

Prepared in cooperation with the
CITY OF LINCOLN, NEBRASKA

Age of Ground Water at City of Lincoln's Municipal Well Field Near Ashland, Nebraska

—Gregory V. Steele

The Platte River alluvial aquifer, which underlies the Platte River Valley, is an important source of water for public supply in central and eastern Nebraska. Knowing the age of ground water can help scientists and water managers better understand the dynamics of the ground-water system. In turn, this knowledge will help in calibrating ground-water-flow models and aid in developing a conceptual understanding of how long it takes for recharge water to reach certain areas of the aquifer. Although previous studies (Davis, 1992; Steele and Verstraeten, 1999; Verstraeten and others, 1999) reported the interaction of surface water and ground water at the municipal well field near Ashland for the city of Lincoln, Nebraska (fig. 1), and quantified, to some degree, the interaction of the Platte River with the underlying alluvial aquifer, no significant amount of work had been done to quantify the age of the ground water at this well field. Therefore, in 2001 the U.S. Geological Survey (USGS) and the city of Lincoln engaged in a cooperative study to determine the areal and vertical age distribution of the water at selected monitoring-well sites in the well field at Ashland. This fact sheet summarizes the results of that study.

Background

The Platte River and the hydraulically connected Platte River alluvial aquifer are essential sources of water to municipal, agricultural, and domestic wells. The city of Lincoln obtains its public-water supply from a municipal well field near Ashland. Recharge to the alluvial aquifer predominantly comes from precipitation, inflow from

hydraulically connected sand and gravel aquifers, and inflow from the Platte River. Recharge from the Platte River can quickly affect the quality and quantity of the ground water, either favorably or adversely (Steele and Verstraeten, 1999). Knowing the age distribution of the ground water in the well field will help water managers determine how quickly ground water flows and, to some extent, the sensitivity of the aquifer to contamination.

Description of Study Area

The study area lies near Lincoln's municipal well field in the Platte River Valley. In this area the Platte River is a

wide, braided, sand-bed stream. Alluvial clay, sand, and gravel of Quaternary age fill the Platte River Valley and compose the Platte River alluvial aquifer (herein referred to as the alluvial aquifer) that overlies limestone bedrock of Pennsylvanian age.

Flow in the study area primarily includes surface-water flow in the Platte River and ground-water flow in the alluvial and other hydraulically connected aquifers. Flow in the Platte River near Ashland includes runoff from about 84,200 square miles of drainage area upstream from the study area and contributions from ground water (Steele and Verstraeten, 1999). Mean daily flow for the Platte River

