	1
	12.33. 9.242	Qc/Trc	3860	69	3846	-	1
	12.33.16.111	Trc	3900	126	3830	51	1
	12.33.17.311	Trc	3958	77	3898	3/55	1
					3900	4/57	1
	12.33.27.344	Qal	3780	25	3769	2/55	1
	12.33.34.221	Qal	3790	18	3773	2/55	1
	12.33.36.324	Trc	4255	105	4176	2/55	1
	12.34. 5.412	Qal	4000	18	3988	-	1
	12.34. 6.113	Trc/Trsr	3930	250	3730	8/53	1
	12.34.11.212	Trc/Trsr	3975	283	3749	11/54	1
	12.34.31.134	Trc	4300	113	4220	-	1
	12.34.35.331	Trc	4120	23	4102	11/54	1
	12.34.36.433	Qal/Trc	4143	44	4128	6/55	1
	12.34.36.434	Qal/Trc	4140	42	4128	6/55	1
	12.35. 2.111	Trc	3840	167	3785	4/56	1
	12.35. 7.243	Trc/Trsr	3905	258	3734	5/56	1
	12.35.15.323	Trc/Trsr	3960	279	3724	10/54	1
	12.35.20.333	Trc	4250	200	4165	-	1
	12.35.25.123	Trc/Trsr	4000	300	3715	12/39	1
	12.35.26.233	Trc/Trsr	3965	244	3846	10/54	1
	12.35.29.143	Trc	4185	35	4163	11/54	1
	12.35.32.434	Trc	4150	90	4080	-	1
	12.35.35.422	Trc	4030	21	4009	11/54	1
	12.36. 2.112	Trsr	3860	165	3760	-	1
	12.36.10.224	Trsr	3925	175	3762	-	1
	12.36.10.434	Trsr	3975	227	3788	-	1
	12.36.11.333	Trc	3965	60	3921	11/54	1
	12.36.14.311	Trsr	3950	285	3690	10/55	1
	12.36.18.242	Trsr	3940	20	3924	11/54	1
	12.36.29.132	Qal	3960	20	3944	11/54	1
	12.36.29.242	Trsr	4000	296	3719	11/54	1
	12.36.33.222	Trsr	3900	250	3668	-	1
	12.36.34.142	Trsr	3950	540	3715	-	1
	12.37.18.424a	Trsr	3900	209	3702	10/54	1
	12.37.18.442	Trsr	3880	193	3707	10/54	1
	12.37.19.133	Trsr	3950	250	3725	-	1
	12.37.30.133	Trsr	3900	225	3695	-	1
	12.37.30.422	Trsr	3850	150	3720	-	1
	13.31. 1.124	Qal/Trc	3900	50	3860	-	1
	13.31.25.344	Trc	4025	140	3899	18	1
	13.31.26.123	Trc	3950	195	3800	-	1
	13.31.26.244	Trc	4025	85	3950	-	1
	13.31.34.244	Trc	3980	175	3828	-	1
	13.31.34.444	Qc	4030	34	4018	-	1

Table A.1: Continued

Well No.	Location	Formation	Land-Surf. Elev.	Well Depth	Water-Level Elev.	Date (mo/yr)	Source
	13.31.36.211	Qc	4011	76	3955	-	1
	13.32. 4.311	Trc	4000	279	3770	11/53	1
	13.32.14.211	Trc	3836	164	3717	11/53	1
	13.32.18.200	Trc	3875	223	3696	11/53	1
	13.33. 1.311	Trsr	3861	176	3745	5/54	1
	13.33. 2.122	Qc/Trsr	3900	700	3749	7/54	1
	13.33. 3.344	Tr?	3873	-	3742	61	2
	13.33. 3.444	Tr?	3866	-	3738	61	2
	13.33. 4.443	Tr?	3870	-	3741	61	2
	13.33. 5.244	Trc	3890	138	3753	9/54	1
	13.33. 5.442	Trsr	3885	235	3680	-	1
			3913	-	3789	61	2
	13.33. 6.111	Tr?	3902	-	3813	61	2
	13.33. 8.444	Tr?	3833	-	3710	61	2
	13.33. 9.222	Tr?	3867	-	3736	61	2
	13.33. 9.341	Tr?	3839	-	3714	61	2
	13.33.10.121	Tr?	3864	-	3736	61	2
	13.33.10.144	Tr?	3829	-	3723	61	2
	13.33.10.222	Tr?	3857	-	3735	61	2
	13.33.10.332	Tr?	3818	-	3760	61	2
	13.33.11.111	Tr?	3862	-	3733	61	2
	13.33.11.144	Trsr	3812	244	3701	4/54	1
	13.33.11.312	Qc	3820	50	3790	-	1
	13.33.11.322	Trsr	3817	241	3700	8/53	1
	13.33.16.122	Tr?	3823	-	3711	61	2
	13.33.16.322	Tr?	3796	-	3699	60	2
					3745	61	2
	13.33.24.412	Trsr	3802	151	3678	3/55	1
	13.33.28.121	Trc/Trsr	3800	77	3727	3/55	1
	13.33.33.124	Trsr	3972	211	3770	3/55	1
	13.34. 1.133	Trsr	3650	80	3590	-	1
	13.34. 4.134	Trsr	3760	140	3632	8/53	1
	13.34. 8.333	Trsr	3927	250	3694	8/53	1
	13.34.10.211	Trsr	3750	150	3635	-	1
	13.34.17.444	Trsr	3960	320	3712	8/53	1
	13.34.20.333	Trsr	4000	287	3720	-	1
	13.34.22.311	Trsr	3900	240	3700	-	1
	13.34.23.432	Trsr	3840	222	3655	10/54	1
	13.35. 5.113	Trsr	3677	93	3600	4/54	1
	13.35. 6.143	Trsr	3650	78	3590	4/54	1
	13.35. 6.221	Trsr	3670	70	3610	-	1
	13.35.13.321	Trsr	3850	250	3630	-	1
	13.35.19.112	Trsr	3885	280	3615	5/56	1
	13.35.27.343	Trsr	3935	286	3675	10/54	1
	13.35.31.444	Trsr	3915	280	3657	10/54	1
	13.36.14.134	Trsr	3800	185	3652	10/55	1
	13.36.20.332	Trsr	3810	285	3716	2/55	1
	13.36.27.332	Trsr	3847	167	3716	2/55	1

Table A.1: Continued

Well No.	Location	Formation	Land-Surf. Elev.	Well Depth	Water-Level Elev.	Date (mo/yr)	Source
	13.36.27.334	Trsr	3811	173	3717	11/54	1
	13.37.30.343	Trsr	3975	365	3689	11/54	1
	14.32.24.222	Tr?	3977	-	3889	61	2
	14.32.24.344	Tr?	3916	-	3850	61	2
	14.32.24.444	Tr?	3914	-	3847	61	2
	14.32.25.242	Tr?	3900	-	3844	61	2
	14.32.36.422	Tr?	3889	-	3840	61	2
	14.33.19.242	Tr?	3994	-	3872	61	2
	14.33.19.344	Tr?	3942	-	3859	61	2
	14.33.20.244	Tr?	3994	-	3867	61	2
	14.33.29.444	Tr?	3929	-	3824	61	2
	14.33.30.123	Tr?	3928	-	3847	61	2
	14.33.30.213	Tr?	3940	-	3856	61	2
	14.33.30.314	Tr?	3899	-	3848	61	2
	14.33.31.112	Tr?	3899	-	3861	61	2
	14.33.31.242	Tr?	3898	-	3826	61	2
	14.33.31.323	Tr?	3900	-	3832	61	2
	14.33.31.414	Tr?	3905	-	3803	61	2
	14.33.31.444	Tr?	3915	-	3822	61	2
	14.33.32.333	Tr?	3910	-	3822	61	2
	14.33.32.444	Tr?	3928	-	3815	61	2
	14.33.33.422	Tr?	3919	-	3803	61	2
	14.34. 1.141	Qc/To	3930	100	3840	-	1
	14.34. 5.422	Qc	3965	120	3860	6/54	1
	14.34.13.141	Qc	3885	130	3767	-	1
	14.34.15.112	Qc	3920	100	3830	-	1
	14.34.15.212	Qc	3921	125	3811	-	1
	14.34.16.111	Qc	3940	97	3853	5/54	1
	14.34.21.332	Qc/Trsr	3870	100	3790	-	1
	14.34.28.231	Qc/Trsr	3784	80	3714	-	1
	14.34.29.121	Qc/Trsr	3925	75	3855	-	1
	14.34.34.243	Trsr	3742	135	3623	-	1
	14.34.35.244	Trsr	3750	140	3627	-	1
	14.35. 3.313	Qc	3900	187	3744	5/54	1
	14.35. 4.222	Qc	3890	175	3735	-	1
	14.35.10.442	Qc/Trsr	3880	165	3724	-	1
	14.35.16.131	Qc/Trsr	3800	151	3670	5/54	1
	14.35.28.231	Trsr	3722	150	3582	-	1
	14.36. 6.113	Qc	3890	160	3745	-	1
	14.36. 7.111	Qc	3840	165	3700	-	1
	14.36.10.111	Qc/Trsr	3800	151	3672	4/54	1
	14.36.11.122	Qc/Trsr	3770	175	3615	-	1
	14.36.12.122	Qc/Trsr	3770	165	3615	-	1
	14.36.12.434	Qc/Trsr	3725	145	3590	-	1
	14.36.25.233	Trsr	3730	80	3660	-	1
	14.36.28.234	Trsr	3710	73	3696	5/54	1
	14.36.29.224	Trsr	3690	80	3620	-	1
	14.37. 6.311	Qc/Trsr	3740	190	3654	5/54	1

Table A.1: Continued

Well No. Location	Formation	Land-Surf. Elev.	Well Depth	Water-Level Elev.	Date (mo/yr)	Source
14.37. 6.324	Qc/Trsr	3740	220	3560	-	1
14.37.30.121	Trsr	3615	40	3585	-	1
15.34. 4.121	To	4279	86	4213	-	1
15.34. 5.224	To	4272	100	4202	-	1
15.34.11.432	To	4185	65	4130	-	1
15.34.15.413	To	4220	205	4138	2/55	1
15.34.22.311	To	4155	60	4105	-	1
15.34.22.311a	To	4177	90	4097	-	1
15.34.25.334	To	4085	65	4040	-	1
15.34.30.312	To	4112	32	4107	-	1
15.34.31.224	To	4050	30	4040	-	1
15.34.32.241	To	4040	69	3974	6/54	1
15.35. 2.413	To	4131	182	3977	-	1
15.35. 7.122	To	4190	175	4035	-	1
15.35.10.334	To	4175	179	4002	2/55	1
15.35.10.433	To	4152	180	4002	-	1
15.35.14.211	To	4130	290	3900	-	1
15.35.15.222	To	4127	190	3991	9/53	1
15.35.20.443	To	4009	227	3950	5/54	1
15.35.21.334	To	4009	166	3963	8/53	1
15.35.22.133	To	4045	93	3961	5/54	1
15.35.24.310	To/Trsr	4035	180	3885	-	1
15.35.28.331	To/Trsr	3722	150	3592	-	1
15.35.33.344	To/Trsr	3910	165	3760	-	1
15.35.35.411	To/Trsr	3910	140	3777	-	1
15.36.10.224	To	3985	40	3965	-	1
15.36.22.211	To	3930	100	3850	-	1
15.36.24.312	Qal	3850	26	3835	4/54	1
15.36.34.342	Trc	3850	209	3675	-	1
15.37. 6.311	To	4015	131	3892	4/54	1
15.37.18.124	To	3925	68	3867	-	1
15.37.18.344	Qal/To	3895	21	3879	-	1
15.37.19.312	Qal	3865	30	3852	-	1
15.37.30.112	Qal/Qc	3840	35	3810	-	1
15.37.30.121	Qal/Qc	3820	53	3804	-	1
16.34. 6.444	To	4550	230	4338	9/53	1
16.34.19.112	To	4452	245	4346	6/54	1
16.34.21.222	To	4415	140	4285	-	1
16.34.22.233	To	4349	140	4215	-	1
16.34.28.211	To	4385	140	4251	9/53	1
16.34.33.111	To	4350	130	4237	2/55	1
16.34.33.433	To	4255	84	4182	9/53	1
16.34.35.242	To	4235	265	3995	-	1
16.35. 3.133	To	4375	182	4211	-	1
16.35. 3.312	To	4365	169	4205	-	1
16.35. 3.422	To	4360	146	4229	8/53	1
16.35. 4.321	To	4375	210	4224	8/53	1
16.35. 9.314	To	4360	161	4209	45	1

