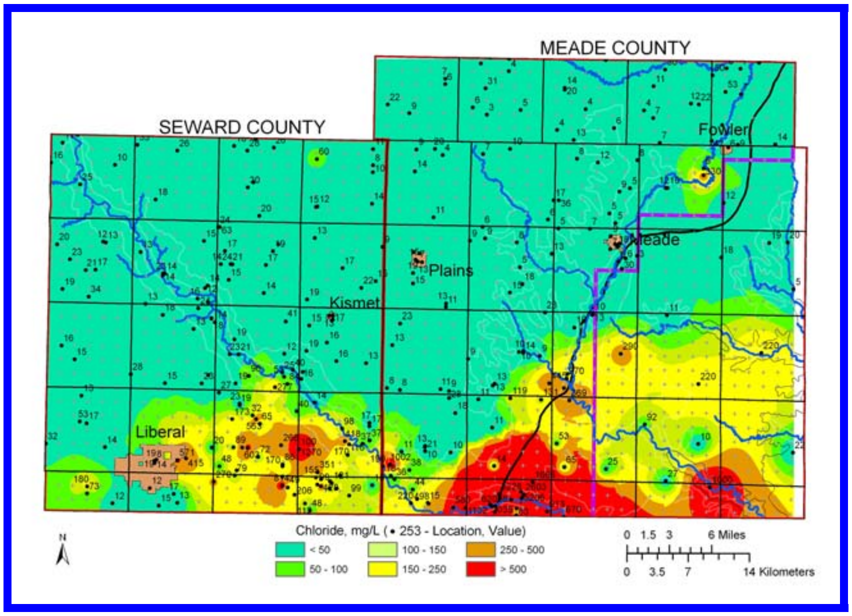
Kansas Geological Survey

WATER QUALITY IN THE HIGH PLAINS AQUIFER AND THE CIMARRON RIVER IN SEWARD AND MEADE COUNTIES, KANSAS

Part of Data, Research, and Technical Support for Ogallala-High Plains Aquifer Assessment, Planning, and Management – FY 2005

By

D.O. Whittemore, E.R. Grieve, D.P. Young, and B.B. Wilson



Kansas Geological Survey Open File Report 2005-27
September 2005

GEOHYDROLOGY

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ACKNOWLEDGMENTS

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INTRODUCTION

The Cimarron River flows from the northeastern corner of New Mexico to the northwestern corner of the panhandle of Oklahoma, to southeastern corner of Colorado, and enters the southwestern corner of Kansas. The river crosses the High Plains aquifer in southwest Kansas in a broad bow shape from Morton County through northwest Stephens County, southernmost Grant County, and the southwest corner of Haskell County, from northwest to southeast Seward County, and through southwest Meade County (Figure 1). The North Fork of the Cimarron River enters the Cimarron River in southeast Grant County and drains from a watershed area that includes northern Morton County and southern Stanton and Grant counties. Flow in the Cimarron River has historically not been continuous across southwest Kansas but has typically been ephemeral in the middle of its course, particularly in eastern Morton, and in Stevens and Grant counties (see report on the lithology and water levels in the Cimarron River basin by Young et al., 2005). The North Fork of the Cimarron River is also ephemeral.

Ground-water table declines in the High Plains aquifer caused by high-volume, consumptive pumping of ground water for irrigation have occurred under the Cimarron River in southwest Kansas. These water-level declines have decreased or eliminated ground-water discharge to the perennial stretches of the river, thereby decreasing flow to or shortening the length of the perennial reaches. The primary area of perennial stretch shortening has occurred in northwest Seward County and the main location of current decrease in perennial streamflow is in southeast Seward County and southwest Meade County.

Natural saltwater derived from evaporite mineral dissolution intrudes from the Permian bedrock into the overlying High Plains aquifer in southeast Seward County and southwest Meade County. The saltwater is primarily of sodium-chloride chemical type, reflecting the dissolution of halite (rock salt) in the Permian strata. The evaporite minerals anhydrite ($CaSO_4$) and gypsum ($CaSO_4 \cdot 2H_2O$) are also present in the Permian strata and their dissolution increases the sulfate content of the saline water. The dissolved calcium concentration is limited by carbonate mineral equilibria. Saline water that intrudes to the High Plains aquifer affects the usability of water in parts of the aquifer for irrigation and domestic use due to the high sodium and chloride contents.

The saline water in the High Plains aquifer discharges into the overlying Cimarron River in southeast Seward County and southwest Meade County. The river generally increases in salinity through this area. The decrease in fresh ground-water discharge, caused by declines in ground-water levels, from the High Plains aquifer upstream of the saline water intrusion has resulted in an increase in the salinity of the river.

This report presents maps of the salinity distribution in the High Plains aquifer in Seward and Meade counties based on available data from several sources. It describes water-level changes in the Cimarron River corridor, the shortening of the perennial stretch of the river in Seward County, and the decrease in the river flow at the U.S. Geological Survey (USGS) gaging station in Meade County. It also discusses the resulting increase in salinity in the river caused by the decrease in fresh ground-water discharge from the High Plains aquifer.

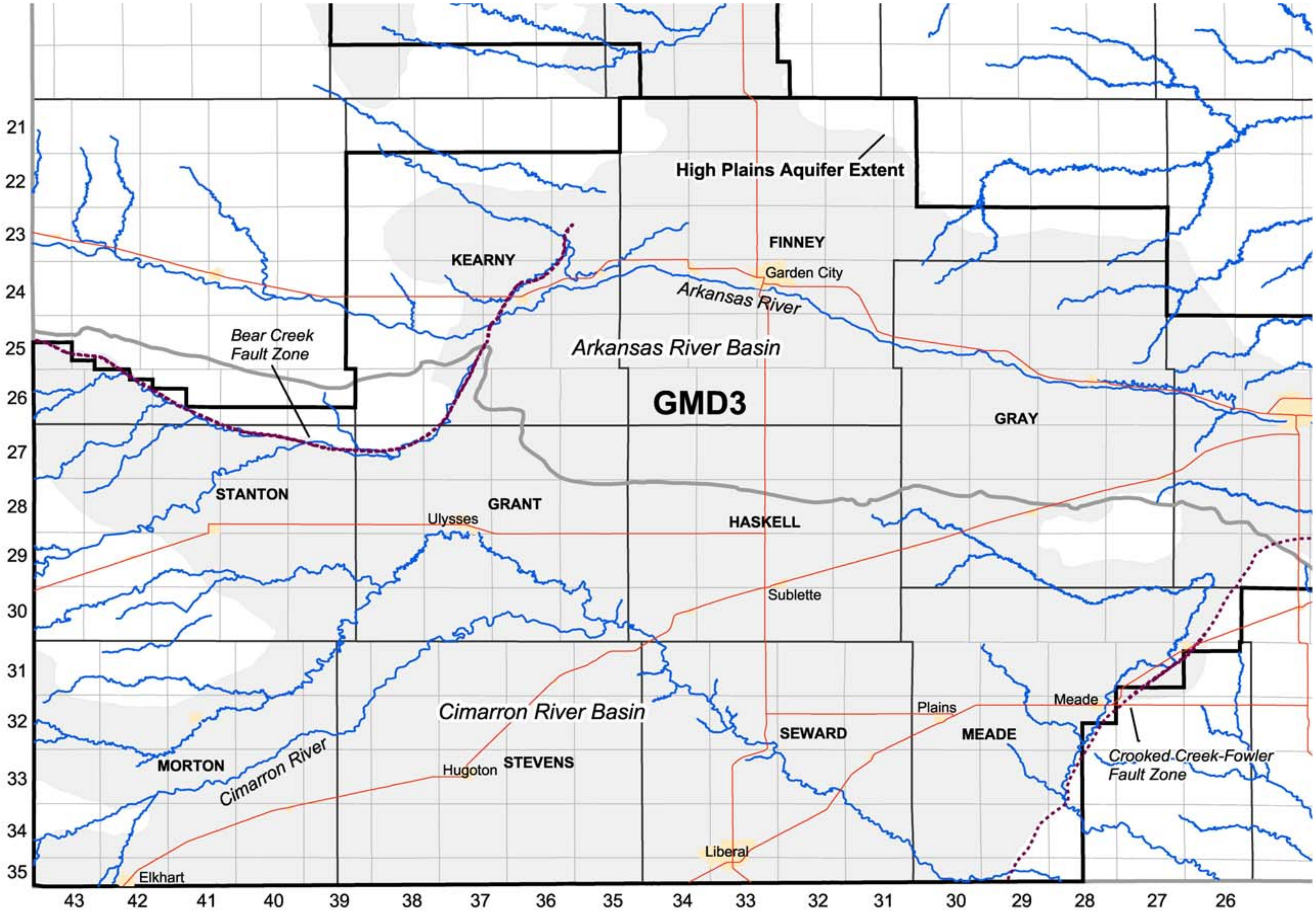


Figure 1. Base map of southwest Kansas showing political and basin boundaries, highways, rivers and streams, the High Plains aquifer extent, and the Bear Creek and Crooked Creek-Fowler faults. The study area for this report is Seward and Meade counties.

