SALINE-WATER CONTAMINATION IN QUATERNARY DEPOSITS AND THE POPLAR RIVER, EAST POPLAR OIL FIELD, NORTHEASTERN MONTANA

By Joanna N. Thamke and Steven D. Craigg

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
barrel (42 gal) (bbl)	0.1590	cubic meter
barrel per day (bbl/d)	0.1590	cubic meter per day
barrel per year (bbl/yr)	0.1590	cubic meter per year
cubic foot per second (ft^3/s)	0.028317	cubic meter per second
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon (gal)	3.785	liter
gallon per day (gal/d)	0.003785	cubic meter per day
gallon per year (gal/yr)	0.003785	cubic meter per year
gallon per minute (gal/min)	0.06309	liter per second
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Temperature can be converted to degrees Celsius (°C) or degrees Fahrenheit (°F) by the equations:

$$°C = 5/9\ (°F - 32)$$

$$°F = 9/5\ (°C) + 32$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Abbreviated units and symbols used in this report:

µS/cm	microsiemen per centimeter at 25 degrees Celsius
mg/L	milligram per liter
g/mL	gram per milliliter
mmho/m	millimho per meter
≥	greater than or equal to
<	less than

Abbreviations used in this report:

BIA	Bureau of Indian Affairs, U.S. Department of the Interior
BLM	Bureau of Land Management, U.S. Department of the Interior
EPA	U.S. Environmental Protection Agency
MBMG	Montana Bureau of Mines and Geology
MCL	Maximum Contaminant Level
SMCL	Secondary Maximum Contaminant Level
USGS	U.S. Geological Survey

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Abstract

The extent of saline-water contamination in Quaternary deposits in and near the East Poplar oil field may be as much as 12.4 square miles and appears to be present throughout the entire saturated zone. The saline-water contamination affects 9-60 billion gallons of ground water. Saline-contaminated water in Quaternary deposits east of the Poplar River generally moves westward toward the river and then southward in the Poplar River valley. Saline ground water discharges into the Poplar River, and increases the dissolved-solids and chloride concentrations in the river. The probable source of saline-water contamination in the Quaternary deposits is brine that is a byproduct of the production of crude oil in the East Poplar oil field study area. There may be at least one source of saline-water contamination in the Quaternary deposits still contributing saline water to the aquifer.

Three types of water quality characterize the Quaternary deposits; a fourth type of water quality characterizes the brine. Type 1 is the uncontaminated water quality—principally sodium bicarbonate and sodium sulfate. Types 2 and 3 are contaminated ground-water quality—principally a sodium chloride, with dissolved-solids and chloride concentrations larger than in Type 1. The concentrations of dissolved-solids, sodium, and chloride are significantly larger in Type 3 than in Type 2 water quality, indicating considerably more contamination. Type 3 water quality is similar to Type 4, which represents the brine as it is injected into brine-injection wells.

Electromagnetic apparent conductivity data collected in an area of about 21.6 square miles correlate well with ground-water quality. These data were collected and interpreted in conjunction with water-quality data to delineate possible saline-water contamination plumes. Monitoring wells were subsequently drilled in some areas without existing water wells to confirm most of the delineated saline-water plumes; however, several possible plumes do not contain either existing water wells or monitoring wells. Analysis of ground-water samples from both existing and newly drilled monitoring wells confirms the presence of 7.3 square miles of contamination, as much as 2.0 square miles of which is considerably contaminated (Type 3). Electromagnetic apparent conductivity data in areas with no wells delineate an additional 5.1 square miles of possible contamination, 3.2 square miles of which might be considerably contaminated (Type 3). Brine-injection wells, oil wells, pipelines, and storage-tank facilities appear to be probable sources of the saline-water contamination in many of the plumes.

INTRODUCTION

The presence of saline-water contamination in Quaternary alluvium along the Poplar River was first noted in the late 1970's, when landowners reported increased salinity of their domestic well water. A reconnaissance investigation by Levings (1984) determined that water in the Quaternary alluvium was contaminated by brine (water having a dissolved-solids concentration greater than 35,000 mg/L) from the production of oil. Levings indicated that additional study was necessary to determine the areal extent of contamination, rates of movement of brine, geochemical reactions that may occur, and changes in water quality with depth in the alluvium.

In the late 1980's, other well owners indicated that water in Quaternary glacial deposits also was becoming more saline. In response to the reported increased salinity of ground water used for domestic and stock supplies within and near the East Poplar oil field, the USGS, in cooperation with the Water Resources Office of the Fort Peck Tribes, conducted a follow-up investigation of shallow water in Quaternary alluvium and glacial deposits. This investigation not only expanded on the previous study of Levings (1984), but also extended that study area southward and eastward to include the glacial deposits east of the Poplar River.

Purpose and Scope

This report describes the results of an investigation to determine the extent, magnitude, and movement of saline-water contamination in Quaternary deposits and the Poplar River in the East Poplar oil field study area. Specifically, the report describes (1) the geologic setting of the East Poplar oil field study area, (2) the general hydrogeology of Quaternary deposits in terms of occurrence and movement of ground water, hydraulic characteristics of the deposits, water quality, and electromagnetic apparent conductivity, and (3) saline-water contamination in Quaternary deposits and the Poplar River, and possible sources of that contamination.

As part of this investigation, existing geologic and hydrologic data were compiled, additional wells were drilled and inventoried, water samples were collected, an electromagnetic geophysical survey was conducted, and streamflow of the Poplar River was measured. All data were analyzed to determine the extent, magnitude, and movement of saline-water contamination. This is the second report published during the investigation; the first report contained the hydrologic data that were collected (Thamke and others, 1996).

Location and Geographic Setting

The East Poplar oil field study area encompasses the East Poplar oil field (about 30 mi^2) and an additional 40 mi^2 around the oil field in northeastern Montana, on the Fort Peck Indian Reservation. The southern extent of the study area is about 2 mi north of the town of Poplar (fig. 1). The study area is located in Tps. 28 and 29 N., and Rs. 50 and 51 E., in and adjacent to the Poplar River valley. The Poplar River flows generally southward through the study area.

The study area is in the northern part of the Great Plains physiographic province, within the glaciated section of the Missouri Plateau (Fenneman, 1931). Topography of the study area consists of a broad glacial bench of relatively low relief, dissected by the Poplar River and its tributaries (fig. 2).

Dryland farming is practiced on the glacial bench and in some parts of the Poplar River valley. Livestock ranching also is practiced in parts of the study area. Oil wells, brine-injection wells, storage tanks, evaporation pits, pipelines, and various other structures associated with oil production are present throughout the study area (fig. 3).

Brief History of the East Poplar Oil Field

Oil production in the East Poplar oil field began in 1952 (Brunson, 1985, p. 889). The discovery well was drilled into Ordovician rocks to a depth below land surface of 9,163 ft and was completed on March 10, 1952 in the Mississippian Madison Group at depths of 5,524-5,827 ft (table 1 lists the generalized stratigraphic column). The major oil-producing formation is the Charles Formation of the Madison Group. A few wells were completed in the Mississippian Heath Formation and Kibbey Sandstone, the Mission Canyon Limestone of the Madison Group, and the Devonian Nisku Formation. Producing horizons typically are at depths of about 5,500-6,000 ft. The average production during 1985 was about 600 bbl/d of oil, with a 6.5 percent decline rate per year (Brunson, 1985, p. 890). Minor gas production has been obtained from the Upper Cretaceous Judith River Formation (Brunson, 1985, p. 890; Monson, 1989).

Along with the crude oil, brine (water having a dissolved-solids concentration greater than 35,000 mg/L) has been produced. The production of brine ranged from as much as 17,000 bbl/d, or 6.2 million bbl/yr, in 1985 to 5.5 million bbl/yr in 1995 (Brunson, 1985, p. 890; [Montana] Board of Oil and Gas Conservation, 1995a-d). The dissolved-solids concentration in the brine is as much as 201,000 mg/L (Thamke and others, 1996, table 6). Currently (1996), four brine-injection wells are active, although at least 16 others were active at times during the oil-field's history (Thamke and others, 1996, table 2; table 2 of this report). Of the four active brine-injection wells, one is completed in the Upper Cretaceous Judith River Formation and three are completed in a Lower Cretaceous sandstone that is called the "Dakota Sandstone" by the oil companies and the Fort Peck Tribes. Since 1985, a moratorium has been in effect on new permitting of brine-injection

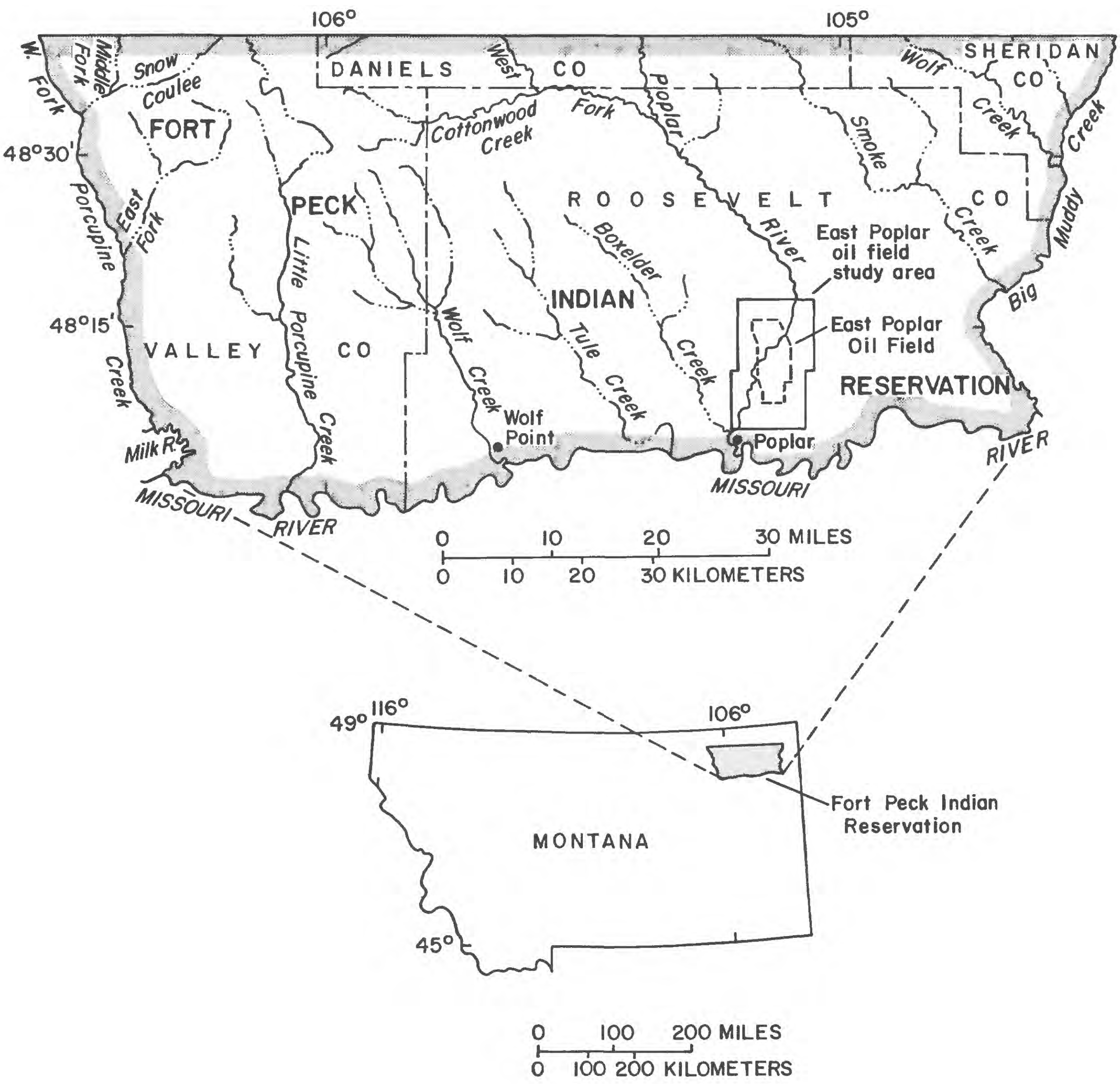

Figure 1. Location of the East Poplar oil field study area, northeastern Montana.

A

B

Figure 2. General physiographic features of the East Poplar oil field study area, northeastern Montana. (A) Aerial view north showing the low topographic relief of glacial deposits. (B) Aerial view southeast showing confluence of Culbertson Creek (foreground) and the Poplar River. Shut-in oil well Murphy 69 is on the north side of the river.

A

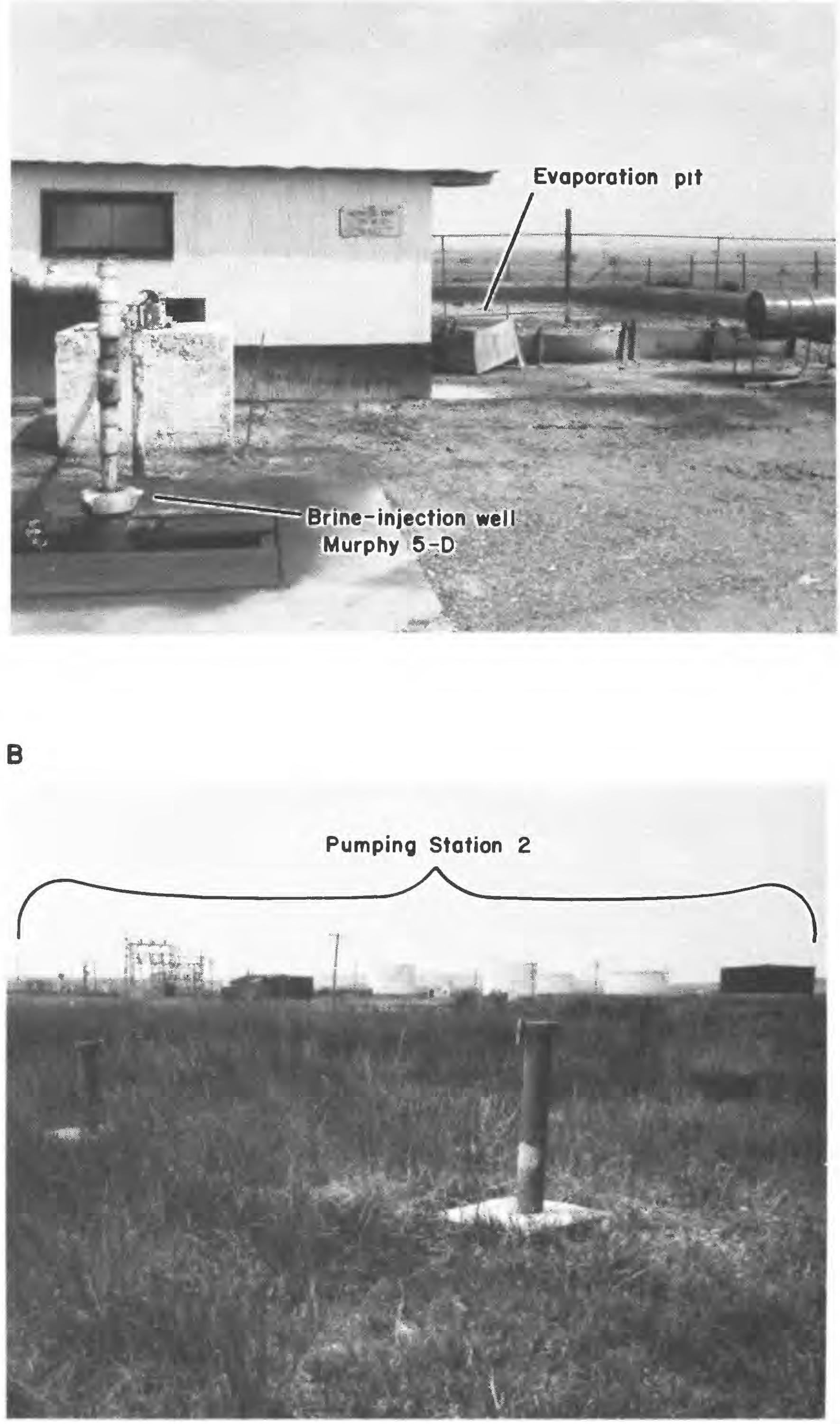

Figure 3. Various surface structures associated with oil production in the East Poplar oil field study area, northeastern Montana. (A) View east (from NE 1/4 NW 1/4 SE 1/4 SE 1/4, sec. 19, T. 29 N., R. 51 E.) of a brine-injection well (Murphy 5-D; pl. 3), and an evaporation pit (behind pump house). (B) View northwest (from NE 1/4 NW 1/4 NW 1/4 NW 1/4, sec. 32, T. 29 N., R. 51 E.) of monitoring wells (FPB92-1 and FPB93-2; Thamke and others, 1996, table 1) near storage tank facilities (Pumping Station 2).

