KANSAS GEOLOGICAL SURVEY
OPEN-FILE REPORT 90-56

GEOCHEMICAL IDENTIFICATION OF SALTWATER SOURCES IN THE LOWER ARKANSAS RIVER VALLEY, KANSAS

by

Donald O. Whittemore

Kansas Geological Survey
1930 Constant Avenue
University of Kansas
Lawrence, KS 66047-3726

Project Completion Report

Kansas Water Office Contract No. 90-7

GEOCHEMICAL IDENTIFICATION OF SALTWATER SOURCES IN THE LOWER ARKANSAS RIVER VALLEY, KANSAS

Donald O. Whittemore

Kansas Geological Survey
Lawrence, Kansas

Kansas Geological Survey Open-File Report 90-56

August 3, 1990

INTRODUCTION

Saline water is present in the Arkansas River and in the alluvial aquifer of the river valley between Great Bend and Wichita. The poor quality water affects the amount of usable water available for the urban and agricultural areas within and adjacent to the river valley, primarily Reno, Sedgwick, and Harvey counties. The U.S. Geological Survey (USGS) in conjunction with the U.S. Bureau of Reclamation (USBR), Kansas Water Office (KWO), and Groundwater Management District No. 2 (GMD2) is quantitatively defining the hydrologic and hydrochemical interaction between the Arkansas River and the underlying and adjacent alluvial aquifer system from Hutchinson to Wichita to determine the flow system and water-quality profile between the river and aquifer. The information will be used for proper management and protection of waters in the alluvial aquifer and the Equus Beds.

The studies of the USGS with the USBR, KWO, and GMD2 involve collection of hydrologic, geologic, and water-quality data for the Arkansas River valley and development of a computer model of the stream-aquifer interactions. Initial results showed a plume of saline ground water exists within the alluvial aquifer underlying and adjacent to the Arkansas River based on waters sampled from groups of observation wells installed in the river valley. Anomalous patterns of chloride concentrations within the general plume and the presence of oil fields and salt mining within and adjacent to the study area suggested different sources of saltwater contaminating the ground waters. Both natural salt solution and oil-field brine pollution have been identified in locations adjacent to the study area, including the Equus Beds aquifer in Harvey and Reno counties (Whittemore and Basel, 1982; Burrton Task Force, 1984; Whittemore, 1984; Whittemore et al., 1985; Whittemore et al., 1986), the Great Bend Prairie aquifer in Stafford, Pratt, and Reno counties (Whittemore and Hathaway, 1983; Whittemore et al., 1987), southern Wichita (Whittemore, 1988), and the Arkansas River valley northwest of Hutchinson (Whittemore, 1983). Past contamination of ground waters just to the east-southeast of Hutchinson by brines associated with salt-solution mining is suggested by data in Williams (1946).

Identification and quantification of the sources of saltwater are crucial to management and protection of the ground water and remediation of saline water problems because the various sources behave differently. Natural saltwater from underlying Permian strata is a continuous source, while oil-field brine and salt-mining pollution were greater in the past and now act as slugs of contaminated water moving in the aquifer system. In addition, decreases in river flow and water levels in the alluvial aquifer from consumptive water use could be altering the movement of the saline ground-water plume. Lack of information on source identification and plume dynamics will decrease the value of the solute-transport model of the USGS in simulating the true movement of fresh and saline waters in the stream-aquifer system.

The Kansas Geological Survey (KGS) joined the Lower Arkansas River investigation to provide information on the sources and movement of saline water based on geochemical methods. The results and conclusions of this study are given in this report. The objectives of the KGS work were the following:

1. Determine the different sources of saltwater contaminating ground waters in the alluvial aquifer and river waters of the Arkansas River valley between Hutchinson and Wichita, especially salt dissolution versus oil-field brines.
2. Quantify the different types of saltwater sources currently present in the stream-aquifer system.
3. Determine recent changes in the movement of the different types of saline water in the alluvial aquifer, i.e, relatively static gradients of saline water to freshwater, advancing plume fronts, or plume areas being diluted by fresher water.

DESCRIPTION OF STUDY AREA

The main study area lies along the Arkansas River valley between Hutchinson and Wichita, comprising a rectangular strip approximately 36 miles long by 12 miles wide (Figure 1). Ground waters were also included from 3 observation wells near Salt Creek upstream of its junction with the Arkansas River about 6 to 8 miles west of Hutchinson. The surface geology is Arkansas River alluvium covered in some areas along the northern part of the valley by sand dunes and along the southern edge of the valley by loess. The underlying Permian bedrock is primarily the Ninnescah Shale, although the Wellington Formation probably underlies alluvium in the section of the study area near Wichita.

One large oil and gas field, the Burrton Field, and several small oil and oil and gas fields lie within the study area (Figure 2). Oil production began from a few of these in the early 1930's and has continued to the present. Salt-solution mining of halite has been active in the Hutchinson area since the late 1800's.

The main observation network consists of 143 wells at 49 sites (Figure 2 and Table 1). The first set of 101 wells was drilled to form 5 cross sections across the Arkansas River valley. The second set of 42 wells was drilled to provide points parallel to the river. All of the wells except one are screened in alluvial sediments. Most sites include 3 wells, one drilled to a shallow depth in the alluvium (designated as the A well in the site identification), one to an intermediate depth (B well), and one screened at the base of the alluvium above the Permian bedrock (C well). Several sites where the thickness of the alluvium is relatively small include only the A and C wells, while several sites with a greater thicknesses of alluvium have 4 wells screened from shallow depths to the base of the alluvium. The shallowest wells at the latter sites are designated by AA. One well (EB 237D) is screened in the Permian bedrock just below the alluvium. The well depths range from 19 to 319 ft; the deepest are generally along the center of the river valley.

The cross-section sets of wells are named after nearby towns or a city. The names in order of downstream direction are Hutchinson, Haven, Mount Hope, Bentley, and Maize.

PROCEDURE

Investigation Approach

The different sources of saltwater contributing to saline water in the stream-aquifer system were identified by geochemical methods developed at the Kansas Geological Survey (Whittemore et al., 1981; Whittemore, 1984, 1988). The method involves mixing curves of

Table 1. Location and Screened Interval for Observation Wells Sampled in the KGS Study. The wells are ordered first according to the site identification number and second by ascending well letter which indicates increasing depth. Total well depth is listed for the last 3 wells.

Well ID	T. R. Sec. location	Screened interval, ft below land surface
EB 201A	25S 01W 07CCCC	69 - 79
EB 201B	25S 01W 07CCCC	117 - 127
EB 201C	25S 01W 07CCCC	160 - 170
EB 202A	25S 02W 24BBBB	55 - 65
EB 202B	25S 02W 24BBBB	133 - 143
EB 202C	25S 02W 24BBBB	180 - 190
EB 203A	25S 02W 26BABB	33 - 43
EB 203B	25S 02W 26BABB	102 - 112
EB 203C	25S 02W 26BABB	210 - 220
EB 204A	25S 02W 26CCBD	125 - 135
EB 204B	25S 02W 26CCBD	185 - 195
EB 204C	25S 02W 26CCBD	223 - 233
EB 205A	26S 02W 04AAAA	40 - 50
EB 205B	26S 02W 04AAAA	108 - 118
EB 205C	26S 02W 04AAAA	170 - 180
EB 206A	26S 02W 04CCDC	70 - 80
EB 206B	26S 02W 04CCDC	170 - 180
EB 206C	26S 02W 04CCDC	250 - 260
EB 207A	26S 02W 08DDDC	54 - 64
EB 207B	26S 02W 08DDDC	140 - 150
EB 207C	26S 02W 08DDDC	235 - 245
EB 208A	24S 03W 35DCDD	32 - 37
EB 208B	24S 03W 35DCDD	62 - 67
EB 208C	24S 03W 35DCDD	112 - 117
EB 209AA	25S 03W 10AAAA	25 - 35
EB 209A	25S 03W 10AAAA	67 - 77
EB 209B	25S 03W 10AAAA	100 - 110
EB 209C	25S 03W 10AAAA	166 - 176
EB 210A	25S 03W 15BBCB	80 - 90
EB 210B	25S 03W 15BBCB	155 - 165
EB 210C	25S 03W 15BBCB	228 - 238
EB 211A	25S 03W 16DCBC	40 - 50
EB 211B	25S 03W 16DCBC	90 - 100
EB 211C	25S 03W 16DCBC	144 - 154
EB 212A	25S 03W 20CDDC	38 - 48
EB 212C	25S 03W 20CDDC	92 - 102
EB 213A	24S 04W 05DDDD	67 - 77
EB 213B	24S 04W 05DDDD	180 - 190
EB 213C	24S 04W 05DDDD	277 - 287
EB 214AA	24S 04W 08DDDD	44 - 54
EB 214A	24S 04W 08DDDD	80 - 90
EB 214B	24S 04W 08DDDD	185 - 195
EB 214C	24S 04W 08DDDD	274 - 284
EB 215A	24S 04W 17DDDA	45 - 55
EB 215B	24S 04W 17DDDA	100 - 110
EB 215C	24S 04W 17DDDA	272 - 282

Table 1. (Continued)

Well ID	T. R. Sec. location	Screened interval, ft below land surface
EB 216A	24S 04W 21CBCB	75 - 85
EB 216B	24S 04W 21CBCB	195 - 205
EB 216C	24S 04W 21CBCB	299 - 309
EB 217A	24S 04W 29ADDD	60 - 70
EB 217B	24S 04W 29ADDD	135 - 145
EB 217C	24S 04W 29ADDD	240 - 250
EB 218A	24S 04W 32ADDA	20 - 30
EB 218B	24S 04W 32ADDA	45 - 55
EB 218C	24S 04W 32ADDA	93 - 103
EB 219A	25S 04W 04BCCC	35 - 45
EB 219B	25S 04W 04BCCC	90 - 100
EB 219C	25S 04W 04BCCC	120 - 130
EB 220A	26S 01W 14AAAC	15 - 25
EB 220C	26S 01W 14AAAC	37 - 47
EB 221A	26S 01W 14CBAD	15 - 25
EB 221C	26S 01W 14CBAD	41 - 51
EB 222A	26S 01W 14CCCD	38 - 48
EB 222C	26S 01W 14CCCD	69 - 79
EB 223A	26S 01W 27BAAA	45 - 55
EB 223C	26S 01W 27BAAA	86 - 96
EB 224A	26S 01W 28CCCC	57 - 67
EB 224B	26S 01W 28CCCC	93 - 103
EB 224C	26S 01W 28CCCC	150 - 160
EB 225A	27S 01W 05BBBB	50 - 60
EB 225B	27S 01W 05BBBB	115 - 125
EB 225C	27S 01W 05BBBB	166 - 176
EB 226A	27S 01W 07BBAB	32 - 42
EB 226B	27S 01W 07BBAB	118 - 128
EB 226C	27S 01W 07BBAB	170 - 180
EB 227A	27S 02W 13BBBC	45 - 55
EB 227B	27S 02W 13BBBC	84 - 94
EB 227C	27S 02W 13BBBC	117 - 127
EB 228A	23S 04W 30BBBB	9 - 19
EB 228B	23S 04W 30BBBB	47 - 57
EB 228C	23S 04W 30BBBB	75 - 85
EB 229A	23S 05W 25CCCC	28 - 38
EB 229B	23S 05W 25CCCC	72 - 82
EB 229C	23S 05W 25CCCC	97 - 107
EB 230AA	24S 05W 02BBBB	36 - 46
EB 230A	24S 05W 02BBBB	80 - 90
EB 230B	24S 05W 02BBBB	112 - 122
EB 230C	24S 05W 02BBBB	176 - 186
EB 231A	23S 05W 34CCDA	19 - 29
EB 231B	23S 05W 34CCDA	50 - 60
EB 231C	23S 05W 34CCDA	78 - 88
EB 232A	24S 05W 09AAAD	38 - 48
EB 232B	24S 05W 09AAAD	80 - 90
EB 232C	24S 05W 09AAAD	134 - 144

Table 1. (Continued)

Well ID	T. R. Sec. location	Screened interval, ft below land surface
EB 233A	24S 05W 17AAAA	77 - 87
EB 233B	24S 05W 17AAAA	98 - 108
EB 233C	24S 05W 17AAAA	135 - 145
EB 234A	24S 05W 17CCCC	57 - 67
EB 234C	24S 05W 17CCCC	100 - 110
EB 235A	24S 05W 30BBBB	35 - 45
EB 235C	24S 05W 30BBBB	55 - 65
EB 236A	23S 04W 33CCCC	53 - 63
EB 236B	23S 04W 33CCCC	150 - 160
EB 236C	23S 04W 33CCCC	210 - 220
EB 237C	24S 05W 27DDAA	35 - 45
EB 237D	24S 05W 27DDAA	75 - 85
EB 238A	26S 02W 19AADD	51 - 61
EB 238C	26S 02W 19AADD	79 - 89
EB 239A	23S 05W 28AADA	39 - 49
EB 239C	23S 05W 28AADA	59 - 69
EB 240AA	24S 05W 11AAAA	70 - 80
EB 240A	24S 05W 11AAAA	150 - 160
EB 240B	24S 05W 11AAAA	240 - 250
EB 240C	24S 05W 11AAAA	303 - 313
EB 241AA	24S 04W 36BBBB	30 - 40
EB 241A	24S 04W 36BBBB	105 - 115
EB 241B	24S 04W 36BBBB	220 - 230
EB 241C	24S 04W 36BBBB	309 - 319
EB 242AA	24S 04W 22ABBB	40 - 50
EB 242A	24S 04W 22ABBB	114 - 124
EB 242B	24S 04W 22ABBB	206 - 216
EB 242C	24S 04W 22ABBB	296 - 306
EB 243A	25S 03W 05CBCB	40 - 50
EB 243B	25S 03W 05CBCB	101 - 111
EB 243C	25S 03W 05CBCB	217 - 227
EB 244A	25S 02W 20CCCC	31 - 41
EB 244C	25S 02W 20CCCC	110 - 120
EB 245A	26S 02W 10AAAA	40 - 50
EB 245B	26S 02W 10AAAA	144 - 154
EB 245C	26S 02W 10AAAA	216 - 226
EB 246A	26S 01W 18DADA	35 - 45
EB 246B	26S 01W 18DADA	88 - 98
EB 246C	26S 01W 18DADA	144 - 154
EB 247A	24S 03W 21DDAA	17 - 20
EB 247B	24S 03W 21DDAA	76 - 86
EB 247C	24S 03W 21DDAA	117 - 127
EB 248A	24S 06W 01AAAA	45 - 55
EB 248B	24S 06W 01AAAA	90 - 100
EB 248C	24S 06W 01AAAA	125 - 135
EB 249AA	24S 04W 19BBBB	15 - 25
EB 249A	24S 04W 19BBBB	90 - 100
EB 249B	24S 04W 19BBBB	168 - 178
EB 249C	24S 04W 19BBBB	305 - 315

Table 1. (Continued)

Well ID	T. R. Sec. location	Screened interval, ft below land surface
EB 400A	23S 07W 02CCCC	47 - 50
EB 400C	23S 07W 02CCCC	133 - 136
EB 401C	23S 07W 20AAAA	45 - 65

Table 2. Location of Sampling Sites on the Arkansas River for the KGS Study.

Well cross section	T. R. Sec. location	Descriptive location, relation to well site
Hutchinson	24S 05W 09AAA	S. bank river, W. side bridge, N. of EB232
Haven	24S 04W 21CBC	S. bank river, E. side bridge, W. of EB216
Mt. Hope	25S 03W 15BBC	S. bank river, just N. of EB210
Bentley	25S 02W 26CC	S. bank river, E. side bridge, W. of EB204
Malze	26S 01W 14CBA	S. bank river, just N. of EB221

ratios of chemical constituents, primarily anions of halides (chloride, bromide, and iodide) and sulfate, versus chloride concentration (a measure of salinity). Mixtures of different saltwater sources were estimated based on the chemistry of freshwater and saltwater end members. Recent changes in the movement of different types of saline water in the alluvial aquifer plume were determined based on chemical deviations of adsorbed constituents from conservative mixing of fresh and saline waters. The methods require high-quality analyses of a variety of different waters within the study area and were supplemented by existing data from within and surrounding the area.

Method of Data Acquisition

The GMD2 collected ground-water samples from the 143 observation wells in the network installed in the Arkansas River valley between Hutchinson and Wichita by the USGS, USBR, and the GMD2. The cross-section series of samples were obtained during October and November, 1989, while the parallel series were collected in April, 1990. The GMD2 also obtained ground water from 3 observation wells in alluvial deposits near Salt Creek west of Hutchinson. The GMD2 pumped the wells sufficiently to obtain a representative sample and preserved and shipped the samples in ice chests that were sent to the KGS.

Arkansas River water was collected from each of the 5 cross-section locations near the well site closest to the river. The sample was from the south side of the river in each case; locations are listed in Table 2.

The samples were filtered through 0.45 um membrane filters before analysis in the KGS laboratories. Specific conductance was measured with a Labline conductivity meter. Bicarbonate was determined using an automated titrimeter. The laboratory pH of the sample was recorded before the titration began. Calcium, magnesium, sodium, potassium, and strontium concentrations were measured on a inductively-coupled argon plasma spectrophotometer. Determinations of chloride, sulfate, bromide, and inorganic iodine contents were made using colorimetric methods on a Technicon AutoAnalyzer. Nitrate concentration was quantified based on a UV absorption method on the AutoAnalyzer. Measurement of fluoride was by a specific ion electrode and pH/mV meter. The accuracy of the major constituent concentrations was checked by computing the charge-balance error.

RESULTS

Chemical properties and dissolved cation concentrations for the ground-water and river water samples sampled for this project and analyzed at the KGS are listed in Table 3; dissolved anion contents are given in Table 4. The analyses are grouped first by the 3 observation wells near the junction of Salt Creek with the Arkansas River west of Hutchinson, second according to the 5 cross-section sets of wells from upstream to downstream in the Arkansas River valley, third by the parallel series of wells in a downstream direction, and finally by downstream stations of the Arkansas River. Wells within each cross-section group are ordered from the south or southeast to the north or northeast end of the transect. See Table 1 for the location and depth information for the sample sites.

Chloride concentrations in the ground waters range from 10.4 to 4,090 mg/L, while sulfate contents range from 4 to 1,120 mg/L. Specific conductance ranges from 439-13,000 umho/cm (or uS) at 25 ^{o}C. Values for both constituents and conductance increase with depth at most well sites. The most saline waters are primarily located at the base of the deepest alluvium in the western half of the main study area and in the deep wells near Salt Creek. Chloride concentrations generally decrease away from the river and in a downstream direction. Two areas of anomalous salinity are east-southeast of Hutchinson north of the Arkansas River valley and the central section of the Haven cross section. The salinities are anomalous because the shallow and intermediate intervals of the aquifer in the two areas contain waters with higher chloride contents than expected for the general pattern in the study region.