Table A.1: Continued

Well No. Location	Formation	Land-Surf. Elev.	Well Depth	Water-Level Elev.	Date (mo/yr)	Source
16.35.24.134	To	4227	102	4170	9/53	1
16.36. 4.224	To	4368	207	4195	12/53	1
16.35. 6.113	To	4410	160	4260	-	1
16.35. 6.441	To	4350	110	4251	5/54	1
16.35.11.144	To	4206	81	4125	9/53	1
16.36.14.134	To	4188	108	4123	9/53	1
16.36.15.432	To	4196	111	4135	9/53	1
16.36.15.441	To	4177	53	4124	9/53	1
16.36.18.444	To	4265	120	4155	9/53	1
16.36.20.212	To	4223	58	4143	9/53	1
16.36.20.222	To	4197	58	4141	9/53	1
16.36.20.422	To	4197	120	4083	9/53	1
16.36.21.234	To	4167	35	4137	9/53	1
16.36.22.213	To	4187	103	4135	1/53	1
16.36.23.121	To	4145	110	4048	3/54	1
16.36.23.123	To	4110	37	4089	3/54	1
16.36.26.333	To	4100	87	4055	5/54	1
17.34. 3.140	To/Kp	4714	235	4514	-	1
17.34.10.433	To/Kp	4710	150	4510	10/53	1
17.34.22.414	To	4562	200	4387	-	1
17.34.26.234	To	4580	245	4360	-	1
17.34.28.244	To	4550	170	4400	-	1
17.34.33.343	To	4555	225	4345	-	1
17.35. 4.424	To/Kp	4530	230	4330	-	1
17.35. 8.111	To	4515	219	4311	-	1
17.35. 9.131	To	4480	210	4290	-	1
17.35. 9.243	To	4465	230	4292	-	1
17.35.19.421	Trc	4560	300	4285	-	1
17.35.23.341	To	4410	155	4310	-	1
17.35.24.322	To	4360	109	4265	-	1
17.35.30.211	To	4470	151	4321	-	1
17.35.32.424	To	4400	204	4210	-	1
17.36. 3.142	To/Kp	4430	250	4195	-	1
17.36. 7.222	Jm/Trc	4537	428	4217	38	1
17.36.13.120	To	4350	210	4150	-	1
17.36.15.332	To	4370	190	4195	-	1
17.36.21.312	To	4318	135	4207	9/53	1
17.36.28.431	To	4295	142	4176	12/53	1
17.36.32.341	To	4325	156	4178	9/53	1
17.36.34.240	To	4278	140	4152	9/53	1
18.34.15.422	To/Kp	4760	174	4654	9/53	1
18.36.31.442	Jm/Trc	4434	210	4243	9/53	1

Sources:
1: Berkstresser and Mourant, 1966
2: Galloway, 1962

APPENDIX B

WATER QUALITY ANALYSES

Table B.1: Explanation

a. Type: W = Well
S = Surface Water
Sp = Spring

b. Formation: P116 = Piezometer 1, 16 ft depth
P122 = Piezometer 1, 22 ft depth
P222 = Piezometer 2, 22 ft depth
P240 = Piezometer 2, 40 ft depth
P255 = Piezometer 2, 55 ft depth
P320 = Piezometer 3, 20 ft depth
P335 = Piezometer 3, 35 ft depth
P415 = Piezometer 4, 15 ft depth
P421 = Piezometer 4, 21 ft depth
P621 = Piezometer 6, 21 ft depth
P631 = Piezometer 6, 31 ft depth
P650 = Piezometer 6, 50 ft depth
Rev = Revuelto Creek
CaSL = Canadian River at State Line
CaTa = Canadian River at Tascosa
CaAm = Canadian River at Amarillo
CaLM = Lake Meredith
Tr = Triassic
PSA = San Andres
PY = Yeso
PW = Wolfcampian

c. Source: 1 = Collected this study
2 = USGS WATSTORE
3 = Water resources data for New Mexico and Texas, various years
4 = Berkstresser and Mourant, 1966
5 = Bureau of Reclamation files
6 = Griggs and Hendrickson, 1951
7 = Bassett and Bentley, 1983

Table B.1: Selected water-quality analyses of Canadian River and groundwater within and near study area

Location	Type[a]	Date	Fm.[b]	S[c]	T	pH	S.C.	TDS	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl	NO_3	Fe	F
		Canadian River Channel Piezometers																	
13.33.15.130	W	5/23/83	P116	5	-1	7.9	22500	14736	357	128	5920	21.1	467	0.0	350	6920	0.0	0.0	0.44
13.33.15.130	W	5/23/83	P122	5	-1	7.8	24500	15246	341	126	6160	19.6	634	0.0	830	6760	0.0	0.0	0.43
13.33.14.210	W	5/23/83	P222	5	-1	7.8	24000	15779	365	148	5600	10.6	560	0.0	925	6600	0.0	0.0	0.58
13.33.14.210	W	5/23/83	P240	5	-1	7.9	26000	16037	418	145	5920	23.2	461	0.0	980	7360	0.0	0.0	0.59
13.33.14.210	W	5/23/83	P255	5	-1	8.0	24000	14530	352	164	5200	19.3	457	0.0	1045	6600	0.0	0.0	0.58
13.33.14.210	W	7/07/83	P255	5	-1	7.6	21000	15500	413	129	5370	35.2	362	0.0	949	8280	0.0	0.0	0.10
13.33.14.240	W	10/18/83	P255	4	17	7.0	21000	14273	360	130	4800	19.0	255	0.0	920	7788	0.4	-1	-1
13.33.12.230	W	5/23/83	P320	5	-1	8.1	26000	15564	237	172	5920	23.6	455	0.0	1375	6840	0.0	0.0	0.78
13.33.12.230	W	5/23/83	P335	5	-1	8.2	39500	22947	439	205	8360	31.0	580	0.0	1720	10720	0.0	0.0	0.40
13.33.12.230	W	10/18/83	P335	4	18	6.9	38300	24714	420	170	8700	28.0	520	0.0	1600	13275	0.4	-1	-1
13.33.12.410	W	5/23/83	P415	5	-1	7.9	16500	11145	303	148	3536	15.5	516	0.0	960	5200	0.0	0.0	0.27
13.33.12.410	W	5/23/83	P421	5	-1	8.0	21000	12644	203	129	4980	19.9	565	0.0	1200	5320	0.0	0.0	0.36
13.34.05.120	W	5/23/83	P621	5	-1	8.2	12800	7573	91	50	2792	13.8	666	0.0	560	3720	0.0	0.0	0.67
13.34.05.120	W	5/23/83	P631	5	-1	7.9	23000	13521	255	149	5260	28.2	588	0.0	970	5920	0.0	0.0	0.31
13.34.05.120	W	5/23/83	P650	5	-1	7.7	30100	19135	456	163	7720	43.2	555	0.0	1285	8160	0.0	0.0	0.43
13.34.05.120	W	7/07/83	P650	5	-1	7.2	26700	20600	496	178	7090	62.6	654	0.0	1550	10600	0.0	0.0	0.10
13.34.05.120	W	10/18/83	P650	4	18	6.6	30500	20783	580	145	6900	35.0	849	0.0	1440	10832	0.4	-1	-1
		Revuelto Creek																	
13.33.21.13	S	10/ 1/59	Rev	3	-1	7.8	890	590	74	17	104	0.0	266	0.0	222	25	0.8	-1	-1
13.33.21.13	S	1/ 1/60	Rev	3	-1	7.9	1580	1060	77	24	254	0.0	284	0.0	455	96	2.1	-1	-1
13.33.21.13	S	3/ 6/60	Rev	3	-1	7.8	2290	1540	72	40	407	0.0	314	0.0	579	258	1.6	-1	-1
13.33.21.13	S	7/ 7/60	Rev	3	-1	8.0	565	363	30	5.6	91	0.0	246	0.0	76	15	1.8	-1	-1
13.33.21.13	S	10/26/60	Rev	3	-1	7.8	1540	1030	63	28	252	0.0	268	0.0	455	87	0.4	-1	-1
13.33.21.13	S	4/23/61	Rev	3	-1	7.7	3110	1910	74	59	544	0.0	458	0.0	478	515	0.8	-1	-1
13.33.21.13	S	10/26/61	Rev	3	-1	7.7	1340	889	76	30	183	0.0	232	0.0	397	75	0.4	-1	-1
13.33.21.13	S	6/12/62	Rev	3	-1	8.2	1990	1360	65	27	362	0.0	300	0.0	624	115	0.8	-1	-1
13.33.21.13	S	11/ 8/62	Rev	3	-1	7.7	2680	1620	76	31	477	0.0	344	0.0	352	502	0.3	-1	-1
13.33.21.13	S	2/15/63	Rev	3	-1	7.9	1920	1300	72	40	313	0.0	278	0.0	607	115	2.3	-1	-1
13.33.21.13	S	7/ 7/63	Rev	3	-1	8.0	1060	696	49	16	157	0.0	208	0.0	321	34	1.3	-1	-1
13.33.21.13	S	10/ 1/63	Rev	3	-1	7.4	1240	854	89	31	148	0.0	218	0.0	418	48	0.3	-1	-1
13.33.21.13	S	3/ 1/64	Rev	3	-1	8.1	2330	1530	78	43	393	0.0	312	0.0	598	254	1.3	-1	-1
13.33.21.13	S	11/18/64	Rev	3	-1	8.1	1660	1100	32	17	319	0.0	276	0.0	484	75	6.9	-1	-1
13.33.21.13	S	6/26/65	Rev	3	-1	8.0	662	416	20	4.6	122	0.0	227	0.0	119	21	0.2	-1	-1
13.33.21.13	S	1/10/66	Rev	3	-1	8.2	3680	2150	66	43	680	0.0	424	0.0	374	765	0.2	-1	1
13.33.21.13	S	10/ 2/66	Rev	3	-1	8.1	2240	1350	61	31	390	0.0	314	0.0	362	344	0.1	-1	0.6
13.33.21.13	S	7/26/67	Rev	3	-1	8.0	565	351	40	10	75	0.0	267	0.0	66	10	4.1	-1	0.6
13.33.21.13	S	1/15/68	Rev	3	-1	8.0	1920	1310	80	45	305	0.0	290	0.0	590	137	1.0	-1	0.9
13.33.21.13	S	5/10/68	Rev	3	-1	7.4	988	632	60	18	135	5.4	234	0.0	256	29	2.7	80	0.5
13.33.21.13	S	12/ 2/68	Rev	3	-1	8.1	2460	1560	75	43	421	0.0	316	0.0	504	350	0.2	-1	1.0
13.33.21.13	S	9/ 8/69	Rev	3	-1	7.6	1010	709	51	18	170	0.0	203	0.0	287	72	0.1	-1	0.7
13.33.21.13	S	7/16/70	Rev	3	-1	8.1	1310	871	75	33	171	7.6	188	0.0	360	120	3.6	-1	0.8
13.33.21.13	S	8/13/71	Rev	3	-1	7.9	5320	2940	91	55	910	7.4	233	0.0	550	1200	-1	-1	0.6
13.33.21.13	S	3/ 7/72	Rev	3	-1	8.4	4240	2530	55	45	830	0.0	349	7.0	500	900	-1	-1	1.0
13.33.21.13	S	6/12/72	Rev	3	-1	7.7	1680	1110	60	27	260	7.3	145	0.0	540	130	-1	-1	0.6

Table B.1: Continued

Location	Type[a]	Date	Fm.[b]	S[c]	T	pH	S.C.	TDS	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl	NO_3	Fe	F
13.33.21.13	S	3/ 5/73	Rev	3	-1	8.2	2570	1760	74	60	430	4.1	273	0.0	840	210	-1	-1	0.8
13.33.21.13	S	8/14/73	Rev	3	-1	7.7	1350	914	68	31	180	6.0	224	0.0	460	47	-1	-1	0.6
13.33.21.13	S	2/ 7/74	Rev	3	-1	8.1	3320	1980	65	48	590	4.1	282	0.0	540	580	-1	-1	0.7
13.33.21.13	S	9/10/74	Rev	3	-1	8.1	1790	1120	63	23	270	6.3	220	0.0	490	150	0.6	-1	1.0
13.33.21.13	S	4/14/75	Rev	3	-1	-1.0	1250	768	29	16	210	2.9	212	0.0	330	64	0.8	-1	0.5
13.33.21.13	S	11/12/75	Rev	3	-1	8.2	4460	2500	64	41	830	5.6	413	0.0	400	990	0.1	-1	1.0
13.33.21.13	S	6/ 9/76	Rev	3	-1	8.4	653	419	9	3.0	140	1.9	211	0.0	130	23	1.2	-1	0.6
19.33.21.13	S	1/12/77	Rev	3	-1	8.1	4740	2620	49	34	870	3.8	404	0.0	250	1200	0.1	-1	0.9
13.33.21.13	S	6/22/77	Rev	3	-1	8.9	790	555	5	1.0	200	2.2	250	11.0	130	67	1.2	-1	0.7
13.33.21.13	S	2/ 1/78	Rev	3	-1	8.6	6000	2980	56	44	1000	5.1	420	1.0	260	1400	0.1	-1	0.9
13.33.21.13	S	12/19/78	Rev	3	-1	8.4	4800	2720	65	40	930	6.6	300	0.0	290	1200	0.01	-1	0.7
13.33.21.13	S	4/10/79	Rev	3	-1	8.5	5500	3170	59	50	1100	5.4	380	0.0	320	1400	0.06	-1	1.0
13.33.21.13	S	8/16/79	Rev	3	-1	8.4	268	232	3	1.0	73	2.8	87	0.0	72	15	0.64	-1	0.4
13.33.21.13	S	2/21/80	Rev	3	-1	9.4	2050	1330	57	32	360	3.7	240	0.0	450	270	0.61	-1	0.7
13.33.21.13	S	11/20/80	Rev	3	-1	8.4	1500	993	58	32	250	5.1	280	0.0	420	83	-1	-1	0.6
13.33.21.13	S	2/19/81	Rev	3	-1	8.6	3900	2360	63	44	740	4.2	340	0.0	360	950	-1	20	0.8
13.33.21.13	S	11/19/81	Rev	3	-1	8.4	2070	1300	60	30	360	4.1	270	0.0	410	290	-1	15	0.5
13.33.21.13	S	2/25/82	Rev	3	-1	8.6	4000	2610	55	39	860	4.6	300	0.0	340	1100	-1	60	0.9
13.33.21.13	S	5/19/82	Rev	3	-1	8.1	5600	3520	65	80	1100	8.0	490	0.0	510	1500	-1	10	1.2
13.33.21.13	S	8/12/82	Rev	3	-1	8.6	1000	634	41	15	160	4.0	178	0.0	240	55	-1	7	0.5
13.33.21.13	S	4/13/83	Rev	3	-1	8.3	2220	1190	63	48	360	3.4	229	0.0	660	180	-1	10	0.6
13.33.21.13	S	8/10/83	Rev	3	-1	8.7	1210	-1	46	21	190	5.0	198	0.0	320	70	-1	6	0.7
		Canadian River above New Mexico - Texas State Line																	
13.13.37	S	9/25/69	CaSL	3	-1	7.8	890	474	30	12	124	4.6	166	0.0	108	102	-1	-1	0.6
13.13.37	S	10/21/69	CaSL	3	-1	8.6	000	3110	110	56	949	7.8	260	0.0	408	1380	.40	-1	0.5
13.13.37	S	2/24/70	CaSL	3	-1	7.9	8800	4760	138	75	1550	9.3	308	0.0	445	2370	.40	-1	0.6
13.13.37	S	5/12/70	CaSL	3	-1	8.0	6640	3880	116	71	1230	6.2	256	0.0	546	1750	0.00	-1	0.0
13.13.37	S	7/15/70	CaSL	3	-1	7.8	1150	713	26	11	210	4.0	170	0.0	170	188	.90	-1	0.7
13.13.37	S	1/11/71	CaSL	3	-1	7.8	6860	3990	120	60	1300	7.0	326	0.0	400	2000	-1	-1	0.6
13.13.37	S	4/13/71	CaSL	3	-1	8.6	8100	4980	120	100	1500	11.0	278	0.0	780	2100	.20	40	0.8
13.13.37	S	6/14/71	CaSL	3	-1	8.11	2500	6900	150	72	2400	11.0	385	-1	600	3800	-1	-1	0.8
13.13.37	S	8/ 9/71	CaSL	3	-1	8.3	645	372	18	5	110	3.5	159	0.0	100	51	-1	-1	0.7
13.13.37	S	12/13/71	CaSL	3	-1	7.8	6760	4080	130	60	1300	7.9	327	0.0	460	1800	-1	-1	0.7
13.13.37	S	4/13/72	CaSL	3	-1	8.0	7590	4720	110	76	1400	9.2	260	0.0	450	2100	-1	-1	0.6
13.13.37	S	7/17/72	CaSL	3	-1	8.4	3000	1710	57	28	500	6.3	195	0.0	300	670	1.80	-1	0.7
13.13.37	S	12/11/72	CaSL	3	-1	8.5	7630	4740	140	75	1600	7.9	378	0.0	480	2300	.45	-1	0.6
13.13.37	S	4/ 6/73	CaSL	3	-1	8.1	3080	1760	62	31	580	3.8	268	0.0	320	720	.75	-1	0.3
13.13.37	S	11/ 8/74	CaSL	3	-1	8.4	5234	2980	100	46	940	5.5	294	0.0	410	1300	.44	-1	0.6
13.13.37	S	3/24/75	CaSL	3	-1	8.3	8000	4460	130	80	1600	9.9	307	0.0	450	2300	.38	-1	0.8
13.13.37	S	6/24/75	CaSL	3	-1	8.0	670	369	17	6	110	3.8	130	0.0	46	130	.35	-1	0.3
13.13.37	S	12/ 9/75	CaSL	3	-1	8.4	8500	5190	140	76	1700	9.9	314	0.0	390	2500	-1	-1	0.5
13.13.37	S	6/ 9/76	CaSL	3	-1	8.3	1240	696	12	4	240	2.8	198	0.0	140	210	-1	-1	0.6
13.13.37	S	12/15/76	CaSL	3	-1	8.4	10000	5540	140	85	1800	9.0	318	0.0	440	2700	.46	-1	0.6
13.13.37	S	4/20/77	CaSL	3	-1	7.4	1300	705	15	5	240	3.1	200	0.0	130	230	.76	-1	0.5
13.13.37	S	9/28/77	CaSL	3	-1	8.1	5800	3210	99	61	960	8.6	270	0.0	340	1500	.09	-1	0.7

