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Geochemical Evolution of Ground Water in the Great Plains (Dakota) Aquifer of Nebraska: Implications for the Management of a Regional Aquifer System

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Abstract

The Great Plains (Dakota) aquifer system is one of the most extensive in North America, extending from the Arctic Circle to New Mexico, and underlies approximately 94% of Nebraska. In Nebraska, we do not have the physical ground water monitoring data at the scale that is necessary to manage ground water flow systems. However, first-order management strategies for this regional aquifer can be developed by understanding the geochemical evolution of the ground water. Using major-ion water chemistry data from 203 wells in 19 counties in eastern Nebraska, reconnaissance $\delta^{18}\text{O}$, δD , and $\delta^{87}\text{Sr}$ data, and two geochemical models, PHREEQC and SNORM, we determine that modern meteoric water, NaCl brines from underlying formations, and cold glacial melt water are the primary sources for the water in the Dakota Aquifer. Based on these three water sources and the geochemical evolution of the various water types, the following first-order management strategies are suggested. In areas where CaSO_4 and Ca-Na SO_4 type water occur, Pleistocene-age glacial meltwater is the source. This water supply is not easily renewable. It is recommended that detailed water resource evaluation be conducted before extensive development occurs. The source of $\text{Ca} (\pm \text{Mg}) \text{HCO}_3$ type water is from recharge by local precipitation and should be managed to maintain them as a renewable resource. In mixed ground water type areas, the ground water chemistry reflects the interaction of two distinct water types, one of which is meteoric water and the other is either CaSO_4 and Ca-Na SO_4 -type water or NaCl-type water. If the relatively fresh ground water is extracted at a rate that changes the location of the interface between the endmembers, then monitoring changes in water chemistry in a well over time could be used as an early warning system for the onset of potential problems related to overpumping.

Introduction

The Great Plains aquifer system (GPAS) is one of the most extensive in North America, extending from the Arctic Circle in Canada to New Mexico (Figure 1) (Helgesen *et al.* 1982; Jorgenson *et al.* 1993). In a stratigraphic context, the names Dakota Formation, Dakota Group, and Dakota Sandstone have all been used to refer to the Lower Cretaceous sandstones that comprise the GPAS in the western glaciated plains. Hence, the term Dakota aquifer system has also been used in reference to the GPAS. In this paper, we will refer to this system as the Dakota Aquifer because the name has local, as well as regional, name recognition and the GPAS terminology has not been generally adopted. The Dakota Aquifer includes stratigraphic units beyond the limits of the Dakota Formation. In addition to the Dakota Group, the system includes the Swan River Formation of Manitoba and eastern Saskatchewan, the Inyan Kara Formation and the Omadi Sandstone of the Plains states, and the Mannville Group of south-central Alberta and Saskatchewan.

The Dakota has generally been considered to be a classic example of an artesian aquifer system (Lennox *et al.* 1988). Upham (1895) and Darton (1905) proposed the analogy

of pipe flow for ground water movement in the Dakota in which recharge enters sandstone beds in mountains to the west and discharges in the east where the sandstones outcrop or subcrop beneath the glacial drift. Current thinking about the source of ground water in and movement through the Dakota Aquifer indicates that the flow in the aquifer is far more complex (*e.g.*, Jorgensen and Signer 1984). The complexities in the flow system are directly reflected in the natural spatial variations in ground water chemistry, in which extreme differences in water quality can occur on local scales (Rutulis 1984; Lawton *et al.* 1984). As a result, water quality strongly influences the use of the Dakota as a source of potable water.

The Dakota Aquifer underlies 94% of Nebraska (Ellis 1984) and is utilized in two areas. In western Nebraska, oil, natural gas, and saline ground water are produced from the D and J sandstones in the upper parts of the Dakota Group (Figure 2). These oil producing zones extend to depths greater than 2,130 m (7,000 feet). In eastern and northeastern Nebraska, the sandstones within the Dakota Formation are used as a source of ground water where shallow Quaternary deposits cannot provide an adequate water supply. Lawton *et al.* (1984) indicated that 37 towns withdraw

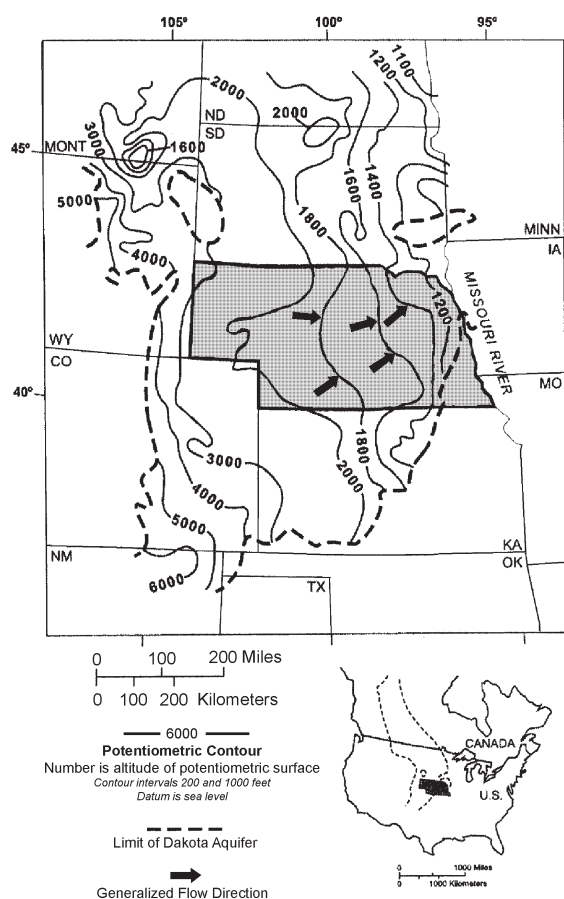


Figure 1. Extent of and recent potentiometric surface map of the Great Plains (Dakota) Aquifer in the region around Nebraska. The North American extent of the aquifer is shown at the lower right of the figure. (Modified from Leonard *et al.* 1984).

an estimated 22,710 to 30,280 m³/day (6 to 8 million gal/day [mgd]) from the Dakota. Withdrawals for irrigation and industrial purposes were on the order of 102,195 and 7570 m³/day (27 and 2 mgd), respectively. In the vicinity of Lincoln and Omaha, Nebraska's major metropolitan areas, urban expansion is placing increased demands on the Dakota aquifer system. Water quality is one of the primary constraints on the use of the Dakota as a source of water.

Although the demand on the Dakota Aquifer is increasing, we currently do not have an adequate understanding of the flow system(s) to develop appropriate management strategies. To develop these strategies, it is important to understand the movement of water into and through the ground water system. Unfortunately, ground water monitoring data does not exist at the scale that would be necessary to define spatial and vertical variations in the ground water flow systems. Although we do not have the physical ground water monitoring data, we do have a substantial archive of ground water chemistry data that can serve as a proxy record for the history of the ground water. Our basic hypothesis is that first-order management strategies can be developed by interpreting the geochemical evolution of the ground water using water chemistry data, geochemical modeling, and an understanding of the local as well as regional hydrogeologic framework.

