A Hydrochemical Approach to the Analysis of Ground-Water Flow in the

Spiritwood Aquifer System

Dickey and Parts of LaMoure and Sargent Counties, North Dakota

By

Robert B. Shaver

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Water Resources Investigation No. 1
North Dakota State Water Commission

A HYDROCHEMICAL APPROACH TO THE ANALYSIS OF GROUND-WATER FLOW IN THE SPIRITWOOD AQUIFER SYSTEM, DICKEY COUNTY AND PARTS OF LaMOURE AND SARGENT COUNTIES, NORTH DAKOTA

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ABSTRACT

A hydrochemical approach to the analysis of ground-water flow was applied to a segment of the Spiritwood aquifer system located in southeastern North Dakota. The Spiritwood aquifer is a glacial-drift aquifer which occupies a buried-valley complex. The aquifer consists of sand and gravel interbedded with occasional silt and clay layers. The average thickness of the aquifer based on 163 test holes is 33 feet. The aquifer is buried by a 150-200 foot thick glacial-drift sheet which consists primarily of till. The Pierre and Niobrara Formations of Cretaceous age directly underlie the aquifer in the study area. Partial chemical analyses were made on water samples collected from 122 State Water Commission observation wells, 31 domestic-stock wells, and 10 irrigation wells all of which are completed in the Spiritwood aquifer. In addition, partial chemical analyses were made on water samples collected from seven State Water Commission observation wells, one domestic well, and one irrigation well all of which are completed in overlying fluvial deposits within the glacial drift. The distribution of the major cations (Ca^{2+}, Mg^{2+}, Na^{+}), anions (HCO_3^{-}, SO_4^{2-}, Cl^{-}), and total dissolved solids was examined in relation to the mineralogy, transmissivity, and regional topography. A literature search provided a basic understanding of the chemical processes operative in glaciated-prairie environments. Standard statistical procedures including linear regression were applied to the water-quality data. In addition, Piper and Schoeller diagrams and contour maps of the major chemical constituents were prepared and analyzed. Recharge areas of the aquifer are characterized by a Ca-HCO_3-type water and by dissolved solids concentrations of less than 750 mg/l. Discharge areas or areas of sluggish flow in the aquifer are characterized

by a Na-HCO_3-SO_4-type water, by a significantly higher Cl^- concentration, and by dissolved solids concentrations exceeding 1,000 mg/l. Over most of the study area, the aquifer acts as a buried line sink. Water moves into the aquifer both downward through the overlying drift and upward through the underlying bedrock formations. The mixing process in the aquifer is dominated by the hydrochemical facies of the overlying glacial drift. The variation in water chemistry from top to bottom of the aquifer is minor. In the discharge area associated with Bear Creek valley, ground-water flow is upward through the top of the Niobrara Formation, the Spiritwood aquifer and the glacial drift overlying the Spiritwood aquifer. The mixing process in this area of the aquifer is impacted to a greater extent by the hydrochemical facies of the underlying shale. The variation in water chemistry from top to bottom of the aquifer is large. Over much of the study area the bedrock formation (Pierre Shale or Niobrara Shale) directly underlying the Spiritwood aquifer was determined by the water chemistry of the Spiritwood aquifer. For the most part, high sulfate concentrations occur where the Pierre Formation directly underlies the Spiritwood aquifer. The basal Pembina Member of the Pierre Formation contains appreciable amounts of gypsum and selenite. The hydrochemical analysis resulted in an overall improvement in the conceptual model of the hydrologic system.

INTRODUCTION

Approximately four-fifths of the State of North Dakota is covered by Pleistocene glacial drift. Glacio-fluvial deposits within the drift are the principal aquifers. Individual well yields are high (up to 1000 gpm) and water quality is acceptable for a wide range of applications. In general, these aquifers are characterized by a relatively small saturated thickness (less than 100 feet) and limited areal extent. As a result, an aquifer management program must consider both short term well interference (well spacing) and long term sustained yield. Up to this time, the North Dakota State Water Commission has focused primarily on the problem of short term well interference (well spacing). The thrust of the data collection program has been aimed at defining the geometric and hydraulic properties of the aquifers. The quantification of recharge, leakage, and discharge has either been neglected or treated inadequately.

In the past, the State Water Commission has collected water chemistry data almost solely for the purpose of determining if a water supply is suitable for human consumption or industrial and irrigation applications. Little attention has been given to the origin and distribution of the major cations and anions in the aquifer system. Back (1966) applied the concept of a hydrochemical facies to provide a model for explaining the distribution and origin of principal types of ground water in selected areas. According to Back and Hanshaw (1965), "Hydrochemical facies reflect the effects of chemical processes in the lithologic environment and the prevailing ground-water flow patterns. The mineralogic framework determines which facies will develop, and the vertical and horizontal flow pattern controls the distribution of the facies. The ground-water flow pattern is controlled primarily by the distribution of head within the hydrologic system. The distribution of head is controlled by the relative elevations and locations of recharge and discharge areas and by variations in the transmissivity of the system. Therefore, the three fundamental factors controlling the chemical character of ground water are the mineralogy, transmissivity, and regional topography of the hydrologic system."

The objectives of this investigation are to 1) interpret the distribution of the major cations (Ca^{2+}, Mg^{2+}, Na^{+}) and anions (HCO_3^{-}, SO_4^{2-}, Cl^{-}) in relation to the mineralogy, transmissivity, and regional topography associated with a segment of the Spiritwood aquifer system located in southeastern North Dakota (fig. 1), and 2) evaluate the utility of selected graphical and statistical methods used to analyze a hydrochemical data set. The overall purpose of this report is to further define the factors controlling the distribution of recharge and discharge to the Spiritwood aquifer system by the interpretation of hydrochemical data.

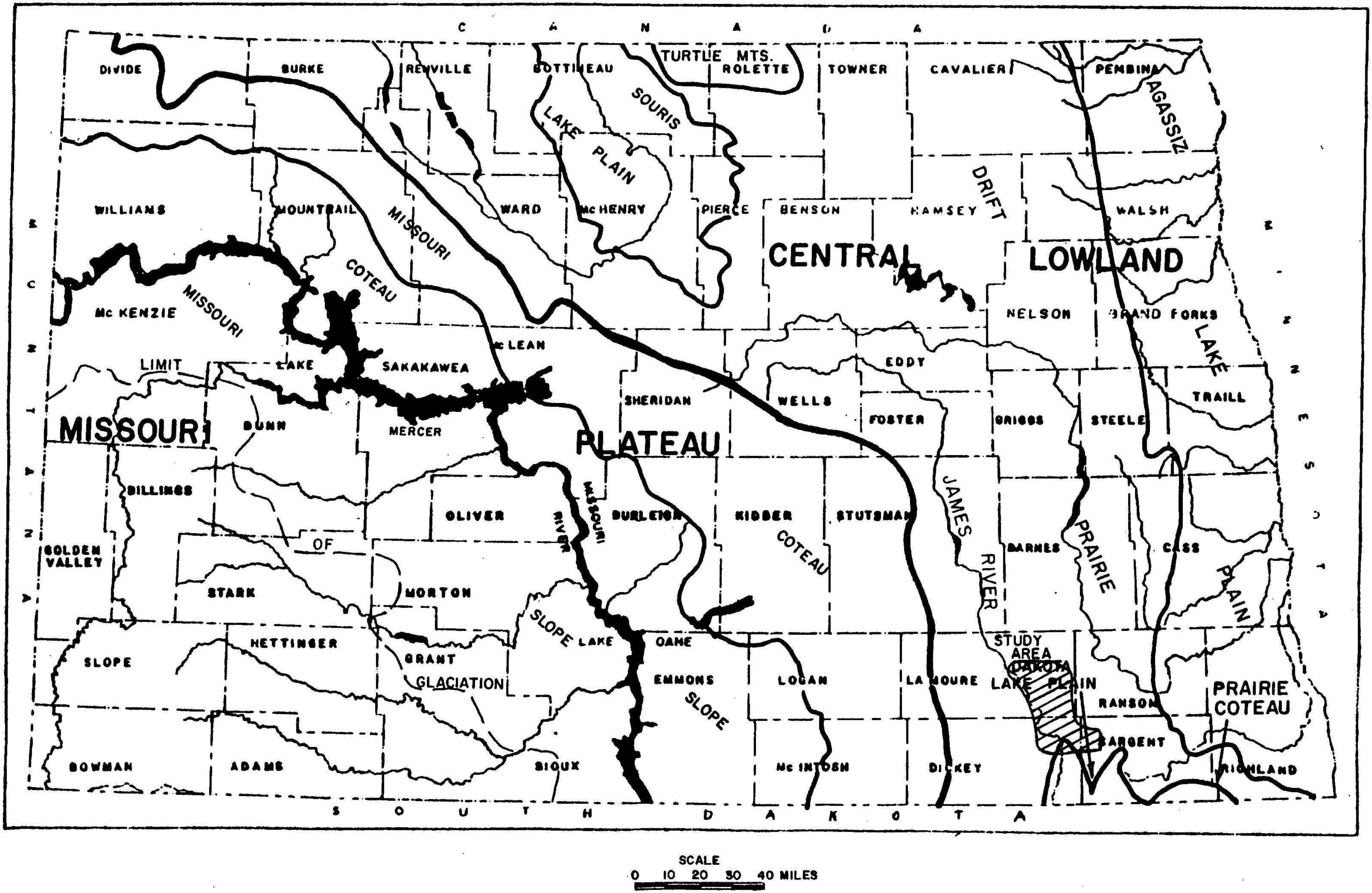


FIGURE 1.—Study area location

LOCATION-NUMBERING SYSTEM

The location-numbering system used in this report is based upon the location of a well or test hole in the Federal system of rectangular surveys of public lands (fig. 2). The first number denotes the township north of a baseline and the second number denotes the range west of the Fifth Principal Meridian. The third number indicates the section in which the well or test hole is located. The letters a, b, c, and d designate, respectively, the northeast, northwest, southwest, and southeast quarter section, quarter-quarter section, and quarter-quarter-quarter section (10 acre tract). Thus well 131-59-12AAA would be located in the NE¼NE¼NE¼ Section 12, Township 131 North, Range 59 West. Consecutive terminal numerals are added if more than one well is located within a 10 acre tract.

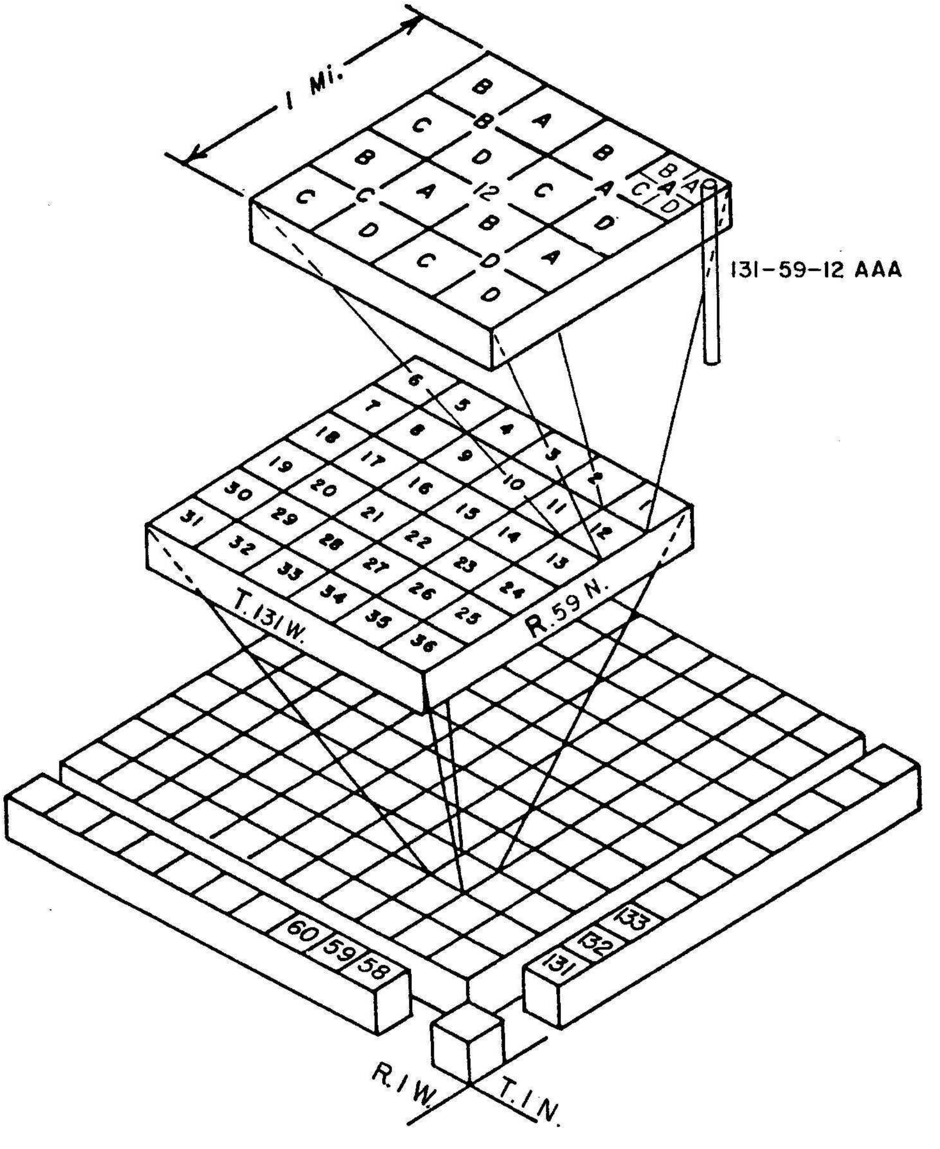


FIGURE 2.—Location-numbering system

METHODS OF INVESTIGATION

Partial chemical analyses were made on samples gathered from 122 State Water Commission observation wells, 31 domestic/stock wells, and 10 irrigation wells, all of which are completed in the Spiritwood aquifer within the study area (table 1). Partial chemical analyses were made on seven State Water Commission observation wells, one domestic well, and one irrigation well, all of which are completed in glaciofluvial deposits overlying the Spiritwood aquifer (table 2). Partial chemical analyses were made on four domestic/stock wells all of which are completed in the Niobrara Formation (table 3). Piezometer nests were completed at four sites in the study area to assess vertical variation in water chemistry within the Spiritwood aquifer and the overlying glacial drift. Partial chemical analyses from the wells completed at these nest sites are shown in Table 4.

The water samples were collected and analyzed over a period from 1974 to 1984. Temporal variations in water quality are possible within the study area and may affect the overall identification of hydrochemical facies. Davison and Vonhof (1978) investigated temporal hydrochemical variations in a semi-confined buried-channel aquifer. The semi-confining unit consisted of a fractured sandy till. The average thickness of the till was 45 feet over the study area. Temporal hydrochemical variation was larger in the shallow wells screened in the top of the aquifer just below the till than in the deeper wells screened near the base

TABLE 1 -- Chemical analyses Spiritwood aquifer

(Analytical results are in milligrams per liter except where indicated)

Location	Depth of Well (feet)	Date of Collection	(SiO_2)	(Fe)	(Mn)	(Ca)	(Mg)	(Na)	(K)	(HCO_3)	(CO_3)	(SO_4)	(Cl)	(F)	(NO_3)	(B)	Total Dissolved Solids	Total Hardness		Percent Sodium	SAR	Specific Conductance	pH
																		as $CaCO_3$	Noncarbonate				
130-57- 5BBB$_1$	153-156	9-21-77	34	1.9	.56	98	26	110	7.4	436	0	230	14	0.2	1.0	.52	739	350	0	40	2.6	955	8.0
130-57- 8DDD$_1$	143-146	4-26-78	32	2.1	.16	82	28	150	7.6	387	0	220	71	0.3	0.4	.68	785	320	3	50	3.6	1220	7.6
130-57-17BBB	198-201	7-24-80	37	1.5	.15	120	29	130	7.4	381	0	300	79	0.2	1.0	.14	893	420	110	40	2.8	1310	7.7
131-57-31CCC	198-201	7-24-80	45	.80	.07	84	34	140	7.3	506	0	220	28	0.4	0.5	.17	809	350	0	46	3.2	1170	8.0
131-58-20BBB	188-191	7-23-80	38	.40	.08	69	24	200	6.8	522	0	210	61	0.4	1.0	.44	868	270	0	61	5.3	1290	8.0
131-58-27AAA	208-211	11- 6-75	21	.25	.58	110	35	67	8.0	446	0	160	16	0.2	0.6	.48	639	420	54	25	1.4	1020	7.6
131-58-32BCC$_1$	148-151	7-23-80	32	.38	.01	13	16	340	6.4	601	0	230	95	0.8	0.1	1.1	1030	100	0	87	15.0	1570	8.2
131-58-34BBB	158-161	11- 6-75	22	.87	.06	51	23	190	8.9	487	0	160	52	0.4	2.4	.88	752	220	0	64	5.6	1210	7.6
132-58-16BBA$_2$	166-169	5-22-75	22	.84	.04	44	17	800	14	558	0	1.6	1080	0.9	3.0	2.2	2260	180	0	90	26	4100	8.1
132-58-21BBB$_1$	178-181	5-21-75	20	3.2	.04	53	21	840	12	674	0	1.6	1090	1.0	1.0	.43	2380	220	0	89	25	4230	7.9
132-58-30DAA	147-152	10- 4-82	30	.32	.02	20	8.5	820	17	550	0	0.0	860	0.8	6.6	2.0	2040	85	0	94	39	3540	8.1
132-58-31AAA	150-155	10- 7-82	29	.22	.06	23	9.5	460	14	624	0	140	290	0.7	6.7	.67	1280	96	0	90	20	2150	8.2
131-59- 1DDA	163-166	5-14-76	32	1.3	.16	57	24	240	8.0	529	0	230	73	0.5	0.8	1.2	929	240	0	68	6.7	1460	7.7
131-59- 1CCC	172-175	10-27-76	29	1.6	.22	58	23	260	6.9	529	0	260	93	0.4	1.0	1.7	996	240	0	69	7.3	1470	8.2
131-59- 2AAA	158-161	9-27-74	19	2.1	.26	65	21	220	8.1	520	0	230	61	0.7	1.0	.98	890	250	0	65	6.1	1430	7.7
131-59- 2BCC	176-186	9-14-82	30	3.5	.34	54	17	250	12	520	0	210	72	0.6	4.5	1.5	911	205	0	71	7.7	1430	8.1
131-59- 2CCC	?	8- 4-83	31	1.0	.39	51	18	230	9.0	535	0	230	70	0.8	0.3	0.7	906	201	0	70	7.1	1450	7.8
131-59- 3BAA	197-200	9- 4-81	21	.44	.19	46	26	270	11	545	0	260	93	0.9	1.0	0.8	998	220	0	72	7.9	1460	8.0
131-59- 4AAD	151-157	8- 3-83	31	1.5	.21	52	18	250	9.7	532	0	250	46	0.6	0.1	.68	922	204	0	72	7.7	1410	7.7
131-59- 5AAA	187-190	9- 4-81	30	.71	.12	45	31	210	12	553	0	200	46	0.5	1.0	.68	849	240	0	64	5.9	1240	7.9
131-59- 5BAA$_1$	166-171	9-22-82	27	.28	.19	40	19	220	13	509	0	180	33	0.5	7.6	.42	792	178	0	71	7.1	1250	8.1
131-59- 5BBB	158-161	10- 1-74	19	.29	.10	42	21	200	9.3	490	0	200	31	0.6	7.4	1.1	773	190	0	68	6.3	1220	8.0
131-59- 8ABB	155-160	9-21-82	29	.58	.03	36	16	230	12	501	0	190	38	0.6	6.2	.74	806	156	0	74	7.9	1250	8.0
131-59-10BBA	196-199	11-17-76	29	.92	.12	48	17	250	7.0	536	0	240	56	0.5	1.0	.89	914	190	0	73	7.9	1350	8.2
131-59-10ADD	TD=210	8- 2-83	31	0.1	.14	58	16	260	9.9	516	0	250	82	0.5	1.0	.81	963	211	0	72	7.8	1480	8.0
131-59-11AAC	184-214	8- 2-83	34	1.3	.17	58	22	260	9.9	512	0	250	85	0.5	0.2	.75	974	235	0	70	7.3	1500	7.9
131-59-12CCC$_1$	211-231	8- 4-83	31	.95	.24	60	24	230	9.7	500	0	260	99	0.5	7.6	.68	970	248	0	66	6.3	1550	7.8
131-59-12CCC$_2$	208-211	11-17-76	29	1.2	.24	57	21	270	7.3	521	9	250	89	0.4	1.0	1.1	993	230	0	71	7.7	1460	8.4
131-59-15AAA	188-194	9-27-74	26	.51	.24	61	21	240	8.6	560	0	210	78	0.7	8.3	1.2	932	240	0	68	6.7	1480	7.6
131-59-15BBB	178-184	9-25-74	19	2.1	.22	51	18	300	8.3	630	0	180	110	0.8	0.4	1.2	1000	200	0	76	9.2	1630	7.9
131-59-15DCA	161-186	7-15-77	13	.83	.18	58	18	130	6.8	440	0	110	33	0.4	1.0	.59	589	220	0	55	3.8	1010	8.1
131-59-16CCC	164-204	8- 3-77	23	1.6	.08	40	15	210	7.1	509	0	130	63	0.3	2.5	1.0	745	160	0	73	7.2	1180	8.3
131-59-17DCC	121-124	11- 5-76	28	.79	.48	82	23	100	7.1	439	0	120	41	0.2	1.0	.83	620	300	0	41	2.5	943	8.2
131-59-22ABB	197-200	9-21-82	28	.85	.29	82	18	67	7.2	369	0	46	12	0.2	3.6	.24	447	279	0	34	1.7	683	7.9
131-59-22BAA	196-199	9-15-76	32	.79	.34	59	18	40	5.5	304	18	33	4.9	0.1	1.0	.26	363	220	0	28	1.2	556	8.7
131-59-22BAD	213-216	9-15-76	33	.65	.24	55	15	100	6.2	377	20	66	17	0.2	1.0	.34	501	200	0	51	3.1	759	8.7

TABLE I.—cont.

Location	Depth of Well (feet)	Date of Collection	(SiO_2)	(Fe)	(Mn)	(Ca)	(Mg)	(Na)	(K)	(HCO_3)	(CO_3)	(SO_4)	(Cl)	(F)	(NO_3)	(B)	Total Dissolved Solids	Total Hardness		Percent Sodium	SAR	Specific Conductance	pH
																		as $CaCO_3$	Noncarbonate				
131-59-22BDA$_1$	215-218	9-15-76	32	.69	.40	81	26	32	4.5	340	17	73	6.2	0.2	1.0	.23	441	310	3	18	0.8	661	8.6
131-59-22BDA$_2$	212-215	9-15-76	30	.63	.52	80	27	20	4.9	330	11	65	4.4	0.0	1.0	.23	408	310	21	12	0.5	627	8.5
131-59-22BDA$_3$	199-224	9-21-76	31	1.3	.44	78	23	86	6.2	423	0	110	24	0.1	0.2	0.3	569	290	0	39	2.2	858	8.2
131-59-22CCA	TD=172	7-27-76	31	1.4	0.6	81	29	9.6	5.9	381	0	40	2.5	0.6	1.0	.11	391	320	8	6	.23	527	8.2
131-59-22DCA	137-157	7-31-75	20	.44	.58	63	30	18	5.9	292	0	62	5.1	0.6	2.5	0.0	352	280	40	12	0.5	571	7.9
131-59-22CBB$_1$	158-161	7-27-82	27	0.0	.42	60	17	95	8.6	384	0	96	12	0.4	1.0	.29	507	220	0	47	2.8	796	7.9
131-59-27CBB$_1$	127-132	1-19-83	31	.32	.05	21	9.5	480	11	668	0	92	290	1.0	1.0	1.6	1270	92	0	91	22	2060	8.3
131-59-35BCC$_1$	125-130	7-28-82	28	.42	.06	22	8.0	370	10	612	0	150	150	1.4	1.0	.74	1040	88	0	89	17	1040	8.2
132-59- 3CCC	118-121	10-30-74	21	.19	.72	63	25	260	11	550	0	310	60	0.4	0.3	1.2	1020	260	0	67	7.0	1700	7.6
132-59- 4BBA	165-170	7-29-83	32	2.6	.65	120	33	150	12	533	0	290	28	0.2	1.0	.57	933	435	0	42	3.1	1350	7.8
132-59- 4CCB	174-178	1- 3-84	27	.69	.54	89	29	83	10	487	0	100	14	0.3	1.0	.54	595	342	0	34	2.0	952	8.0
132-59- 4CCC	195-198	8- 1-79	29	.06	.22	69	24	260	9.4	516	0	330	67	0.4	1.0	.97	1050	270	0	67	6.9	1560	7.9
132-59- 4DCC	158-161	8- 1-79	29	.02	.44	87	25	230	9.5	558	0	330	35	0.3	1.0	1.2	1020	320	0	60	5.6	1500	7.9
132-59- 9CDD	162-165	7-23-80	30	.17	.32	91	30	210	8.8	540	0	290	39	0.5	0.4	.92	967	350	0	56	4.9	1430	7.9
132-59-17DCD$_1$	188-193	9-22-82	29	.06	.14	36	15	270	12	513	0	200	71	0.7	8.5	.83	896	152	0	78	9.6	1420	8.1
132-59-18DCC	245-250	9-22-82	25	.73	.43	100	29	42	9.8	435	0	100	4.1	0.2	4.7	.22	530	369	13	19	0.9	845	7.9
132-59-19AAA	238-241	8- 1-79	29	.65	.24	36	15	270	8.9	540	0	230	45	0.5	1.0	1.2	903	150	0	78	9.6	1390	8.0
132-59-21BBA	213-216	7-12-79	7.9	.24	.44	93	29	84	8.9	452	0	130	13	0.2	1.0	.37	591	350	0	34	1.9	933	7.9
132-59-21BAA	150-165	9-14-82	29	.94	.22	49	22	270	13	527	0	250	73	0.6	0.3	1.6	970	213	0	72	81	1520	8.0
132-59-21C	195-210	7-14-77	13	1.1	.24	67	25	180	8.5	519	0	220	29	0.4	1.0	.94	802	270	0	58	4.8	1230	8.0
132-59-23BAB	155-165	9-15-82	32	.98	.05	32	21	330	13	586	0	210	120	0.7	5.5	.073	1050	167	0	80	11	1720	8.0
132-59-27ADD	156-159	7-23-80	32	.10	.15	56	22	290	7.7	593	0	290	69	0.5	0.6	.99	1060	230	0	72	8.3	1610	8.1
132-59-27CDC$_1$	209-214	3- 8-83	31	.32	.21	45	14	370	10	484	0	380	150	1.3	1.0	.74	1240	170	0	81	12	1970	8.0
132-59-28B	200-225	7-14-77	13	1.2	.42	90	28	97	7.5	460	0	170	15	0.3	1.0	.31	651	340	0	38	23	1000	8.1
132-59-29DAA	183-188	9-14-82	29	1.4	.52	100	28	18	7.9	390	0	100	3.5	0.2	0.1	.18	481	365	45	9	0.4	762	7.8
132-59-33CBC	170-180	8- 3-83	34	1.4	.12	69	23	160	10	474	0	200	16	0.5	5.5	.62	753	267	0	55	4.2	1130	7.7
132-59-32CCC	177-182	9-14-82	31	1.4	.07	42	21	200	13	488	0	170	30	0.5	0.2	1.1	750	192	0	68	6.3	1190	8.0
132-59-33CCC	170-180	9-14-82	31	1.1	.12	51	25	200	14	518	0	200	25	0.6	7.8	1.1	812	230	0	64	5.7	1280	8.0
132-59-32DAA	203-208	8- 4-83	31	.91	.15	59	23	210	11	511	0	240	26	0.6	1.4	.62	856	242	0	64	5.9	1300	7.7
132-59-35CCC	177-180	9- 4-81	30	.31	.34	53	26	240	11	533	0	230	89	0.5	1.0	.85	945	240	0	67	6.7	1390	8.2
132-59-35ABC	172-187	8- 2-83	33	1.4	.34	64	26	260	10	548	0	240	74	0.4	0.3	0.7	980	267	0	67	6.9	1530	7.8
132-59-36BCC	154-157	8- 2-83	30	2.7	.16	57	21	260	9.9	574	0	250	76	0.5	4.8	.62	996	229	0	70	7.5	1550	7.7
133-59- 4AAA	342-345	8-27-81	30	.06	1.3	65	24	350	15	223	0	150	480	0.3	1.0	0.3	1230	260	77	73	9.5	2050	8.0
133-59- 4DCC	205-210	9- 7-83	32	.02	.16	68	28	260	13	416	0	390	100	0.5	1.3	1.2	1100	285	0	65	6.8	1730	8.0
133-59- 5CDD$_1$	197-202	9- 7-83	32	.32	.17	51	19	250	9.9	479	0	320	36	0.5	1.0	1.1	957	205	0	71	7.5	1470	8.0
133-59- 6CBC	233-243	7-26-83	29	2.5	.25	57	26	190	9.5	511	0	220	48	0.4	0.1	.64	835	249	0	61	5.2	1300	7.8

TABLE I.—cont.