ORIGIN OF SALINITY IN THE HIGH PLAINS AQUIFER

Frye (1942) indicated that higher chloride concentrations in shallow ground water of southwest Meade County are associated with the eastern, upside of the Crooked Creek-Fowler fault zone where depth to Permian bedrock below the land surface becomes shallow. Gutentag et al. (1981) reported that near the Cimarron River in southeast Seward County and southwest Meade County wells completed in the Permian Whitehorse Formation yield saline water with total dissolved solids (TDS) concentrations of up to 33,900 mg/L. They found that the TDS content of ground water increased with depth in the High Plains aquifer and the underlying Permian bedrock at a site (T. 34 S., R. 30 W. Sec. 30BBB) in the uplands adjacent to the Cimarron River valley in southwestern Meade County. The TDS concentrations ranged from 403 mg/L in the shallowest well screened in the High Plains aquifer, to 2,420 mg/L in the deeper part of the aquifer, and to19,500 mg/L in the Whitehorse Formation. On the basis of these findings, Gutentag et al. (1981) concluded that the lower part of the High Plains aquifer over a large area south and east of US Highway 54 may be affected by the upward movement of chloride-rich ground water from the Permian strata. Krothe and Oliver (1982) also noted saline water in the High Plains aquifer in Seward and Meade counties.

Much oil and gas is produced in Seward and Meade counties. Production of petroleum in the state is accompanied by substantial quantities of sodium-chloride saltwater that must be disposed in deep formations. If the saltwater is not properly disposed, contamination of ground-water resources can occur as it has in the High Plains aquifer in south-central Kansas. In 1983, Southwest Kansas Groundwater Management District No. 3 (GMD3) requested that the Kansas Geological Survey (KGS) determine the source of saline water with high chloride contents affecting the High Plains aquifer within T.34S., R.31W. and R.32W, and T.35S., R.31W. and R.32W. The district collected ground waters in July and August 1983, and sent samples to the Kansas Department of Health and Environment (KDHE) laboratories in Topeka for partial chemical analysis and to the KGS for salinity identification by the methods described in Whittemore et al. (1981) and Whittemore (1984a, 1995). The district office of the KDHE collected two oil-field brine samples for analysis in the study. Chemical data for the samples are listed in Appendix A. Data for earlier samples collected from some of the same and a few different wells in the study area are also listed in Appendix A along with the chemistry for samples from three observation wells drilled by the KGS in the early 1970's in a cooperative project with the USGS. One of these latter wells is located just to the north of the study area.

The KGS geochemically identified the source of the saline water in the High Plains aquifer as dissolution of evaporite minerals (primarily halite, or rock salt) in Permian strata based on mixing curves on a plot of bromide/chloride ratio versus chloride concentration (Whittemore, 1984b). The bromide/chloride ratios of the ground water did not fit what would be expected at the observed chloride concentrations if oil brine was the salinity source. In 1992, GMD3 collected and sent to the KGS three water samples from wells in the High Plains aquifer and a brine from an oil well in the same area studied in 1984. The geochemical identification of the salinity source (Whittemore, unpublished letter to GMD3) was the same as for the previous 1984 study. One of the wells sampled in 1992 was the same as in the 1984 study (SE/4 Sec. 5, T.35S., R.31W). Three samples collected from 1982 to 1983 contained 420-429 mg/L chloride, while the 1992 sample from the same location had a chloride concentration of 583 mg/L. The long-term pumping by irrigation wells may be causing up-coning of deeper, natural saline water.

In 1999, the USGS constructed four wells at a site on the west valley wall above the Cimarron River in southeast Seward County (McMahon, 2001). Three of the wells were screened at different depths in the High Plains aquifer (45-65, 200-210, and 326-336 ft below land surface) and one well was screened in the underlying Permian bedrock (396-436 ft bls). The chloride contents of the water sampled in 1999 from the shallow and intermediate depth wells in the High Plains aquifer were 71 and 52 mg/L, respectively, and increased to 1,861 mg/L at the base of the High Plains aquifer, and, in a sample obtained in 2000, to 4,051 in the Permian strata. The bromide/chloride ratios for the samples fit the mixing of freshwater with halite-dissolution based on the mixing curve approach of Whittemore (1995). In contrast to the increasing salinity in the High Plains aquifer at the Cimarron site, the USGS (McMahon, 2001) found that the chloride concentration in four wells they constructed of different depths in the High Plains aquifer southeast of Liberal ranged from 20 mg/L in the shallowest well (160 ft deep) to 9 and 10 mg/L in the wells of intermediate depth (319 and 436 ft deep) to 13 mg/L in the well near the aquifer base (570 ft deep).

Higher dissolved solids concentrations can be found in ground water in the alluvium of the Cimarron River than in the adjacent High Plains aquifer, even where there is no substantial contribution from the saline water intrusion from the underlying Permian formations. This was first noticed by McLaughlin (1942, 1946) who indicated that the higher concentrations of the constituents could have resulted from concentration of dissolved solids due to a shallow water table and high evapotranspiration rates in the river valley. This process is expected to be especially important where phreatophytes such as salt cedar (tamarisk) and phragmites (common reed) are densely distributed in the valley. Fragmites are especially dense in the floodplain at the highway bridge northeast of Liberal and below the USGS well site near the Cimarron River in southeast Seward County (based on observations by the KGS in 2004).

DISTRIBUTION OF SALINITY IN THE HIGH PLAINS AQUIFER

Water-Quality Data

Data were assembled from several sources for chemical analyses of ground waters sampled from wells screened in the High Plains aquifer west of the Crooked Creek-Fowler fault zone and in unconsolidated deposits and bedrock aquifers east of the fault zone in Seward and Meade counties. The data were from the USGS online data base (234 records), USGS NAWQA (National Water Assessment) program (McMahon, 2000; 7 records), KGS analyses for samples from selected wells of the USGS NAWQA program (unpublished, 6 records), KGS irrigation water study (Hathaway et al., 1978; 45 records), KGS cooperative irrigation water study with the Kansas Department of Agriculture (KDA) (unpublished; 15 records), KDHE ambient ground-water quality program (obtained from EPA online data base; 15 records), KDHE public water supply data base (21 records), Southwest Kansas Groundwater Management District No. 3 (GMD3) data (130 records), and an M.S. thesis of Kansas State University (Borell, 1998; 46 records).

The USGS online data were for samples collected during 1939-1989. The USGS NAWQA and KGS NAWQA data were samples obtained in 1999. The waters for the KGS irrigation study by Hathaway et al. (1978) were sampled in 1976. The samples for the KGS-KDA cooperative investigation of irrigation well waters were collected during 1992-1998. The KDHE data from the ambient ground-water quality program were for samples obtained during 1990-1997. The KDHE data for the public water supply wells were obtained as a spreadsheet from KDHE and were for samples collected during 1987-1993. The GMD3 data represented samples collected during 1988-1993 and were from a data set on which the KGS worked with the GMD3 to correct errors. Borell (1998) collected waters from wells during 1997 and 1998.

Records were removed from the data base for samples collected from wells screened in the bedrock underlying the High Plains aquifer west of the Crooked Creek-Fowler fault zone. Some of the data sets, such as those from the USGS online data base and the KDHE data bases, include multiple samples for the same well. There are also multiple sampling dates for the same well locations that were found by comparing all of the data sets. The most recent data were selected for a combined data base for use in preparing maps illustrating the distribution of water quality. The objective of the maps is to display the general pattern in the salinity of the water. Although there might be some changes in the salinity with time, such as caused by upconing of deeper saline water by irrigation pumping, and by local anthropogenic contamination, the use of data for the entire period was thought to be more valuable than eliminating points for older samples. Elimination of older data would leave holes in the distribution of points on the maps and decrease the ability to discern areas of naturally fresh and saline water in the High Plains aquifer. Long-term monitoring would be necessary to determine and salinity trends with time.