Calcium, magnesium, and strontium concentration ranges for the ground waters are 31-624 mg/L, 5.7-127 mg/L, and 0.24-6.5 mg/L, respectively, and are relatively well correlated. Ranges for sodium and potassium contents are 27-2,410 mg/L and 1.4-12.0 mg/L, respectively, and are not as well correlated as the alkaline earth cations. Bicarbonate (175-517 mg/L or 144-424 mg/L as $CaCO_3$ alkalinity) ranges over a smaller percentage interval than any of the other

Table 3. Chemical Properties and Cation Concentrations for Waters from Wells in the Arkansas River Valley and from the Arkansas River. Analyses were by the KGS. Wells are grouped starting with the most upstream locations in the Arkansas River valley. Well sites EB236 and EB238 have been included with the Haven and Mount Hope cross sections, respectively.

Site ID	Date sampled	Sp.C., umho/cm	pH, lab	Ca, mg/L	Mg, mg/L	Na, mg/L	K, mg/L	Sr, mg/L
Wells near junction of Salt Creek with the Arkansas River								
EB 400A	89-12-04	2330	8.40	97	10.0	370	4.7	0.54
EB 400C	89-12-04	10840	8.40	188	51.8	2125	6.3	2.22
EB 401C	89-12-04	5500	8.10	154	37.0	954	5.2	1.63
Parallel wells upstream of Hutchinson cross section								
EB 239A	90-04-17	3220	8.05	157	30.4	491	3.5	1.35
EB 239C	90-04-17	4080	8.00	236	52.5	561	5.0	2.42
EB 248A	90-04-18	700	8.20	68	11.0	71	2.5	0.48
EB 248B	90-04-18	1520	8.10	45	10.5	274	1.8	0.47
EB 248C	90-04-18	11100	8.00	191	56.3	2243	1.5	2.44
Hutchinson cross-section wells								
EB 228A	89-10-23	672	8.25	81	12.0	51	2.6	0.46
EB 228B	89-10-23	466	7.80	53	9.7	32	2.2	0.40
EB 228C	89-10-23	439	7.80	49	10.0	28	2.4	0.41
EB 229A	89-10-23	2100	8.10	115	20.0	301	4.0	0.89
EB 229B	89-10-23	4360	7.90	286	52.0	569	6.1	2.34
EB 229C	89-10-23	6350	7.80	521	101	666	7.6	4.32
EB 230AA	89-10-23	3100	8.10	117	19.0	522	4.8	0.87
EB 230A	89-10-23	3650	8.00	142	24.0	618	5.2	1.08
EB 230B	89-10-23	3940	7.90	203	36.0	591	6.3	1.58
EB 230C	89-10-23	2060	8.20	46	13.0	381	2.7	0.46
EB 231A	89-10-23	1420	8.20	68	11.0	223	3.4	0.51
EB 231B	89-10-23	3210	8.00	140	27.0	517	5.1	1.15
EB 231C	89-10-23	4030	8.00	236	48.0	573	6.0	1.97
EB 232A	89-10-24	510	8.20	52	7.1	48	2.1	0.25
EB 232B	89-10-24	2400	8.20	42	10.0	464	2.4	0.43
EB 232C	89-10-24	3720	8.10	60	16.0	740	3.0	0.69
EB 233A	89-11-07	555	8.30	77	6.6	36	2.7	0.23
EB 233B	89-11-07	568	8.20	80	6.7	37	2.6	0.24
EB 233C	89-11-07	458	8.20	62	10.0	27	1.9	0.35
EB 234A	89-11-07	675	8.30	61	13.2	49	1.5	0.35
EB 234C	89-11-07	578	8.30	50	21.7	37	2.2	0.64
EB 235A	89-11-07	890	8.00	77	12.3	73	1.6	0.38
EB 235C	89-11-07	620	8.20	46	25.0	42	2.0	0.59
Parallel wells between Hutchinson and Haven cross sections								
EB 240AA	90-04-18	1420	8.20	52	9.3	238	2.5	0.41
EB 240A	90-04-18	3080	8.00	100	22.9	525	3.1	0.98
EB 240B	90-04-18	4360	8.00	122	31.4	773	2.6	1.27
EB 240C	90-04-18	8330	7.95	202	58.4	1530	2.6	2.37
EB 237C	90-04-18	1070	7.70	97	18.1	87	2.0	0.56
EB 237D	90-04-18	960	8.30	83	30.0	81	1.9	1.01

Table 3. (continued)

Site ID	Date sampled	Sp.C., umho/cm	pH, lab	Ca, mg/L	Mg, mg/L	Na, mg/L	K, mg/L	Sr, mg/L
		Parallel wells between Hutchinson and Haven cross sections (continued)						
EB 249AA	90-04-17	850	8.15	98	14.1	75	3.7	0.62
EB 249A	90-04-17	780	8.00	58	9.3	105	1.8	0.41
EB 249B	90-04-17	1260	7.80	88	17.1	148	2.3	0.68
EB 249C	90-04-17	632	8.10	49	12.2	75	1.8	0.45
			Haven cross-section wells					
EB 236A	90-04-17	1060	7.90	67	15.6	136	3.0	0.69
EB 236B	90-04-17	1120	8.00	83	21.1	135	2.9	0.89
EB 236C	90-04-17	1360	7.90	129	29.1	101	3.1	1.25
EB 213A	89-11-07	1420	8.00	121	25.0	126	3.3	1.02
EB 213B	89-11-07	1100	8.30	89	20.0	109	2.8	0.82
EB 213C	89-11-08	3100	8.00	116	42.0	487	3.9	2.05
EB 214AA	89-11-07	1480	8.10	111	20.0	153	3.7	1.18
EB 214A	89-11-07	1520	8.30	106	18.0	172	3.6	0.83
EB 214B	89-11-07	905	8.20	55	11.0	118	2.5	0.46
EB 214C	89-11-07	6445	8.20	143	47.0	1195	5.5	2.36
EB 215A	89-11-07	1940	8.10	110	21.0	246	4.1	2.25
EB 215B	89-11-07	10930	8.10	553	109	1623	11.0	6.49
EB 215C	89-11-07	13010	8.00	321	88.0	2410	7.6	3.84
EB 216A	89-11-08	7010	8.00	624	127	610	12.0	5.29
EB 216B	89-11-08	1850	8.20	126	25.0	201	3.3	1.00
EB 216C	89-11-08	6374	8.20	258	66.0	999	5.9	2.60
EB 217A	89-11-08	1260	8.20	94	15.0	148	2.7	0.69
EB 217B	89-11-08	865	8.20	47	8.6	121	2.5	0.35
EB 217C	89-11-08	1040	8.10	61	15.0	132	2.5	0.57
EB 218A	89-11-08	1320	8.30	137	19.0	94	2.5	0.62
EB 218B	89-11-08	1140	8.20	94	11.0	129	2.3	0.40
EB 218C	89-11-08	770	8.20	89	14.0	62	2.3	0.51
EB 219A	89-11-08	750	8.20	91	13.1	53	1.8	0.40
EB 219B	89-11-08	950	8.40	97	28.0	64	3.3	1.11
EB 219C	89-11-08	1370	8.30	136	52.0	100	3.8	2.35
	Parallel wells between Haven and Mount Hope cross sections							
EB 242AA	90-04-17	1480	7.95	113	18.7	167	3.3	0.94
EB 242A	90-04-17	3790	7.80	251	45.5	447	5.0	2.20
EB 242B	90-04-17	970	8.05	61	13.2	132	2.5	0.61
EB 242C	90-04-17	2180	8.10	55	13.8	399	1.4	0.57
EB 241AA	90-04-10	1050	8.10	81	14.8	110	3.6	0.69
EB 241A	90-04-10	1500	8.10	86	16.2	199	3.6	0.72
EB 241B	90-04-10	2470	8.00	143	27.6	318	4.4	1.18
EB 241C	90-04-10	10480	8.00	295	84.6	1887	5.5	3.49
EB 247A	90-04-10	970	8.00	114	17.7	68	3.6	0.89
EB 247B	90-04-10	930	8.20	77	16.3	94	3.0	0.75
EB 247C	90-04-10	958	8.30	57	19.0	114	2.8	0.98
EB 243A	90-04-10	1240	8.20	80	16.7	152	3.9	0.71
EB 243B	90-04-10	1510	8.10	99	20.0	184	4.1	0.94
EB 243C	90-04-10	8800	8.00	223	64.9	1596	5.5	2.77

Table 3. (continued)

Site ID	Date sampled	Sp.C., umho/cm	pH, lab	Ca, mg/L	Mg, mg/L	Na, mg/L	K, mg/L	Sr, mg/L
			Mount Hope cross-section wells					
EB 208A	89-11-30	1035	8.25	101	14.4	102	3.4	0.67
EB 208B	89-11-30	1065	8.20	95	16.4	112	3.1	0.72
EB 208C	89-11-30	913	8.20	59	15.2	109	3.1	0.73
EB 209AA	89-11-30	1020	8.20	86	16.2	103	3.6	0.69
EB 209A	89-11-30	970	8.20	76	14.3	110	2.9	0.65
EB 209B	89-12-05	1035	8.15	58	11.1	143	4.2	0.53
EB 209C	89-11-30	2050	8.15	86	22.7	301	3.2	1.00
EB 210A	89-11-30	2550	8.15	94	19.9	403	4.9	0.78
EB 210B	89-11-30	2790	8.10	124	23.9	415	4.3	1.03
EB 210C	89-11-30	7050	8.20	170	46.7	1251	2.8	1.93
EB 211A	89-11-08	860	8.10	63	11.0	93	2.4	0.44
EB 211B	89-11-08	1510	8.10	88	16.0	192	3.3	0.68
EB 211C	89-11-08	1310	8.20	78	15.0	163	3.1	0.62
EB 212A	89-11-08	435	8.20	52	10.4	21	2.3	0.25
EB 212C	89-11-08	685	8.10	84	16.9	40	2.1	0.42
			Parallel well between Mount Hope and Bentley cross sections					
EB 244A	90-04-09	2790	8.10	120	26.6	419	5.5	1.05
EB 244C	90-04-09	3100	8.10	127	28.9	483	4.3	1.26
			Bentley cross-section wells					
EB 201A	89-11-30	715	8.20	77	11.7	65	3.0	0.57
EB 201B	89-11-29	718	8.20	76	12.7	65	3.3	0.60
EB 201C	89-11-29	818	8.25	72	14.0	83	3.3	0.80
EB 202A	89-11-29	723	7.80	78	13.2	57	2.9	0.63
EB 202B	89-11-29	715	8.25	63	12.5	78	2.9	0.63
EB 202C	89-11-29	920	8.20	78	16.4	94	3.1	1.07
EB 203A	89-11-29	2700	8.10	119	27.5	409	4.3	1.11
EB 203B	89-11-29	1555	8.15	80	18.4	219	3.3	0.76
EB 203C	89-11-29	993	8.15	81	17.9	104	3.4	1.05
EB 204A	89-11-29	2800	8.05	114	25.1	426	4.8	1.13
EB 204B	89-11-29	1090	8.15	91	21.7	108	3.4	1.26
EB 204C	89-11-29	1100	8.20	89	22.0	112	3.2	1.33
EB 205A	89-11-29	1740	8.05	152	27.9	161	4.0	1.17
EB 205B	89-11-29	1800	8.10	112	22.5	213	4.1	1.00
EB 205C	89-11-29	4480	8.10	280	109	584	3.7	5.39
EB 206A	89-11-30	895	8.30	44	7.5	135	2.2	0.30
EB 206B	89-11-30	975	8.25	33	5.7	165	1.7	0.27
EB 206C	89-11-30	1910	8.25	35	8.5	358	1.9	0.38
EB 207A	89-11-29	848	8.15	98	17.5	64	2.4	0.57
EB 207B	89-11-29	632	8.10	79	13.6	46	2.2	0.45
EB 207C	89-11-29	740	8.15	79	18.0	54	2.6	0.68
EB 238A	90-04-09	785	8.20	81	18.4	63	1.9	0.53
EB 238C	90-04-09	765	8.20	76	16.8	68	2.0	0.59

Table 3. (continued)

Site ID	Date sampled	Sp.C., umho/cm	pH, lab	Ca, mg/L	Mg, mg/L	Na, mg/L	K, mg/L	Sr, mg/L
Parallel wells between Bentley and Maize cross sections								
EB 245A	90-04-09	1880	8.20	137	28.7	212	3.6	1.15
EB 245B	90-04-09	3490	8.10	88	22.8	602	4.0	0.96
EB 245C	90-04-09	4580	8.10	126	35.5	808	4.1	1.63
EB 246A	90-04-09	2700	8.10	86	18.9	458	3.6	0.81
EB 246B	90-04-09	2040	8.10	103	25.8	281	3.7	1.12
EB 246C	90-04-09	1760	8.10	103	27.9	223	3.2	1.24
Maize cross-section wells								
EB 220A	89-12-05	900	8.10	83	16.8	81	5.1	0.71
EB 220C	89-12-05	830	7.95	74	13.9	76	2.9	0.62
EB 221A	89-12-05	1920	8.40	73	18.5	296	7.0	1.00
EB 221C	89-12-05	2280	8.20	112	26.6	314	4.8	1.17
EB 222A	89-12-05	2150	8.40	146	28.5	254	5.3	1.22
EB 222C	89-12-05	1960	8.05	161	32.7	183	4.5	1.58
EB 223A	89-12-05	1260	8.40	106	19.7	123	3.8	0.93
EB 223C	89-12-05	1265	8.15	91	21.2	131	3.9	1.00
EB 224A	89-12-05	1055	8.15	31	5.8	178	2.1	0.24
EB 224B	89-12-05	2850	8.20	67	13.6	508	3.1	0.55
EB 224C	89-12-05	3970	8.10	104	23.0	704	3.4	0.97
EB 225A	89-12-05	563	8.40	36	6.8	82	1.8	0.25
EB 225B	89-12-05	1245	8.40	40	7.1	217	2.6	0.29
EB 225C	89-12-05	1290	8.40	44	8.5	219	2.7	0.37
EB 226A	89-12-05	620	8.40	66	11.7	57	2.3	0.44
EB 226B	89-12-05	638	8.20	77	12.5	51	2.4	0.46
EB 226C	89-12-05	669	8.10	77	15.1	52	2.5	0.60
EB 227A	89-12-05	680	8.30	66	14.3	69	1.8	0.45
EB 227B	89-12-05	753	8.40	77	18.6	66	1.8	0.64
EB 227C	89-12-05	780	8.05	83	19.8	64	1.9	0.71
Arkansas River waters								
Hutchinson	89-12-04	2700	8.30	104	23.1	429	5.0	0.91
Haven	89-12-04	2650	8.30	108	24.0	417	5.1	0.95
Mount Hope	89-12-04	2610	8.40	107	24.1	402	5.4	0.96
Bentley	89-12-05	2610	8.40	106	24.0	404	4.9	0.96
Maize	89-12-05	2600	8.40	104	24.0	393	5.5	0.95

Table 4. Chemical Properties and Anion Concentrations for Waters from Wells in the Arkansas River Valley and from the Arkansas River. Analyses were by the KGS. Wells are grouped starting with the most upstream locations in the Arkansas River valley. Well sites EB236 and EB238 have been included with the Haven and Mount Hope cross sections, respectively.

Site ID	Date sampled	HCO_3, mg/L	SO_4, mg/L	Cl, mg/L	F, mg/L	NO_3, mg/L	Br, mg/L	I, ug/L
Wells near junction of Salt Creek with the Arkansas River								
EB 400A	89-12-04	319	65	539	0.30	0.7	0.11	3.4
EB 400C	89-12-04	268	359	3283	0.32	2.3	0.55	14.5
EB 401C	89-12-04	286	196	1528	0.35	4.0	0.28	5.6
Parallel wells upstream of Hutchinson cross section								
EB 239A	90-04-17	284	189	803.0	0.61	1.6	0.64	19.8
EB 239C	90-04-17	269	250	1077.0	0.48	1.6	0.77	18.9
EB 248A	90-04-18	315	32	33.9	0.25	38.0	0.11	3.4
EB 248B	90-04-18	338	55	274.0	0.30	23.0	0.13	5.7
EB 248C	90-04-18	287	439	3330.0	0.36	1.2	0.59	10.5
Hutchinson cross-section wells								
EB 228A	89-10-23	329	56	10.8	0.40	31.0	0.08	4.0
EB 228B	89-10-23	189	67	13.5	0.30	0.0	0.08	13.9
EB 228C	89-10-23	191	55	12.5	0.30	0.0	0.07	16.3
EB 229A	89-10-23	258	97	477	0.59	21.0	0.40	6.0
EB 229B	89-10-23	259	143	1226	0.41	4.3	0.95	10.0
EB 229C	89-10-23	251	142	1932	0.31	2.9	1.58	12.6
EB 230AA	89-10-23	280	136	786	0.52	0.4	0.66	26.1
EB 230A	89-10-23	269	169	962	0.53	0.3	0.76	24.6
EB 230B	89-10-23	241	176	1072	0.42	0.4	0.78	24.0
EB 230C	89-10-23	202	132	468	0.43	0.2	0.19	8.7
EB 231A	89-10-23	243	91	273	1.12	0.2	0.25	6.6
EB 231B	89-10-23	285	184	807	0.57	0.4	0.61	18.9
EB 231C	89-10-23	235	225	1093	0.38	1.5	0.70	16.8
EB 232A	89-10-24	256	16	25.5	0.25	13.0	0.03	2.3
EB 232B	89-10-24	361	103	532	0.40	3.1	0.11	8.7
EB 232C	89-10-24	379	172	927	0.39	2.4	0.19	11.4
EB 233A	89-11-07	263	25	17.0	0.24	37.0	0.07	2.2
EB 233B	89-11-07	272	25	16.5	0.24	36.0	0.07	2.2
EB 233C	89-11-07	266	13	10.4	0.37	5.6	0.02	1.9
EB 234A	89-11-07	416	4	21.9	0.38	0.5	0.10	7.2
EB 234C	89-11-07	330	23	18.4	0.69	0.4	0.05	23.2
EB 235A	89-11-07	366	23	63.7	0.29	56.0	0.11	3.3
EB 235C	89-11-07	347	17	17.0	0.60	18.0	0.06	2.4
Parallel wells between Hutchinson and Haven cross sections								
EB 240AA	90-04-18	236	79	283.0	0.60	0.3	0.11	19.4
EB 240A	90-04-18	188	226	760.0	0.49	1.3	0.30	6.6
EB 240B	90-04-18	215	255	1160.0	0.42	1.1	0.40	10.3
EB 240C	90-04-18	224	324	2425.0	0.36	0.7	0.45	15.0
EB 237C	90-04-18	517	16	77.8	0.23	25.0	0.13	238.0
EB 237D	90-04-18	489	10	83.4	0.47	0.4	0.12	93.0

Table 4. (continued)