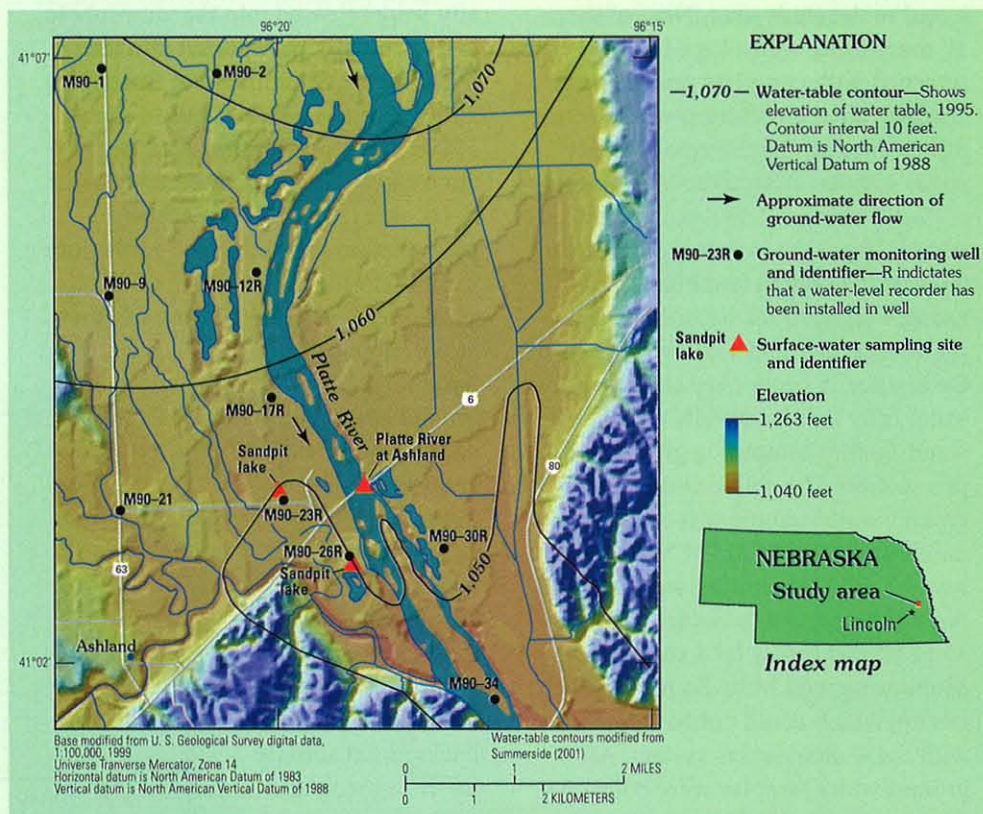


Figure 1. Map showing location of study area near Ashland, Nebraska.

near Ashland for water year 2001 (October 1, 2000, to September 30, 2001) was 6,046 cubic feet per second (Hitch and others, 2002).

Ground-water flow in the study area predominantly parallels the Platte River (Summerside, 2001) (fig. 1). Depths to water in the study area vary from 20 feet below the land surface on the western edge of the study area to less than 5 feet near the Platte River. Sand and gravel deposits have been mined extensively adjacent to the Platte River, and sandpit lakes now exist where this mining has occurred. Some of these sandpit lakes are large, covering hundreds of acres. Additional information on surface-water and ground-water flows and the general hydrology of the study area were reported by Steele and Verstraeten (1999).

Sampling Design and Methods

In April and May 2001, 3 composite surface-water samples (Platte River and two sandpit lakes) and 1 composite and 26 discrete ground-water samples from 10 monitoring wells were collected in the study area. Nine of the 10 monitoring wells were fully screened with complete gravel packs. Because most monitoring wells were fully screened, the discrete ground-water samples from these wells were collected using a 2-foot paired packer system (fig. 2) to isolate the deepest, intermediate-depth (excluding monitoring well M90-21 because of its shallow depth), and shallowest parts of the aquifer. A cautionary statement for using fully screened wells to obtain water-quality samples is given later in this section. The single composite ground-water sample was collected at monitoring well M90-34, which also was the only monitoring well that was not fully screened (screened from 35 to 80 feet below land surface). Monitoring well M90-34 has a 6-inch casing, which could not be sampled with the 4-inch packer system. All ground-water samples were collected using a submersible pump either placed in the packer system or, in the case of well M90-34, located near the

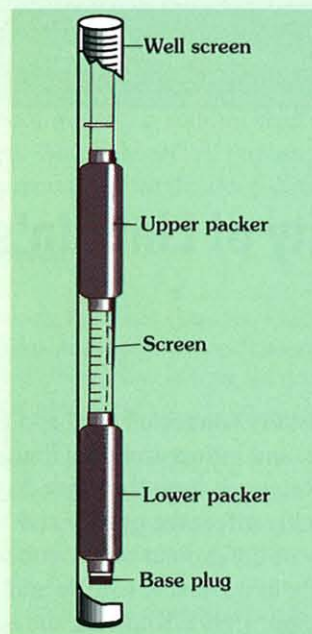


Figure 2. Straddle packer used to isolate parts of the aquifer for ground-water sampling.

center of the screened interval.

Chlorofluorocarbons (CFCs) are stable synthetic halogenated alkanes used as aerosol propellants, cleaning agents, solvents, and blowing agents in the production of foam rubber and plastics. They first were produced in the 1930s as refrigerants that unintentionally were released into the atmosphere and eventually transported into the hydrosphere (Plummer and Busenberg, 2000). From the mid-1960s to mid-1990s CFC concentrations in the atmosphere have increased at a nearly linear rate (fig. 3). Consequently, precipitation that fell to the earth since the mid-1940s has a unique CFC signature. This CFC signature in the atmosphere is the basis for CFC ground-water age dating (Plummer and Busenberg, 2000).