A total of 327 records of chemical analyses of ground water were selected for use in generating maps of the total-dissolved solids (TDS), chloride, and sufate concentrations in ground waters in Seward and Meade counties. Seven of these records represented samples from multiple depths at the two multi-level wells of the USGS NAWQA program southeast of Liberal and near the Cimarron River in southwest Kansas. An average of the data for the four multi-level wells near Liberal was used for a single point on the maps because the ranges in TDS, chloride, and sulfate concentrations are not large for the ground-waters from the different wells. A weighted average for the sample data from the three wells at the NAWQA Cimarron River site was used; the middle well was weighted three times relative to the other two wells to represent the main thickness of the aquifer. Ground water from the well screened at the base of the aquifer at the Cimarron River site has a much greater salinity than in the middle and at the water table of the aquifer. The weighted average should be a better representation of the aquifer at this location.

The TDS content in the records used for mapping was calculated from the sum of constituents when values for all major constituent concentrations (calcium, magnesium, sodium, bicarbonate, sulfate, and chloride) existed in a record. The bicarbonate concentration was multiplied by 0.4917 to represent an amount equivalent to what would be precipitated if the water were evaporated to dryness and the remaining solids were weighed (Hem, 1985). Values of TDS measured by evaporation to dryness were used if the record did not include analyses of all major constituents. There are 308 points with TDS values and 322 points with both chloride and sulfate data that were used in the maps. The ranges in the TDS, chloride, and sulfate concentrations in the records are 190-10,280 mg/L, 2-5,410 mg/L, and 5-1,200 mg/L, respectively. The TDS, chloride, and sulfate concentration data are listed in Appendix A.

Salinity Pattern

The distribution of TDS, chloride, and sulfate concentrations are displayed in Figures 2-4. The colored areas show different intervals of concentrations that were divided based on the total range and values representing water-quality criteria. The criteria are recommended limits for drinking waters (secondary standards) of 500 mg/L for TDS content and 250 mg/L for both chloride and sulfate concentrations. The colored intervals on the maps incorporate a similar color scheme of green to lighter green to yellow to orange to red for increasing concentration. Concentration values are included next to the points representing the well locations on the figures. The decimal figures for these values were removed for plotting to simplify the numbers on the map. The boundaries of the concentration intervals and other map features were generated using ESRI ArcGIS software.

The general concentration patterns on the TDS and chloride maps (Figures 2 and 3) are similar. Most of the area of the High Plains aquifer in Seward and Meade counties (west of the Crooked Creek-Fowler fault zone) has fresh ground waters with TDS and chloride contents less than 500 mg/L and 50 mg/L, respectively. The freshest waters occur in the High Plains aquifer in northern Meade County; TDS and chloride contents are <250 mg/L and <10 mg/L in parts of this region. Areas of the High Plains aquifer west of the Crooked Creek-Fowler fault zone and areas of other unconsolidated or bedrock aquifers east of the fault zone with TDS and chloride concentrations exceeding 500 mg/L and 50 mg/L, respectively, generally occur from south-central through southeast Seward County and across southern Meade County. The division between fresh waters and saline waters is usually defined as 1,000 mg/L TDS. Areas with TDS greater than 1,000 mg/L and chloride exceeding the recommended drinking water limit of 250 mg/L exist in parts of south-central and southeast Seward County and southern Meade County.

The pattern in the sulfate concentration distribution (Figure 4) exhibits both substantial differences and similarities to the TDS and chloride concentration patterns (Figures 2 and 3). The lowest sulfate contents occur in the High Plains aquifer in northern Meade County, as do the lowest TDS and chloride concentrations. However, a broad area with sulfate concentrations between 100 and 250 mg/L extends from the northwest, north-central, and west-central Seward County through the central and into the southeast parts of the county. In much of this area, the chloride contents are <50 mg/L. The source of the sulfate could be from anhydrite or gypsum dissolution in underlying Permian rocks that underlie the High Plains aquifer in most of Seward County or from dissolved sulfate (from the oxidation of pyrite) in ground water in lower Cretaceous rocks that underlie the aquifer in the northwest part of the county. Evapotranspiration concentration of dissolved solids in shallow waters along the Cimarron River valley during

Figure 2. Distribution of total dissolved solids concentration in ground water in aquifers in Seward and Meade counties. The blue line extending from northwest to southeast Seward County and through southwest Meade County is the Cimarron River. Most of the blue lines in northern, central, and southeast Meade County are streams that are part of the Crooked Creek drainage basin. The vertical red line is the boundary between Seward and Meade counties. The purple line within Meade County is part of the eastern boundary of GMD3. The black line extending from southwest to northeast Meade County represents the eastern extent of the saturated part of the High Plains aquifer in the figure. These same features appear on Figures 3 and 4. The map was produced using ArcGIS.

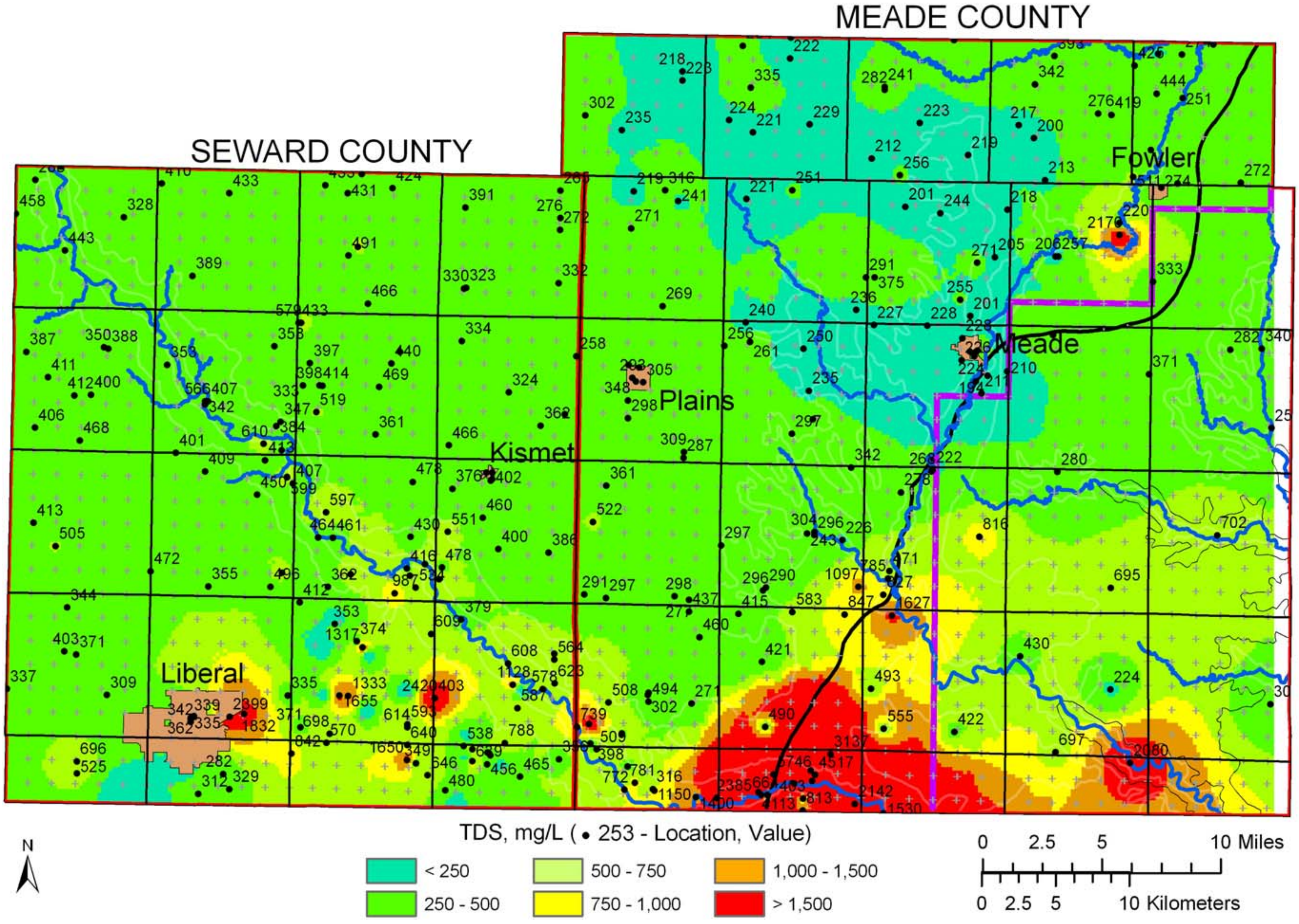

MEADE COUNTY
SEWARD COUNTY
Fowler
Meade
Plains
Kismet
Liberal
N
TDS, mg/L (• 253 - Location, Value)
< 250
250 - 500
500 - 750
750 - 1,000
1,000 - 1,500
> 1,500
0 2.5 5 10 Miles
0 2.5 5 10 Kilometers

Figure 3. Distribution of chloride concentration in ground water in aquifers in Seward and Meade counties. Features on the map are the same as in Figures 2 and 4 and are described in the caption for Figure 2. The map was produced using ArcGIS.