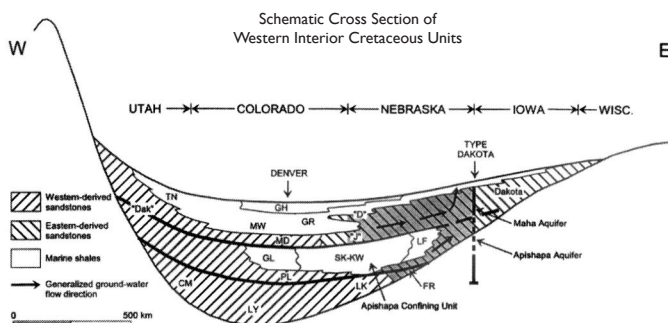


Figure 2. Schematic east-west cross section of Western Interior Cretaceous Units. The vertical scale is exaggerated, does not portray regional thickness patterns, and is generalized to display interpreted stratigraphic relations. Abbreviations as follows: DAK, Dakota Sandstone; TN, Tununk Shale; GH, Greenhorn Formation; MW, Mowry Shale; GR, Graneros Shale; D, D-sandstone; J, J-sandstone; SK-KW, Skull Creek and Kiowa Formations; LF, Longford Member; LK, Lakota Formation; LY, Lyne Formation; MD, Muddy Formation; GL, Glencairn Formation; PL, Plainview Formation; FR, Fall River Formation; CM, Cedar Mtn. Formation. Shading indicates those units present in Nebraska. The heavy black lines represent the base of major marine cycles. (Modified from Witzke and Ludvigson 1994.)

Study Area and Regional Hydrogeologic Setting

The study area consists of 19 counties in eastern Nebraska where the Dakota Aquifer is used as a primary or secondary source of water (Figure 3). In this paper, we use the stratigraphic nomenclature for the Dakota Formation provided in Witzke and Ludvigson (1994) and relate it to the hydrologic nomenclature of Jorgensen *et al.* (1993). Key characteristics of the Dakota Formation are that it had an eastern source for its sediments and it maintains its integrity across parts of Nebraska, South Dakota, North Dakota, Kansas, Iowa, and Minnesota. The eastern-derived sandstone- and siltstone-dominated strata interfinger westward in the subsurface of western Nebraska, northeastern Colorado, and the central to eastern Dakotas with the marine strata of the Mowry and Belle Fourche shales (Figure 2; Witzke and Ludvigson 1994).

The Dakota Formation thickens from less than 30 m (100 feet) in eastern Colorado to 185 m (600 feet) in northeast Nebraska and exceeds 260 m (900 feet) in central Nebraska. The western limits of the Dakota Formation are operationally defined by the vertical cutoff where the Newcastle or J Sandstones form a tongue of eastern derived sediments with a sequence of marine shales (Witzke and Ludvigson 1994; Gries 1962). The Dakota Formation in the Nebraska panhandle is the westward extension of the clastic wedge that occurs in the eastern part of the state. In the western area, the D and J sandstone units at depths of 1,220 m (4,000 feet) to 1,830 m (6,000 feet) are used for oil and gas production. These two oil producing sandstone units are separated by tens of feet of marine shales. The Dakota Formation of eastern Nebraska including the D and J sandstones in western Nebraska are part of the Maha Aquifer (Figure 2).

The Apishapa Aquifer (Figure 2), which is the lower of the two major aquifers of the GPAS, is not likely to occur extensively in eastern Nebraska (Jorgensen *et al.* 1993). It consists of permeable, partially cemented, medium to very fine-grained sandstone. Although the Apishapa Aquifer may extend to some degree into the eastern half of Nebraska, it is likely to be in hydraulic connection with the overlying Maha Aquifer (Figure 2).

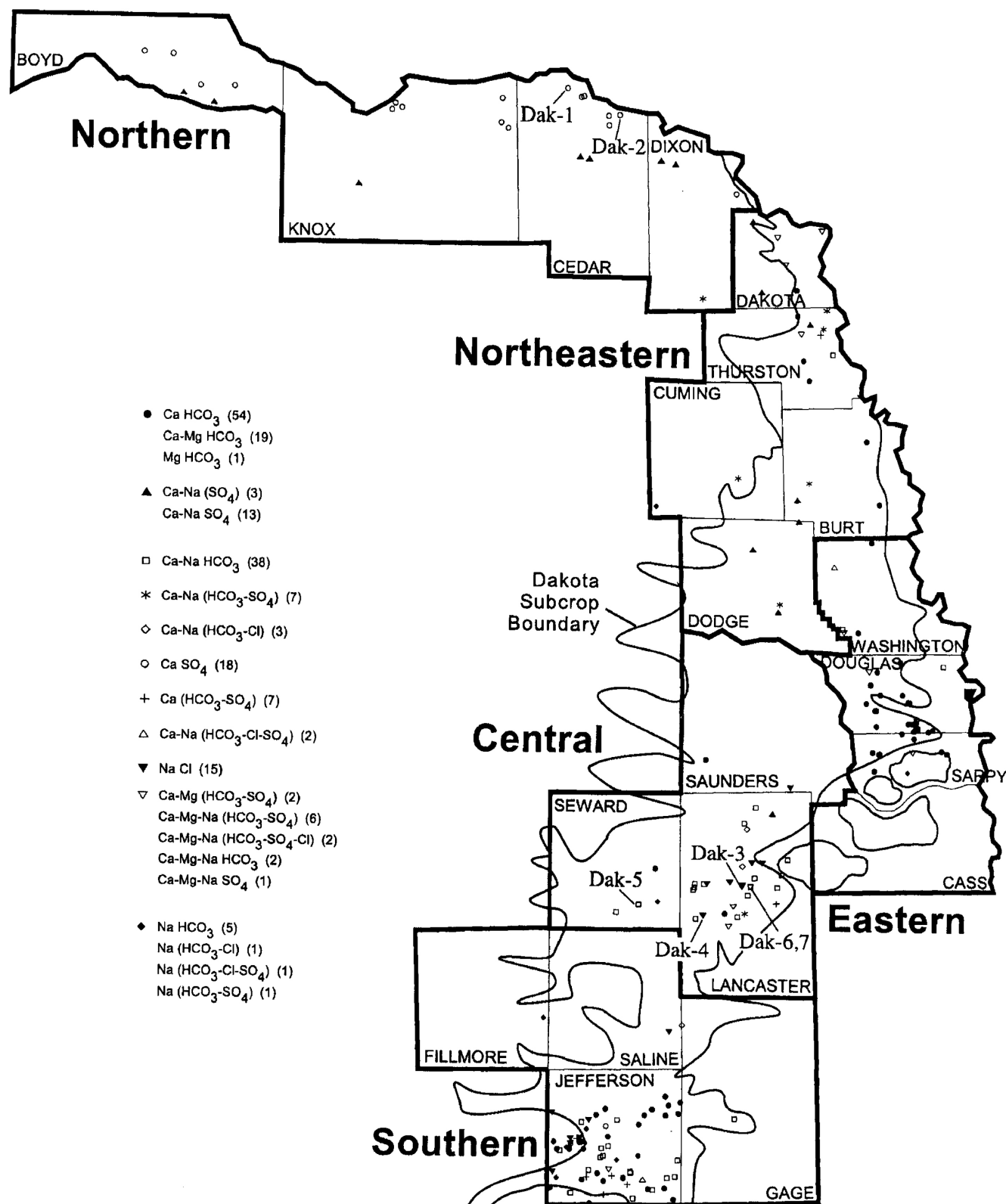


Figure 3. Sample locations and ground water chemistry type across eastern Nebraska by region.