Site ID	Date sampled	HCO3, mg/L	SO4, mg/L	Cl, mg/L	F, mg/L	NO3, mg/L	Br, mg/L	I, ug/L
Parallel wells between Hutchinson and Haven cross sections (continued)								
EB 249AA	90-04-17	400	42	58.4	0.48	5.8	0.20	7.8
EB 249A	90-04-17	367	29	58.7	0.45	1.5	0.05	11.5
EB 249B	90-04-17	308	35	226.0	0.39	2.1	0.08	19.3
EB 249C	90-04-17	297	35	38.5	0.44	2.2	0.04	9.3
Haven cross-section wells								
EB 236A	90-04-17	316	44	154.0	0.78	0.0	0.10	7.4
EB 236B	90-04-17	366	115	114.0	0.62	0.2	0.10	10.6
EB 236C	90-04-17	321	72	239.0	0.64	0.0	0.13	5.3
EB 213A	89-11-07	293	79	258	0.49	9.8	0.24	3.7
EB 213B	89-11-07	319	84	148	0.56	0.6	0.09	5.2
EB 213C	89-11-08	195	429	652	0.88	0.0	0.20	47.1
EB 214AA	89-11-07	249	88	275	0.43	35.0	0.20	5.4
EB 214A	89-11-07	246	83	290	0.43	34.0	0.27	6.4
EB 214B	89-11-07	301	59	105	0.56	0.1	0.06	6.5
EB 214C	89-11-07	272	409	1770	0.40	0.2	0.32	13.2
EB 215A	89-11-07	214	62	445	0.53	51.0	1.15	24.0
EB 215B	89-11-07	207	113	3610	0.26	2.9	14.60	290.0
EB 215C	89-11-07	258	535	4090	0.20	1.2	0.68	14.0
EB 216A	89-11-08	188	209	2226	0.23	1.2	6.10	71.0
EB 216B	89-11-08	256	50	437	0.26	3.1	0.93	5.7
EB 216C	89-11-08	250	226	1873	0.13	2.0	0.61	7.8
EB 217A	89-11-08	339	88	192	0.43	0.4	0.52	14.4
EB 217B	89-11-08	262	44	119	0.41	1.6	0.07	3.8
EB 217C	89-11-08	323	38	151	0.28	2.4	0.06	3.5
EB 218A	89-11-08	355	19	235	0.22	14.0	0.94	6.8
EB 218B	89-11-08	385	18	164	0.22	18.0	0.61	15.5
EB 218C	89-11-08	366	23	59.1	0.29	5.2	0.15	6.9
EB 219A	89-11-08	330	28	51.7	0.23	25.0	0.09	4.1
EB 219B	89-11-08	271	254	20.8	0.64	1.4	0.02	29.1
EB 219C	89-11-08	175	590	13.2	0.90	0.9	0.07	50.0
Parallel wells between Haven and Mount Hope cross sections								
EB 242AA	90-04-17	374	50	249.0	0.53	23.0	0.62	22.8
EB 242A	90-04-17	262	47	1077.0	0.38	15.0	4.40	38.0
EB 242B	90-04-17	347	62	107.0	0.57	0.1	0.08	22.9
EB 242C	90-04-17	326	108	469.0	0.65	0.3	1.04	11.0
EB 241AA	90-04-10	232	66	149.0	0.59	39.0	0.24	4.4
EB 241A	90-04-10	264	120	258.0	0.57	2.2	0.12	9.6
EB 241B	90-04-10	182	134	605.0	0.44	1.0	0.23	6.1
EB 241C	90-04-10	255	404	3175.0	0.51	1.2	0.57	21.7
EB 247A	90-04-10	330	101	81.7	0.61	0.7	0.12	2.5
EB 247B	90-04-10	311	75	98.7	0.56	0.1	0.09	6.3
EB 247C	90-04-10	304	81	104.0	0.50	0.1	0.09	8.7
EB 243A	90-04-10	342	138	136.0	0.71	12.0	0.17	7.3
EB 243B	90-04-10	259	153	249.0	0.51	4.0	0.16	9.4
EB 243C	90-04-10	260	351	2569.0	0.28	1.8	0.46	15.6

Table 4. (continued)

Site ID	Date sampled	HCO3, mg/L	SO4, mg/L	Cl, mg/L	F, mg/L	NO3, mg/L	Br, mg/L	I, ug/L
				Mount Hope cross-section wells				
EB 208A	89-11-30	354	132	82.2	0.90	0.4	0.12	3.1
EB 208B	89-11-30	343	120	104	0.55	0.2	0.13	5.4
EB 208C	89-11-30	306	75	97.2	0.50	0.0	0.07	7.9
EB 209AA	89-11-30	282	95	117	0.45	20.0	0.09	4.4
EB 209A	89-11-30	298	85	103	0.48	19.0	0.09	4.4
EB 209B	89-12-05	302	71	135	0.54	0.5	0.05	15.6
EB 209C	89-11-30	266	128	445	0.47	0.2	0.12	10.8
EB 210A	89-11-30	227	166	605	0.62	0.4	0.40	15.0
EB 210B	89-11-30	219	218	659	0.50	0.3	0.40	16.8
EB 210C	89-11-30	272	303	2022	0.31	1.9	0.34	10.2
EB 211A	89-11-08	237	66	105	0.54	13.0	0.11	3.0
EB 211B	89-11-08	207	115	299	0.51	0.9	0.13	5.3
EB 211C	89-11-08	210	97	246	0.52	1.1	0.10	3.6
EB 212A	89-11-08	195	17	22.9	0.14	21.0	0.05	2.7
EB 212C	89-11-08	339	36	20.0	0.19	32.0	0.05	3.5
				Parallel well between Mount Hope and Bentley cross sections				
EB 244A	90-04-09	255	191	639.0	0.49	0.5	0.43	18.9
EB 244C	90-04-09	234	271	702.0	0.51	0.0	0.40	19.2
				Bentley cross-section wells				
EB 201A	89-11-30	298	57	50.8	0.50	0.1	0.07	15.4
EB 201B	89-11-29	303	51	50.9	0.49	0.8	0.06	6.7
EB 201C	89-11-29	340	53	66.3	0.41	1.6	0.06	6.1
EB 202A	89-11-29	247	45	42.6	0.38	69.0	0.07	3.8
EB 202B	89-11-29	281	49	50.2	0.41	22.0	0.07	5.5
EB 202C	89-11-29	331	81	86.1	0.39	0.3	0.07	8.4
EB 203A	89-11-29	299	304	536	0.57	18.0	0.37	18.6
EB 203B	89-11-29	293	135	268	0.43	1.8	0.16	16.6
EB 203C	89-11-29	335	84	106	0.27	0.2	0.07	9.0
EB 204A	89-11-29	238	146	697	0.56	0.7	0.16	9.9
EB 204B	89-11-29	313	108	132	0.26	0.5	0.09	14.8
EB 204C	89-11-29	317	108	132	0.28	1.1	0.08	13.3
EB 205A	89-11-29	275	176	319	0.68	0.6	0.17	11.7
EB 205B	89-11-29	215	118	392	0.47	0.3	0.15	9.8
EB 205C	89-11-29	161	1120	803	0.55	0.8	0.18	8.7
EB 206A	89-11-30	282	41	121	0.56	0.2	0.07	8.3
EB 206B	89-11-30	256	58	144	0.60	0.7	0.07	8.8
EB 206C	89-11-30	308	115	379	0.59	2.0	0.09	12.4
EB 207A	89-11-29	373	37	54.2	0.23	33.0	0.17	9.2
EB 207B	89-11-29	364	18	18.0	0.27	5.6	0.03	5.0
EB 207C	89-11-29	395	29	31.8	0.19	3.3	0.04	4.0
EB 238A	90-04-09	325	67	29.7	0.25	37.0	0.10	6.1
EB 238C	90-04-09	334	45	43.8	0.22	20.0	0.18	8.4

Table 4. (continued)

Site ID	Date sampled	HCO3, mg/L	SO4, mg/L	Cl, mg/L	F, mg/L	NO3, mg/L	Br, mg/L	I, ug/L
			Parallel wells between Bentley and Maize cross sections					
EB 245A	90-04-09	324	175	332.0	0.47	0.2	0.21	8.3
EB 245B	90-04-09	248	185	860.0	0.50	0.6	0.19	6.6
EB 245C	90-04-09	264	396	1097.0	0.31	0.0	0.25	22.2
EB 246A	90-04-09	258	155	632.0	0.52	0.0	0.16	10.2
EB 246B	90-04-09	283	147	417.0	0.28	0.0	0.13	17.2
EB 246C	90-04-09	287	142	335.0	0.29	0.0	0.12	17.2
			Maize cross-section wells					
EB 220A	89-12-05	226	84	101	0.51	37.0	0.14	4.0
EB 220C	89-12-05	213	64	99.2	0.40	24.0	0.11	4.0
EB 221A	89-12-05	259	201	355	0.54	0.9	0.19	11.1
EB 221C	89-12-05	236	213	477	0.46	1.7	0.27	11.8
EB 222A	89-12-05	267	256	403	0.49	6.9	0.24	13.4
EB 222C	89-12-05	226	189	401	0.38	1.0	0.22	5.6
EB 223A	89-12-05	264	148	178	0.51	0.5	0.09	5.5
EB 223C	89-12-05	263	91	211	0.38	0.5	0.08	5.3
EB 224A	89-12-05	209	58	174	0.35	20.0	0.09	3.3
EB 224B	89-12-05	249	143	696	0.40	0.7	0.17	9.3
EB 224C	89-12-05	231	180	1059	0.27	1.6	0.22	8.4
EB 225A	89-12-05	233	27	35.2	0.46	22.0	0.10	3.0
EB 225B	89-12-05	319	66	191	0.54	3.3	0.08	5.3
EB 225C	89-12-05	312	74	204	0.47	6.2	0.09	3.9
EB 226A	89-12-05	293	39	22.2	0.34	22.0	0.11	5.9
EB 226B	89-12-05	368	19	19.6	0.23	3.2	0.04	4.0
EB 226C	89-12-05	371	24	23.4	0.20	3.0	0.04	3.1
EB 227A	89-12-05	335	31	30.9	0.19	15.0	0.08	4.2
EB 227B	89-12-05	360	41	37.7	0.17	11.0	0.06	4.8
EB 227C	89-12-05	362	58	37.5	0.19	11.0	0.07	4.6
			Arkansas River waters					
Hutchinson	89-12-04	287	157	629	0.49	17.0	0.21	7.1
Haven	89-12-04	283	159	602	0.51	16.0	0.26	7.5
Mount Hope	89-12-04	278	161	595	0.52	16.0	0.28	8.1
Bentley	89-12-05	274	160	598	0.53	14.0	0.28	7.7
Maize	89-12-05	270	161	582	0.53	13.0	0.27	8.1

major and minor constituents. Saturation of the waters with respect to calcite probably limits both calcium and bicarbonate levels.

Fluoride concentrations in the ground waters range from 0.13 to 1.12 and are all lower than the upper limit allowed for the public drinking-water supplies at the temperature of the waters. However, nitrate contents exceed the drinking-water standard of 45 mg/L in 3 of the shallow observation well waters. Nitrate values range from <0.1 to 69 mg/L and generally decrease with depth in the alluvial aquifer indicating a surface source of contamination. Bromide and iodide concentrations both range widely, 0.02-14.6 mg/L and 1.9-290 ug/L, respectively. Values of pH measured in the laboratory (7.7-8.4) for both the ground and river waters are within the expected range for natural waters not significantly unaffected by factors related to well construction.

The 5 samples of Arkansas River water have a relatively narrow range in all dissolved inorganic constituents determined. The values are approximately in the middle of all the concentration ranges of the constituents. The specific conductance, chloride, sodium, bicarbonate, and nitrate contents decreased slightly in the downstream direction of the river, while sulfate, fluoride, bromide, and iodide values generally increased slightly. The other dissolved inorganics showed no clear trend.

DISCUSSION

Determination of the chemical characteristics and salinity sources of the ground and river waters was based on graphs of dissolved constituent ratios versus chloride concentration. The x-axis in the plots displays the chloride content and represents the salinity of the water. The y-axis displays the ratio or chemical characteristic as a function of the salinity. All of the ratios except one are weight ratios of either sodium, sulfate, bromide, or inorganic iodine over chloride concentration. Equivalent concentrations are used to calculate the (Ca+Mg)/(Na+K) ratio.

Mixing lines are shown on the ratio versus chloride graphs. The lines represent the conservative mixing between two end-member waters with different ratios and/or chloride values. The mixing lines involve calculations of the volumes of the different end-member waters. The end-member waters are selected on the basis of both the distribution of the data and the geochemical characteristics of the natural ground waters and the different saltwater sources.

The best ratio for the geochemical identification of salinity sources for the study area is Br/Cl because both constituents are conservative and there are substantial differences in the ratio for evaporite-solution and oil-field brines. In the course of the investigation, the chemical signature of waste brine from the evaporative precipitation of halite from waters obtained from salt-solution mining was found to be distinctive enough to also be used in identifying saltwater sources. Although chloride is often associated with nitrate, the highest nitrate concentrations in the study area are generally at shallow depths of the aquifer where chloride values are less than 100 mg/L. Probably less than a few tens of mg/L chloride is derived from a source related to the highest nitrate contents. Furthermore, the waters with the highest nitrate levels do not shift points on the various mixing graphs in an obvious manner.

Quantification of different types of salinity at a site was estimated based on calculation of a Br/Cl versus chloride mixing curve that fits the probable saltwater source, the contaminated water in question, and the probable original water in the aquifer at that location. The other ratio versus chloride graphs either help to confirm the salinity source identification, provide additional insight into factors affecting the water chemistry, or allow a determination of possible recent changes in the movement of saline waters in the aquifer.

The different ratios used for the graphs are listed along with chloride and sulfate concentrations in Table 5. The factors of 10^4 and 10^6 used as multipliers for the Br/Cl and I/Cl ratios, respectively, are for convenient representation of the values referenced to the order of magnitude ratio for most halite-solution brines. The ground and river waters are separated into 5 groups in the table, representing all of the waters in each of the cross-section areas. Observation wells in the parallel series and the 3 Salt Creek wells are grouped with the closest cross-section. Capitol letter symbols on the mixing curve graphs for the observation well waters were chosen for shallow, intermediate, and deep wells in each cross-section group (Table 6), and are

Table 5. Ratios Used in Mixing-Curve Graphs for Samples from Observation Wells in the Arkansas River Valley and from the Arkansas River. All ratios with chloride as the denominator are weight ratios; meq/L values were used in the cation ratio. Sample data are listed according the groups plotted on the different mixing-curve graphs. Parallel wells were grouped with the nearby cross-section wells. The Salt Creek wells are included in the Hutchinson cross-section group. The Arkansas River water collected at each cross section is listed at the end of the group.

Site ID	Cl, mg/L	SO_4, mg/L	Na/Cl	(Ca+Mg)/(Na+K) in meq/L	SO_4/Cl	Br/Cl x 10^4	I/Cl x 10^6
Waters in the Hutchinson cross-section area							
EB 400A	539	65	0.686	0.3492	0.1206	2.04	6.31
EB 400C	3283	359	0.647	0.1473	0.1094	1.68	4.42
EB 401C	1528	196	0.624	0.2577	0.1283	1.83	3.66
EB 239A	803	189	0.611	0.4819	0.2354	7.97	24.66
EB 239C	1077	250	0.521	0.6561	0.2321	7.15	17.55
EB 248A	33.9	32	2.094	1.3634	0.9440	32.45	100.29
EB 248B	274	55	1.000	0.2599	0.2007	4.74	20.80
EB 248C	3330	439	0.674	0.1451	0.1318	1.77	3.15
EB 228A	10.8	56	4.722	2.2009	5.1852	74.07	370.37
EB 228B	13.5	67	2.370	2.3771	4.9630	59.26	1029.63
EB 228C	12.5	55	2.240	2.5542	4.4000	56.00	1304.00
EB 229A	477	97	0.631	0.5596	0.2034	8.39	12.58
EB 229B	1226	143	0.464	0.7447	0.1166	7.75	8.16
EB 229C	1932	142	0.345	1.1763	0.0735	8.18	6.52
EB 230AA	786	169	0.664	0.3242	0.1730	8.40	33.21
EB 230A	962	136	0.642	0.3354	0.1757	7.90	25.57
EB 230B	1072	176	0.551	0.5060	0.1642	7.28	22.39
EB 230C	468	132	0.814	0.2022	0.2821	4.06	18.59
EB 231A	273	91	0.817	0.4391	0.3333	9.16	24.18
EB 231B	807	184	0.641	0.4070	0.2280	7.56	23.42
EB 231C	1093	225	0.524	0.6270	0.2059	6.40	15.37
EB 232A	25.5	16	1.882	1.4843	0.6275	11.76	90.20
EB 232B	532	103	0.872	0.1442	0.1936	2.07	16.35
EB 232C	927	172	0.798	0.1336	0.1855	2.05	12.30
EB 233A	17.0	25	2.118	2.6820	1.4706	41.18	129.41
EB 233B	16.5	25	2.242	2.7107	1.5152	42.42	133.33
EB 233C	10.4	13	2.596	3.2021	1.2500	19.23	182.69
EB 234A	21.9	4	2.237	1.9032	0.1918	45.66	328.77
EB 234C	18.4	23	2.011	2.5694	1.2500	27.17	1260.87
EB 235A	63.7	23	1.146	1.5092	0.3611	17.27	51.81
EB 235C	17.0	17	2.471	2.3171	1.0000	35.29	141.18
EB 240AA	283	79	0.841	0.3225	0.2792	3.89	68.55
EB 240A	760	226	0.691	0.2999	0.2974	3.95	8.68
EB 240B	1160	255	0.666	0.2574	0.2198	3.45	8.88
EB 240C	2425	324	0.631	0.2234	0.1336	1.86	6.19
Hutchinson	629	157	0.682	0.3773	0.2496	3.34	11.29
Waters in the Haven cross-section area							
EB 237C	77.8	16	1.118	1.6501	0.2057	16.71	3059.13
EB 237D	83.4	10	0.971	1.8503	0.1199	14.39	1115.11

Table 5. (continued)