Location	Depth of Well (feet)	Date of Collection	(SiO_2)	(Fe)	(Mn)	(Ca)	(Mg)	(Na)	(K)	(HCO_3)	(CO_3)	(SO_4)	(Cl)	(F)	(NO_3)	(B)	Total Dissolved Solids	Total Hardness as $CaCO_3$	Total Hardness Noncarbonate	Percent Sodium	S A R	Specific Conductance	pH
133-59- 6DDD	197-202	9- 8-83	31	.51	.09	45	21	270	9.5	512	0	260	100	0.6	1.0	.26	991	199	0	74	8.3	1600	8.0
133-59- 7BAA$_1$	292-297	9- 8-83	32	.06	.28	56	28	270	9.7	573	0	160	150	0.6	1.0	.68	990	255	0	69	7.4	1620	8.2
133-59- 7BAA$_2$	197-202	9- 8-83	34	.47	.32	51	24	250	9.5	468	12	160	150	0.6	1.0	.48	924	226	0	70	7.2	1510	8.4
133-59- 7DAA	216-225	10- 4-82	30	2.1	.32	51	25	240	10	481	0	290	32	0.7	7.3	1.2	927	230	0	68	6.9	1400	7.8
133-59- 9ADA	200-210	7-26-83	26	1.1	.23	75	22	250	13	450	0	400	64	0.5	0.0	.76	1070	278	0	65	6.5	1590	7.6
133-59- 9BBB$_1$	211-216	9- 7-83	31	.20	.13	75	31	240	11	416	0	430	63	0.6	1.0	.64	1090	315	0	61	5.9	1640	8.1
133-59-14CCC	167-170	8-27-81	30	.58	.24	82	33	240	12	502	0	380	57	0.5	1.0	.68	1080	840	0	60	5.7	1520	7.9
133-59-14CDD	167-170	8-27-81	30	1.2	.56	96	36	230	13	475	0	340	100	0.4	1.0	.35	1080	390	0	55	5.1	1550	7.7
133-59-15AAA	167-170	8-27-81	31	.94	.37	82	38	230	14	480	0	330	100	0.4	1.0	.65	1060	360	0	57	5.3	1550	7.8
133-59-15CCC	188-191	9-25-75	21	1.5	.07	84	32	180	9.2	562	0	250	22	0.5	0.0	5.1	882	340	0	53	4.2	1350	7.7
133-59-19BAA	196-199	8-27-81	31	1.5	.16	86	43	130	12	530	0	210	33	0.3	1.0	0.0	809	390	0	41	2.9	1130	7.8
133-59-20BBB	197-200	8-25-81	30	.20	.13	56	32	270	12	550	0	240	120	0.5	1.0	.45	1030	270	0	67	7.2	1510	8.1
133-59-20ABB	197-200	8-25-81	30	.33	.32	78	40	180	12	555	0	240	40	0.4	1.0	.05	895	360	0	51	4.1	1290	7.9
133-59-21BAA	231-234	8-26-81	31	.27	.35	94	43	110	10	562	0	160	27	0.3	1.0	0.0	754	410	0	36	2.4	1070	8.1
133-59-26ADD	176-187	8-27-82	25	.50	.32	22	55	350	13	415	0	340	100	1.3	0.4	2.1	1060	78	0	89	17.0	1700	8.1
133-59-27CCC$_1$	164-169	8-26-82	28	.25	.12	55	19	300	20	472	0	410	44	0.5	0.5	1.5	1110	215	0	73	8.8	1680	7.9
133-59-27CCC$_2$	178-183	9-14-82	29	.80	.33	64	18	280	15	482	0	380	31	0.5	0.3	1.6	1060	234	0	71	8.0	1560	7.8
133-59-27DCC	168-173	8-26-82	28	1.1	.10	73	33	170	12	530	0	230	17	0.5	0.0	.74	826	318	0	53	4.1	1270	8.0
133-59-28CDD	204-209	8-27-82	26	.44	.08	54	27	220	13	490	0	250	50	0.7	7.5	1.2	891	246	0	65	6.1	1380	8.1
133-59-28CCC	195-200	8-27-82	27	.66	.11	53	25	250	13	498	0	210	110	0.6	0.2	1.2	936	235	0	68	7.0	1490	7.9
133-59-29DCC	198-203	9-23-82	28	1.2	.11	65	23	180	13	495	0	200	17	0.4	6.3	.95	779	257	0	59	4.9	1200	8.0
133-59-30CDD	214-219	9-23-82	29	1.4	.11	71	37	180	13	528	0	240	24	0.5	10.0	8.5	867	329	0	53	4.3	1330	8.0
133-59-30CCC	225-230	9-23-82	29	.43	.25	67	26	140	11	482	0	170	19	.05	5.0	.75	706	274	0	51	3.7	1090	8.1
133-59-31AAA	TD=223	9-15-82	29	5.2	.15	68	30	190	14	516	0	260	19	0.5	6.9	.69	877	294	0	57	4.8	1320	7.9
133-59-31DDB	TD=237	9-15-82	30	3.9	.11	62	32	190	14	516	0	260	26	0.5	7.7	.71	881	286	0	58	4.8	1340	8.0
133-59-32BBB	198-201	9-25-75	20	1.5	.20	61	29	190	10	496	0	250	19	0.5	4.2	4.5	834	270	0	59	5.0	1270	7.7
133-59-34AAA$_3$	TD=165	9-14-82	31	1.7	.24	77	28	200	12	527	0	270	28	0.6	4.9	1.2	915	307	0	57	4.9	1400	7.9
133-59-34AAA$_2$	168-173	8-26-82	27	1.2	.17	79	31	220	12	511	0	320	37	0.6	0.9	1.1	982	325	0	58	5.3	1490	7.5
133-59-35AAA	193-198	8-26-82	27	1.4	.30	70	28	250	12	420	0	350	59	0.7	0.0	1.1	1030	290	0	64	6.4	1590	8.3
133-59-35ABB	162-165	8-28-81	30	.84	.47	76	34	250	12	542	0	330	72	0.6	1.0	.58	1070	330	0	61	6.0	1550	7.9
134-59-31CBB	177-182	11- 2-83	28	.46	.04	28	11	280	11	475	0	300	23	0.5	11.0	1.2	928	115	0	83	11.4	1640	7.8
134-59-31CCC	178-184	5-22-75	21	.68	.04	33	21	260	6.8	486	0	300	39	.06	1.0	1.4	924	170	0	76	8.7	1430	8.1
132-60- 1DCC	203-208	9-23-82	28	.59	.09	57	30	220	15	515	0	260	28	0.5	11.0	.74	905	266	0	63	5.8	1390	8.0
132-60-10BAA	203-208	8-26-82	28	.03	.23	33	12	260	11	594	0	170	46	0.8	0.0	1.3	855	132	0	79	9.9	1340	8.1
132-60-11BAA	203-208	9-23-82	27	.08	.68	84	26	170	15	489	0	260	15	0.4	6.3	.61	846	317	0	52	4.1	1270	8.1
132-60-12BBB	210-216	8- 1-79	30	.06	.16	61	17	120	9.2	467	0	92	19	0.3	1.0	.67	580	220	0	53	3.5	902	8.0

TABLE 1.–cont.

Location	Depth of Well (feet)	Date of Collection	(SiO_2)	(Fe)	(Mn)	(Ca)	(Mg)	(Na)	(K)	(HCO_3)	(CO_3)	(SO_4)	(Cl)	(F)	(NO_3)	(B)	Total Dissolved Solids	Total Hardness as $CaCO_3$	Total Hardness Noncarbonate	Percent Sodium	SAR	Specific Conductance	pH
133-60- 1CCC	209-214	9- 8-83	32	1.8	.43	110	33	57	9.0	395	0	160	5.6	0.3	1.0	.20	605	410	0	23	1.2	893	8.1
133-60- 1DDD	193-196	11-16-76	31	.17	.26	63	25	230	7.6	554	12	140	110	.05	0.4	1.1	894	260	0	65	6.2	1370	8.4
133-60- 2BCC	230-240	10- 5-82	30	.63	.14	54	25	220	11	456	0	280	34	0.7	6.2	.96	888	238	0	66	6.2	1340	8.1
133-60- 2CDD	255-260	9- 8-83	32	1.1	.17	83	32	200	12	452	0	250	110	0.3	1.0	.51	945	339	0	55	4.7	1450	8.2
133-60- 4DCC	211-216	11- 2-83	28	.49	.06	46	24	230	12	473	0	270	29	0.5	0.7	.90	875	214	0	69	6.9	1370	7.8
133-60- $5DAA_1$	217-222	1- 4-84	28	.23	.07	53	28	190	12	487	8	210	31	0.4	1.0	.71	802	247	0	61	5.2	1240	8.4
133-60-10ABB	220-225	7-28-83	32	.79	.09	58	32	180	11	472	0	270	32	0.5	0.0	.64	850	276	0	57	4.7	1290	7.8
133-60-$10BBB_1$	227-232	9- 8-83	32	.24	.08	52	25	210	13	443	0	320	23	0.4	1.0	1.1	896	233	0	65	6.0	1350	7.8
133-60-10DDC	204-210	9-15-82	27	1.1	.06	27	13	250	12	468	0	250	29	0.6	6.6	1.4	849	121	00	80	9.9	1320	8.0
133-60-11BBB	227-232	9- 8-83	33	.71	.10	50	25	200	11	485	0	240	28	0.5	1.0	.98	829	228	0	64	5.7	1250	7.9
133-60-12BAA	197-202	9- 8-83	29	.35	.67	110	32	67	11	365	0	180	9.3	0.3	1.0	.24	621	406	110	26	1.4	896	7.9
133-60-12CCC	215-225	9-15-82	30	5.1	.21	100	29	99	12	482	0	170	7.5	0.3	3.9	.46	694	369	0	36	2.2	1050	8.0
133-60-23AAA	217-220	8-25-81	31	.49	.17	88	39	140	11	517	0	210	41	0.3	1.0	.05	817	380	0	44	3.1	1140	8.0
133-60-23ABB	211-214	8-27-81	28	.03	.09	49	31	230	12	500	0	250	73	0.5	1.0	.70	921	250	0	65	6.3	1330	8.2
133-60-23BBC	215-219	7-28-83	32	.45	.06	215	11	280	11	488	0	260	44	0.6	0.4	.89	905	108	0	83	12	1380	8.1
133-60-24AAA	207-210	8-27-81	30	.02	.70	83	25	160	12	521	0	190	26	0.4	1.0	.45,	786	310	0	52	4.0	1090	8.3
133-60-24BAA	217-220	8-27-81	31	2.0	.20	93	46	150	13	548	0	260	36	0.4	1.0	.30	903	420	0	43	3.2	1260	7.7
133-60-25BBB	218-221	8- 1-79	30	.41	.14	52	24	260	9.1	479	0	290	90	0.4	1.0	1.1	994	230	0	70	7.5	1500	8.0
133-60-25CCC	208-213	9-23-82	29	.14	.04	22	6.0	240	9.5	517	0	82	12	0.6	5.1	.71	662	80	0	85	12	994	8.1
133-60-26DCC	202-207	9-23-82	28	.88	.08	45	15	110	13	449	0	65	2.0	0.5	5.9	.53	507	174	0	56	3.7	809	8.2
133-60-36CCD	215-225	8-27-82	22	.18	.07	19	8.5	290	12	595	0	160	3.8	1.1	0.4	1.6	846	83	0	87	14	1350	8.2
133-60-36BAA	218-223	9-23-82	28	.13	.05	32	11	220	12	542	0	96	29	0.7	7.2	1.1	704	125	0	77	8.4	1090	8.2
133-60-36DDD	212-215	9-24-75	21	.19	.48	61	21	100	9.0	463	0	78	12	0.5	1.0	4.2	536	240	0	46	2.8	868	7.8
134-60-16CCC	212-215	11-16-76	28	1.4	.08	52	17	290	9.1	413	0	290	150	0.1	9.7	1.0	1050	200	0	75	8.9	1600	8.0
134-60-19BBB	233-253	7-26-83	32	.38	.74	79	23	88	9.2	462	0	91	12	0.4	3.8	.40	568	292	0	39	2.2	873	8.0
134-60-20ADD	317-322	9-28-83	29	.10	5.8	580	130	430	25	211	0	2200	130	0.3	1.0	.91	3640	1983	1800	32	4.2	4020	7.9
134-60-25DDD	200-205	11- 2-83	28	.58	.10	25	9.5	290	11	487	0	320	36	0.5	0.2	1.1	962	102	0	85	12.5	1540	7.7
134-60-26ABD	213-219	7-27-83	32	2.0	.05	22	8.5	280	11	455	0	300	25	0.4	8.9	.84	915	90	0	85	13	1380	8.0
134-60-26BBB	218-221	11-16-76	29	.69	.07	41	14	280	8.1	399	0	410	25	0.2	5.9	1.3	1010	160	0	78	9.6	1490	8.2
134-60-26CBB	225-230	9- 8-83	31	.21	.07	51	24	260	12	418	0	390	27	0.5	1.0	1.0	1000	226	0	70	7.5	1500	8.3
134-60-26DCC	198-201	111-17-76	28	1.2	.06	47	15	230	8.3	506	0	260	13	0.2	3.1	1.0	856	180	0	72	7.5	1300	8.2
134-60-28ADD	178-181	7-22-80	33	.41	.13	55	27	190	6.8	481	0	240	29	0.4	0.6	.48	820	250	0	62	5.2	1220	8.1
134-60-29AAA	238-241	7-22-80	31	.15	.21	68	32	160	5.8	481	0	210	28	0.3	0.5	.44	773	300	0	53	4.0	1160	7.8
134-60-$29BBB_2$	278-281	7-22-80	33	1.1	.16	73	21	95	6.1	453	0	90	21	0.3	0.1	.48	564	270	0	43	2.5	867	8.0
134-60-29DAA	217-222	9-29-83	34	.49	.47	89	32	120	10	462	0	140	23	0.4	0.0	.41	678	354	0	42	2.8	954	8.1
134-60-29DDD	207-212	9-29-83	28	.61	.13	73	22	120	10	415	0	140	20	0.3	4.4	.44	623	273	0	48	3.2	954	8.0

TABLE I.—cont.

Location	Depth of Well (feet)	Date of Collection	(SiO_2)	(Fe)	(Mn)	(Ca)	(Mg)	(Na)	(K)	(HCO_3)	(CO_3)	(SO_4)	(Cl)	(F)	(NO_3)	(B)	Total Dissolved Solids	Total Hardness as $CaCO_3$	Total Hardness Noncarbonate	Percent Sodium	SAR	Specific Conductance	pH
134-60-30BBB	230-235	9-28-83	29	.22	.10	71	23	100	10	438	0	110	15	0.3	3.6	.38	579	272	0	43	2.7	902	8.0
134-60-30CBB	205-210	9-28-83	33	.43	.11	59	21	140	11	479	0	110	22	0.4	0.2	.46	634	234	0	55	4.0	954	8.3
134-60-32DDD	218-224	11-14-74	18	1.3	.14	65	33	140	7.1	480	0	170	25	0.5	5.6	.55	702	300	0	50	3.5	1120	7.9
134-60-33BCC	217-222	9-29-83	27	.62	.14	64	21	130	10	426	0	150	22	0.3	4.9	.42	640	246	0	52	3.6	984	8.1
134-60-35BBB	190-195	9- 9-83	30	.07	.08	49	21	250	13	423	0	340	33	0.5	1.0	1.0	947	209	0	71	7.5	1400	8.3
134-60-35CBB$_1$	195-200	1- 4-84	28	.25	.10	47	23	230	10	451	0	320	24	0.6	0.8	1.3	907	212	0	69	6.9	1370	8.1
134-60-35CCC	255-261	11-14-74	18	1.8	.14	74	30	200	7.9	490	0	240	69	0.5	1.0	.63	884	310	0	58	4.9	1400	8.0
134-60-36ABD	185-200	8- 4-77	22	.75	.08	23	8.9	260	6.6	532	0	220	15	0.0	1.0	1.2	821	94	0	85	12	1260	8.3
134-60-36CCB	200-225	10-30-76	24	.56	.08	35	18	290	6.4	488	7	280	54	0.3	1.0	1.8	958	160	0	79	10	1400	8.4
134-61- 4AAA	263-266	9- 8-82	25	.02	.07	31	15	340	11	625	0	120	180	0.5	1.0	.69	1030	139	0	83	12	1730	8.3
134-61- 4DDD	256-259	8- 1-79	30	.20	.14	33	12	200	9.0	524	0	110	22	0.3	1.0	.33	676	130	0	75	7.6	1040	8.2
134-61-10CBB	237-242	7-14-83	29	.04	.12	31	13	200	11	526	0	120	24	0.3	0.0	.49	660	131	0	75	7.6	1090	7.8
134-61-13DAD	257-262	9-28-83	32	.01	.70	68	18	100	9.8	425	0	81	21	0.3	1.0	.36	541	244	0	46	2.8	836	8.0
134-61-14DDD	258-261	7-26-79	29	.63	.16	60	17	130	8.1	486	0	100	15	0.3	1.0	.63	601	220	0	55	3.8	942	8.2
134-61-24DAA	217-222	9-28-83	33	.59	.30	70	20	100	10	454	0	88	18	0.4	0.4	.36	565	257	0	45	2.7	872	8.1
134-61-24DCC$_1$	228-231	1- 3-84	32	1.5	.09	51	16	150	11	486	0	100	18	0.3	1.0	.54	620	193	0	61	4.7	983	8.1
134-61-24DCC$_2$	225-235	7-26-79	32	.51	.16	62	21	130	7.5	486	0	100	15	0.3	1.0	1.1	610	240	0	53	3.7	957	7.9
134-61-25DDD	209-214	9-28-83	30	.25	.05	38	16	170	10	486	0	110	16	0.3	5.3	.49	635	161	0	68	5.8	1000	8.1
134-61-36ADD	212-217	9-28-83	22	.07	.04	14	5.0	360	11	780	0	53	140	1.2	0.7	2.1	993	56	0	92	21	1680	8.3

TABLE 2 — Chemical analyses: glacio fluvial deposits above the Spiritwood aquifer

(Analytical results are in milligrams per liter except where indicated)

Location	Depth of Well (feet)	Date of Collection	(SiO_2)	(Fe)	(Mn)	(Ca)	(Mg)	(Na)	(K)	(HCO_3)	(CO_3)	(SO_4)	(Cl)	(F)	(NO_3)	(B)	Total Dissolved Solids	Total Hardness		Percent Sodium	SAR	Specific Conductance	pH
																		as $CaCO_3$	Noncarbonate				
131-59- 4DB*	20-35 18-28	7-14-77	12	2.1	.30	83	30	7.5	3.1	278	0	100	5	0.2	22	0.0	402	330	100	47	0.2	749	8.3
131-59- 9CCB	22-30	8- 6-75	17	.23	.31	64	27	5.0	4.0	254	0	66	3.8	0.2	2.5	.04	315	270	62	4	0.1	524	7.9
132-59-17DCD$_3$	58-63	9-22-82	28	.10	.47	130	41	48	12	436	0	210	7.6	0.2	1.0	.27	694	494	140	17	0.9	1060	7.9
132-59-27CDD	49-54	10-29-82	27	.57	.43	120	52	45	5.9	369	0	220	10	0.2	1.0	0.1	664	514	210	16	0.9	989	8.0
133-59- 5CDD$_2$	54-59	9- 7-83	30	.09	.46	99	29	74	10	395	0	120	4.9	0.2	1.0	.29	564	36	43	30	1.7	816	7.7
133-59- 9BBB$_2$	60-65	9- 7-83	30	.47	.63	110	33	55	9.3	475	0	130	9.0	0.6	1.0	.17	613	410	21	22	1.2	948	8.1
133-60- 5DAA$_2$	60-65	9-29-83	28	2.6	.38	120	34	59	11	364	0	180	5.9	0.3	2.7	.31	623	440	140	22	1.2	883	7.9
133-60-10BBB$_2$	77-82	9- 8-83	32	.23	.67	120	32	50	10	345	0	160	4.1	0.3	1.0	.33	581	431	150	20	1.1	756	7.8
134-60-35CBB$_2$	65-70	1- 5-84	26	.03	.34	100	28	44	11	411	0	94	5.8	0.3	1.0	.26	513	365	28	20	1.0	798	8.1

*Composite sample at pivot from two wells

TABLE 3 — Chemical analyses: Niobrara formation

(Analytical results are in milligrams per liter except where indicated)

Location	Depth of Well (feet)	Date of Collection	(SiO_2)	(Fe)	(Mn)	(Ca)	(Mg)	(Na)	(K)	(HCO_3)	(CO_3)	(SO_4)	(Cl)	(F)	(NO_3)	(B)	Total Dissolved Solids	Total Hardness as $CaCO_3$	Total Hardness Noncarbonate	Percent Sodium	SAR	Specific Conductance	pH
131-59-23BCC	200-220	8-4-83	29	.14	.36	84	28	9.0	5.3	334	0	49	17	0.2	1.2	.01	388	325	51	6	0.2	600	7.7
132-59-11CCB	235-295*	7-29-83	6.7	.08	.02	11	5.0	930	16	786	0	17	1100	1.9	1.0	2.4	2480	48	0	97	58.0	4520	7.8
132-60-4BAB	247-300*	8-27-82	8.2	.26	.01	11	5.0	960	21	605	0	170	1000	1.9	0.0	2.1	2480	48	0	97	60.0	4390	8.0
132-60-10DAA	220-245*	8-2-83	9.4	.15	.01	15	5.5	470	12	789	0	3.3	330	1.3	0.0	1.5	1240	60	0	93	26.0	2190	7.8

*Open hole over interval shown

TABLE 4 – Chemical analyses: piezometer nests

(Analytical results are in milligrams per liter except where indicated)

Location	Depth of Well (feet)	Date of Collection	(SiO_2)	(Fe)	(Mn)	(Ca)	(Mg)	(Na)	(K)	(HCO_3)	(CO_3)	(SO_4)	(Cl)	(F)	(NO_3)	(B)	Total Dissolved Solids	Total Hardness		Percent Sodium	SAR	Specific Conductance	pH
																		as $CaCO_3$	Noncarbonate				
134-61-13DAD$_1$	257-262	8-30-84	30	.03	.76	69	19	100	10	459	0	84	18	0.4	1.0	.45	559	250	0	45	2.8	87.6	8.1
134-61-13DAD$_2$	132-137	8-30-84	30	.02	.89	83	23	76	9.5	459	0	88	11	0.4	1.0	.42	549	302	0	35	1.9	859	8.0
134-61-13DAD$_3$	68-73	8-30-84	31	.04	.35	63	19	39	9.8	344	0	36	1.9	0.4	1.0	.32	371	235	0	26	1.1	582	8.1
133-60-2CDD$_1$	255-260	9-8-83	32	1.1	.17	83	32	200	12	452	0	250	110	0.3	1.0	.51	945	339	0	55	4.7	1450	8.2
133-60-2CDD$_2$	195-200	8-29-84	31	.02	.13	48	15	230	15	465	0	270	32	0.4	1.0	1.3	873	182	0	71	7.5	1320	8.1
133-60-2CDD$_4$	26-31	8-29-84	25	.02	.18	64	20	65	9.1	371	0	58	2.7	0.3	1.0	.48	429	242	0	36	1.8	664	8.1
133-60-36DDD$_1$	212-215	8-29-84	32	.04	.23	60	20	110	12	463	0	84	13	0.4	1.0	.63	561	232	0	49	3.2	867	8.0
133-60-36DDD$_2$	236-241	8-29-84	31	.28	.18	69	24	110	12	475	0	110	18	0.4	1.0	.64	611	271	0	46	2.9	956	7.9
132-59-27CDC$_1$	209-214	8-29-84	30	.05	.23	45	14	370	12	503	0	410	150	1.5	1.0	1.9	1280	170	0	81	12	2000	8.0
132-59-27CDC$_3$	150-155	8-29-84	31	.18	.32	61	20	210	12	504	0	210	59	0.5	1.0	1.3	854	234	0	65	6.0	1310	8.2

of the aquifer. The temporal hydrochemical variations were not large enough to obscure the spatial distribution of hydrochemical facies from top to bottom in the aquifer.