Table B.1: Continued

Location	Type[a]	Date	Fm.[b]	S°	T	pH	S.C.	TDS	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl	NO_3	Fe	F
13.13.37	S	2/ 1/78	CaSL	3	-1	8.9	9200	5410	150	88	1900	11.0	320	1.0	440	2900	.38	-1	0.6
13.13.37	S	5/24/78	CaSL	3	-1	8.1	6490	3590	110	77	1200	10.0	-1	0.0	350	1800	.02	-1	0.6
13.13.37	S	7/19/78	CaSL	3	-1	8.6	2100	1310	54	16	430	4.7	200	0.0	85	550	.57	-1	0.6
13.13.37	S	9/26/78	CaSL	3	-1	8.4	1200	720	22	6	200	4.1	83	0.0	58	290	.73	-1	0.5
13.13.37	S	2/28/79	CaSL	3	-1	8.31	0500	5630	140	79	1900	13.0	660	0.0	480	2900	.40	-1	0.6
13.13.37	S	7/11/79	CaSL	3	-1	8.2	1800	1030	40	10	330	4.3	140	0.0	170	380	.10	-1	0.6
13.13.37	S	10/18/79	CaSL	3	-1	8.4	6750	4060	99	68	1300	11.0	530	0.0	410	2000	.04	-1	0.5
13.13.37	S	2/21/80	CaSL	3	-1	8.4	1180	734	36	21	200	6.2	180	0.0	140	190	.13	-1	-1
13.13.37	S	10/24/80	CaSL	3	-1	8.5	5813	-1	110	54	1100	11.0	500	0.0	-1	-1	.18	-1	-1
13.13.37	S	1/13/81	CaSL	3	-1	8.5	9380	5320	140	77	1700	7.5	670	0.0	440	2700	.51	-1	0.7
13.13.37	S	6/ 3/81	CaSL	3	-1	8.6	3000	-1	51	23	490	5.0	220	0.0	230	650	.13	40	0.4
13.13.37	S	9/16/81	CaSL	3	-1	8.3	980	559	30	14	170	5.0	130	0.0	110	150	.26	12	0.8
13.13.37	S	3/23/82	CaSL	3	-1	8.5	9000	5410	130	85	1700	9.0	670	0.0	93	2800	-1	40	0.6
13.13.37	S	12/ 8/82	CaSL	3	-1	8.1	1000	638	36	14	150	4.2	150	0.0	110	150	-1	-1	0.5
13.13.37	S	4/12/83	CaSL	3	-1	8.4	3700	2130	78	40	620	5.5	-1	-1	330	840	-1	30	0.6
		Canadian River at Tascosa, Texas																	
0730000	S	1/ 1/69	CaTa	3	4	7.8	5280	3040	90	64	926	6.9	264	0	512	1280	3.7	-1	-1
0730000	S	3/ 1/69	CaTa	3	6	7.6	5200	2890	59	54	949	-1	198	0	419	1300	2.6	-1	-1
0730000	S	9/ 1/69	CaTa	3	23	7.8	641	386	32	12	91	-1	179	0	95	56	2.4	-1	0.5
0730000	S	4/14/70	CaTa	3	14	7.9	915	549	28	11	160	-1	228	0	122	104	0.6	-1	0.5
0730000	S	6/20/70	CaTa	3	-1	7.6	3900	2370	90	60	690	1	208	0	524	890	0.0	-1	0.6
0730000	S	9/21/70	CaTa	3	21	7.7	1570	934	49	17	271	-1	208	0	192	290	0.4	-1	-1
0730000	S	10/16/70	CaTa	3	7	8.0	1710	979	39	18	300	-1	199	0	190	320	1.1	-1	0.5
0730000	S	3/ 3/71	CaTa	3	2	7.8	6520	3780	96	70	1200	-1	180	0	520	1800	0.0	-1	-1
0730000	S	7/28/71	CaTa	3	25	8.1	455	276	21	6.8	68	3.1	145	0	46	41	2.0	-1	0.4
0730000	S	5/ 6/72	CaTa	3	-1	8.2	2150	1270	59	34	360	-1	302	-1	280	380	0.2	-1	-1
0730000	S	7/ 3/72	CaTa	3	23	8.1	662	384	26	8.4	100	-1	180	0	67	72	1.5	-1	-1
0730000	S	10/ 2/72	CaTa	3	23	8.0	1110	655	42	16	170	4.1	210	0	170	140	-1	-1	0.7
0730000	S	12/13/72	CaTa	3	1	8.2	2600	1410	56	42	400	-1	230	0	260	520	-1	-1	0.7
0730000	S	6/13/73	CaTa	3	20	7.2	951	1620	57	28	240	-1	148	0	260	280	-1	-1	0.4
0730000	S	11/27/73	CaTa	3	8	8.0	3610	2130	84	53	620	7.7	256	-1	440	790	-1	-1	-1
0730000	S	1/16/73	CaTa	3	7	8.1	3640	2110	88	43	630	6.3	232	0	340	880	-1	-1	-1
0730000	S	6/ 2/74	CaTa	3	25	7.8	1010	583	59	20	120	6.7	228	-1	120	130	-1	-1	-1
0730000	S	8/12/74	CaTa	3	26	7.5	698	387	52	17	67	4.5	244	-1	51	57	-1	-1	-1
0730000	S	10/ 1/74	CaTa	3	8	8.2	3260	1890	72	38	560	6.2	239	-1	350	740	-1	-1	-1
0730000	S	5/ 1/75	CaTa	3	15	8.2	3510	2090	50	57	620	7.7	224	0	450	780	-1	-1	0.6
0730000	S	8/29/75	CaTa	3	21	7.7	1480	826	45	15	250	4.4	225	-1	110	280	-1	-1	-1
0730000	S	2/18/76	CaTa	3	10	8.2	4120	2540	97	60	740	6.5	280	0	490	1000	-1	-1	0.6
0730000	S	5/25/76	CaTa	3	14	7.7	727	423	37	13	100	4.2	214	0	63	85	-1	-1	0.9
0730000	S	9/28/76	CaTa	3	14	7.9	673	369	35	11	84	3.7	151	0	53	99	-1	-1	0.5
0730000	S	10/ 6/76	CaTa	3	19	8.5	2610	1500	80	31	420	5.6	244	8	260	560	-1	-1	0.5
0730000	S	4/ 6/77	CaTa	3	25	8.4	4030	2470	87	58	750	7.4	284	8	460	950	-1	-1	0.6

Table B.1: Continued

Location	Type[a]	Date	Fm.[b]	S°	T	pH	S.C.	TDS	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl	NO_3	Fe	F
		Canadian River near Amarillo																	
0633000	S	10/19/48	CaAm	3	-1	-1	2550	1740	150	63	339	-1	338	0.0	525	380	15.0	-1	-1
0633000	S	5/ 3/49	CaAm	3	-1	-1	2190	1410	102	45	322	-1	223	0.0	449	345	2.5	-1	-1
0633000	S	10/ 2/50	CaAm	3	-1	7.9	712	434	34	13	95	-1	163	0.0	99	74	.5	-1	-1
0633000	S	7/13/51	CaAm	3	-1	8.2	2860	1820	178	59	359	-1	135	0.0	642	482	4.5	-1	-1
0633000	S	9/25/51	CaAm	3	-1	7.0	1220	708	50	41	150	-1	374	0.0	129	120	0.0	-1	3.6
0633000	S	11/ 5/51	CaAm	3	-1	7.8	1870	1150	86	38	262	-1	224	0.0	370	258	8.2	-1	.8
0633000	S	3/25/52	CaAm	3	-1	7.7	1300	827	64	44	135	-1	341	0.0	109	118	82.0	-1	3.6
0633000	S	8/ 5/52	CaAm	3	-1	7.1	1150	648	49	25	139	-1	203	0.0	162	132	1.0	-1	2.0
0633000	S	11/ 5/52	CaAm	3	-1	8.2	1310	957	62	43	162	-1	315	0.0	129	134	112.0	-1	4.4
0633000	S	4/10/53	CaAm	3	-1	7.5	1490	944	70	48	171	-1	317	0.0	150	159	111.0	-1	5.2
0633000	S	8/ 7/53	CaAm	3	-1	8.0	700	438	30	10	106	-1	196	0.0	77	71	3.0	-1	1.0
0633000	S	12/15/53	CaAm	3	-1	8.2	2190	1400	121	55	277	-1	289	0.0	326	345	75.0	-1	2.4
0633000	S	6/25/54	CaAm	3	-1	7.5	1200	792	62	45	125	-1	363	0.0	109	120	26.0	-1	4.0
0633000	S	9/30/54	CaAm	3	-1	8.0	2560	1550	90	38	424	-1	283	0.0	314	525	.5	-1	1.2
0633000	S	2/ 5/55	CaAm	3	-1	7.4	2590	1720	138	57	371	-1	346	0.0	402	440	69.0	-1	2.8
0633000	S	8/ 9/55	CaAm	3	-1	7.8	601	354	37	11	74	-1	174	0.0	64	60	1.2	-1	1.2
0633000	S	1/23/56	CaAm	3	-1	7.5	2360	1560	132	50	329	-1	299	0.0	370	390	75.0	-1	3.6
0633000	S	6/23/56	CaAm	3	-1	8.1	1950	1210	97	38	275	-1	275	0.0	314	308	6.0	-1	1.6
0633000	S	1/20/55	CaAm	3	-1	8.0	1240	835	67	36	147	-1	297	0.0	127	132	78.0	-1	4.0
0633000	S	3/28/57	CaAm	3	-1	7.2	1820	1100	97	37	235	-1	280	0.0	260	270	21.0	-1	2.8
0633000	S	8/ 5/57	CaAm	3	-1	7.8	448	293	20	7	70	-1	162	0.0	46	32	2.5	-1	1.4
0633000	S	1/ 5/58	CaAm	3	-1	7.6	2440	1550	138	46	334	-1	260	0.0	392	420	53.0	-1	1.6
0633000	S	4/25/58	CaAm	3	-1	7.4	1970	1240	89	31	303	-1	258	0.0	313	312	34.0	-1	1.2
0633000	S	9/26/58	CaAm	3	-1	7.5	1570	981	71	24	232	-1	222	0.0	218	252	15.0	-1	1.0
0633000	S	2/ 7/59	CaAm	3	-1	7.4	2660	1640	118	44	397	-1	262	0.0	399	478	39.0	-1	1.4
0633000	S	7/ 3/57	CaAm	3	-1	7.2	925	579	40	14	147	-1	182	0.0	138	128	3.5	-1	.7
0633000	S	12/17/59	CaAm	3	-1	7.5	642	409	27	8	108	-1	179	0.0	82	71	4.0	-1	.5
0633000	S	7/ 2/60	CaAm	3	-1	7.8	1370	849	57	19	216	-1	221	0.0	205	202	8.2	-1	.9
0633000	S	11/25/60	CaAm	3	-1	7.4	2490	1540	101	39	395	-1	302	0.0	382	442	0.0	-1	1.0
0633000	S	5/31/61	CaAm	3	-1	6.9	2080	1260	90	44	287	-1	222	0.0	408	245	5.6	-1	1.0
0633000	S	10/ 7/61	CaAm	3	-1	7.0	1500	1000	84	31	201	-1	217	0.0	303	180	28.0	-1	1.1
0633000	S	1/26/62	CaAm	3	-1	6.9	1890	1390	86	33	250	-1	240	0.0	284	280	3.8	-1	1.1
0633000	S	6/ 6/62	CaAm	3	-1	6.6	1630	1010	74	30	228	-1	284	0.0	228	218	27.0	-1	1.6
0633000	S	2/14/63	CaAm	3	-1	6.6	2370	1460	110	40	347	-1	258	0.0	354	410	39.0	-1	1.3
0633000	S	6/20/63	CaAm	3	-1	6.6	932	548	43	15	132	-1	184	0.0	115	127	5.1	-1	.7
0633000	S	1/ 7/64	CaAm	3	-1	7.4	1290	768	74	32	131	-1	297	0.0	140	140	18.0	-1	2.0
0633000	S	7/15/64	CaAm	3	-1	8.2	1150	724	51	35	130	18.0	326	0.0	91	108	62.0	-1	2.7
0633000	S	11/11/64	CaAm	3	-1	7.4	1720	1090	93	38	231	-1	252	0.0	228	265	60.0	-1	2.0
0633000	S	3/23/65	CaAm	3	-1	7.7	1430	931	73	39	132	-1	284	0.0	192	180	84.0	-1	1.3
0633000	S	8/ 2/65	CaAm	3	-1	7.3	3770	2290	171	60	556	-1	194	0.0	624	760	.5	-1	-1
0633000	S	12/15/65	CaAm	3	-1	7.4	2960	1780	123	49	429	7.4	236	0.0	432	570	20.0	-1	1.1
0633000	S	6/25/66	CaAm	3	-1	8.1	1150	676	54	29	132	13.0	237	0.0	127	138	26.0	-1	1.0
0633000	S	1/15/67	CaAm	3	-1	7.6	2570	1580	116	46	365	11.0	219	0.0	368	470	46.0	-1	1.8
0633000	S	8/ 9/67	CaAm	3	-1	8.1	2840	2150	99	36	441	7.6	180	0.0	286	562	1.0	-1	.8
0633000	S	1/10/68	CaAm	3	-1	8.0	2930	1770	125	44	448	9.1	231	0.0	380	592	26.0	-1	2.3