Site ID	Cl, mg/L	SO_4, mg/L	Na/Cl	(Ca+Mg)/(Na+K) in meq/L	SO_4/Cl	Br/Cl x 10^4	I/Cl x 10^6
Waters in the Haven cross-section area (continued)							
EB 249AA	58.4	42	1.284	1.8022	0.7192	34.25	133.56
EB 249A	58.7	29	1.789	0.7931	0.4940	8.52	195.91
EB 249B	226	35	0.655	0.8924	0.1549	3.54	85.40
EB 249C	38.5	35	1.948	1.0424	0.9091	10.39	241.56
EB 236A	154	44	0.883	0.7720	0.2857	6.49	48.05
EB 236B	114	115	1.184	0.9884	1.0088	8.77	92.98
EB 236C	239	72	0.423	1.9744	0.3013	5.44	22.18
EB 213A	258	79	0.488	1.4544	0.3062	9.30	14.34
EB 213B	148	84	0.736	1.2645	0.5676	6.08	35.14
EB 213C	652	429	0.747	0.4343	0.6580	3.07	72.24
EB 214AA	275	88	0.556	1.0643	0.3200	7.27	19.64
EB 214A	290	83	0.593	0.8939	0.2862	9.31	22.07
EB 214B	105	59	1.124	0.7022	0.5619	5.71	61.90
EB 214C	1770	409	0.675	0.2111	0.2311	1.81	7.46
EB 215A	445	62	0.553	0.6678	0.1393	25.84	53.93
EB 215B	3610	113	0.450	0.5158	0.0313	40.44	80.33
EB 215C	4090	535	0.589	0.2214	0.1308	1.66	3.42
EB 216A	2226	209	0.274	1.5492	0.0939	27.40	31.90
EB 216B	437	50	0.460	0.9452	0.1144	21.28	13.04
EB 216C	1873	226	0.533	0.4197	0.1207	3.26	4.16
EB 217A	192	88	0.771	0.9105	0.4583	27.08	75.00
EB 217B	119	44	1.017	0.5730	0.3697	5.88	31.93
EB 217C	151	38	0.874	0.7368	0.2517	3.97	23.18
EB 218A	235	19	0.400	2.0225	0.0809	40.00	28.94
EB 218B	164	18	0.787	0.9868	0.1098	37.20	94.51
EB 218C	59.1	23	1.049	2.0294	0.3892	25.38	116.75
EB 219A	51.7	28	1.025	2.3893	0.5416	17.41	79.30
EB 219B	20.8	254	3.077	2.4905	12.2115	9.62	1399.04
EB 219C	13.2	590	7.576	2.4879	44.6970	53.03	3787.88
EB 242AA	249	50	0.671	0.9766	0.2008	24.90	91.57
EB 242A	1077	47	0.415	0.8312	0.0436	40.85	35.28
EB 242B	107	62	1.234	0.7113	0.5794	7.48	214.02
EB 242C	469	108	0.851	0.2231	0.2303	22.17	23.45
Haven	602	159	0.693	0.4030	0.2641	4.32	12.46
Mount Hope cross-section and nearby parallel wells							
EB 241AA	149	66	0.738	1.0784	0.4430	16.11	29.53
EB 241A	258	120	0.771	0.6429	0.4651	4.65	37.21
EB 241B	605	134	0.526	0.6745	0.2215	3.80	10.08
EB 241C	3175	404	0.594	0.2637	0.1272	1.80	6.83
EB 247A	81.7	101	0.832	2.3425	1.2362	14.69	30.60
EB 247B	98.7	75	0.952	1.2442	0.7599	9.12	63.83
EB 247C	104	81	1.096	0.8761	0.7788	8.65	83.65
EB 243A	136	138	1.118	0.7995	1.0147	12.50	53.68
EB 243B	249	153	0.739	0.8121	0.6145	6.43	37.75
EB 243C	2569	351	0.621	0.2367	0.1366	1.79	6.07

Table 5. (continued)

Site ID	Cl, mg/L	SO_4, mg/L	Na/Cl	(Ca+Mg)/(Na+K) in meq/L	SO_4/Cl	Br/Cl x 10^4	I/Cl x 10^6
			Mount Hope cross-section and nearby parallel wells (continued)				
EB 208A	82.2	132	1.241	1.3759	1.6058	14.60	37.71
EB 208B	104	120	1.077	1.2299	1.1538	12.50	51.92
EB 208C	97.2	75	1.121	0.8701	0.7716	7.20	81.28
EB 209AA	117	95	0.880	1.2300	0.8120	7.69	37.61
EB 209A	103	85	1.068	1.0225	0.8252	8.74	42.72
EB 209B	135	71	1.059	0.6017	0.5259	3.70	115.56
EB 209C	445	128	0.676	0.4674	0.2876	2.70	24.27
EB 210A	605	166	0.666	0.3584	0.2744	6.61	24.79
EB 210B	659	218	0.630	0.4489	0.3308	6.07	25.49
EB 210C	2022	303	0.619	0.2262	0.1499	1.68	5.04
EB 211A	105	66	0.886	0.9858	0.6286	10.48	28.57
EB 211B	299	115	0.642	0.6765	0.3846	4.35	17.73
EB 211C	246	97	0.663	0.7150	0.3943	4.07	14.63
EB 212A	22.9	17	0.917	3.5486	0.7424	21.83	117.90
EB 212C	20.0	36	2.000	3.1119	1.8000	25.00	175.00
Mount Hope	595	161	0.676	0.4154	0.2706	4.71	13.61
			Waters in the Bentley cross-section area				
EB 244A	639	191	0.656	0.4451	0.2989	6.73	29.58
EB 244C	702	271	0.688	0.4126	0.3860	5.70	27.35
EB 201A	50.8	57	1.280	1.6544	1.1220	13.78	303.15
EB 201B	50.9	51	1.277	1.6612	1.0020	11.79	131.63
EB 201C	66.3	53	1.252	1.2841	0.7994	9.05	92.01
EB 202A	42.6	45	1.338	1.9494	1.0563	16.43	89.20
EB 202B	50.2	49	1.554	1.2033	0.9761	13.94	109.56
EB 202C	86.1	81	1.092	1.2574	0.9408	8.13	97.56
EB 203A	536	304	0.763	0.4581	0.5672	6.90	34.70
EB 203B	268	135	0.817	0.5728	0.5037	5.97	61.94
EB 203C	106	84	0.981	1.1959	0.7925	6.60	84.91
EB 204A	697	146	0.611	0.4156	0.2095	2.30	14.20
EB 204B	132	108	0.818	1.3221	0.8182	6.82	112.12
EB 204C	132	108	0.848	1.2618	0.8182	6.06	100.76
EB 205A	319	176	0.505	1.3904	0.5517	5.33	36.68
EB 205B	392	118	0.543	0.7940	0.3010	3.83	25.00
EB 205C	803	1120	0.727	0.8996	1.3948	2.24	10.83
EB 206A	121	41	1.116	0.4744	0.3388	5.79	68.60
EB 206B	144	58	1.146	0.2930	0.4028	4.86	61.11
EB 206C	379	115	0.945	0.1566	0.3034	2.37	32.72
EB 207A	54.2	37	1.181	2.2246	0.6827	31.37	169.74
EB 207B	18.0	18	2.556	2.4600	1.0000	16.67	277.78
EB 207C	31.8	29	1.698	2.2450	0.9119	12.58	125.79
EB 238A	29.7	67	2.121	1.9919	2.2559	33.67	205.39
EB 238C	43.8	45	1.553	1.7196	1.0274	41.10	191.78
EB 245A	332	175	0.639	0.9875	0.5271	6.33	25.00
EB 245B	860	185	0.700	0.2384	0.2151	2.21	7.67
EB 245C	1097	396	0.737	0.2612	0.3610	2.28	20.24
Bentley	598	160	0.676	0.4104	0.2676	4.68	12.88

Table 5. (continued)

Site ID	Cl, mg/L	SO_4, mg/L	Na/Cl	(Ca+Mg)/(Na+K) in meq/L	SO_4/Cl	Br/Cl x 10^4	I/Cl x 10^6
			Waters in the Maize cross-section area				
EB 246A	632	155	0.725	0.2921	0.2453	2.53	16.14
EB 246B	417	147	0.674	0.5895	0.3525	3.12	41.25
EB 246C	335	142	0.666	0.7600	0.4239	3.58	51.34
EB 220A	101	84	0.802	1.5117	0.8317	13.86	39.60
EB 220C	99.2	64	0.766	1.4307	0.6452	11.09	40.32
EB 221A	355	201	0.834	0.3956	0.5662	5.35	31.27
EB 221C	477	213	0.658	0.5643	0.4465	5.66	24.74
EB 222A	403	256	0.630	0.8610	0.6352	5.96	33.25
EB 222C	401	189	0.456	1.3279	0.4713	5.49	13.97
EB 223A	178	148	0.691	1.2684	0.8315	5.06	30.90
EB 223C	211	91	0.621	1.0839	0.4313	3.79	25.12
EB 224A	174	58	1.023	0.2596	0.3333	5.17	18.97
EB 224B	696	143	0.730	0.2012	0.2055	2.44	13.36
EB 224C	1059	180	0.665	0.2306	0.1700	2.08	7.93
EB 225A	35.2	27	2.330	0.6520	0.7670	28.41	85.23
EB 225B	191	66	1.136	0.2714	0.3455	4.19	27.75
EB 225C	204	74	1.074	0.3017	0.3627	4.41	19.12
EB 226A	22.2	39	2.568	1.6766	1.7568	49.55	265.77
EB 226B	19.6	19	2.602	2.1363	0.9694	20.41	204.08
EB 226C	23.4	24	2.222	2.1860	1.0256	17.09	132.48
EB 227A	30.9	31	2.233	1.4667	1.0032	25.89	135.92
EB 227B	37.7	41	1.751	1.8417	1.0875	15.92	127.32
EB 227C	37.5	58	1.707	2.0372	1.5467	18.67	122.67
Maize	582	161	0.675	0.4156	0.2766	4.64	13.92

Table 6. Letter Symbols Used for Observation Well Waters on the Mixing-Curve Graphs. The well groups are listed in Table 5. The letter R is used for all the Arkansas River water samples.

	Cross-section area				
Well depth	Hutchinson	Haven	Mount Hope	Bentley	Maize
Shallow	A	F	K	S	X
Intermediate	B	G	L	T	Y
Deep	C	H	M	U	Z

consistent for all the graphs. Both the AA and A wells are included together in the shallow well symbols. All of the Arkansas River waters are represented by the letter R.

Br/Cl Versus Chloride Mixing Graphs

The distribution of Br/Cl values versus chloride concentration for ground waters and Arkansas River waters analyzed in this study are shown in Figure 3. The range in Br/Cl ratios is smaller for low chloride concentrations than for high chloride concentrations. The freshwaters have Br/Cl values in the range for other freshwaters collected in the Equus Beds and Great Bend Prairie aquifers. The saline waters with the lowest Br/Cl ratios appear chemically similar to ground waters affected by mixing with Permian saltwaters in other areas of Kansas. The highest Br/Cl values for saline waters on the figure are similar to those for oil-field brines. A third group of points for saline waters has Br/Cl ratios lying between the expected Permian saltwater and oil-field brine sources of salinity.

Halite-solution source of salinity

Eight saline waters with chloride contents of 1,528 to 4,090 mg/L from deep wells in the Hutchinson (EB 400C, EB 401C, EB 240C, EB 248), Haven (EB 214C, EB 215C), and Bentley (EB 210C, EB 241C, EB 243C) cross-section areas form a group of points with a narrow range in Br/Cl on Figure 3. The group is interpreted as representing the mixture of evaporite- (salt) solution waters from the underlying Permian bedrock with natural waters at the base of the alluvial aquifer. The Br/Cl weight ratios fall within the 0.00006-0.0002 range for waters from observation wells screened in Permian bedrock in the eastern Great Bend Prairie (Whittemore, 1989).

Two mixing curves were calculated and drawn on Figure 3 to enclose the saline waters with primarily a natural Permian source of salinity and most of the freshwaters with a chloride content less than 50 mg/L. The two curves form the boundaries of a mixing zone. Points falling within and below the mixing zone are interpreted as being recharge affected by varying amounts of natural Permian water. Points falling above the zone have been affected by another or an additional source of salinity to the natural Permian ground water, or have been concentrated by evapotranspiration processes to increase the chloride content while retaining the same Br/Cl ratio. The same two mixing curves are drawn on the 3 additional Br/Cl mixing plots.

Ground-water contamination from oil-field brine

Many observation wells yielded waters with appreciably higher Br/Cl ratios than the freshwater and halite-solution mixing zone. Ten well waters with chloride concentrations greater than 100 mg/L have Br/Cl weight ratios over 0.002 (Figure 3). All 10 wells are located in the Haven cross-section area. The most probable saltwater source that could cause such high Br/Cl ratios for well waters with elevated chloride contents is formation brine associated with oil and gas production. Oil-field brine contamination has been identified as the source of salinity in the Burrton area of eastern Reno and western Harvey counties just to the northeast of the Haven cross-section (Whittemore and Basel, 1982; Burrton Task Force, 1984). The Burrton oil and gas field extends to the southwest across the Haven cross-section (Figure 2). Other smaller oil and gas fields are scattered across the western and easternmost parts of the study area.

Figure 4 shows points for only the wells in the Haven cross-section area and the Arkansas River waters. The two curves defining the mixing zone for freshwaters and Permian bedrock waters are drawn along with curves for the mixing of oil-field brine and natural waters in the alluvial aquifer. The high chloride end members for the latter curves are based on chemical data for oil brines from the area, while the lower chloride end members are points selected within the middle of the freshwater and Permian water mixing zone such that the curves pass though or close to one or more of the 10 contaminated ground waters with Br/Cl values above 0.002.

High-quality analytical data including bromide determinations exist for 8 oil brines from the study region (Whittemore, unpublished). The range, mean, and median for the Br/Cl weight ratios of the brines is 0.00395-0.00471, 0.00419, and 0.00405, respectively. Two of the brines were collected from the Stroud North and Bacon oil fields which lie near the Hutchinson cross-section. One brine was from the East Burrton Field in western Harvey County. The other 5 brines were sampled within the Burrton Field, including one from western Harvey County and 4 from sites close to the observation wells in the Haven cross-section line. Four of the saltwaters were produced from strata in the Mississippian System, 2 from the Hunton Group, and 2 from the Simpson Group. There is no clear correlation in the Br/Cl ratios with either location or formation.

The 10 ground waters with Br/Cl above 0.002 and chloride concentration greater than 100 mg/L are from 5 of the observation well sites (EB 215, EB 216, EB 217, EB 218, EB 242) in the Haven transect or near the transect. Six of the waters are from the shallow wells (all 5 sites), 3 are from the intermediate wells (EB 215B, EB 216B, EB 218B), and only one is from a deep well (EB 242C). Four additional well waters with chloride content more than 100 mg/L plot above the mixing zone for freshwater and underlying Permian water. Three of these (EB 213A, EB 214AA, EB 214A) are from the shallow wells just to the north of the main polluted area and the other is the deep well EB 216 C. Three other wells in the Haven cross-section area with chloride contents from 59 to 79 mg/L plot above the Permian water mixing zone. One is the deep well at site EB 218 where both the intermediate and shallow parts of the aquifer contain some oil-brine pollution. Another is the shallow well EB 249AA at the southwest end of the Burrton oil field; the points for the 3 deeper wells at this location fall within the Permian mixing zone. The third is the deep well EB 237C located at the eastern edge of the Yoder oil field; no intermediate or shallow wells were drilled at the site.

The chloride concentration of the original water at each well before oil-brine contamination can be estimated by using calculated mixing curves such as drawn on Figure 4. The rounded average Br/Cl ratio (0.0042) and chloride content (90,000 mg/L) of oil brines in the region was used for the saltwater end point for all the polluted sites except EB 218 and EB 242, for which 0.0044 was used for Br/Cl, and site EB 216, for which 0.0040 was used for Br/Cl. The slightly different end points for the latter 3 sites were selected to better fit the relatively high and low Br/Cl values, respectively, and the expected uncontaminated water for the 3 sites.

The estimated chloride value for the unpolluted water is the end of a mixing curve in the middle of the mixing zone for freshwater and natural Permian water. Error in the uncontaminated chloride related to the true location in the Permian mixing zone can be estimated by determining the intersection of the oil-brine mixing curve with the top and the bottom, if the brine curve is extrapolated, boundaries of the Permian zone. Errors in the natural chloride value due to a difference in the true oil-brine ratio can be approximately estimated by pivoting the mixing curve about the contaminated ground water lying on the curve; a higher ratio for the actual oil brine or brine mixture that caused the pollution would give a greater chloride value for the uncontaminated ground water and vice versa. The chloride concentration added to the original unpolluted water is the difference between the current amount and the chloride estimated for the original water. Estimated values for the original uncontaminated concentration and the oil-brine addition to the chloride content of the ground waters are listed in Table 7. Curves were not drawn for each of the points above the natural Permian mixing zone, but enough to allow illustration of the curves for most of the points.

Most of the oil-brine pollution is in shallow to intermediate portions of the aquifer in a down-gradient direction of ground-water flow from the Burrton oil field. This suggests that the contamination originated from the infiltration of saltwater disposed in surface pits, a practice that was widely used in the 1930's in the area. A similar depth and down-gradient flow distribution of salinity was observed and the same conclusion was drawn for ground-water pollution in the Burrton area of the Equus Beds to the northeast of the Haven cross section (Burrton Task Force, 1984). The brine pollution that infiltrated to the aquifer apparently has dispersed and migrated in the ground-water flow direction along the top of less permeable clay beds. Where the clay lenses thin or are not present, the saline water can move to lower depths if the density is still appreciably greater than that of the uncontaminated water or if the natural flow direction is downwards.

The chloride concentrations estimated to exist naturally at the shallow wells of sites EB 213, EB 214, EB 215, and EB 216 are higher than expected. There is the possibility that some of the estimated halite-solution source of chloride could have entered the shallow aquifer as a result of early disposal of oil brines into injection wells in the Wellington Formation. All of the

Table 7. Additions of Chloride from Pollution by Oil-Field Brine and Evaporation-Pan Brine to Well Waters as Estimated from Mixing Curves.

Well ID	Chloride, mg/L		
	Current total	Expected natural	Added by pollution
Oil-field brine pollution, Haven cross-section area			
EB 213A	258	210	48
EB 214AA	275	250	25
EB 214A	290	250	40
EB 215A	445	200	245
EB 215B	3610	200	3410
EB 216A	2230	700	1530
EB 216B	437	230	217
EB 216C	1873	1850	23
EB 217A	192	80	112
EB 218A	235	35	200
EB 218B	164	37	127
EB 218C	59	40	19
EB 237C	78	60	28
EB 242AA	249	120	129
EB 242A	1077	120	957
EB 242C	469	230	239
EB 249AA	58	30	28
Evaporation-pan waste, Hutchinson cross-section area			
EB 229A	477	50	217
EB 229B	1226	150	1076
EB 229C	1932	50	1882
EB 230AA	786	50	736
EB 230A	962	100	862
EB 230B	1072	200	872
EB 230C	468	380	88
EB 231A	273	40	233
EB 231B	807	150	657
EB 231C	1093	370	723
EB 239A	803	100	703
EB 239C	1077	220	857
EB 240A	760	560	200
EB 240B	1160	910	260

Burrton oil field to the north of the Arkansas River overlies the Wellington saltwater aquifer, an area along the eastern edge of the Hutchinson Salt Member where dissolution of the salt has formed a discontinuous zone of solution cavities (Gogel, 1981). The Wellington aquifer was used in the past as a disposal zone for oil brines before deep-well injection became the accepted practice. A problem observed with the shallow disposal was the flow of saltwater from the Wellington around some wells during pressure injection.