Hackbarth (1981) measured the variation in water chemistry in three shallow wells that were between 15 and 25 feet deep in the Athabasca Oil Sands area, Alberta. The coefficient of variation of total dissolved solids for the well sampled monthly for 34 months was 34 percent. The coefficient of variation for individual constituents was generally higher than 34 percent. The coefficient of variation of total dissolved solids with respect to time, generally decreased with depth.

The magnitude of temporal hydrochemical variations is related to the physical and chemical characteristics of the flow system. In general greater temporal hydrochemical variations occur at or near the water table in shallow ground water flow systems. Shallow flow systems within the glaciated plains are characterized by large seasonal variations in recharge and CO_2 production. Variations in recharge and CO_2 production impact the leaching and dissolution processes and ultimately the delivery of dissolved constituents to the water table. Large temporal hydrochemical variations can occur at greater depths in flow systems where overlying aquitards are absent and where vertical hydraulic gradients are large. In these areas, the flow system is characterized by the relatively rapid downward movement of recharge water from the surface.

Over most of the study area, the Spiritwood aquifer is buried by an approximately 150 foot thick drift sheet which consists predominantly of till. For the most part, there is no direct hydraulic connection between the Spiritwood aquifer and the shallow ground-water flow system.

Partial chemical analyses were made on seven water samples collected over a period from 1975 to 1984 from an irrigation well located in 131-59-22BAD. The well is located in an area of the Spiritwood aquifer characterized by significant downward leakage through an overlying sequence of silty sands and sandy silts. Till and clay are absent. There are four high capacity irrigation wells (800 gpm) which are completed in this area of the aquifer. Irrigation withdrawals from these wells have increased the vertical hydraulic gradients in the area. The result is an increase in the rate of downward leakage. The chemical analyses from the irrigation well at 131-59-22BAD support an increase in vertical leakage from the overlying sandy silts and silty sands. The analyses show a decreasing trend in total dissolved solids from 597 mg/l (July 1975) to 482 mg/l (July, 1984). Although the chemical constituents vary temporally at this site the hydrochemical facies remains the same ($Ca-Mg-HCO_3$ type).

Based on the physical characteristics of the Spiritwood aquifer system and the chemical analyses from the irrigation well located at 131-59-22BAD, temporal hydrochemical variations are not large enough to affect the overall identification of hydrochemical facies in the study area.

The State Water Commission observation wells were constructed using 1¼ inch diameter polyvinyl-chloride (pvc) or acrylonitrilebutadiene-styrene (abs) casing and 1¼ inch diameter plastic (abs) or galvanized steel screen. Screen lengths varied from 3 to 5 feet. An .018 slot size was commonly used. A check valve was attached to the bottom of each screen. The casing, screen and check valve were assembled prior to insertion into the drill hole. Once inserted, the hole was "back-flushed" through the screen to clean the formation. After "back-flushing", the well was blown with air to collapse the formation around the screen. Drilling cuttings were then shoveled into the well annulus. The well annulus was not sealed with bentonite or cement. Most of the observation wells were screened in the bottom half of sand and gravel intervals that average approximately 33 feet in thickness. When the well was blown with air, the decrease in hydrostatic pressure generally caused the entire aquifer interval of sand and gravel to collapse into the well annulus. Experience has shown that it is also common for overlying sand and gravel units to collapse into the well annulus when the well is blown with air. Till and clay cuttings are then shoveled into the well annulus. The cuttings can bridge anywhere along the well annulus thereby not providing a continuous seal to the top of the aquifer. In these observation wells a significant volume of water can be moving downward along the annulus. The observation wells are screened in the basal intervals of relatively thick, high transmissivity sand and gravel deposits. As a result, contamination along the well annulus is not considered large enough to affect the overall identification of hydrochemical facies within the Spiritwood aquifer. In low transmissivity deposits such as till or lacustrine clay, the vertical flow component along the annulus may be large in relation to horizontal flow component of the formation adjacent to the well screen. In this case, the well annulus should be sealed with bentonite or cement to prevent contamination.

The piezometer nests were completed in the same manner as the observation wells except that after "back flushing", silica sand was placed around the screened interval using a tremie pipe. The annulus was filled with a cement slurry from the top of the sand pack to land surface.

The State Water Commission observation wells were sampled by air lifting the water out of the well using a small diameter rubber hose attached to a portable air compressor. The domestic/stock wells were all equipped with submersible pumps. Samples were gathered from hydrants at the well discharge head or from faucets outside of the house to avoid domestic water treatment facilities. The irrigation wells were all equipped with turbine pumps. Samples were gathered from faucets or small gate valves installed near the discharge head or from leaks on the center pivot irrigation systems.

The specific conductance and water temperature were measured at each sampling site. The water temperature was measured at land surface and does not represent an in-situ temperature. As a result, the water temperature was omitted in the tables. The pH values shown in the tables were measured in the laboratory. An in situ or field pH measurement was not made. Prior to 1977, two samples were collected from each well. A 250-milliliter sample was filtered and acidified immediately upon collection. Analysis of Fe^{2+} and Mn^{2+} were made on this sample. All other cation and anion concentrations were determined on a raw 1000-milliliter sample. Beginning in 1977, three samples were collected from each well:

1) 250 milliliter - raw
2) 500 milliliter - filtered
3) 500 milliliter - filtered and acidified

HCO_3^-, CO_3^{2-}, Cl^-, lab pH and lab specific conductance, were determined on the raw 250 milliliter sample. SO_4^{2-}, F^-, B, NO_3^-, SiO_2, and total dissolved solids were determined on the filtered, 500 milliliter sample. Ca^{2+}, Mg^{2+}, Na^+, K^+, Fe^{2+} and Mn^{2+} were determined on the filtered and acidified, 500 milliliter sample. A 0.45 micron filter was used to remove suspended sediment, and a 2-milliliter ampule of concentrated nitric acid was added to prevent the precipitation of cation-complexes. The samples were all collected in plastic bottles and sent to the State Water Commission Laboratory in Bismarck for analysis.

Prior to 1981, the concentrations of the major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) were determined using a Beckman, model DU-2, spectrophotometer. Beginning in 1981, the concentrations of the major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) were determined using a Perkins-Elmer Model 4000 atomic-absorption spectrophotometer. The concentrations of HCO_3^-, CO_3^{2-} and Cl^- were determined using a Fisher model 741 titralyzer. The concentration of SO_4^{2-} was determined by a gravimetric method (American Public Health Association, and others, 1975).

Houghton and Berger (1984) examined the effects of well casing composition and sampling method on apparent quality of ground water.

Based on their results, the effects of different well casings are considered negligible with regard to major cations (Ca^{2+}, Mg^{2+}, Na^{+}), anions (HCO_3^{-}+CO_3^{2-}, SO_4^{2-}, Cl^{-}) and total dissolved solids.

The majority of the samples in this study were collected from State Water Commission observation wells by air-lift pumping. According to Houghton and Berger (1984), air-lift pumping causes extensive sample degassing (loss of CO_2) by gas streaming creating a shift in carbonate equilibrium, an increase in sample pH, and precipitation of carbonate minerals. In their study, air-lift samples were compared to gas-squeeze pump samples. The gas-squeeze pump samples were considered to be the most representative of aquifer quality. The impact of air-lift pumping on the chemical properties and constituents is shown in figure 3. Dissolved solids concentrations decreased a mean 3.7 percent. The decrease in dissolved solids is due primarily to the precipitation of carbonate minerals. Evidence for carbonate mineral precipitation is a decrease in Ca^{2+}, Mg^{2+}, and HCO_3^{-}. The impact of air-lift pumping on Na^{+}, SO_4^{2-} and Cl^{-} concentrations is minor. The chemical alteration of water samples by air-lift pumping is not large enough to affect the overall identification of hydrochemical facies in this investigation.

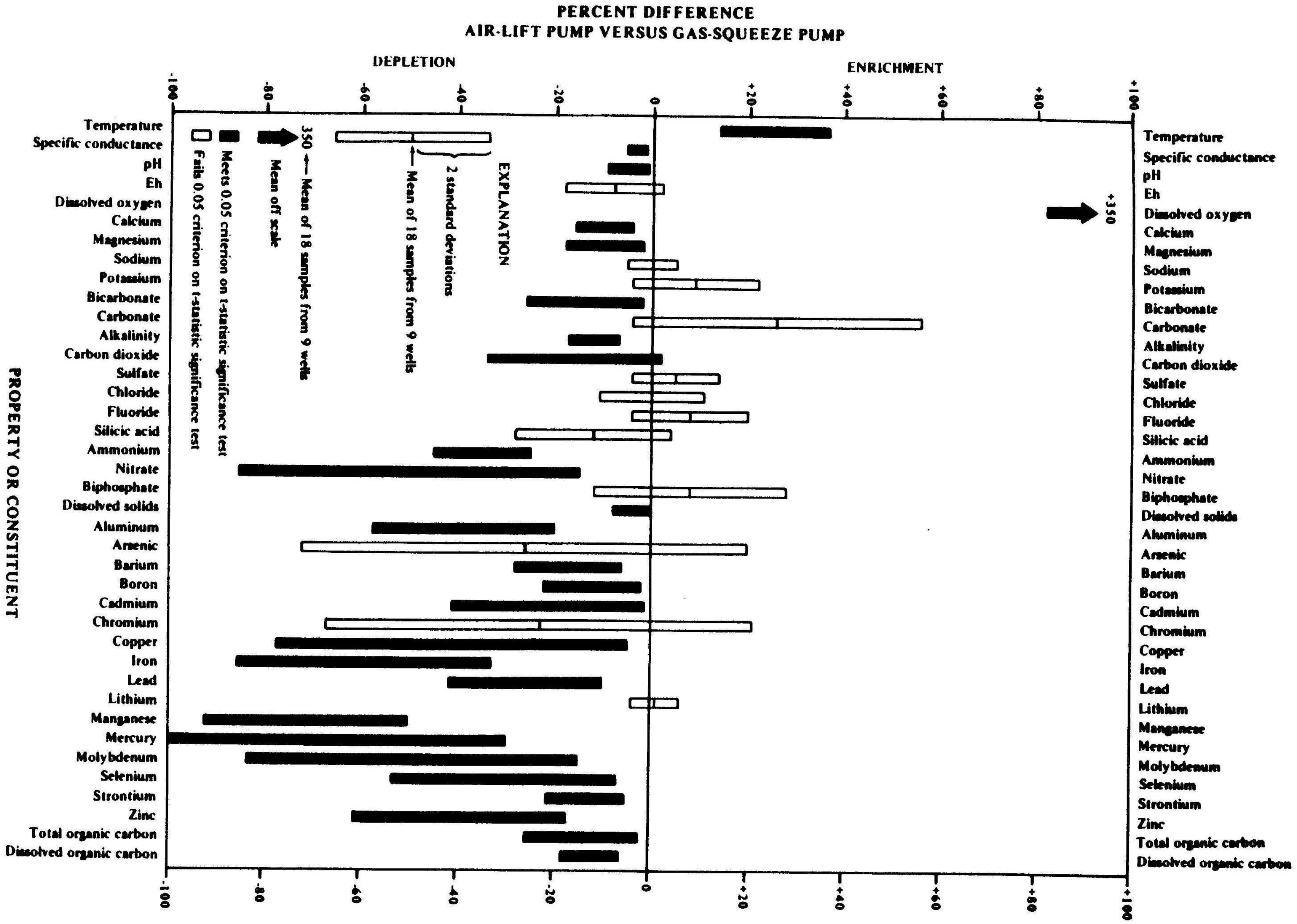


FIGURE 3.-Chemical alterations in ground-water sample produced by air-lift pump. (after Houghton and Berger, 1984)

PREVIOUS WORK

Various hydrogeochemical investigations within glaciated prairie environments of the interior plains region of North America are described in the literature. Rozkowski (1967) demonstrated the influence of dissolution, leaching, precipitation and ion-exchange processes on the ground-water chemistry associated with hummocky moraine. The unsaturated and saturated zones were investigated in recharge, transition and discharge areas. Chemical analyses were determined for soil and till extracts as well as ground and slough water. The geochemistry of the soil and till was also investigated. Ca-Mg-SO_4 type waters were characteristic of recharge areas. In more permeable deposits, the Ca-Mg-HCO_3 type waters were characteristic. Mg-Na-SO_4 type waters were characteristic of discharge areas. The dissolution of calcite, dolomite, and gypsum were the sources of Ca^{2+}, Mg^{2+}, HCO_3^-, and SO_4^{2-}. Na^+ was accounted for by cation exchange in the clays.

VandenBerg and Lennox (1969) provide a discussion of the processes which impact the chemistry of ground water in the Handhills Lake area, Alberta. These included solution, evapotranspiration, cation exchange and sulfate reduction. Contour maps showing equal concentrations of dissolved constituents were prepared and analyzed. Two types of areal variation in ground water composition occurred as a result of:

1) aging of ground water as it moves through the flow system, and
2) inhomogeneities in the flow medium (different lithologies).

Charron (1969) utilized the methods of Schoeller (1957) to analyze water chemistry data. The chemical data coupled with topography, geology, and hydraulic properties provided the framework for the interpretation of the flow system. Hydrogeological and hydrochemical fence diagrams were prepared and analyzed. A discussion of dissolution, cation-exchange and sulfate reduction was presented. Conclusions pertinent to this investigation are the following:

1) Most ground water is saturated or near saturated in $CaCO_3$.

2) Most ground water is not saturated in $CaSO_4$.

3) The absolute Cl^- value is the most important indicator of the degree of sluggishness of a body of ground water.

4) In confined aquifers, the direction of ground-water movement can be determined from the hydrochemistry of ground water.

Cherry (1972) investigated the geochemical processes in shallow ground-water flow systems in five areas in southern Manitoba. Chemical analyses of water samples were interpreted by their saturation levels with respect to calcite, dolomite and gypsum, and by simple dissolution models involving carbonate, sulfate and chloride minerals. Cation exchange, a modifying process, was inferred. The dissolution of calcite, dolomite, and highly soluble sulfate and chloride minerals produced the major ion chemistry in much of the ground water in the five study areas. A hypothesis was presented to account for sulfate and chloride minerals in the drift which involved deep brines being forced to the surface from excess pore pressures due to glacial loading. The cooler temperatures and lower pressure near land surface caused the precipitation of sulfate and chloride minerals.

Bibby (1974) compared the regional ground-water chemistry and water level distribution in a near-surface environment near Edmonton, Alberta. Chemical analyses of water samples were divided into three categories. Those obtained from:

1) wells completed within the drift
2) wells completed within the upper 75 feet of bedrock, and
3) wells completed below the upper 75 feet of bedrock to a depth of 250 feet.

Contour maps were prepared for each category showing equal concentrations of chemical parameters and water level elevations. The study concluded the following:

1) The water level distribution closely resembled surface topography.
2) Over most of the area, flow was downward relative to the water table.
3) Buried-channel sands and gravels acted as highly permeable line-sinks and were a major influence on water level distribution.
4) Soils and drift lithology were major influences on ground water chemistry.
5) Flow direction was a minor influence.

Hackbarth (1975) investigated the regional ground-water chemistry in the Wainwright area, Alberta. Chemical analyses of water samples were obtained from the drift, preglacial sands and gravels, and bedrock formations. Hydrochemical maps were prepared for various depth intervals. Results of the study indicated that the thickness and nature of the glacial drift and the composition of the underlying bedrock were the most important factors influencing water chemistry.

Grisak, and others (1976) investigated the hydrologic and hydrochemical properties of fractured till in the interior plains region of North America. Chemical analyses of water samples obtained from previous studies were evaluated. In part, the study concluded the following:

1) Shallow waters were saturated or oversaturated with respect to calcite and dolomite.

2) Dissolution of calcite and dolomite occurred in soil zones where high CO_2 partial pressures occur.

3) Silicate minerals contributed only small amounts of cations and anions.

4) To account for additional Ca^{2+}, Mg^{2+}, Na^{2+}, SO_4^{2-} and Cl^- it was assumed that sufficient quantities of gypsum, halite, epsomite and other soluble salts were disseminated throughout the drift.

Davison and Vonhof (1978) examined the spatial and temporal hydrochemical variations of ground water in a semiconfined buried-channel aquifer near Esterhazy, Saskatchewan. The study concluded the following:

1) The shallow ground water was primarily a Ca-HCO_3type.

2) The deeper (longer flow path) ground water was primarily a Na-SO_4 type.

3) Concentrations of Na^+, SO_4^{2-}, Cl^-, and total dissolved solids increased with increasing depth and length of flow path.

4) Dissolution of calcite, dolomite, halite, and sulfate minerals such as gypsum and cation exchange accounted for the concentrations of Ca^{2+}, Mg^{2+}, Na^+, HCO_3^-, SO_4^{2-} and Cl^-.

5) The spatial hydrochemical pattern is explained by the mixing of surficial Ca-HCO_3 recharge waters and deeper Na-SO_4 bedrock (shale) waters.

Moran and others (1978) describe geochemical concepts related to surface mining of lignite in glaciated regions of North Dakota. The hydrogeochemical evolution of soil water and ground water was defined. Important source minerals were carbonates (calcite, dolomite), sulfates (gypsum), iron sulfides (pyrite, marcasite), and clays (smectite). Primary alumino-silicate minerals were considered unimportant as geochemical controls. The following chemical processes were considered important:

1) hydrogen - ion generation by CO_2 production in the upper soil horizons and by pyrite oxidation in the soil or subsoil
2) dissolution of calcite and dolomite
3) cation exchange of Ca^{2+} for Na^+ on clays, and
4) gypsum dissolution

Hackbarth (1981) investigated temporal chemical variations of shallow ground water in the Athabasca oil sands area, Alberta. He concluded that seasonal soil processes control the chemistry of the soil water and recharge water. A good discussion of processes that cause seasonal variations in ground-water chemistry was presented.

Wallick (1981) developed a conceptual model to account for the chemical evolution of ground water in a drainage basin in east-central Alberta. The drainage basin was considered analogous to a large surface mined area. A younger flow system associated with the glacial drift was superimposed on an older flow system associated with the bedrock. The water quality of the drift aquifers was a Ca-Mg-HCO_3 type at depths less than 30 meters. At depths between 30 to 100 meters a Na-HCO_3-SO_4 type predominated. In the deeper bedrock aquifers, the Na-HCO_3-SO_4 and Na-HCO_3-Cl types occurred. The mechanisms operative in the shallow drift zone were oxidation of organic carbon and subsequent dissolution of soil CO_2 to form carbonic acid and oxidation of sulfur and pyrite to form sulfuric acids. The acids were responsible for the dissolution of carbonate and silicate minerals. A model was developed to account for the mixing of the drift and bedrock waters. Chemical diffusion was negligible as compared to mechanical dispersion in the mixing process.

Hendry (1984) investigated the origin of sulfate in till in an area of southern Alberta. The principal source of SO_4^{2-} was from the oxidation of organics in the weathered zone. The oxidiation of organic S resulted in the production of SO_4^{2-} and H^+. The dissolution of calcite and dolomite added Ca^{2+}, Mg^+, and HCO_3^- to solution. Ca^{2+} combined with SO_4^{2-} and caused gypsum to precipitate. Na^+ was added to solution by cation exchange.

Bluemle (1979a), Armstrong and Lutrell (1978) and Armstrong (1980) reported on the geology, basic data, and ground-water resources of Dickey and LaMoure Counties. Bluemle (1979b), Armstrong (1979) and Armstrong (1982) reported on the geology, basic data, and ground-water resources of Ransom and Sargent Counties.

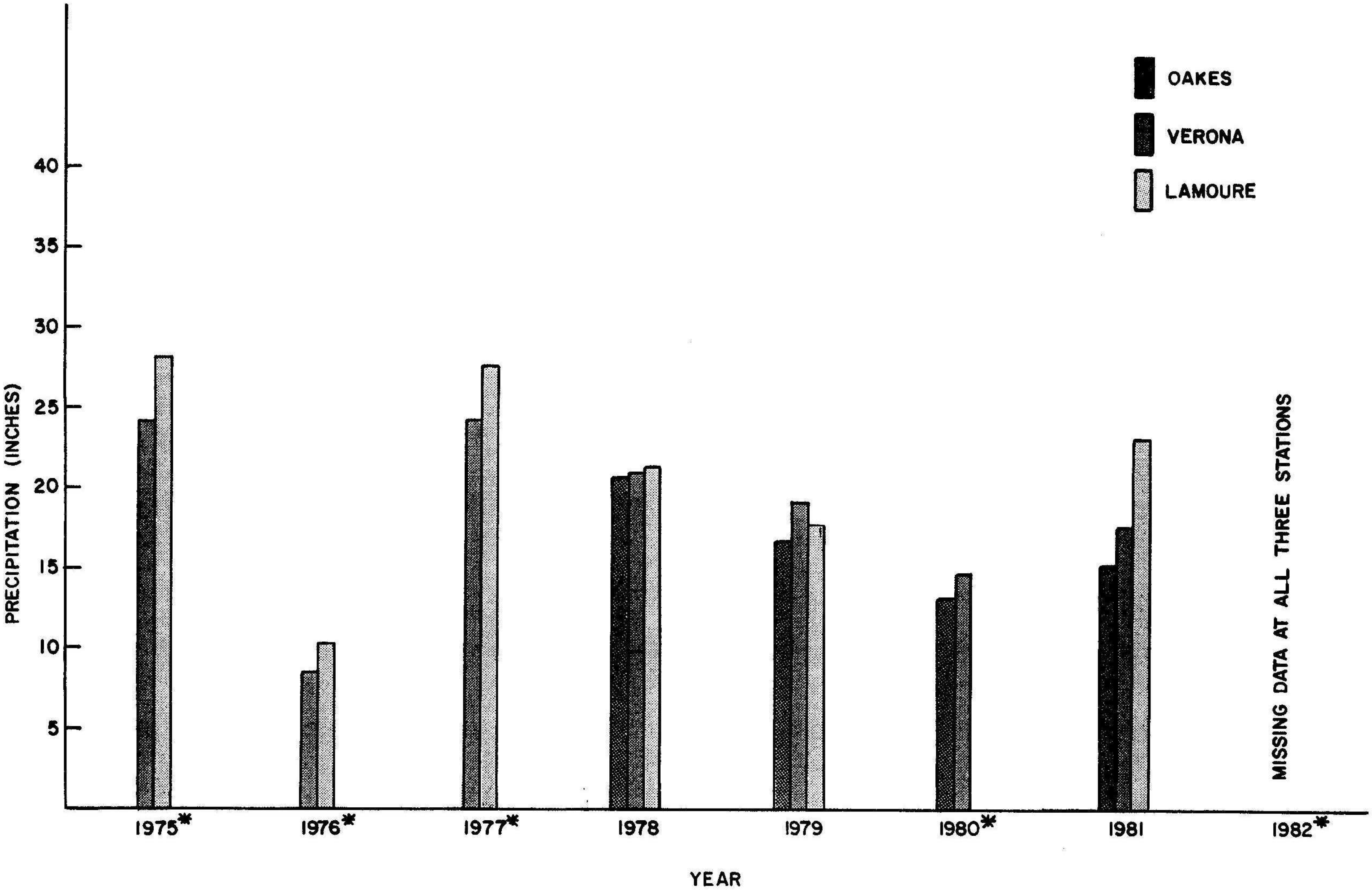
Shaver (1984) reported on the hydrogeology of the Spiritwood aquifer system in Dickey and parts of LaMoure and Sargent Counties. North Dakota State Water Commission open-file reports are available which describe the results of aquifer and response tests conducted on 5 irrigation wells completed in the Spiritwood aquifer within the study area.

PHYSIOGRAPHY

The study area is situated in the Drift Prairie district of the Central Lowland province (fig. 1). The study area is flanked to the west by the James River Valley and is partially drained by Bear Creek (pl. 1). The land surface in the northern part of the study area is rolling with kettles. Drainage is partially integrated to non-integrated. Relief is 30 to 60 feet locally. The land surface in the central and southern part of the study area is gently undulating to undulating. Drainage is poorly integrated. Relief is generally less than 10 feet (Bluemle, 1979a, b). Land surface elevations are highest (approximately 1450 feet above mean sea level) in the northwestern part of the study area between Twin Lakes and the James River Valley. Land surface elevations are the lowest (approximately 1300 feet above mean sea level) in the vicinity of Oakes and within the James River Valley. There is an overall decline in land surface elevation from northwest to southeast in the study area.

CLIMATE

The climate of the study area is semiarid to subhumid. The National Oceanic and Atmospheric Administration (NOAA) receives precipitation data from gauging stations at Oakes, Verona and LaMoure, all within the vicinity of the study area. Annual values of precipitation from 1975 through 1982 for Oakes, Verona, and LaMoure (U. S. Environmental Data Service, 1976-1982) indicate the maximum annual precipitation was 28.07 inches at LaMoure in 1975, and the minimum annual precipitation was 8.41 inches at Verona in 1976 (fig. 4). About 70 percent of the precipitation generally falls from April through August (Armstrong, 1980). Summers are warm with temperatures commonly exceeding 90°F. Winters are cold with temperatures commonly falling below 0°F. Relative humidity, particularly during the summer months is low.



*DUE TO MISSING DATA, PRECIPITATION IS NOT SHOWN AT SOME STATIONS

FIGURE 4.—Annual precipitation at LaMoure, Verona and Oakes

GEOLOGY

The Niobrara Formation of Cretaceous Age unconformably underlies the Pleistocene deposits of the Coleharbor Group in the central and southern part of the study area and conformably underlies the Pierre Formation in the northern part of the study area (pl. 2). The Niobrara Formation is a brown shale with light gray calcareous inclusions. Samples from the formation strongly effervesce in dilute hydrochloric acid leaving a dark brown residue. The Niobrara Formation is a marine sediment.

In the vicinity of Twin Lakes and Verona, the Pierre Formation of Cretaceous Age unconformably underlies the Pleistocene deposits of the Coleharbor Group. The Pierre Formation is a dark black shale with occasional light-gray bentonite layers. The shale is noncalcareous and has a smooth greasy texture. The Pierre Formation is a near shore marine sediment. The basal Pembina Member of the Pierre Formation contains gypsum and/or selenite (Tourtelot, 1962).

The Coleharbor Group unconformably overlies the Cretaceous shales. Bluemle (1979a, b) divides the Coleharbor Group into three main textural facies:

1) till
2) silt and clay
3) sand and gravel

The till facies consist of a non-stratified, non-sorted mixture of clay, silt, sand, gravel, pebbles, cobbles, and boulders. The clay and silt generally make up the matrix. The coarse-grained materials are generally angular to subrounded and consist of igneous, metamorphic, carbonate, and shale fragments. The till facies predominates over most of the study area.