Table B.1: Continued

Location	Type[a]	Date	Fm.[b]	S[c]	T	pH	S.C.	TDS	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl	NO_3	Fe	F
0633000	S	9/ 8/68	CaAm	3	-1	8.8	2700	1660	118	40	418	-1	142	26.0	421	540	10.0	-1	-1
0633000	S	2/15/69	CaAm	3	-1	7.3	3230	2000	128	48	519	-1	226	0.0	428	650	47.0	-1	.3
0633000	S	8/ 1/69	CaAm	3	-1	7.8	1410	838	57	21	215	-1	176	0.0	205	235	5.9	-1	.6
0633000	S	3/15/70	CaAm	3	-1	7.2	1970	1190	88	29	297	-1	202	0.0	272	365	5.4	-1	.8
0633000	S	10/15/70	CaAm	3	-1	7.8	2890	1740	93	42	480	8.2	218	0.0	380	600	3.1	-1	.6
0633000	S	4/25/71	CaAm	3	-1	8.5	4320	2140	110	49	600	-1	216	20.0	500	720	4.8	-1	1.2
0633000	S	12/15/71	CaAm	3	-1	7.8	2980	1350	110	42	480	-1	252	0.0	380	610	3.5	-1	.8
0633000	S	7/10/72	CaAm	3	-1	8.2	1800	1080	78	26	270	7.8	228	0.0	260	300	3.1	-1	.7
0633000	S	12/30/72	CaAm	3	-1	7.4	3210	1280	120	49	530	-1	274	0.0	450	670	1.5	-1	.9
0633000	S	8/29/73	CaAm	3	-1	8.0	1390	850	72	32	180	-1	288	0.0	180	190	2.0	-1	1.5
0633000	S	1/ 4/74	CaAm	3	-1	8.3	1820	1070	76	32	260	15.0	207	0.0	270	290	-1	-1	-1
0633000	S	9/30/74	CaAm	3	-1	8.1	2540	1420	84	33	400	6.3	226	0.0	290	480	-1	-1	-1
0633000	S	3/12/75	CaAm	3	-1	8.0	3430	2040	110	49	550	11.0	264	0.0	450	730	.5	-1	.8
0633000	S	11/20/75	CaAm	3	-1	7.0	974	1170	47	16	130	15.0	154	0.0	110	140	-1	-1	1.1
0633000	S	8/ 3/76	CaAm	3	-1	8.7	731	402	10	3	140	1.8	111	5.0	80	100	.5	-1	.5
0633000	S	2/ 9/77	CaAm	3	-1	8.1	3880	2360	150	55	640	11.0	252	0.0	500	860	.2	-1	.7
0633000	S	8/10/77	CaAm	3	-1	8.2	861	491	21	8	150	3.3	120	0.0	110	130	.6	-1	.5
0633000	S	1/ 5/78	CaAm	3	-1	7.4	6250	4170	360	97	990	6.1	200	0.0	1100	1500	-1	-1	.5
0633000	S	6/24/78	CaAm	3	-1	8.2	2850	1680	120	42	420	7.8	160	0.0	400	600	0.0	-1	.6
0633000	S	12/20/78	CaAm	3	-1	8.3	4400	2780	200	63	720	7.0	190	0.0	680	1000	.05	-1	.4
0633000	S	3/29/79	CaAm	3	-1	-1	6110	3780	290	80	900	6.1	170	0.0	1100	1300	-1	-1	.5
0633000	S	12/20/79	CaAm	3	-1	8.0	3900	2380	190	58	570	7.4	230	0.0	570	850	.15	-1	.7
0633000	S	6/26/80	CaAm	3	-1	8.5	1700	980	74	23	250	8.3	160	6.0	200	330	0.0	-1	.6
0633000	S	12/ 4/80	CaAm	3	-1	8.1	3900	2340	140	48	630	10.0	190	0.0	430	960	.31	-1	.6
0633000	S	8/19/81	CaAm	3	-1	7.9	750	445	33	13	110	6.1	120	0.0	89	120	.22	-1	.8
0633000	S	2/12/82	Caam	3	-1	8.3	4060	2490	170	58	620	6.4	200	0.0	600	900	-1	-1	.5
0633000	S	9/ 1/82	CaAm	3	-1	8.3	1100	778	47	17	220	5.2	150	0.0	150	240	-1	-1	.7
		Lake Meredith																	
07227900	S	1/20/67	CaLM	4	-1	-1	-1	842	70	22	204	5.6	236	0.0	203	220	-1	-1	0.8
07227900	S	8/24/67	CaLM	4	-1	-1	-1	822	64	21	199	5.9	224	0.0	204	210	-1	-1	0.9
07227900	S	12/ 6/67	CaLM	4	-1	-1	-1	894	67	23	226	-1.0	236	0.0	228	220	-1	-1	1.0
07227900	S	8/23/68	CaLM	4	-1	-1	-1	1880	66	42	549	-1.0	169	0.0	518	202	-1	-1	0.7
07227900	S	4/11/69	CaLM	4	-1	-1	-1	991	70	28	228	7.5	240	0.0	254	262	-1	-1	1.0
07227900	S	12/30/69	CaLM	4	-1	-1	-1	875	57	23	220	5.8	191	0.0	230	231	-1	-1	0.8
07227900	S	7/ 6/70	CaLM	4	-1	-1	-1	927	59	23	237	6.0	212	0.0	240	255	-1	-1	0.6
07227900	S	8/ 5/70	CaLM	4	-1	-1	-1	872	50	25	230	6.1	204	0.0	198	259	-1	-1	0.8
07227900	S	8/26/70	CaLM	4	-1	-1	-1	935	60	25	237	6.5	207	0.0	246	255	-1	-1	0,8
07227900	S	9/21/70	CaLM	4	-1	-1	-1	954	61	24	244	6.3	212	0.0	249	260	-1	-1	0.8
07227900	S	11/ 4/70	CaLM	4	-1	-1	-1	943	63	24	240	6.6	214	0.0	240	260	-1	-1	1.0
07227900	S	1/ 5/71	CaLM	4	-1	-1	-1	974	58	24	260	6.4	208	0.0	250	270	-1	-1	0.8
07227900	S	10/19/71	CaLM	4	-1	-1	-1	1010	57	26	270	7.1	202	0.0	260	280	-1	-1	0.8
07227900	S	1/26/72	CaLM	4	-1	-1	-1	1050	62	26	310	-1.0	224	0.0	260	280	-1	-1	0.5
07227900	S	5/17/72	CaLM	4	-1	-1	-1	1020	63	26	270	-1.0	216	0.0	270	280	-1	-1	0.8
07227900	S	7/24/72	CaLM	4	-1	-1	-1	1000	57	25	270	-1.0	198	0.0	260	280	-1	-1	0.8
07227900	S	10/ 5/72	CaLM	4	-1	-1	-1	942	54	23	250	-1.0	200	0.0	250	260	-1	-1	0.8

Table B.1: Continued

Location	Type[a]	Date	Fm.[b]	S[c]	T	pH	S.C.	TDS	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl	NO_3	Fe	F
07227900	S	2/15/73	CaLM	4	-1	-1	-1	942	56	23	250	-1.0	206	0.0	250	250	-1	-1	0.8
07227900	S	5/ 3/73	CaLM	4	-1	-1	-1	960	61	26	240	6.1	212	0.0	250	270	-1	-1	0.8
07227900	S	6/14/73	CaLM	4	-1	-1	-1	972	62	26	250	6.1	214	0.0	260	260	-1	-1	0.6
07227900	S	10/18/73	CaLM	4	-1	-1	-1	1030	59	27	260	6.6	212	0.0	280	280	-1	-1	0.8
07227900	S	1/ 4/74	CaLM	4	-1	-1	-1	1060	64	27	280	8.1	218	0.0	280	290	-1	-1	-1.0
07227900	S	5/ 1/74	CaLM	4	-1	-1	-1	1050	63	28	280	6.6	217	0.0	270	290	-1	-1	-1.0
07227900	S	7/18/74	CaLM	4	-1	-1	-1	1070	55	28	280	8.1	208	0.0	280	310	-1	-1	-1.0
07227900	S	1/22/75	CaLM	4	-1	-1	-1	1080	56	29	280	6.9	202	4.0	300	300	-1	-1	0.8
07227900	S	5/28/75	CaLM	4	-1	-1	-1	1100	59	30	290	7.9	219	0.0	290	310	-1	-1	0.9
07227900	S	9/ 9/75	CaLM	4	-1	-1	-1	1040	58	28	280	7.8	198	0.0	280	290	-1	-1	0.8
07227900	S	1/21/76	CaLM	4	-1	-1	-1	1090	58	29	290	7.2	211	0.0	290	310	-1	-1	0.9
07227900	S	5/ 5/76	CaLM	4	-1	-1	-1	1150	61	30	300	7.5	204	8.0	300	340	-1	-1	0.9
07227900	S	8/24/76	CaLM	4	-1	-1	-1	1150	58	30	300	7.8	202	4.0	310	340	-1	-1	0.9
07227900	S	1/14/77	CaLM	4	-1	-1	-1	1120	59	30	300	8.2	206	4.0	270	330	-1	-1	0.9
07227900	S	1/ 5/78	CaLM	4	-1	-1	-1	1100	63	31	300	8.8	210	0.0	280	330	-1	-1	0.9
07227900	S	12/29/78	CaLM	4	6	-1	1840	1060	44	27	290	8.0	190	0.0	280	310	-1	-1	0.8
07227900	S	2/ 4/80	CaLM	4	5	-1	1910	1160	49	28	330	7.8	190	0.0	300	350	-1	-1	0.8
07227900	S	2/13/81	CaLM	4	7	-1	2140	1250	57	33	350	6.6	180	0.0	300	390	-1	-1	0.8
07227900	S	12/29/81	CaLM	4	6	-1	1530	906	46	21	250	5.8	160	0.0	210	270	-1	-1	0.7
		Triassic Wells																	
10.28.15.143	W	12/10/52	Tr	1	17	8.2	1000	631	16	8.7	212	-1	388	14	120	44	7.8	-1	1
10.31.12.333	W	7/30/48	Tr	1	-1	-1	1820	1270	117	59	227	-1	257	0	581	143	11.0	-1	0.9
10.32.17.313	W	10/ 8/48	Tr	1	-1	-1	1760	1120	2	3.7	431	-1	636	49	267	53	1.2	-1	-1
10.34.10.233	W	12/ 8/58	Tr	1	-1	9.3	1810	1100	3.6	0.0	424	-1	460	57	184	187	.7	0	0.7
11.30. 3.341	W	10/11/48	Tr	1	-1	-1	871	531	25	29	136	-1	372	0	125	26	6.5	-1	-1
11.31. 1.424	W	7/15/48	Tr	1	-1	-1	2130	1410	3	2.4	518	-1	504	49	494	92	.7	-1	1.9
11.31.14.113	W	7/14/48	Tr	1	-1	-1	4890	3310	13	6.3	1200	-1	824	75	1100	510	2.9	-1	0.9
11.31.19.143	W	9/27/48	Tr	1	-1	-1	1680	1050	29	43	307	-1	572	7.9	249	116	16.0	-1	-1
11.31.20.442	W	10/12/48	Tr	1	-1	-1	5520	3900	9.5	4.5	1370	-1	824	49	1760	300	2.9	-1	-1
11.31.22.122	W	10/13/48	Tr	1	-1	-1	1270	1070	82	54	304	-1	88	0	555	31	.1	-1	-1
11.31.23.330	W	10/13/48	Tr	1	-1	-1	3970	2670	5	5.0	970	-1	852	59	968	238	1.8	-1	-1
11.37.17.321	W	12/08/58	Tr	1	-1	7.6	1440	908	45	38	239	-1	496	0	215	111	-1	.06	1
13.32.01.000	Sp	9/21/83	Tr	4	19.4	7.5	570	456	61	21	23	3.5	229	0	60	23	9.3	-1	-1
13.33.01.000	W	9/22/83	Tr	4	18.0	7.0	1610	1375	210	85	49	4.9	355	0	600	42.5	1.3	-1	-1
13.33.24.000	W	9/22/83	Tr	4	18.0	6.9	2800	2122	140	190	205	7.1	761	0	548	255	0.4	-1	-1
13.33.11.322	W	2/25/55	Tr	1	17.0	7.4	932	404	109	32	54	-1	314	0	170	51	3.6	1.4	0.6
14.32.26.424	W	3/26/63	Tr	2	16.0	7.9	814	-1	69	31	-1	-1	220	0	-1	59	-1	-1	-1
14.32.26.423	W	3/26/63	Tr	2	14.0	7.8	843	511	65	35	59	3.2	220	0	140	60	-1	-1	1.6
14.31. 3.422	W	4/10/70	Tr	2	18.0	7.5	517	363	56	31	-1	-1	320	0	56	3.8	-1	-1	0.8
16.26.01.140	W	10/15/47	Tr	6	-1	-1	1400	912	33	34	265	-1	612	0	180	72	9.7	-1	0.3
17.26.07.300	W	10/15/47	Tr	6	-1	-1	1510	973	30	31	279	-1	445	0	303	80	17.0	-1	1.2
17.27.10.100	W	10/15/47	Tr	6	-1	-1	7110	411	58	34	49	-1	338	0	60	26	17.0	-1	0.4