There are 3 areas in the Wellington saltwater aquifer in Kansas that Gogel (1981) identified as having a potentiometric surface with a higher altitude than the water table of the overlying freshwater aquifer. One of these extends from several miles southeast of Hutchinson to south of Burrton, and includes the locations of sites EB 213 to EB 215 along the Haven cross-section and nearby site EB 242. There is the possibility that, if unplugged or poorly plugged boreholes with corroded casing exist in the area, small amounts of saltwater could be slowly flowing from the Wellington aquifer into the alluvial aquifer.

The relative location of points for the Arkansas River waters to each other and to the mixing zone for freshwater and Permian water suggests that ground-water discharge containing some salinity derived from oil-brine affects the Br/Cl ratio between the river sampling locations at the Hutchinson and Haven transects. The chloride concentration of the ground water added between the two sites is smaller, but the bromide content enough greater to increase the ratio. The Br/Cl ratio in the river water increases very slightly from the Haven to the Mount Hope sampling points, then remains essentially constant at the next two downstream sampling locations.

Ground-water contamination from waste brine associated with salt-solution mining

When the ground waters from the observation wells in the Hutchinson cross-section area are plotted separately from the rest of the well waters on the Br/Cl versus chloride graph, two patterns are apparent for the samples containing more than 200 mg/L chloride (Figure 5). One pattern is the distribution of points within or near to the mixing zone for freshwaters and natural Permian waters. The other is the group of 11 points with a relatively small range in Br/Cl

(0.00064-0.00092). All 11 waters are from a group of 4 well sites (EB 229, EB 230, EB 231, AND EB 239) that are located north of the Arkansas River valley just to the southeast of Hutchinson. Five of the 11 ground waters are from shallow wells and 3 each are from intermediate and deep wells. The narrow range in Br/Cl and the occurrence of the waters in the shallow part of the aquifer at all 4 sites suggest a similar source of contamination that entered the aquifer from the surface.

Although there are a few small oil fields in the general area of the group of 4 well sites, the source of contamination is probably not oil brine because none of the waters have a Br/Cl close to those substantially affected by oil brine in the Haven transect area (Figure 4). The narrow range in the Br/Cl ratios suggests that the probability of various mixtures with oil brine that coincidentally produced the observed values would be very low. The Br/Cl ratios for formation brines from the small oil fields to the southeast of Hutchinson appear to be similar to those for the Burrton Field, based on the fact that the two values available for the Stroud North and Bacon fields are within the range for the Burrton brines and the oil is produced from the same strata.

During the late 1800's and the early 1900's, salt (halite) was commercially produced in or just outside Hutchinson by evaporating brines obtained by salt-solution mining of the Hutchinson Member of the Wellington Formation which underlies the Ninnescah Shale. After much halite was precipitated from brine spread in large pans, the waste brine was drained to prevent precipitation of additional salts that would decrease the purity of the halite (Kirk, 1899). The disposal of much of the waste brine in the early period of salt production apparently was at the surface, as reflected by the saltwater contamination of the alluvial aquifer found by Williams (1946) between Hutchinson and the 4 well sites mentioned above.

When a sodium-chloride water such as seawater or a salt-solution brine is concentrated by evaporation to cause halite precipitation, most of the bromide remains in the residual solution. The chemical evolution of brines produced by evaporation of seawater has been described by Carpenter (1978) based on data in Zherebtsova and Volkova (1966). The ratio of the Br/Cl value for the brine concentrated to the point at which halite precipitation begins over the Br/Cl value for the starting unevaporated seawater is 1.63. During the bulk of halite precipitation, the value for evaporated brine Br/Cl divided by the seawater Br/Cl is 4.2. Precipitation of magnesium sulfate salts begins at a ratio of brine Br/Cl over seawater Br/Cl of 4.6.

Although Ca/Cl, Mg/Cl, and SO_4/Cl ratios for salt-solution brine used by a commercial salt company in Hutchinson (Whittemore and Pollock, 1979) are smaller than for seawater, there was still concern with precipitation of impurities in the halite. Another problem was the formation of carbonate and gypsum scale in the evaporation pans that decreased heat transfer (Kirk, 1899). New brine was continuously added during the salt precipitation process. Therefore, it appears possible that the Br/Cl of the waste brine drained from the evaporation pans would not exceed 4 times that of the Br/Cl in the brine from salt-solution mining.

The Br/Cl of solutions of the Hutchinson salt in Kansas range from about 0.0001 to a little over 0.0003 based on Whittemore and Pollock (1979), Whittemore et al. (1981), and Whittemore (1982). Two samples of salt-solution brines from the Carey Salt Company in Hutchinson had an average Br/Cl of 0.0003, while a solution of a sample of salt core from Lyons had a Br/Cl of 0.0001 based on values in Whittemore and Pollock (1979) and additional analytical data for the same samples. The water used by the Carey Salt Company to dissolve the salt was from wells in the Arkansas River alluvium. However, the water was used for cooling and dust collectors before being routed to the deep wells in the salt bed, which might have affected the Br/Cl somewhat.

If the Br/Cl ratio expected for salt-solution mining (about 0.00025) were increased from 3 to 4 times by the evaporation-pan process for precipitating halite, the resultant waste brine would have a Br/Cl ratio of 0.00075-0.001. A mixing line starting within the mixing zone for freshwater and natural Permian water and passing through the 4 points with the highest Br/Cl ratios and chloride concentrations above 200 mg/L on Figure 5 extends to a Br/Cl of 0.0008 for a brine chloride content. The consistency of the observed data with the probable range in the ratio for evaporation-pan brine strongly suggests that waste brine from the salt-precipitation process is the salinity source affecting the alluvial ground waters to the southeast of Hutchinson. The ground waters at the 4 sites generally lie in a flow direction down-gradient from the location of a present salt company. The very fresh water at all depths of the alluvial aquifer at site EB 228 further suggests that uncontaminated ground water should be much fresher than observed at site EB 229. The A and B wells of site EB 240 also appear to have been affected by the waste brine based on their location above the natural Permian mixing zone, while the AA and C wells at the site plot within the zone and, therefore, do not have detectable additions from the pollution plume.

Estimates of the expected chloride concentrations that would occur naturally at each of the screened intervals of the wells can be made using the mixing curves on Figure 5 in a similar manner as described for the oil-brine pollution in the previous section. The saltwater end point of all the curves has a Br/Cl of 0.0008 at a chloride concentration of 180,000 mg/L. Each of the curves was calculated such that it passed through one or more of the points for aquifer waters plotting above the mixing zone for freshwater and natural Permian saltwater, and extended into the middle of the zone. Curves were not drawn for each of the points above the natural Permian mixing zone, but enough to allow illustration of the curves for most of the points. Table 7 lists both the estimated values for the original uncontaminated concentration and the waste brine addition to the chloride content of the ground waters. As in the case of the estimates for oil-brine pollution, errors related to the true Br/Cl of the unpolluted water at each site and of the brine waste mean that the values in Table 7 are approximate.

Salinity from natural evapotranspiration and/or river flood waters

Several waters with chloride contents above 200 mg/L from observation wells in the Bentley and Maize cross-section areas plot above the mixing zone for freshwater and Permian saltwater (Figure 6). The group of 10 wells includes both wells at site EB 244, the shallow well at site EB 245, the shallow and intermediate wells at EB 203, the shallow well at EB 205, and both wells at both sites EB 221 and EB 222. Oil-field brine is not believed to be the cause of the increased Br/Cl because there are few oil fields in the region of the two transect areas. The oil fields near the Maize cross section are generally in a ground-water flow direction down gradient from the Maize wells. None of the wells at the two sites closest to oil fields in the two transect areas (EB 220 and EB 225) fall in the higher chloride and Br/Cl ratio group.

The group of 10 well waters forms a trend of relatively constant Br/Cl with increasing chloride concentration in comparison with the decreasing Br/Cl with increasing chloride for the other wells in the two transect areas with greater than 200 mg/L chloride. A characteristic of many of the sites in the Bentley and Maize cross-sections region is that the chloride content of the shallow wells with over 200 mg/L chloride is generally close to or greater than the concentration in the intermediate well and sometimes in the deep well at the site. Both the Br/Cl trend and the depth distribution of chloride suggest that natural evapotranspiration processes have concentrated shallow ground waters. The Br/Cl of a saline water should not change during evaporative concentration as long as the chloride content remained below the point at which chloride salts could precipitate and cause fractionation of one constituent relative to the other. The two horizontal lines on Figure 6 represent such a change in chloride at constant Br/Cl. The lines extend out from the Permian mixing zone and bracket the group of 10 waters.

The sites in the group of higher Br/Cl lie in areas where ground-water tables appear to be very shallow. All sites except EB 203 are on the south side of the Arkansas River in a general area where there are some marshes and drainages that parallel the Arkansas River. The largest of these drainages is Big Slough, a name implying a marshy or backwater environment with a shallow water table. In addition, the levee along the Arkansas River in the area has prevented direct drainage of some of the smaller waterways for a number of years. The conditions are those in which evapotranspiration could be expected to concentrate shallow ground and surface waters. The vertical component of ground-water flow at each site would then dictate whether waters affected by the concentration process would reach deeper parts of the alluvial aquifer.

Past periods of river flooding would have brought water from upstream with a mixed geochemical signature into the broad, low-lying areas near the river. Although greater flows usually have lower chloride concentrations, flushing of salts from soils or salt marshes by intense rainfall following an extended dry period could bring slightly saline waters onto the floodplain. Salt marshes occur upstream of the study region in the Great Bend Prairie. The large number of surface pits used for oil-brine disposal in the past also has provided an appreciable source of salts in soils for leaching by runoff.

A curve is drawn on Figure 6 that represents the mixing of Arkansas River water at Mount Hope with very fresh water. Several of the well waters in the group with higher Br/Cl fall on or relatively close to the curve. Therefore, an alternative explanation for the composition of the waters is that they reflect the infiltration of past flood waters from the Arkansas River. The origin of the slightly saline waters could also be derived from a combination of the flood infiltration and evapotranspiration concentration processes.

Several of the well waters from the Mount Hope cross-section area also plot appreciably above the mixing zone for freshwater and natural Permian saltwater (Figure 3). The waters are from the shallowest wells at sites EB 241 and EB 243 and the shallow and intermediate level wells at site EB 210. The intermediate depth waters at sites EB 241 and EB 243 also lie slightly above the Permian mixing zone. All 3 of the sites are close to the river, suggesting that infiltration of river waters during high flow or flooding could have affected the shallow ground water in the alluvium. The sites are also much closer to the Burrton oil field than the sites with higher Br/Cl and chloride contents in the Bentley and Maize transect areas discussed above. Thus, the elevated Br/Cl for the Mount Hope ground waters along the river could reflect a stronger influence from flushing of oil-brine pollution.

SO_4/Cl Versus Chloride Mixing Graph

The SO_4/Cl ratios for the ground waters in the Arkansas River alluvium extend over a greater range in terms of orders of magnitude than for the Br/Cl ratios. Figure 7 shows that there is a general decrease in the SO_4/Cl ratio with increasing chloride concentration. However, the scatter of points in the figure does not fit as clearly the different sources of salinity as it does in the Br/Cl versus chloride graphs. All of the points for waters with a chloride content more than

2,000 mg/L that fall within the mixing zone for freshwater and natural Permian saltwater in the Br/Cl figures also plot within a relatively narrow band on Figure 7. The saltwater end for the two mixing curves on Figure 7 were selected to fit the points in this band. The freshwater end members were chosen to give curves that pass through the approximate center of the data distribution. The curves provide a reference for describing relative deviations of the SO_4/Cl ratios.

Nearly all of the points falling below the bottom mixing curve on Figure 7 are for waters from the Hutchinson and Haven cross-section areas, while most of the points located above the upper curve are for waters in the Mount Hope, Bentley, and Maize transects region. In general, the higher the Br/Cl ratio for the ground waters polluted by oil-field brine in the Haven cross-section area, the greater the distance below the lower mixing curve on Figure 7. Saltwaters in oil- and gas-producing strata in Kansas tend to have much lower SO_4/Cl ratios than Permian evaporite solutions. The range and mean of the SO_4/Cl weight ratios for the 8 oil brines from the study area referred to in a previous section are 0.00002-0.0059 and 0.0012; the chloride concentration range for the same waters is 52,400-104,500 mg/L. This ratio is an order of magnitude lower for that used as the saltwater end member for the mixing curves in Figure 7. Thus, the low SO_4/Cl ratios for the Haven site waters reflect varying mixtures of oil-field brine and natural Permian saltwater as salinity sources.

The ground water from well EB 229C has the greatest content of chloride attributed to waste brine from the evaporation pan process used in the past by salt companies in Hutchinson. It also has a SO_4/Cl ratio substantially below the mixing curves in Figure 7. The ratio is not contrary to that possible in the concentrated waste brine because gypsum is also precipitated during the pan evaporation of the salt-solution brine. Gypsum formed most of the scale that collected on the bottom of the pans as described by Kirk (1899). Precipitation of gypsum would remove sulfate from the brine just as halite precipitation removed chloride.

After the shift to lower SO_4/Cl ratios caused by anthropogenic contamination is removed from the Hutchinson and Haven transect areas, many of the points for the ground waters in the

Mount Hope to Maize areas still have higher SO_4/Cl values. The concentration by natural evapotranspiration described above is probably responsible for the shift in the ratios for some of the shallow wells; as in the case of Br/Cl ratios, the SO_4/Cl would remain constant as the chloride content increased as long as gypsum was not precipitated. Some of the ground waters at shallow to intermediate depths near the Arkansas River may be affected by the chemistry of the river water. Points for the river samples all plot as a tight group just above the upper mixing line on Figure 7. Another possible influence on shallow ground waters in the study area could be leaching of gypsum spread on agricultural fields to maintain soil structure.

The ratios appreciably above the mixing curves on Figure 7 for many deep wells could be greater amounts of dissolved gypsum in different portions of the underlying Permian bedrock. This could explain the higher SO_4/Cl values for wells EB 213C, EB 214C, EB 219C, EB 205C, and EB 245C, which all have sulfate contents near or above 400 mg/L and plot in the mixing zone for freshwater and natural Permian saltwater on the Br/Cl graph (Figure 3). The ground water from EB 219C is an example of a Permian water that reflects the solution of gypsum in strata from which any preexisting halite and resultant saltwater has been completely removed; the sulfate and chloride concentrations are 590 and 13 mg/L, respectively.

I/Cl Versus Chloride Mixing Graph

Weight ratios of I/Cl range over a similar number of orders of magnitude as for SO_4/Cl ratios but have absolute values that are 4 orders of magnitude lower. A graph of I/Cl versus chloride concentration (Figure 8) indicates that most of the ratios decrease with increasing chloride in a band enclosed by the two mixing curves. The saltwater end members for the two curves have I/Cl values that are typical for halite-solution brines in Kansas. The freshwater end members of the mixing lines were selected to enclose most of the data. The Arkansas River waters fall as a close group of points in the center of the mixing zone.

There is not as much scatter of points outside the broad mixing zone in Figure 8 as in the Br/Cl and SO_4/Cl graphs. Although I/Cl ratios are appreciably different in various saltwater sources, dissolved iodine, which exists primarily as iodide in ground waters and as iodide and iodate in surface waters, can be adsorbed on fine-grained sediments. Therefore, the deviations in the ratios of anthropogenic salinity sources from natural variations are often subdued.

Ratios of I/Cl in oil-field brines are typically nearly two orders of magnitude greater than for halite-solution saltwaters in Kansas. The range and average in the I/Cl weight ratio for the 8 oil brines from the study region are 0.000109-0.000135 and 0.000121, respectively, while Kansas halite-solutions are usually in the 0.000001-0.000004 range. The iodine in the oil-field saltwater is not completely adsorbed on fine-grained sediments during contamination of an aquifer if the amount of the brine is high enough to keep the dissolved iodine concentration high. Thus, elevated I/Cl ratios can be used to complement salinity determination based on Br/Cl data.

Most of the points on Figure 8 that plot substantially above the upper mixing curve represent ground waters from the Haven cross-section area. The ground waters with higher I/Cl than the mixing line include the 3 waters with the greatest amount of oil-brine pollution as identified from Figure 4. Two of the other shallow waters with chloride contents greater than 200 mg/L and that have been substantially affected by oil brines also have elevated I/Cl values.

When saline water from oil-brine contamination of an aquifer containing some fine-grained sediments is flushed by fresher ground waters, the chloride and bromide concentrations can decrease faster than the dissolved iodine because some iodine can be slowly released to the water by desorption. The resultant higher I/Cl ratio can be an indication, then, of the previous existence of greater amounts of oil-brine pollution than present. This is believed to be the cause for some of the ground waters with I/Cl ratios above the upper mixing curve on Figure 8. The group includes wells EB 237C, EB 242B, EB 249B, and EB 213C in order of increasing chloride in the range 78-652 mg/L. The point for EB 237C also lies above the Br/Cl mixing zone for natural Permian saltwater in Figure 4. The points for all 3 ground waters fall within the Permian Br/Cl mixing zone. However, oil-brine contamination is present at shallower depths at each of the 3 sites. The results suggest that oil-field contamination of the aquifer has been greater in the past and is being flushed out. This fits the primary suspected source as saltwater disposed in surface pits in the 1930's-1940'.

Other points plotting slightly above the upper curve in Figure 8 are for some of the shallow and intermediate level ground waters at the 5 sites southeast of Hutchinson that have been affected by evaporation pan waste from old salt companies. This could be expected from the elevated I/Cl ratios present in the residual brine from the halite precipitation process. The ground waters at the intermediate and deep levels of site EB 219 have high I/Cl SO_4/Cl ratios. Although the site is just south of site EB 218 where oil-brine pollution exists, the high ratios could also possibly be related to the unusual water for the area, i.e., very high sulfate in the presence of very low chloride concentrations.

Cation Ratio Mixing Graphs

Dissolved calcium, magnesium, sodium, and potassium in the alluvial ground waters in the study area are primarily derived from the aquifer sediments or saltwaters entering the aquifer naturally or from anthropogenic activities. The alluvium can contain carbonate minerals that dissolve and release calcium and minor amounts of magnesium, and feldspar fragments that weather to release potassium and some of the other cations. Calcium carbonate equilibrium probably controls the amount of dissolved calcium and bicarbonate in the ground waters. Clay mineral formation during feldspar weathering can affect potassium, and to a smaller degree, the other cation concentrations. None of the alluvial waters has sulfate and calcium contents high enough to be limited by gypsum solubility. Some dissolved cations may be added from the surface by leaching of gypsum for soil treatment and fertilizers used in agriculture.