The silt and clay facies is glaciolacustrine. The lithology ranges from clay to silt to fine sand and can occur as a mixture of the above grain sizes. The silt and clay facies occurs just north of Oakes in both outcrop and in the subsurface.

The sand and gravel facies is glaciofluvial and consists of variable portions of subangular to rounded, poor to well-sorted sand and gravel with occasional thin layers of silt and/or clay. Stratification is common. Surficial exposures of the sand and gravel facies in the study area occur as eskers, as uncollapsed floodplains, and as terrace deposits within the James River Valley. The sand and gravel facies also occurs in the subsurface as an extensive buried-valley complex (Spiritwood aquifer) and as less extensive deposits scattered throughout the till facies.

The Oahe Formation of Holocene age overlies the Coleharbor Group in scattered areas throughout the study area as:

1) pond and slough sediment (clay facies),
2) colluvial sediment (bouldery, gravelly, clay facies),
3) river sediment (sand and silt facies),
4) windblown sediment (sand and silt facies).

GROUND WATER HYDROLOGY

The Spiritwood aquifer consists of variable amounts of sand and gravel with occasional, thin, interbedded silt and clay layers. The sand and gravel is angular to well-rounded and consists of a mixture of Canadian shield silicates, carbonates and shale. Lignite fragments are common. Stratification is indicated by the response of the deposits to drilling.

Aquifer thickness ranges from less than a foot on the flanks of the buried channels to more than 274 feet thick at test hole 134-60-29BBB. The average thickness based on 163 test holes is 33 feet.

An isopach map of the Spiritwood aquifer is shown in plate 3. Geohydrologic sections indicate a complex stream-channel pattern (pls. 4-6). In areas where test drilling was spaced at one-half mile intervals, the channel pattern is braided and occasional long narrow bedrock ridges separate the individual channels.

Two main channel systems occur north of the Dickey-LaMoure County line (pl. 7). The eastern channel trends north-northwest from the Dickey-LaMoure County line toward the city of Grand Rapids. South of Verona, the eastern channel bifurcates and continues southward toward the Dickey-LaMoure County line. A narrow bedrock ridge separates these two channels (geohydrologic section G-G', pl. 5). Channel system width varies from approximately 1½ miles in the vicinity of Twin Lakes to approximately 1 mile just north of the Dickey-LaMoure County line. The channel appears to be truncated by a low-transmissivity barrier which underlies the James River Valley near Grand Rapids. The water level in 134-61-4DDD is approximately 30 feet higher than the water levels in any of the observation wells completed in the Spiritwood aquifer west and north of the James River in the vicinity of Grand Rapids.

The western channel also trends north-northwest of the Dickey-LaMoure County line toward the Twin Lakes area. Channel width varies from approximately 2 miles south of Twin Lakes to 5 miles just north of the Dickey-LaMoure County line. The channel appears to be truncated by a low-transmissivity barrier east and south of Twin Lakes. A continuous narrow bedrock ridge separates the two main channel systems from Twin Lakes southeast to the Dickey-LaMoure County line (geohydrologic section G-G', pl. 5).

South of the Dickey-LaMoure County line, the eastern and western channel systems merge into one channel. The merged channel continues to the southeast just north of the city of Oakes. Both water level and aquifer test data indicate the existence of at least three transverse low-transmissivity barriers located approximately two, four, and six miles southeast of Bear Creek. There are also three tributary channels less than one mile in width in this area. The channel system continues southeast from the Dickey-Sargent County line toward the city of Cogswell. The geohydrologic data in this area of the aquifer is not adequate to determine in detail channel geometry.

Three aquifer tests and two response tests have been conducted using five irrigation wells completed in the Spiritwood aquifer within the study area. The purpose of these tests was to determine aquifer hydraulic properties and geometry (local boundary configurations).

The transmissivity, hydraulic conductivity, and storage coefficient calculated from these tests ranged from 18,000 ft^2/day to 37,700 ft^2/day, 380 ft/day to 600 ft/day, and .0002 to .0004, respectively. The average transmissivity, hydraulic conductivity, and storage coefficient is 24,800 ft^2/day, 455 ft/day, and .00025 respectively. Leakage was indicated from some of the test results. The complexity of the aquifer system precluded the quantification of leakage utilizing analytical techniques.

Water occurs in the Spiritwood aquifer under confined conditions. The confining lithologies consist of Cretaceous shales below the aquifer and glacial drift above the aquifer. Over most of the study area, the glacial drift consists primarily of till. Glaciofluvial and glaciolacustrine deposits comprise a significant percentage of the drift in the area north of Oakes and south of the Dickey-LaMoure County line. The glaciofluvial deposits and fractures and joints within the till probably facilitate more rapid downward movement of recharge to the Spiritwood aquifer.

The potentiometric surface map is based on water levels measured April 27-28, 1983 (pl. 7). For the most part, ground-water flows from northwest to southeast. Available vertical hydraulic head data indicates downward ground-water flow within the overlying drift over most of the study area. Upward ground-water flow within the overlying drift is indicated along Bear Creek Valley and other topographic low areas northeast of Oakes and southeast toward Cogswell (Lake Taayer, Dill Slough, Pickell Slough).

There are no observation wells completed within the underlying Cretaceous shales. The direction of ground-water flow within the shale directly underlying the Spiritwood aquifer is inferred by the water chemistry data. Interpretation of the data indicates that movement of ground water is upward into the Spiritwood aquifer from the underlying Cretaceous shales over most of the study area.

PROCESSES IN THE CHEMICAL EVOLUTION OF GROUND WATER

The processes described by previous investigators to account for chemical variation in glaciated prairie environments include the following:

1) dissolution/precipitation of calcite, dolomite, and gypsum
2) oxidation of pyrite
3) oxidation of organic sulfur
4) cation exchange
5) sulfate reduction
6) evapotranspiration
7) membrane effects

The water chemistry at any point in the flow system is the result of various combinations of the above processes which operate interactively. Therefore, it is difficult to verify the impact of each process on the observed water chemistry. A detailed description of the chemical evolution of ground water in the study area requires the application of more sophisticated geochemical models. Unfortunately, the existing water chemistry data set is not adequate to drive models of this type. In situ measurements of water temperature, pH and EH were not made. Chemical alterations caused by air-lift pumping are too severe. The following discussion presents a plausible outline of geochemical processes that occur in the study area. The processes are implied and based on the comparison of available hydrochemical data in the study area to that of other more detailed hydrochemical investigations in similar terrains.

The rate of dissolution is governed by such factors as temperature, pressure, lithology, rate of flow and time of contact. Increased dissolution is favored by higher temperature and pressure. Low rates of ground-water flow associated with materials of low hydraulic conductivity increase contact time thereby increasing the potential for dissolution.

A principal reactent in the dissolution process is carbonic acid (H_2CO_3). The soil biota and atmosphere contribute CO_2 to the ground-water flow system. The primary source of CO_2 is oxidation of organic material in soils. The CO_2 combines with water to form carbonic acid. Carbonic acid reacts with calcite ($CaCO_3$) and/or dolomite ($Ca, Mg(CO_3)_2$) leaving Ca^{2+}, Mg^{2+}, and HCO_3^- in solution. The above reactions are summarized by the following:

1) $H_2CO_3+CaCO_3 \rightleftharpoons Ca^{2+}+2HCO_3^-$

2) $2H_2CO_3+CaMg(CO_3) \rightleftharpoons Ca^{2+}+Mg^{2+}+4HCO_3^-$

Within the study area the glacial drift contains considerable amounts of carbonates that were derived from Paleozoic rocks of the northern Red River Valley. In analyzing till samples throughout Dickey and LaMoure Counties, Bluemle (1979a) reported carbonate percentages ranging from 8 to 31 percent. In general, lower percentages are associated with the deeper till intervals. Thin fluvial deposits (less than a few feet thick) consisting of poorly-sorted, angular limestone and/or dolomite fragments are also common throughout the till.

The relationship between Ca^{2+} and HCO_3^- is shown in figure 5. If dissolution of calcite is the single source of Ca^{2+} and HCO_3^-, the analyses would fall along the 45 degree line which passes through the origin. All analyses except for one, fall below the calcite dissolution line indicating a Ca^{2+} deficit. The Ca^{2+} deficit increases with increased dissolved solids concentrations. Analyses from wells completed in the glaciofluvial deposits overlying the Spiritwood aquifer consistently

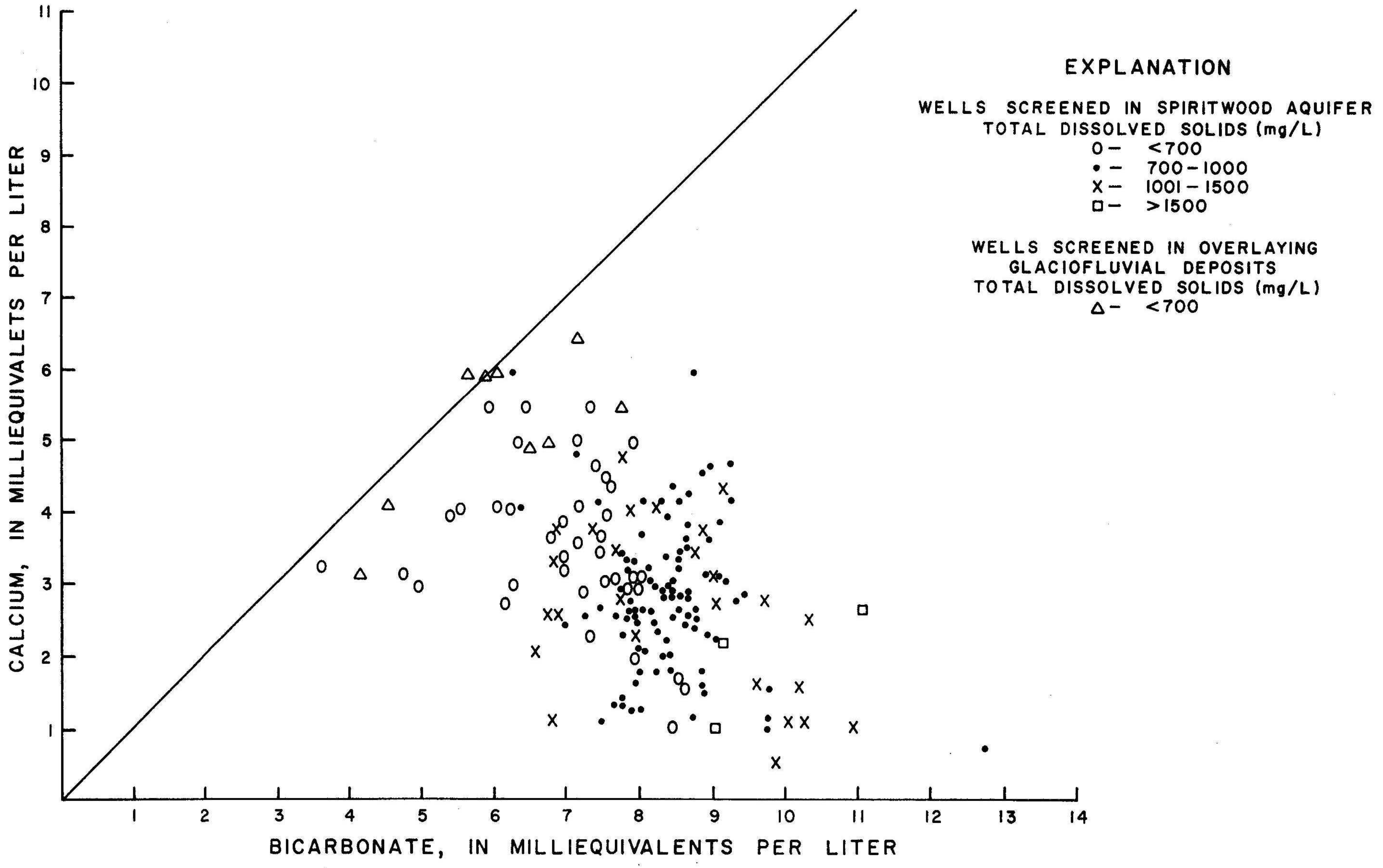


FIGURE 5.-Relationship between calcium and bicarbonate

have smaller Ca^{2+} deficits which reflect shorter residence times. For the most part, the upper glaciofluvial deposits are overlain by glacial till. The Ca^{2+} deficits in the overlying glaciofluvial deposits are probably the result of cation exchange as water moves downward through the surficial till.

The relationship between Ca^{2+} and HCO_3^- is consistent with dissolution of calcite and/or dolomite as the primary mechanism for Ca^{2+} and HCO_3^- enrichment of ground water early in the flow system. The increased deficit in Ca^{2+} with increased dissolved solids concentrations is probably due to cation exchange on clay minerals within the glacial drift and Cretaceous shales. Areas of the Spiritwood aquifer characterized by low dissolved solids and a Ca-HCO_3 type water suggest relatively rapid downward movement through the drift in the absence of clay.

The relationship between Mg^{2+} and HCO_3^- is shown in figure 6. All analyses have a deficit in Mg^{2+}. The concentration of Mg^{2+} is relatively constant. Analyses from wells completed in the glaciofluvial deposits overlying the Spiritwood aquifer have smaller Mg^{2+} deficits. This relationship is consistent with dissolution of dolomite as the primary mechanism for Mg^{2+} enrichment of ground water early in the flow system. The greater deficit in Mg^{2+} compared to the deficit in Ca^{2+} is due, in part, to the dual source of HCO_3^- from the dissolution of both calcite and dolomite. The relatively constant Mg^{2+} concentration and the decrease in Ca^{2+} concentration with increased dissolved solids is consistent with the cation exchange process. In general, Ca^{2+} is more effective than Mg^{2+} in replacing exchangeable Na^+.

The dissolution of gypsum is a source of Ca^{2+} and SO_4^{2-}. The

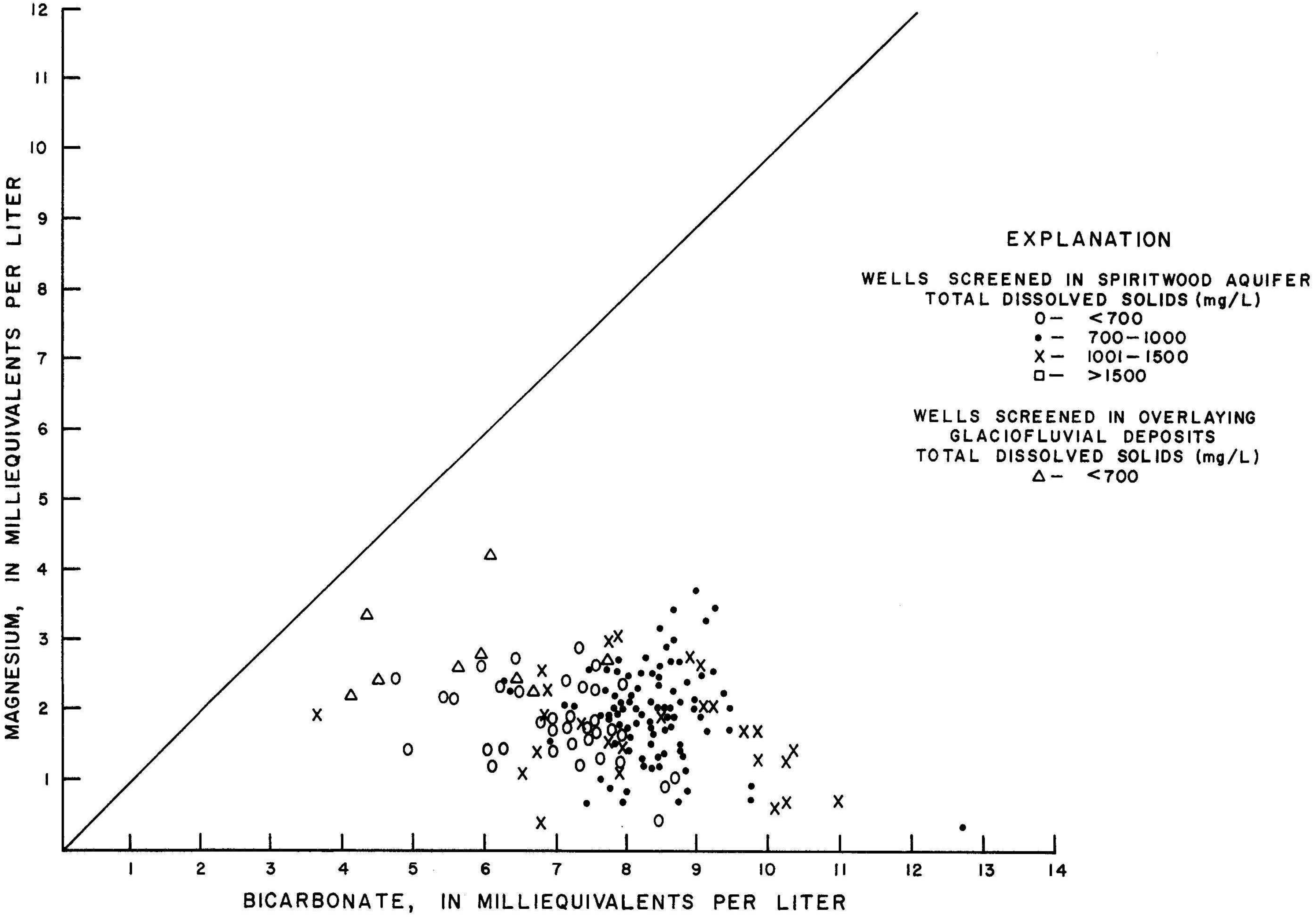


FIGURE 6.—Relationship between magnesium and bicarbonate

following reaction applies.

$$CaSO_4 \cdot 2H_2O \rightleftharpoons Ca^{2+} + SO_4^{2-} + 2H_2O$$

The relationship between Ca^{2+} and SO_4^{2-} is shown in figure 7. If dissolution of gypsum is the single source of both Ca^{2+} and SO_4^{2-}, the analyses would fall along the 45 degree angle line that passes through the origin. For the most part, Ca^{2+} exceeds SO_4^{2-} in the analyses which have less than 700 mg/l dissolved solids. Excess Ca^{2+} may be even greater if other sources of SO_4^{2-} such as oxidation of pyrite and oxidation of organic S are considered.

Ca^{2+} exceeds SO_4^{2-} in all of the analyses from wells completed in the overlying glaciofluvial deposits. The excess Ca^{2+} associated with lower dissolved solids concentrations is consistent with dissolution of calcite and/or dolomite as the primary source of Ca^{2+} early in the flow system.

For the most part, analyses with dissolved solids greater than 700 mg/l show a Ca^{2+} deficit. This could be due to cation exchange; calcite, and dolomite precipitation; or a combination of these processes.

The dissolution of halite (NaCl) is a potential source of both Na^+ and Cl^-. The relationship between Na^+ and Cl^- is shown in figure 8. If dissolution of halite is the single source of Na^+ and Cl^-, the analyses would fall along a 45 degree angle line which passes through the origin. All analyses fall above the 45 degree line indicating an excess of Na^+ with respect to Cl^-. This suggests at least one additional source of Na^+.

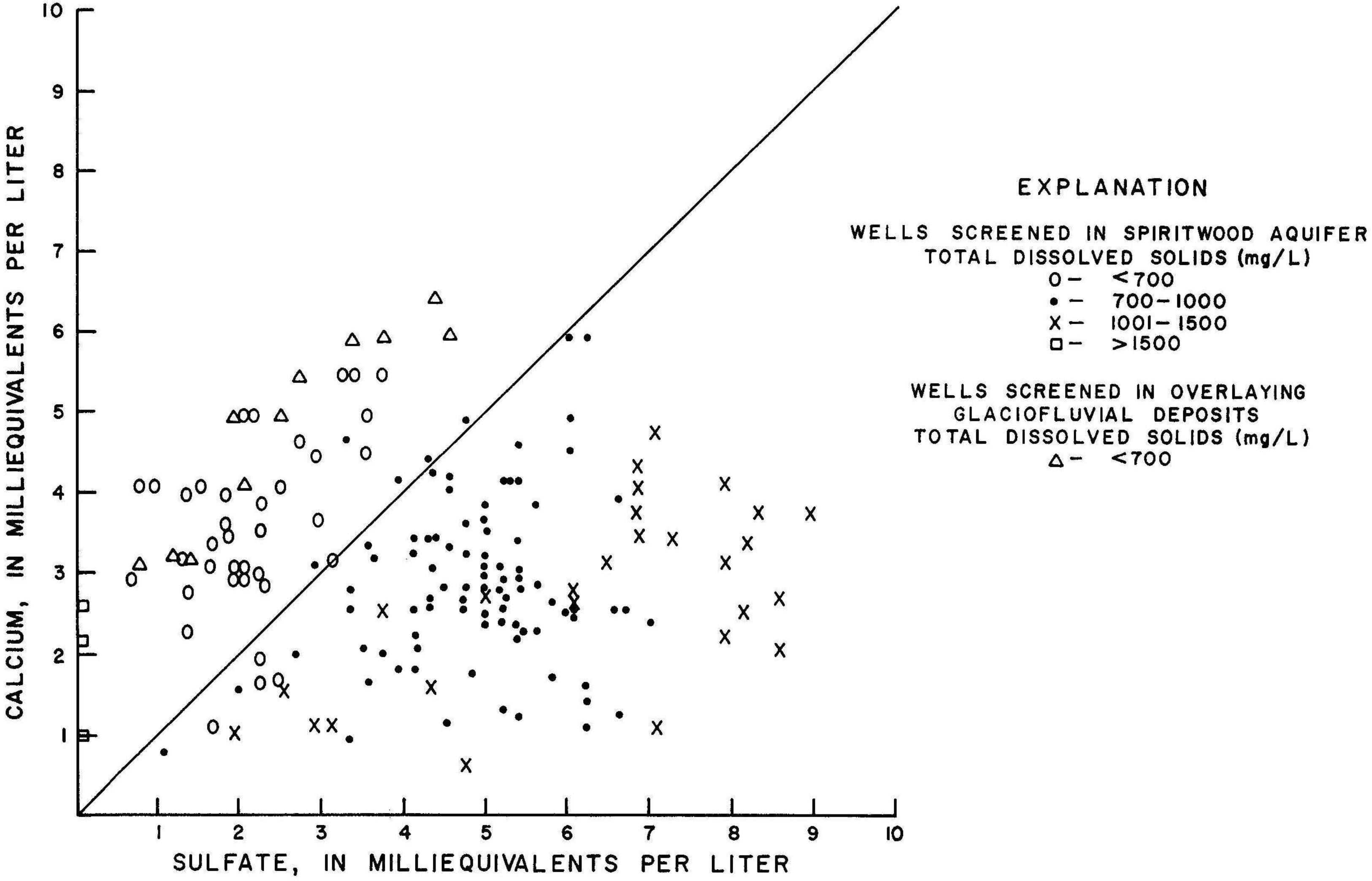


FIGURE 7.—Relationship between calcium and sulfate

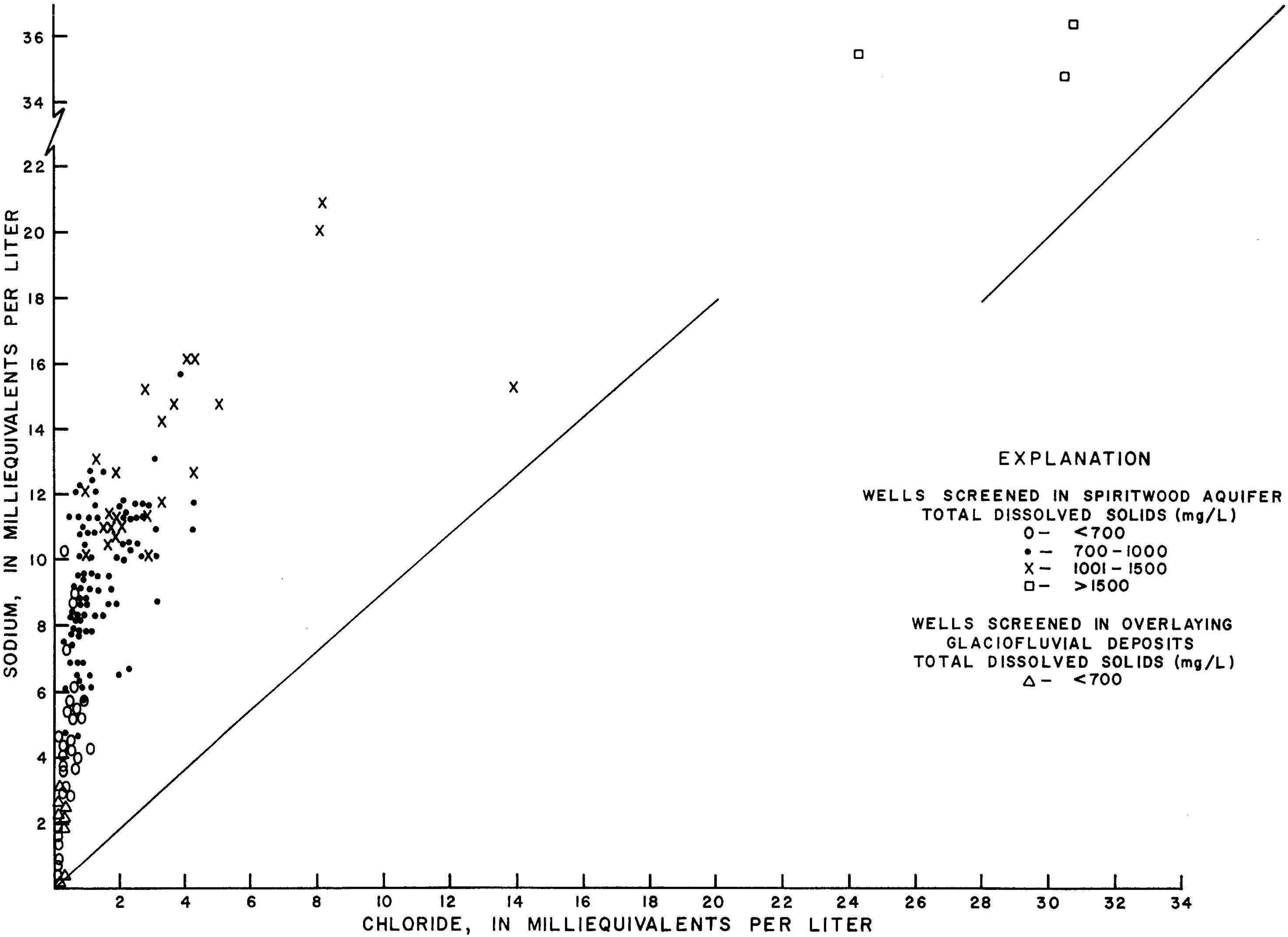


FIGURE 8.—Relationship between sodium and chloride

The dissolution of highly soluble sulfate minerals such as mirabillite ($Na_2SO_4 \cdot H_2O$) and glauberite ($Na_2Ca(SO_4)_2$) may contribute Na^+ and SO_4^{2-} to solution (Cherry, 1972). The relationship between Na^+ and SO_4^{2-} is shown in figure 9. If the dissolution of sodium sulfate minerals is the single source of Na^+ and SO_4^{2-}, the analyses would fall along a 45 degree angle line which passes through the origin. For the most part, the analyses fall above the 45 degree line indicating an excess in Na^+ with respect to SO_4^{2-}. This suggests at least one additional source of Na^+.