Table B.1: Continued

Location	Type[a]	Date	Fm.[b]	S[c]	T	pH	S.C.	TDS	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl	NO_3	Fe	F
Permian Wells																			
Water wells in San Miguel County																			
11.15.21.110	W	9/26/47	Psa	6	-1	-1	511	295	68	22	14	-1	302	0.0	19	6	17.0	-1	0.4
12.12.04.110	W	8/04/47	Py	6	-1	-1	2550	2350	486	135	18	-1	152	0.0	1610	4	0.2	-1	0.3
12.12.11.200	W	8/06/47	Py	6	-1	-1	723	475	67	28	60	-1	331	0.0	130	3	0.3	-1	0.3
12.12.36.100	W	10/24/47	Py	6	-1	-1	1990	1720	351	91	43	-1	186	0.0	1130	9	0.3	-1	0.2
12.14.22.110	W	8/08/47	Py	6	-1	-1	575	374	92	12	18	-1	294	0.0	26	11	42.0	-1	0.2
13.12.26.200	W	10/22/47	Py	6	-1	-1	533	322	46	32	24	-1	218	0.0	102	6	4.2	-1	0.5
15.12.33.100	W	5/20/47	Py	6	-1	-1	1040	645	2	3.4	247	-1	469	0.0	113	35	0.1	-1	1.5
16.12.16.300	W	7/24/47	Pm	6	-1	-1	358	202	60	8.4	3.9	-1	185	0.0	34	3.5	0.7	-1	0.0
18.15.27.100	W	6/20/47	Pm	6	-1	-1	539	334	42	12	76	-1	330	0.0	37	5	0.0	-1	0.8
Ray No 1 Hoover Well																			
11.28.30.232	W	12/11/51	P	1	-1	-1.	10000	7100	890	102	1510	-1	994	-1	1840	2270	-1	-1	-1
Dripping Springs Well																			
13.31.25.120	W	9/22/83	M/P	4	22.8	6.0	70650	80948	1360	610	29000	64	904	0.0	5250	43719	0.4	-1	-1
Well OW-3																			
13.33.15.130	W	7/19/83	P/Tr	5	18.5	-1	50000	49180	792	245	19640	62.9	887	0.0	2810	26800	-1	0.47	0.7
13.33.15.130	W	10/17/83	P/Tr	4	19.0	6.4	69000	49072	800	220	17500	75.0	159	0.0	2880	27435	0.4	-1	-1
Well OW-4																			
13.33.15.130	W	7/19/83	P/Tr	5	17.5	-1	49600	36406	624	182	17940	51.7	830	0.0	2660	19700	-1	0.83	-1
Well DH-2																			
13.34.07.230	W	5/06/83	P/Tr	5	-1	-1	17500	11985	449	102	4240	54.8	1280	0.0	1450	5760	2.8	1.34	0.6
13.34.07.230	W	7/19/83	P/Tr	5	18.0	-1	17800	21138	384	96	7880	36.8	1076	0.0	1710	6580	-1	0.19	0.5
Wells in Wolfcamp aquifer in Texas																			
0258000	W	0/00/00	PW	7	45.6	6.8	-1	164026	1100	1069	60310	-1	302	0.0	13090	88154	-1	-1	-1
0635000	W	0/00/00	PW	7	46.2	7.9	-1	120000	3660	1350	40900	-1	278	0.0	2350	71600	-1	-1	-1
0643000	W	0/00/00	PW	7	47.8	6.8	-1	172000	7960	1540	56200	-1	173	0.0	1600	104000	-1	-1	-1
0651000	W	0/00/00	PW	7	47.3	8.8	-1	142121	6578	841	47193	-1	106	0.0	1735	85566	-1	-1	-1

Table B.2: Results of water quality determinations, Canadian River water between Ute Dam and Revuelto Creek, Oct. 19 and 20, 1983

Sample	Distance from Ute Dam (miles)	Date	TDS mg/l	Cl mg/l	Br mg/l
1	0.2	10-20-83	1350	570	0.56
2	0.5	"	2580	1080	
3	0.8	"	3850	1720	0.59
4	1.1	"	4130	2150	
5	1.5	"	5050	2550	0.69
6	1.9	10-19-83	6450	3250	
7	2.2	"	6150	3300	0.60
8	2.4	10-20-83	5380	2760	
9	2.6	10-19-83	6730	3370	0.71
10	2.9	10-20-83	5550	2880	
11	3.0	10-19-83	7250	3654	
12	3.2	10-20-83	6000	3110	0.37
13	3.5	10-19-83	7650	3860	
14	3.7	10-20-83	8230	4280	
15	3.9	10-19-83	9030	4660	0.50
16	4.0	10-20-83	9150	4760	
17	4.3	10-19-83	9350	4860	
18	4.6	10-20-83	9350	4900	0.60
19	4.9	"	9750	5105	
20	5.3	"	10400	5500	0.67
21	5.6	"	10600	5560	
22	5.9	10-19-83	11400	5910	
23	5.95	10-20-83	10700	5620	0.52

Table B.3: Results of water quality determinations, Canadian River water between Ute Dam and Dunes damsite, Jan 4 and 5, 1984

Sample	Distance from Ute Dam (miles)	Temp (°C)	Sp.Cond. µmhos(25°)	TDS mg/l	Cl mg/l	Br mg/l
1	0.0	14.0	1950	1230	330	0.39
2	0.13	10.0	3557			
3	0.26	8.3	3979			
4	0.37	5.0	967	- seep on N. canyon wall		
5	0.48	4.0	4466			
6	0.60	13.6	10492	2420	900	0.49
7	0.66	16.5	13735	- brine pool		
8	0.72	13.0	18160	- river bends to SE		
9	0.86	12.8	21160			
10	0.92	6.9	9560			
11	0.95	6.9	9560			
12	1.08	4.9	8696	- river bends to NE		
13	1.17	3.0	10180			
14	1.20	3.0	11070			
15	1.26	2.2	11213			
16	1.37	2.7	10650			
17	1.44	2.2	11210	5740	3060	0.73
18	1.51	3.0	10710	- at piez site 1		
19	1.61	3.0	10710			
20	1.69	3.2	10280			
21	1.90	3.0	10710	- at USGS gaging station		
22	1.97	3.0	10180	- at Hwy 54 bridge		
23	2.01	3.2	10280			
24	2.13	3.1	8720	- river bends to SSW		
25	2.42	3.0	9460	6110	6020	0.75
26	2.57	3.2	10990			
27	2.65	3.3	11310	- river bends to E		
28	2.71	3.5	11230			
29	2.76	3.0	10890			
30	2.99	1.2	12980			
31	3.10	1.6	13160			
32	3.12	1.2	14120	- at RR bridge		
33	3.24	3.0	12860			
34	3.36	2.7	14080			
35	3.51	2.5	16000	8740	4600	1.01
36	3.63	1.8	15860			
37	3.81	2.9	15050			
38	3.92	2.9	16130			
39	4.01	3.9	15220			
40	4.07	1.1	15520	- river bends to N		
41	4.10	1.0	15960			

Table B.3: Continued

Sample	Distance from Ute Dam (miles)	Temp (°C)	Sp.Cond. µmhos(25°)	TDS mg/l	Cl mg/l	Br mg/l
42	4.39	1.0	13460			
43	4.62	1.0	16150			
44	4.74	1.4	17050			
45	4.89	2.0	16480			
46	5.03	2.2	18380			
47	5.11	2.2	18570			
48	5.21	3.5	12110			
49	5.36	4.0	19140	11400		0.85
50	5.44	5.7	18400			
51	5.64	2.4	19340	- at piez site 3		
52	5.74	3.9	16960			
53	5.93	3.8	18750			
54	6.14	3.0	19460			
55	6.24	3.8	19620			
56	6.33	4.0	19660	11000	5940	0.88
				- just upstream of Revuelto		
57	7.09	5.0	8830			
58	7.30	5.3	10230			
59	7.65	6.1	10770			
60	7.83	6.1	11090			
61	8.06	4.9	10700	- river bends to east		
62	8.22	5.2	10600	6260	2980	0.69
63	8.39	4.8	11410			
64	8.60	5.1	9970			
65	8.86	4.0	10170			
66	9.15	3.1	9070			
67	9.28	3.9	8820			
68	9.43	3.6	8920	5450	2580	0.65
69	11.06	0.4	6890			
70	11.33	0.7	6420	3880	2880	0.47
71	11.55	0.9	6370			
72	11.98	0.5	6670			
73	12.17	0.7	6810			
74	12.29	0.6	7230			
75	12.50	0.7	7200			
76	12.72	1.0	7310			
77	12.96	1.0	7580			
78	13.14	1.2	7650			
79	13.46	1.6	7740			
80	13.66	1.5	7830			
81	13.77	1.6	7930			

Table B.3: Continued

Sample	Distance from Ute Dam (miles)	Temp (°C)	Sp.Cond. µmhos(25°)	TDS mg/l	Cl mg/l	Br mg/l
82	14.00	1.6	7930			
83	14.19	2.0	8070	4740	5280	0.59
84	14.37	2.0	8190			
85	14.68	2.7	8390			
86	14.99	2.3	8790			
87	15.25	2.1	9100			
88	15.37	2.2	9060			
89	15.54	1.7	9550	5660	2640	0.75
90	15.78	2.0	9630	- mouth of Tuscocuillo		
91	16.02	3.0	9110			
92	16.36	2.5	9180			
93	16.85	2.0	8870			
94	17.23	3.0	8590			
95	17.28	3.9	7940			
96	17.67	3.6	7810			
97	18.15	3.6	7690			
98	18.53	4.1	7920	4660	2120	0.64
99	18.71	5.2	7900			
100	19.03			5310	2480	0.60
101	20.73			5340	2480	0.64
102	22.62			5520	2580	0.62
103	24.03			5130	2360	0.60

Revuelto Creek:

Sample	Distance upstream from confluence	Temp (°C)	Sp.Cond. µmhos(25°)	TDS mg/l	Cl mg/l	Br mg/l
1	0.11			1290	93	0.47
5	2.41			1430	157	0.45
11	4.31			1280	48	0.49
18	6.59			1180	50	0.53
22	7.62			1360	73	0.80
24	8.88			950	35	0.46

THE UNIVERSITY OF ARIZONA
TUCSON, ARIZONA 85721

DEPARTMENT OF GEOSCIENCES
LABORATORY OF ISOTOPE GEOCHEMISTRY
TEL. (602) 621-6014

John Ward
Hydro Geo Chem, Inc.
744 N. Country Club
Tucson, AZ 85716

Dear John,

Here is written "proof" of your isotopic analyses. Again, sorry that it took so long to get your numbers to you. Since Song-lin called you last week, we have a repeat analysis on one of your ^{18}O's that we felt was strange in comparision to the deuterium value; as you can see, the number is virtually identical. Perhaps you can explain it?

As you asked, I will bill you seperately for these samples. The other two that you sent along with these, H-9 and H-13, will be billed and reported to Gary Walter.