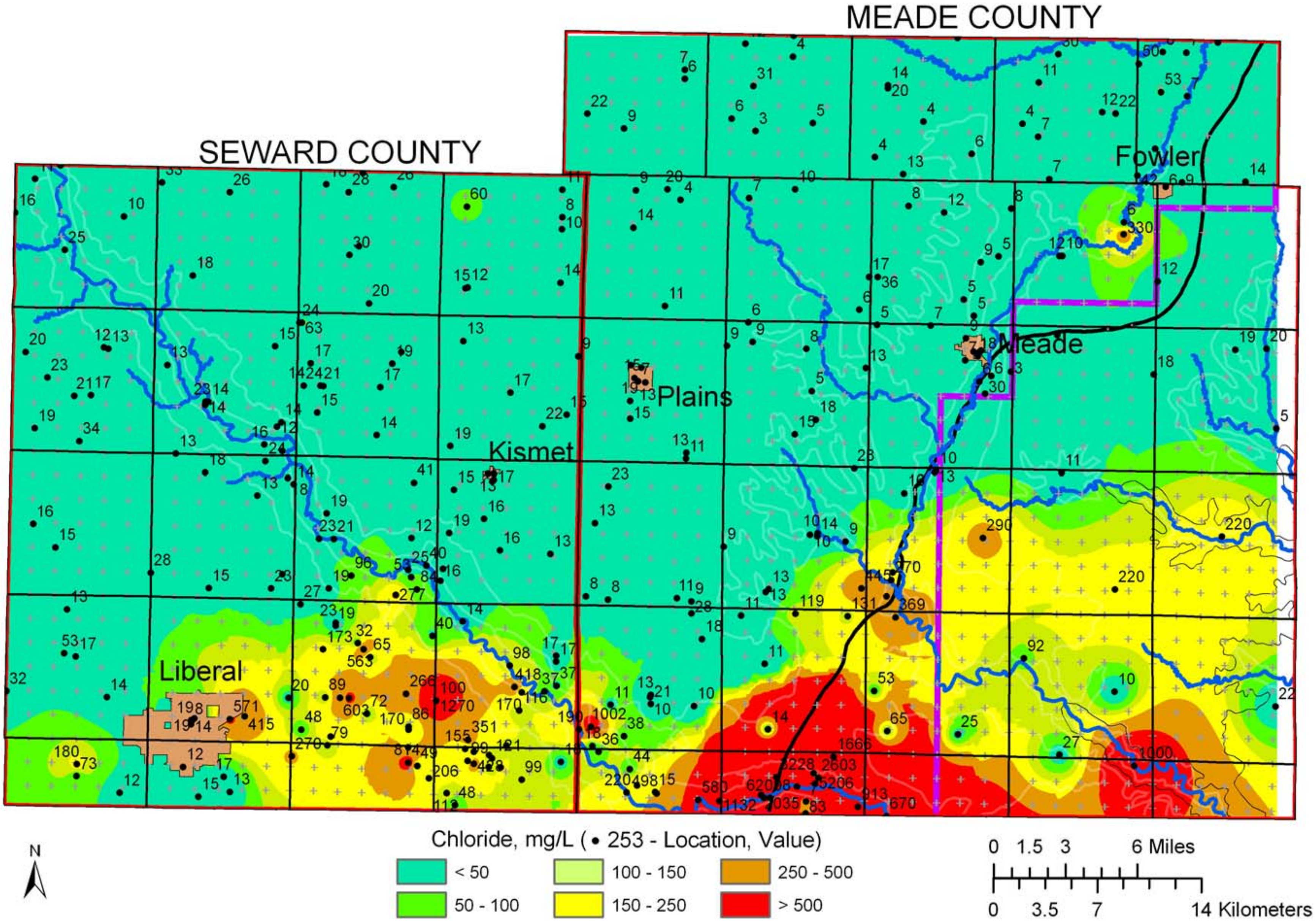
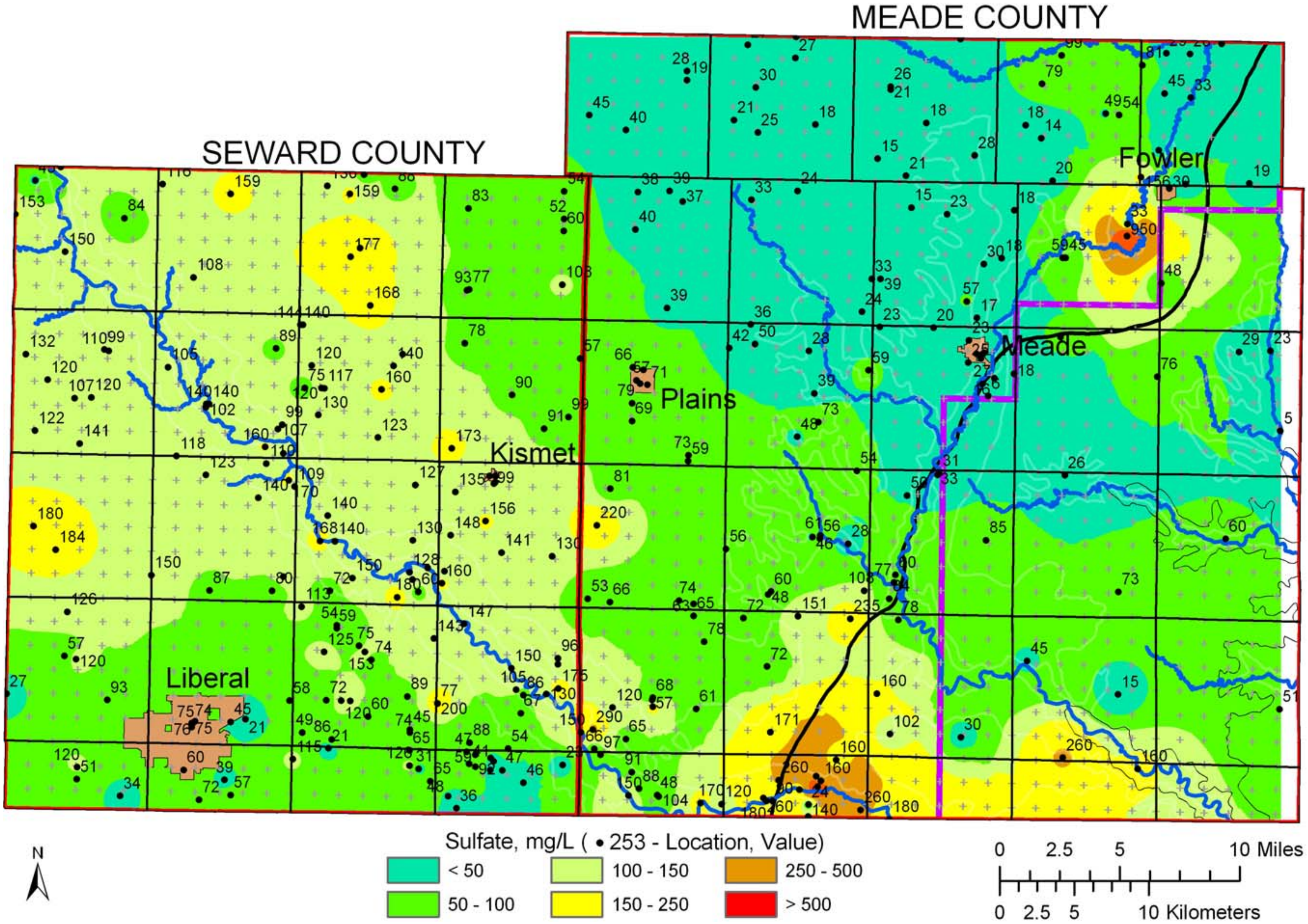

MEADE COUNTY
SEWARD COUNTY
Fowler
Meade
Plains
Kismet
Liberal
N
Chloride, mg/L (• 253 - Location, Value)
< 50
50 - 100
100 - 150
150 - 250
250 - 500
> 500
0 1.5 3 6 Miles
0 3.5 7 14 Kilometers

Figure 4. Distribution of sulfate concentration in ground water in aquifers in Seward and Meade counties. Features on the map are the same as in Figures 2 and 3 and are described in the caption for Figure 2. The map was produced using ArcGIS.