Some of the analyses with low dissolved solids concentrations fall below the 45 degree line indicating a deficit in Na^+ with respect to SO_4^{2-}. The Na^+ deficit suggests at least one additional source of SO_4^{2-}, or a process that removes Na^+. All but one of the analyses from the overlying glaciofluvial sediments fall below the 45 degree line indicating a deficit in Na^+ with respect to SO_4^{2-}. The two analyses lowest in Na^+ concentration are from surficial glaciofluvial deposits. At these two locations the aquifer is unconfined and lacks a clay-rich overburden. The dissolution of sodium sulfate minerals does not appear to be an important geochemical control early in the ground-water flow system.

The analyses in figure 9 are probably shifted to the right somewhat because of sources of SO_4^{2-} other than dissolution of sulfate minerals. These sources include oxidation of pyrite and oxidation of organics. Multiple sources of SO_4^{2-} are probable in the study area which means an even greater excess of Na^+ over SO_4^{2-} than shown in figure 9.

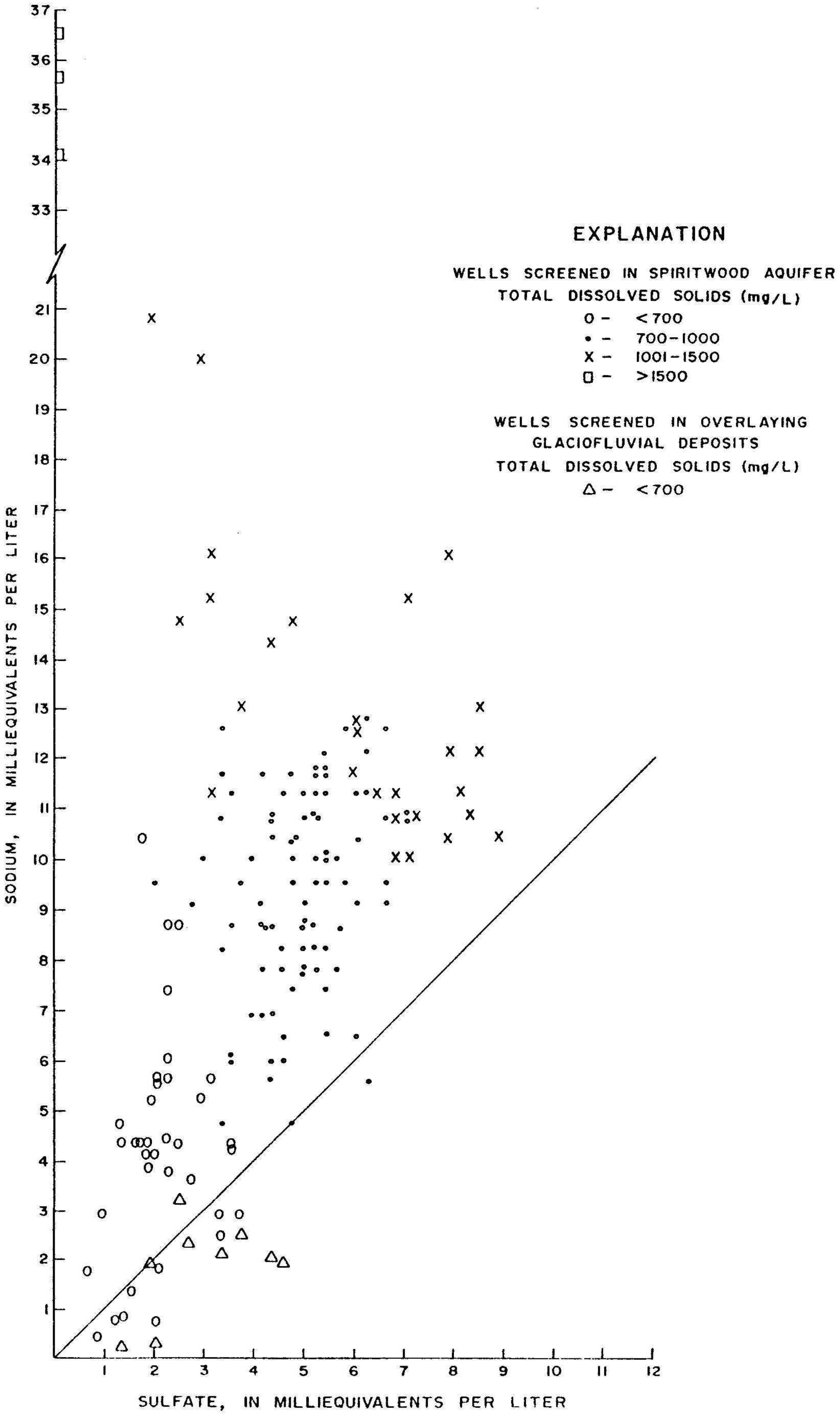


FIGURE 9.— Relationship between sodium and sulfate

The amount of Na^+ equal to Cl^- on an equivalent basis was subtracted from the total Na^+ in each analysis. The relationship between the remaining Na^+ and total SO_4^{2-} is shown in figure 10. As in figure 9 the analyses in figure 10 for the most part show an excess of Na^+ over SO_4^{2-}. At least one additional source of Na^+ is indicated other than halite and sulfate mineral dissolution. The additional source of Na^+ is probably cation exchange on clay minerals.

The oxidation of pyrite in the presence of calcite, under alternate wet and dry conditions is a potential source of Ca^{2+} and SO_4^{2-}. The following reactions apply:

$$FeS_{2(s)}+\tfrac{1}{2}O_2+H_2O \rightleftharpoons Fe^{2+}+2SO_4^{2-}+2H^+$$

$$Fe^{2+}+\tfrac{1}{4}O_2+H^+ \rightleftharpoons Fe^{3+}+\tfrac{1}{2}H_2O$$

$$Fe^{3+}+3H_2O \rightleftharpoons Fe(OH_3)_{(s)}+3H^+$$

$$H^++CaCO_3 \rightleftharpoons Ca^{2+}+HCO_3^-$$

The occurrence of pyrite near the top of the saturated zone has not been investigated within the study area. Williams (1984) analyzed the till underlying glacial Lake Dakota using x-ray defraction techniques. Pyrite was not detected in any of the analyses. Pyrite oxidation is not considered an important geochemical control in the study area.

The oxidation of organic S is also a potential source of SO_4^{2-} (Hendry, 1984). Lignite fragments are ubiquitous in the glacial drift within the study area and are a potential source of organic S.

Most of the previous investigators either ignored the chemical weathering of silicates or stated that their importance was minor. Wallick (1981) states that silicate mineral weathering is an important process in the chemical evolution of ground water in the absence of

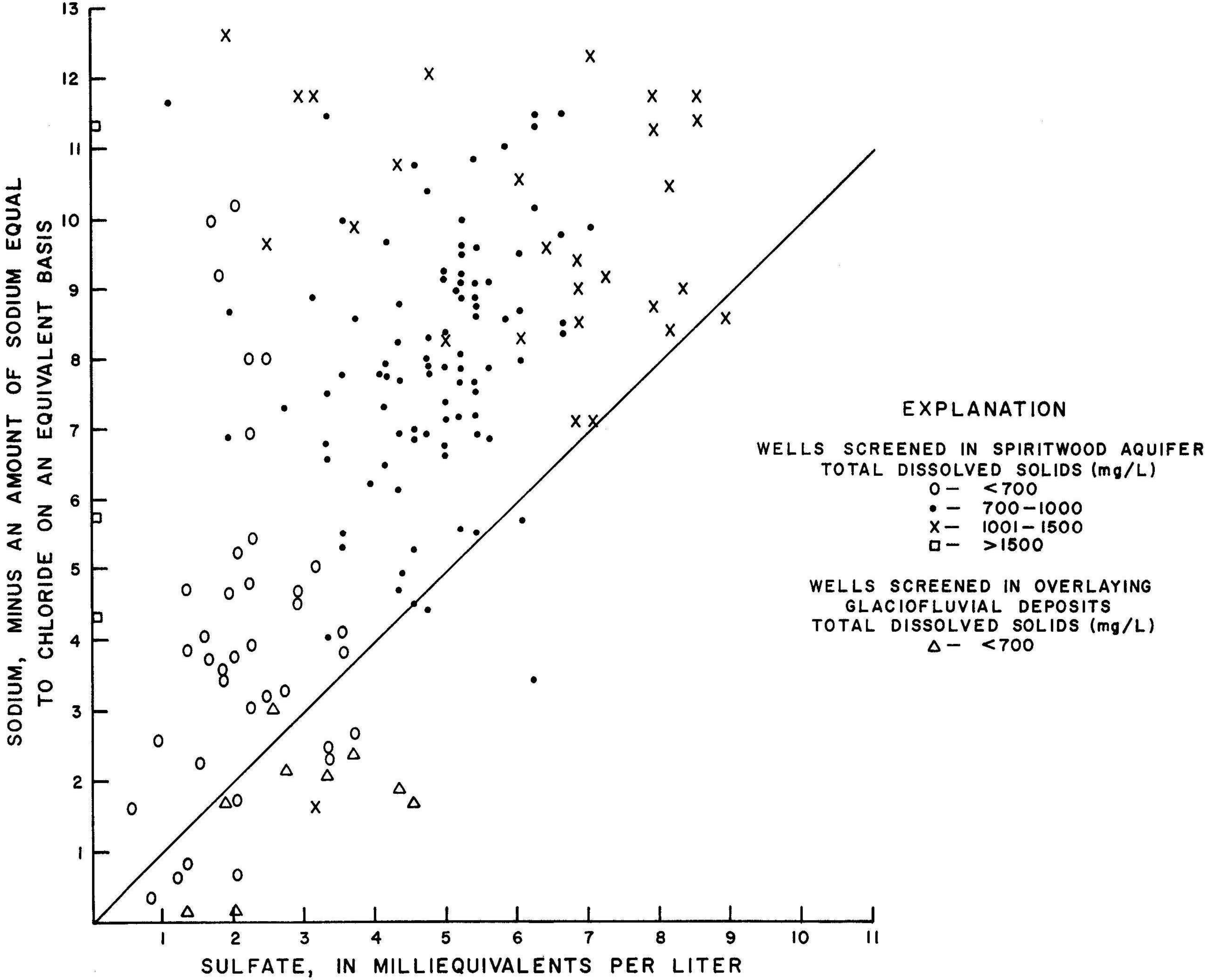


FIGURE 10.—Relationship between sodium minus an amount of sodium equal to chloride on an equivalent basis and sulfate

carbonates in the parent material. The weathering of silicate minerals is slow relative to carbonate mineral weathering. Carbonate minerals are ubiquitous in the glacial drift which suggests that silicate mineral weathering is not an important geochemical control in the study area.

The selective removal and addition of certain cations from solution occurs as a result of cation exchange and adsorption/desorption on clay minerals and/or organics. Isomorphous substitution is a property of clay minerals which involves ionic substitution within the crystal lattice. The result is the creation of a large electrical charge relative to surface area. The electrical charge on the surface layers causes the accumulation of ions of opposite charge, known as counterions. These counterions comprise an absorbed layer in which ion exchange takes place. The adsorption capacity for clays is considerable due to a large surface area per unit volume. For example, the total surface area of 1 gram of smectite clay in which .67 mol of magnesium occurs in isomorphous substitution for aluminum is 750 M^2. (Freeze and Cherry, 1979). The smectite clays exhibit a high capacity for isomorphous substitution and cation exchange.

Rozkowski (1967) states that the cation exchange is governed not only by clay mineralogy but by:

1) salinity of the water
2) temperature
3) pH

Generally, higher temperatures and pH favor cation exchange. Lower salinity waters induce increased adsorption of divalent cations (Ca^{2+}

and Mg^{2+}) and decreased adsorption of monovalent cations (Na^+ and K^+). Schoeller (1962) in VandenBerg and Lennox (1969) gives the following order in which cations tend to become fixed on clay minerals.

$H^+ > Rb^+ > Ba^{++} > Sr^{++} > Ca^{++} > Mg^{++} > K^+ > Na^+ > Li^+$

The order is of a general nature and depends on clay type, water salinity, temperature and pH. Rozkowski (1967) described the decrease in absorbed sodium and increase in abosrbed calcium in the tills within his study area by the following reaction:

$$2Na(\text{Clay minerals}) + Ca^{2+}(\text{water}) \quad Ca(\text{clay minerals}) + 2Na^+(\text{water}).$$

No attempt was made by other investigators previously cited to identify and quantify the impact of cation exchange on the chemical evolution of ground water. They state that cation exchange is an important geochemical control because of the occurrence of smectite which has a high exchange capacity.

Conceptually, one would expect to find Ca^{2+} rich smectite clays in the leached recharge areas and Na^{2+} rich smectite in the discharge areas. The mapping of this relationship and the quantification of cation exchange is difficult due to the very small mass ratio of ions in solution to ions on the exchange complex. Considerable exchange can take place without noticeably altering the clay composition (Wallick, 1981).

For the most part, recharge to the Spiritwood aquifer occurs through a 150 to 200 foot thick glacial drift sheet which consists primarily of till. The geochemistry of the till within the study area has not been investigated.

Williams (1984) investigated the geochemistry of a local shallow ground water flow system associated with Glacial Lake Dakota, in an area located approximately two miles south of Oakes. X-ray defraction analyses were made on the till underlying the Glacial Lake Dakota sediments. Smectite, muscovite/illite, chlorite, and kaolinite were identified from the analyses. The overlying sand of Glacial Lake Dakota contains appreciable amounts of detrital shale which is derived from the Pierre Formation. The geochemistry of the detrital shale was also determined by X-ray defraction analysis. Smectite, muscovite/illite, and chlorite were identified from the analyses.

Falcone (1983) determined the clay mineralogy of two till units in Cass County, North Dakota, using x-ray defraction techniques. The average clay mineral composition of the surficial till (Unit G) was smectite (68.9%), illite (16.5%), and chlorite plus kaolinite (14.4%). The average clay mineral composition of the underlying till (Unit D) was smectite (55.3%), illite (31.1%), and chlorite plus kaolinite (13.6%).

Groenewold, and others (1983) used x-ray defraction techniques to determine the clay mineralogy of surficial tills near the Falkirk and Center lignite surface mine sites in western North Dakota. Smectite (Na-montmorillorite) and illite were the dominant clay minerals. Chlorite and mica were generally present in all samples.

Tourtolot (1962) used x-ray defraction techniques to determine the clay mineralogy of 13 samples of the Pierre Formation located within the eastern facies belt which includes eastern North Dakota. Smectite content ranged from 18 to 45 percent and averaged 39 percent. Mixed layered illite and smectite ranged from 36 to 54 percent and averaged 44 percent. Illite ranged from 9 to 18 percent and averaged 16 percent. Kaolinite averaged 2 percent.

Bluemle (1979a) reports a shale composition of the tills in Dickey and LaMoure Counties that ranges from 5 to 76 percent. Part of the shale is derived locally from the Pierre Formation.

Based on the above investigations, the till overlying the Spiritwood aquifer in the study area probably contains appreciable amounts of smectite. As a result the potential for cation exchange is probably significant.

In the presence of organic material (natural gas, oil, coal, or carbonaceous shale) sulfate ions in ground water can be reduced to sulfide ions by the action of certain anaerobic bacteria. The bacteria is Sporvibrio desulfuricans and its varieties. The generalized reactions are the following:

1) reduction: $SO_4^{2-}+8H^++8e \rightleftharpoons 4H_2O+S^{2-}$

2) oxidation: $CH_4+8OH^- \rightleftharpoons CO_2+6H_2O+8e$

3) complete reaction: $SO_4^{2-}+CH_4 \rightleftharpoons S^{2-}+H^++HCO_3^-+H_2O$

From the above reactions, sulfate reduction is accompanied by the oxidation of organic compounds, by the production of CO_2 which in turn will produce HCO_3^- and hydrogen sulfide (H_2S). The H^+ and HCO_3^- ions combine to form H_2CO_3 which in the presence of calcite, dolomite, and organics can introduce Ca^{2+}, Mg^{2+} and HCO_3^-into solution. In the absence of carbonates, sulfate reduction results in a more acidic water. Sulfate reduction may be occurring in the narrow tributary channel to the Spiritwood aquifer approximately 6 miles northeast of Oakes. An analysis of a water sample from domestic well 132-58-31BAA (not shown in Table 1) completed in this tributary channel indicates a total dissolved solids content of 2250 mg/l, 8.2 mg/l SO_4^{2-}, and the presence of an H_2S odor.

Evaporation and transpiration from the water table can increase the salinity. In general, large intervals between periods of deep percolation, sparse rainfall, high temperatures, and low humidity all contribute to a higher salinity recharge water in areas underlain by a shallow water table. These factors are particularly characteristic of the summer months within the glaciated plains of North Dakota.

The chemistry of deep formation waters is impacted by membrane effects. Shales act as semi-permeable membranes which affect the rates of transport of ions of different size and charge. Membrane effects have been proposed to explain the concentration of brines in deep sedimentary basins (Back and Hanshaw, 1965). The Cretaceous shales overlying the sandstone formations of the Dakota Group may act as semi-permeable membranes. Membrane effects may be an important geochemical control in the Cretaceous sediments underlying the Spiritwood aquifer. Within the glacial drift membrane effects are not considered an important geochemical control.

STATISTICAL ANALYSIS

Histograms

Histograms were prepared and statistical functions were calculated for the distributions of Ca^{2+}, Mg^{2+}, Na^{+}, HCO_3^{-}, SO_4^{2-}, Cl^{-} and total dissolved solids (fig. 11). Based on the calculated mean and standard deviation, a normal distribution for each chemical parameter was synthesized. The synthesized normal distribution is shown superimposed on each histogram for comparative purposes.

Of the six major cations and anions, the HCO_3^{-} distribution more closely approximates a normal distribution. In each case the actual distributions show a more compressed range in concentration (more peakedness), than the synthesized normal distributions. HCO_3^{-} has the smallest range, 9.32 epm and SO_4^{2-} has the largest range, 45.80 epm. The total dissolved solids (calculated) range from 12.72 epm (363 mg/l) to 111.95 epm (3640 mg/l).

Regression Analysis

Scatterplots were prepared to compare the absolute values of each of the three major cations (Ca^{2+}, Mg^{2+}, Na^{+}) to total cations and the absolute values of each of the three major anions (HCO_3^{-}, SO_4^{2-}, Cl^{-}) to total anions (fig. 12). The scatterplots of Ca^{2+} and Mg^{2+} have correlation coefficients of -0.29 and -0.04, respectively, indicating the lack of a linear relationship. The scatterplots of both Ca^{2+} and Mg^{2+} are characterized by a pattern of almost complete scatter. This pattern of scatter suggests multiple sources (dissolution) and sinks (precipitation and cation exchange) of Ca^{2+} and Mg^{2+}.

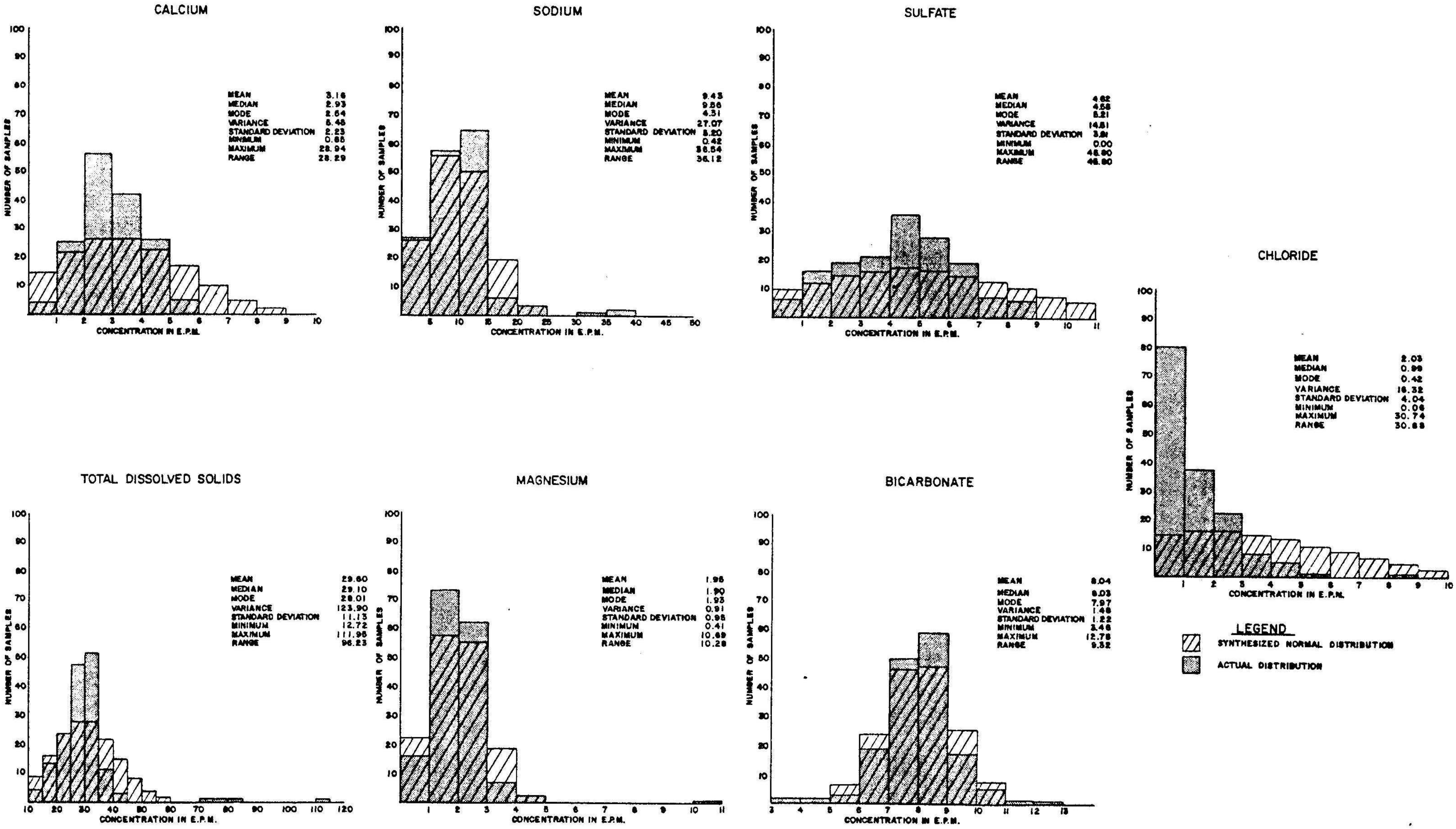


FIGURE 11.-Histograms and general statistical parameters for selected cations and anions

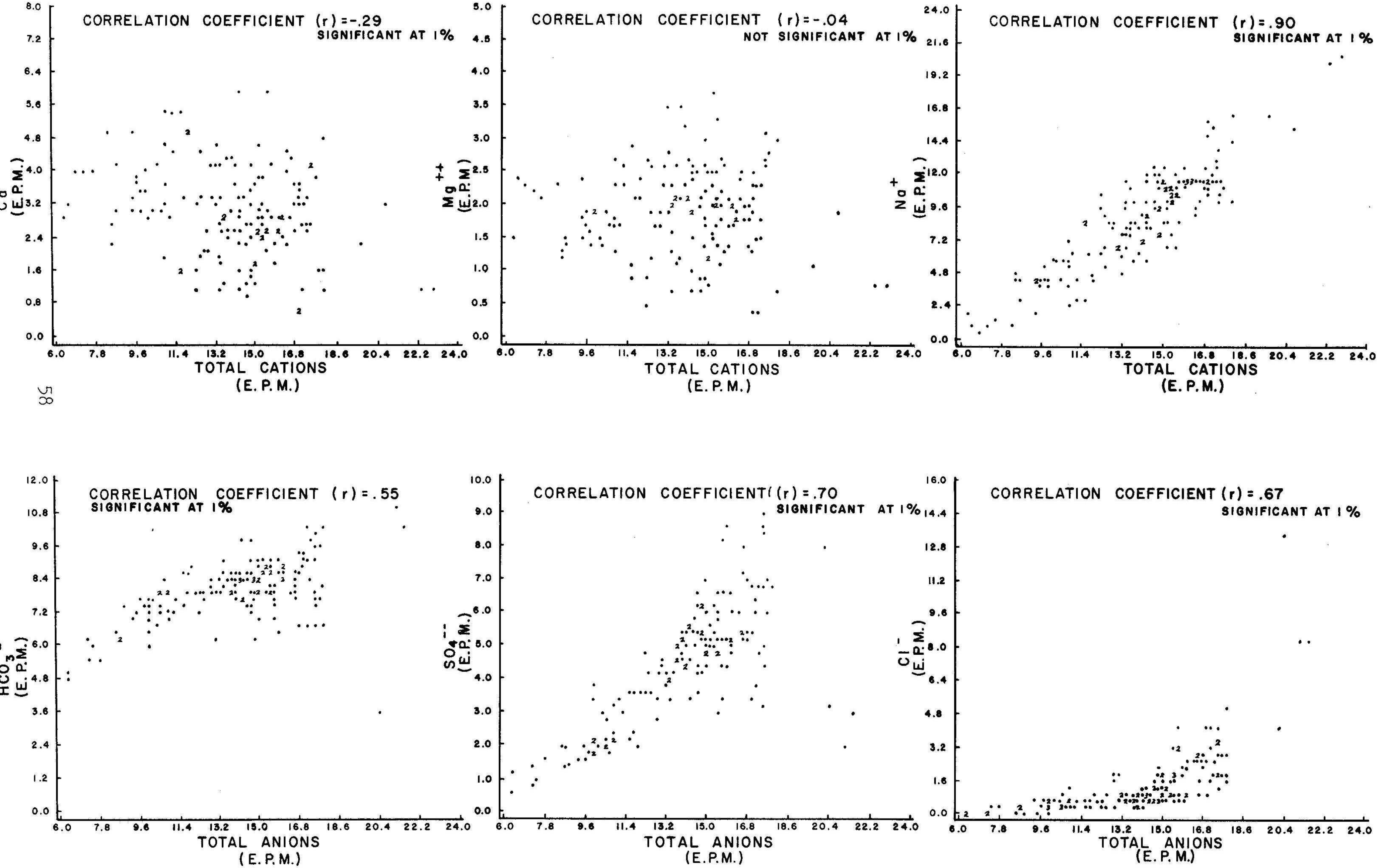


FIGURE 12.-SCATTERPLOTS OF ABSOLUTE CONCENTRATION OF MAJOR CATIONS AND ANIONS VERSUS TOTAL CATIONS AND ANIONS

The scatterplot of Na^+ versus total cations shows the strongest linear relationship with a correlation coefficient of +0.90. The strong linear relationship suggests a single major geochemical control for Na^+, which is probably cation exchange. The concentration of Na^+ is directly proportional total dissolved solids concentrations.