The Apishapa confining unit (Figure 2), which is composed predominantly of the Kiowa Shale and the equivalent of the Skull Creek Shale, coincides with the eastern edge of the Kiowa-Skull Creek marine shales whereby the Apishapa confining unit does not occur in the eastern one-third of Nebraska.

In northern and northeastern Nebraska, the Dakota Formation is overlain, or partially overlain, by the Great Plains confining system composed predominantly of Upper Cretaceous marine shales that include the Graneros, Greenhorn, and other shale-dominated formations. Progressively southward, the Dakota Formation occurs in the subcrop

and is overlain by Quaternary deposits consisting of glacial till and loess.

On a regional scale, hydraulic head in the Dakota progressively decreases from west to east (Figure 1; Helgesen *et al.* 1984). However, these estimates are primarily for where ground water in the Dakota is confined by the Graneros-Greenhorn Shales. Where Quaternary units overlie the Dakota, the stratigraphic variability results in confined or unconfined conditions within the aquifer.

Dakota Formation Stratigraphy of Eastern Nebraska

The Dakota Formation in eastern Nebraska contains a highly variable series of sandstones and shales that reflect a complex pattern of deposition and erosion associated with alluvial, deltaic, and shoreline sedimentary environments along the eastern margin of the Cretaceous Western Interior Seaway. Witzke and Ludvigson (1994) have defined a general sequence for the Dakota Formation that includes a lower sandstone-dominated Nishnabotna Member and an upper mudstone-dominated Woodbury Member with sandstone channel bodies. From a hydrogeologic perspective, both of these members belong to the Maha Aquifer. The following descriptions are based on their work, except where indicated.

The Woodbury Member is recognized in northeast and east-central Nebraska. Its thickness ranges from 15 to 70 m in the east to about 120 m westward. Although the Woodbury strata is dominated by mudstones and shales, siltstone and sandstone bodies are present ranging in thickness from less than 1 m up to 25 m. In the type Dakota area in northeast Nebraska, the Woodbury sandstones are dominantly very fine to fine grained.

In east-central Nebraska, especially between Omaha and Lincoln, the Woodbury Member is not recognizable and the continuous sandstone bodies of the Nishnabotna Member are the primary hydrostratigraphic unit. The Nishnabotna sandstones vary in thickness from 50 to 90 m in this area. The thickness of the Nishnabotna in Nebraska is not well constrained, but is highly variable and probably no more than 75 m thick. As a result of the down cutting by streams in eastern Nebraska, outliers of the Dakota as much as 130 km² (50 mi²) in areal extent exist. Farther west and to the south, Nishnabotna and Woodbury members cannot be differentiated. Veatch (1969) indicated that the sandstone bodies are geometrically complex and discontinuously interbedded with shales.

In the northern part of the study area, the Dakota Formation is underlain primarily by Lower Paleozoic dolomite, with the exception of northern Knox County, where it rests on the Precambrian Sioux quartzite. From northern Burt and Cuming counties down into the middle of Lancaster and southern Seward counties, the Dakota rests on Pennsylvanian rocks. The Pennsylvanian rocks consist of alternating units of marine limestones and shales. Southward from Lancaster County into Kansas, the Dakota rests on Permian sedimentary rocks that are predominantly limestones and shales in southeastern Nebraska. However, younger Permian strata to the southwest also contain red beds and salt deposits.

Methods

In 1994, 11 samples were collected as part of a reconnaissance ground water study of the Dakota Formation. Samples Dak-1 through 7 were collected in eastern Nebraska. Samples Dak-8, 9, 11, and 12 were collected in western Nebraska from producing oil wells. All samples were analyzed for field parameters (pH, total alkalinity, specific conductance, and temperature), as well as the major ions Na, K, Ca, Mg, Cl, SO₄, and SiO₂. Total dissolved solids (TDS) were calculated. Samples were filtered through 0.45 µm filters within six hours of sample collection. The major ions were analyzed using standard analytical protocol (Fishman and Friedman 1989) at the University of Nebraska-Lincoln Department of Agronomy laboratory. Duplicate samples, process blanks, and one blind standard were submitted to assure data quality. An additional data check included calculating charge balance. Nine of 11 samples had charge balances less than ± 5.2%. The other two samples, Dak-3 and 12, had charge balances of -11 %.

Aliquots of each sample were analyzed for δ¹⁸O, δD, and δ⁸⁷Sr. Stable isotope analyses were completed at the Environmental Isotope Laboratory (EIL) at the University of Waterloo. Oxygen determinations were made using a Micromass 903 triple collector SIRA mass spectrometer following the procedures of Epstein and Mayeda (1953). Deuterium determinations were made on a Micromass 602C mass spectrometer following the zinc reduction preparation method of Coleman *et al.* (1982). Oxygen and hydrogen results are reported as parts per thousand (‰) with respect to V-SMOW using the (δ) notation where

$$\delta_{\text{sample}} = (R_{\text{sample}} - R_{\text{standard}}) / R_{\text{standard}} \times 1000$$

R_{sample} is the ratio of ¹⁸O/¹⁶O or ²H/¹H in the sample, and R_{standard} is the ratio of the international standard. The analytical precision for δ¹⁸O and δ²H are 0.2 ‰ and 2.0 ‰, respectively.