Table 1. Generalized stratigraphic column for the Montana part of the Williston Basin (Modified from Balster, 1980, and Rice, 1976a)

Erathem	System	Series	Group	Geologic unit
Cenozoic	Quaternary	Holocene		Alluvium; Fan alluvium and colluvium, dune sand
Cenozoic	Quaternary	Pleistocene		Glacial deposits, Sprole Silt, Wiota Gravel; Fan alluvium and colluvium, dune sand
Cenozoic	Tertiary	Pliocene		Flaxville Formation
Cenozoic	Tertiary	Paleocene		Fort Union Formation
Mesozoic	Cretaceous	Upper Cretaceous		Hell Creek Formation
Mesozoic	Cretaceous	Upper Cretaceous	Montana Group	Fox Hills Sandstone
Mesozoic	Cretaceous	Upper Cretaceous	Montana Group	Bearpaw Shale
Mesozoic	Cretaceous	Upper Cretaceous	Montana Group	Judith River Formation
Mesozoic	Cretaceous	Upper Cretaceous	Montana Group	Claggett Shale
Mesozoic	Cretaceous	Upper Cretaceous	Montana Group	Eagle Sandstone
Mesozoic	Cretaceous	Upper Cretaceous	Montana Group	Telegraph Creek Formation
Mesozoic	Cretaceous	Upper Cretaceous	Colorado Group	Niobrara Formation
Mesozoic	Cretaceous	Upper Cretaceous	Colorado Group	Carlile Shale
Mesozoic	Cretaceous	Upper Cretaceous	Colorado Group	Greenhorn Formation
Mesozoic	Cretaceous	Upper Cretaceous	Colorado Group	Belle Fourche Shale
Mesozoic	Cretaceous	Lower Cretaceous	Colorado Group	Mowry Shale
Mesozoic	Cretaceous	Lower Cretaceous	Colorado Group	Newcastle Sandstone
Mesozoic	Cretaceous	Lower Cretaceous	Colorado Group	Skull Creek Shale
Mesozoic	Cretaceous	Lower Cretaceous	Colorado Group; "Dakota Sandstone"	Fall River Sandstone
Mesozoic	Cretaceous	Lower Cretaceous	"Dakota Sandstone"	Fuson Shale
Mesozoic	Cretaceous	Lower Cretaceous	"Dakota Sandstone"	Lakota Formation
Mesozoic	Jurassic	Upper Jurassic		Morrison Formation
Mesozoic	Jurassic	Upper Jurassic / Middle Jurassic	Ellis Group	Swift Formation
Mesozoic	Jurassic	Middle Jurassic	Ellis Group	Rierdon Formation
Mesozoic	Jurassic	Middle Jurassic	Ellis Group	Piper Formation
Mesozoic	Jurassic	Middle Jurassic		Nesson Formation
Mesozoic	Triassic			Spearfish Formation
Paleozoic	Permian			Spearfish Formation
Paleozoic	Permian			Minnekahta Limestone
Paleozoic	Permian			Opeche Formation
Paleozoic	Pennsylvanian			Minnelusa Sandstone
Paleozoic	Pennsylvanian			Tyler Formation
Paleozoic	Mississippian		Big Snowy Group	Heath Formation
Paleozoic	Mississippian		Big Snowy Group	Otter Formation
Paleozoic	Mississippian		Big Snowy Group	Kibbey Sandstone
Paleozoic	Mississippian		Madison Group	Charles Formation
Paleozoic	Mississippian		Madison Group	Mission Canyon Limestone
Paleozoic	Mississippian		Madison Group	Lodgepole Limestone
Paleozoic	Devonian, Silurian, Ordovician, and Cambrian rocks, undivided			Sedimentary rocks consisting of sandstone, siltstone, shale, limestone, and dolomite
	Precambrian			Crystalline igneous and metamorphic rocks

Table 2. Approximate quantities of brine injected through brine-injection wells in the East Poplar oil field study area

[Site-numbering system illustrated in figure 4. Abbreviations: bbl/d, barrels per day; gal, gallon; gal/yr, gallons per year; Kjr, Judith River Formation (Upper Cretaceous); Kd, "Dakota Sandstone" (Lower Cretaceous); Mm, Madison Group (Mississippian); Mmc, Mission Canyon Limestone of Madison Group; Ab, abandoned; Ac, active. Symbol: --, no data or not applicable; ?, uncertain]

Site number and well name	Geologic unit receiving injected water	Well depth below land surface (feet)	Site status	Average injection rate of water (bbl/d)	Maximum injection rate of water (bbl/d)	Time interval during which injection occurred	Approximate quantity of brine injected over time interval (millions of gal)		Remarks
							Based on average injection rate	Based on maximum injection rate	
28N51E02ACDB01 Murphy 2-D	Kjr	834	Ab	--	--	01/62 - (?)	--	--	Reported injection test of 2,880 bbl/d of water in 1961; at this rate about 44,150,400 gal/yr would have been injected for an unknown number of years. Abandonment date unknown.
28N51E03BCAC01 Murphy 80-D	Kd	3,575	Ac	2,700	4,500	01/64 - present (12/95)	1,283	2,138	--
28N51E04BCAC01 Murphy 59-D	Kd	3,365	Ab	4,500	6,500	06/61 - 06/86	1,725	2,491	--
28N51E10ABAC01 Huber 4	Mm	6,063	Ab	--	--	10/70 - (?)	--	--	Injection rate and abandonment date unknown.
28N51E10ABAD01 Huber 1-W	Kjr	881	Ab	--	--	10/61 - (?)	--	--	Reported injection rate of 696 bbl/d of water; at this rate about 10,669,700 gal/yr would have been injected for an unknown number of years. Abandonment date unknown.
28N51E10DACA01 Grace 110X-D	Mmc	7,000	Ab	1,827	3,000	10/73 - 05/85	324	533	--
28N51E10DBAD01 Murphy 8-D	Kjr	780(?)	Ac	7,100	8,400	01/73 - present (12/95)	2,395	2,833	--
28N51E22BDBD01 TXO SWD-1	Kjr	850	Ab	--	--	05/81 - 06/84	--	--	Injection rate unknown.
28N51E22CBCB01 Mesa 1-W (Biere 1)	Kjr	998	Ab	--	--	07/70 - 09/84	--	--	Injection rate unknown.
29N50E11CDCA01 Grace (Goings Gov't) SWD-1	Kd	3,825(?)	Ab	--	--	03/77 - 08/90	--	--	Injection rate unknown.
29N50E25DCDB01 Murphy 46	Mm	5,864	Ab	--	--	04/56 - 08/59(?)	--	--	Reported injection rate of 2,302 bbl/d of water; at this rate about 117,515,000 gal total (or 35,290,000 gal/yr) would have been injected.
29N51E07BCDB01 Grace (Buck Elk) 2	Kjr	5,933	Ab	525	1,500	12/67 - 01/86	153	437	Brine reportedly was injected sporadically.
29N51E07BDB 01 Polumbus (Buck Elk) 1-W	Kjr	1,207	Ab	--	--	02/61 - 05/68	--	--	Reported injection rate of 600 bbl/d of water; at this rate about 73,584,000 gal total (or 9,198,000 gal/yr) would have been injected.
29N51E08DCCA01 Murphy (Empire State) Smith 1	Mm	5,982	Ab	--	--	08/60 - (?)	--	--	Injection rate and abandonment date unknown.
29N51E16BAC 01 Murphy (Empire State) Rehder 7	Mm	5,750	Ab	--	--	09/60 - (?)	--	--	Injection rate and abandonment date unknown.
29N51E16DDDB01 Murphy (Owens-Simons) 1	Mm	5,780	Ab	--	--	10/60 - (?)	--	--	Injection rate and abandonment date unknown.
29N51E19DDBA01 Murphy 5-D	Kd	3,583	Ac	3,000	5,000	02/76 - present (12/95)	912	1,520	--
29N51E28CC 01 Murphy 29-D	Kjr	--	Ab	3,225	4,725	04/81(?) - 10/87	321	471	--
29N51E30DDDD01 Murphy 1-D	Kd	3,431	Ac	4,500	7,500	09/57 - present (12/95)	2,639	4,398	--
29N51E33BBAB01 Murphy 6-D	--	--	Ab	--	--	--	--	--	Injection rate and completion and abandonment dates unknown.

wells in the Judith River Formation. During 1993, about 6.1 million bbl of brine were disposed of through these four active brine-injection wells (Debi Madison, Fort Peck Tribes, Office of Environmental Protection, oral commun., 1994).

Historical data about the approximate quantities of brine injected through brine-injection wells were obtained from EPA and BLM well records, and are shown in table 2; the locations of known active and abandoned injection wells are shown on plate 3. Since brine injection began in the mid-1950's, reported average-daily injection rates for individual injection wells have ranged from 525 to 7,100 bbl/d of water (22,050-298,200 gal/d); reported maximum-daily injection rates have a range of 1,500-8,400 bbl/d (63,000-352,800 gal/d) of water (table 2). For most wells, the time interval for injection along with the approximate quantities of brine injected also are shown in table 2. Smaller, unknown quantities of brine have been directed into storage and evaporation pits (Levings, 1984). According to BLM records, minor attempts have been made to reinject brine into oil-producing zones for secondary recovery, but at present (1996) no such activity is occurring.

Murphy Oil USA, Inc. currently operates most of the wells in and near the East Poplar oil field, although various oil companies have been involved in past production activities. These companies include Ajax Oil Co., Amarco Resource Corp., Ashland Oil Inc., Carter Oil Co., Empire State Oil Co., Grace Petroleum Corp., Humble Oil and Refining Co., Juniper Petroleum Corp., MAPCO Production Co., Mesa Petroleum Co., Natol Petroleum Corp., Phillips Petroleum Corp., Richfield Oil Co., States Oil Co., Tenneco Oil Co., Texas Oil and Gas, and Union Oil Co. of California.

Previous Investigations

Several geologic investigations have been conducted in the vicinity of the study area, mainly because the East Poplar oil field lies at the western edge of the energy-rich Williston Basin. Listing all these investigations is beyond the scope of this report. However, some of the major reports on geologic structure, stratigraphy, and hydrogeology are cited in this section; other references are cited throughout the text and listed in the "Selected References" section.

In an early geologic investigation, Collier (1918) discussed the geology of northeastern Montana. The glacial geology of eastern Montana area was described by Alden (1932) and Howard (1960). The surface geology of the study area vicinity was mapped at a scale of 1:62,500 by Colton (1963a,b). Stratigraphic correlation charts of geologic formations that underlie the general vicinity of the study area were prepared by Rice (1976a) and Balster (1980). Stratigraphic studies include reports by Towse (1954), Gill and Cobban (1973), Rice (1976b), and Monson (1989). Geologic structure of the general area was identified by Jensen (1951), Dobbin and Erdmann (1955), and Colton and Bateman (1956). In a series of subsurface geologic maps, Feltis (1982a-i) published information for the altitudes of the tops and the thicknesses of major Cretaceous and Jurassic formations.

Several hydrogeologic investigations in the vicinity of the study area also have been conducted. Swenson (1955) discussed the geology and ground-water resources of the Missouri River valley in northeastern Montana. Feltis (1979) reported on shallow ground-water conditions in the upper part of the Poplar River basin. Levings (1982a,b) presented potentiometric-surface maps of water in major Cretaceous formations in the general vicinity of the study area. Donovan and Bergantino (1987) reported on ground-water resources of the Fort Peck Indian Reservation, emphasizing water in the preglacial Missouri River valley, and Donovan (1988) reported on the high-yield aquifers of northeastern Montana.

Specifically relating to the current study area, Levings (1984) conducted a reconnaissance investigation of saline-water contamination in alluvial deposits along a short reach of the Poplar River in the East Poplar oil field. The general hydrogeology of the Fort Peck Indian Reservation was discussed by Thamke (1991), and Thamke and Craigg (1993). Preliminary interpretations of saline-water contamination in the study area were given by Craigg and Thamke (1992, 1993, 1995), Mendes and others (1992), and Thamke and others (1992, 1993). Thamke and others (1996) published hydrologic data collected during this investigation.

Methods of Investigation

The investigation of saline-water contamination included a comprehensive review of existing data and extensive collection of additional field data. Existing data for water wells, monitoring wells, oil wells, brine-injection wells, and ground- and surface-water quality were obtained from various sources, including the

USGS, BLM, EPA, BIA, U.S. Public Health Service and Indian Health Service, Fort Peck Tribes (Water Resources Office, Minerals Office, and Office of Environmental Protection), Murphy Oil USA, Inc., and MBMG. Detailed information about the types of data obtained from these sources was presented in Thamke and others (1996).

As an initial step in this investigation, existing water wells were inventoried for physical parameters and water from privately owned wells in the study area was sampled and analyzed for chemical quality. To further delineate the lateral extent of potential saline-water contamination, an electromagnetic geophysical survey was conducted over an area of about 22 mi^2. Monitoring wells subsequently were installed and sampled in selected areas of high conductivity to confirm the existence of the saline-water plumes delineated by the geophysical methods. Selected monitoring wells also were used for aquifer testing to determine aquifer characteristics, which indicate the rate of ground-water flow. Streamflow and water quality of the Poplar River were measured to determine areas of saline-water discharge and effects on the river. These data and the methods used to collect them are discussed in detail in Thamke and others (1996); where appropriate, additional discussion is given in this report. Data from the well inventory, electromagnetic geophysical survey, monitoring-well installation, aquifer testing, streamflow measurements, and water-quality sampling were used to interpret the extent, magnitude, and movement of saline-water contamination in Quaternary deposits.

Site-Identification Systems

A site number is used as the primary identification for wells. This site number is based on the rectangular system for the subdivision of public lands (fig. 4); the number consists of as many as 14 characters and is assigned according to the location of a site within a given township, range, and section. The first three characters specify the township and its position north (N) of the Montana Base Line, whereas the next three characters specify the range and its position east (E) of the Montana Principal Meridian. The next two characters indicate the section; the next four characters indicate the position of the site within the section. The first letter denotes the quarter section (160-acre tract); the second letter denotes the quarter-quarter section (40-acre tract); the third letter denotes the quarter-quarter-

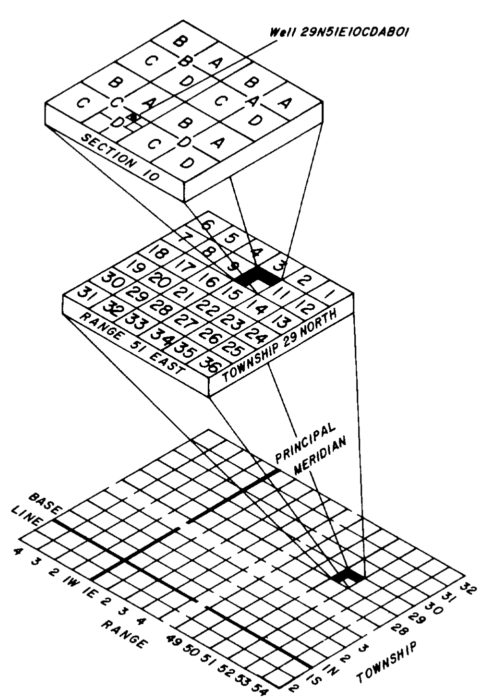

Figure 4. Site-numbering system for wells.

quarter section (10-acre tract); and the fourth letter denotes the quarter-quarter-quarter-quarter section (2.5-acre tract). These lettered subdivisions of the section are indicated as A, B, C, and D in a counterclockwise direction, beginning in the northeast quadrant. The last two characters form a sequence number based on the order that a site was inventoried in that tract. For example, site number 29N51E10CDAB01 represents the first well inventoried in the NW1/4 NE1/4 SE1/4 SW1/4 sec. 10, T. 29 N., R. 51 E.