HCO_3^- increases linearly over low total anion concentrations and levels off over high total anion concentrations (fig. 12). This same relationship was shown by Toth (1966 and 1968). The amount of HCO_3^- is established rather quickly in the flow system by the dissolution of carbonates with H_2CO_3 near the water table. Further dissolution of carbonates away from recharge areas is minor due to CO_2 depletion or buffering. Thus, absolute HCO_3^- concentration, once established remains relatively constant. The small range in concentration of HCO_3^- as compared to other cations and anions is consistent with the dissolution of carbonates early in the flow system and/or the occurrence of only one process controlling its concentration.

Addition of HCO_3^- can occur in areas where sulfate reduction is operative. These areas can be identified by the lack of SO_4^{2-} and in many cases the presence of hydrogen sulfide gas (H_2S).

The scatterplots of absolute SO_4^{2-} and Cl^- versus total anions have correlation coefficients of +0.70 and +0.67, respectively. The concentrations of SO_4^{2-} and Cl^- are directly proportional to total dissolved solids concentrations.

The scatterplots of both SO_4^{2-} and Cl^- are characterized by an increase in the ratio of SO_4^{2-} and Cl^- to total anions at approximately

14 epm total anion concentrations. The increased ratio of SO_4^{2-} and Cl^- to total anions may be due to the influence of upward moving bedrock water. The geochemistry of the underlying Cretaceous marine shales differs significantly from the overlying glacial drift. This geochemical discontinuity plays an important role in the development of hydrochemical patterns in the Spiritwood aquifer and will be addressed in later sections of the report.

Scatterplots also were prepared to compare the percent concentrations of each of the three major cations (Ca^{2+}, Mg^{2+}, Na^+) and each of the three major anions (HCO_3^-, SO_4^{2-}, Cl^-) to total dissolved solids (fig. 13). The interpretation of percent concentration data can be misleading. The inversely proportional relationship of percent Ca^{2+}, Mg^{2+} and HCO_3^- versus total dissolved solids is not due to a decrease in absolute Ca^{2+}, Mg^{2+} or HCO_3^-. This is apparent when figure 13 is analyzed in conjunction with figure 12. The decrease in percent HCO_3^- versus total dissolved solids is due to a levelling off of absolute HCO_3^- coupled with an increase in absolute SO_4^{2-} and Cl^-. The decrease in percent Ca^{2+} and Mg^{2+} versus total dissolved solids is due to the overwhelming increase in absolute Na^+.

Based on the assumption that total dissolved solids are directly proportional to length of flow path and residence time, the scatterplots in figures 12 and 13 indicate a chemical evolution of ground water from a $Ca\text{-}HCO_3$ type to a $Na\text{-}SO_4\text{-}Cl$ type.

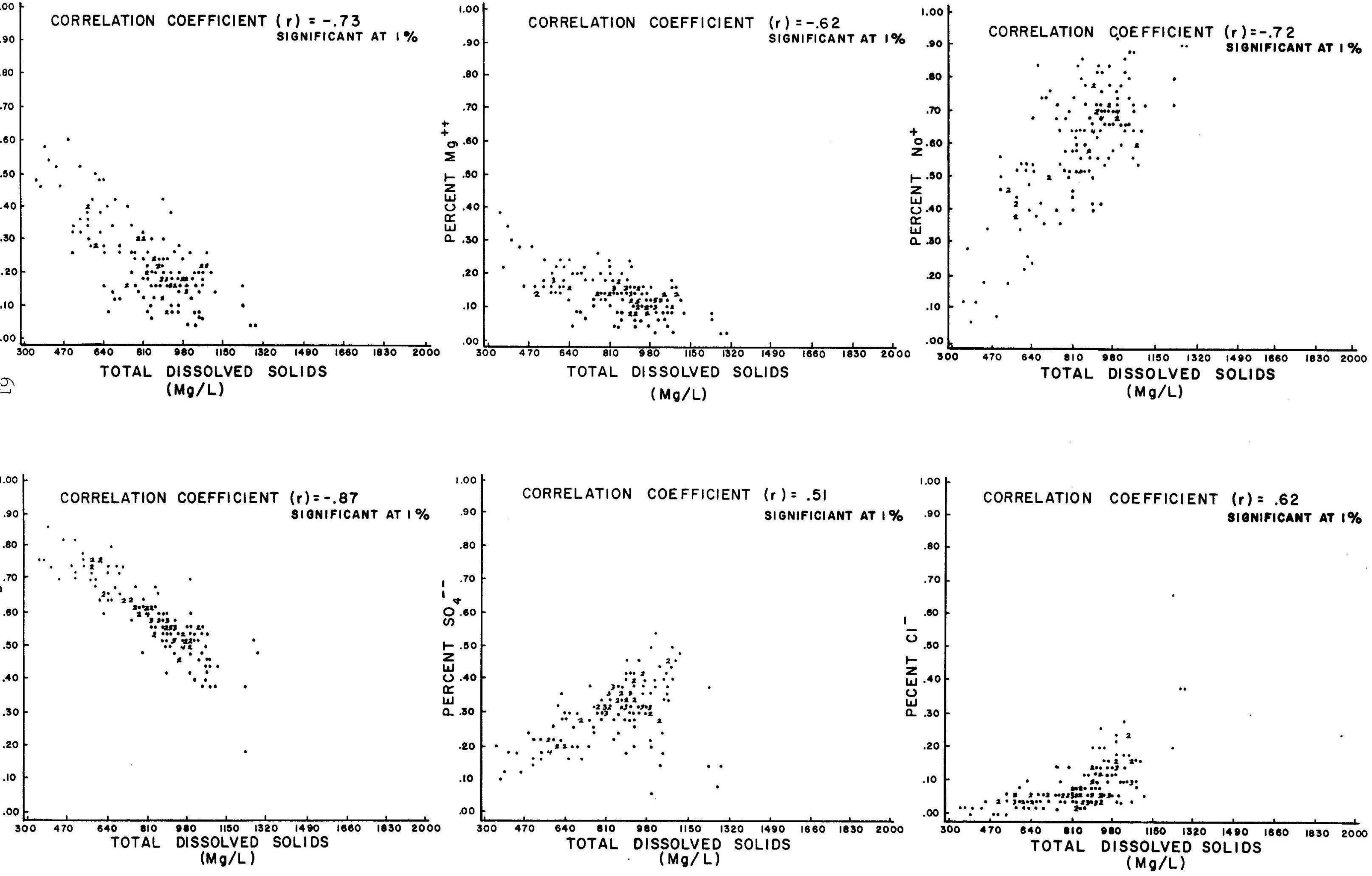


FIGURE 13.—SCATTERPLOTS OF PERCENT CONCENTRATION OF MAJOR CATIONS AND ANIONS VERSUS TOTAL DISSOLVED SOLIDS

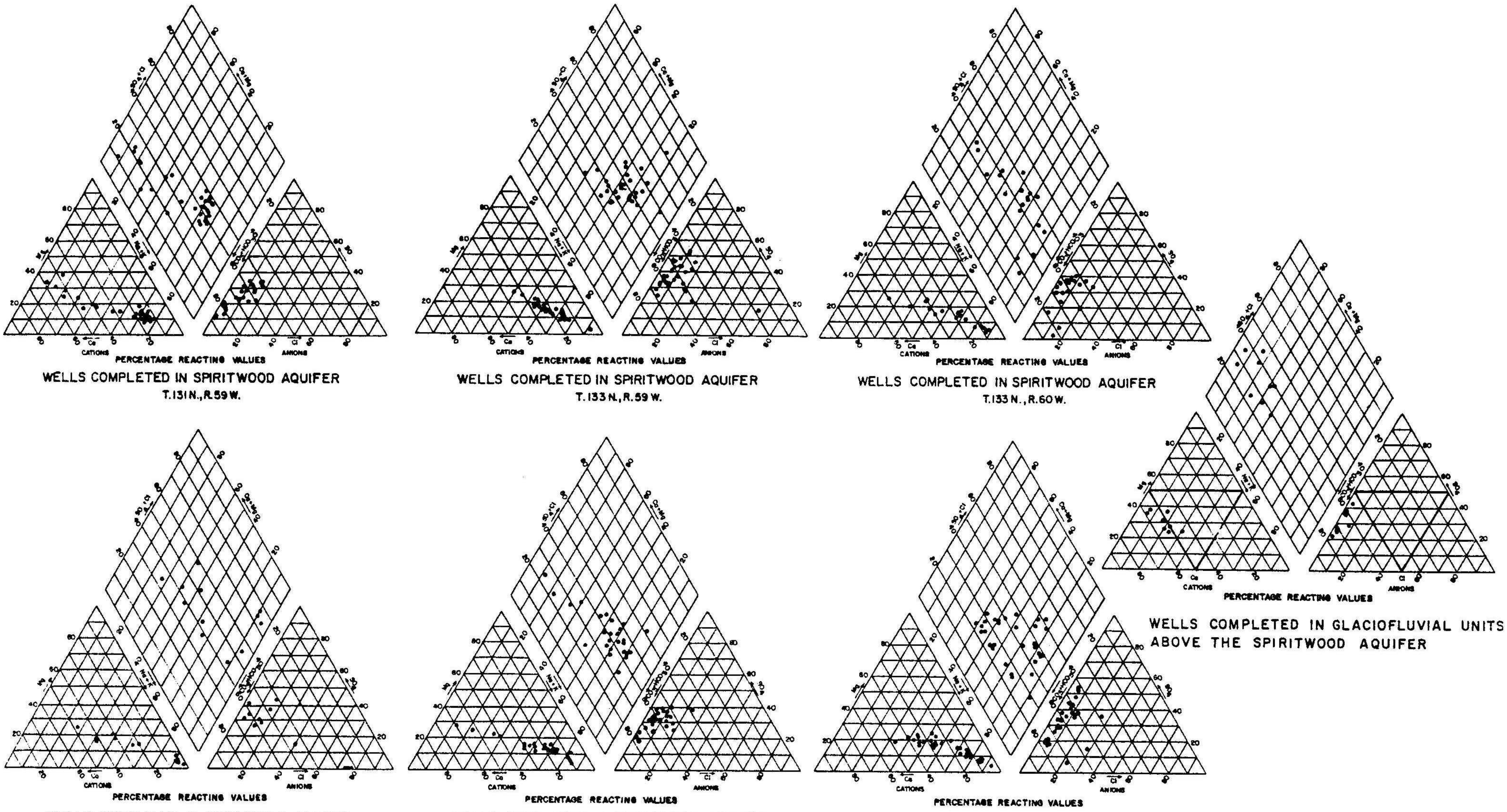
GRAPHICAL PRESENTATION AND INTERPRETATION OF CHEMICAL ANALYSES

Piper Diagrams

Chemical analyses of water samples collected from wells completed in the Spiritwood aquifer and from wells completed in the overlying glaciofluvial deposits were plotted on Piper trilinear diagrams (fig. 15). Ground water from the overlying glaciofluvial deposits is a $Ca-HCO_3$ type. Ground water from the Spiritwood aquifer ranges from a $Ca-HCO_3$ type to a $Na-HCO_3-SO_4$ type. The distribution of analyses shown in the Piper diagrams, coupled with the regression analyses indicates a decrease in relative Ca^{2+} and Mg^{2+} with depth. Absolute Na^+, SO_4^{2-} and Cl^- increase with depth.

A $Ca-HCO_3$ type ground water, low in total dissolved solids occurs in some areas of the Spiritwood aquifer. This hydrochemical facies is primarily associated with shorter residence time ground water which occurs in the overlying glaciofluvial deposits. The occurrence of a relatively low total dissolved solids, $Ca-HCO_3$ type water in the Spiritwood aquifer suggests more rapid downward movement of recharge in the absence of clay, coupled with minor upward flow from the underlying marine shales.

A $Na-HCO_3-SO_4$ type water, relatively high in Cl^- occurs in some areas of the Spiritwood aquifer. This hydrochemical facies is indicative of discharge areas, rather sluggish areas in the flow system, and/or areas characterized by significant upward flow from the underlying marine shales.



WELLS COMPLETED IN SPIRITWOOD AQUIFER
T. 131 N., R. 59 W.

WELLS COMPLETED IN SPIRITWOOD AQUIFER
T. 133 N., R. 59 W.

WELLS COMPLETED IN SPIRITWOOD AQUIFER
T. 133 N., R. 60 W.

WELLS COMPLETED IN GLACIOFLUVIAL UNITS ABOVE THE SPIRITWOOD AQUIFER

WELLS COMPLETED IN SPIRITWOOD AQUIFER
T. 130 N., R. 57 W.
T. 131 N., R. 57 W.
T. 131 N., R. 58 W.
T. 132 N., R. 58 W.

WELLS COMPLETED IN SPIRITWOOD AQUIFER
T. 132 N., R. 59 W.
T. 132 N., R. 60 W.

WELLS COMPLETED IN SPIRITWOOD AQUIFER
T. 134 N., R. 59 W.
T. 134 N., R. 60 W.
T. 134 N., R. 61 W.

FIGURE 14.-Piper diagrams

To assess the relationship between hydrochemical facies and location in the flow system, the spatial distribution of the chemical analyses was analyzed. This was accomplished by preparing Schoeller diagrams for each chemical analysis, organizing the analyses into categories with similar ionic distributions, and plotting the various categories on an aquifer map.

Schoeller Diagrams

The Schoeller diagrams were divided into four categories (Fig. 15). Category #1 comprises those analyses in which:

1) Ca^{2+} is the dominant cation.
2) HCO_3^- is the dominant anion.
3) Absolute Cl^- is low, less than 1 epm, generally less than 0.5 epm.
4) Total dissolved solids are low, less than 750 mg/l.

Category #1 was divided into two groups. Group one analyses are from wells completed in the overlying glaciofluvial deposits less than 100 feet deep. Total dissolved solids are less than 700 mg/l and absolute Cl^- is less than 0.3 epm. Group two analyses are from wells completed in the Spiritwood aquifer. Total dissolved solids are less than 750 mg/l and absolute Cl^- is less than 1.0 epm. The group two analyses are the most important analyses for locating areas of significant recharge.

Category #2 is the most common type of water in the Spiritwood aquifer and is characterized by the following:

1) Na^+ is the most abundant cation.
2) Ca^{2+}, for the most part, exceeds Mg^{2+}.
3) HCO_3^- is the most abundant anion.
4) Total dissolved solids range from 501 to 1030 mg/l.

Category #3 comprises those analyses in which:

1) Na^+ is the most abundant cation.
2) SO_4^{2-} is the most abundant anion or SO_4^{2-} is within 2 epm of absolute HCO_3^-.
3) Total dissolved solids range from 785 mg/l to 1240 mg/l.

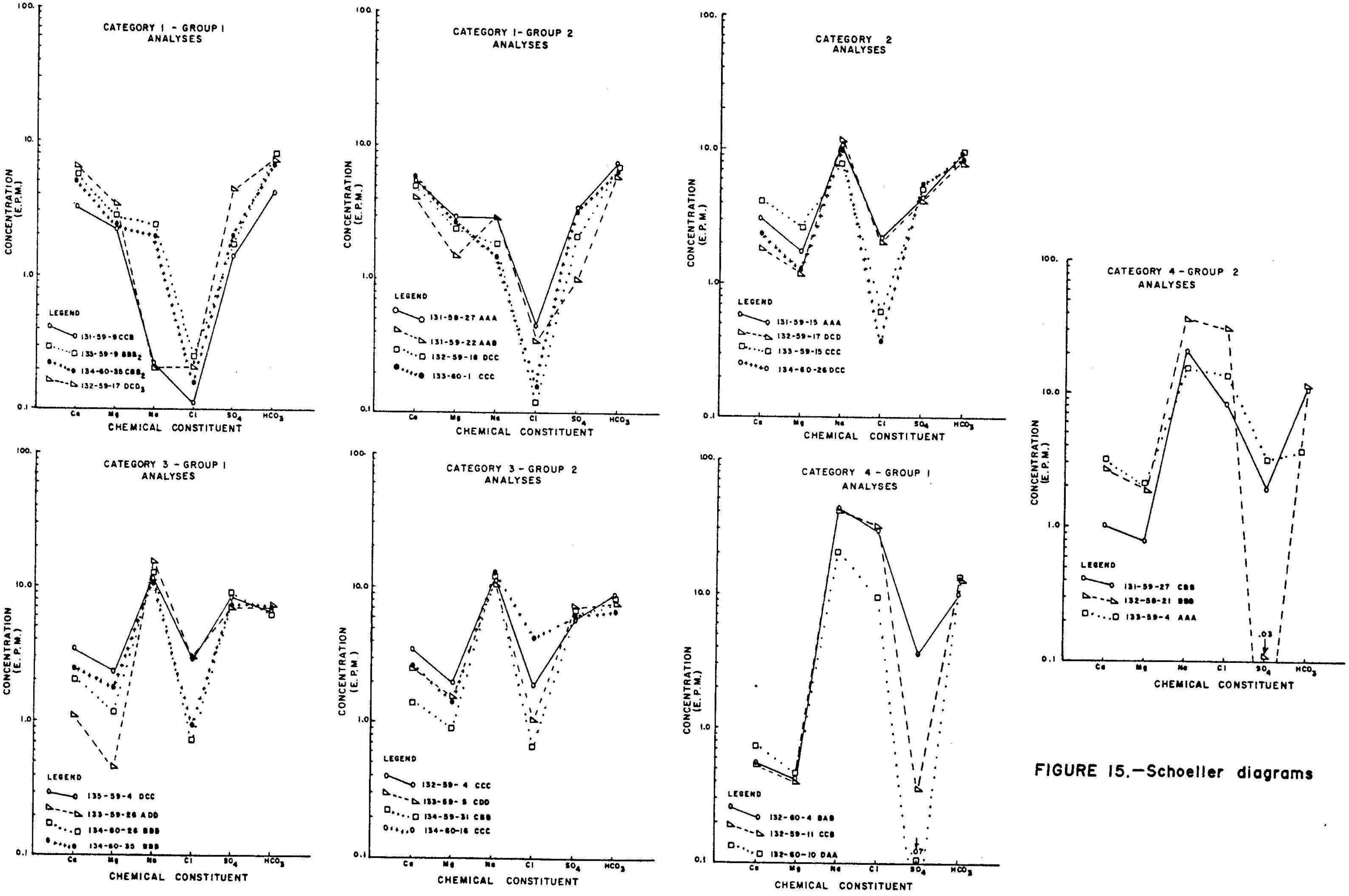


FIGURE 15.—Schoeller diagrams

Category #3 was divided into two groups. Group one analyses have SO_4^{2-} as the most abundant anion with total dissolved solids ranging from 947 mg/l to 1110 mg/l. Group two analyses are those in which HCO_3^- is the most abundant anion and SO_4^{2-} is not more than 2 epm below the concentration of HCO_3^-. Total dissolved solids range from 785 mg/l to 1240 mg/l.

Category #4 comprises those analyses in which:

1) Na^+ is the most abundant cation, and it greatly exceeds Ca^{2+} or Mg^{2+}.
2) Cl^- is for the most part the most abundant anion.
3) SO_4^{2-} is generally low.
4) Total dissolved solids are relatively high ranging from 1040 mg/l to 2480 mg/l.

The water in Category #4 is for the most part a Na-Cl-HCO_3 type water and is divided into two groups. Group one analyses are from wells completed in the Niobrara Formation. Group two analyses are from wells completed in the Spiritwood aquifer. The areal distribution of the various categories, except those of category 1, group 1 and category 4, group 1 are shown in plate 8. The subcrop of the Pierre Formation is also delineated in plate 8.

Category 1, group 2 type ground water is found in five different areas of the Spiritwood aquifer (pl. 8). The first area is 8 to 10 miles east of Oakes toward Cogswell. Available lithologic logs from wells completed in this area indicate that the Spiritwood aquifer is overlain by relatively thick lacustrine sandy silt. Till and/or clay lithologies are in places absent. The occurrence of category 1, group

2 type water in this area of the Spiritwood aquifer is probably due to the relatively rapid downward movement of recharge through the overlying lacustrine sandy silt.

Category 1, group 2 water also occurs in a tributary channel to the Spiritwood aquifer approximately two miles east of Oakes. In this area, the Spiritwood aquifer is again overlain by a relatively thick interval of lacustrine sandy silt. An aquifer test was conducted in this tributary channel using the irrigation well located at 131-59-22BAD. The results of the test indicated that leakage from the overlying glaciolacustrine sediments was significant (Shaver, 1984). The occurrence of category 1, group 2 type water in this area of the Spiritwood aquifer is due to relatively rapid downward flow through the overlying lacustrine sandy silt.

Another area of category 1, group 2 water occurs approximately 6 to 7 miles north of Oakes. In the vicinity of observation wells 132-59-17CDD, 132-59-17DCD and 132-59-21BBA, the Spiritwood aquifer is overlain by a relatively thick glaciofluvial deposit consisting primarily of silty sand and silty clay (pl. 4, geohydrologic-section E-E'). A thin interval of glacial till separates the overlying glaciofluvial deposits from the Spiritwood aquifer. The occurrence of category 1, group 2 type water at 132-59-21BBA is probably due to leakage from the overlying glaciofluvial deposits.

The mechanisms operative to account for category 1, group 2 type water in the vicinity of 132-59-18DCC are not apparent. Available data has not revealed an overlying glaciofluvial deposit which could provide rapid downward movement of recharge at this site.

An area of category 1, group 2 water also occurs approximately 6 to 7 mles east of LaMoure. Observation wells 133-60-1CCC and 133-60-12BAA have screened intervals near the top of the Spiritwood aquifer. This choice of screened interval was made because of the existence of numerous clay layers in the basal part of the aquifer. Over much of the study area, the Spiritwood aquifer receives recharge from overlying glacial drift, and the underlying marine shales. The water chemistry in the basal parts of the Spiritwood aquifer may be influenced to a greater extent by the underlying marine shales. The upper parts of the aquifer may be influenced to a greater extent by the glacial drift. This could account for category 1, group 2 type water at 133-60-1CCC and 133-60-12BAA. The observation well at 133-60-1DDD also has a screened interval near the top of the aquifer. The water chemistry, however, differs significantly from that at 133-60-1CCC and 133-60-12BAA. The water chemistry of the Spiritwood aquifer at 133-60-1CCC and 133-60-12BAA is very similar to the water chemistry of the overlying glaciofluvial deposits. This indicates that locally there is little change in water chemistry as ground water flows downward through a 100+ foot thick interval of glacial till. One possible explanation is the occurrence of relatively high transmissivity conduits (glaciofluvial deposits and/or fractures and joints) within the glacial drift which provide for rapid downward flow of ground water. Existing data is insufficient to determine the significance and spatial distribution of high transmissivity conduits.

A local topographic high overlies the Spiritwood aquifer in the area located approximately 6 to 7 miles east of LaMoure. The topographic high consists of sand, silt, and clayey silt. These lithologies have relatively high infiltration capacities. The local topographic high coupled with a relatively high infiltration capacity also may contribute to make this a relatively good recharge area.

An area of category 1, group 2 water occurs at domestic well 134-60-19BBB approximately four miles north of LaMoure (pl. 6 geologic section J-J'). The water chemistry is very close to that of category 2, in which Na^+ exceeds Ca^{2+}. The low total dissolved solids in this area is the result of the following:

1) The area is a local topographic high.
2) Surface drainage is channeled toward the Twin Lakes area which provides a local surface reservoir, for eventual downward infiltration.
3) The till at 134-61-13DAD is relatively thin and contains significant glaciofluvial intervals which facilitate the rapid downward flow of ground water.
4) The upward flow of ground water into the aquifer from the underlying shales does not occur or is negligible.

Category 2 type water is the most common within the study area (pl. 8). It is a $Na-HCO_3-SO_4$ type water. This type water probably represents a mixture of downward flowing glacial drift water and upward flowing water from the underlying marine shales. Overall, the transmissivity of the glacial drift is higher than that of the underlying shales. Over most of the study area, the amount of water moving downward through the glacial drift exceeds the amount of water moving upward from underlying shales. Therefore, within the Spiritwood aquifer, the glacial drift hydrochemical facies probably dominates the mixing process.

Category 3, group 1 and group 2 waters are characterized by relatively high SO_4^{2-}. This type of water occurs for the most part along the eastern flank of the eastern channel system (pl. 8). The spatial distribution of the category 3, group 1 and group 2 analyses generally corresponds to areas where the Pierre Formation directly underlies the aquifer. The basal Pembina Member of the Pierre Formation contains gypsum. This relationship indicates that the Spiritwood aquifer acts as a buried-line sink over much of the study area.

West of the Twin Lakes area, the Pierre Formation also directly underlies the aquifer (pl. 8). Category 3 type water however, is absent in this area. One possible explanation is that upper members of the Pierre Formation which lack sulfate minerals may underlie the Spiritwood aquifer in this area. Another possible explanation is that upward flow of ground water into the aquifer from the underlying marine shales does not occur or is negligible. The lack of upward flow from the underlying shales could result from the combination of the inferred low-transmissivity barrier south of Twin Lakes and the James River valley topographic low to the southwest. Preliminary interpretation of water levels measured during the late fall and early winter of 1983 indicate a transverse flow component directed toward the James River valley away from the Twin Lakes area. This indicates that the James River valley acts as a local discharge area to this segment of the Spiritwood aquifer. The importance of the Spiritwood aquifer as a buried line-sink in this area is therefore diminished. However, vertical hydraulic gradient data from the underlying shale is lacking in the area to verify this explanation.

Category 3, group 2 type water is also found in observation well 132-59-27CDC$_1$. The chemical analysis indicates a relatively high absolute Cl^- concentration as compared to other analyses in this category. Vertical hydraulic head data at this site indicates upward flow of ground water with respect to the water table. The relatively high Cl^-, SO_4^{2-} and total dissolved solids reflects upward flow of water from the underlying Niobrara Formation. The water chemistry data provides further evidence that Bear Creek valley is a local discharge area to the Spiritwood aquifer.