MEADE COUNTY
SEWARD COUNTY
Fowler
Meade
Plains
Kismet
Liberal
N
Sulfate, mg/L (• 253 - Location, Value)
< 50
50 - 100
100 - 150
150 - 250
250 - 500
> 500
0 2.5 5 10 Miles
0 2.5 5 10 Kilometers

recent geologic time may have also contributed to higher sulfate concentrations in the parts of the aquifer that formerly had a shallow water table.

The concentration patterns are affected not only by the distribution of saline water intrusion from the Permian bedrock into the High Plains aquifer and within other overlying sediments and Permian strata east of the Crooked Creek-Fowler fault zone, but also by the occurrence of clay units in the High Plains aquifer that can retard the upward movement of saline water and the different depths of wells from which the samples were taken. For example, the multi-level well site of the USGS NAWQA program in southeast Seward County near the Cimarron River (McMahon, 2000) shows that ground water in the High Plains aquifer can range from TDS, chloride, and sulfate concentrations of 370 mg/L, 71 mg/L, and 37 mg/L, respectively, in the shallow aquifer to 4,030 mg/L, 1,861 mg/L, and 261 mg/L, respectively, near the aquifer base. In general, saline waters apparently intrude from Permian strata to varying degrees into the overlying High Plains aquifer in south-central and southeastern Seward County and southwestern Meade County, with the greatest intrusion affecting the aquifer along the Cimarron River valley in southwest Meade County where the aquifer thins as it approaches the Crooked Creek-Fowler fault zone.

WATER-QUALITY CHANGES IN THE CIMARRON RIVER

Spatial Change in Salinity along the River

The Cimarron River gains flow from ground-water discharge in Seward County and the southwest corner of Meade County. The ground-water discharge is fresh in central Seward County but becomes slightly saline in southeast Seward County. The salinity of the ground-water discharge increases substantially in southwest Meade County. The source of the salinity is the natural intrusion of saltwater from the Permian bedrock into the overlying High Plains aquifer, then into the alluvial aquifer, and finally into the river. Upward ground-water flow is concentrated in the valley due to the lower hydraulic head of water at the lower elevation of the river channel than in the surrounding uplands. The areal distributions of TDS and chloride concentrations in the High Plains aquifer in Figures 2 and 3 indicate where the saline water enters the river valley.

The Permian bedrock underlying the High Plains aquifer contains saltwater with a chloride content up to at least 20,000 mg/L along the Cimarron River corridor in southeast Seward and southwest Meade counties. The Permian water also contains a high sulfate content derived from the dissolution of anhydrite or gypsum. The sulfate concentration is substantially less than that of chloride in the saline water due to the smaller solubility of anhydrite and gypsum than halite (rock salt). The chemistry of Cimarron River water in southwest Meade County at the Kansas Highway 23 bridge north of Forgan, Oklahoma (Figure 5), fits the mixing of saltwater in Permian bedrock in the area with freshwater in the High Plains aquifer. The chloride concentration increases at a greater rate than sulfate content with increasing salinity of the river water (Figure 6). The sulfate/chloride ratio decreases with increasing chloride concentration in the river (Figure 7). Fresh ground water with a chloride concentration <50 mg/L in the High Plains aquifer in Seward County typically has a sulfate/chloride mass ratio >1 as indicated in Figure 7 and by the higher sulfate than chloride concentrations for the same locations in the chloride and sulfate distribution maps (Figures 3 and 4). Saline water at the base of the High Plains aquifer and in the underlying Permian strata in southeast Seward and southwest Meade counties has a sulfate/chloride ratio <0.2. The two curves in Figure 7 are lines for the conservative (no chemical reaction) mixing of two end-point compositions. The curves bound a zone of mixing of freshwater in the High Plains aquifer in Seward County with saline water in the High Plains aquifer and Permian bedrock. The points for water samples from the Cimarron River in Figure 7 fall in the middle of the mixing zone.

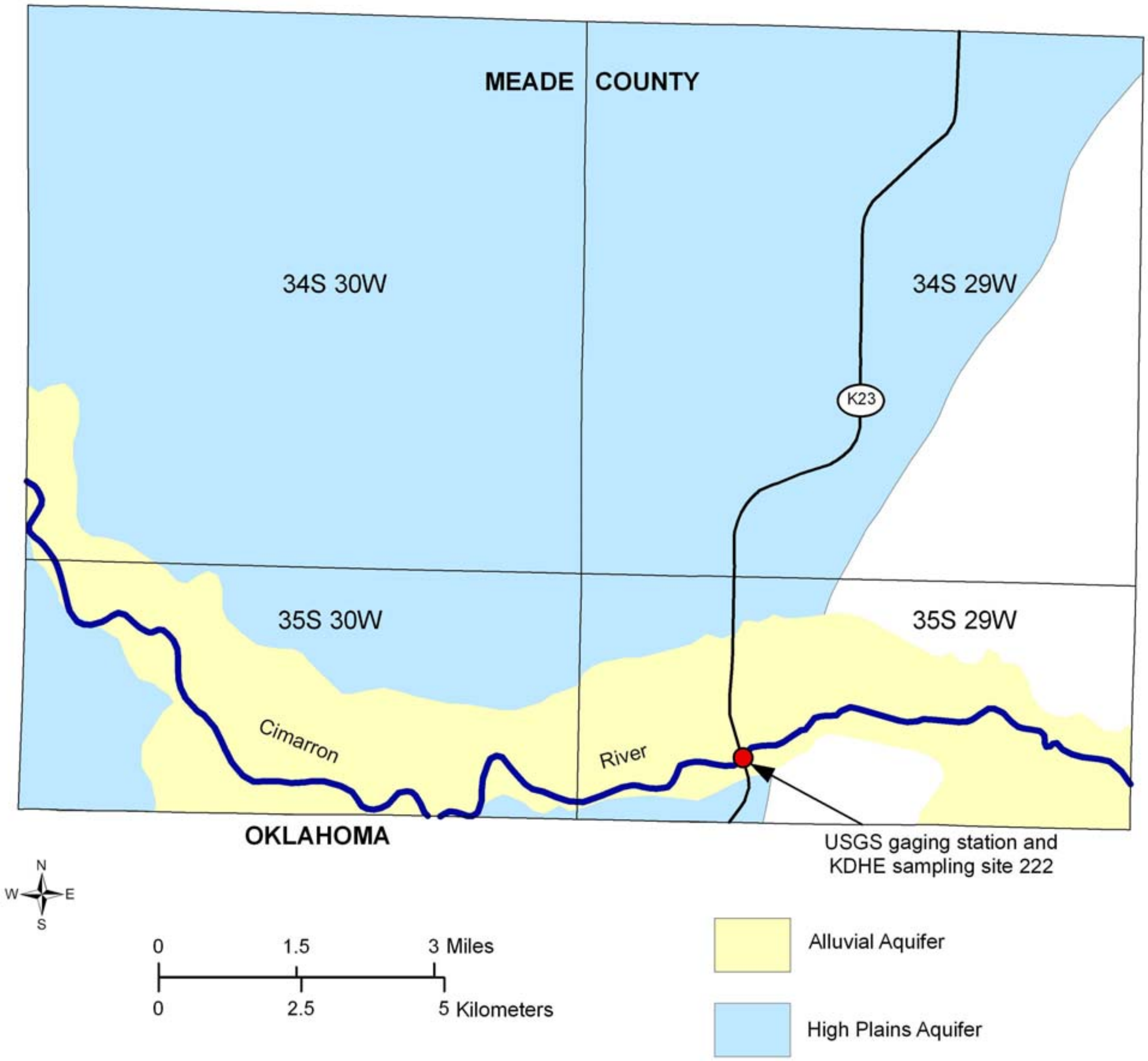


Figure 5. Location of the USGS streamflow gaging station and KDHE water-quality sampling site 222 on the Cimarron River in southwest Meade County north of Forgan, Oklahoma. The station and site are located near the eastern extent of the High Plains aquifer.