Wells also are identified by an alpha-numeric well name, allowing for ease of cross reference between wells plotted on illustrations in this report and on relevant illustrations and tables given in Thamke and others (1996). The well name consists of as many as three alpha characters and as many as four numeric characters and an alpha character to designate the sequence during which wells were drilled. The alpha character denotes the well type: (FPB)--USGS monitoring well installed during this investigation; (W)--USGS monitoring well or privately owned well inventoried by Levings (1984); and (M)--privately owned well or MBMG observation well. The numeric characters for USGS-installed monitoring wells denote the sequence during which wells were drilled; for example, well FPB93-3 is the third well drilled in 1993 during this investigation. The numeric part of well names identified by the letter "M" is assigned only as a convenient cross reference between relevant illustrations and tables. Brine-injection wells and sampled oil wells are identified using the name assigned by the particular oil company; for example, Murphy 1-D is a brine-injection well, and Murphy 58 is an oil well.

Streamflow measurement sites along the Poplar River are identified by an alpha-numeric system. The alpha-numeric part of the site number follows the system used by Levings (1984) and is based on the downstream order of measurement, beginning with the farthest upstream site (PR-0) and ending with the farthest downstream site (PR-9) in the study area. One measurement site (PR-8) was located at a long-term USGS streamflow-gaging station (06181000), and one measurement site (PR-1) was located at a USGS miscellaneous streamflow-measurement station (06180600).

Acknowledgments

The authors thank the Fort Peck Tribes for their support extended to the USGS throughout this investigation. Special appreciation is given to the Water Resources Office and the Office of Environmental Protection of the Fort Peck Tribes for supplying data about existing domestic wells. We also wish to thank individual landowners in the reservation for their cooperation in allowing access to their lands for inventorying, sampling, or drilling wells and collecting electromagnetic-geophysical data, and for their valuable contributions of historical information about oil-field operations as well as the occurrence and use of water resources in the study area. Mr. O.A. (Bud) Lien, a private landowner in the reservation, deserves special thanks for allowing the use of his large garages for the storage of various drilling and well-completion materials, and for allowing parking of drill rigs, trailers, air compressors, and grouters. We also wish to thank the Lockman and Trottier families for their support extended during field operations. Thomas M. Mendes deserves special mention for the collection of electromagnetic-geophysical and water-level data and assisting in the preliminary interpretation of the data while employed with the USGS during summer 1991 and 1992. The authors also appreciate the technical advice provided by the employees of Geonics, Ltd.

GEOLOGIC SETTING

Regionally, the study area is located near the western edge of the Williston Basin, a broad, northwest-trending structural depression in eastern Montana, western North Dakota, northwestern South Dakota, southwestern Manitoba, and southeastern Saskatchewan. The Williston Basin (fig. 5), one of the largest structural basins in North America, is about 500 mi long and 300 mi wide, and encompasses an area of about 134,000 mi^2 (Hamke and others, 1966, p. 5). The basin also is one of the oldest structural basins in North America; it was subsiding and affecting sedimentation patterns throughout most of Paleozoic and early Mesozoic time. The basin ceased subsiding and exerting control on sedimentation by Cretaceous time (Rice and Shurr, 1978, p. 267). Present structural configuration and structural features of the Williston Basin (domes, anticlines, synclines) are a result of the Laramide Orogeny, during latest Cretaceous and early Paleocene time (Hamke and others, 1966, p. 24; Rice and Shurr, 1978, p. 267).

The study area lies atop the Poplar Dome (also referred to as the Poplar Anticline). The dome trends northwest and is about 30 mi long and 25 mi wide. As

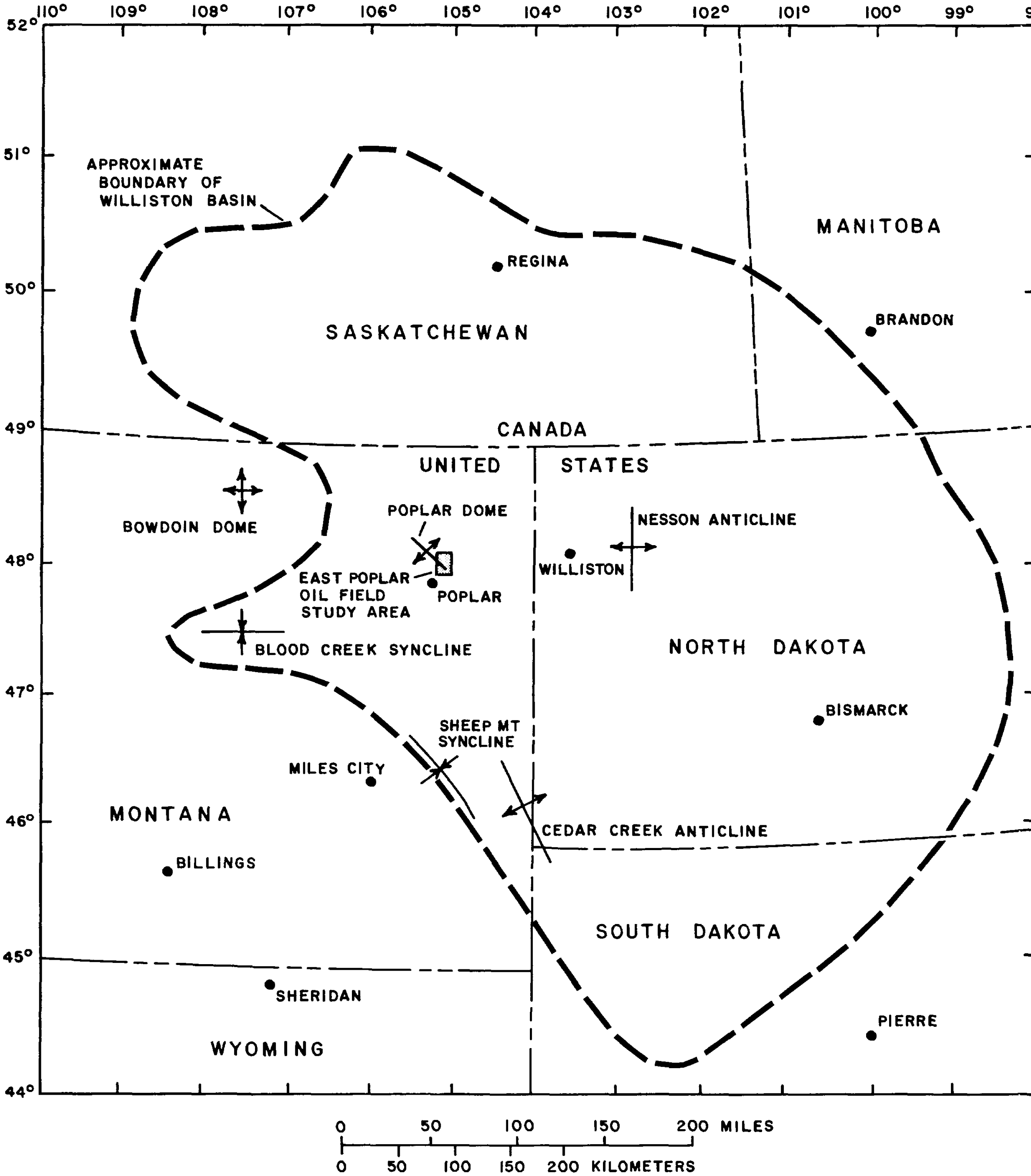

Figure 5. Location of Williston Basin, major structural features, and East Poplar oil field study area (modified from Hamke and others, 1966, fig. 1).

reported by Hamke and others (1966, p. 24), the dome consists of a principal domal structure with a structural closure of about 300 ft, and a smaller subsidiary dome with a structural closure of about 100 ft. When superimposed on the broad, regional structure of the Poplar Dome, the structural framework of the smaller East Poplar oil field study area is not complex. Geologic units essentially are flat-lying and no faults have been mapped (Colton and Bateman, 1956; Colton, 1963a,b).

Geologic units underlying the East Poplar oil field study area range in age from Precambrian through Cenozoic. Precambrian units consist solely of crystalline igneous and metamorphic rocks. Paleozoic through Cenozoic units consist of various sedimentary units; combined thickness of this sedimentary section probably is about 10,000 ft. The vertical distribution of these units is shown in table 1; detailed basin-wide geologic descriptions of these units were given by Hamke and others (1966). The principal geologic units that are exposed in the study area are the Upper Cretaceous Bearpaw Shale, Hell Creek Formation, and Fox Hills Sandstone; Tertiary Flaxville and Fort Union Formations; Quaternary glacial and related deposits; and Quaternary alluvial deposits.

Colton (1963a,b) mapped and described the geologic units exposed in the vicinity of the study area. The surface geology of the study area is shown in figure 6 (pl. 1). Detailed discussion of all geologic units is beyond the scope of this report; however, units that are most relevant for the purposes of this investigation are described in general terms below.

Mississippian Madison Group

The Madison Group consists of three formations deposited in marine environments. These are the Lodgepole Limestone, Mission Canyon Limestone, and Charles Formation (table 1). The Charles Formation is the major oil-producing unit of the East Poplar oil field (Brunson, 1985, p. 889), although minor zones in the Devonian Nisku Formation and the Mississippian Kibbey and Heath Formations also produce oil.

The Lodgepole Limestone was described by Hamke and others (1966, p. 16) as a generally brown to gray, dense, argillaceous, shaley, cherty limestone. Thickness of the Lodgepole, determined from the oil-well log of East Poplar oil field discovery well (Murphy 1, located in sec. 2, T. 28 N., R. 51 E.) is about 570 ft.

The Mission Canyon Limestone was described by Hamke and others (1966, p. 16) as a yellowish-gray and yellowish-brown, dense, massive limestone. Thickness of the Mission Canyon in the discovery well is about 760 ft.

The Charles Formation was described by Hamke and others (1966, p. 16-17) as principally an evaporitic unit, consisting mainly of massive salt beds, anhydrite, and limestone. Thickness of the Charles in the discovery well is about 400 ft.

Cretaceous Rocks

The vertical distribution of Cretaceous rocks in the study area is shown in table 1. The combined thickness of all Cretaceous units in the oil-field discovery well is about 3,500 ft. The Cretaceous rocks most relevant to this investigation are the Lakota Formation and Fall River Sandstone-"Dakota Sandstone", Judith River Formation, and Bearpaw Shale. General characteristics of these units are given below; Donovan (1988) gave concise descriptions of other Cretaceous rocks.

Lakota Formation--Fall River Sandstone--"Dakota Sandstone"

The Lower Cretaceous Lakota Formation generally consists of nonmarine, cross-bedded, coarse-grained sandstone that is conglomeratic in the basal part; reported maximum thickness is 110 ft, as described by Hamke and others (1966, p. 21). The reported thickness of the Lakota in the study area is between about 70 and 200 ft.

The Lower Cretaceous Fall River Sandstone (of the Colorado Group) in the Williston Basin consists of as much as 210 ft of fine-grained quartzose sandstone (Hamke and others, 1966, p. 21). The Fall River Sandstone of the Williston Basin occupies the same interval as the "Dakota Sandstone" of adjacent areas (see Balster, 1980). Although the USGS and the MBMG do not use the term "Dakota Sandstone" (Lower Cretaceous) in the Williston Basin (W.A. Bryant, U.S. Geological Survey, Denver, Colo., oral commun., 1994; Donovan, 1988, p. 18; and Bergantino, 1994), Ballard and others (1983) use the Dakota (Lower Cretaceous) terminology.

The Lakota Formation interval, as well as other parts of the Lower Cretaceous section (Fall River Sandstone and possibly parts of the Fuson Shale or its equivalent in the north-central Montana plains, the Kootenai Formation), have been referred to as "Dakota Sandstone" by drillers and oil-field geologists as well. In addition, the informal terms "Dakota silt" or "basal Colorado silt" have been applied to the interval above the Fall River Sandstone (essentially the interval occupied by the lower parts of the Skull Creek Shale in the Williston Basin). Use of this terminology has resulted in some confusion when referring to this stratigraphic interval, because at least four brine-injection wells are reported to have been completed in the "Dakota Sandstone" (Thamke and others, 1996, table 2). Depending on the nomenclature used, these four injection wells could have been completed in either the Fall River Sandstone, the "Dakota Sandstone," or the Lakota Formation. Therefore, to avoid further confusion and to follow the historical usage in the East Poplar oil field, the term "Dakota Sandstone" will be used in this report when referring to brine-injection wells completed in Lower Cretaceous rocks. Examination of oil-well logs in the East Poplar oil field indicate that most distances between the top of the unit picked as "Dakota Sandstone" and the top of the Upper Jurassic Morrison Formation are between about 350 and 400 ft. This "thickness," however, includes any intervening Lower Cretaceous rocks.

Judith River Formation

The Upper Cretaceous Judith River Formation (of the Montana Group) consists of a sequence of interbedded, light-colored sandstone and sandy shale (Hamke and others, 1966, p. 22). Water in the Judith River Formation occurs under confined (artesian) conditions, according to BLM well records for well 29N51E19DCAC01. Thickness of the Judith River beneath the study area is about 100 ft; depth from land surface to the top of the formation, on the basis of oil-well logs in the study area, ranges from about 700 to 1,000 ft. The Judith River Formation has been a major unit for disposal of oil-field brine by subsurface injection in the past, but since 1985 no new brine-injection wells have been allowed to be completed in the formation; currently, only one brine-injection well completed in the formation in the oil field is active (Thamke and others, 1996, table 2). Minor production of natural gas also has been obtained from the Judith River Formation; this gas is used for operational purposes in the East Poplar oil field (Brunson, 1985, p. 890; Monson, 1989).

Bearpaw Shale

The Upper Cretaceous Bearpaw Shale (of the Montana Group) conformably overlies the Judith River Formation. The Bearpaw consists mainly of dark-gray marine shale and claystone. Bentonite is present as thin beds and also is disseminated throughout some shale zones; the upper part of the formation contains some beds of sandy shale (Colton, 1963a,b; Hamke and others, 1966, p. 22). Colton and Bateman (1956) also reported that the Bearpaw contains ironstone nodules and hard ellipsoidal concretions; many concretions may contain marine fossils. Minor fractures are present in the upper, eroded surface of the Bearpaw, as noted during field observations. On the basis of oil-well records in the study area, the approximate range of thickness of the Bearpaw Shale is about 700-1,000 ft. The depth to the top of the Bearpaw ranges from zero in outcrop areas to 120 ft (Colton, 1963a,b). The approximate subsurface altitude and configuration of the top of the Bearpaw are shown in figure 7 (pl. 1); the subsurface top of the formation lies between about 1,930 ft and 2,120 ft above sea level. The top surface of the Bearpaw east of the Poplar River appears to slope gently towards the west; the apparent trough beneath the Poplar River valley probably represents stream erosion concurrent with deposition of alluvium, rather than a geologic structure.