Similar to CFCs, tritium (^3H) also has dispersed throughout the hydrosphere. Prior to 1952 the natural background activity of ^3H in precipitation was about 1 to 10 tritium units (TU) (Davis and

DeWiest, 1966). Beginning in 1952, large amounts of ^3H were added to this natural background value from above-ground testing of thermonuclear weapons. At the maximum, in 1963, the quantity of human-generated ^3H was 100 to 1,000 times greater than that of natural ^3H (Fontes, 1980). Tritium's half-life, 4,500 days (12.32 years) (Lucas and Unterwieser, 2000), allows it to be used as a dating tool for relatively young water (less than 50 years) (Mann and others, 1982).

Analyses of CFCs (CFC-12, dichlorodifluoromethane, CF_2Cl_2 ; CFC-11, trichlorofluoromethane, CFCl_3 ; and CFC-113, trichlorotrifluoroethane, $\text{C}_2\text{F}_3\text{Cl}_3$) along with ^3H concentrations were used to determine the age of relatively young ground water—less than 50 years old. Concentrations of CFCs, along with selected dissolved gases (argon, carbon dioxide, methane, nitrogen, and oxygen) were analyzed in water collected from all ground-water monitoring wells. Recharge elevation, estimated from topographic maps, and recharge temperature, determined from the dissolved gases data, were used to determine the estimated total atmospheric pressure at recharge, which is used to calculate the apparent age of the ground water. Tritium concentrations were collected at selected sites to complement the results of the CFC data. Detailed information, including the calculations involved, on the use and limitations of these two age-dating techniques can be found in textbooks such as Cook and Herczeg (2000).

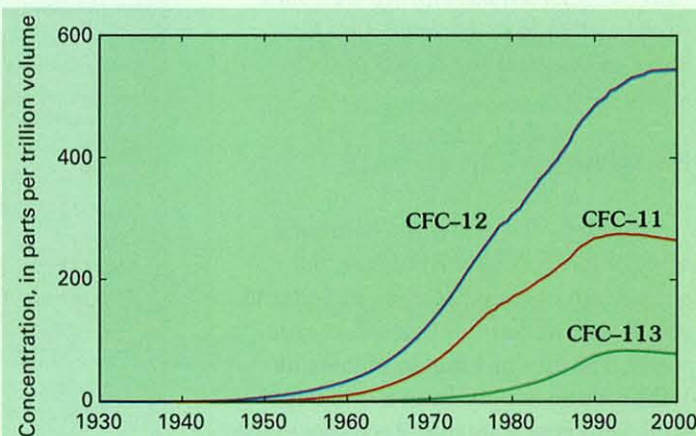


Figure 3. Atmospheric mixing ratios of CFC-11, CFC-12 and CFC-113 in North American air (Plummer and Busenberg, 2000).

Ground-water age, when determined by analyzing for CFC concentrations in water samples, is based on the minimum estimate of time that has elapsed since the newly recharged water has come into contact with the saturated zone (Szabo and others, 1996; Plummer and Busenberg, 2000). For this report, the estimated age of the water is referred to as "apparent" because of potential complicating factors described in the following paragraph. Water that is determined to be of "modern" age generally refers to water that contains CFC concentrations that are within the possible range of modern air for the CFC concentration. For this report, "modern" refers to water whose apparent age is less than 10 years, the period during which CFC concentrations in the atmosphere have peaked and are no longer increasing (fig. 3).

Complications in CFC age estimates can arise from factors such as thickness of the unsaturated zone, mixture of young and old water, errors in estimating recharge temperature, degradation of CFCs (redox conditions from anaerobic, sulfate-reducing, or methanogenic environments), dispersion of ground-water flow, and CFC contamination (Plummer and Busenberg, 2000). These processes can affect CFC concentrations. Therefore, concentrations of CFCs from water samples were tested for sensitivity. Testing for sensitivity included reviewing mixing scenarios and ground-water-flow characteristics. Degradation of CFCs was evaluated through analysis of redox, sulfate-reducing, and methanogenic conditions from physical and chemical characteristics and dissolved-gases concentrations determined during the study. Additionally, potential CFC contamination was evaluated by comparing CFC air mixture concentrations with the concentrations in water samples for the three different CFCs.