Strontium isotope analyses were completed at the University of Wyoming. Sr was isolated using Sr Spec resin. Sr isotopic ratios were measured on a Micromass Sector 54 Thermal Ionization mass spectrometer. An average ⁸⁷Sr/⁸⁶Sr ratio of 0.710250 ± 0.00001 (2σ) and a normalized ⁸⁸Sr/⁸⁶Sr = 0.1194 were measured for the NBS 987 Sr standard. ⁸⁷Sr/⁸⁶Sr values are measured routinely at the 2-sigma level to ± 0.001 % or better. Because small numerical differences in ⁸⁷Sr/⁸⁶Sr may be highly significant, we express the Sr compositions ratios as a per mil deviation from modern sea water. The following transformation, where the 0.70920 represents the ⁸⁷Sr/⁸⁶Sr for modern sea water, was used:

$$\delta^{87}\text{Sr} = ([^{87}\text{Sr}/^{86}\text{Sr}/0.70920] - 1) \cdot 1000$$

The 11 samples were supplemented by data from the archives of the U.S. Geological Survey (USGS), an unpublished Ph.D. dissertation on ground water in Jefferson County (Veatch 1969), and an unpublished M.S. thesis on ground water in Douglas, Sarpy, and Washington counties (O'Connor 1987). These sources provided 363 analyses of which 243 had a complete set of major ions and field parameters (pH, total alkalinity, temperature, Na, K, Ca, Mg, Cl, SO₄, and SiO₂). One hundred and ninety-two wells were included in the 243 analyses. We used the most recent data for each well for our analysis. Where multiple analyses occurred, the reported

Table 1. Major Ion, $\delta^{87}\text{Sr}$, $\delta^{18}\text{O}$, and δD Data for Reconnaissance Ground Water Samples from the Dakota Formation. (*na* indicates data is not available)

Study Sample Number	Water Temp. (°C)	pH	Major Ions (mg/L)								Total Dissolved Solids (mg/L)	Water Type	$^{87}\text{Sr}/^{86}\text{Sr}$	$\delta^{87}\text{Sr}$	$\delta^{18}\text{O}$	δD
			Na	K	Ca	Mg	Cl	HCO_3	SO_4	SiO_2						
Dak-1	18	7.0	44	16	230	40	47	160	710	10	1180	CaSO_4	0.71079	2.2	-16.5	-123
Dak-2	17	7.0	44	15	230	40	44	170	700	9.4	1170	CaSO_4	0.71019	1.4	-17.1	-127
Dak-3	15	6.7	4200	17	160	81	7900	330	770	22	13,310	NaCl	0.70880	-0.56	-8.6	-67
Dak-4	13	7.3	520	8	88	19	800	300	100	26	1710	NaCl	0.70901	-0.27	-9.2	-66
Dak-5	15	7.3	86	5	43	8	33	290	45	20	380	Ca-Na HCO_3	0.70918	-0.03	-9.6	-66
Dak-6	14	6.7	36	4	64	14	34	270	31	28	340	CaNa HCO_3	0.70889	-0.44	-7.7	-54
Dak-7	15	6.3	52	9	85	23	90	220	130	31	528	Ca-Na HCO_3	0.70880	-0.56	-7.2	-51
Dak-8	na	7.7	1850	7	7	1	1100	2300	460	36	4590	$\text{SO}_4\text{-Cl Na HCO}_3\text{-Cl}$	0.70807	-1.6	-10.3	-84
Dak-9	41	6.2	44,400	130	1820	400	70,500	230	2500	25	120,000	NaCl	0.70815	-1.5	-6.6	-66
Dak-11	29	7.3	13,100	48	50	34	16,100	1900	2500	36	32,800	NaCl	0.70800	-1.7	-6.1	-63
Dak-12	50	7.3	11,200	58	240	39	17,700	680	5700	36	35,300	NaCl	0.70826	-1.3	-7.4	-64

Table 2. Average Major Ion Concentrations for Water Types from the Dakota Formation in Eastern Nebraska. (Values for F, SiO_2 , B, and Fe were not available for all samples.)

Water Type	Number of Samples	Temp (°C)	pH	Major Ions (mg/L)								B (µg/L)	Fe (µg/L)	Total Dissolved Solids (mg/L)
				Na	K	Ca	Mg	Cl	HCO_3	SO_4	F			
CaSO_4	16	17	7.4	59	17	220	40	55	157	624	1.5	229	2490	1110
Ca-Na SO_4	16	16	7.4	157	27	210	47	82	218	753	2.1	581	3887	1400
$\text{Ca- and Ca-Mg HCO}_3$	73	14	7.3	25	4.1	91	17	8.9	358	39	0.4	139	862	380
NaCl	13	14	7.6	4612	18	152	64	6557	430	885	1.2	1592	1529	12,500
Ca-Na HCO_3	36	13	7.1	60	5	77	13	32	310	65	0.4	243	1114	430
Other Types	38													
Total	192													

values were usually within 10% of each other and there were not any apparent time-dependent trends in the data. In addition to the major ions, the USGS and Veatch (1969) included data for F, B, and, in some cases, Fe and Mn. All of the water samples were plotted on Piper diagrams (Piper 1944) and classified using the scheme of Davis and DeWeist (1966).

Two geochemical modeling programs, PHREEQC and SNORM, were used on selected samples to interpret the geochemical evolution of the ground water. We used PHREEQC (Parkhurst 1995) to calculate saturation indices and reaction paths. SNORM (Bodine and Jones 1986; Jones and Bodine 1987) computed the normative salt assemblage from the solute concentration data in a conventional water analysis. The salt norm can be visualized as the solid residuum that coexists with an infinitely small, last vestige of solution upon evaporation of the sample to dryness at 25°C. Three major normative water categories can be identified: (1) meteoric or weathering norms, which are characterized by alkali-bearing sulfate and carbonate salts; (2) marine-like norms, which have a halite-bishofite-carnalite-kieserite-anhydrite association; and (3) diagenetic norms, which yield Ca-bearing chlorides (antarcticite and tachyhydrite) and sylvite.

Results

We discuss the results by geographic areas: northern, north-eastern, eastern, central, southern, and western. Our reconnaissance data are given in Table 1. The location of the water samples are shown on Figure 3 in the context of their water classification. Average values for the major water types are given in Table 2.

Northern Area

In northern Nebraska (Boyd, Knox, Cedar, and Dixon counties), CaSO_4 -type waters predominate along with some Ca-Na SO_4 waters. Both of these water types are associated with the Dakota where it is overlain by confining shale units. The Ca-Na waters generally occur to the south of the Ca -dominated waters. The average TDS in the CaSO_4 and Ca-Na SO_4 -type waters are 1100 and 1400 mg/L, respectively.

Two CaSO_4 samples, Dak-1 and 2, from Cedar County have $\delta^{18}\text{O}$ of -16.5‰ and -17.1‰ and δD values of -123‰ and -128‰ (Table 1). These values fall along the Meteoric Water Line (MWL) (Figure 4), but are significantly depleted compared to modern precipitation (Figure 4; Harvey 1999), and

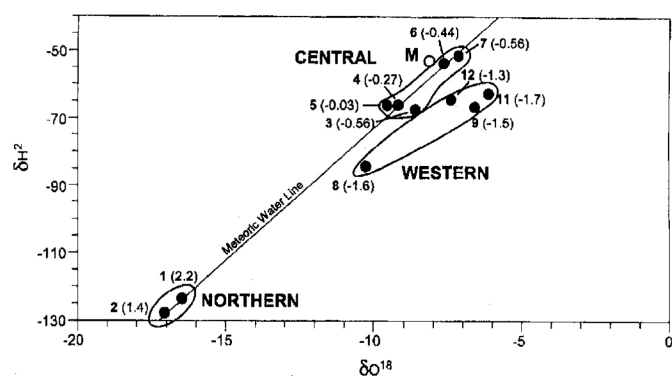


Figure 4. Plot of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for Dakota ground water samples. Bold numbers represent sample numbers. Values in parentheses—()—are the $\delta^{87}\text{Sr}$ for these samples. M = average $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for meteoric water in eastern Nebraska (Harvey 1999).

shallow ground water found elsewhere in Nebraska. The $\delta^{87}\text{Sr}$ values for these two samples are 2.2‰ and 1.4‰, respectively.