The Bearpaw Shale crops out mainly along low hills west of the Poplar River (fig. 6, 7); only about the upper 120 ft of the Bearpaw is exposed in the study area. Tertiary units in the study area are present in minor locations only in the northern part of the study area and are not relevant in this investigation; hence, these units are not discussed in this text. Throughout the rest of the study area, Quaternary deposits unconformably directly overlie the Bearpaw Shale. On the basis of lithologic descriptions from USGS monitoring wells, the depth to the top of the Bearpaw Shale in the study area has a range of about 22-55 ft (FPB92-14 and W-11, respectively) beneath alluvial deposits of the Poplar River valley, and about 56-99 ft (FPB93-3 and FPB93-5, respectively) beneath glacial deposits east of the river (Levings, 1984, table 3; Thamke and others, 1996, table 3).

Quaternary Deposits

Quaternary units in the study area include Wiota Gravel, Sprole Silt, glacial till, fan alluvium and colluvium, and alluvium (fig. 6). Minor thicknesses and extents of glacial outwash, lake deposits, and dune sand also are present, but are not discussed separately in this report (dune sand, however, is shown in fig. 6, the geologic map).

Pleistocene Wiota Gravel (shown as Qw in fig. 6) consists of unconsolidated deposits of clay, silt, and quartzitic sand and gravel. Thickness in the study area is uncertain, but Colton (1963a,b) reported a maximum thickness of 55 ft to the south of the study area.

Pleistocene Sprole Silt (shown as Qs in fig. 6) overlies the Wiota Gravel and consists of poorly bedded to massive deposits of silt. Colton (1963a,b) reported a maximum thickness of 100 ft for the Sprole Silt to the south of the study area.

Pleistocene glacial till (shown as Qt in fig. 6) is a complex, unstratified, and heterogeneous admixture of clay, silt, sand, gravel, and boulders deposited by glaciers. Colton (1963a,b) reported that thickness generally is about 15 ft, but locally may be as much as 250 ft. In the study area, till is present mainly beneath the topographic bench east of the Poplar River (fig. 6).

Pleistocene and Holocene fan alluvium and colluvium (shown as Qac in fig. 6) underlies flood plains and consists of slope-wash deposits derived from topographically higher deposits; lithologically the slope-wash deposits are similar to Holocene alluvium (described below). These deposits are not vertically extensive; Colton (1963a,b) reported that the maximum thickness is 20 ft. Laterally, however, these deposits can be more than 1 mi wide, although the average width is much smaller (fig. 6).

Holocene alluvium (shown as Qal in fig. 6) consists of stream-deposited clay, silt, sand, and gravel. The sand and gravel deposits typically occur as lenses of varying thickness. Detailed lithologic descriptions for 19 USGS monitoring wells completed in alluvium along the Poplar River are given in Thamke and others (1996, table 3).

For the purposes of this report, Pleistocene Wiota Gravel, Sprole Silt, glacial till, and dune sand are undifferentiated and are referred to as "glacial deposits"; Pleistocene and Holocene fan alluvium and colluvium and Holocene alluvium are undifferentiated and referred to as "alluvium." Lithologic logs from eight USGS monitoring wells drilled during this investigation indicate that the combined thickness of glacial deposits in the study area ranges from at least 56 to about 100 ft (Thamke and others, 1996, table 3). The combined thickness of alluvium ranges from 22 to 56 ft throughout the Poplar River valley (Thamke and others, 1996, table 3). Colton (1963a,b) reported that, in the vicinity of the study area, thickness of these deposits averages about 50 ft; Levings (1984, table 3) gave a range in thickness of 43-54 ft. Lithologic logs from monitoring wells drilled during this investigation indicate that, in most places, alluvium ranges in thickness from about 32 to 52 ft; a thickness of 22 ft, reported in USGS monitoring well FPB92-14 (located in NE1/4 SE1/4 NW1/4 NE1/4 sec. 21, T. 29 N., R. 51 W.), indicates a local subsurface high of the Bearpaw Shale (Thamke and others, 1996, table 3).

GENERAL HYDROGEOLOGY OF QUATERNARY DEPOSITS

The Quaternary deposits are the sole developed source of ground water for residents of the study area. In general, wells completed in Quaternary deposits provide sufficient yields and, in uncontaminated areas, potable water for domestic purposes. Few wells are completed below the Quaternary deposits because of the lack of water in the underlying Upper Cretaceous Bearpaw Shale which is 700-1,000 ft thick.

Ground-Water Occurrence and Movement

Water in Quaternary deposits occurs mainly under unconfined (water-table) conditions, although locally, conditions are semiconfined due to the heterogeneity of clays, silts, sands, and gravels. Depth to water below land surface in the study area generally ranges from about 5 to 44 ft in alluvium and about 7 to 130 ft in glacial deposits (Thamke and others, 1996, table 1). Fresh water in the Quaternary deposits in the study area is recharged by infiltration of precipitation, streamflow, and fresh water movement from upgradient areas. Water in the Quaternary deposits is discharged by streamflow, evapotranspiration, springs, and water withdrawals. Generalized potentiometric surface and direction of ground-water movement in Quaternary deposits are shown in figure 6 (pl. 1). The altitude of static water level in 1990-93 ranged from about 1,950 to 2,060 ft above sea level (Thamke and others, 1996, table 1). Water in Quaternary deposits east of the Poplar River generally moves westward toward the river where it merges with southward-flowing ground water in the Poplar River valley. Downward movement of water from Quaternary deposits into the underlying Bearpaw Shale probably is not significant because of the relatively impermeable nature of the Bearpaw; downward movement of water from Quaternary deposits into the Bearpaw probably occurs only locally to shallow depths, where minor fractures are present in the upper, eroded surface of the Bearpaw.

Hydraulic Characteristics

Two constant-discharge aquifer tests were conducted during August 1993 to determine general hydraulic characteristics of the Quaternary deposits. Because of the various deposits of clay, silt, sand, and gravel throughout the study area, the hydraulic characteristics may differ locally; hence, ranges are given for the selected hydraulic characteristics.

A constant-discharge aquifer test was conducted on August 18, 1993, in alluvium along the Poplar River, using one pumped well and three observation wells (NW1/4 NE 1/4 sec. 09, T. 29 N., R. 51 E. in Thamke and others, 1996, tables 1, 3, and 4; pl. 1). The general geology of the site consists of Holocene alluvium that unconformably overlies the Bearpaw Shale.

On the basis of lithologic logs of the USGS-installed wells used for the test (FPB92-15, FPB92-16, FPB92-17, and FPB93-1; Thamke and others, 1996, table 3), these deposits consist of interbedded sand of various grain sizes, gravelly sand, and gravel and cobbles; total thickness of the sequence ranges from about 37 to 42 ft. Because topographic relief at the test site is about 0.2 ft, the range in thickness indicates that the surface of the Bearpaw Shale is slightly irregular.

The other constant-discharge aquifer test was conducted on August 19, 1993, in glacial deposits east of the Poplar River, using one pumped well, two observation wells (SE1/4 SE1/4 sec. 33, T. 28 N., R. 51 E. in Thamke and others, 1996, tables 1, 3, and 5; pl. 1). The general geology of the site consists of Pleistocene glacial deposits that unconformably overlie the Bearpaw Shale. On the basis of lithologic logs of the USGS-installed wells used for the test (FPB93-4A, FPB93-4B, and FPB93-4C; Thamke and others, 1996, table 3), these deposits consist of interbedded and unconsolidated clay, silt, sand, and gravel of various sizes, with about 13-20 ft of gravel (Wiota Gravel) consistently present at the base; total thickness of the sequence of deposits is about 60 ft.

The aquifer-test data at the alluvium test site were analyzed using standard curve-matching procedures for unconfined aquifers (delayed gravity-response type curves) of Neuman (1972, 1975). The data plots for this site clearly indicate delayed yield from storage. At the alluvium test site, the mean transmissivity value computed for the three observation wells is 1,900 ft^2/d and the mean hydraulic conductivity value is 63 ft/d. The hydraulic conductivity value is based on a horizontal hydraulic gradient of one; the hydraulic gradient at this site is probably much smaller than one. These values are reasonable for an unconfined sand and gravel aquifer. The aquifer-test data at the glacial deposits test site were analyzed using Theis (1935) methods as described in Lohman (1972). At the glacial deposits test site, the value computed for transmissivity was 3,100 ft^2/d; the computed hydraulic conductivity at this site was 165 ft/d. The hydraulic conductivity value is based on a horizontal hydraulic gradient of one; the hydraulic gradient at this site is probably much smaller than one.

The computed values for storage coefficient are 0.001-0.004 at the site of the alluvium and 0.003-0.01 at the site of the glacial deposits and are anomalously small for an unconfined aquifer. Lohman (1972, p. 40) suggested that the reason for this type of anomaly is that in shorter term aquifer tests of unconfined aquifers, where early time data are used for analysis, "it (storage coefficient) is only an apparent value observed before gravity drainage (is) completed." Therefore, published values of storage coefficient averaging 0.21-0.27 for sand and 0.22-0.25 for gravels are considered to be more reliable than those computed for this study; for example, see Johnson (1967, p. D70).

Ground-Water Quality

The quality of water in Quaternary deposits in the study area is highly variable and is dependent on location relative to sources of contamination. Dissolved solids, reported in milligrams per liter, is the sum of all dissolved constituents in the water and is predominantly composed of the major ions in solution. Sodium, bicarbonate, and chloride are the dominant ions in water from most wells completed in the Quaternary deposits. Of these dominant ions, only chloride generally exhibits a conservative behavior and generally is present in natural water at low concentrations (Hem, 1985). Therefore, concentrations of dissolved solids and chloride ions are used in this investigation to classify types of ground water.

The EPA has established regulations and standards for public drinking-water supplies. These regulations and standards are not used to regulate the quality of water produced from individual privately owned wells, but to serve as guidelines with which to evaluate the water quality. Primary Drinking-Water Regulations[1] are not established for dissolved solids and chloride. However, Secondary Drinking-Water Standards[2] specify SMCL's of 500 mg/L for dissolved solids and 250 mg/L for chloride. Dissolved-solids concentrations in water sampled during 1989-93 from

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[1]National Primary Drinking-Water Regulations are established for contaminants which, if present in drinking water, may cause adverse human health effects. Either a Maximum Contaminant Level (MCL) or a treatment technique is specified by these regulations for regulated contaminants. MCL's are health-based and enforceable (U.S. Environmental Protection Agency, 1996).

[2]Secondary Drinking-Water Standards are established for contaminants that can adversely affect the taste, odor, or appearance of water and result in discontinuation of use of the water. These regulations specify Secondary Maximum Contaminant Levels (SMCL), which are esthetically based and nonenforceable (U.S. Environmental Protection Agency, 1996).

wells completed in the Quaternary deposits ranged from 427 to 91,100 mg/L; 26 of the 27 privately owned wells contained water with dissolved-solids concentrations that exceed the SMCL (Thamke and others, 1996, table 6). Chloride concentrations in water sampled during 1989-93 from wells completed in the Quaternary deposits ranged from 7.3 to 58,000 mg/L; 15 of the 27 privately owned wells contained water with chloride concentrations that exceed the SMCL (Thamke and others, 1996, table 6).

On the basis of dominant ions and dissolved-solids concentration, Levings (1984) identified three principal water-quality types from alluvium in the Poplar River valley; a fourth water-quality type, representing the actual brine produced with the crude oil, also was identified. Distinguishing characteristics of the four water types are: Type 1 water is not dominated by the chloride anion and dissolved-solids and chloride concentrations are similar to water in Quaternary deposits in other parts of the reservation; Type 2 water is dominated by the chloride anion and the chloride concentration range typically is 330-4,800 mg/L; Type 3 water is dominated by the chloride anion and the chloride concentration is typically greater than 5,200 mg/L; Type 4 water is actual samples from brine-injection wells. These general water types have been defined in greater detail for this investigation and provide a useful classification to describe water-quality variability within the current study area. Water-quality diagrams (Stiff, 1951) illustrate these representative water-quality types (fig. 8, pl. 1). The water-quality diagrams represent unit concentrations of the major ions, in milliequivalents per liter. Unit concentrations take into account both mass and ionic charge and, therefore, the total milliequivalents per liter of cations (left side of graph) should equal that of the anions (right side of graph). The range in unit concentration of the major ions in water from the wells is too large to use the same scale for all diagrams; therefore, a different scale is used for each of the four water types in figure 8. The characteristics of these four water types are listed in table 3.

Type 1 water from wells completed in the Quaternary deposits is located mostly in the northern and southern thirds of the study area and represents the uncontaminated water quality (fig. 8). The chemical composition of Type 1 water ranges from a sodium bicarbonate to a sodium sulfate, with a few instances of magnesium sulfate, magnesium bicarbonate, or calcium bicarbonate chemical compositions. The dissolved-solids and chloride concentrations of Type 1 water range from 427 to 2,680 mg/L and 7.3 to 260 mg/L, respectively (Thamke and others, 1996, table 6; table 3 in this report). Privately owned wells completed in the Quaternary deposits with Type 1 water are used for drinking-water supply.

Type 2 water from wells completed in the Quaternary deposits is located in various parts of the study area and represents natural ground water that has been moderately contaminated by brine (fig. 8). The chemical composition of Type 2 water is sodium chloride. The dissolved-solids and chloride concentrations of Type 2 water range from 1,170 to 8,860 mg/L and 330 to 4,800 mg/L, respectively (Thamke and others, 1996, table 6; table 3 in this report). Privately owned wells completed in Quaternary deposits containing Type 2 water generally are not used for drinking-water purposes, because the large dissolved-solids and chloride concentrations make the water unpalatable.

Type 3 water from wells completed in the Quaternary deposits is located in two locations—one near the center and one near the southwest quarter of the study area. Type 3 water represents ground water that has been considerably contaminated by brine. The chemical composition of Type 3 water principally is sodium chloride with a few cases of magnesium chloride. The dissolved-solids and chloride concentrations in Type 3 are much larger than Type 2 water, ranging from 10,100 to 91,100 mg/L and 5,200 to 58,000 mg/L, respectively (Thamke and others, 1996, table 6). Privately owned wells completed in Quaternary deposits containing Type 3 water were used in the past for domestic purposes, but are now unused for any domestic purpose.

Type 4 water, which is very similar to Type 3 water, represents the actual brine that is disposed into brine-injection wells. The chemical composition of Type 4 water is sodium chloride. The dissolved-solids and chloride concentrations in brine range from 47,700 to 201,000 mg/L and 27,000 to 120,000 mg/L, respectively (Thamke and others, 1996, table 6).

Electromagnetic Apparent Conductivity

Electromagnetic geophysical methods can be used to measure the cumulative electrical conductivity of the soil and water matrix. The unit of conductivity for these methods is millimho per meter (mmho/m).