Gutentag et al. (1981) measured flow and sampled a 30-mile reach of the Cimarron River from northwest Seward County to southwest Meade County on November 14, 1974 (Figure 8). Measurements during that time of year avoided the effects of evapotranspiration by phreatophytes along the river. The chloride concentration remained at 21 ±2 mg/L from northwest to central Seward County. The chloride concentration rose steadily in the river water in southeastern Seward County, reaching 186 mg/L at the Seward-Meade county line. The chloride content then increased substantially in the southwest corner of Meade County to 620 mg/L at the KDHE sampling station No. 222 near Forgan, Oklahoma (Figure 5). The chloride content was 650 mg/L at a location about 2 miles east of the station 222 location. The chloride values in the KDHE database for station 222 on 10/22/74 and 12/3/74 were 640 mg/L and 590 mg/L, respectively. The largest increase in chloride concentration occurred a few miles west of the center of the Crooked Creek-Fowler fault zone. This increase fits the high salinity of the ground water in this area as shown in Figures 2 and 3.

Borell (1998) collected seven river-water samples along part of the stretch of the Cimarron River from which Gutentag et al. (1981) collected waters (Figure 8). The river flow at the USGS gaging station on February 21, 1998, when Borell collected river waters, was 44 ft^3/sec

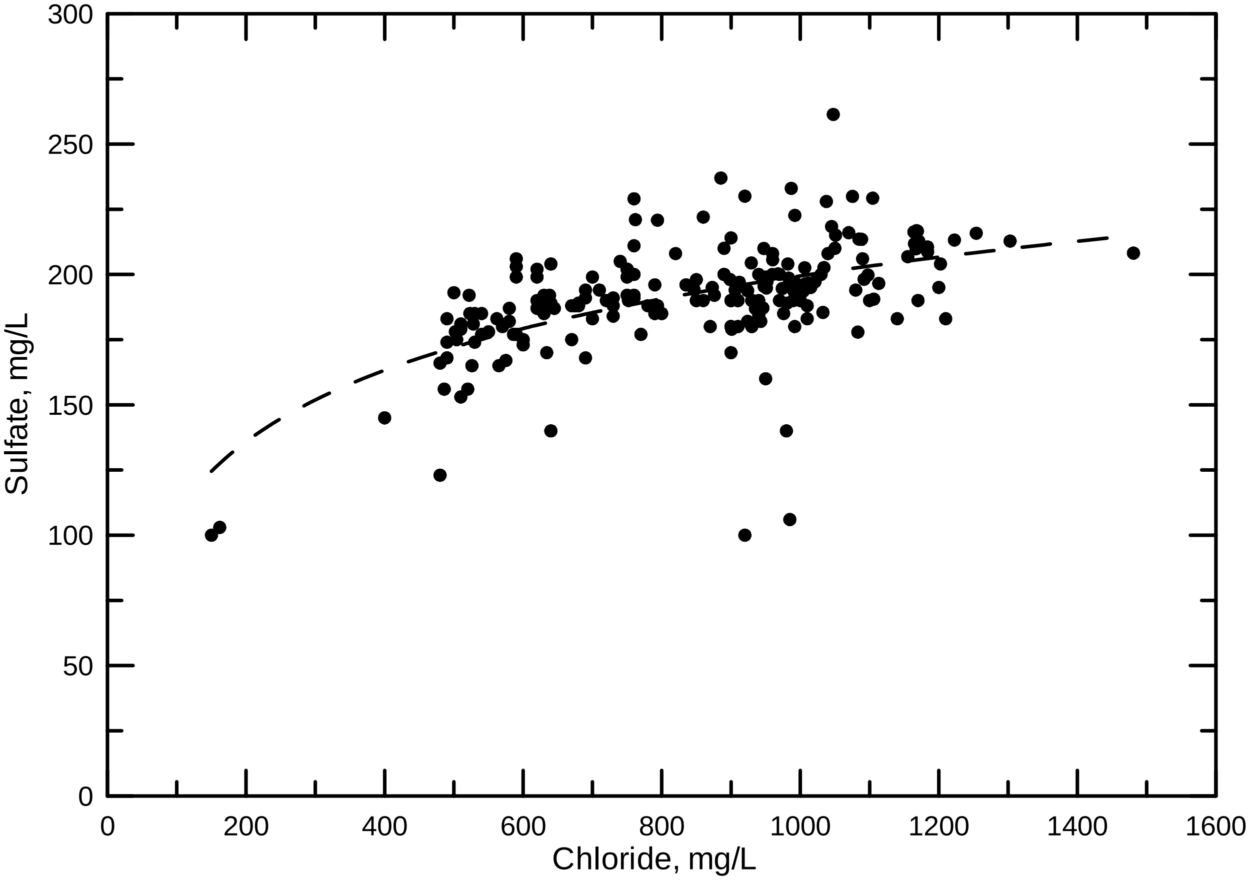


Figure 6. Sulfate versus chloride concentration for the Cimarron River in southwest Meade County near Forgan, Oklahoma. Data are from the USGS and KDHE for 1967-2004.

in comparison with 55.7 ft^3/sec on November 14, 1974, when Gutentag et al. conducted their sampling. Borell found consistently higher chloride concentrations during 1998 than Gutentag et al. found during 1974. Three of the sampling locations for 1974 and 1998 were at the same or nearly the same locations; the 1974 and 1998 chloride concentrations for these sites were, respectively, 215 and 290 mg/L, 580 and 952 mg/L, and 650 and 1,141 mg/L. Although salinity increases with decreasing flow (Figure 9), the smaller flow during 1998 is not enough to account for the substantial salinity increases along the river compared to 1974.

Temporal Change in River Flow and Salinity

River waters typically increase in TDS concentration with decreasing flow because high flows represent periods when a substantial percentage of the river water can be precipitation