Northeastern Area

Ground water in Dakota and Thurston counties are predominantly Ca-Na- SO_4 , Ca-Na (HCO_3 - SO_4), and Ca-Mg-Na (HCO_3 - SO_4) \pm Cl waters and are associated with the subcrop contact between the Dakota Formation and overlying Cretaceous shales. In southern Thurston County and eastern Burt County, CaHCO_3 waters become prevalent. Ca-Na- SO_4 and Ca-Na (HCO_3 - SO_4) waters occur in Cuming, Dodge, and western Burt counties. Total dissolved solids in Ca-Na SO_4 waters range from 1200 to nearly 1900 mg/L. Ca-Na (HCO_3 - SO_4) waters have TDS that range from 640 to 1120 mg/L. Ca- HCO_3 and Ca-Mg-Na (HCO_3 - SO_4) \pm Cl waters have TDS generally less than 500 mg/L.

Eastern Area

Waters from Washington, Douglas, and Sarpy counties are dominantly Ca- HCO_3 or Ca-Mg- HCO_3 waters having TDS less than 500 mg/L.

Western Area

Three of the four samples (Dak 9, 11, 12) collected from Scottsbluff, Morrill, and Cheyenne counties in western Nebraska are NaCl brines. TDS ranges from 33,000 to 120,000 mg/L. Dak-8 has a TDS of 4600 mg/L and is a Na (HCO_3 -Cl)-type water. The NaCl waters have a relatively narrow range of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values, -6.1‰ to -7.4‰ and -63‰ to -66‰, respectively. They fall along a trajectory that is consistent with evaporation. $\delta^{87}\text{Sr}$ for these waters ranges from -1.3‰ to -1.7‰. Dak-8 has a $\delta^{87}\text{Sr}$ of -1.6‰, which is similar to the NaCl waters, but distinct $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of -10.3‰ and -84‰, respectively.

Central Area

Ground water from the Dakota Formation in Lancaster, Saunders, and Seward counties are predominantly Ca-Na- HCO_3 and NaCl-type waters. Other water types that occur include Ca-Na (HCO_3 -Cl), Ca-Mg (HCO_3 - SO_4) and Ca-Na (HCO_3 - SO_4) \pm Cl. The Ca-Na- HCO_3 waters are dominantly to the east and south of Lincoln as well as to the west. These waters have TDS that are generally less than 400 mg/L but range from 300 to 500 mg/L. For Ca-Na- HCO_3 -type waters Dak-5 and 6 (Table 1), the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values are -9.6‰

and -66.0‰ and -7.7‰ and -54.7‰, respectively. These data, along with Dak-7, fall along the MWL (Figure 4). The $\delta^{87}\text{Sr}$ for these waters are distinct from those in the Northern area and range from -0.3‰ to -0.6‰. The NaCl waters, which occur in and around Lincoln, have TDS ranging from 1300 mg/L to more than 25,000 mg/L. The $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values for Dak-4 are -65.8‰ and -8.6‰, respectively, and they plot along the meteoric water line. Sample Dak-3 is displaced to slightly heavier $\delta^{18}\text{O}$ values and falls along an evaporative trajectory. The $\delta^{87}\text{Sr}$ values for Dak-3 and 4 are -0.6‰ and -0.3‰, respectively, and are distinctly different from the values from western Nebraska.

Southern Area

Ground water from the Dakota Formation in Fillmore, Saline, Gage, and Jefferson counties are predominantly Ca- HCO_3 , Ca-Na HCO_3 , and NaCl-type waters. The NaCl waters occur near the boundary between the Dakota Formation and overlying confining shales. The TDS of the CaHCO_3 waters range from 315 to 530 mg/L, with the majority of the values being less than 425 mg/L. The NaCl-type waters have TDS that ranges from 2100 to 13,000 mg/L. The majority of the Ca-Na HCO_3 waters have TDS less than 450 mg/L but range from 200 to 1060 mg/L.

Normative Mineral Assemblages

For the CaSO_4 waters, the normative mineral assemblage has greater than 50% anhydrite (CaSO_4), 10% to 26% polyhalite ($\text{K}_2\text{MgCa}(\text{SO}_4)_4 \cdot 2\text{H}_2\text{O}$) and bloedite ($\text{Na}_2\text{Mg}(\text{SO}_4)_2 \cdot 4\text{H}_2\text{O}$), and 3% to 13% magnesite (MgCO_3). The Ca-Na SO_4 -type waters have less than 43% anhydrite, 30% to 45% glauberite ($\text{Na}_2\text{Ca}[\text{SO}_4]_2$) and 7% to 10% magnesite. The Ca and Ca-Mg HCO_3 -type waters are dominated by calcite and dolomite, which comprise 70% to 75% and 60% to 70%, respectively, of the normative assemblage. Aphthitalite ($\text{K}_3\text{Na}[\text{SO}_4]_2$) and thenardite (Na_2SO_4) are 5% to 25% of the salt norm. When this percentage is less than 10, pirssonite ($\text{Na}_2\text{Ca}[\text{CO}_3]_2$) becomes prevalent and comprises 16% to 41% of the normative assemblage.

For the Ca-Na HCO_3 -type waters, calcite and dolomite comprise 54% to 65% for the assemblage having subordinate and variable amounts of thenardite (12% to 21%) and halite (10% to 30%). NaCl-type waters are dominated by normative halite, which comprise 75% to 90% of the assemblage. The remaining part of the assemblage consists of less than 11% of each of the following mineral pairs: thenardite and glauberite, calcite and dolomite, or trona ($\text{Na}_3\text{H}[\text{CO}_3]_2 \cdot 2\text{H}_2\text{O}$) and burkeite ($\text{Na}_6\text{CO}_3[\text{SO}_4]_2$).

Mineral Equilibrium

Although there are at least five distinct water types that occur in the Dakota Formation, the calculated mineral saturation indices are similar. Chalcedony and quartz are typically in equilibrium (S.I. = 0 ± 0.37 ; Hitchon 1995) or slightly oversaturated. These indices reflect the quartz arenite to sublitharenite characteristics of these first-cycle sandstones (Witzke and Ludvigson 1994). Carbonate and Fe-bearing minerals including pyrite and marcasite in the Dakota Formation are the most common authigenic cements and these are reflected in the saturation indices. Typically, calcite and dolomite are in equilibrium or slightly oversaturated. Dolomite is generally undersaturated. Fe-bearing species, such as $\text{Fe}(\text{OH})_3$, geo-

thite (FeOOH), and hematite (Fe_2O_3), are strongly oversaturated. Siderite (FeCO_3) is variably saturated, ranging from strongly undersaturated to being at equilibrium.