Table 3. Characteristics of water types and correlation of electromagnetic apparent conductivity used to delineate saline-water plumes in Quaternary deposits in the East Poplar oil field study area

[Abbreviations: Cl, chloride; HCO_3, bicarbonate; Mg, magnesium; Na, sodium; SO_4, sulfate; mg/L, milligrams per liter; mmho/m, millimho per meter; mi^2, square miles; N/A, not applicable; 10V, 10-meter, vertical-dipole orientation; 20H, 20-meter, horizontal-dipole orientation; 20V, 20-meter, vertical-dipole orientation; 40H, 40-meter, horizontal-dipole orientation. Symbols: ≥, greater than or equal to; <, less than]

Water type	Water use	Major ions	Dissolved-solids concentration range (mg/L)	Chloride concentration range (mg/L)	Electromagnetic apparent conductivity in Area 1 (fig. 11 and 12, pl. 2)	Electromagnetic apparent conductivity in Area 2 (fig. 13 and 14, pl. 2)	Subarea designation (fig. 16, pl. 1)	Saline-water plume type (pl. 3)	Areal extent within geophysical survey (mi^2)
Type 1--Uncontaminated	Suitable for most domestic purposes.	Na-HCO_3, Na-SO_4, Mg-SO_4, Mg-HCO_3, Ca-HCO_3	427-2,680	7.3-260	< 40 mmho/m (10V) or < 60 mmho/m (20H)	< 40 mmho/m (20V) or < 60 mmho/m (40H)	Subarea 1--low electromagnetic apparent conductivity	N/A	9.2
Type 2--Moderately contaminated ground water	Suitable for some domestic purposes; generally not used for drinking water.	Na-Cl	1,170-8,860	330-4,800	≥ 40 mmho/m (10V) and ≥ 60 mmho/m (20H); exclusive of subarea 3	≥ 40 mmho/m (20V) and ≥ 60 mmho/m (40H); exclusive of subarea 3	Subarea 2--moderate electromagnetic apparent conductivity	Type 2	7.6
Type 3--Considerably contaminated ground water	Unsuitable for any domestic purpose.	Na-Cl Mg-Cl	10,100-91,100	5,200-58,000	≥ 50 mmho/m (10V) and ≥ 70 mmho/m (20H)	≥ 50 mmho/m (20V) and ≥ 70 mmho/m (40H)	Subarea 3--high electromagnetic apparent conductivity	Type 3	5.0
Type 4--Brine (from oil production)	N/A	Na-Cl	47,700-201,000	27,000-120,000	N/A	N/A	N/A	N/A	N/A

The conductivity is affected by clay content and mineralogy, moisture saturation with depth, moisture salinity, and moisture temperature (McNeill, 1980a). Cultural features, such as metal fences, power lines, buried cables, wells, pipelines, and other conductive structures, also may affect conductivity readings. The conductivity is controlled more by porosity, water content, and water quality than by the conductivities of the rock matrix (Zohdy and others, 1974). Conductivity values are low for water with small concentrations of dissolved ions (small dissolved-solids concentrations) and conductivity can substantially increase for water with large concentrations of dissolved solids, because the ions in solution conduct the electrical current. For example, an aquifer containing saline water will have higher conductivities than if the same aquifer contained fresh water. Dissolved-solids concentrations of water sampled during 1989-93 from wells completed in Quaternary deposits in this study area range from 427 to 91,100 mg/L.

Electromagnetic geophysical methods have been used for geologic mapping, mapping the distribution of contaminants in ground water, identifying salinity levels in ground water, delineating areas of coastal saline-water intrusion, and mapping soil salinity. Many studies have successfully used electromagnetic geophysical methods to delineate areas where ground-water quality differs appreciably across the study area. For example, Grady and Haeni (1984) used electromagnetic geophysical methods to determine the extent of ground-water contamination at a municipal solid-waste landfill in Connecticut. Jansen and others (1992) also used these methods to locate areas of heavy-metal sludge disposal. In addition, saline-water migration in ground water was delineated using these methods in Kentucky by Lyverse and Unthank (1988), and in northeastern Montana by Reiten (1991). The success of these studies, in addition to the wide range of dissolved-solids concentrations sampled from wells completed in the Quaternary deposits in the East Poplar oil field study area, indicated that electromagnetic geophysical techniques would be useful in delineating large areas of saline-water contamination during this investigation.

The electromagnetic geophysical equipment used in this investigation consisted of electronic consoles, a transmitter coil, and a receiver coil all connected by a reference cable (fig. 9). The transmitter coil is energized with an alternating current at an audio frequency and placed on the land surface with the receiver coil located a short distance (10, 20, or 40 m) away. The alternating current passes through the transmitter coil, in the orientation of the dipole (which is perpendicular to the plane of the coil), and generates a primary magnetic field that penetrates the earth. This primary magnetic field induces a small current in the earth, which generates a secondary magnetic field out of phase with the first. The secondary magnetic field is a function of the intercoil spacing, the dipole orientation, the operating frequency, and the ground conductivity (McNeill, 1980b). The receiver coil senses both the primary and secondary magnetic fields and the measurement indicated by the instrument is the electromagnetic apparent conductivity. The intercoil spacing can be 10, 20, or 40 m. The two coils can be oriented with horizontal dipoles (coils up on edge and coplanar) or with vertical dipoles (coils flat on ground and coplanar). Figure 9 illustrates the instrument in the horizontal-dipole orientation.

The approximate effective depth of exploration for the horizontal-dipole orientation typically is 75 percent of the intercoil spacing distance. The approximate effective depth of exploration for the vertical-dipole orientation is 150 percent of the intercoil spacing distance (McNeill, 1980b, p. 6). The approximate effective depths of exploration at the three intercoil spacings for both dipole orientations are listed in table 4. The horizontal-dipole orientation is relatively sensitive to variations in the near-surface material (such as fences, power lines, buried metal), whereas the vertical-dipole orientation is relatively sensitive to vertical conductors (such as well casing).

Before conducting the electromagnetic geophysical survey, water from existing wells was sampled to determine salinity concentration of ground water in specific parts of the aquifer. General areas of saline water were delineated on the basis of the well data; this general delineation served as a guide for areas in which to conduct the electromagnetic geophysical survey. Electromagnetic apparent conductivity was measured in both known uncontaminated and known contaminated areas to ensure that the instruments could distinguish saline plumes. The development of the electromagnetic geophysical survey method and calibration techniques for the equipment were explained in Thamke and others (1996).

Measurement stations were spaced at intervals of either 0.1 or 0.2 mi. It was important to ensure that the

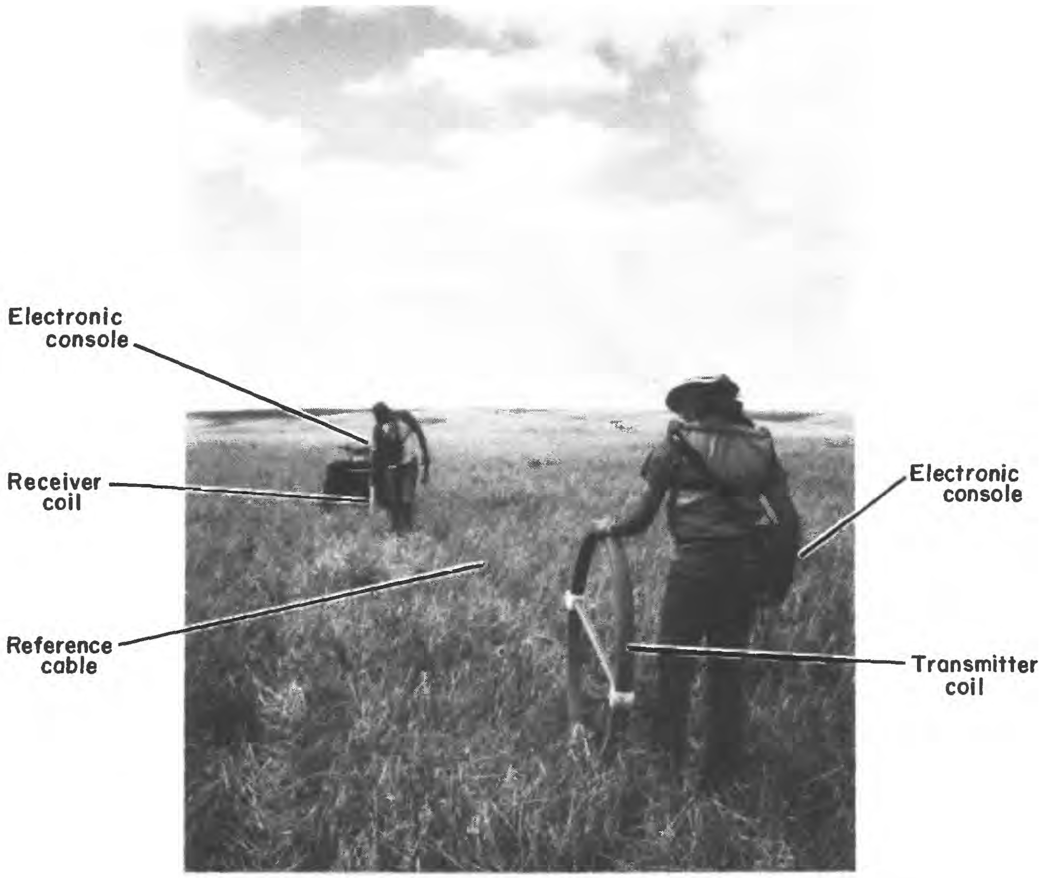


Figure 9. Electromagnetic geophysical equipment in the horizontal-dipole orientation.

Table 4. Approximate effective depths of exploration at three intercoil spacings and dipole orientations for variable-depth ground-conductivity electromagnetic geophysical methods

[Data from McNeill, 1980b]

Intercoil spacing		Exploration depth			
		Horizontal dipoles		Vertical dipoles	
Meters	Feet	Meters	Feet	Meters	Feet
10	33	7.5	25	15	49
20	66	15	49	30	98
40	131	30	98	60	197

soil matrix was relatively uniform between stations to avoid anomalous, localized effects. Before conducting the electromagnetic geophysical survey, local uniformity of the aquifer material was tested in several parts of the study area. To test for local uniformity, the center of the measurement station was identified, and electromagnetic apparent conductivity readings were taken at several intervals around the measurement station in a clockwise direction. Electromagnetic apparent conductivity values varied insignificantly between intervals. This test verified that differences in the electromagnetic apparent conductivity at various locations throughout the study area would most likely be due to differences in ground-water chemistry and that the aquifer material is sufficiently homogeneous that local variations have little effect on electromagnetic apparent conductivity readings. Because contrasts in the chemistry of the ground water were large, the overall effect of geologic variations in the strata on the electromagnetic instrument readings was considered to be minimal.

Electromagnetic apparent conductivity data were recorded on field maps that contained pertinent information including topography and location of cultural features such as oil wells and pipelines. Anomalously high single conductivity values at or near oil wells and pipelines were not considered in the interpretations.

Electromagnetic apparent conductivity was measured in two areas (figs. 10-15, pl. 2). Area 1 is about 9.5 mi^2 and is underlain primarily by alluvium along the Poplar River and partly by a few glacial deposits along the area boundaries. Area 2 is about 12.1 mi^2 and is underlain primarily by glacial deposits and partly by alluvium along the Poplar River.

Electromagnetic geophysical measurements during summer 1991 were made with 10-m and 20-m intercoil spacings in Area 1 and 20-m and 40-m intercoil spacings in Area 2. During initial interpretation, data collected from all three spacings appeared to be relevant. Therefore, measurements during summer 1992 were made with 10-m, 20-m, and 40-m intercoil spacings at both areas. The electromagnetic apparent conductivity values during 1991-92 ranged from 10 mmho/m to 160 mmho/m. The contoured electromagnetic apparent conductivity values for each of the three intercoil spacings at both dipole orientations are shown in figures 10-15.

Interpretation of the electromagnetic geophysical data required determination and selection of the most relevant sets of measurements. Electromagnetic apparent conductivity values that measured conductivity over an effective depth of exploration that extended to the depth of the bottom of the saturated zone were assumed to be the most representative values for the entire thickness of the saturated zone. In addition, the electromagnetic apparent conductivity values associated with these depths correlated well with dissolved-solids and chloride concentrations in ground water. Consequently, effective depths of exploration of 15 m and 30 m were selected to represent the electromagnetic apparent conductivity of the entire saturated alluvium (Area 1) and glacial deposits (Area 2), respectively. Data from other effective depths of exploration other than 15 m were not used for interpretation in Area 1 because an effective depth of exploration of 7.5 m does not penetrate the entire depth of the saturated zone and effective depths of exploration of 30 m and 60 m are substantially deeper than the base of the saturated zone. Similarly, exploration depths other than 30 m were not used for interpretations in Area 2 because effective depths of exploration of 7.5 m and 15 m do not penetrate the entire depth of the saturated zone and an effective depth of exploration of 60 m is substantially deeper than the base of the saturated zone.

Three subareas (fig. 16, pl. 1)) of electromagnetic apparent conductivity were delineated using information from figures 11 and 12 (for Area 1) and figures 13 and 14 (for Area 2). Water wells sampled during 1989-93 and corresponding water type are also included in figure 16. Subarea 1 represents an area of low electromagnetic apparent conductivity; water from wells completed in this subarea generally was Type 1 (uncontaminated). Subarea 2 represents an area of moderate electromagnetic apparent conductivity; water from wells completed in this subarea generally was Type 2 (moderately contaminated). Subarea 3 represents an area of high electromagnetic apparent conductivity; water from wells completed in this subarea generally was Type 3 (considerably contaminated).

The relations between electromagnetic geophysical measurements of apparent conductivity and water quality are consistent almost everywhere; however, three anomalies exist in the relation derived for Area 1 and two anomalies exist in the relation derived for Area 2 (fig. 16). These anomalies exist most likely because of factors other than water quality that may affect electromagnetic apparent conductivity values, because delineation of saline-water contamination may be less accurate at the edges of the electromagnetic geophysical survey grid, or because delineation of water type is based on ranges of dissolved-solids and chloride concentrations which overlap.

In Area 1, in secs. 15, 16, and 21, T. 29 N., R. 51 E., water from wells M-52, M-54, and FPB92-14, which are located in subareas 2 and 3 (indicating moderate and high electromagnetic apparent conductivity), was Type 1 with chloride concentrations less than 16 mg/L. The lithologic descriptions of cuttings from these wells indicate that the Bearpaw Shale is about 25 ft shallower in this area than in other areas. The electromagnetic apparent conductivity patterns shown on figure 16 for these sections likely represent the influence from this shallow conductive Bearpaw Shale. The second anomaly in Area 1 is in sec. 17 and exists for well W-4. The electromagnetic geophysical measurements indicate that the well is in a low electromagnetic apparent conductivity subarea (subarea 1); however, water from well W-4 was Type 2 with a chloride concentration of 3,000 mg/L in 1989. This well is near an area of moderate electromagnetic apparent conductivity (subarea 2) and the edge of the geophysical-survey grid, where delineation of saline-water contamination subareas evidently is less accurate. The third anomaly in the relation between electromagnetic conductivity and chloride concentration in Area 1 is in sec. 32 and exists for wells FPB92-4 and FPB92-5. The electromagnetic geophysical measurements indicate that these wells are in or near a moderate electromagnetic apparent conductivity subarea (subarea 2); however, water from both of these wells was Type 3 with chloride concentrations of 8,500 and 5,800 mg/L, respectively. The thick, unsaturated deposits (about 22 and 23 ft, respectively) may disproportionately lower the electromagnetic apparent conductivity relative to the Type 3 water in the relatively thin, saturated alluvium (about 4 and 2 ft, respectively).

In Area 2, monitoring well FPB92-12 located in sec. 22 is completed in an area of moderate electromagnetic apparent conductivity (subarea 2); however, water from this well was Type 1 with a chloride concentration of 15 mg/L. The lithologic description of cuttings from this well indicates 57 ft of relatively impermeable clay, which may cause moderate electromagnetic apparent conductivity values, or may cause contaminated water to flow preferentially around this clay. In the second anomaly, located in sec. 33, water from wells M-36 and M-38 completed just south of an area of moderate electromagnetic apparent conductivity (subarea 2) was Type 1 with chloride concentrations of 40 and 34 mg/L, respectively. The lithologic descriptions of cuttings from these wells indicate more than 70 ft of clay, which may cause moderate electromagnetic apparent conductivity values.

GENERAL HYDROLOGY OF THE POPLAR RIVER

The Poplar River, a tributary to the Missouri River, is perennial in the study area. Flow is partly regulated by a dam, constructed during the 1970's on the East Fork Poplar River, 2 mi north of the international boundary. Within the study area, tributaries that enter the Poplar River are intermittent or ephemeral.

Mean monthly discharge at site PR-8 (streamflow-gaging station 06181000) (pl. 3), computed from 17 years of streamflow data collected during 1975-79 and 1982-93, ranged from 6.1 ft^3/s in January to 399 ft^3/s in April (U.S. Geological Survey, published annually). About 64 percent of the annual streamflow occurred from March to April. Mean annual discharge during the period of record was 96 ft^3/s.