The concentrations of the bivalent cations calcium and magnesium relative to the monovalent cations sodium and potassium in ground waters is also strongly controlled by adsorption/desorption equilibria with clay minerals. Increasing concentrations of the monovalent cations (mainly sodium) in an aquifer water as the result of saltwater intrusion or pollution will upset the general equilibrium between the previous ground water and the clays. Some of the monovalent cations will be exchanged for bivalent cations, thereby increasing the bivalent/monovalent cation ratio in the water. Conversely, flushing of saline water that has existed in aquifer sediments can cause release of some of the high concentration of adsorbed sodium on the clays and adsorptive replacement by calcium and magnesium, resulting in a decrease in the bivalent/monovalent cation ratio in the ground water.

Before the Br/Cl methodology had been refined for saltwater source identification, the ratio Na/Cl had often been used as a means of distinguishing between oil-field brine and halite-solution sources of contamination. Oil-field saltwaters in Kansas typically have Na/Cl weight ratios within the range 0.4-0.6, while halite-solution brines usually have a ratio near the theoretical value for dissolution of NaCl, 0.65. The Na/Cl identification method would sometimes work when the concentration of the saltwater contamination was so high that the exchange of cations on clay minerals did not alter the ratio enough to appreciably change the original ratio. However, adsorption of sodium on clay minerals can often cause a greater change in the Na/Cl ratio of saltwater introduced into an aquifer than the difference between 0.5 and 0.65. The effect is illustrated in Figure 9 for the waters in the study area.

The mixing curve in Figure 9 is drawn from the Na/Cl value for halite solution (0.65) to a freshwater end member such that the calculated line passes through the approximate center of the points. The tight cluster of points for the Arkansas River samples also lies on the mixing curve. Comparison of Figure 9 with Figures 3-6 shows the great advantage in using Br/Cl over Na/Cl for salinity-source characterization. In general, the greatest deviations from the curve are lower Na/Cl ratios for some of the ground waters in the Hutchinson and Haven cross-section region. The points include both aquifer waters polluted by oil brine and pan-evaporation waste from salt-solution mining.

The value of a Na/Cl plot is careful interpretation of large deviations from a conservative mixing curve after identification of salinity sources has been completed using mainly the Br/Cl mixing-curve method. Because changes in the Na/Cl ratio are often controlled more strongly by cation exchange on clays than differences in the original ratios for saltwater sources, the use of the ratio (Ca+Mg)/(Na+K) can be better for determining advancement or retreat of saline water in an aquifer. Comparison of Figure 10 with Figure 9 shows that the deviations of points from a central mixing curve are greater for the cation-ratio graph than in the Na/Cl plot. The cation ratio is calculated using equivalent/L concentrations to better reflect the cation exchange process. Ratio values are listed in Table 5 for all the waters.

The mixing curve on Figure 10 was calculated using a saline-water end member that has an approximate average ratio of the ground waters with the highest chloride concentrations. The freshwater end member was chosen such that the mixing curve would pass through the center of most of the data. In general, the range in the cation ratio at a given chloride value increases with increasing chloride. Variations in the cation ratios are sensitive to many factors, especially at lower total-dissolved-solids and chloride concentrations. Therefore, well waters plotting substantially above or below the central mixing curve and having chloride contents greater than 100 mg/L are the main focus of the discussion below.

The 3 ground waters in the Haven cross-section area with the greatest amount of oil-brine contamination, EB 215B, EB 216A, and EB 242A, all have (Ca+Mg)/(Na+K) ratios well above the central mixing line on Figure 10. Most of the other waters containing a measurable oil-brine contribution to chloride also lie above the cation mixing line; of these, well waters EB 213A, EB 214AA, EB 216B, and EB 218A plot appreciably above the mixing curve. The cation values with the largest positive deviations suggest that saline water is advancing in the portions of the aquifer represented by the points. The values with smaller positive differences from the mixing line could represent waters that are slowly advancing, relatively stagnant, or in the process of being flushed. In the latter case, the current ratio would be expected to be declining relative to past values for more saline water. The one well water with an appreciable amount of oil-brine contamination that has a large negative difference in the cation ratio relative to the central mixing line is EB 242C. The data suggest that oil brine pollution was much greater in the past and that the sediments in the well-screen interval are very permeable, allowing more rapid movement and flushing of contamination.

All 5 of the ground waters southeast of Hutchinson with chloride contents over 1,000 mg/L and a predominant source of salinity from evaporation-pan waste associated with salt-solution mining, EB 229B, EB 229C, EB 230B, EB 231C, and EB 239C, plot well above the cation-mixing curve on Figure 10. Points for the shallow waters at these sites fall from somewhat above to below the mixing curve. The relative position of the points for the different aquifer depths indicates that past pollution from the waste brine was probably much greater in the shallow horizons of the aquifer at the 4 sites, the saline water plume is actively advancing in the deep portion of the aquifer at site EB 229, and that the chloride content of the intermediate levels of the aquifer at all sites and the deep part at sites EB 230 and EB 239 could be in the process of flushing, but not as advanced as the shallow depths.

The cation ratio for the intermediate and deep wells at site EB 232 are anomalously low. Either the natural halite-solution source for the salinity in the waters has an anomalous cation ratio, or the salinity was appreciably greater in the past and is now decreasing. Anomalous Permian water is considered as a possibility because points for the deep well at site EB 400 and both the intermediate and deep wells at site EB 248 have low ratios. The major constituent data reported in this study for site EB 232 are similar to the values for previous samples from these wells, suggesting that the anomaly is not due to non-representative samples.

Other ground waters with cation ratios appreciably below the mixing curve are from all 3 depths at sites EB 206 and EB 225, and from the shallow and intermediate wells at site EB 224. The possibility that flushing of saline waters could be occurring at these locations should be considered.

The high cation ratios for well waters from EB 205A, EB 222C, and EB 236C fall substantially above the cation mixing curve in Figure 10. The possibility the concentration of saline water is increasing at some of these well depths should also be considered. The high cation ratio for well water EB 205 is probably related to the anomalously high SO_4/Cl value; the high sulfate concentration allows more dissolved calcium in equilibrium with calcite due to formation of sulfate ion pairs. The high cation ratio for the shallow water at this site may also be related to the deeper water. The intermediate well water at site EB 205 is also above the cation mixing line, but not as much as for the shallow and deep wells.

CONCLUSIONS

Geochemical characterization of ground waters in the alluvial aquifer of the Arkansas River valley from Hutchinson to Wichita indicates that there are primarily 3 different sources, and possibly 4, that contribute to salinity. In addition, evapotranspiration concentrates surface and shallow ground waters and can further increase salinities in certain portions of the valley.

The predominant source of salinity is natural intrusion of saltwaters from Permian strata underlying the aquifer, both within and upstream of the study area. The highest concentrations of natural saltwater are distributed within the deepest portions of the aquifer from Hutchinson to Mount Hope. Permian saltwater also comprises the main source of dissolved solids in the Arkansas River that flows through the region. Infiltration of river water during high flows or floods has affected ground waters near the river.

The second saltwater source is pollution from oil-field brines disposed in surface pits that probably occurred mainly during the 1930's to 1940's. Most of the contamination is at shallow and intermediate depths of the aquifer within and in a down-gradient flow direction from the Burrton oil field. The polluted area is an extension of the saline-water plume delineated by the Burrton Task Force to the northeast. The oil brine contributes from about 200 to 3,400 mg/L of the chloride concentration in 6 observation well waters, and lesser amounts in several other well waters in the Haven cross-section area. The salinity of the ground water appears to be increasing at one shallow well, EB 216A, and may also be increasing at EB 218A. The chloride concentration is probably relatively constant at a few other locations, while decreasing at most of the screened intervals where detected. The data suggest that clay layers in the aquifer are important in controlling the location of the contamination. Where oil-brine contamination has entered deeper portions of some aquifer locations, the salinity has apparently traveled faster in more permeable sediments because it is being more actively flushed.

The third major source of salinity occurs at a group of 5 observation well sites south of Hutchinson, EB 229, EB 230, EB 231, EB 239, and EB 240. The saltwater source is identified as waste brine from evaporation pans used in the late 1890's and early 1900's by salt companies in Hutchinson. The brine placed in the pans was from salt-solution mining of the Hutchinson

Member of the Wellington Formation. The contamination has spread to all levels of the alluvium at 4 of the 5 sites, but is now most concentrated in the intermediate and deep portions of the aquifer. The brine contributes from about 200 to almost 1,900 mg/L chloride dissolved in the ground waters at 13 out of the 16 wells at the 5 sites, and about 90 mg/L at another well. The chloride concentration currently appears to be increasing at well EB 229C, may be relatively constant at well EB 229B, and is probably decreasing to varying degrees at the other wells. The data indicates that the rate of salinity decrease is generally greater in the shallow aquifer sediments.

A fourth possible source of saltwater is flow of halite-solution brine mixed with oil brine that flowed up around disposal wells or in unplugged, poorly cased boreholes as a result of brine injection into the Wellington aquifer. Part of the Burrton oil field north of the Arkansas River is in an area where the potentiometric altitude of the Wellington aquifer is above that of the alluvial aquifer. This could explain the higher than expected chloride content identified as derived from halite-solution in the shallow wells of sites EB 213 to EB 216 along the Haven cross section.

Shallow and, in some cases, intermediate depths of the alluvial aquifer next to the Arkansas River contain water with a chemistry related to the river water, indicating infiltration of river water during high flows or floods. Decreases in river flows over the last few decades could change the salinity input from this source. However, water table declines from consumptive pumping in the vicinity of the river could lead to increased infiltration of saline waters during lower flows. Although there is no clear chemical evidence for appreciable recent increases in natural saltwater intrusion from the underlying bedrock, greater pumping stresses in the future could change the situation.

Evapotranspiration has increased the salinity of shallow ground waters primarily in an area with a shallow water table, marshes, and slow moving drainage on the south side of the Arkansas River between Mount Hope and Wichita. The drainage known as the Big Slough runs through this area. Some of the shallow saline waters can affect intermediate levels of the aquifer where the vertical component of ground-water flow is downwards.

Although nitrate concentrations exceed drinking water standards at 3 of the shallow observation wells, the values are not high enough to be associated with the addition of more than a few tens of mg/L chloride from a related source.

The implications of the results for the flow modeling investigations are 1) the aquifer contamination from evaporation pan waste associated with past salt-solution mining and from the pollution from the Burrton oil field should be treated as areas with a migrating saline plume; 2) the rest of the study area should be modeled as having a relatively constant input of natural sources of salinity, mainly various amounts of saltwater from the underling Permian bedrock, but also including inputs of river water during high flows and floods near the Arkansas River and concentration of some shallow ground waters by evapotranspiration. If possible, the flow models should consider the importance of clay layers in controlling the flow of brine pollution from the surface and restricting Permian saltwater flow from the subsurface in the alluvial aquifer.

RECOMMENDATIONS

The USGS augered holes and constructed observation wells at 4 sites in the alluvial aquifer to the east and southeast of Hutchinson during the first half of 1990. In February, 1990, Carey Salt Company also installed wells in the aquifer in the area of the new USGS wells. The locations of the new wells is to the north and northwest of the saline-water plume derived from evaporation-pan waste identified in this report. Waters from the wells should be sampled and geochemically characterized to determine the continuity of the waste brine plume, the probable natural additions to salinity in the area, and whether the plume is being appreciably diluted or augmented by more recent saltwater contamination. The results should assist in the modeling of the pollution plume.

The area where oil-brine was disposed in the past into the Wellington aquifer should be examined further for evaluation of past contamination from saltwater flowing up along wells during pressure injection. The possibility of saltwater actively flowing up unplugged or poorly-plugged oil or disposal wells with corroded casing should be assessed in the location where the potentiometric altitude of the Wellington aquifer lies above the water table of the overlying alluvial aquifer.

Long-term sampling of the observation wells should be valuable for assessing the rate of dilution of the two large pollution plumes to the southeast of Hutchinson and along the east edge of the Burrton oil field. Monitoring of the water quality from the other wells will allow determination of the effects of future pumping stresses on the aquifer and the long-term decreases in river flow. The addition of the new wells in the Arkansas River valley greatly increases the number of sampling points in the existing network of the Equus Beds Groundwater Management District. A long-term sampling frequency of once every two years should be satisfactory for determination of salinity changes, if the District cannot handle annual collection. The District could conduct sampling during alternate years in the Burrton and Hollow Nikkel network and the Arkansas River valley network.

Analyses for specific conductance, chloride, and sulfate concentrations should be sufficient for assessment of salinity variations. If the conductance and concentrations changed appreciably from one sampling time to another, a more complete analysis would be appropriate to determine any differences in water type. In addition, sampling for nitrate content is recommended for wells yielding waters with high nitrate concentrations. Several of these wells could be added to the annual sampling program of the GMD.

REFERENCES

Burrton Task Force, 1984, Proposed Burrton intensive groundwater use control area: Available from Kansas Department Health and Environment, Topeka, KS, 103 p.

Carpenter, A.B., 1978, Origin and chemical evolution of brines in sedimentary basins: Oklahoma Geol. Survey Circular 79, Norman, OK, p. 60-77.

Gogel, T., 1981, Discharge of saltwater from Permian rocks to major stream-aquifer systems in central Kansas: Kansas Geol. Survey Chemical Quality Series 9, 60 p.

Kirk, M.Z., 1899, Chapter IX, Salt, in Haworth, E., Annual bulletin on mineral resources of Kansas, for 1898: Kansas Geol. Survey, Lawrence, KS, p. 67-123.

Whittemore, D.O., 1982, Identification of saltwater sources affecting groundwater in the Blood Orchard area, Sedgwick County, Kansas: Kansas Geol. Survey Open File Report 82-9, Lawrence, KS, 17 p.

Whittemore, D.O., 1983, Identification of saltwater sources affecting groundwater from M. Bell irrigation well, Reno County: Kansas Geol. Survey Open File Report 83-17, Lawrence, KS, 9 p.

Whittemore, D.O., 1984, Initial report on the geochemical identification of the source of salinity in groundwaters in northwestern Harvey County: Kansas Geol. Survey Open File Report 84-6, Lawrence, KS, 11 p.

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, Butterworth Publishers, Stoneham, MA, p. 505-514.

Whittemore, D.O., Sophocleous, M., Bryson, W.R., Schoof, J., and Bell, T.C., 1985, An interagency study of oilfield brine pollution in Kansas: Groundwater Contamination and Reclamation Symposium, Amer. Water Resources Assoc., p. 109-116.

Whittemore, D.O., Bryson, W.R., Dealy, M.R., O'Connor, R.E., and Schoof, J., 1986, Management of oil-field-brine pollution in Kansas via a state task force: Transactions, 36th Annual Conference on Environmental Engineering, University of Kansas, Lawrence, KS, 14 p.

Whittemore, D.O., 1988, Bromide as a tracer in ground-water studies: Geochemistry and analytical determination: Proceedings Ground Water Geochemistry Conference, National Water Well Assoc., Dublin, OH, p. 339-360.

Whittemore, D.O., and Pollock, L.M., 1979, Determination of salinity sources in water resources of Kansas by minor alkali metal and halide chemistry: Kansas Water Resources Research Institute Contribution 208, Manhattan, KS, 28 p.

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

Whittemore, D.O. and Basel, C.L., 1982, Identification of saltwater sources affecting groundwater in the Burrton area, Harvey County, Kansas: Kansas Geol. Survey Open File Report 82-5, Lawrence, KS, 11 p.

Whittemore, D.O. and Hathaway, L.R., 1983, Identification of saltwater sources affecting groundwater from R. Newell irrigation well, Reno County: Kansas Geol. Survey Open File Report 83-14, Lawrence, KS, 5 p.

Whittemore, D.O., McClain, T.J., Cobb, P.M., Davis, R.K., and Marks, E.T., 1987, Geochemistry of ground waters in the saline intrusion area of Groundwater Management District No. 5, south-central Kansas: prepared for Groundwater Management District No. 5.

Williams, C.C., 1946, Ground-water conditions in Arkansas River valley in the vicinity of Hutchinson, Kansas: Kansas Geol. Survey Bulletin 64, 1964 Reports of Studies, Part 5, p. 145-216.

Zherebtsova, I.K., and Volkova, N.N., 1966, Experimental study of behavior of trace elements in the process of natural solar evaporation of Black Sea water and Sasyk-Sivash brine: Geochemistry International, 3: 656-670.

Figure 1. Location of Study Area.

Figure 2. Map of Study Area with Location of Observation Wells and Arkansas River Stations Used for Sampling Locations in the KGS Study, and Oil and Gas Fields.

Figure 3. Weight Ratio of Br/Cl Versus Chloride Concentration for All Ground Water and Arkansas River Samples. See Table 6 for explanation of symbols.

Figure 4. Weight Ratio of Br/Cl Versus Chloride Concentration for Ground Waters in the Haven Cross-Section Area and Arkansas River Waters. See Table 6 for explanation of symbols.

Figure 5. Weight Ratio of Br/Cl Versus Chloride Concentration for Ground Waters in the Hutchinson Cross-Section Area and Arkansas River Waters. See Table 6 for explanation of symbols.