Discussion

Evolution of CaSO_4 and Ca-Na SO_4 Waters

In northern Nebraska, the Ca SO_4 and Ca-Na SO_4 waters occur where the Dakota is overlain by confining shale units. The δD and $\delta^{18}\text{O}$ of these waters have values of -125‰ and -17‰ , respectively, and are extremely depleted relative to modern precipitation and modern shallow ground water (Harvey, in press). However, they appear to be meteoric in origin (Figure 4). Using the $\delta^{18}\text{O}$ -T correlation of Harvey (in press), the depleted values for δD and $\delta^{18}\text{O}$ in Cedar County suggest that mean yearly atmospheric temperatures during recharge were potentially 15°C colder than current conditions. There are at least three possible explanations for these apparently cold recharge values: (1) these waters originated in the high altitudes of the Front Range where yearly average temperatures are lower; (2) recharge is modern but represents δD - and $\delta^{18}\text{O}$ -depleted winter precipitation; and (3) recharge originated in eastern Nebraska but during a colder climate.

The current potentiometric surface (Helgesen *et al.* 1984) indicates that regional ground water flow is from the southwest to the northeast. Although a hydraulic connection may exist between the bedrock sediments in the Front Range in Colorado and the Dakota Aquifer of eastern Nebraska (Helgesen *et al.* 1984), it is unlikely that this connection passes beneath the Denver basin. Waters flowing deep in sedimentary basins encounter elevated temperatures and undergo isotopic exchange reactions with the aquifer materials, altering their δD and $\delta^{18}\text{O}$ compositions (Clayton *et al.* 1966; Frapet *et al.* 1984). Our samples from western Nebraska clearly reflect these types of alterations and are saline brines. If the ground water in the northern area had migrated from western Nebraska following the current potentiometric surface, we would not only expect altered δD and $\delta^{18}\text{O}$ compositions, but according to Carlson and Sibray (1992) TDS values greater than $10,000\text{ mg/L}$ occur in the Dakota Formation southwest of this area. If these high TDS waters are flowing to the northeast, the TDS values in the northern area should be similar to, or higher than the $10,000\text{ mg/L}$ value. This is not observed.

Three arguments can be made against the second explanation. First, less than 25% of precipitation occurs during the winter months. Second, the aquifer in this part of the state is for the most part confined. These two factors would minimize vertical recharge. Third, the modern hydraulic gradients do not favor deep recharge. Therefore it would seem that this part of the Dakota Formation was recharged with Pleistocene to Early Holocene glacial meltwater.

The isotopically light waters occur just south of the Missouri River, which is the boundary of the last major glacial advance. Siegel (1991), Siegel and Mandle (1984), and Matheney and Gerla (1996) have suggested the importance of recharge from glacial meltwater into bedrock aquifers. Prior to and during the deposition of Pleistocene glacial sediments (*i.e.*, till, glaciolacustrine), the Dakota was subaerially exposed along the Sioux Ridge (Witzke *et al.* 1983). This configuration provided the opportunity for recharge of the Dakota Aquifer to occur along the base of overriding ice sheets many times during the Pleistocene. If these waters do repre-

sent recharge from the north, then the potentiometric surface was opposite of what it is today (Stotler *et al.* 1999).

Although the predominance of anhydrite in the normative mineralogy could simply reflect dissolution of evaporitic gypsum, this is unlikely considering the depositional environment of the Dakota. A more likely interpretation is that these waters are the result of the oxidation of pyrite and the production of sulfuric acid to produce the abundant normative anhydrite. Pyrite is common in the upper Woodbury member and typically follows siderite in the Nishnabotna paragenetic sequence (Ludvigson *et al.* 1987). The weathering of pyrite produces an acidic solution enriched in iron and sulfate. In a natural neutralization process, this acidic solution dissolves additional calcite. Together these processes result in CaSO_4 waters.

The abundant gypsum and glauberite in the norm for the Ca-Na SO_4 waters not only reflects the importance of sulfatic-weathering solutions, but also indicates the weathering of siliceous crystalline rocks having more calcic lithologies than those seen by the CaSO_4 waters. Although we do not yet have stable isotope confirmation, we speculate that the Ca-Na SO_4 waters were also recharged by glacial melt water and represent CaSO_4 waters that have evolved to more Na-rich compositions through ion exchange. This is consistent with the average $\text{Na}/(\text{Ca} + \text{Mg})$ ratio for the Ca-Na SO_4 , which is 0.70, being approximately two times greater than this ratio in the CaSO_4 waters. For the exchange process to occur, clays must have been in contact with more saline waters having higher $\text{Na}/(\text{Ca} + \text{Mg})$ ratios. The origin of the saline waters is not known, but the occurrence of saline brines having TDS greater than $10,000\text{ mg/L}$ to the south indicates that saline water has likely been available in the past. Commonly clays in saline environments will also have boron available for exchange. Boron concentrations in the Ca-Na SO_4 waters are two times greater than those in the CaSO_4 waters, which further supports the likelihood of ion exchange.

Mixed Water Types in the Northeastern Area

The Ca-Na SO_4 waters occur where the Dakota is confined by the Cretaceous Carlile and Greenhorn-Graneros formations. These waters also occur in Dodge County. The $\text{Ca-Mg-Na} (\text{HCO}_3\text{-SO}_4 \pm \text{Cl})$ and Ca-Na or $\text{Ca} (\text{HCO}_3\text{-SO}_4)$ waters are associated with the contact of the Dakota and the Graneros-Greenhorns formations, primarily in Dakota and Thurston counties. Ca HCO_3 waters occur in areas where the Dakota is overlain by Pleistocene glacial till and/or loess. The complex distribution of water types is likely related to the transition of the Dakota from a predominantly confined to an unconfined aquifer similar to that observed in Kansas. Macfarlane (1995) indicates that, as a result of thinning and erosional down cutting through the confining units overlying the Dakota Aquifer, there are variable degrees of recharge through the confining units and the establishment of local flow systems in Kansas. In relative terms, where the confining unit is thin or has been removed, the Dakota can receive a relatively greater amount of local recharge.

Based on the limited data, we propose the following scenario to explain the available data. Compositionally, the recharge waters are likely to be CaHCO_3 -type waters having relatively low TDS. Where the confining unit is thick and most coherent, the waters are Ca-NaSO_4 waters and represent the regional ground water flow component. As the confining unit

thins and the vertical hydraulic conductivity allows for local recharge, the hydrogeologic conditions and associated water chemistry becomes more variable. The compositional relationships suggest that there may be interaction between the Ca-NaSO₄ endmember and a CaHCO₃ endmember. The extent to which this mixing takes place is a function of dispersion and the time that the water has been in the aquifer. In addition, the interaction may have also been facilitated by the hypothesized changes in flow direction as a result of glaciation.