Fully screened (long-screen) monitoring wells are not ideal for the collection of water-level or water-quality data. Church and Granato (1996) report that long-screened wells tend to increase the risk of bias in that they tend not to provide representative water-quality samples even in fairly

homogeneous aquifers. Actual concentrations from water samples obtained from long-screened wells tend to be underestimated or overestimated; therefore, they cannot be relied upon for accurate data. However, Church and Granato (1996) report that use of packers in long-screened monitoring wells provided more accurate water-quality data than a composite sample. Clustered monitoring wells were not available for this study. Therefore, the results presented herein may not reflect actual concentrations, but they likely provide more accurate data than a single composite sample would provide. It was assumed that the data collected during this study accurately reflects the water quality at each discrete interval.

Ancillary Water-Quality Data

Excluding the two sandpit lakes, water samples were collected from all sites (fig. 1) and were analyzed to determine ratios of stable isotopes [deuterium (^2H) and oxygen-18 (^{18}O)], physical characteristics (specific conductance, pH, water temperature, and concentration of dissolved oxygen), and chemical characteristics (concentrations of major ions and nutrients). Water samples collected from the sandpit lakes only were analyzed for ratios of stable isotopes and physical characteristics. These data provided ancillary information to determine the overall characteristics of the ground water. The stable isotopes of hydrogen (^2H and ^1H , deuterium and protium, respectively) and oxygen (^{18}O and ^{16}O), the chemical components of water, serve as a natural tracer for the origin of ground water because they are "integral constituents of water molecules, not something that is dissolved in the water like other tracers that are commonly used in hydrology" (Kendall and Caldwell, 1998, p. 79). Analyzing the chemical characteristics of the water helps identify potential mixing of different water as well as anoxic conditions that could be present and thus potentially degrade the usefulness of the CFC data.

Results of the water analyses for stable isotopes typically are expressed as $\delta^2\text{H}$ and $\delta^{18}\text{O}$, which present the

isotopic ratio, in parts per thousand (‰), or per mil, of the water sample relative to the standard—Vienna Standard Mean Oceanic Water (VSMOW). Water samples often exhibit distinct signatures, which can be useful in identifying the timing and location of precipitation or recharge sources, flow paths, and evaporative effects. Values of $\delta^2\text{H}$ versus $\delta^{18}\text{O}$ were plotted and compared to a Global Meteoric Water Line (GMWL) developed by Craig (1961) and Local Meteoric Water Lines (LMWLs) developed by Harvey and Welker (2000) and Harvey (2001) from meteoric stations in Nebraska. Water samples that plot below the LMWL generally indicate that secondary fractionation such as evaporation occurred.

Age of Ground Water and Related Discussion

Results of age-dating analysis indicate that the ground-water samples varied in apparent age from the mid-1940s to modern (table 1). Monitoring wells whose water had the oldest apparent age (mid-1940s to the late 1950s) generally were farthest from the Platte River and in the northwest part of the study area—wells M90-1, M90-2, and M90-9 (table 1). The source of water for these monitoring wells likely was either from inflow from adjacent aquifers in the northwest part of the study area or from upgradient areas in the alluvial aquifer. However, one monitoring well (M90-21) (fig. 1) that lies about as far from the Platte River as three others (wells M90-1, M90-2, and M90-9) yielded water samples with a younger apparent age—mid-1980s. This monitoring well is one of the shallowest in the study area. One reason this monitoring well could yield younger water is that the source of water to this well could be more localized than the other three. Sensitivity analysis shows that this well could contain about 50 percent modern water. This is substantiated by the presence of large dissolved-oxygen concentrations (about 3 milligrams per liter). Dissolved-oxygen concentrations are discussed in more detail later in this section. Per well, all water samples from monitoring

wells M90-1, M90-2, M90-9, and M90-21 showed a similar apparent age that was independent of depth. This indicates that in the northwest and west parts of the study area little vertical stratification of water occurred within the alluvial aquifer.