Water samples were collected periodically at site PR-1 (pl. 3) during 1979-93 and at site PR-8 during 1975-81 and 1986-94 (Thamke and others, 1996, table 12). Analysis of the major ions in the stream water indicates that the water is a sodium bicarbonate type (similar to Type 1 ground water) with a dissolved-solids concentration range of 553-1,030 mg/L at site PR-1 and 167-1,490 mg/L at site PR-8 during most streamflow conditions. At low flow conditions of less than about 15 ft^3/s, water at site PR-8 can become a sodium chloride type (similar to Type 2 ground water) with a dissolved-solids concentration range of 1,320-2,190 mg/L.

SALINE-WATER CONTAMINATION

The water-quality data collected from existing wells and surface-water sites confirm the presence of saline-water contamination in the Quaternary deposits and the Poplar River; however, the distribution of the wells alone was insufficient to determine lateral extent of contamination. To determine the lateral extent of the saline-water contamination, data from the electromagnetic geophysical survey were interpreted in conjunction with the water-quality information for existing wells and wells that were drilled subsequent to the electromagnetic geophysical survey. The vertical extent of saline-water contamination was interpreted from the water-quality information at sites that contained both shallow and deep wells. The magnitude of saline-water contamination was interpreted from the ground-water-quality data and hydraulic characteristics information. The movement of saline-water contamination was interpreted from ground-water hydraulic gradients, as well as historical ground-water-quality information. Streamflow and water-quality data for the Poplar River were interpreted in conjunction with ground-water-quality data to determine the effects of saline-water discharge on the Poplar River. The specific source areas of saline-water contamination were determined from the electromagnetic geophysical data and the locations of probable sources of contamination shown on plate 3.

Quaternary Deposits

The Quaternary deposits contain salinity levels representative of uncontaminated, moderately contaminated, and considerably contaminated water. Levings (1984) determined that saline contamination of the alluvial aquifer was from brine associated with oil production. Information collected during this investigation indicates that the lateral extent of saline contamination in the alluvial and glacial deposits is substantial, and that at least one specific source may still be contributing brine to the Quaternary deposits.

Lateral Extent

The lateral extent of saline-water contamination in the Quaternary deposits may be as much as about 12.4 mi^2 (pl. 3). This extent is within the boundary of the electromagnetic geophysical survey and is estimated on the basis of water-quality data and the electromagnetic apparent conductivity delineation of subareas 2 and 3 in figure 16. Small parts of subarea 1 that contain one or more water wells that produce Type 2 water are considered parts of confirmed saline-water plumes; subareas 2 and 3 that contain one or more water wells that produce Type 2 or Type 3 water are considered confirmed saline-water plumes; subareas 2 and 3 that do not contain water wells are considered possible saline-water plumes; and parts of or the entirety of subareas 2 and 3 that contain one or more water wells that produce Type 1 water are not considered saline-water plumes. The saline-water plumes are defined as Type 2 or Type 3, depending on the type of water derived from wells completed in these areas. The extent and number of plumes are discussed in relation to available water-quality information from sampled water wells.

The collective lateral extent of confirmed Type 2 saline-water contamination in the Quaternary deposits is 5.3 mi^2 (pl. 3). Four Type 2 saline-water plumes were confirmed. The northernmost confirmed Type 2 saline-water plume has an area of less than 0.1 mi^2 and is located in the southwestern part of sec. 16, T. 29 N., R. 51 E. Water from a 17-ft-deep privately owned well (W-9) completed in the shallow part of the alluvium on the edge of this plume in section 21 was Type 2 water with a chloride concentration of 1,100 mg/L; this well is unused. The second confirmed Type 2 saline-water plume has an area of 0.2 mi^2 and is located in the eastern part of sec. 20, T. 29 N., R. 51 E.; one water well is located near this plume, and one water well is located in this plume. Water from a 44-ft-deep privately owned well (W-6) completed in alluvium near this plume was Type 2 water with a chloride concentration of 2,300 mg/L in 1982; the well is now unused and is inaccessible for water-quality sampling. Water from a 56-ft-deep monitoring well (FPB92-13) completed in alluvium in this plume was Type 2 water with a chloride concentration of 4,600 mg/L. The third confirmed Type 2 saline-water plume has an area of 0.8 mi^2 and is located in secs. 19, 20, 29, 30, and 31, T. 29 N., R. 51 E. Water from a 45-ft-deep monitoring well (W-10) completed in alluvium in the northern part of this plume was Type 2 water with a chloride concentration of 3,400 mg/L in 1982; the well is now plugged and destroyed. Three monitoring wells (W-11, FPB92-6, and FPB92-10) completed at various depths in the alluvium in the southern part of this plume contained Type 2 water with chloride concentrations equal to 4,800 mg/L, 4,600 mg/L, and 2,100 mg/L, respectively. The southernmost, and largest, confirmed Type 2 saline-water plume has an area of 4.3 mi^2 and is located in the southern part of sec. 3, and parts of secs. 9, 10, 15, 16, 17, 20, 21, 22, 27, and 28, T. 28 N., R. 51 E. Water from privately owned and monitoring wells (M-14, M-15, M-18, M-20, M-22, M-24, M-25, and M-27) completed at various depths in this plume was Type 2 and contained chloride concentrations of 430-3,700 mg/L during 1989-91.

The collective lateral extent of possible Type 2 saline-water contamination in Quaternary deposits is 1.9 mi^2 (pl. 3). These areas are delineated by moderate electromagnetic apparent conductivity readings in areas that have no water wells for confirmation by analysis of water samples. Sixteen Type 2 saline-water plumes are possible, as shown on the following page.

Location	Plume area (square miles)
NE 1/4 sec. 8, T. 29 N., R. 51 E.	0.1
SW 1/4 sec. 8, NW 1/4 sec. 17, T. 29 N., R. 51 E.	0.1
North-central sec. 17, T. 29 N., R. 51 E.	less than 0.1
NE 1/4 sec. 19, T. 29 N., R. 51 E.	less than 0.1
SE 1/4 sec. 19, T. 29 N., R. 51 E.	less than 0.1
2 plumes--N 1/2 sec. 20, T. 29 N., R. 51 E.	less than 0.1
S 1/2 sec. 29, sec. 32, T. 29 N., R. 51 E.	0.3
West-central sec. 30, T. 29 N., R. 51 E.	less than 0.1
SW 1/4 sec. 31, T. 29 N., R. 51 E.	less than 0.1
W 1/2 sec. 34, T. 29 N., R. 51 E.	0.2
Central sec. 34, T. 29 N., R. 51 E.	less than 0.1
N 1/2 sec. 3, T. 28 N., R. 51 E.	0.1
E 1/2 sec. 3, T. 28 N., R. 51 E.	less than 0.1
NE 1/4 sec. 11, T. 28 N., R. 51 E.	less than 0.1
Sec. 11, E 1/2 sec. 15, T. 28 N., R. 51 E.	0.7

The collective lateral extent of confirmed Type 3 saline-water contamination in the Quaternary deposits may be as much as 2.0 mi^2 (pl. 3). Three Type 3 saline-water plumes were confirmed. The northern-most Type 3 saline-water plume has an area of 0.9 mi^2 and is located in secs. 31 and 32 and the southern edge of secs. 29 and 30, T. 29 N., R. 51 E. The Poplar River flows through the center of this plume. Ten monitoring wells completed at various depths in the alluvium in this plume contain Type 3 water with chloride concentrations of 7,700 mg/L or larger (wells W-15, FPB92-1, FPB92-2A, FPB92-3, FPB92-4, FPB92-5, FPB92-7, FPB92-8, FPB92-9, and FPB92-11). The second confirmed Type 3 saline-water plume has an area of 0.2 mi^2 and is located in the western and northern parts of sec. 9, T. 28 N., R. 51 E. Water from a 104-ft-deep monitoring well (FPB93-5 in this plume) is Type 3 with a chloride concentration of 6,300 mg/L. The southernmost confirmed Type 3 saline-water plume has an area of 0.9 mi^2 and is located in the central and southern parts of sec. 21, the southwestern part of sec. 22, the northwestern part of sec. 27, and the northern part of sec. 28, T. 28 N., R. 51 E. Water from two monitoring wells (FPB93-3 and FPB93-3A in this plume) completed in the top and the bottom of the saturated glacial deposits is Type 3 with chloride concentrations equal to or greater than 35,000 mg/L; water from two domestic wells (M-28 and M-31) completed in this plume is Type 3 with chloride concentrations equal to 7,900 mg/L and equal to or greater than 22,000 mg/L, respectively.

The collective lateral extent of possible Type 3 saline-water contamination in Quaternary deposits is 3.2 mi^2 (pl. 3). These areas are delineated by high electromagnetic apparent conductivity readings in areas that have no water wells for confirmation by analysis of water samples. Thirteen Type 3 saline-water plumes in Quaternary deposits are possible, as shown below.

Location	Plume area (square miles)
NW 1/4 sec. 17, SW 1/4 sec. 8, T. 29 N., R. 51 E.	less than 0.1
E 1/2 sec. 20, T. 29 N., R. 51 E.	less than 0.1
NE 1/4 sec. 30, NW 1/4 sec. 29, T. 29 N., R. 51 E.	0.2
Center sec. 3, T. 28 N., R. 51 E.	0.4
SW 1/4 sec. 3, sec. 10, sec. 11, sec. 15, sec., 16, T. 28 N., R. 51 E.	2.2
6 plumes--SE 1/4 sec. 11; NE 1/4 sec. 20; north-central and northeast sec. 21; and 2 plumes in north-central sec. 22, T. 28 N., R. 51 E.	0.2
W 1/2 sec. 27, T. 28 N., R. 51 E.	0.2
Center sec. 28, T. 28 N., R. 51 E.	less than 0.1

Vertical Extent

The vertical extent of saline-water contamination in the Quaternary deposits can be estimated using the water-quality information from the monitoring and privately owned wells completed in the plumes. Most monitoring wells drilled during this investigation were completed at the base of the Quaternary deposits, above the Bearpaw Shale, with a perforated interval at the base of the Quaternary deposits (Thamke and others, 1996, table 3). Three monitoring wells were completed within the top of the saturated Quaternary deposits; each near a well that was completed at the base of the Quaternary deposits. Privately owned wells, however, have been completed at various depths throughout the Quaternary deposits (Thamke and others, 1996, table 1). The depths of wells that confirm saline-water contamination plumes were included in the previous discussion to indicate the general depth of saline-water contamination in the different plumes.

Possible surface or subsurface sources of contamination, time of the source input (recent or old), and distance from the source may be indicated by characteristics of vertical stratification of chloride concentration and density. Saline water is more dense than fresh water and tends to migrate downward over time and distance from its source. Therefore, a recent surface source may be indicated by dense, saline water near the surface of the saturated deposits. A subsurface source may be indicated by dense, saline water near the source point(s), either at the bottom of the aquifer or in locations throughout the aquifer. Subsurface sources of saline water may result in deeper saline water being overlain by fresh water. Likewise, a long-term surface or shallow subsurface source that is still contributing saline water to the aquifer may be indicated by the presence of dense, saline water throughout the aquifer. A recent, nearby source (at any depth) may be indicated by vertical stratification of chloride and density, whereas an older, distant source may be indicated by either a lack of stratification due to dilution and dispersion or a vertical stratification where chloride concentration and water density increase with depth due to downward migration of dense, saline water.

The vertical extent of saline-water contamination was examined using water-quality information from three sets of wells (each set containing a deep and a shallow well) completed in Quaternary deposits (wells FPB92-2A and FPB92-2B at site 29N51E32BABB, FPB92-1 and FPB93-2 at site 29N51E32BBBA, and FPB93-3 and FPB93-3A in 28N51E22CBCB, Thamke and others, 1996, tables 1 and 3). The vertical extent of a confirmed Type 3 contamination plume in T. 29 N., R. 51 E., is delineated by two sets of wells located along the northern part of the plume. In the first set of wells, the deeper well FPB92-2A is 46 ft deep and is perforated at 31-41 ft below land surface, at the base of the alluvium; the shallower well, FPB92-2B was 27 ft deep and was perforated at 12-22 ft below land surface, within the top of the saturated alluvium (this well is now destroyed; Thamke and others, 1996, table 3). Water sampled from well FPB92-2A in July 1993 was Type 3 and had a dissolved-solids concentration of 46,100 mg/L, a chloride concentration of 35,000 mg/L, a density of 1.051 g/mL, and a specific conductance of 102,000 μS/cm. Water sampled from well FPB92-2B during initial well development in September 1992 had a specific conductance of 17,600 μS/cm. In the second set of wells, the deeper well FPB92-1 is 53 ft deep and is perforated at 38-48 ft below land surface, within the base of the alluvium; the shallower well, FPB93-2 is 27 ft deep and is perforated at 18-27 ft below land surface, within the top of the saturated alluvium. Water sampled from well FPB92-1 in July 1993 was Type 3 and had a dissolved-solids concentration of 91,100 mg/L, a chloride concentration of 58,000 mg/L, a density of 1.060 g/mL, and a specific conductance of 127,000 μS/cm. Water sampled from well FPB93-2 in July 1993 was Type 2 and had a dissolved-solids concentration of 6,450 mg/L, a chloride concentration of 3,200 mg/L, a density of 1.004 g/mL, and a specific conductance of 12,300 μS/cm. The water-quality information from these two sets of wells indicates that saline-water contamination is present throughout the entire vertical extent of the saturated zone, and that the chloride concentration and density of water in this saline-water contamination plume increase with depth in the alluvium. The vertical stratification of chloride concentration and density differences in the aquifer may have developed over time as the dense, saline water settled deeper in the aquifer, indicating an older source of saline contamination or the differences may indicate a subsurface source of contamination.

In the third set of wells, the deeper well FPB93-3 is 81 ft deep and is perforated at 52-57 ft below land surface, at the base of the glacial deposits; the shallower well, FPB93-3A is 49 ft deep and is perforated at 41-46 ft below land surface, at the top of the saturated glacial deposits. Water sampled from well FPB93-3 was Type 3 and had a dissolved-solids concentration of 58,700 mg/L, a chloride concentration of 35,000 mg/L, a density of 1.046 g/mL, and a specific conductance of 98,600 µS/cm. Water sampled from well FPB93-3A was also Type 3 and had a dissolved-solids concentration of 63,500 mg/L, a chloride concentration of 38,000 mg/L, a density of 1.045 g/mL, and a specific conductance of 97,200 µS/cm. The water-quality information from these two wells indicates that saline-water contamination is present throughout the entire depth of the saturated zone, and that the chloride concentrations decreased very slightly with depth. The density of water in this saline-water contamination plume varied insignificantly with depth in the glacial deposits. The presence of dense, saline water of similar characteristics throughout the aquifer may indicate that the source of saline contamination may still be contributing saline water to the aquifer or that the source inputs are recent enough that an insufficient period of time has elapsed to develop vertical chloride and density gradients.

Magnitude

The magnitude of the amount of water in the Quaternary deposits of the study area that is possibly affected by saline-water contamination ranges from about 9 to 60 billion gal (27,600-184,000 acre-ft). This volume is based on estimates of the saturated thickness of the Quaternary deposits for the lateral extent of confirmed and possible Type 2 and Type 3 saline-water contamination plumes and the porosity of the Quaternary deposits. The saturated thickness of the Quaternary deposits ranges from 17 to 46 ft; the lateral extent of the confirmed and possible Type 2 and Type 3 saline-water contamination plumes is 12.6 mi^2; and the porosity of gravels, sands, and clays (typically found in Quaternary deposits) has a range of 20-50 percent (Heath, 1983, p. 7).