Evolution of CaHCO₃ and Ca-MgHCO₃ waters

Waters from the eastern area are almost exclusively CaHCO₃ and Ca-MgHCO₃ waters having TDS less than 500 mg/L. The Nishnabotna Member of the Dakota Formation is the predominant hydrogeologic unit in this area. The prevalent occurrence of calcite and dolomite along with pirssonite as normative minerals suggests that carbonic acid hydrolysis of silicate minerals is the dominant process controlling the water chemistry. The saturation indices for the iron minerals also indicate their importance in controlling the iron concentrations in the water. The low TDS in these bicarbonate-dominated waters is consistent with these ground waters having been recharged relatively recently.

Evolution and Source of NaCl Waters in Eastern Nebraska

The NaCl waters occur in the vicinity of Lincoln, as well as near the contact between the Greenhorn-Graneros formations and the Dakota Formation in western Jefferson County. There are several possible mechanisms for the formation of these saline waters, which include: long-term water rock interaction; connate water in which the original water is removed, but solutes are retained by membrane filtration; evaporative concentration; and the dissolution of halite.

Ground water can only evolve to a Cl-rich brine if it encounters highly soluble chloride minerals. Although currently undersaturated with halite, the normative halite abundances (> 85%) and Na/Cl systematics (Figure 5) clearly support the conclusion that the salinity was derived from the dissolution of halite. It is unlikely that appropriate conditions existed for the formation of evaporites during the deposition of the Dakota Formation (Witzke and Ludvigson 1994). We therefore conclude that the saline water did not form as a result of water-rock interaction as the ground water migrated through the Dakota Formation.

As indicated, the Na/Cl ratios are consistent with the dissolution of halite as well as the dilution or evaporation of sea water (Figure 5). The majority of NaCl waters have Na and Cl concentrations that are similar to modern sea water or fall along a line that represents the dilution of sea water. If these Dakota waters represent connate or diluted connate water, the normative mineralogy should be similar to that of sea water, which is characterized by about 77% halite along with normative carnallite (KMgCl₃·6H₂O) and bischofite (MgCl₂·6H₂O) (Jones and Bodine 1987). However, the normative mineralogy of our samples has greater than 85% halite and does not have any of the key normative index minerals for sea water, carnallite, and bischofite. These normative characteristics preclude connate sea water or a diluted sea water from being the source of the saline waters. The δ¹⁸O and δD data also suggest that these saline waters are similar to modern meteoric water and preclude evaporation as a major process in producing the observed salinity.

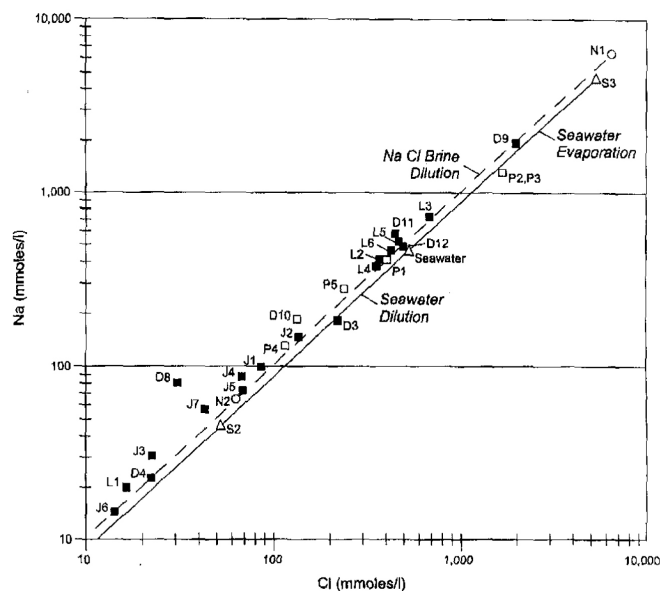


Figure 5. Plot of Na versus Cl for ground water used in this study. Open triangles Δ = values associated with sea water and its evaporation (S3) or dilution (S1). Open circles \circ = values associated with the dissolution of halite (N1) and its corresponding dilution. Open squares \square = ground water samples from the Pennsylvanian limestones. Closed squares \blacksquare = ground water samples from the Dakota Formation in Jefferson County (J), Lancaster County (L), and Table 1 (D).

In 1887, a 751 m (2,463 feet) exploratory well was drilled in what is now west Lincoln. Three saline zones were identified during the drilling (Condra and Reed 1939). Zone 1 was in the lower part of the Dakota. The other two zones were in formations in the Pennsylvanian Shawnee Group (Lecompton-Oread formations) and the Kansas City Group (Drum Formation). Waters from these zones flowed to the surface under artesian conditions. Compositions of Pennsylvanian-derived NaCl waters and those in the Dakota are compared on Figure 5. The majority of the Dakota NaCl waters from Lancaster County have Na and Cl concentrations similar to the saline ground water in the Shawnee Group that was obtained from a well at the Lincoln Post Office (Figure 5). In addition, other characteristic ratios for the saline waters in the Dakota from Lancaster County compare well to those found in the Pennsylvanian waters, in particular, the Ca/(HCO₃ + SO₄), Na/Cl, and the SO₄/Cl ratios (Table 3). The average Ca/Mg and Mg/Cl ratios of Dakota and Pennsylvanian waters are also within a factor of three. Based on these similarities, we speculate that these saline waters have a similar origin.

Condra and Reed (1939) indicated that the salt water from the Pennsylvanian zones cannot be the source of the saline waters in the Dakota because these zones are separated from the Dakota by "thick, impervious zones" that do not allow the saline fluids to move upward. This assumes that the integrity of these overlying beds is such that water is not allowed to move vertically. In other parts of the Dakota Aquifer, specifically in South Dakota, other workers have indicated that where pre-Cretaceous limestones underlie the Dakota they can be significant sources of water to this aquifer (Swenson 1968; Bredehoeft *et al.* 1983). Moreover, in the South Dakota area, Kolm and Peter (1984) argue for fracture controlled vertical leakage. Even without fractures, significant amounts of water can move vertically through rel-

Table 3. Characteristic Molar Ratios for NaCl-Type Waters from the Dakota Aquifer Compared to Ratios from Saline Waters in Pennsylvania Limestones and Simulated by PHREEQC (See text for the details for each simulation.)