Water samples collected from monitoring wells that were immediately adjacent to the Platte River (wells M90-12R, M90-17R, and M90-30R) exhibited areal variation in apparent age. Water samples collected from all three depths at monitoring well M90-12R, which is the monitoring well farthest upstream, showed ages that varied from the early to late 1960s. However, about 1 mile south of this well, the apparent age of the water from monitoring well M90-17R varied substantially with depth, from the late 1950s (deepest water sample) to the mid- to late 1980s (intermediate-depth and shallow water samples). In addition, analysis of the dissolved gases indicates that the recharge temperature of the water at monitoring well M90-17R ranged from 12.2 to 16.5 degrees Celsius ($^{\circ}\text{C}$) (table 1). Therefore, some of the water in this part of the aquifer probably originated from the nearby Platte River. Water samples from monitoring well M90-30R were the only samples collected on the eastern side of the Platte River and adjacent to several sandpit lakes. At this site the apparent age of the water ranged from the mid- to late 1970s to the early 1980s.

Monitoring wells that were adjacent to sandpit lakes (near wells M90-23R and M90-26R) (fig. 1) show evidence that the source of their water is the sandpit lakes. Several factors indicated this: (1) the apparent age of the samples was modern, (2) the amount of dissolved oxygen in the samples was generally more than 3.0 milligrams per liter, and (3) recharge temperatures were substantially less than the mean annual temperature of 10°C (table 1). The young apparent age along with the last two factors—dissolved-oxygen concentrations and recharge temperatures—showed that the water likely originated from a surface-water body. Large dissolved-oxygen concentrations

in the ground-water samples do not seem to be representative of typical ground-water conditions in the study area. Typical conditions, those that would seem to be more natural for the study area, indicate that the alluvial aquifer is predominantly a zone of reduction, as indicated by the small dissolved-oxygen concentrations (less than 1.0 milligram per liter) (table 2), and the presence of methane (CH_4) in

water samples as indicated in the dissolved-gases samples.

The dates derived from the ^3H data generally agreed with the CFC ages, especially in monitoring wells that were away from the Platte River. However, one ^3H sample from monitoring well M90-17R was not concordant with the CFC data. This likely is a result of a problem with using a fully screened monitoring well.

Table 1. Results of analyses for age dating of ground water at city of Lincoln's municipal well field near Ashland, Nebraska, 2001

[$^{\circ}\text{C}$, degrees Celsius; CFC, chlorofluorocarbon; ^3H , tritium; ^3H date given with respect to older than 1963 (>1963) or younger than 1963 (<1963); 1963 was the year atmospheric thermonuclear bomb testing was banned by treaty; --, not sampled]

Ground-water monitoring well identifier (fig. 1)	Depth (feet)	Date	Time	Recharge		Apparent age	
				Temperature ($^{\circ}\text{C}$)	Elevation (feet)	CFC	^3H
M90-1	25	04/03/01	1720	10.0	1,077	mid-1940s	--
	60		1550	10.0	1,077	mid-1940s	--
	100		1350	10.0	1,077	mid-1940s	--
M90-2	30	04/17/01	1320	10.5	1,200	mid- to late 1950s	--
	60		1200	11.0	1,200	early 1960s	--
	90		1000	10.0	1,200	mid-1950s	>1963
M90-9	24	04/19/01	1200	10.3	1,200	late 1950s	--
	39		1100	11.0	1,200	mid-1950s	--
	54		0950	10.5	1,200	early 1950s ¹	>1963
M90-12R	25	04/05/01	1720	11.4	1,070	mid- to late 1960s	--
	35		1600	11.0	1,070	late 1960s	--
	55		1430	11.0	1,070	early 1970s	<1963
M90-17R	25	04/05/01	1130	16.0	1,065	mid-1980s	--
	35		1030	12.2	1,065	early to mid-1980s	--
	60		0900	16.5	1,065	mid- to late 1950s	<1963
M90-21	30	04/04/01	1200	3.0	1,065	mid-1980s ²	--
	38		1040	2.7	1,065	mid-1980s ²	--
M90-23R	23	04/12/01	1440	.1	1,200	modern	--
	43		1300	7.5	1,200	early to mid-1980s	--
	63		1050	.2	1,200	modern	--
M90-26R	23	04/18/01	1330	1.5	1,200	modern	--
	33		1150	.4	1,200	modern	--
	43		1020	.2	1,200	modern	--
M90-30R	22	04/10/01	1320	10.8	1,200	mid- to late 1970s	--
	32		1210	8.2	1,200	early 1980s ¹	--
	38		1030	9.9	1,200	mid- to late 1970s	--
M90-34	60	05/01/01	1120	8.6	1,200	late 1980s	<1963

¹Possibly degraded.