Sincerely,

Lisa

Lisa Warneke, Research Assistant

Sample		$\delta^{18}O$ (°/oo)	δD (°/oo)	both w.r.t. SMOW
HGC 1	47E DAM	-2.49/-2.58	-22.4	
HGC 2	OW-3	-9.84	-71.2-71.7	

AGRICULTURE
CHEMICAL ANALYSIS
PETROLEUM

BC LABORATORIES INC

J. J. EGLIN, REG. CHEM. ENGR.
3016 UNION AVE BAKERSFIELD, CALIFORNIA 93305
MAIN OFFICE 4100 PIERCE ROAD, BAKERSFIELD CA 93308 PHONE 327-4911

Hydro Geo Chem, Inc.
744 North Country Club Road
Tucson, Arizona 85716

Date Reported: 10/18/83
Date Received: 10/3/83
Laboratory No.: 10729

WATER ANALYSIS

Sample Description: 5. 9/22/83 1400

Constituents	Parts/million
Calcium	1,360.
Magnesium	610.
Sodium	29,000.
Potassium	64.
Carbonate	0.
Bicarbonate	904.
Chloride	43,719.
Sulfate	5,250.
Nitrate	(<) 0.4
Total Dissolved Solids	80,948.
Boron	3.5
Silica	37.
Hardness as $CaCO_3$	5,913. (345 gr/gal)
Electrical Conductivity, Micromhos	70,650.
pH	6.6

B C LABORATORIES, INC.

BY J. J. Eglin
J. J. Eglin

ad

Field Parameters

Well:	"Dripping Springs" (Permian-Yeso?)
Location:	13.31.25.12
Date:	9-22-83
Time:	1400
Temp:	22.8°C
pH:	6.02
Alkalinity:	765 mg/l

AGRICULTURE
[CHE]MICAL ANALYSIS
PETROLEUM
BC LABORATORIES INC
J. J. EGLIN, REG. CHEM. ENGR.
3016 UNION AVE BAKERSFIELD, CALIFORNIA 93305
MAIN OFFICE 4100 PIERCE ROAD, BAKERSFIELD CA 93308 PHONE 327-4911

Hydro Geo Chem, Inc.
744 North Country Club Road
Tucson, Arizona 85716

Date Reported: 10/18/83
Date Received: 10/3/83
Laboratory No.: 10730

WATER ANALYSIS

Sample Description: 6. 9/22/83 1600

Constituents	Parts/million
Calcium	210.
Magnesium	85.
Sodium	49.
Potassium	4.9
Carbonate	0.
Bicarbonate	355.
Chloride	42.5
Sulfate	600.
Nitrate	1.3
Total Dissolved Solids	1,375.
Boron	0.08
Silica	27.
Hardness as $CaCO_3$	875. (51.1 gr/gal)
Electrical Conductivity, Micromhos	1,610.
pH	7.3

B C LABORATORIES, INC.

BY J. J. Eglin
J. J. Eglin

ad

Field Parameters

Well:	"Logan Cemetary Windmill" (Triassic)
Location:	13.33.1.43
Date:	9-22-83
Time:	1600
Temp:	18.0°C
pH:	6.96
Alkalinity:	300 mg/l

AGRICULTURE
CHEMICAL ANALYSIS
PETROLEUM

BC LABORATORIES INC
J. J. EGLIN, REG. CHEM. ENGR.
3016 UNION AVE BAKERSFIELD, CALIFORNIA 93305
MAIN OFFICE 4100 PIERCE ROAD, BAKERSFIELD CA 93308 PHONE 327-4911

Hydro Geo Chem, Inc.
744 N. Country Club
Tucson, Arizona 85716

Date Reported: 12/2/83
Date Received: 11/7/83
Laboratory No.: 12515

Attention: Mr. John Ward

WATER ANALYSIS

Sample Description: #1

Constituents	Parts/million
Calcium	37.
Magnesium	23.
Sodium	340.
Potassium	4.9
Carbonate	0.
Bicarbonate	343.
Chloride	332.
Sulfate	190.
Nitrate	(<) 0.4
Total Dissolved Solids, By Summation	1,270.
Boron	0.21

(<) refers to "less than"

B C LABORATORIES, INC.

BY J. J. Eglin
J. J. Eglin

kc

Field Parameters

Ute Dam seepage (sluice box)
Location: 13.33.21.2
Date: 10-17-83
Time: 1600
Temp: 15.5°C
pH: 7.85
Alkalinity: 270 mg/l
Spec. cond. (25°) = 2040 μmhos

AGRICULTURE
[?]EMICAL ANALYSIS
PETROLEUM

BC LABORATORIES INC

J. J. EGLIN, REG. CHEM. ENGR.
3016 UNION AVE BAKERSFIELD, CALIFORNIA 93305
MAIN OFFICE 4100 PIERCE ROAD, BAKERSFIELD CA 93308 PHONE 327-4911

Hydro Geo Chem, Inc.
744 N. Country Club
Tucson, Arizona 85716

Date Reported: 12/2/83
Date Received: 11/7/83
Laboratory No.: 12516

Attention: Mr. John Ward

WATER ANALYSIS

Sample Description: #2

Constituents	Parts/million
Calcium	800.
Magnesium	220.
Sodium	17,500.
Potassium	75.
Carbonate	0.
Bicarbonate	159.
Chloride	27,435.
Sulfate	2,880.
Nitrate	(<) 0.4
Total Dissolved Solids, By Summation	49,072.
Boron	3.2

(<) refers to "less than"

B C LABORATORIES, INC.

BY J. J. Eglin
J. J. Eglin

kc

Field Parameters

Well: OW-3 (Lower Triassic-upper Permian?)
Location: 13.33.15.13
Date: 10-17-83
Time: 1740
Temp: 19.0°C
pH: 6.36
Alkalinity: 836 mg/l
Spec. cond. (25°) = 78,400 μmhos

AGRICULTURE
CHEMICAL ANALYSIS
PETROLEUM

BC LABORATORIES INC
J. J. EGLIN, REG CHEM ENGR
3016 UNION AVE BAKERSFIELD, CALIFORNIA 93305
MAIN OFFICE 4100 PIERCE ROAD, BAKERSFIELD CA 93308 PHONE 327-4911

Hydro Geo Chem, Inc.
744 N. Country Club
Tucson, Arizona 85716

Date Reported: 12/2/83
Date Received: 11/7/83
Laboratory No.: 12517

Attention: Mr. John Ward

WATER ANALYSIS

Sample Description: #3

Constituents	Parts/million
Calcium	580.
Magnesium	145.
Sodium	6,900.
Potassium	35.
Carbonate	0.
Bicarbonate	849.
Chloride	10,832.
Sulfate	1,440.
Nitrate	(<) 0.4
Total Dissolved Solids, By Summation	20,783.
Boron	1.5

(<) refers to "less than"

B C LABORATORIES, INC.

BY J. J. Eglin
J. J. Eglin

kc

Field Parameters

Well:	Piezometer site 6:50' (Channel deposits)
Location:	13.34.5.12
Date:	10-18-83
Time:	1000
Temp:	18.0°C
pH:	6.60
Alkalinity:	803 mg/l

AGRICULTURE
[illegible]ICAL ANALYSIS
PETROLEUM

BC LABORATORIES INC
J. J. EGLIN, REG. CHEM. ENGR.
3016 UNION AVE BAKERSFIELD, CALIFORNIA 93305
MAIN OFFICE 4100 PIERCE ROAD, BAKERSFIELD CA 93308 PHONE 327-4911

Hydro Geo Chem, Inc.
744 N. Country Club
Tucson, Arizona 85716

Date Reported: 12/2/83
Date Received: 11/7/83
Laboratory No.: 12519

Attention: Mr. John Ward

WATER ANALYSIS

Sample Description: #5

Constituents	Parts/million
Calcium	360.
Magnesium	130.
Sodium	4,800.
Potassium	19.
Carbonate	0.
Bicarbonate	255.
Chloride	7,788.
Sulfate	920.
Nitrate	(<) 0.4
Total Dissolved Solids, By Summation	14,273.
Boron	1.0

(<) refers to "less than"

B C LABORATORIES, INC.

BY J. J. Eglin
J. J. Eglin

kc

Field Parameters

Well: Piezometer site 2:55'
(Channel deposits)
Location: 13.33.14.24
Date: 10-18-83
Time: 1400
Temp: 17.0°C
pH: 6.95
Alkalinity: 325 mg/l
Spec. cond. (25°) = 25,000 μmhos

AGRICULTURE
CHEMICAL ANALYSIS
PETROLEUM

BC LABORATORIES INC
J. J. EGLIN, REG. CHEM. ENGR.
3016 UNION AVE BAKERSFIELD, CALIFORNIA 93305
MAIN OFFICE 4100 PIERCE ROAD, BAKERSFIELD CA 93308 PHONE 327-4911

Hydro Geo Chem, Inc.
744 N. Country Club
Tucson, Arizona 85716

Date Reported: 12/2/83
Date Received: 11/7/83
Laboratory No.: 12518

Attention: Mr. John Ward

WATER ANALYSIS

Sample Description: #4

Constituents	Parts/million
Calcium	420.
Magnesium	170.
Sodium	8,700.
Potassium	28.
Carbonate	0.
Bicarbonate	520.
Chloride	13,275.
Sulfate	1,600.
Nitrate	(<) 0.4
Total Dissolved Solids, By Summation	24,714.
Boron	1.0

(<) refers to "less than"

B C LABORATORIES, INC.

BY J. J. Eglin
J. J. Eglin

kc

Field Parameters

Well: Piezometer site 3:35' (Channel deposit)
Location: 13.33.12.23
Date: 10-18-83
Time: 1130
Temp: 18.0°C
pH: 6.90
Alkalinity: 452 mg/l
Spec. cond. (25°) = 44,500 μmhos

AGRICULTURE
MICAL ANALYSIS
PETROLEUM

BC LABORATORIES INC

J. J. EGLIN, REG. CHEM. ENGR.
3016 UNION AVE BAKERSFIELD, CALIFORNIA 93305
MAIN OFFICE 4100 PIERCE ROAD, BAKERSFIELD CA 93308 PHONE 327-4911

Hydro Geo Chem, Inc.
744 North Country Club Road
Tucson, Arizona 85716

Date Reported: 10/18/83
Date Received: 10/3/83
Laboratory No.: 10727

WATER ANALYSIS

Sample Description: 1. 9/21/83 1000

Constituents	Parts/million
Calcium	61.
Magnesium	21.
Sodium	23.
Potassium	3.5
Carbonate	0.
Bicarbonate	229.
Chloride	23.0
Sulfate	60.
Nitrate	9.3
Total Dissolved Solids	456.
Boron	1.5
Silica	25.
Hardness as $CaCO_3$	239. (14.0 gr/gal)
Electrical Conductivity, Micromhos	570.
pH	7.6

B C LABORATORIES, INC.

BY [signature]
J. J. Eglin

ad

Field Parameters

Triassic Spring
Location: 13.32.1
Date: 9-21-83
Time: 1000
Temp: 19.4°C
pH: 7.50
Alkalinity: 200 mg/l

AGRICULTURE
CHEMICAL ANALYSIS
PETROLEUM

BC LABORATORIES INC

J. J. EGLIN, REG. CHEM. ENGR.
3016 UNION AVE · BAKERSFIELD, CALIFORNIA 93305
MAIN OFFICE 4100 PIERCE ROAD, BAKERSFIELD CA 93308 PHONE 327-4911

Hydro Geo Chem, Inc.
744 North Country Club Road
Tucson, Arizona 85716

Date Reported: 10/18/83
Date Received: 10/3/83
Laboratory No.: 10728

WATER ANALYSIS

Sample Description: 4. 9/22/83 1030

Constituents	Parts/million
Calcium	140.
Magnesium	190.
Sodium	205.
Potassium	7.1
Carbonate	0.
Bicarbonate	761.
Chloride	255.
Sulfate	548.
Nitrate	(<) 0.4
Total Dissolved Solids	2,122.
Boron	0.10
Silica	16.
Hardness as $CaCO_3$	1,132. (66.1 gr/gal)
Electrical Conductivity, Micromhos	2,800.
pH	7.5

B C LABORATORIES, INC.

BY J. J. Eglin
J. J. Eglin

ad

Field Parameters

Well:	"Revuelto Creek Windmill: (Triassic)
Location:	13.33.24
Date:	9-22-83
Time:	1000
Temp:	18.0°C
pH:	6.93
Alkalinity:	580 mg/l

of the waters could be made by comparing variations in the iodide/chloride values with concentrations and ratios of other major and minor constituents and isotopic ratios of the waters.

Oilfield brines usually have bromide/chloride ratios falling within the range 10×10^4 to 60×10^4. The approximate center of this range is the value for seawater, 34×10^4. Iodide/chloride ratios in oilfield brines typically are above 60×10^6, commonly exceed 100×10^6, and range to well over 1000×10^6. Therefore, sample 5A, identified as collected from an abandoned oil or gas well, does not appear to be formation water associated with oil and gas, but halite-solution brine that has entered the well.

REFERENCES

Basel, C.L., J.D. Defreese, and D.O. Whittemore, 1982. Interferences in automated phenol red method for determination of bromide in water: Analytical Chemistry 54: 2090-2094.

Whittemore, D.O., 1984. Geochemical identification of salinity sources: in R.H. French, ed., Salinity in Watercourses and Reservoirs (Proceedings of the International Conference on State-of-the-Art Control of Salinity) Ann Arbor Science, Woburn, Mass. (in press).

Whittemore, D.O., C.L. Basel, O.K. Galle, and T.C. Waugh, 1981. Geochemical identification of saltwater sources in the Smoky Hill River Valley, McPherson, Saline, and Dickinson Counties, Kansas: Kansas Geological Survey Open-File Report 81-6, 78 p.