Category 4, group 1 water is, for the most part, a Na-Cl-HCO_3, Na-HCO_3-Cl type water. This type water is associated with the Niobrara Formation which is a marine shale. One analysis from a domestic well which is completed at the top of the Niobrara Formation (131-59-23BCC) is a Ca-HCO_3 type water, low in total dissolved solids (table 3). In this part of the study area, the Niobrara Formation is overlain by a sequence of sandy silt and silty sand which provides rapid downward movement of recharge. The well annulus was not sealed from the top of the Niobrara Formation to land surface. A considerable volume of water is probably moving into the well through the annulus. As a result, the chemical analysis may not be representative of the Niobrara Formation.

Category 4, group 2 type water is characterized by high Cl^- concentrations. This type water is associated with isolated deposits of sand and gravel. These deposits can be quite deep as in 133-59-4AAA and probably represent sluggish areas of the flow system. This type water also occurs in the narrow buried tributary 5 to 6 miles northeast of Oakes. SO_4^{2-} is less than 0.1 epm in observation wells 132-58-30DAA, $21BBB_2$, and $16BAA_2$. Absolute HCO_3^- is high. This may be an area in which sulfate reduction occurs. The impact on water levels in this tributary from irrigation withdrawals to the southwest is both subdued and delayed. This indicates a poor hydraulic connection between the tributary and the main buried channel to the southwest. The occurrence of category 4, group 2 type water in this area of the aquifer is the result of a sluggish flow system associated with a narrow buried valley, in which sulfate reduction may be occurring.

AREAL DISTRIBUTION OF MAJOR CATIONS AND ANIONS

An analysis of the areal distribution of the major chemical constituents provides additional insight into the ground-water flow system. Contour maps were prepared showing total dissolved solids, absolute and percent concentrations of the major cations (Ca^{2+} + Mg^{2+}, Na^{+}) and anions (HCO_3^- + CO_3^{2-}, SO_4^{2-}, Cl^-).

Total dissolved solids concentration is directly proportional to length of flow path and residence time. In an idealized flow system, contours of equal total dissolved solids concentration are oriented transverse to the direction of flow. Lower total dissolved solids are associated with recharge areas and higher total dissolved solids are associated with discharge areas.

The flow system in the study area is complex. Inhomogeneities intersected along a flow path impact the chemical evolution of ground water. Areas in the flow system where total dissolved solids contours are not aligned transverse to the direction of flow are due to changes in topography, transmissivity, and mineralogy, or any combination of the above.

Total dissolved solids concentrations less than approximately 750 mg/l occur in five areas of the Spiritwood aquifer (pl. 9). The first area is located in the northwest part of the study area in the vicinity of Twin Lakes. The second area is located in the north-central part of the study area in the vicinity of 133-59-12. The third area is a long narrow band extending northwest from observation well 132-59-29DAA to 133-60-26DCC in the west-central part of the study area. The fourth area is located in the southwest part of the study area in the vicinity of 131-59-22. The fifth area is located in the southeast part of the study area in the vicinity of Dill Slough. The nature of the flow system in areas 1, 2, 4, 5, and the southeastern portion of area 3 was discussed in the previous section of this report. The northwest portion of the narrow band of low total dissolved solids in area 3 was not distinguished by the categorization of Schoeller diagrams. The chemical analyses from observation wells 133-60-26DCC, 133-60-36DDD and 132-60-12BBB are a $Na-HCO_3$ type water. Except for sodium being the dominant cation, the three analyses are very similar to the $Ca-HCO_3$ type waters of category 1, group 2.

This area of the Spiritwood aquifer is overlain by a local topographic high. The surficial lithologies consist of wind blown silt, sand, and possibly fluvial sand up to a depth of about 50 feet. A distortion in the potentiometric surface is associated with this local topographic high (pl. 7). An 80 foot thick glaciofluvial unit of clayey silt, sand and gravel occurs to a depth of 152 feet at test hole 133-60-27DDD. The local topographic high provides the driving force for the downward movement of ground water. The surficial silt and sand, with high infiltration capacities provide a good catchment area. Finally, the occurrence of a thick, deeper glaciofluvial interval may provide a high transmissivity conduit for rapid downward flow of ground water to the Spiritwood aquifer.

Over much of the study area, the total dissolved solids contours are aligned roughly parallel with the principal transmissivity axes of the aquifer. The areas of high transmissivity are associated with thicker intervals of sand and gravel. Except in the Twin Lakes area, the underlying marine shales provide recharge to the Spiritwood aquifer. The volume of cross-sectional flow in the thin flank areas of the aquifer is small as compared to the thicker high transmissivity areas of the aquifer. Ground water higher in total dissolved solids, moving upward from the underlying shales has a greater impact on the mixing process in the flank areas of the aquifer. In the thicker, high transmissivity areas of the aquifer, where the volume of cross-sectional flow is large, the ground water moving upward from the underlying shales is diluted. The impact on the mixing process is therefore diminished.

An area of high total dissolved solids roughly parallels Bear Creek in the southern part of the study area. The analysis from 132-59-27CDC$_1$ is a Na-HCO_3-SO_4 type water, high in Cl^-. Upward flow is indicated by the water levels measured at 132-59-27CDC$_1$ and CDC$_2$. Further upstream, at 132-59-3CCC, a flowing observation well was completed in the Spiritwood aquifer. The water chemistry data coupled with vertical hydraulic head data indicates that Bear Creek valley is a discharge area to the Spiritwood aquifer.

The areal distribution of the major cations (Ca^{2+} + Mg^{2+}, Na^+) and anions (HCO^-_3 + CO_3^{2-}, SO_4^{2-}, Cl^-) in both absolute and relative (percent) concentrations are shown in plates 10-19. The five recharge areas previously described are characterized by the following:

1) high relative Ca^{2+} + Mg^{2+}
2) high absolute Ca^{2+} + Mg^{2+} in areas 2, 4, and 5; low absolute Ca^{2+} + Mg^{2+} in areas 1 and 3.
3) low relative Na^+ in areas 2, 4, and 5; moderate relative Na^+ in areas 1 and 3.
4) low absolute Na^+ in areas 2, 4, and 5; moderate absolute Na^+ in areas 1 and 3
5) high relative HCO_3^- + CO_3^{2-}
6) low relative SO_4^{2-}
7) low absolute SO_4^{2-}
8) low relative Cl^-
9) low absolute Cl^-

The discharge area associated with Bear Creek valley is characterized by the following:

1) low relative $Ca^{2+} + Mg^{2+}$
2) low absolute $Ca^{2+} + Mg^{2+}$
3) high relative Na^+
4) high absolute Na^+
5) low relative $HCO_3^- + CO_3^{2-}$
6) high relative SO_4^{2-}
7) high absolute SO_4^{2-}
8) high relative Cl^-
9) high absolute Cl^-

The absolute and relative concentration contours for most of the cations and anions are aligned parallel to the principal transmissivity axes throughout the aquifer. These high transmissivity axes are characterized by the following:

1) high relative $Ca^{2+} + Mg^{2+}$
2) high absolute $Ca^{2+} + Mg^{2+}$
3) low relative Na^+
4) low absolute Na^+
5) high relative $HCO_3^- + CO_3^{2-}$
6) low relative SO_4^{2-}
7) low absolute SO_4^{2-}
8) low relative Cl^-

Exceptions to some of the above trends occur in the study area. The narrow tributary channel northeast of Oakes is characterized by low relative and absolute sulfate. The low sulfate in this part of the aquifer is probably due to sulfate reduction and not the influence of a recharge area. The Na^+, Cl^- and total dissolved solids are all high, and suggest an area of sluggish ground-water flow. The high $Ca^{2+} + Mg^{2+}$ concentration in observation well 134-60-20DAA, is also not due to the influence of a recharge area. The total dissolved solids are high which suggest that this deep sand and gravel deposit is located in an area of sluggish ground-water flow.

The high absolute and relative SO_4^{2-} concentration in the northeast part of the study area, southwest of Verona, suggests the influence of a discharge area. The high absolute Ca^{2+} and Mg^{2+} suggests the influence of a recharge area. The high SO_4^{2-} and Ca^{2+}+ Mg^{2+} in this area is due to upward ground-water flow from the Pierre Formation which contains gypsum and selenite.

In applying water chemistry data to ground-water flow system analysis, the distribution of the major cations and anions must be examined in relation to topography, transmissivity and mineralogy. Ignoring any one of these hydrochemical controls can lead to misinterpretation of the ground-water flow system.

VERTICAL VARIATION OF WATER CHEMISTRY WITHIN THE SPIRITWOOD AQUIFER

Vertical variation of water chemistry within the Spiritwood aquifer was not considered in the analysis of the areal distribution of chemical constituents. The hydrochemical data implies that over much of the study area, the Spiritwood aquifer acts as a buried-line sink. Water flows into the aquifer from both the overlying glacial drift and the underlying marine shale formations. Thus, the Spiritwood aquifer contains a mixture of two distinct hydrochemical facies. Near the base of the aquifer, the mixing process is influenced to a greater extent by the chemical facies associated with the underlying shale. Near the top of the aquifer, the mixing process is influenced to a greater extent by the chemical facies associated with the overlying glacial drift.

During August, 1984 piezometer nests were installed at four sites in the study area to evaluate vertical variation in water chemistry. The sites are located at 134-61-13DAD, 133-60-2CDD, 133-60-36DDD and 132-59-27CDC. Lithologic logs of the deepest drill hole at each site are included in appendix 1. These logs were compiled by an on-site geologist. The screened intervals of the piezometers at each site are shown at the bottom of the lithologic log. Chemical analyses from water samples collected at each nest site are shown in table 4.

The piezometer nest at 134-61-13DAD is located in the northwest part of the study area in the vicinity of Twin Lakes. Piezometer 134-61-13DAD$_3$ is completed in a glaciofluvial deposit that overlies the Spiritwood aquifer. The screened interval is from 68 to 73 feet below land surface.

Piezometer 134-61-$13DAD_2$ is completed near the top of the Spiritwood aquifer. The screened interval is from 132 to 137 feet below land surface. Piezometer 134-61-$13DAD_3$ is completed near the base of the Spiritwood aquifer. The screened interval is from 257 to 262 feet below land surface. Water levels decrease with increasing depth in the glacial drift which indicates downward ground-water flow.

The distribution of selected cations and anions in water samples collected from each piezometer located at 134-61-13DAD is shown on a Schoeller diagram (fig. 16). The chemical analysis from piezometer 134-61-$13DAD_3$ indicates a Ca-HCO_3 type water with a total dissolved solids concentration of 371 mg/l. The chemical analysis from piezometer 134-61-$13DAD_2$ also indicates a Ca-HCO_3 type water with a total dissolved solids concentration of 549 mg/l. The chemical analysis from piezometer 134-61-$13DAD_1$ indicates a Na-HCO_3 type water with a dissolved solids concentration of 559 mg/l.

There is a significant increase in concentration of each of the three selected cations and anions as water flows downward from the overlying glaciofluvial deposit to the top of the Spiritwood aquifer. Within the Spiritwood aquifer at this site, the water chemistry is relatively uniform. From top to bottom in the aquifer there is a small increase in Na^+ and a small decrease in Ca^{2+} and Mg^{2+}. Cl^- increases, SO_4^{2-} decreases slightly and HCO_3^- remains the same.

The Pierre Formation directly underlies the Spiritwood aquifer in this area. As previously stated, the Pierre Formation contains appreciable gypsum. The occurrence of high SO_4^{2-} in the Spiritwood aquifer corresponds to areas where the Pierre Formation directly underlies the Spiritwood aquifer. The slight decrease in

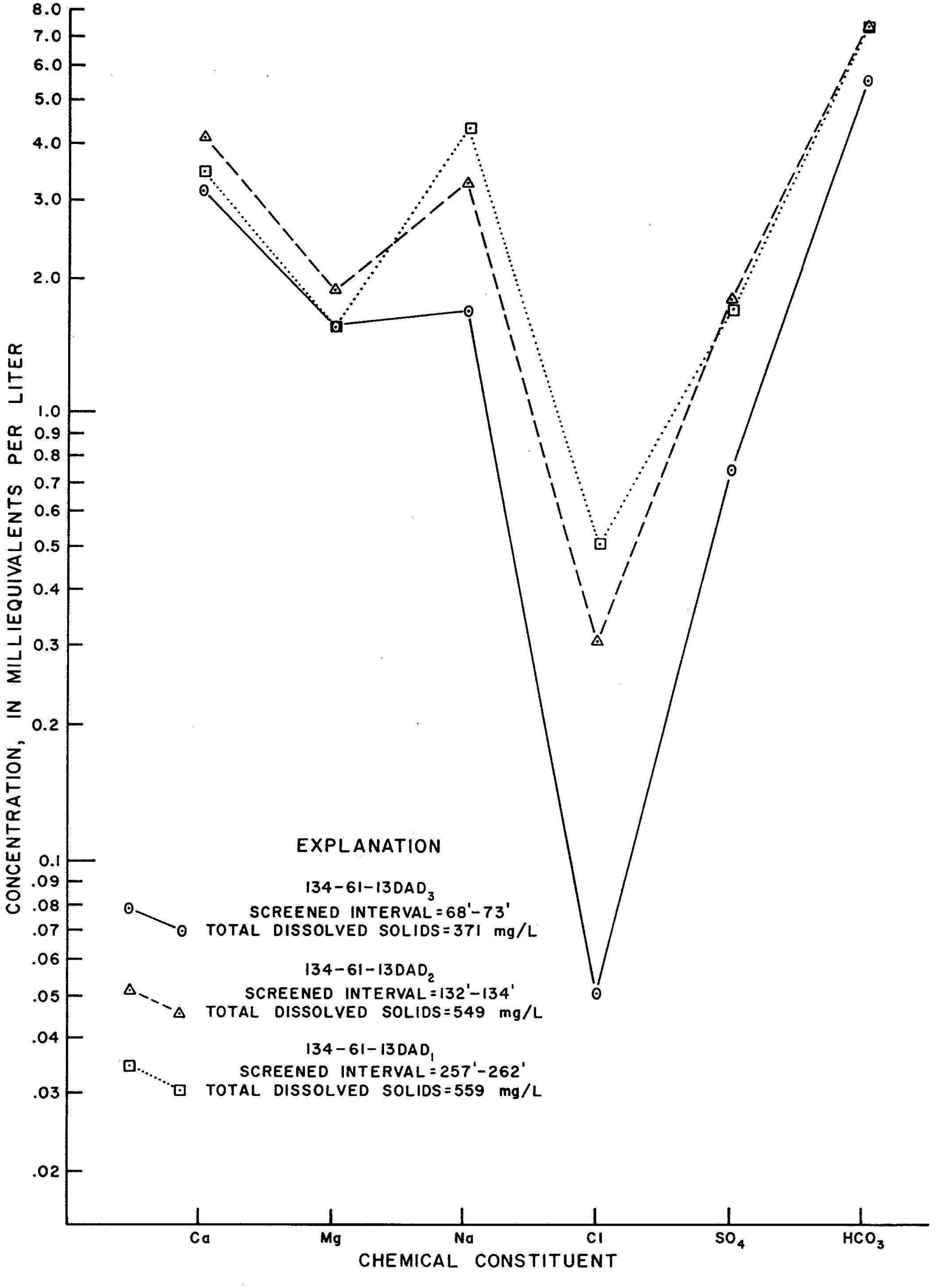


FIGURE 16.—Diagram showing concentration of selected cations and anions at piezometer nest 134-61-13DAD

SO_4^{2-} from top to bottom in the Spiritwood aquifer indicates that upward flow from the underlying Pierre Formation does not occur.

The piezometer nest at 133-60-2CDD is located in the northern part of the study area approximately five miles east of LaMoure. Piezometer 133-60-$2CDD_4$ is completed in a glaciofluvial deposit that overlies the Spiritwood aquifer. The screened interval is from 26 to 31 feet below land surface. Piezometer 133-6C-$2CDD_2$ is completed near the top of the Spiritwood aquifer. The screened interval is from 195 to 200 feet below land surface. Piezometer 133-6C-$2CDD_1$ is completed near the base of the Spiritwood aquifer. The screened interval is from 255 to 260 feet below land surface. Water levels decrease with increasing depth in the glacial drift which indicates downward ground-water flow.

The distribution of selected cations and anions in water samples collected from each piezometer located at 133-6C-2CDD is shown on a Schoeller diagram (fig. 17). The chemical analysis from piezometer 133-60-$2CDD_4$ indicates a Ca-HCO_3 type water with a total dissolved solids concentration of 429 mg/l. The chemical analysis from piezometer 133-60-$2CDD_2$ indicates a Na-HCO_3 type water with a total dissolved solids concentration of 873 mg/l. The chemical analysis from piezometer 133-60-$2CDD_1$ also indicates a Na-HCO_3 type water with a total dissolved solids concentration of 945 mg/l.

The ground water evolves from a Ca-HCO_3 type to a Na-HCO_3 type as it flows downward through the glacial drift to the top of the Spiritwood aquifer. The concentrations of Ca^{2+} and Mg^{2+} decrease and the concentrations of Na^+, HCO_3^-, SO_4^{2-} and Cl^- increase. The decrease in Ca^{2+} and Mg^{2+}

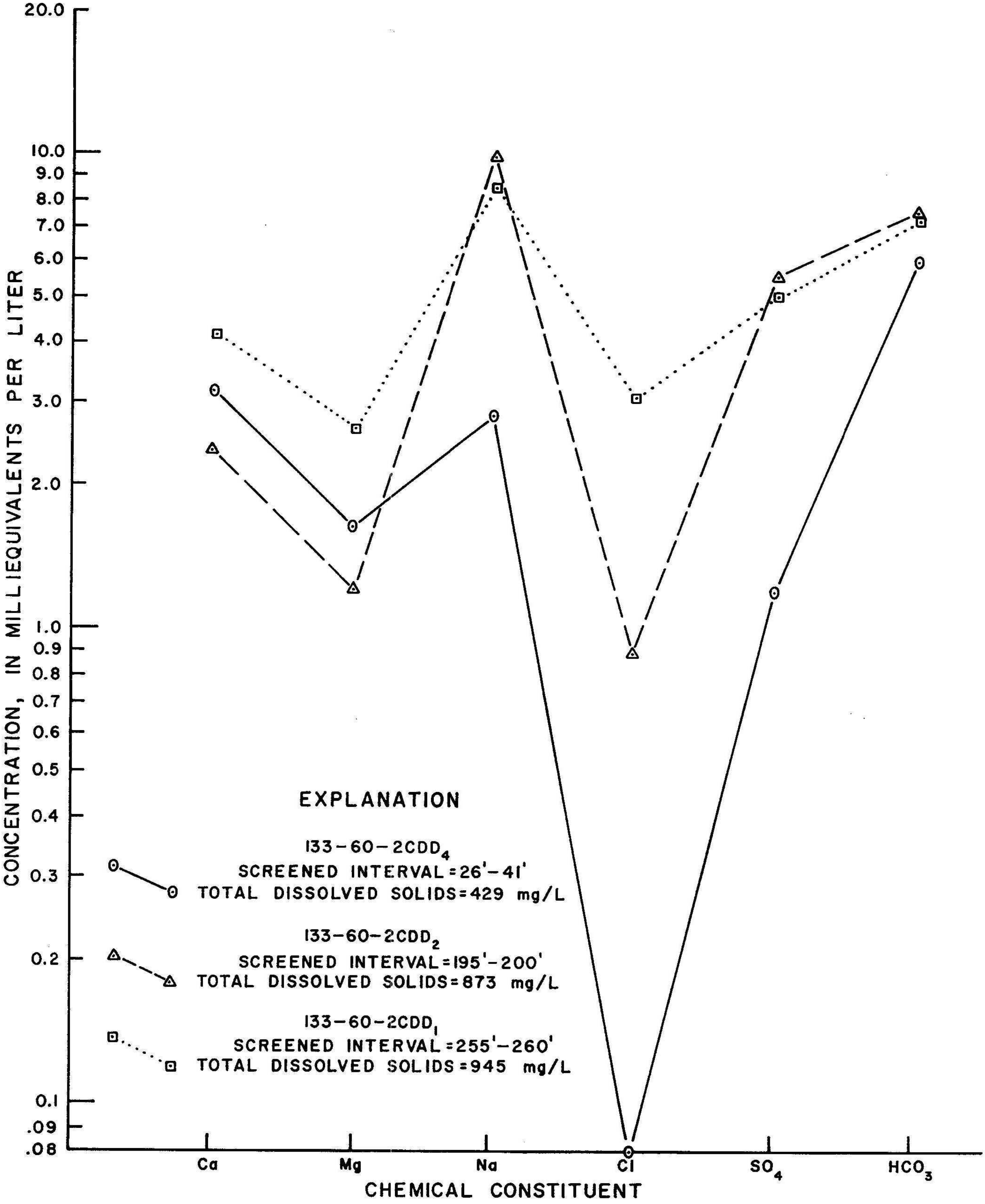


FIGURE 17.—Diagram showing concentration of selected cations and anions at piezometer nest 133-60-2CDD

coupled with an increase in Na^+ is probably due to cation exchange on clay minerals in the till. The increase in Na^+ coupled with a doubling of total dissolved solids implies slow downward flow of water in the presence of clay. High transmissivity conduits (joints, fractures, glaciofluvial units) which provide rapid downward flow of water appear to be lacking in this area.

At this site, the water chemistry near the top of the Spiritwood aquifer differs from the water chemistry near the base of the aquifer. The dissolved solids concentration increases eight percent from top to bottom in the aquifer. Near the base of the aquifer, the concentrations of Ca^{2+}, Mg^{2+}, Cl^- increase and the concentrations of Na^+, $SO_4{}^{2-}$, and $HCO^-{}_3$ decrease slightly. Carlson (1964) reports up to 69.9 percent $CaCO_3$ concentrations in the Niobrara Formation. The high lime content of the Niobrara Formation is the probable cause of Ca^{2+} enrichment, near the base of the Spiritwood aquifer.

The hydraulic conductivity of shale ranges from 10^{-7} to 10^{-3} ft/day (Freeze and Cherry, 1979). The low hydraulic conductivity coupled with the marine origin of the Niobrara Formation is conducive to the occurrence of high Cl^- concentrations. Cl^- is a very conservative ion and therefore is considered the most important indicator of upward flow into Spiritwood aquifer from the underlying Niobrara Formation.

The piezometer nest at 133-60-36DDD is located in the west-central part of the study area on the Dickey-LaMoure County line. Piezometer 133-60-36DDD_1 is completed near the top of the Spiritwood aquifer. The screened interval is from 212 to 215 feet below land surface. Piezometer 133-60-36DDD_2 is completed near the base of the Spiritwood aquifer. The screened interval is from 236 to 241 feet below land surface. Two other piezometers at this site are completed in the till overlying the Spiritwood aquifer. No water samples have been collected from these two wells. Water levels decrease with increasing depth in the glacial drift which indicates downward ground-water flow.

The distribution of selected cations and anions in water samples collected from piezometers 133-60-36DDD$_1$ and 133-60-36DDD$_2$ is shown on a Schoeller diagram (fig. 18). The chemical analysis from piezometer 133-60-36DDD$_1$, indicates a Na-HCO$_3$ type water with a total dissolved solids concentration of 561 mg/l. The chemical analysis from piezometer 133-60-36DDD$_2$ also indicates a Na-HCO$_3$ type water with a total dissolved solids concentration of 611 mg/l.

At this site the water chemistry near the top of the Spiritwood aquifer differs from the water chemistry near the base of the aquifer. The difference is similar to that measured in the piezometer nest located at 133-60-2CDD. The total dissolved solids concentration increases eight percent from top to bottom in the aquifer. Near the base of the aquifer, the concentrations of Ca^2, Mg^{2+}, Cl^-, $SO_4{}^{2-}$, and $HCO_3{}^-$ increase and the concentration of Na^+ remains the same. As with the piezometer nest located at 133-60-2CDD, the change in water chemistry near the base of the Spiritwood aquifer is the result of the upward flow of ground water from the underlying Niobrara Formation.

The piezometer nest at 132-59-27CDC is located approximately five miles northeast of Oakes in Bear Creek valley. Piezometer 132-59-27CDC$_3$ is completed near the top of the Spiritwood aquifer. The screened interval is from 150 to 155 feet below land surface. Piezometer 132-59-27CDC$_1$

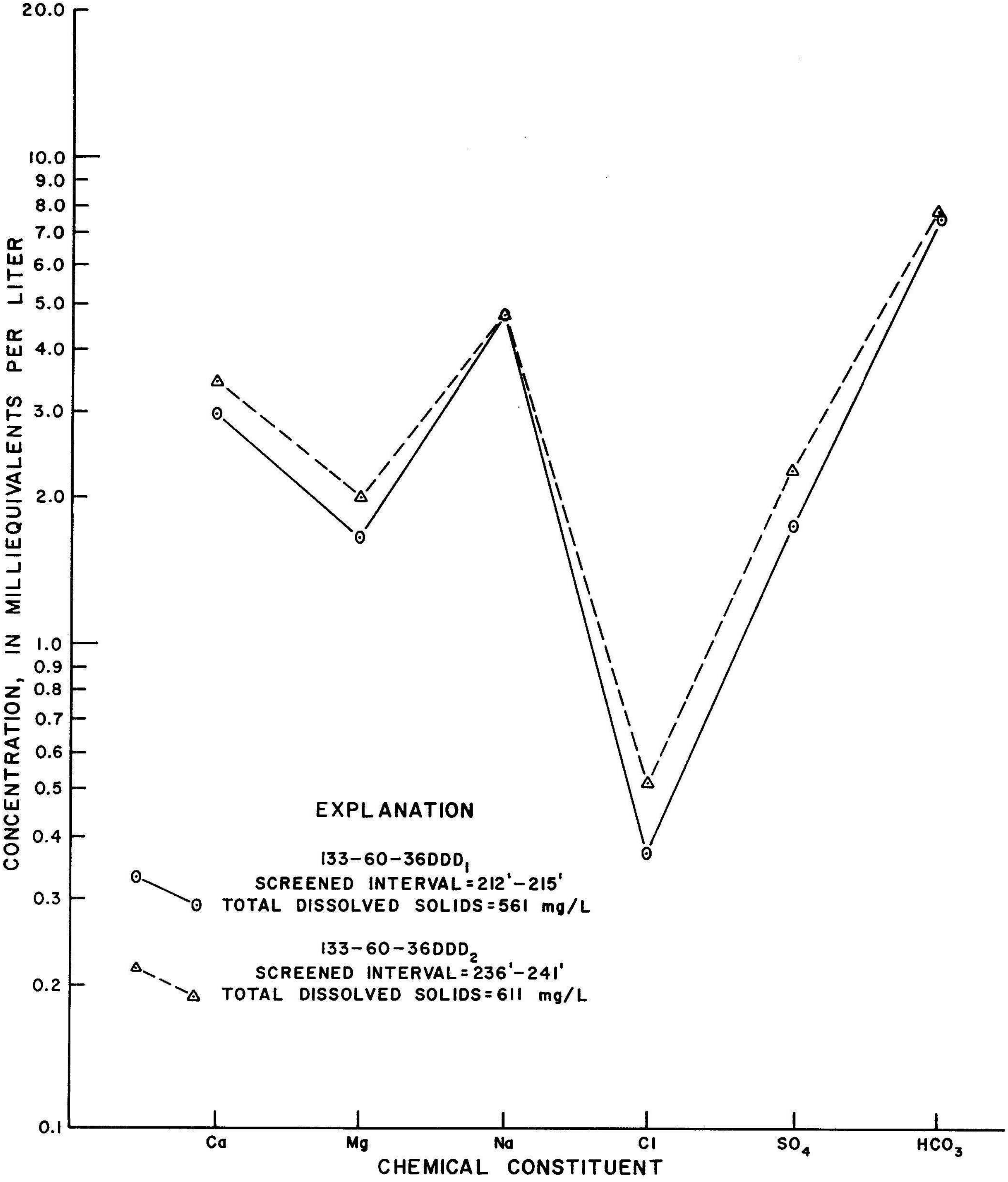


FIGURE 18.—Diagram showing concentration of selected cations and anions at piezometer nest 133-60-36DDD

is completed near the base of the Spiritwood aquifer. The screened interval is from 209 to 214 feet below land surface. Piezometer 132-59-27CDC$_2$ is completed in the till overlying the Spiritwood aquifer. No water sample has been collected from this well. At this nest site, water levels increase with increasing depth in the glacial drift which indicates upward ground-water flow (discharge area).