²Possibly mixed with modern water.

Table 2. Results of statistical analyses for ground-water samples by depth at city of Lincoln's municipal well field near Ashland, Nebraska, 2001

[all values in milligrams per liter unless noted; number in parentheses represents number of samples; Min, minimum; Med, median; Max, maximum; $\mu\text{S}/\text{cm}$, microsiemens per centimeter at 25 degrees Celsius; $^{\circ}\text{C}$, degrees Celsius; <, less than]

	Deep well (10)			Intermediate-depth well (8)			Shallow well (9)		
	Min	Med	Max	Min	Med	Max	Min	Med	Max
Physical characteristics									
Specific conductance ($\mu\text{S}/\text{cm}$)	418	549	911	460	524	765	448	531	1,260
pH (standard units)	6.9	7.5	7.7	6.9	7.4	7.7	6.9	7.5	7.7
Temperature ($^{\circ}\text{C}$)	9.0	12.0	16.5	9.0	13.0	18.0	6.5	12.0	17.5
Dissolved oxygen	.1	.3	4.8	.1	.8	6.0	.1	.6	7.3
Chemical characteristics									
Calcium	43	54	110	42	48	75	43	49	110
Magnesium	8.7	14	22	9.3	13	16	9.2	14	38
Sodium	20	37	92	25	36	63	23	38	170
Potassium	2.6	8.8	10	6.6	8.3	10	2.7	8.5	16
Sulfate	52	76	160	52	77	130	51	78	250
Chloride	7.0	16	33	8.3	16	23	8.0	15	34
Fluoride	.3	.4	.6	.4	.5	.6	.3	.4	.7
Dissolved solids	267	351	595	295	324	492	284	323	847
Nitrate	<.05	<.05	.88	<.05	<.05	.41	<.05	<.05	.61

Analyses of the water samples for stable isotopes collected in the study area indicate that most of the water samples plotted below the LMWLs reported by Harvey and Welker (2000) and Harvey (2001) (fig. 4). Specifically, water samples from monitoring wells M90-23R and M90-30R, as well as the sandpit lake near monitoring well M90-23R, all indicate an evaporative signature (fig. 4). This suggests that the source of water for the two monitoring wells is the adjacent sandpit lakes. Most of the stable isotope values from the three westernmost monitoring wells (M90-1, M90-9, and M90-21) fall on or between two LMWLs (fig. 4). This suggests that the source of water for these monitoring wells is predominantly meteoric (water from precipitation). Values for water samples from the other monitoring wells in the study area generally fell in an area below the LMWL and appear to represent a mixture of evaporation-affected water (from surface-water bodies) and meteoric water.

Statistical analysis of the physical characteristics from the water samples showed that the maximum specific-conductance value [1,260 microsiemens

per centimeter ($\mu\text{S}/\text{cm}$) at 25 $^{\circ}\text{C}$] (table 2) was measured in a shallow monitoring well, but the deep monitoring wells had a slightly larger median specific-conductance value (549 $\mu\text{S}/\text{cm}$) than the intermediate-depth and shallow monitoring wells. The maximum dissolved-oxygen con-

centration (7.3 milligrams per liter) was measured in a shallow monitoring well, but the largest median dissolved-oxygen concentration (0.8 milligram per liter) was measured in the intermediate-depth monitoring wells. The other median values for the physical and chemical characteristics did not vary appreciably by depth (table 2).

Analyses of the chemical characteristics of the water samples showed that most of the samples were predominantly a sodium bicarbonate type. In most water samples, in terms of milliequivalents, calcium was the dominant cation. However, calcium was only slightly larger than sodium plus potassium (40 to 60 percent versus 20 to 40 percent, respectively). The dominant anion, in terms of milliequivalents, was bicarbonate (60 to 80 percent).

Water samples that contained large concentrations of sulfate also contained large concentrations of sodium. Most water samples showed similar chemical characteristics and did not vary appreciably by depth or location.