Canadian River Basin samples,
northeastern New Mexico

D. Whittemore 12-28-83

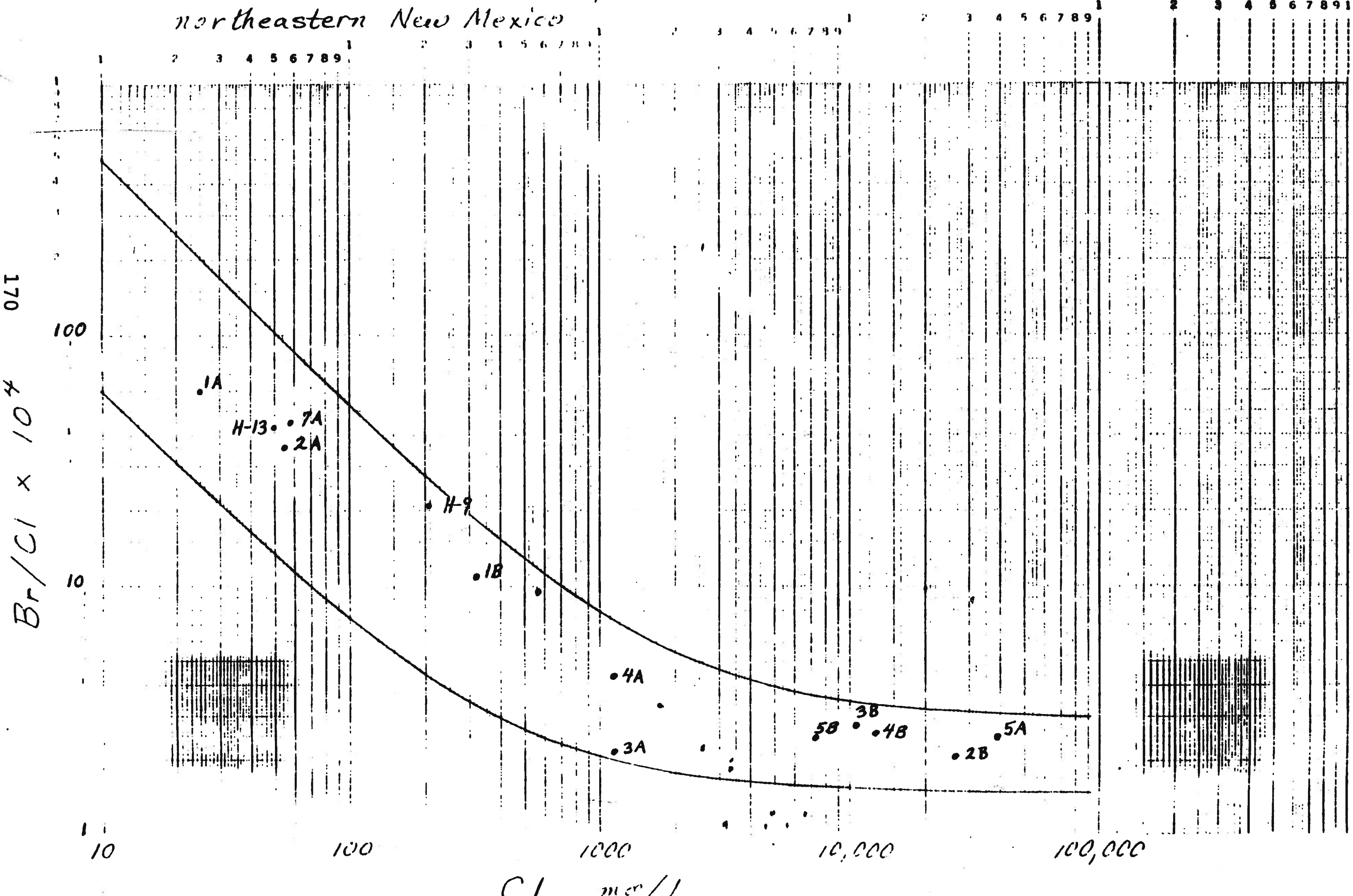


Figure 1. Bromide/chloride ratio versus chloride concentration.

APPENDIX C

WATER BUDGET TABLES

Table C.1: Monthly water-budget results for Lake Meredith
Inflow = Amarillo flow + reservoir rainfall
Outflow = Diversions + Dam seepage + Evaporation
Residual = Outflow - Inflow + Change in Storage
All values in acre-feet except precipitation and evaporation

Date	Lake Meredith Month-end Storage	Change in Storage	Amarillo Flow	Precip (in.)	Inflow	Pan Evap (in.)	Diver-sions	Out-flow	Resi-dual
OCT 64	2220.	2220.	732.	0.44*	750.	7.629*	0.	238.	1708.
NOV 64	3280.	1060.	1160.	0.57*	1189.	4.184*	0.	165.	37.
DEC 64	4100.	820.	524.	0.48*	552.	2.812*	0.	137.	405.
JAN 65	4460.	360.	429.	0.35*	452.	3.044*	0.	167.	75.
FEB 65	4890.	430.	388.	0.19	401.	3.954*	0.	223.	252.
MAR 65	5570.	680.	594.	0.92	659.	6.815*	0.	365.	386.
APR 65	5060.	-510.	332.	0.39	358.	9.947*	0.	490.	-378.
MAY 65	17710.	12650.	21330.	4.10	21843.	11.387*	0.	1044.	-8149.
JUN 65	157400.	139690.	195200.	8.63	199587.	13.546*	0.	5014.	-54883.
JUL 65	162800.	5400.	14650.	0.37	14841.	14.405*	0.	5407.	-4035.
AUG 65	176400.	13600.	24170.	2.90	25741.	12.554*	0.	4966.	-7174.
SEP 65	181900.	5500.	13170.	0.95	13693.	9.206*	0.	3754.	-4439.
OCT 65	210100.	28200.	42380.	0.84	42842.	7.629*	0.	3147.	-11495.
NOV 65	214300.	4200.	11250.	0.01*	11256.	4.184*	0.	1958.	-5098.
DEC 65	214700.	400.	2420.	0.68	2828.	2.812*	0.	1410.	-1018.
JAN 66	216100.	1400.	666.	0.32	858.	3.044*	0.	1507.	2049.
FEB 66	219000.	2900.	2830.	0.92	3382.	3.954*	0.	1889.	1407.
MAR 66	218400.	-600.	2090.	0.00*	2090.	6.815*	0.	3091.	401.
APR 66	215900.	-2500.	559.	0.40	799.	9.947*	0.	4406.	1107.
MAY 66	211600.	-4300.	813.	0.02	825.	11.387*	0.	4942.	-183.
JUN 66	214800.	3200.	10660.	4.39	13257.	17.000	0.	7266.	-2791.
JUL 66	216700.	1900.	8420.	1.97	9602.	17.390	0.	7532.	-170.
AUG 66	228500.	11800.	26050.	4.24	28629.	10.930	0.	4886.	-11943.
SEP 66	231400.	2900.	6320.	1.14	7033.	7.730	0.	3620.	-513.
OCT 66	227600.	-3800.	593.	0.60	963.	8.090	0.	3727.	-1036.
NOV 66	225000.	-2600.	656.	0.01	662.	6.040	190.	3032.	-230.
DEC 66	223300.	-1700.	756.	0.03	774.	4.080	0.	1969.	-505.
JAN 67	222900.	-400.	1510.	0.01	1516.	5.110	5.	2413.	497.
FEB 67	222200.	-700.	858.	0.20	980.	3.760	21.	1854.	174.
MAR 67	220600.	-1600.	688.	0.20	808.	5.750	320.	2964.	556.
APR 67	228900.	8300.	14490.	2.58	16081.	8.250	576.	4372.	-3409.
MAY 67	225800.	-3100.	2570.	1.37	3415.	9.730	537.	4972.	-1543.
JUN 67	259100.	33300.	30870.	3.19	32997.	8.350	653.	4804.	5107.
JUL 67	312400.	53300.	99410.	5.33	103319.	8.000	132.	4518.	-45501.
AUG 67	320800.	8400.	19820.	2.63	21793.	7.670	977.	5289.	-8103.
SEP 67	322900.	2100.	13890.	0.45	14228.	5.800	0.	3331.	-8797.
OCT 67	320700.	-2200.	19470.	0.41	19778.	6.580	0.	3740.	-18237.
NOV 67	319300.	-1400.	6180.	0.26	6373.	2.510	0.	1586.	-6187.
DEC 67	320200.	900.	4940.	0.23	5113.	1.870	0.	1267.	-2945.
JAN 68	324800.	4600.	5210.	1.05	5998.	2.730	0.	1719.	321.
FEB 68	326600.	1800.	2640.	0.39	2936.	2.710	0.	1727.	592.

Table C.1: Continued

Date	Lake Meredith Month-end Storage	Change in Storage	Amarillo Flow	Precip (in.)	Inflow	Pan Evap (in.)	Diver-sions	Out-flow	Resi-dual
MAR 68	325200.	-1400.	1100.	0.33	1348.	3.410	803.	2879.	131.
APR 68	322400.	-2800.	662.	1.54	1817.	12.000	930.	7516.	2899.
MAY 68	328200.	5800.	11630.	2.26	13344.	10.150	2740.	8417.	873.
JUN 68	326200.	-2000.	7570.	4.13	10702.	12.000	3554.	10213.	-2489.
JUL 68	325300.	-900.	14450.	1.03	15223.	11.036	4240.	10320.	-5803.
AUG 68	328000.	2700.	16070.	3.01	18353.	11.758	3734.	10264.	-5388.
SEP 68	317600.	-10400.	1270.	0.15	1381.	10.809	4326.	10220.	-1561.
OCT 68	312900.	-4700.	3830.	1.44	4898.	8.739	3562.	8382.	-1216.
NOV 68	306800.	-6100.	988.	0.52	1369.	3.816	3862.	6100.	-1369.
DEC 68	300700.	-6100.	408.	0.26*	597.	1.975	4192.	5471.	-1226.
JAN 69	296900.	-3800.	919.	0.01	926.	4.136	3694.	6042.	1316.
FEB 69	294500.	-2400.	2740.	1.86	4073.	4.460	3576.	6086.	-387.
MAR 69	294900.	400.	3180.	0.55	3574.	3.205	2354.	4235.	1061.
APR 69	288300.	-6600.	184.	0.36	439.	9.334	5243.	10141.	3102.
MAY 69	305400.	17100.	33130.	3.90	35958.	10.592	4458.	10110.	-8748.
JUN 69	354200.	48800.	76870.	4.07	80092.	12.112	6068.	13082.	-18210.
JUL 69	369700.	15500.	38950.	2.36	40858.	13.567	7128.	15113.	-10245.
AUG 69	376600.	6900.	29910.	3.37	32634.	14.114	6997.	15291.	-10443.
SEP 69	463000.	86400.	105400.	2.49	107745.	7.128	4332.	9389.	-11955.
OCT 69	468500.	5500.	23900.	1.64	25458.	5.550	4594.	8647.	-11311.
NOV 69	464500.	-4000.	4670.	0.44	5084.	3.842	4699.	7590.	-1494.
DEC 69	459900.	-4600.	2970.	0.07	3035.	2.664	4486.	6582.	-1053.
JAN 70	457700.	-2200.	3400.	0.02*	3419.	2.279	3320.	5165.	-454.
FEB 70	454400.	-3300.	1320.	0.00*	1320.	4.919	3688.	7225.	2605.
MAR 70	450400.	-4000.	1790.	0.52	2271.	4.517	2862.	6139.	-132.
APR 70	469700.	19300.	29710.	0.58	30261.	9.224	4868.	11364.	403.
MAY 70	461200.	-8500.	2440.	0.26	2685.	16.008	5793.	16704.	5519.
JUN 70	450900.	-10300.	1340.	0.73	2015.	16.204	6180.	17024.	4709.
JUL 70	438100.	-12800.	6340.	1.60	7793.	17.938	7098.	18850.	-1744.
AUG 70	445600.	7500.	19960.	1.60	21427.	15.344	7445.	17640.	3713.
SEP 70	438300.	-7300.	8980.	0.42	9362.	11.320	5490.	13034.	-3628.
OCT 70	430900.	-7400.	4380.	0.58	4897.	6.756	4609.	9166.	-3132.
NOV 70	424700.	-6200.	1870.	0.36	2191.	6.008	3947.	8037.	-354.
DEC 70	417500.	-7200.	921.	0.00*	921.	3.950	4844.	7623.	-498.
JAN 71	412700.	-4800.	1350.	0.11*	1446.	4.329	5047.	8032.	1786.
FEB 71	410100.	-2600.	1560.	0.99	2459.	4.763	3991.	7366.	2306.
MAR 71	403200.	-6900.	750.	0.08*	819.	8.944	4923.	10624.	2905.
APR 71	396100.	-7100.	1650.	0.66	2206.	11.612	5256.	12418.	3113.
MAY 71	391500.	-4600.	9620.	0.77	10262.	14.646	6601.	15462.	600.
JUN 71	391300.	-200.	20950.	2.34	22900.	16.866	6046.	16202.	-6898.
JUL 71	400700.	9400.	36950.	2.49	39067.	15.510	6709.	16261.	-13405.
AUG 71	416800.	16100.	45220.	2.13	47084.	11.238	5282.	12499.	-18485.
SEP 71	416800.	0.	17150.	4.03	20676.	10.207	6502.	13087.	-7589.
OCT 71	413000.	-3800.	4340.	2.06	6125.	7.710	4923.	9931.	5.