Movement

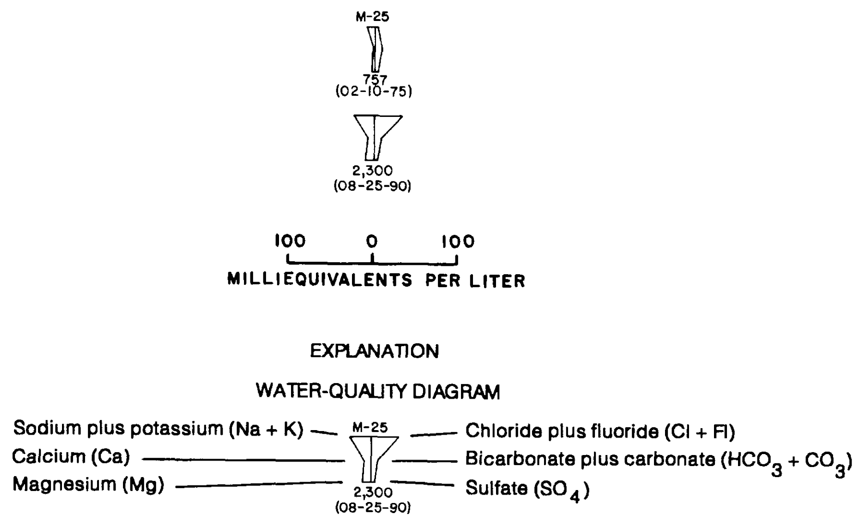
Contaminated water in Quaternary deposits east of the Poplar River generally moves westward toward the river then southward in the Poplar River valley. The variation in water density from saline-water contamination in the Quaternary deposits may result in a significant downward vertical component of flow for the more dense contaminated water. Factors that may affect the vertical density gradients of contaminated ground water include the source of saline-water contamination (surface or subsurface) and the timing of saline-water contamination (a distinct vertical density gradient may have developed from an older saline-water contamination event, whereas little to no vertical density gradient may have developed from a recent or current saline-water contamination event). In isolated areas, dense, saline water may settle in small depressions on the surface of the Bearpaw Shale.

The effect of saline-water movement on water quality in Quaternary deposits is illustrated by water-quality diagrams shown in figures 17-19 for selected wells. The water-quality diagrams represent the chemical composition of selected water samples collected from wells completed in Quaternary deposits for confirmed Type 2 and Type 3 saline-water contamination plumes (Thamke and others, 1996, table 6; Levings, 1984, table 2).

The effect of saline-water movement into areas that have little or no contamination in Quaternary deposits is to increase dissolved-solids and chloride concentrations; the effect of saline-water movement away from contamination areas in Quaternary deposits is to decrease dissolved-solids and chloride concentrations. In some cases, the effects are more dramatic than others, depending on the chemical characteristics of the source, quantity of contaminated water, proximity to source, and ground-water flow characteristics in the area. The following three examples show the effects of saline-water movement into and out of areas over different periods of time.

In the first example, uncontaminated water became moderately contaminated within a 15-year period because of the movement of a moderately contaminated (Type 2) saline-water plume; this example is illustrated in the water-quality diagrams for well M-25 (fig. 17). Well M-25 is a privately owned well completed in Quaternary deposits of a confirmed Type 2 plume located in parts of secs. 3, 9, 10, 15, 16, 17, 20, 21, 22, 27, and 28, T. 28 N., R. 51 E. (pl. 3). Water collected from well M-25, which was uncontaminated in 1975, became moderately contaminated by 1990 as Type 2 saline water had moved into the area of the well.

In the second example, uncontaminated water became considerably contaminated within a 4-6 year period because of the movement of a considerably contaminated (Type 3) saline-water plume; this example is illustrated in the water-quality diagrams for wells M-28 and M-31 (fig. 18). Wells M-28 and M-31 are privately owned and completed in Quaternary deposits of a con-



Number below diagram is computed dissolved-solids concentration, in milligrams per liter. Date below diagram is date of sample collection. Number above diagram is well name

Figure 17. Chemical composition and dissolved-solids concentration of water sampled from well M-25 in the East Poplar oil field study area, northeastern Montana.

firmed Type 3 plume located in the central and southern parts of sec. 21, the southwestern part of sec. 22, the northwestern part of sec. 27, and the northern part of sec. 28, T. 28 N., R. 51 E. (pl. 3). Water collected from both wells during 1985 was uncontaminated. Water collected from well M-28 in 1989 was moderately contaminated. Water collected from well M-28 in 1991 and well M-31 in 1989 had become considerably contaminated. By 1993, water collected from well M-31 was similar to the brine produced from the oil field (Type 4). The increasing trend in dissolved-solids concentration in water from M-28 and M-31 may indicate that the source of the contamination was active during 1985-93. Because no further construction has occurred in this area (Debi Madison, Fort Peck Tribes, Office of Environmental Protection, oral commun., 1997), the source of the contamination may still be active.

In the third example, considerably contaminated ground water became less contaminated within a 7-11-year period because of the movement and dilution of a considerably contaminated (Type 3) saline-water plume; this example is illustrated in the water-quality diagrams for wells W-11, W-15, and W-16 (fig. 19). These wells are completed in Quaternary deposits of confirmed Type 2 and Type 3 plumes located in parts of secs. 19, 20, 29, 30, 32, and most of sec. 31, T. 29 N., R. 51 E. (pl. 3). Water collected from all three wells was considerably contaminated in 1982. In 1989, water collected from well W-11 had become moderately contaminated and water collected from well W-15 was still considerably contaminated; however, dissolved-solids and chloride concentrations had decreased substantially. Well W-16 was plugged and destroyed; then well FPB92-11 was drilled at the same site and perforated at the same interval as W-16. In 1993, based on water from well FPB92-11, water at the site was still considerably contaminated, but dissolved-solids and chloride concentrations had decreased substantially. Wells W-11 and W-15 are located on the upgradient edges of the plumes, and well FPB92-11 is located on the edge of the plume. In each of these wells, the decreasing dissolved-solids and chloride concentrations probably were due to dilution by fresh water as the plume moved towards the Poplar River and upgradient saline water source inputs were decreased or terminated. The quality of water in these wells had not returned to uncontaminated concentrations at the date of their most recent sampling. The density of water collected from wells in this plume increases with depth in the alluvium; therefore, movement of saline-water contamination may follow the top of the Bearpaw Shale and in isolated areas, may settle in small depressions. In this plume, the elevation of the top of the Bearpaw Shale is about 30 ft lower on the southeast side of the Poplar River compared to the northwest side. The plume also extends past the Poplar

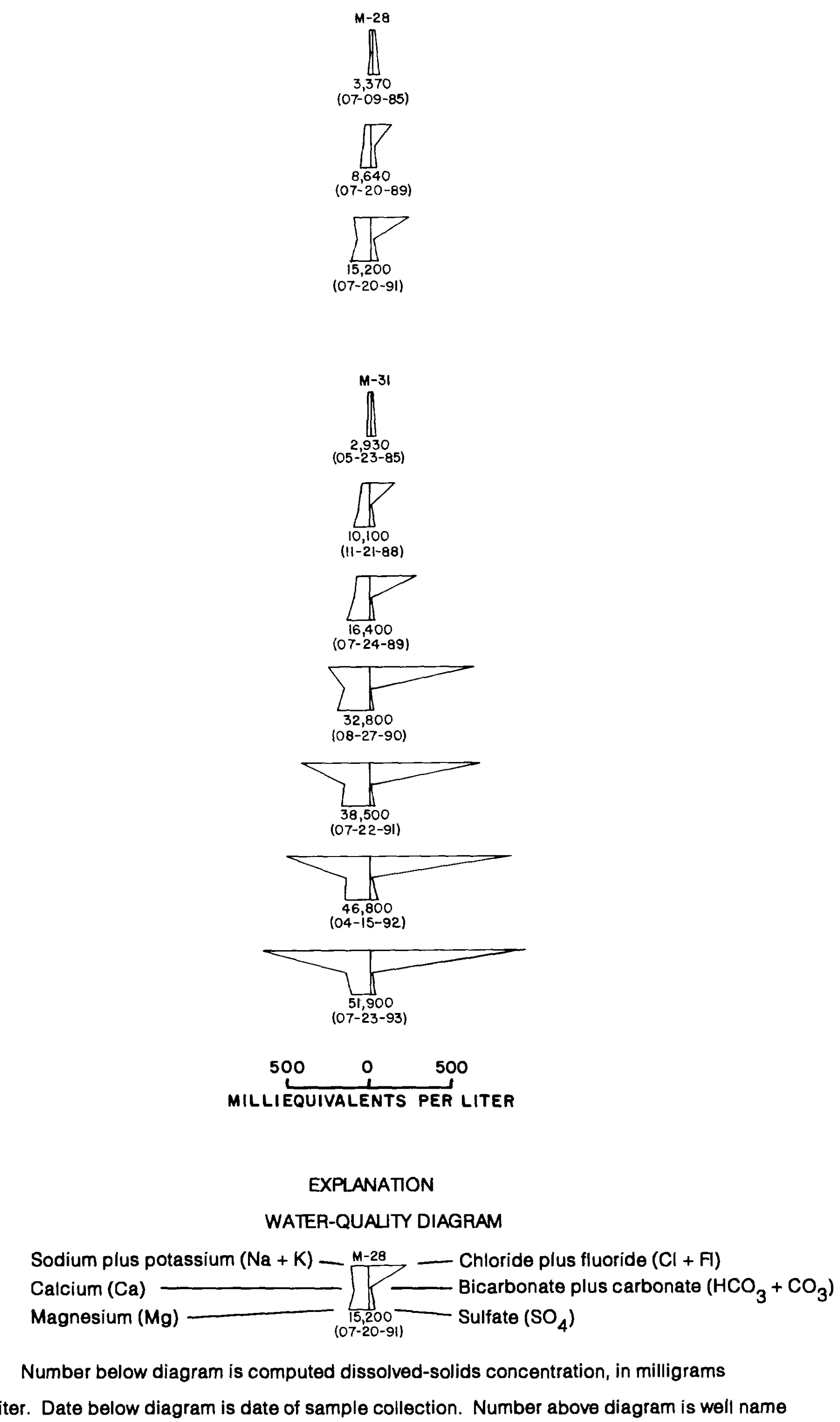


Figure 18. Chemical composition and dissolved-solids concentration of water sampled from wells M-28 and M-31 in the East Poplar oil field study area, northeastern Montana.

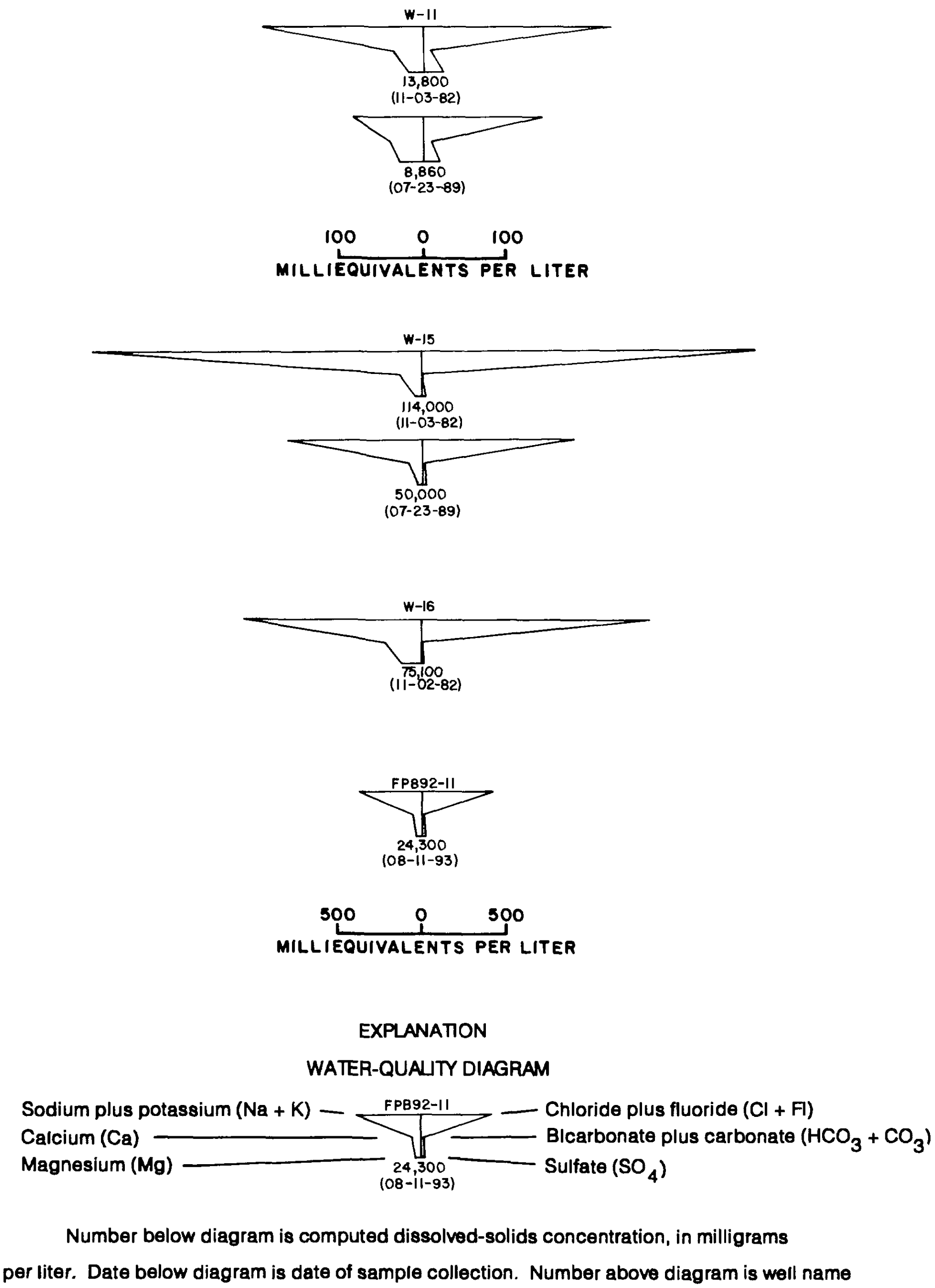


Figure 19. Chemical composition and dissolved-solids concentration of water sampled from wells W-11, W-15, W-16, and FPB92-11 in the East Poplar oil field study area, northeastern Montana.

River, indicating that some saline-water contamination may have moved beneath the river to the other side of the alluvial valley.

Poplar River

The Poplar River is and will continue to be the recipient of some if not most of the saline-water contamination in the Quaternary deposits of the study area because of ground-water discharge to the river. Levings (1984) determined that a downstream increase in chloride concentration and downstream change in water type from sodium bicarbonate to sodium chloride were indications of saline ground-water discharge to the Poplar River. Information collected during the current investigation indicates that saline ground water is still discharging to the Poplar River; and there is a possibility that saline ground-water discharge to the Poplar River will occur in another downgradient area in the future.

Four sets of streamflow measurements and five sets of water-quality measurements were conducted along a 9-mi reach of the Poplar River valley to determine gains and losses in streamflow and changes in water quality (Thamke and others, 1996, pl. 1 and table 11). In general, the precision of streamflow measurements indicates that apparent gains or losses of about 5 percent or less might be the result of measurement error rather than actual gains or losses in streamflow. Chloride loads, in tons per day, were also computed for sites with measured streamflow and chloride concentrations to describe downstream variation along the Poplar River, according to the following equation:

$$L = Q \cdot C \cdot K \quad (1)$$

where:

L = chloride load, in tons per day;
Q = streamflow, in cubic feet per second;
C = chloride concentration, in milligrams per liter; and
K = units conversion constant (0.0027).