The distribution of selected cations and anions in water samples collected from piezometers 132-59-27CDC$_1$ and 132-59-27CDC$_3$ is shown on a Schoeller diagram (fig. 19). The chemical analysis from piezometer 132-59-27CDC$_3$ indicates a Na-HCO_3 type water with a total dissolved solids concentration of 854 mg/l. The chemical analysis from piezometer 132-59-27CDC$_1$ indicates a Na-HCO_3-SO_4 type water with a total dissolved solids concentration of 1280 mg/l.

At this site, the water chemistry at the top of the Spiritwood aquifer differs significantly from the water chemistry near the base of the aquifer. The total dissolved solids concentration increases 33 percent from top to bottom in the aquifer. Near the base of the aquifer the concentrations of Na^+, SO_4^{2-}, and Cl^- increase and the concentrations of Ca^{2+} and Mg^{2+} decrease. HCO_3^- remains the same.

Unlike the nest sites at 133-6C-2CDD and 133-60-36DDD, Ca^{2+} and Mg^{2+} decrease near the base of the aquifer and SO_4^{2-} increases substantially. Since this is a discharge area, an upward vertical hydraulic gradient may exist in the bedrock formations underlying the Niobrara Formation. The Carlile Formation which underlies the Niobrara Formation is a marine shale that contains abundant gypsum. The gypsum may be a source of SO_4^{2-} in Spiritwood aquifer in this area.

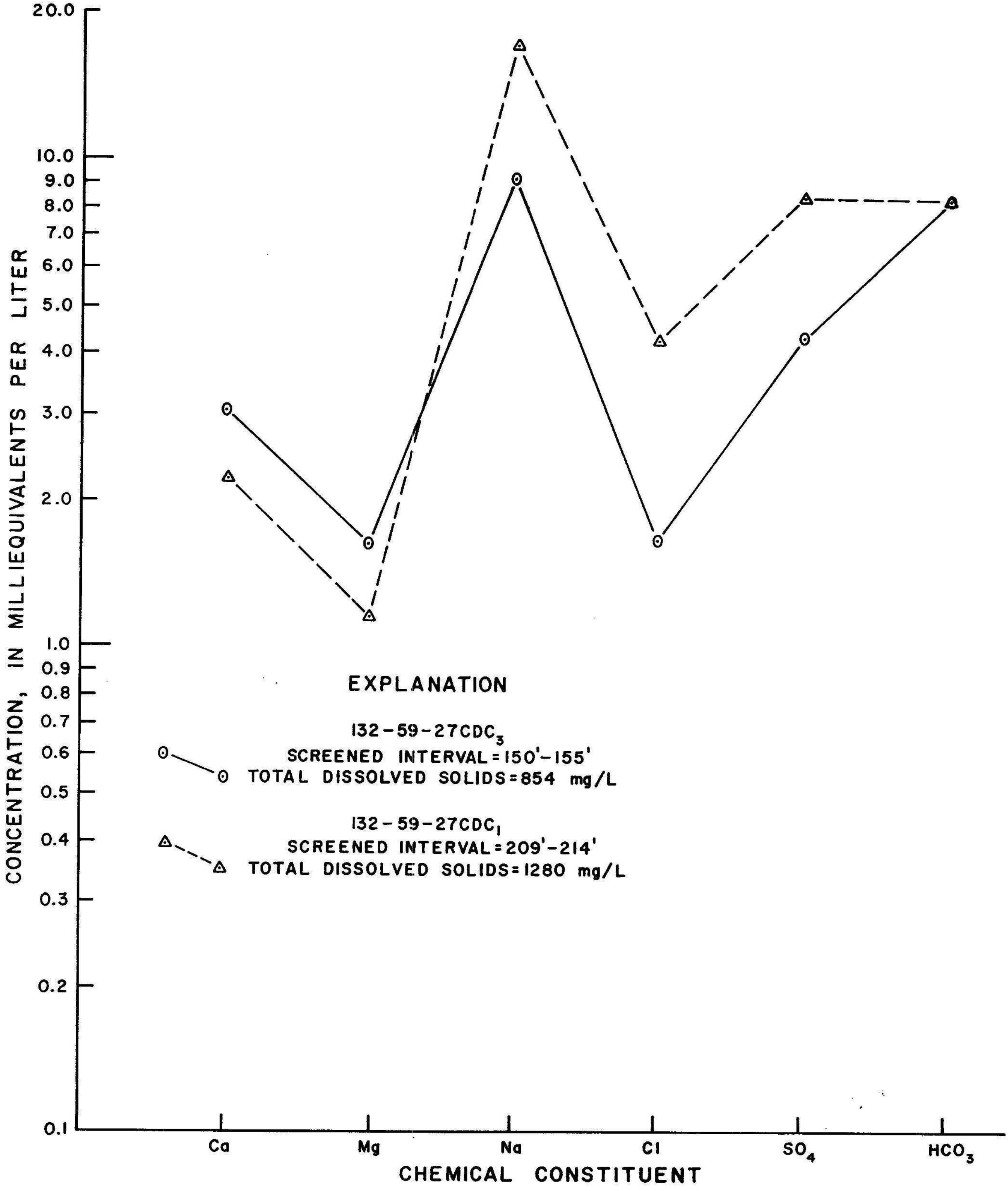


FIGURE 19.—Diagram showing concentration of selected cations and anions at piezometer nest 132-59-27CDC

At this site, the concentration of Cl^- is high near the base of the Spiritwood aquifer and is also high near the top of the aquifer. The high Cl^- concentration at the top and bottom of the aquifer indicates a greater volume of upward flow from the underlying shale formation(s) as compared to the other nest sites. The volume of water moving into the Spiritwood aquifer from a unit area of underlying shale is described by the Darcy equation:

$$Q = KIA$$

where,

Q = discharge $[L^3/\text{time}]$
K = hydraulic conductivity $[L/\text{time}]$
I = hydraulic gradient [dimensionless]
A = unit area $[L^2]$

It is assumed that the hydraulic conductivity of the underlying shale is relatively constant in the study area. Therefore, changes in discharge from the underlying shale into the Spiritwood aquifer are primarily the result of changes in hydraulic gradient.

Three generalized patterns of ground-water flow were distinguished in the study area by the water chemistry and hydraulic head data obtained from the piezometer nests. The first pattern of ground-water flow occurs in the northwest part of the study area in the vicinity of Twin Lakes. A schematic of this local flow system is shown in figure 20. The Spiritwood aquifer is situated between a topographic high and a topographic low. The aquifer is truncated to the northwest and southeast by low transmissivity barriers. Ground-water flow in this area of the Spiritwood aquifer is toward the James River valley which is a regional discharge area. Upward flow into the Spiritwood aquifer from the underlying shale is negligible and probably only occurs along the southwestern margin of the aquifer which is adjacent to the James River valley. The water chemistry is relatively uniform from top to bottom in the aquifer and is similar to the water chemistry of the overlying

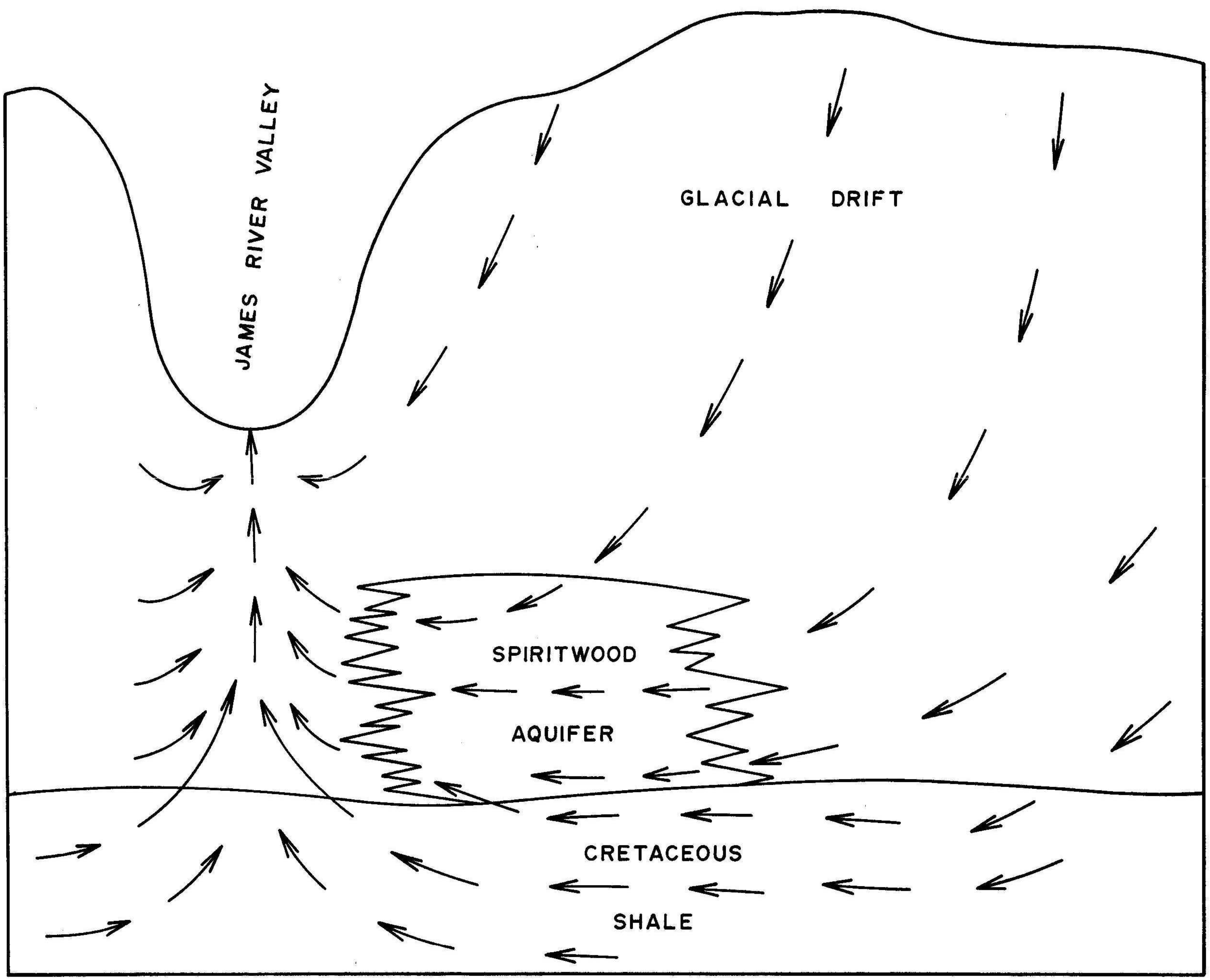


FIGURE 20.— Schematic of ground-water flow in the northwest part of the study area

glacial drift.

The second pattern of ground-water flow is the most common in the study area and is shown schematically to the left in figure 21. In this flow pattern, the Spiritwood aquifer acts as a buried-line sink. Ground water flows into the Spiritwood aquifer from the overlying glacial drift and underlying Cretaceous shales. The volume of water derived from the overlying glacial drift is greater than the volume of water derived from the underlying shale. The mixing process in the aquifer is dominated by the hydrochemical facies of the overlying glacial drift. The variation in water chemistry from top to bottom of the aquifer is minor.

The third pattern of ground-water flow in the study area occurs along Bear Creek valley, north of Oakes. A schematic of this ground-water flow pattern is also shown in figure 21. Bear Creek valley is a local discharge area. Ground-water flow is upward through the top of the Niobrara Formation, the Spiritwood aquifer and the glacial drift overlying the Spiritwood aquifer. In this area of the aquifer, a greater volume of water is derived from the underlying shale. The mixing process in the aquifer is impacted to a greater extent by the hydrochemical facies of the underlying shale. The variation in water chemistry from top to bottom of the aquifer is large.

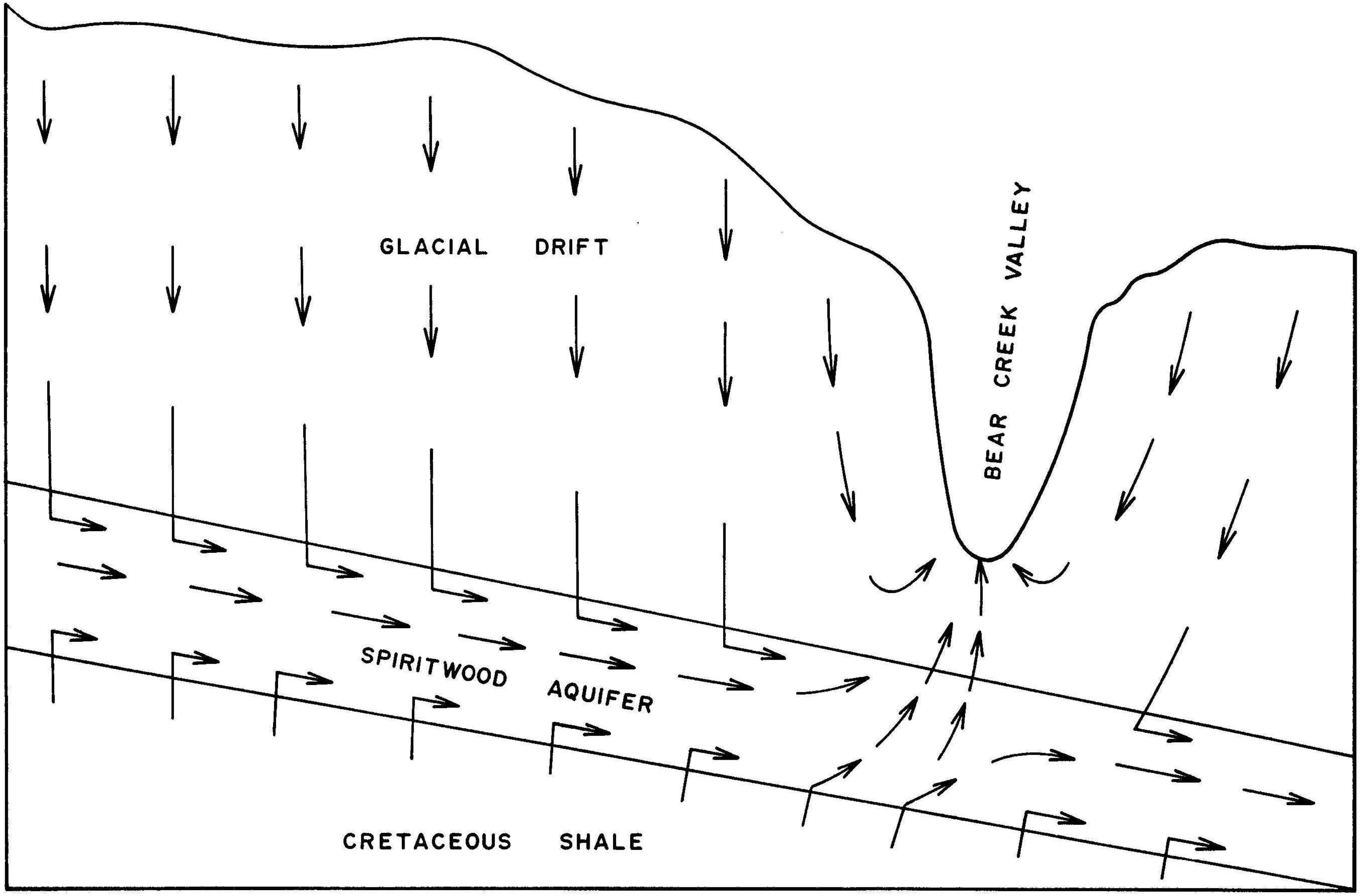


FIGURE 21.—Schematic of ground-water flow in the central part of the study area, northwest of Bear Creek valley, and in the vicinity of Bear Creek valley

SUMMARY AND CONCLUSIONS

The hydrochemical data indicate that the Spiritwood aquifer acts as a buried-line sink over most of the study area. Ground water moves downward into the aquifer from the overlying glacial drift and upward into the aquifer from the underlying Cretaceous shales. The mixing process in the aquifer is dominated by the hydrochemical facies of the overlying glacial drift. The variation in water chemistry from top to bottom of the aquifer is minor.

The hydrochemical data provides additional evidence to support the existence of two discharge areas in the Spiritwood aquifer within the study area. The most significant discharge area is located just north of Oakes along Bear Creek valley. In this area, water flows upward into the Spiritwood aquifer from the underlying Cretaceous shales and upward out of the Spiritwood aquifer into the overlying glacial drift. A greater volume of water is derived from the underlying shale. The mixing process in this area of the aquifer is impacted to a greater extent by the hydrochemical facies of the underlying shale. The variation in water chemistry from top to bottom of the aquifer is large. A minor discharge area is located in the northwest part of the study area west of Twin Lakes. Water flows downward into the Spiritwood aquifer from the overlying glacial drift and flows laterally out of the western flank of the aquifer toward the James River valley. For the most part, discharge areas and areas of sluggish flow in the Spiritwood aquifer are characterized by a $Na\text{-}HCO_3\text{-}SO_4$ type water, high in absolute Cl^- with total dissolved solids concentrations exceeding 1000 mg/l.

Areas of significant recharge in the Spiritwood aquifer are characterized by a $Ca\text{-}HCO_3$ type water with total dissolved solids concentrations of less than 750 mg/l. The most useful chemical parameters in distinguishing recharge areas are low total dissolved-solids concentrations coupled with high relative (percent) Ca^{2+} and HCO_3^- concentrations.

In general, the principal transmissivity axes of the aquifer are characterized by lower total dissolved solids concentrations. The thinner, flank areas of the aquifer are characterized by higher total dissolved-solids concentrations. In comparison to the principal transmissivity axes of the aquifer, the volume of cross-sectional flow in the flank areas of the aquifer is small. As a result, the upward flow of ground water characterized by higher total dissolved-solids concentrations from the underlying Cretaceous shale has a greater impact on the mixing process.

The principal aquifer management tool of the hydrogeologist is some type of digital or analog model. The confidence placed on a model is in part a function of how accurately the conceptual model describes the physical system. Within the study area, the water levels and hydraulic gradients in the aquifer are well defined. The glacial drift is characterized by lithologic and structural (joints, fractures) inhomogeneities. As a result, there is significant spatial variation in recharge, discharge and transmissivity. A hydrochemical approach to the analysis of ground-water flow can be useful in better identifying the spatial variation in recharge, discharge and transmissivity.

FUTURE WORK

A number of chemical processes operate interactively to produce a given water chemistry at any point in the ground-water flow system. To adequately describe the chemical evolution of ground water requires the application of more sophisticated chemical models. For example, this study indicates a loss of Ca^{2+} as ground water flows downward through the glacial drift. The loss of Ca^{2+} could be due to cation exchange, calcite, dolomite, and gypsum precipitation or a combination of these processes. The application of a chemical model which calculates the equilibrium distribution of an ion with respect to a mineral phase can be used to identify areas in the flow system where mineral precipitation may or may not occur. The precipitation and/or dissolution of a particular mineral species can significantly impact the hydraulic conductivity of a fractured and jointed porous media.

The existing data set is not adequate to drive chemical speciation models. In situ measurements of temperature, pH, and possibly redox potential should be made at each piezometer nest site in the study area. Air-lift sampling techniques produce unacceptable chemical alterations (Houghton, Berger, 1983). Gas-squeeze pumps and bailers should be utilized to minimize chemical alterations of water samples.

Computer models are also available which can simulate the composition of ground water that results from the mixing of two different chemical facies. A model of this type can be used to determine the proportions of ground water in the Spiritwood aquifer derived from the overlying glacial drift and underlying Cretaceous shales. Knowing the proportions of ground-water derived from each source will lead to a better understanding of the recharge process.

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APPENDIX 1.

134-61-13DAD$_1$
NDSWC 6259

Date Drilled: 8/16/83

	Thickness	Depth
Topsoil	1	1
Clay, yellow brown, silty, very sandy, interbedded clay and sand, oxidized (till)	21	22
Sand, medium to coarse, gravelly, rounded to subrounded, predom. detrital shale, some silicates and carbonates, oxidized	17	39
Clay, olive gray, silty, sandy, pebbly (till), lignite fragments in till matrix, layer of sand and gravel from 50'- 52'	35	64
Sand, gravelly, subrounded to rounded, predom. detrital shale, some silicates and carbonates	8	72
Clay, olive gray, silty, sandy, pebbly (till), layer of silt and sand from 104'- 106'	40	112
Sand, fine to medium, clayey and very silty, rounded, predom. detrital shale, some silicates and carbonates, lignitic	10	122
Sand, fine to medium, clayey and very silty, rounded, cleaner than above	5	137
Gravel, fine, sandy, subrounded to rounded, predom. detrital shale, with quartz, silicates and carbonates, lignitic (Spiritwood aquifer)	23	160
Gravel, sandy, rounded, more detrital lignite than above, layer of clay from 240'-242', cobbly from 260'- 279'(Spiritwood aquifer)	119	279
Clay, brownish black, slightly silty, bentonitic (Pierre Fm.)	33	312

Piezometers

Location	Screened Interval
134-61-13DAD$_1$	257'- 262'
134-61-13DAD$_2$	132'- 137'
134-61-13DAD$_3$	68'- 73'

133-60-02CDD$_1$
NDSWC 6246

Date Drilled: 7/27/83

	Thickness	Depth
Topsoil	1	1
Gravel, very coarse sand to fine gravel, oxidized	1	2
Clay, yellow brown to dark yellow orange, banded, very silty (fluvial)	8	10
Clay, yellow brown, silty, pebbly, oxidized (till)	8	18
Clay, olive gray, silty, pebbly (till)	9	27
Sand, fine, well sorted, angular, 50% quartz and 50% detrital lignite	5	32
Silt, olive gray, clayey	5	37
Clay, olive gray, silty, sandy, pebbly, bouldery, layer of sand from 42'- 48', layer of sand and gravel from 101'- 105'	156	193
Sand, very coarse sand to fine gravel, angular to rounded, composed of quartz, silicates, carbonates, and shale, lignitic (Spiritwood aquifer)	7	200
Gravel, very coarse sand to fine gravel, rounded, interbedded coarse gravel, composition as above (Spiritwood aquifer)	61	261
Shale, brown, silty, white specks (Niobrara Fm.)	21	282

Piezometers

Location	Screened Interval
133-60-2CDD$_1$	255'- 260'
133-60-2CDD$_2$	195'- 200'
133-60-2CDD$_3$	117'- 122'
133-60-2CDD$_4$	26'- 31'

133-60-36DDD$_1$
NDSWC 9448

Date Drilled: 9/23/75

	Thickness	Depth
Clay, moderate yellowish brown, silty, sandy, pebbly, oxidized (till)	17	17
Clay, olive gray, silty, sandy, pebbly (till)	17	34
Clay, medium dark gray, silty, sandy (lacustrine)	6	40
Clay, medium dark to olive gray, silty, sandy, pebbly, gravelly with occasional thin gravel layers (till)	164	204
Sand, very fine to very coarse, gravelly, subangular to rounded, predom. quartz, with minor carbonates, silicates, and shale, lignitic (Spiritwood aquifer)	39	243
Shale, brownish gray to dark greenish gray, silty, sandy (Niobrara Fm.)	17	260

Piezometers

Location	Screened Interval
133-60-36DDD$_1$	212'- 215'
133-60-36DDD$_2$	236'- 241'
133-60-36DDD$_3$	120'- 125'
133-60-36DDD$_5$	40'- 45'

132-59-27CDC$_1$
NDSWC 12260

Date Drilled: 7/28/83

	Thickness	Depth
Topsoil	1	1
Sand, very fine to coarse, oxidized	11	12
Gravel, very fine to very coarse, oxidized	13	25
Clay, olive brown, silty, sandy, pebbly, oxidized to 26' (till)	13	38
Silt, olive gray, clayey	43	81
Clay, olive gray, silty, sandy, pebbly (till)	2	83
Silt, olive gray, clayey	6	89
Clay, olive gray, silty, sandy, pebbly (till)	32	121
Sand, very fine, silty	10	131
Clay, silty, interbedded sandy clay and sand	10	141
Clay, olive gray, silty, sandy, pebbly (till)	6	147
Gravel, very coarse sand to fine pebble gravel, angular to subrounded, lignite fragments (Spiritwood aquifer)	47	194
Cobbles (Spiritwood aquifer)	1	195
Gravel, very fine to very coarse, sandy (Spiritwood aquifer)	18	213
Gravel, bouldery (Spiritwood aquifer)	5	218
Shale, medium gray, calcareous, white specks (Niobrara Fm.)	42	260

Piezometers

Location	Screened Interval
132-59-27CDC$_1$	209'- 214'
132-59-27CDC$_2$	105'- 110'
132-59-27CDC$_3$	150'- 155'