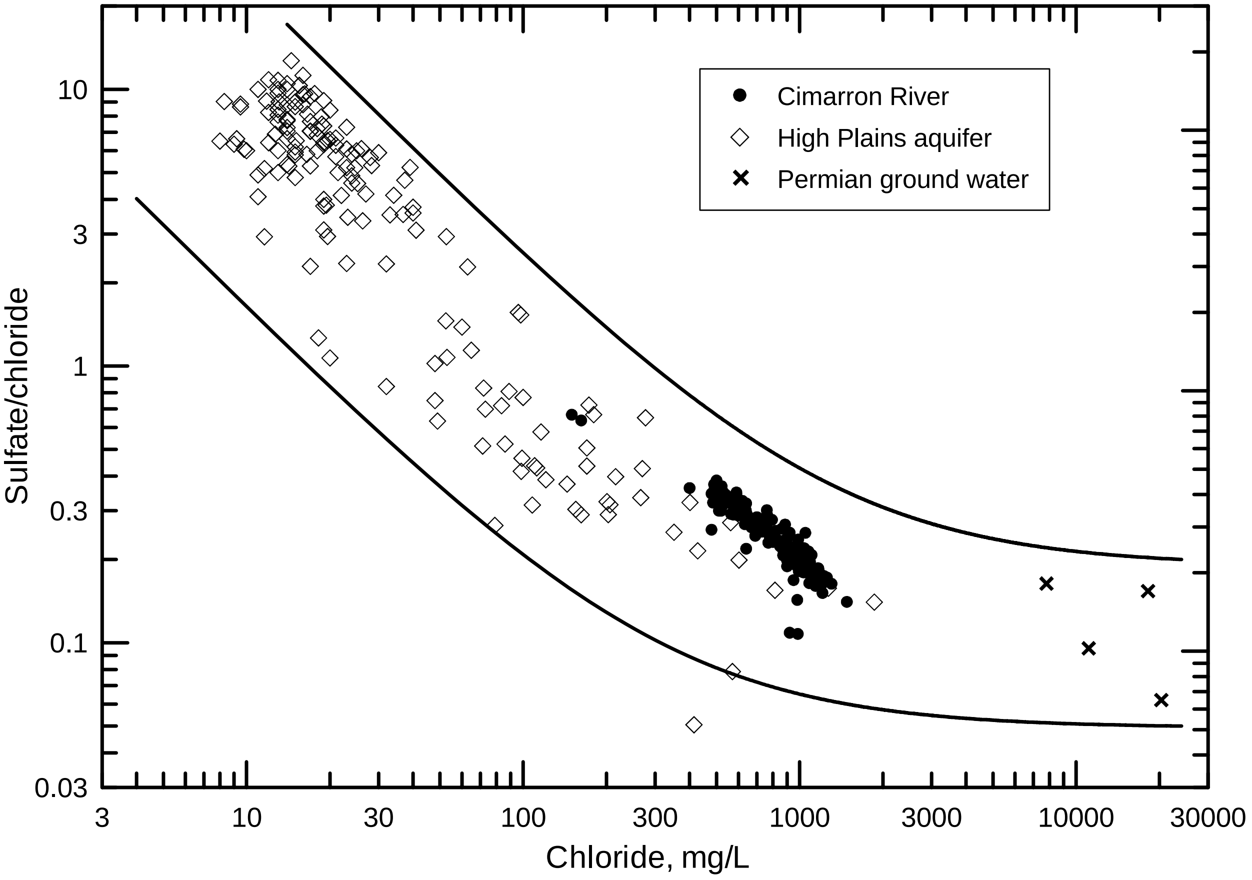


Figure 7. Sulfate/chloride mass ratio versus chloride concentration for the Cimarron River in southwest Meade County near Forgan, Oklahoma, ground water in the High Plains aquifer in Seward County, and ground water in Permian strata in southeast Seward and southwest Meade counties. The two curves are mixing lines that bound a zone of mixing between freshwater in the Cimarron River and saline ground water. Cimarron River data are from the USGS and KDHE for 1967-2004. High Plains aquifer data are for the data base generated for this report. Permian data are from Gutentag et al. (1981) and McMahon (2001).

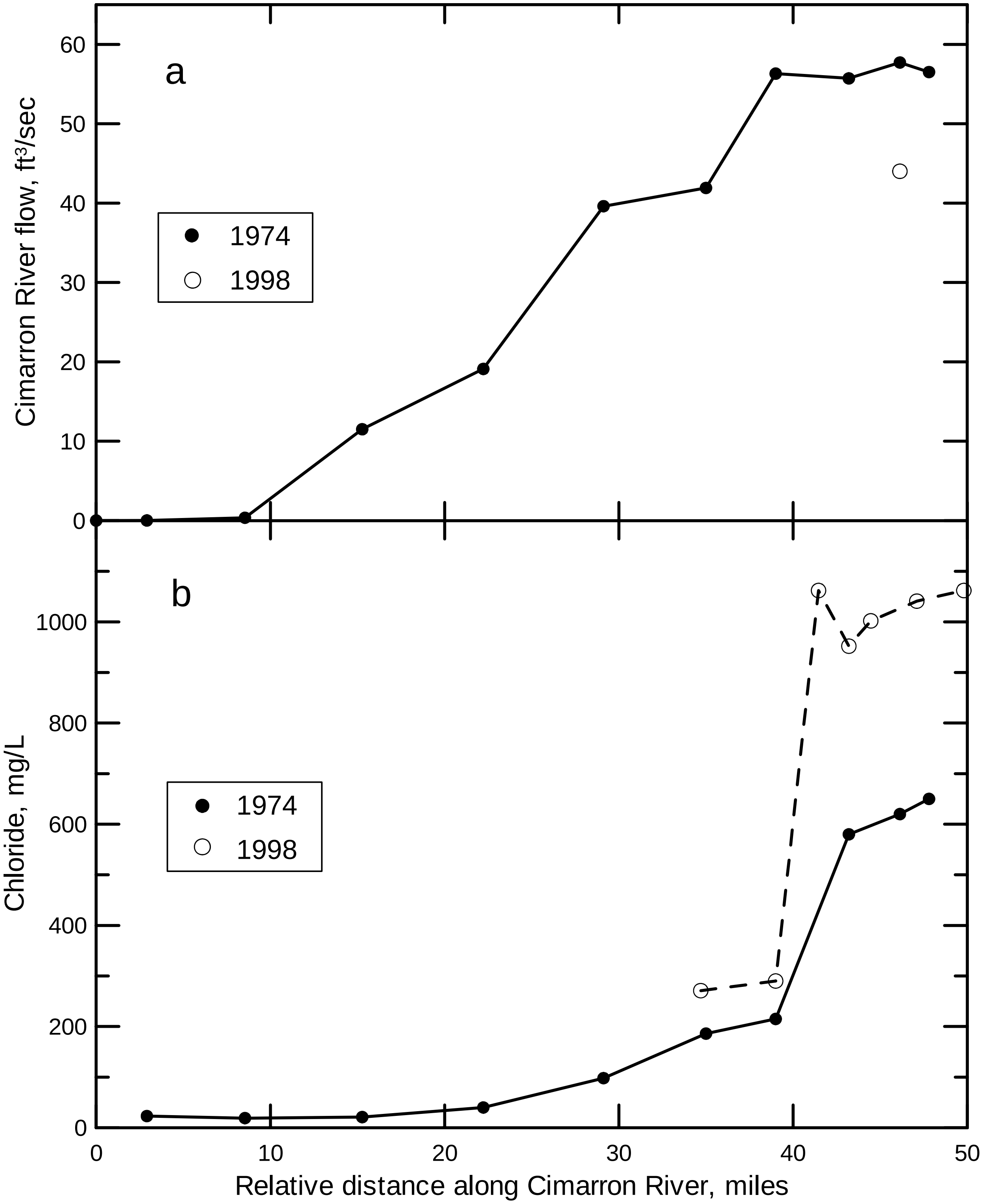


Figure 8. Profiles of flow and chloride concentration along the Cimarron River on November 14, 1974, and February 21, 1998. The Seward-Meade county border is located at about mile 35. Data for 1974 are from Gutentag et al. (1981) and for 1998 are from Borell (1998) (chloride) and USGS (flow).

runoff and low flows generally represent discharge of ground water. The salinity contrast between runoff and ground-water discharge is appreciable for the Cimarron River as indicated in Figure 9. Chloride concentration has ranged from <200 mg/L in high flow up to about 1,500 mg/L in low flow.

The chloride concentration of Cimarron River water at the USGS gaging station (near Forgan, Oklahoma) and KDHE water-quality sampling site (No. 222) at the Kansas Highway 23 bridge in southwest Meade County (Figure 5) has been increasing substantially with time (Figure 10). The chloride concentration of lower flows in the river ranged between 450 and 700 mg/L in the late 1960s and rose to between 900 and 1,200 mg/L by the late 1990s. The increase in chloride with time reflects a decrease in freshwater discharge from the High Plains aquifer to the river in central Seward County as a result of ground-water level declines in the aquifer. The natural discharge of saline ground water is still continuing but there is less freshwater from upstream to dilute the saline water.