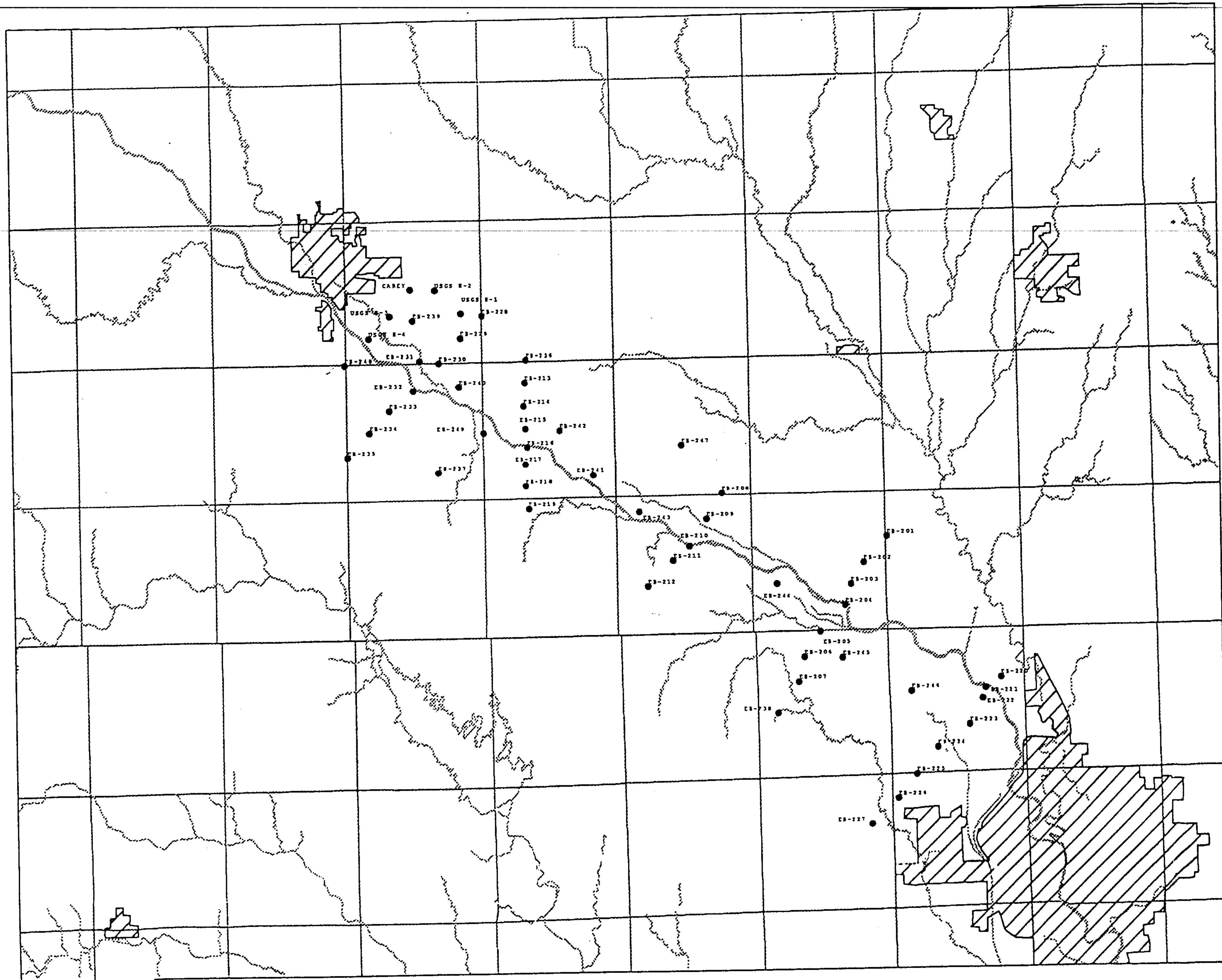
Figure 6. Weight Ratio of Br/Cl Versus Chloride Concentration for Ground Waters in the Bentley and Maize Cross-Section Region and Arkansas River Waters. See Table 6 for explanation of symbols.

Figure 7. Weight Ratio of SO_4/Cl Versus Chloride Concentration for All Ground Water and Arkansas River Samples. See Table 6 for explanation of symbols.

Figure 8. Weight Ratio of I/Cl Versus Chloride Concentration for All Ground Water and Arkansas River Samples. See Table 6 for explanation of symbols.

Figure 9. Weight Ratio of Na/Cl Versus Chloride Concentration for All Ground Water and Arkansas River Samples. See Table 6 for explanation of symbols.

Figure 10. Ratio of (Ca+Mg)/(Na+K) Versus Chloride Concentration for All Ground Water and Arkansas River Samples. The cation ratio is calculated using equivalent/L concentration values. See Table 6 for explanation of symbols.

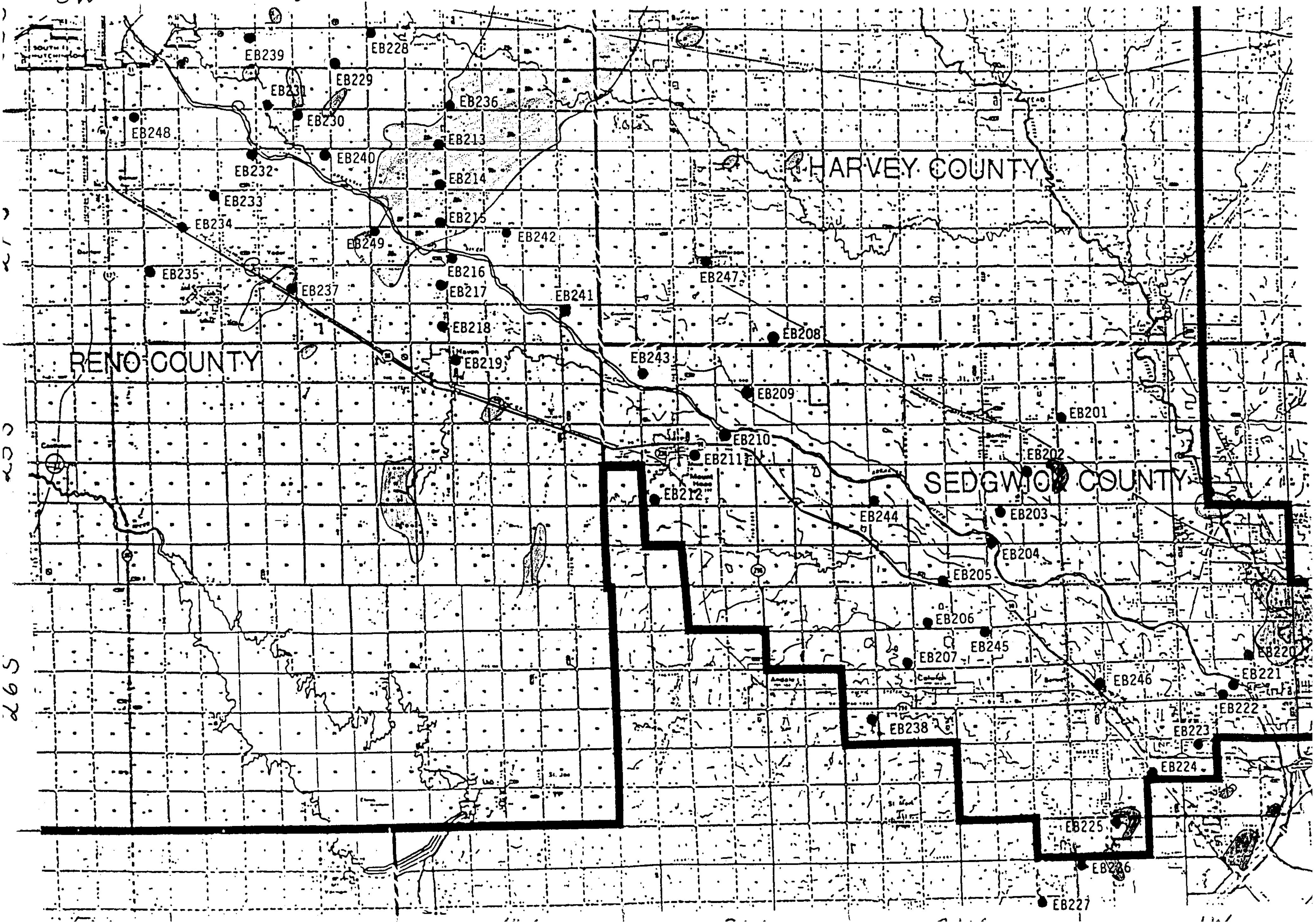


Scale 1:350,000

Fig 1

GROUNDWATER MANAGEMENT DISTRICT NO. 2
ARKANSAS RIVER AND EQUUS BEDS INTERACTION STUDY
HUTCHINSON, HAVEN, MT. HOPE, BENTLEY, AND MAIZE CROSS SECTIONS

Fig 2



Data for all wells

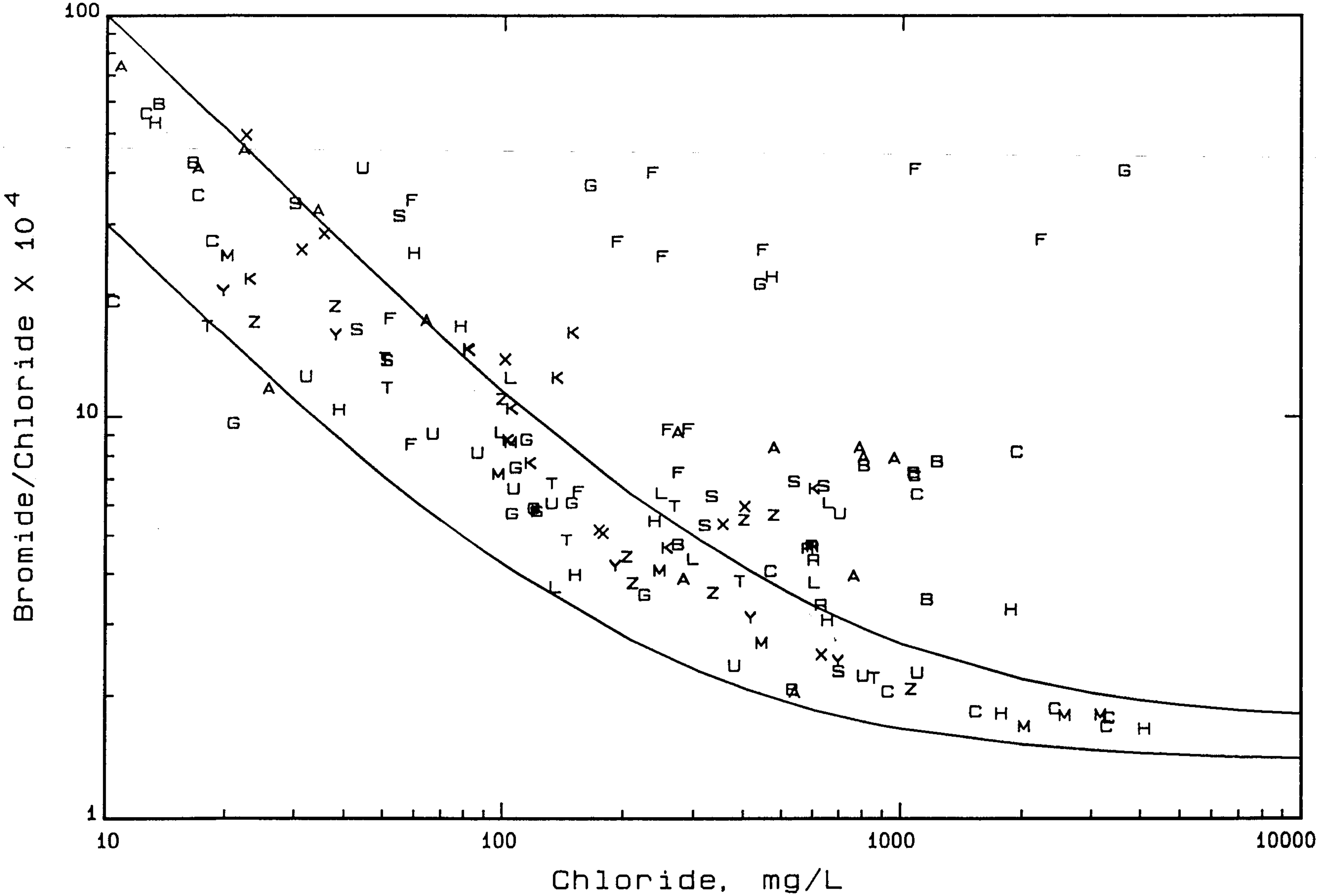


Fig. 3.

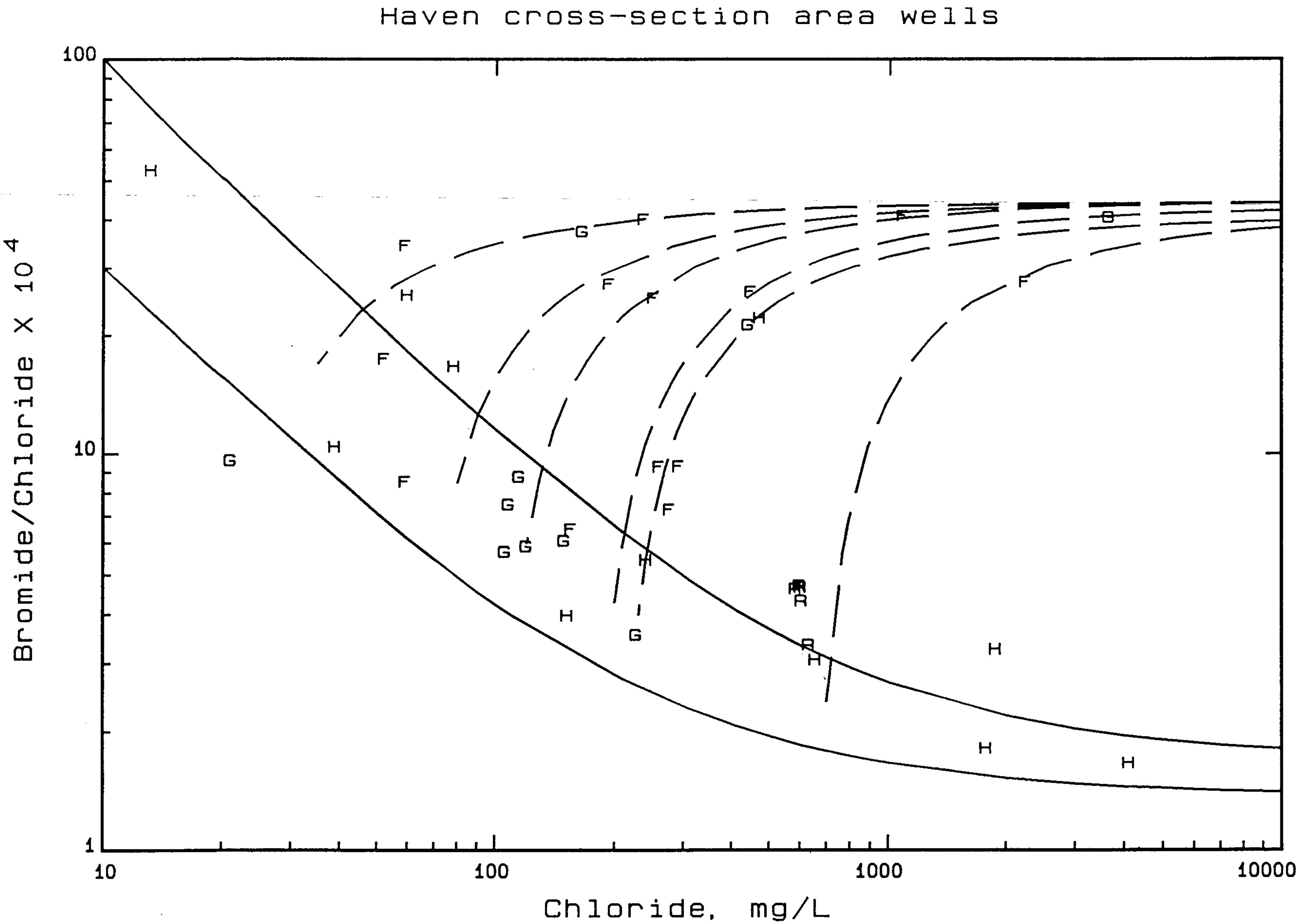
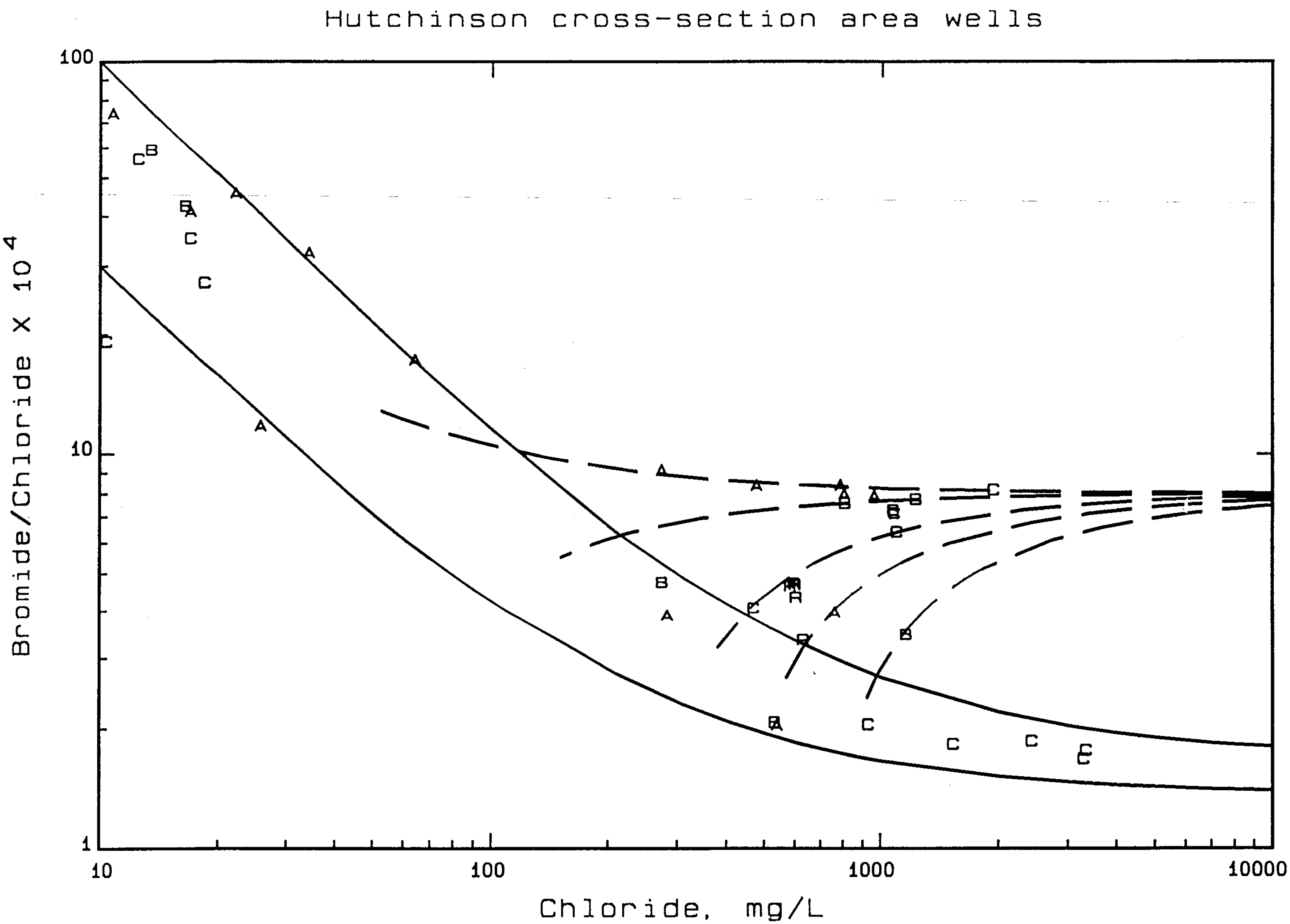

Haven cross-section area wells
Bromide/Chloride X 10^4
Chloride, mg/L
100
10
1
10
100
1000
10000

Fig. 4.



Hutchinson cross-section area wells
Bromide/Chloride X 10^4
100
10
1
10
100
1000
10000
Chloride, mg/L

Fig. 5.