The hydrologic system is very complex in the study area because the ground-water flow in the alluvial aquifer depends on pumpage from the well

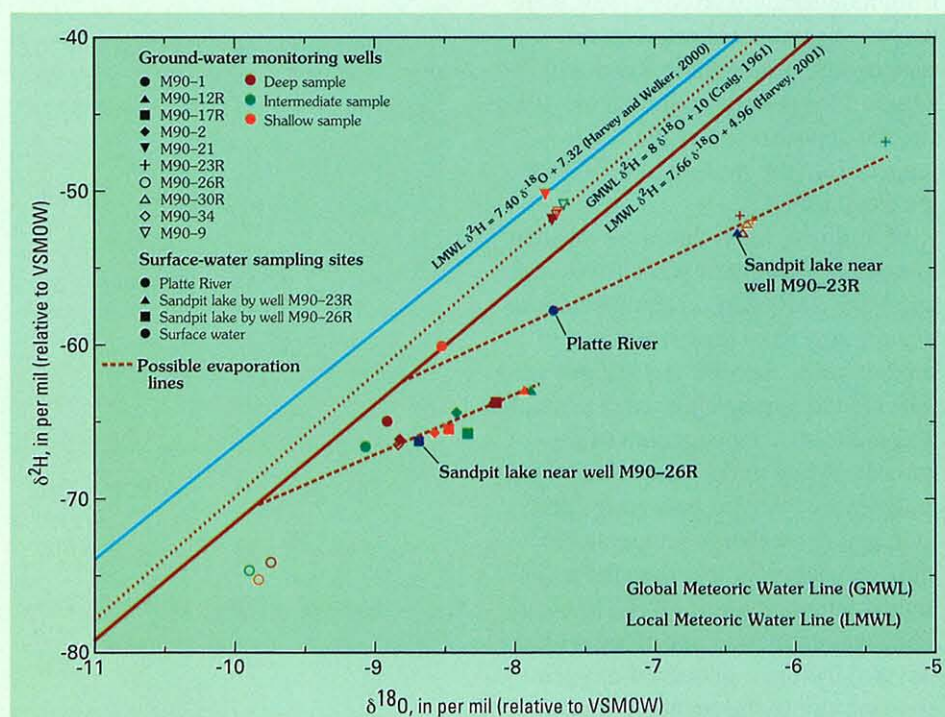


Figure 4. Oxygen-18 ($\delta^{18}\text{O}$) versus deuterium ($\delta^2\text{H}$) for water samples collected in study area, 2001 (VSMOW, Vienna Standard Mean Oceanic Water).

field, as well as the hydraulic properties of the aquifer (such as hydraulic conductivity and porosity). Therefore, the complexity of the hydrologic system makes the age-dating, stable-isotope, and water-chemistry data difficult to interpret and quantify without additional data. Analysis of the hydrologic system in the study area was beyond the scope of this study.

Conclusions

Age-dating analysis indicated that most water samples from the monitoring wells in the city of Lincoln's well field near Ashland, Nebraska, varied areally in apparent age. Water collected from monitoring wells to the northwest and west of the well field exhibited the oldest apparent ages (mid-1940s to late 1950s). The source of water in these monitoring wells likely was either from inflow from adjacent aquifers in the northwest part of the study area or from upgradient areas in the alluvial aquifer. Water from monitoring wells immediately adjacent to the Platte River varied in apparent age from the late 1950s to the mid- to late 1980s. Therefore, some of the water in this part of the aquifer probably originated from the nearby Platte River.

Monitoring wells that were adjacent to sandpit lakes on the west side of the Platte River exhibited effects of water from the sandpit lakes. Samples from these wells appeared young, contained large dissolved-oxygen concentrations, and indicated low recharge temperatures—the last two being atypical of natural ground-water conditions for this area. Also, water samples from monitoring wells downgradient of sandpit lakes all indicated similar signatures—a mixture of evaporated and meteoric water.

Analysis of stable isotope data suggests that the monitoring wells on the west side of the study area derived their water from precipitation, whereas monitoring wells adjacent to sandpit lakes tended to contain water with an evaporative signature. Water samples from the other monitoring wells tended to be a mixture of evaporation-affected

water (from surface-water bodies) and meteoric water. Water chemistry analysis indicated the water was predominantly a sodium bicarbonate type. Water chemistry did not vary appreciably with depth of sample.