Table C.1: Continued

Date	Lake Meredith Month-end Storage	Lake Meredith Change in Storage	Amarillo Flow	Precip (in.)	Inflow	Pan Evap (in.)	Diver-sions	Out-flow	Resi-dual
NOV 71	445400.	32400.	22140.	2.46	24395.	5.473	4003.	7864.	15869.
DEC 71	445400.	0.	4070.	0.47	4501.	2.206	3753.	5518.	1017.
JAN 72	442000.	-3400.	3910.	0.14*	4037.	4.329	3326.	6425.	-1013.
FEB 72	438000.	-4000.	1890.	0.05	1935.	4.784	4001.	7358.	1423.
MAR 72	431200.	-6800.	858.	0.20	1036.	10.459	4837.	11705.	3869.
APR 72	420900.	-10300.	648.	0.04*	683.	13.075	6253.	14674.	3691.
MAY 72	420100.	-800.	5430.	2.13	7312.	11.145	5196.	12424.	4312.
JUN 72	430500.	10400.	8790.	3.08	11562.	12.483	6512.	14719.	13557.
JUL 72	472500.	42000.	81440.	3.13	84153.	11.471	6376.	13665.	-28487.
AUG 72	503000.	30500.	56270.	1.72	57976.	12.385	6714.	15689.	-11787.
SEP 72	542700.	39700.	61630.	0.31	61956.	9.698	5623.	13151.	-9104.
OCT 72	539400.	-3300.	17010.	1.36	18438.	7.013	6440.	11995.	-9743.
NOV 72	538600.	-800.	3010.	1.70	4781.	2.139	1544.	3501.	-2080.
DEC 72	536100.	-2500.	1900.	0.19	2098.	0.961	4604.	5702.	1104.
JAN 73	534300.	-1800.	2570.	0.24	2818.	1.844	3944.	5671.	1053.
FEB 73	531200.	-3100.	2190.	0.28	2479.	2.993	3837.	6396.	816.
MAR 73	536800.	5600.	8650.	4.37	13202.	5.714	4171.	8734.	1132.
APR 73	545300.	8500.	14940.	2.26	17313.	7.185	4438.	10119.	1306.
MAY 73	537900.	-7400.	1470.	1.05	2564.	11.427	4995.	13724.	3760.
JUN 73	525400.	-12500.	389.	0.73	1137.	15.227	6546.	17862.	4225.
JUL 73	520400.	-5000.	14420.	2.60	17063.	13.441	6647.	16600.	-5464.
AUG 73	510900.	-9500.	11940.	0.77	12716.	14.395	6404.	16949.	-5268.
SEP 73	498600.	-12300.	884.	2.53	3393.	8.752	5437.	11890.	-3803.
OCT 73	487900.	-10700.	526.	0.91	1413.	8.364	5074.	11154.	-959.
NOV 73	478300.	-9600.	557.	0.17	720.	5.014	4542.	8271.	-2049.
DEC 73	470900.	-7400.	833.	0.50	1308.	3.293	4714.	7266.	-1442.
JAN 74	466900.	-4000.	1410.	0.10	1505.	1.691	3967.	5453.	-52.
FEB 74	460800.	-6100.	875.	0.20	1063.	5.755	4406.	8558.	1395.
MAR 74	458900.	-1900.	5640.	2.50	7973.	8.795	5432.	11534.	1660.
APR 74	447600.	-11300.	287.	0.23*	498.	12.120	6844.	14970.	3172.
MAY 74	442100.	-5500.	7170.	3.10	9986.	15.486	7397.	17590.	2104.
JUN 74	429600.	-12500.	4260.	2.03	6070.	15.646	8169.	18274.	-296.
JUL 74	413400.	-16200.	2520.	0.91	3316.	16.853	8957.	19613.	97.
AUG 74	434800.	21400.	49770.	7.30	56340.	11.563	6428.	14056.	-20884.
SEP 74	431000.	-3800.	18960.	0.62	19518.	6.877	5088.	9763.	-13555.
OCT 74	451500.	20500.	36500.	4.69	40838.	6.722	4440.	9145.	-11193.
NOV 74	447100.	-4400.	3650.	0.31	3934.	4.392	4422.	7589.	-745.
DEC 74	441400.	-5700.	1940.	0.44	2340.	3.730	4391.	7109.	-931.
JAN 75	438300.	-3100.	3720.	0.15	3856.	2.511	4425.	6368.	-589.
FEB 75	437800.	-500.	3660.	1.12	4668.	1.687	3741.	5147.	-21.
MAR 75	433200.	-4600.	1820.	0.19	1989.	6.282	4859.	9120.	2530.
APR 75	427500.	-5700.	2830.	1.05	3766.	9.317	5318.	11473.	2007.
MAY 75	419200.	-8300.	2450.	2.60	4725.	12.865	6884.	15097.	2072.
JUN 75	436200.	17000.	31670.	3.53	34788.	12.557	6992.	15093.	-2695.
JUL 75	453900.	17700.	18450.	5.03	23103.	11.545	6509.	14337.	8934.

Table C.1: Continued

Date	Lake Meredith Month-end Storage	Lake Meredith Change in Storage	Amarillo Flow	Precip (in.)	Inflow	Pan Evap (in.)	Diver-sions	Out-flow	Resi-dual
AUG 75	445700.	-8200.	10100.	0.74	10778.	12.842	7373.	15962.	-3016.
SEP 75	430600.	-15100.	1300.	2.04	3119.	9.550	6432.	12732.	-5487.
OCT 75	418400.	-12200.	791.	0.00*	791.	9.223	5867.	11849.	-1142.
NOV 75	410600.	-7800.	440.	1.27	1541.	4.536	4758.	7840.	-1501.
DEC 75	404500.	-6100.	333.	0.06*	385.	2.865	4184.	6232.	-252.
JAN 76	398600.	-5900.	627.	0.01*	636.	4.190	3858.	6675.	139.
FEB 76	392500.	-6100.	672.	0.16*	807.	6.784	4451.	8769.	1862.
MAR 76	385500.	-7000.	824.	1.31	1916.	8.697	4790.	10181.	1265.
APR 76	380100.	-5400.	2160.	1.54	3431.	9.235	4947.	10594.	1764.
MAY 76	374300.	-5800.	6540.	0.93	7300.	10.551	6245.	12588.	-512.
JUN 76	364500.	-9800.	3200.	1.01	4008.	14.943	7377.	16050.	2242.
JUL 76	353500.	-11000.	3730.	1.33	4772.	12.951	6964.	14364.	-1408.
AUG 76	349000.	-4500.	13310.	3.64	16131.	13.764	8115.	15877.	-4754.
SEP 76	381600.	32600.	53270.	7.64	59573.	7.895	5887.	10761.	-16212.
OCT 76	375100.	-6500.	3580.	0.48	3972.	7.629*	4763.	9435.	-1037.
NOV 76	369000.	-6100.	958.	0.61*	1451.	4.184*	4255.	6930.	-621.
DEC 76	364400.	-4600.	772.	0.30*	1012.	2.182*	3698.	5225.	-387.
JAN 77	361100.	-3300.	1560.	0.15	1679.	3.044*	3716.	5704.	726.
FEB 77	357200.	-3900.	1600.	0.23	1782.	3.954*	4255.	6748.	1066.
MAR 77	349200.	-8000.	220.	0.35	494.	10.120	5063.	10911.	2416.
APR 77	349200.	0.	9180.	1.86	10637.	9.947*	4910.	10663.	26.
MAY 77	353000.	3800.	7790.	5.94	12493.	11.387*	5813.	12425.	3732.
JUN 77	343200.	-9800.	4350.	1.38	5420.	14.731	7161.	15448.	228.
JUL 77	332100.	-11100.	7440.	1.62	8682.	16.890	8391.	17747.	-2035.
AUG 77	365100.	33000.	52670.	6.80	58110.	11.709	6909.	13771.	-11339.
SEP 77	370800.	5700.	28750.	1.12	29655.	10.161	6663.	12720.	-11235.
OCT 77	358800.	-12000.	85.	0.36	370.	7.860	6171.	10828.	-1542.
NOV 77	350100.	-8700.	91.	0.15	209.	5.356	4439.	7674.	-1234.
DEC 77	342200.	-7900.	106.	0.08	168.	4.564	5132.	7903.	-165.
JAN 78	336100.	-6100.	292.	0.28	507.	0.807	4913.	5638.	-969.
FEB 78	334300.	-1800.	357.	0.75	926.	1.901	4046.	5344.	2618.
MAR 78	327800.	-6500.	507.	0.19	650.	7.032	5648.	9626.	2476.
APR 78	317200.	-10600.	90.	0.63	557.	11.990	7077.	13584.	2427.
MAY 78	327500.	10300.	20430.	4.10	23539.	9.827	6232.	11737.	-1502.
JUN 78	357000.	29500.	42370.	2.88	44650.	13.566	6446.	14265.	-885.
JUL 78	342300.	-14700.	1540.	0.92	2253.	17.364	8274.	17989.	1036.
AUG 78	330900.	-11400.	2250.	2.27	3990.	14.298	7010.	14975.	-415.
SEP 78	334900.	4000.	17380.	2.90	19603.	10.329	5579.	11414.	-4189.
OCT 78	331800.	-3100.	7870.	0.32	8113.	7.616	5426.	9758.	-1455.
NOV 78	326700.	-5100.	988.	0.51	1371.	2.690	4365.	6063.	-408.
DEC 78	318900.	-7800.	370.	0.09	437.	1.732	5110.	6292.	-1945.
JAN 79	314400.	-4500.	730.	0.38	1009.	3.044*	5128.	6970.	1461.
FEB 79	309700.	-4700.	579.	0.06	623.	3.954*	4846.	7155.	1832.
MAR 79	304100.	-5600.	473.	0.98	1184.	6.592	5221.	8843.	2059.
APR 79	296500.	-7600.	310.	0.57	719.	8.042	6385.	10692.	2374.

Table C.1: Continued

Date	Lake Meredith Month-end Storage	Change in Storage	Amarillo Flow	Precip (in.)	Inflow	Pan Evap (in.)	Diver-sions	Out-flow	Resi-dual
MAY 79	290700.	-5800.	1680.	4.95	5186.	10.315	6756.	12140.	1154.
JUN 79	296500.	5800.	18960.	3.97	21805.	11.328	6473.	12429.	-3576.
JUL 79	285600.	-10900.	332.	0.93	983.	15.539	8365.	16246.	4363.
AUG 79	294900.	9300.	15370.	3.20	17663.	11.930	7499.	13757.	5394.
SEP 79	290400.	-4500.	1940.	1.50	3003.	9.967	6847.	12059.	4556.
OCT 79	278400.	-12000.	121.	2.43	1802.	10.274	7314.	12552.	-1250.
NOV 79	274800.	-3600.	5080.	0.44	5381.	3.103	5211.	6956.	-2025.
DEC 79	268400.	-6400.	950.	0.14	1045.	4.705	5642.	8122.	678.
JAN 80	266500.	-1900.	5330.	1.12	6086.	2.325	4979.	6335.	-1651.
FEB 80	270800.	4300.	14920.	0.42	15204.	3.323	5059.	6886.	-4017.
MAR 80	269300.	-1500.	2550.	2.67	4352.	7.395	6035.	9786.	3934.
APR 80	260100.	-9200.	1050.	1.04	1743.	9.207	6374.	10925.	-19.
MAY 80	266300.	6200.	16890.	4.31	19799.	9.839	6655.	11561.	-2038.
JUN 80	262200.	-4100.	6870.	3.15	8970.	15.154	8234.	15560.	2490.
JUL 80	244500.	-17700.	80.	0.67	510.	17.926	9804.	18100.	-110.
AUG 80	235800.	-8700.	5940.	1.55	6909.	16.358	9004.	16399.	790.
SEP 80	223700.	-12100.	2520.	0.43	2782.	9.882	7210.	11650.	-3232.
OCT 80	205100.	-18600.	35.	0.26	189.	8.974	6120.	10062.	-8727.
NOV 80	198300.	-6800.	164.	0.41	403.	3.667	5520.	7240.	36.
DEC 80	192900.	-5400.	1080.	0.66	1460.	2.982	5660.	7079.	220.
JAN 81	187700.	-5200.	537.	0.15	622.	2.501	4780.	5988.	166.
FEB 81	182600.	-5100.	247.	0.10	303.	5.448	4480.	6822.	1419.
MAR 81	179200.	-3400.	816.	1.98	1905.	6.822	4980.	7816.	2511.
APR 81	171900.	-7300.	219.	1.10	815.	10.646	5940.	10183.	2068.
MAY 81	166800.	-5100.	2780.	2.88	4316.	10.390	6840.	10922.	1506.
JUN 81	171600.	4800.	18840.	3.12	20530.	14.119	7820.	13380.	-2350.
JUL 81	172200.	600.	14340.	1.41	15104.	13.946	8800.	14294.	-210.
AUG 81	300300.	128100.	184900.	4.25	188052.	10.536	6730.	12482.	-47470.
SEP 81	334400.	34100.	50980.	2.70	53095.	7.696	5940.	10458.	-8537.
OCT 81	333500.	-900.	7740.	2.03	9330.	5.643	5370.	8763.	-1468.
NOV 81	329400.	-4100.	2670.	1.35	3716.	3.586	5220.	7461.	-356.
DEC 81	324100.	-5300.	2070.	0.06	2117.	2.934	5700.	7587.	170.
JAN 82	318100.	-6000.	1710.	0.03	1733.	5.213	5540.	8630.	897.
FEB 82	314500.	-3600.	1330.	0.37	1611.	4.827	4750.	7601.	2391.
MAR 82	309000.	-5500.	1290.	0.58	1725.	8.028	5820.	10320.	3095.
APR 82	300700.	-8300.	1140.	0.38	1422.	10.506	5800.	11537.	1815.
MAY 82	299700.	-1000.	3830.	2.85	5944.	9.022	4330.	9296.	2353.
JUN 82	329400.	29700.	48090.	6.20	52895.	10.614	5230.	11283.	-11912.
JUL 82	390400.	61000.	78670.	7.48	85153.	12.588	7540.	15507.	-8646.
AUG 82	422600.	32200.	38690.	0.57	39208.	11.600	8050.	15772.	8764.
SEP 82	427800.	5200.	23100.	1.51	24484.	9.576	7060.	13554.	-5730.

*: In precipitation column means data taken from Borger; otherwise data is from Sanford Dam.
In pan evaporation column means data for that month is missing and average for month used.