Bentley and Maize cross-section area wells

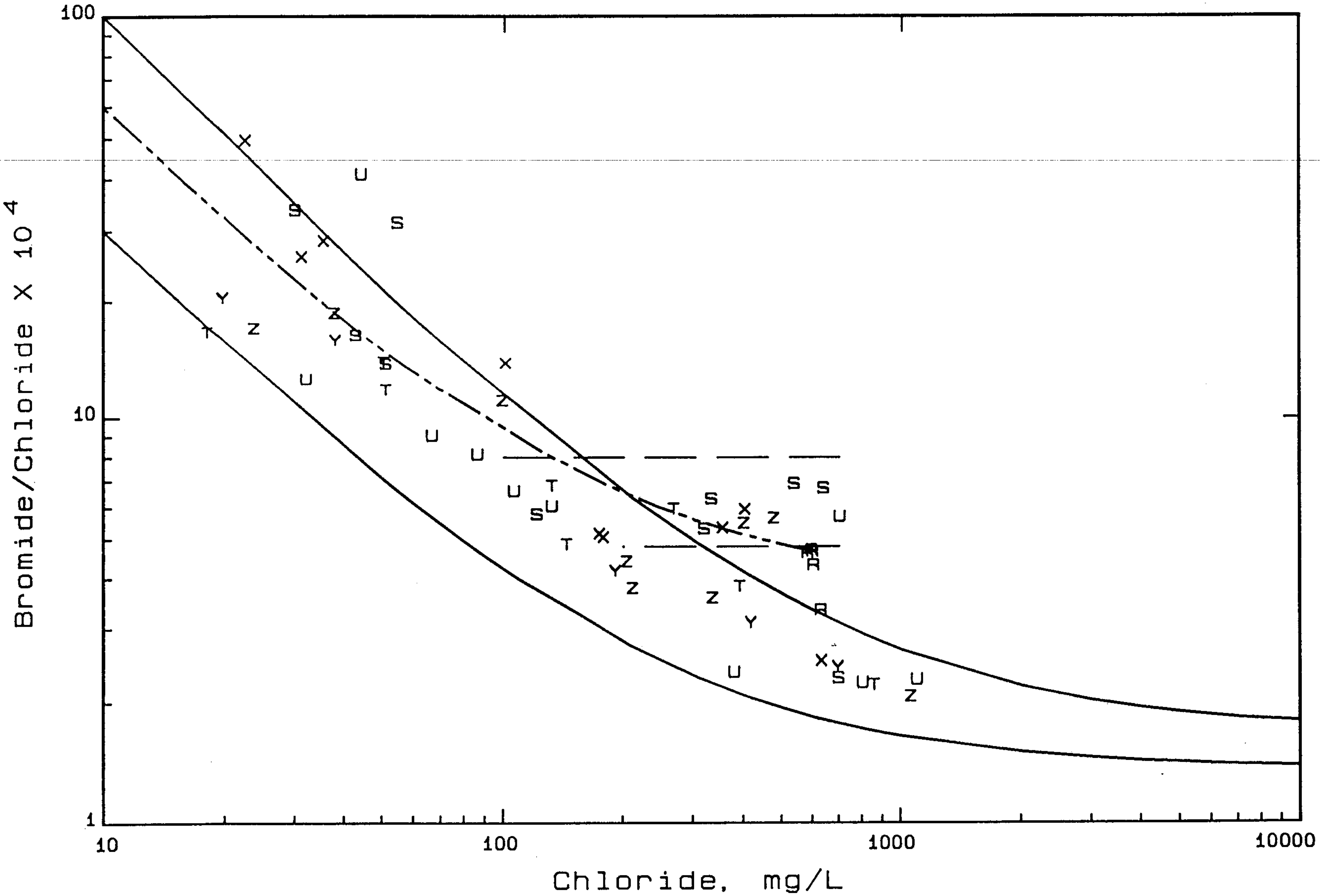


Fig. 6.

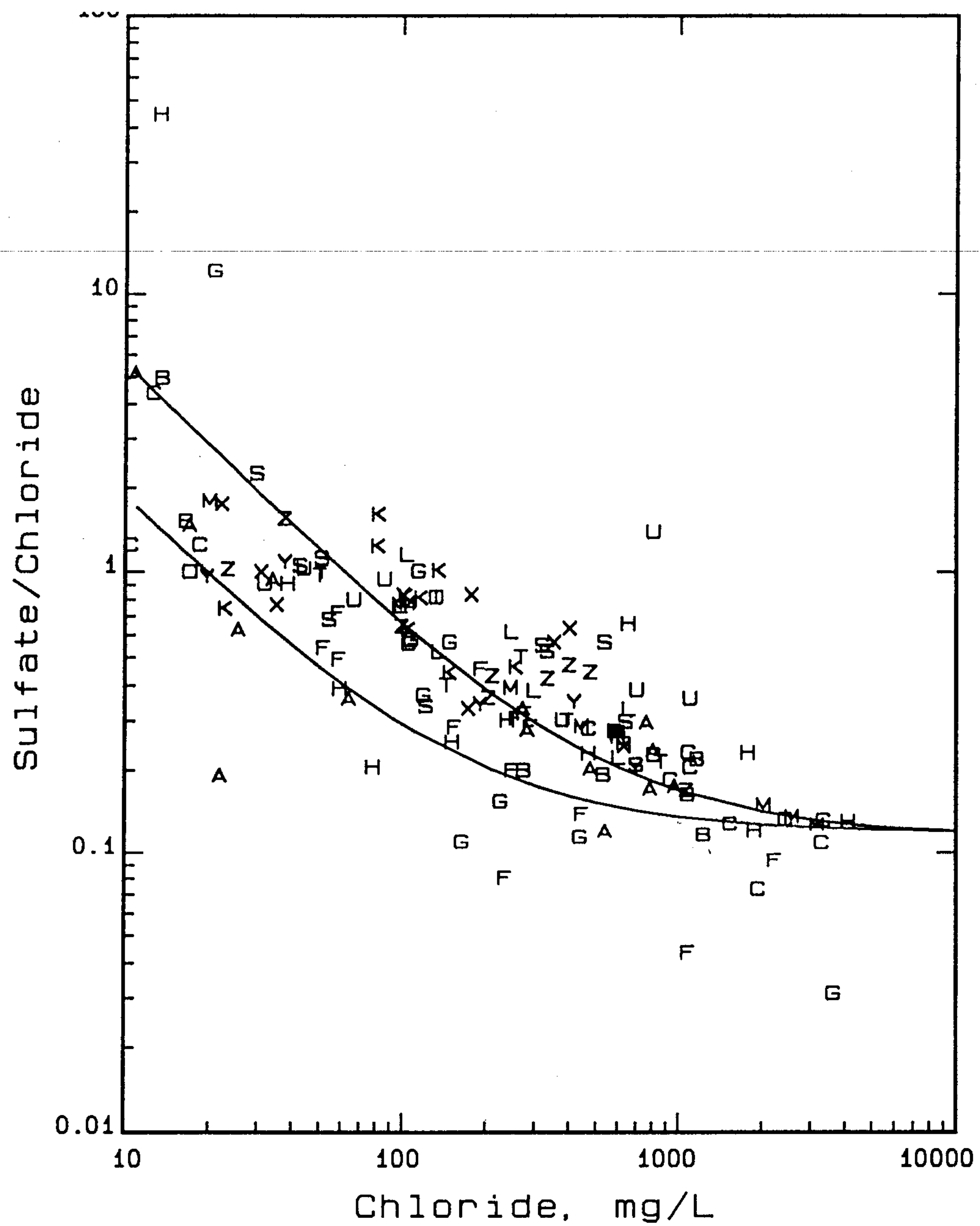


Fig. 7.

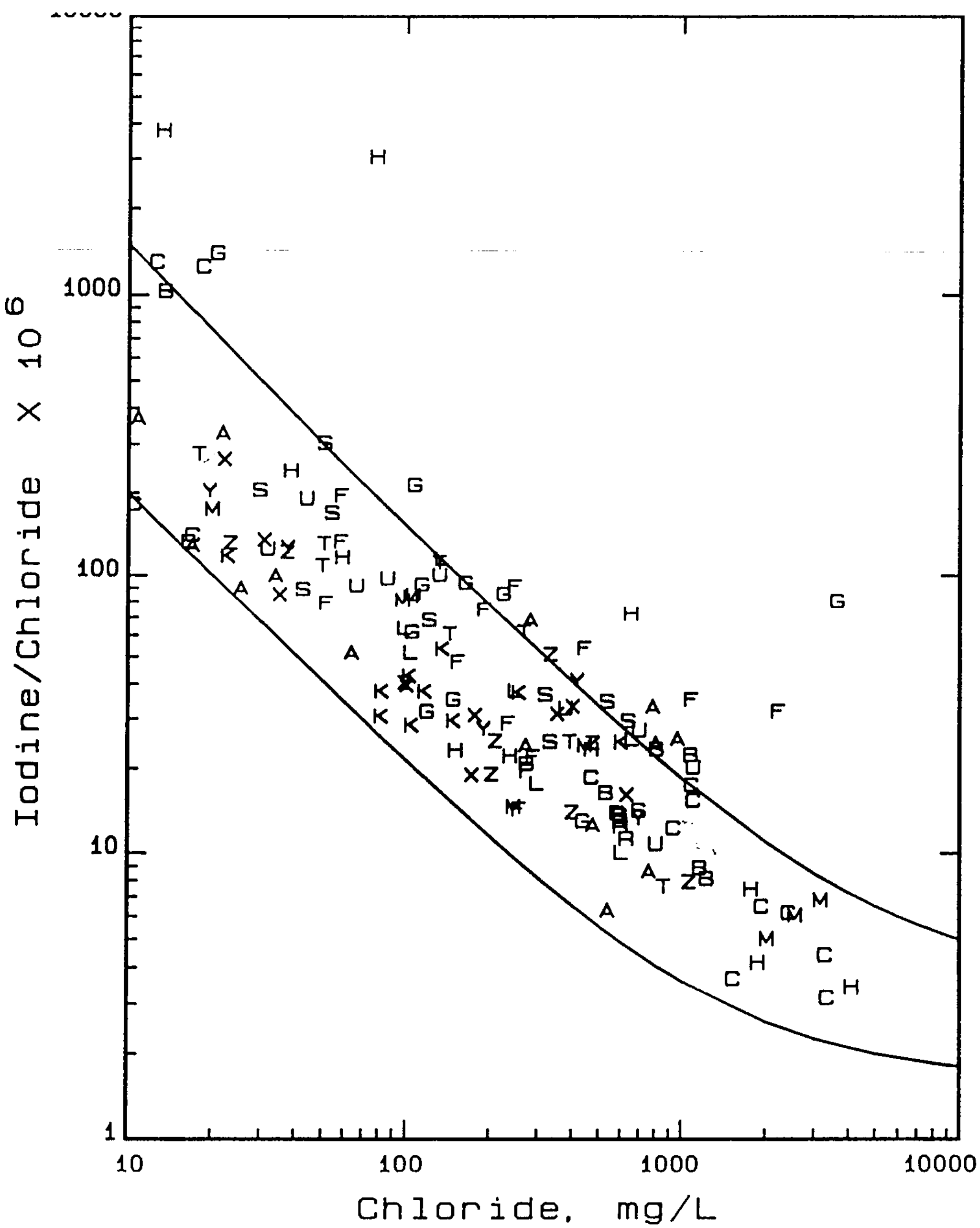

Iodine/Chloride X 10^6
1000
100
10
1
10
100
1000
10000
Chloride, mg/L

Fig. 8.

Data for all wells

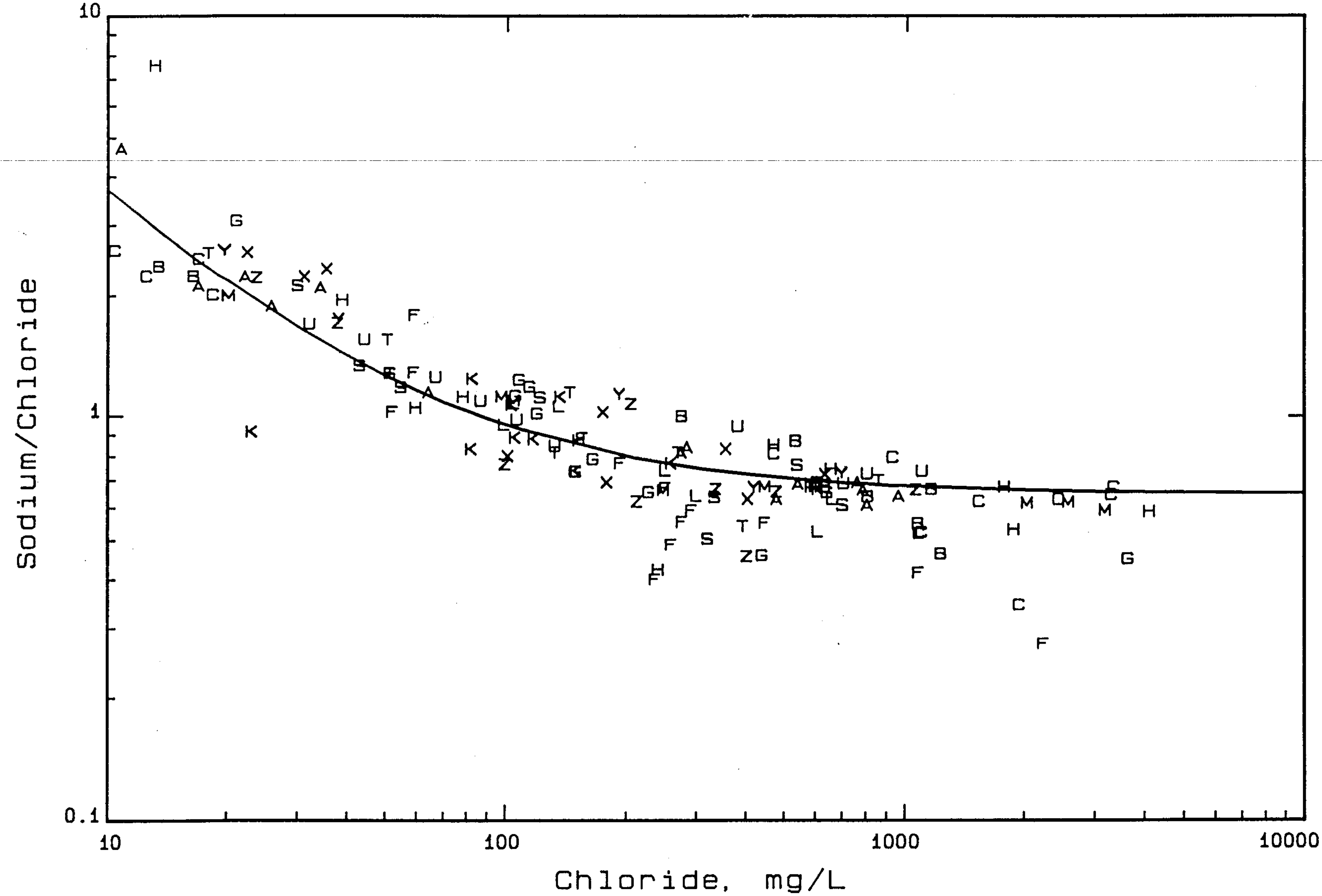


Fig. 9.

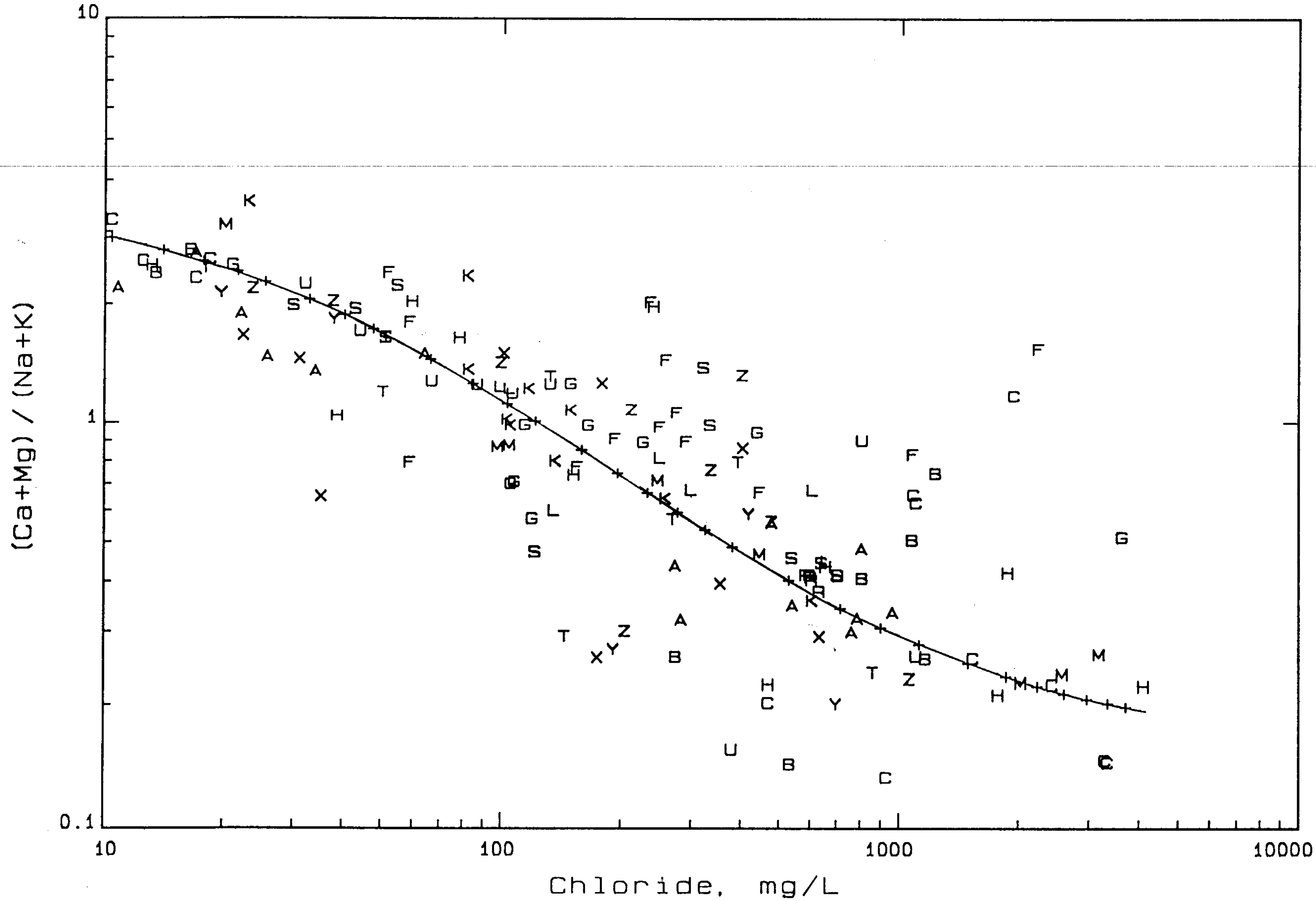


Fig. 10