References

- Church, P.E., and Granato, G.E., 1996, Bias in ground-water data caused by well-bore flow in long-screen wells: *Ground Water*, v. 34, no. 2, p. 262–273.
- Cook, P.G., and Herczeg, A.L., eds., 2000, *Environmental tracers in subsurface hydrology*: Boston, Kluwer Academic, 529 p.
- Craig, Harmon, 1961, Isotopic variations in meteoric waters: *Science*, v. 133, p. 1702–1703.
- Davis, R.K., 1992, The waters edge—hydrochemical interactions between the Platte River and the Lincoln municipal well field, Ashland, Nebraska: University of Nebraska-Lincoln, Ph.D. dissertation, 245 p.
- Davis, S.N., and DeWiest, R.J.M., 1966, *Hydrogeology*: New York, Wiley, 463 p.
- Fontes, J.C., 1980, Environmental isotopes in groundwater hydrology, in Fritz, P. and Fontes, J.C., eds., *Handbook of environmental isotope geochemistry*: Amsterdam, Elsevier Scientific, chap. 3, v. 1, The terrestrial environment, A, p. 75–140.
- Harvey, F.E., 2001, Use of NADP archive samples to determine the isotope composition of precipitation—characterizing the meteoric input function for use in ground water studies: *Ground Water*, v. 39, no. 3, p. 380–390.
- Harvey, F.E., and Welker, J.M., 2000, Stable isotopic composition of precipitation in the semi-arid north-central portion of the U.S. Great Plains: *Journal of Hydrology*, v. 238, p. 90–109.
- Hitch, D.E., Hull, S.H., Steele, G.V., and Turner, M.J., 2002, Water resources data, Nebraska, water year 2001: U.S. Geological Survey Water-Data Report NE-01-1, 393 p.
- Kendall, Carol, and Caldwell, E.A., 1998, Fundamentals of isotope geochemistry, in Kendall, Carol, and McDonnell, J.J., eds., *Isotope tracers in catchment hydrology*: Amsterdam, Elsevier Publications, 839 p.
- Lucas, L.L., and Unterwieser, M.P., 2000, Comprehensive review and critical evaluation of the half-life of tritium: *Journal of Research of the National Institute of Standards and Technology*, v. 105, no. 4, p. 541–549.
- Mann, W.B., Urterweger, M.P., and Coursey, B.M., 1982, Comments of the NBS tritiated-water standards and their use: *International Journal of Applied Radiatometical Isotopes*, v. 33, p. 383–386.
- Plummer, L.N., and Busenberg, Eurybiades, 2000, Chlorofluorocarbons, in Cook, P.G. and Herczeg, A.L., eds., *Environmental tracers in subsurface hydrology*: Boston, Kluwer Academic, p. 442–478.
- Steele, G.V., and Verstraeten, I.M., 1999, Effects of pumping collector wells on river-aquifer interaction at Platte River Island near Ashland, Nebraska, 1998: U.S. Geological Survey Water-Resources Investigations Report 99–4161, 6 p.
- Summerside, S.E., 2001, Configuration of the water table, circa 1995—Fremont and Omaha quadrangles, Nebraska: University of Nebraska-Lincoln, Conservation and Survey Division, 1 sheet, scale 1:250,000.
- Szabo, Zoltan, Rice, D.E., Plummer, L.N., Busenberg, Eurybiades, Drenkard, Stefan, and Schlosser, Peter, 1996, Age-dating of shallow groundwater with chlorofluorocarbons, tritium/helium 3, and flow path analysis, southern New Jersey Coastal Plain: *Water Resources Research*, v. 32, no. 4, p. 1023–1038.
- Verstraeten, I.M., Carr, J.D., Steele, G.V., Thurman, E.M., Bastian, K.C., and Dormedy, D.F., 1999, Surface water-ground water interaction—herbicide transport into municipal collector wells: *Journal of Environmental Quality*, v. 28, p. 1396–1405.

For further information contact:
U.S. Geological Survey
Federal Building, Room 406
100 Centennial Mall North
Lincoln, NE 68508
(402) 437-5082

USGS Nebraska District Home
 Page:
<http://ne.water.usgs.gov>