All NaCl-Type Waters	Ratios Na/ (Ca + Mg)	Ca/ (HCO ₃ +SO ₄)	Ca/Mg	Na/Cl	Mg/Cl	Ca/Cl	SO ₄ /Cl	TDS
Average	28.7	0.24	1.8	1.15	0.021	0.043	0.07	14,000
Maximum	46.6	0.54	5.2	1.43	0.035	0.15	0.21	44,200
Minimum	5.7	0.06	0.9	1.00	0.011	0.014	0.03	1200
Lancaster County NaCl-Type Waters								
Average	33.4	0.22	1.3	1.10	0.017	0.023	0.05	26,000
Maximum	40.9	0.36	1.8	1.20	0.035	0.012	0.08	44,200
Minimum	12.5	0.12	0.8	1.05	0.012	0.061	0.03	1,360
Pennsylvanian Shawnee Group								
Lecompton-Oread	88.3	0.2	3.1	1.04	0.009	0.003	0.02	24,700
Wabunsee								
Scranton Sandstone	42.5	0.18	2.9	1.12	0.02	0.007	0.07	8,300
PHREEQC Simulations								
Sim 1	152	0.68	2.5	1.0	0.002	0.005	0.006	385,000
Sim 2	136	0.60	2.4	1.0	0.002	0.005	0.006	46,000
Sim 3	107	0.49	2.1	1.0	0.003	0.006	0.006	38,700

atively low conductivity layers because of the very large areas underlain by the Dakota (Swenson 1968; Helgesen *et al.* 1984). Fractures and faults are not uncommon in the pre-Cretaceous rocks of eastern Nebraska. More specifically, there is an east-to-west trending structural feature, known as the Denton Arch (Burchett 1982), that crosses the middle part of Lancaster County so that pathways for vertical migration of water from older units are certainly feasible. Because of the potential for vertical movement and the documented artesian conditions, our current conceptual model for the source of the saline waters is from the Pennsylvanian rocks.

The Na to Cl relationships (Figure 5) and the predominance of normative halite for the waters from the Pennsylvanian rocks strongly indicate that the salinity was derived from the dissolution of halite followed by dilution. These relationships are consistent with the geologic history of the Pennsylvanian rocks in Nebraska in which saline beds were deposited along with limestones and a variety of other marine facies as seaways became more restricted in western Nebraska (Carlson 1993).

Additional support for this origin of salinity comes from geochemical modeling using PHREEQC. Our simulation 1 (Table 3) involved a meteoric water equilibrated with CO₂ in the atmosphere that initially interacts and comes into equilibrium with calcium carbonate at a pCO₂ of 2.0. This water then was allowed to equilibrate with halite. As this water would continue to migrate through the Pennsylvanian rocks it would again equilibrate with calcium carbonate. In the context of molar ratios, the simulated values are generally within a factor of two of the actual values. The exceptions to this are the Ca/(HCO₃ + SO₄) and the SO₄/Cl ratios, which indicate that the assumptions regarding the evolution of SO₄ could be improved. To account for differences in the simulated TDS, we diluted the brine with meteoric ground water, which had equilibrated with calcium carbonate. The dilution factors were 7:3 (simulation 2) and 9:1 (simulation 3). These dilutions bring the TDS within an order of magnitude of the observed values. In addition, it also brings the Na/(Ca

+ Mg) and Ca/Mg ratios progressively closer to the observed values. Additional dilution would be expected to bring them even closer to the observed values. Although these simulations are relatively simplistic, they are consistent with our current working hypothesis that waters in residence in the Pennsylvanian limestones have moved upward into the Dakota where they have been diluted and interacted with locally derived meteorically recharged ground water.

Although the NaCl waters in Jefferson County have Na/Cl ratios (Figure 5) and normative halite abundances consistent with halite dissolution, the geologic source of the saline water is probably different. In contrast to the Lincoln area where the Dakota is underlain by Pennsylvanian formations, Jefferson County is underlain by Permian strata. The Permian Cimmaron Series, which has halite deposits, occurs just west of the area where NaCl-type waters have been observed. We speculate that these saline waters are a northward extension of the saline waters in Kansas that have a Permian source (Whittemore *et al.* 1993).

Mixed Water Types in Lancaster and Jefferson Counties

There are a variety of other water types in Lancaster and Jefferson counties that we currently attribute to varying degrees of interaction between NaCl waters and more recently recharged meteoric water. Recharge water of the CaHCO₃ type having stable isotopic signatures similar to modern meteoric have apparently influenced the various water types in, at least, Lancaster County. The present and past occurrence of saline water in the Dakota Formation has likely resulted in significant quantities of sodium being adsorbed on the clays in the shales, siltstones, and sandstones. As fresh CaHCO₃ waters slowly flush saline water from the aquifer, Ca and Mg are adsorbed and Na is released into the solution. The removal of Ca from the solution allows additional calcite, where available, to dissolve and supply additional calcium and bicarbonate to the water. Depending on the extent to which these processes have influenced Na, HCO₃, and Ca concentrations, a variety of waters could be produced. As

was the case in northeastern Nebraska, another factor that will influence the extent to which these processes have taken place, particularly in Jefferson County, is the degree to which the Dakota Formation is confined. Similar explanations have been invoked in Kansas to explain the complex water chemistry related to Dakota Aquifer where it has been affected by saline water and the transition from a confined to unconfined aquifer (Whittemore *et al.* 1993).

Management Implications

A critical component to managing water resources is understanding the source of the ground water that is extracted from a well. According to our analysis, there are three distinct sources for the ground water in the Dakota that include modern meteoric water, NaCl brines from underlying formations, and glacial melt water. Based on these three water sources and our current understanding of the geochemical evolution of the various water types in the Dakota, we suggest the following first-order management strategies.

CaSO₄ and Ca-Na SO₄-Type Water Areas

The source of these waters, which are predominant in the northern and northeastern areas, is Pleistocene age glacial meltwater recharge (Stotler *et al.* 1999). These waters occur where the confining unit is thick and represent the confined ground water flow component. Where these waters occur, it is particularly important that overdevelopment does not occur. As the age of the water implies, the ground water extracted from wells in these areas is being removed from long-term aquifer storage. This water supply is not easily renewable. Because of the small population, the depth of the aquifer, the quality of the ground water and the topography, large scale aquifer development in this region is likely to be minimal. However, where these water types occur it is recommended that additional analysis of the resource be conducted before extensive development occurs.

Ca (± Mg) HCO₃-Type Water Areas

The source of these ground waters is from recharge by relatively recent local precipitation. These waters occur where the Dakota Aquifer is unconfined. Development of the Dakota Aquifer as a water resource in these areas will be limited to the extent to which the ground water resource can be replenished by recharge from meteoric water. Because the ground water in these areas is linked to the local recharge conditions, it will be more susceptible to variations in seasonal or annual precipitation and should be managed accordingly to maintain it as a renewable resource.

Mixed Ground Water-Type Areas

These ground waters most often reflect the interaction of two distinct water types, one of which is meteoric water and the other is either CaSO₄ and Ca-Na SO₄-type water or NaCl-type water. In areas such as Lancaster County, where meteoric recharge waters have likely displaced NaCl water downward, the vertical chemistry profile will be complex in which there will be a progression from relatively fresh CaHCO₃-type water near the top to more saline, mixed ground water types to NaCl waters at depth. Although these complex vertical profiles have been observed, we cannot predict the

vertical or spatial changes in water chemistry. If the fresher ground water is extracted at a rate that cannot be maintained by recharge, then the water chemistry will change as the interface between fresh and saline waters moves. From a water management perspective, monitoring changes in water chemistry in a well over time could be used as an early warning system for the onset of potential problems related to overpumping of the aquifer. In a similar fashion, where the aquifer is under varying degrees of confinement such as in northeast Nebraska, changes in ground water chemistry could be used to assess the extent to which a well is being influenced by water from the regional confined aquifer or local flow systems.

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