In the first set of measurements, conducted during September 1981 as part of the investigation by Levings (1984), streamflow decreased from 1.7 to 0.7 ft^3/s and both the chloride concentration and load increased from 20 to 880 mg/L and 0.1 to 1.7 tons/day, respectively, between sites PR-1 and PR-5. In the second set of measurements, conducted during October 1990, the chloride concentration increased from 12 to 240 mg/L between sites PR-0 and PR-9. In the third set of measurements, conducted during April 1991, streamflow remained essentially constant among the sampling sites at 82-85 ft^3/s and both the chloride concentration and load increased from 11 to 29 mg/L and 2.4 to 6.7 tons/day, respectively, between sites PR-0 and PR-9. In the fourth set of measurements, conducted during July 1991, streamflow remained essentially constant at 44-47 ft^3/s and both the chloride concentration and load increased from 10 to 61 mg/L and 1.3 to 7.2 tons/day, respectively, between sites PR-0 and PR-8. In the fifth set of measurements, conducted during September 1991, streamflow varied slightly from 7.9 to 11 ft^3/s from site PR-1 to PR-8; while both the chloride concentration and load increased from 17 to 160 mg/L and 0.4 to 4.8 tons/day, respectively. On the basis of these five sets of measurements, chloride concentrations and loads consistently increased downstream regardless of gains or losses in streamflow.

The Poplar River flows through several areas underlain by two saline-water contamination plumes (pl. 3) that could be sources of saline ground-water discharge and that appear to affect the water quality of the river. Figure 20 illustrates streamflow and chloride loads along measured reaches of the Poplar River. The reach where the water quality of the Poplar River appears to be most affected is between sites PR-2 and PR-6 (Thamke and others, 1996, pl. 1 and table 11); a smaller part of this reach (PR-2 to PR-5) was first identified by Levings (1984). In 1981, chloride loads increased significantly between sites PR-1 and PR-3, indicating inputs of 2.2 tons/day from ground water in this reach. In 1991, chloride loads increased between PR-2 and PR-6; most significant increases were between PR-4 and PR-6. The reach between PR-2 and PR-5 of the Poplar River flows through a confirmed Type 2 (moderately contaminated) saline-water plume and a confirmed Type 3 (considerably contaminated) saline-water plume. Saline-water-plume delineation between PR-5 and PR-6 is unknown, due to the lack of electromagnetic geophysical measurements in this area; however, increased chloride loads during 1991 indicate possible saline ground-water discharge between these two sites. On the basis of streamflow and water-quality measurements collected from 1981 through 1991, the large downstream increase in chloride load indicates that saline ground water discharges to the Poplar River, presumably from the confirmed saline-water plumes.

Farther downstream, between PR-6 and PR-9, the Poplar River flows through or near a confirmed saline-water plume of moderate contamination (pl. 3) that may affect the water quality of the river in the future. Streamflow and water-quality measurements made during 1991 indicated that streamflow remained fairly constant, while chloride loads remained fairly constant or increased slightly (fig. 20). Chloride concentrations from a well completed in the downgradient part of this plume increased during 1975-90 (discussed in the 'Movement' section of 'Saline-Water Contamination'). A lack of appreciable downstream increases in chloride load between sites PR-6 and PR-9 indicates that, currently (1996), the confirmed Type 2 (moderately contaminated) saline-water plume may not be measurably affecting concentrations in the Poplar River; however, movement of saline-water contamination evidenced by

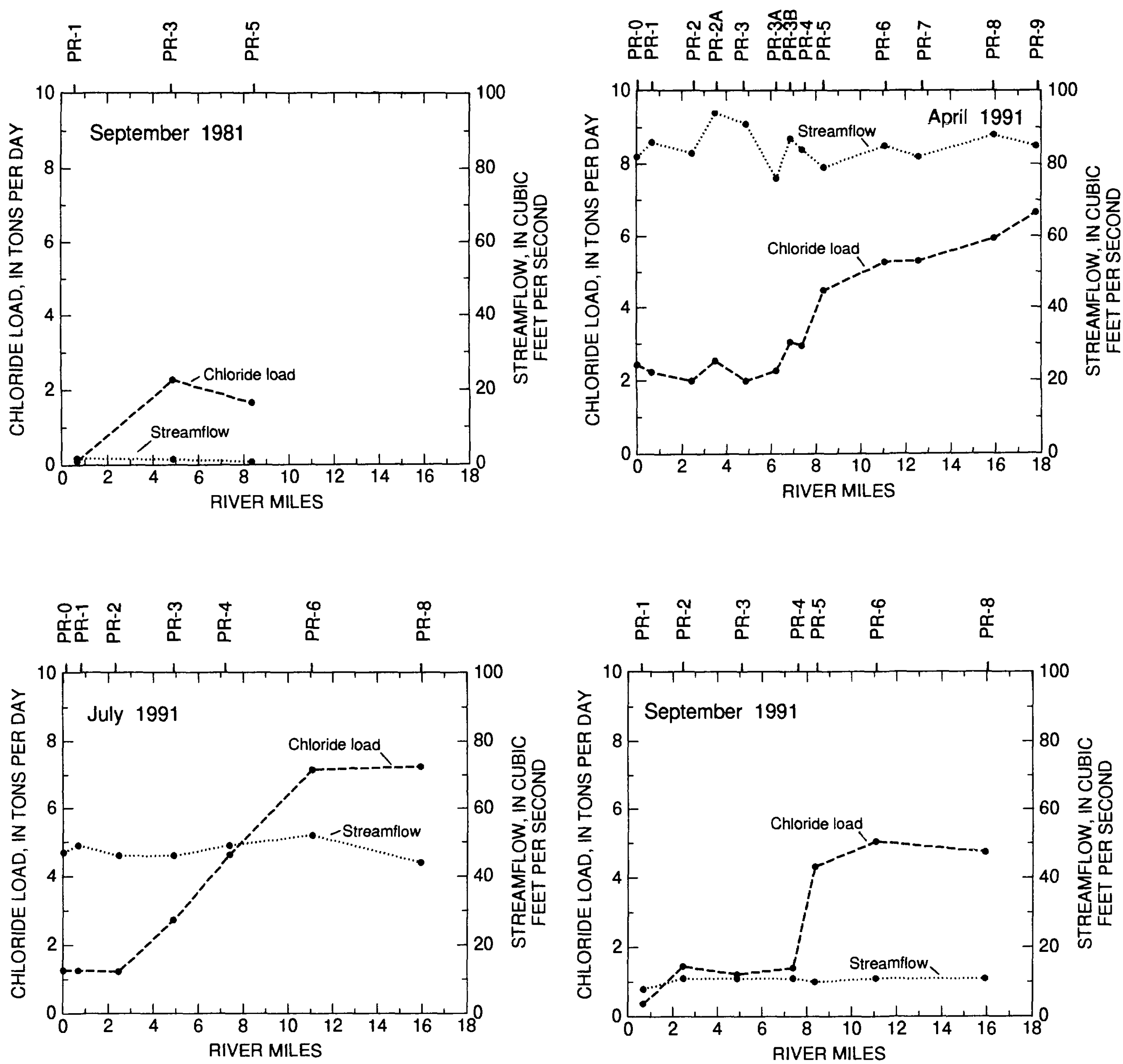


Figure 20. Streamflow and chloride loads for selected sites along the Poplar River, 1981 and 1991, in the East Poplar oil field study area, northeastern Montana.

increased salinity in a nearby well may increase the dissolved-solids and chloride concentrations of saline ground-water discharge to the river in the future.

Possible Sources

Water-quality information from wells in the Quaternary deposits and from sites along the Poplar River indicate that saline-water contamination has occurred in the study area. Three possible and general sources of saline water in Quaternary deposits in the study area are saline seeps, water from the underlying Bearpaw Shale, and brines from the production of oil. Specific sources of saline-water contamination plumes can be discerned from additional interpretation of electromagnetic geophysical data.

General Sources

Saline seeps are common in many parts of eastern Montana as a result of leaching of saline soils derived from marine shales. Typically, the major constituents in water from saline seeps are sodium, magnesium, and sulfate, and concentrations of chloride are low compared to concentrations of sulfate (Donovan and others, 1981; Halvorson, 1988). In contrast, contaminated ground water in the study area has a sodium chloride chemical composition with a large ratio of chloride to sulfate ions. Furthermore, no saline soils and relatively few areas of saline seeps have been mapped in the study area (U.S. Department of Agriculture, 1985; Miller and Bergantino, 1983). Therefore, saline seeps are not a likely source of saline-water contamination in the study area.

The Cretaceous Bearpaw Shale is relatively impermeable; therefore, wells in the study area are perforated in the overlying Quaternary deposits. However, it is possible that minor amounts of water from the small fractures and fissures in the Bearpaw Shale interact with water from Quaternary deposits, depending on vertical gradients in the ground water. Analyses of water from two wells completed in the Bearpaw Shale in the southwest part of the reservation are stored in the National Water Data Storage and Retrieval System (operated and maintained by the U.S. Geological Survey). The major constituents in water from the Bearpaw Shale for these two wells are sodium and sulfate, with chloride concentrations of 180 and 110 mg/L. In contrast, the major constituents in contaminated ground water in Quaternary deposits are sodium and chloride, with chloride concentrations greater than 330 mg/L. This difference in water chemistry, in addition to the impermeable nature of the Bearpaw Shale, indicates that water from the Bearpaw Shale is not a likely source of saline-water contamination in the study area.

Brine is a byproduct of most crude-oil production activities. Most of this brine originates from intraformational dissolution of halite in the oil-producing zone which, in the East Poplar oil field study area, mainly is the Charles Formation of the Mississippian Madison Group. The major constituents in brine are sodium and chloride, a composition that is similar to contaminated ground water in the study area. The strong similarity in water chemistry indicates that brine is a likely source of saline-water contamination in the study area.

Possible sources of the brine and resultant saline-water contamination in Quaternary deposits in the study area are brine-injection wells, oil-production wells, brine-evaporation pits, pipelines, storage tanks, and upward brine migration from subsurface zones through well casing or fractures, although no faults or fracture systems are known in the study area. The approximate quantities of brine injected through brine-injection wells throughout the oil-field's history, calculated from EPA and BLM well records, are shown in table 2; the locations of brine-injection wells, oil wells, brine-evaporation pits and other pits, pipelines, and storage tanks are shown on plate 3.

Specific Source Areas

In several of the saline-water plumes (pl. 3), some electromagnetic geophysical measurements were significantly higher than the measurements used to delineate the plumes. Contouring of these significantly high electromagnetic geophysical measurements from figs. 11-14 appears to delineate specific source areas of brine in these plumes. The electromagnetic apparent conductivity is considered to be significantly high if the value is 20 mmho/m higher than the electromagnetic apparent conductivity used to delineate subarea 3. Consequently, electromagnetic apparent conductivity values for Areas 1 and 2, greater than or equal to 70 or 90 mmho/m, as shown on the following page, were used to delineate areas around or downgradient from probable sources of brine contamination.

The correlation is strong between areas of significantly high electromagnetic apparent conductivities and the location of particular brine-injection wells, oil wells, evaporation pits, pipelines, and storage-tank

Area 1	Area 2	Significantly high electromagnetic apparent conductivity (mmho/m)
10-meter, vertical-dipole orientation	20-meter, vertical-dipole orientation	≥ 70
20-meter, horizontal-dipole orientation	40-meter, horizontal-dipole orientation	≥ 90

facilities (pl. 3). On plate 3, areas of significantly high electromagnetic apparent conductivities are shaded separately from the types of plumes. Probable specific sources may be located in or hydraulically upgradient of the areas of significantly high electromagnetic apparent conductivities. However, the areas of high electromagnetic apparent conductivity may not be all-inclusive; therefore, other specific source areas may exist.

SUMMARY AND CONCLUSIONS

The sole developed source of ground water for residents in and near the East Poplar oil field is the Quaternary deposits, comprised of the Poplar River alluvium and glacial deposits. Depth to water in alluvium generally has a range of about 5-44 ft below land surface; depth to water in glacial deposits has a range of about 7-130 ft. Water in Quaternary deposits east of the Poplar River generally moves westward toward the river where it merges with southward-flowing ground water in the Poplar River valley. The Quaternary deposits are underlain by the relatively impermeable Upper Cretaceous Bearpaw Shale, which limits downward movement of ground water. Representative hydraulic-conductivity values determined from two aquifer tests were 77 ft/d for alluvium and 42 ft/d for glacial deposits; corresponding transmissivity values were 2,400 ft^2/d for alluvium and 800 ft^2/d for glacial deposits.

The quality of water in Quaternary deposits in the study area is highly variable and is dependent on location relative to sources of contamination. Dissolved-solids and chloride concentrations in water sampled during 1989-93 from wells completed in the Quaternary deposits have ranges of 427-91,100 mg/L and 7.3-58,000 mg/L, respectively. Three types of water exist in the Quaternary deposits, and a fourth type of water represents the brine. Uncontaminated water (Type 1) is principally a sodium bicarbonate and a sodium sulfate type water. Moderately contaminated water (Type 2) is a sodium chloride water, with dissolved-solids and chloride concentrations significantly larger than in uncontaminated water. Considerably contaminated water (Type 3) is principally a sodium chloride type; however, the concentrations of dissolved-solids, sodium, and chloride are significantly larger than in moderately contaminated water. Considerably contaminated water is similar to the brine (Type 4), which is produced with the oil and is injected by brine-injection wells.

Electromagnetic apparent conductivity data were collected in an area of about 21.6 mi^2. The data were contoured and interpreted in conjunction with water-quality data to delineate the lateral extent of saline-water contamination plumes in the Quaternary deposits. The extent of saline-water contamination in Quaternary deposits in the East Poplar oil field may be as much as 12.4 mi^2. Electromagnetic apparent conductivity, combined with water chemistry of samples from wells confirms the presence of 7.3 mi^2 of contamination, as much as 2.0 mi^2 of which is considerably contaminated (Type 3). Electromagnetic apparent conductivity data for unsampled areas indicate 5.1 mi^2 of possible contamination, 3.2 mi^2 of which may be considerably contaminated (Type 3).

In contaminated areas, saline water is present throughout the entire vertical extent of the saturated zone of the Quaternary deposits as evidenced by analyses of water samples from nested wells at three sites. At two of the sites, the chloride concentration and density of water in a saline-water contamination plume increases significantly with depth. At the third site, the chloride concentrations and density of water in a saline-water contamination plume did not vary significantly with depth, possibly indicating that the source may still be contributing saline water to the aquifer.

About 9-60 billion gal of water in the Quaternary deposits are possibly affected by saline-water contamination. This range is based on the estimated saturated thickness and porosity of Quaternary deposits affected by confirmed and possible saline-water contamination plumes.

Generally, the saline-water contamination appears to move laterally in the general directions of ground-water flow—laterally toward the river then southward in the Poplar River valley. The movement of saline-water plumes is evidenced by the changes in dissolved-solids and chloride concentrations over time. Increasing concentrations over time indicate that a plume has migrated into the area; decreasing concentrations indicate a departing plume where dilution is re-establishing lower concentrations. Some movement of saline-water contamination may follow the top of the Bearpaw Shale. In one documented case, a considerably contaminated saline-water plume in the alluvium extends to both sides of the Poplar River valley; thus, the saline water may have moved beneath the river to the other side of the valley.

Saline ground water discharges to the Poplar River, as evidenced by a downstream increase in dissolved-solids and chloride concentrations, as well as a downstream change in water type from sodium bicarbonate to sodium chloride. In the northern part of the study area, a saline-water plume probably is discharging to the Poplar River. In the southern part of the study area, a larger, less contaminated saline-water plume is not significantly affecting concentrations in the Poplar River, although increasing dissolved-solids and chloride concentrations in nearby wells indicate that the plume may be approaching the river; thus, saline ground-water discharge may eventually affect this reach of the river as well.

The probable source of saline-water contamination of the Quaternary deposits is brine from the production of crude oil in the East Poplar oil field study area. Dissolved-solids and chloride concentrations of this brine have ranges of about 47,700-201,000 mg/L and 27,000-120,000 mg/L, respectively. Most brine disposal has been by injection into subsurface geologic units; smaller, unknown quantities of brine have been directed into storage and evaporation pits. Within the saline-water contamination plumes, the locations of significantly high electromagnetic apparent conductivity values generally are close to the locations of particular brine-injection wells, oil wells, pipelines, and storage-tank facilities. These areas appear to be probable specific source areas of the saline-water contamination.

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