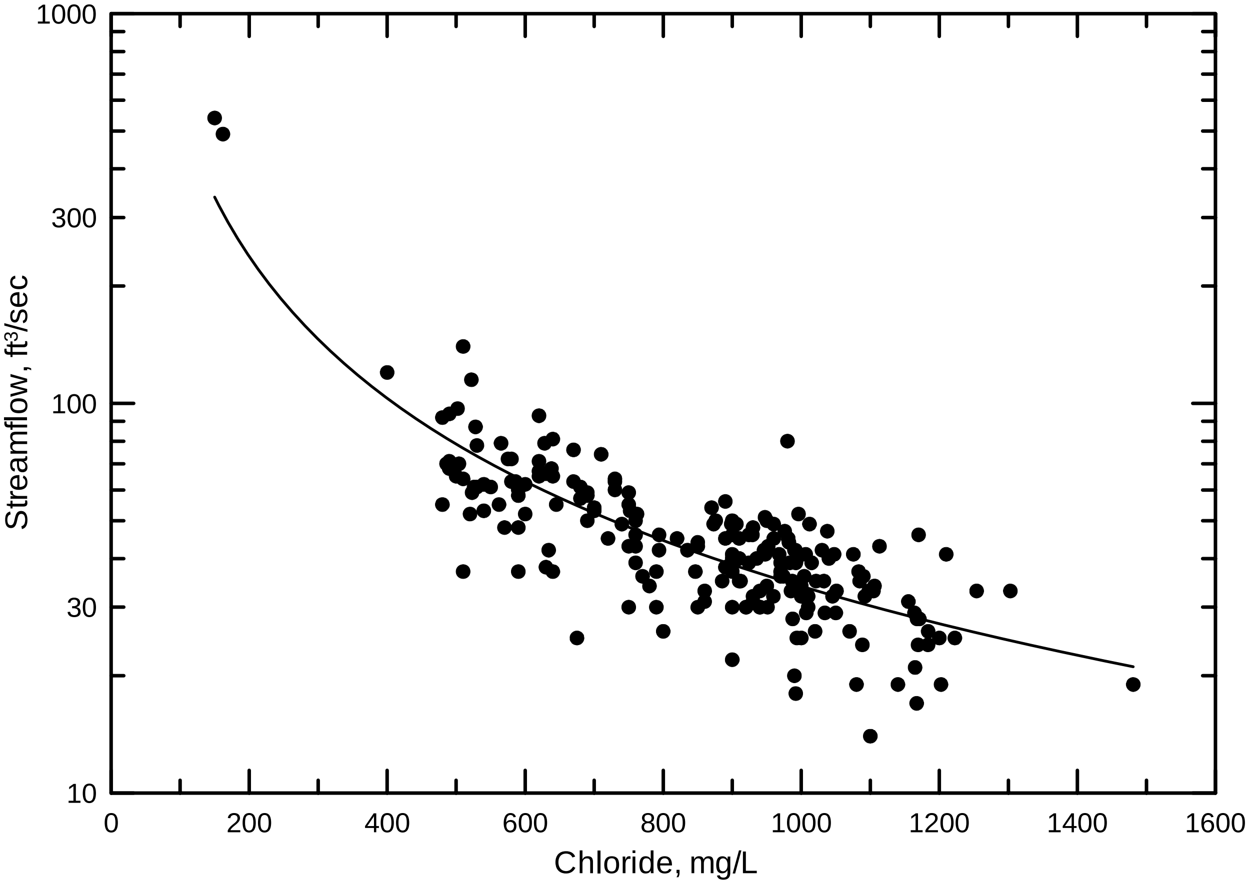


Figure 9. Chloride concentration versus flow in the Cimarron River in southwest Meade County near Forgan, Oklahoma. Data are from the USGS and KDHE for 1967-2004. The curve is a best-fit power function.

Prior to ground-water development, the surface of the ground-water table in the High Plains aquifer along the Cimarron River was relatively near the bottom of the river channel along the entire length of the river in Kansas. A cross section in McLaughlin (1946) along the river indicates that the ground-water table in the summers of 1941 and 1942 was above the river channel in most of the channel in Seward and southwestern Meade counties. A graph in McLaughlin (1946) based on streamflow measurements in 1942 and 1943 showed that the river generally gained flow from northwest Seward to southwest Meade County. A map of water-table contours for the Ogallala-High Plains aquifer in 1940 (Byrne and McLaughlin, 1948) indicates that the change from a ground-water level below to above the river channel was located in the northwest part of T. 32 S., R. 33 W in northwest Seward County. This is approximately the same vicinity as the start of the perennial portion of the river indicated on the USGS Sublette SW topographic quadrangle of 1968 based on aerial photographs of 1966.

Pumping from the aquifer has lowered the water table of the High Plains aquifer substantially below the bed of the Cimarron River from northwest to central Seward County. Well hydrographs and a cross section of water levels relative to the riverbed elevation in Young

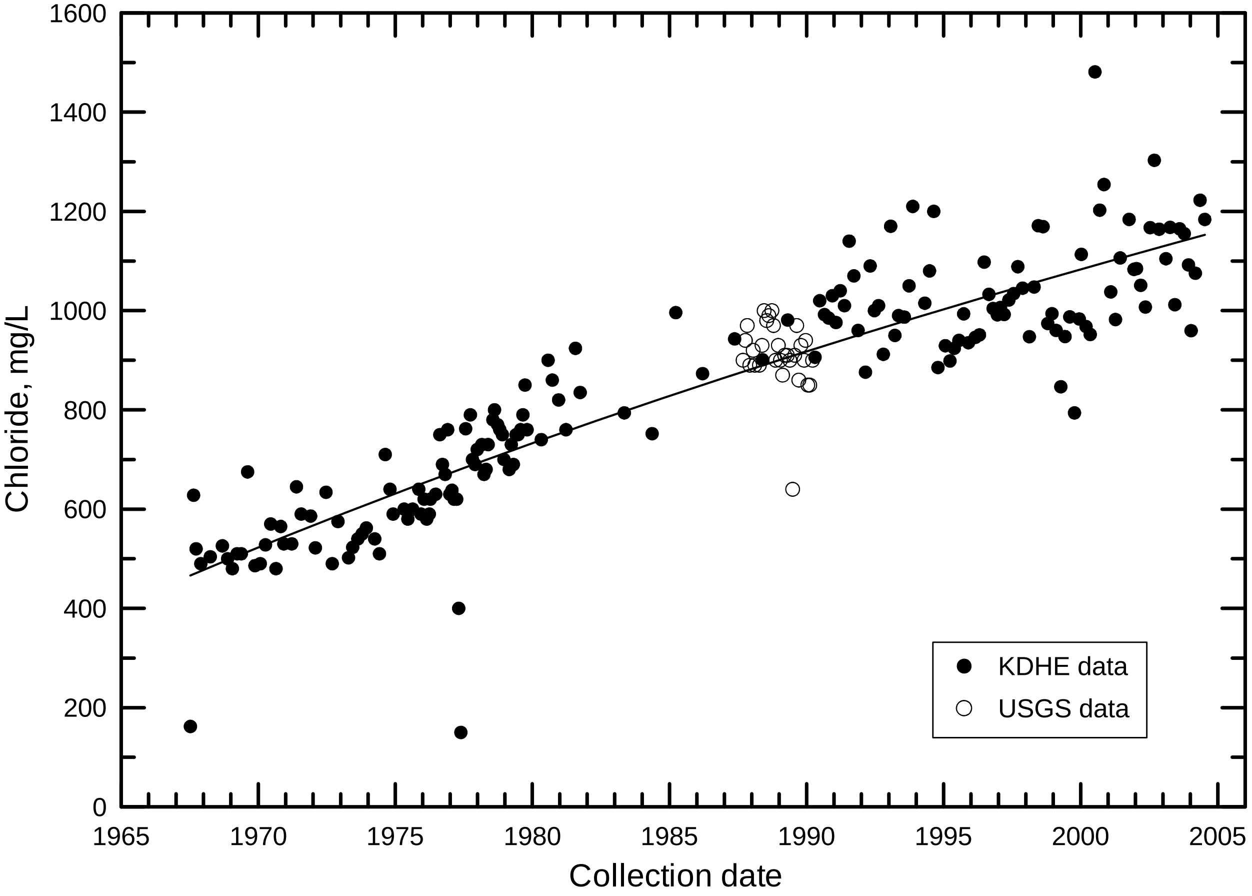


Figure 10. Chloride concentration versus date of sample collection for the Cimarron River in southwest Meade County near Forgan, Oklahoma. Data are from the USGS and KDHE. The curve is a best-fit log function.

et al. (2005) illustrate the water-level declines. The result is a decrease in ground-water discharge to the river, thereby decreasing the river flow with time. This is shown by the decline in the mean annual flow of the Cimarron River at the USGS gaging station in southwest Meade County north of Forgan, Oklahoma (Figure 11). The flow of the river at this gaging station during the last decade (1995-2004) has been less than half of that during 1966-1978. Additional information on changes in Cimarron River flows and High Plains aquifer water levels across the Cimarron basin is in Young et al. (2005).

Fluctuations in the mean annual flow (Figure 11), as well as the mean daily flow in the Cimarron River near Forgan (Figure 12), have also decreased with time. A probable explanation is the decrease in the runoff that can flow down the river channel upstream of the middle of Seward County during wet periods. As ground-water levels dropped in the alluvial aquifer of the river due to long-term water-level declines in the High Plains aquifer, an increasing amount of runoff entering the river valley from rainstorms seeped into the subsurface. Thus, river flow can now only be generated upstream of the middle of Seward County during rainstorms that are so

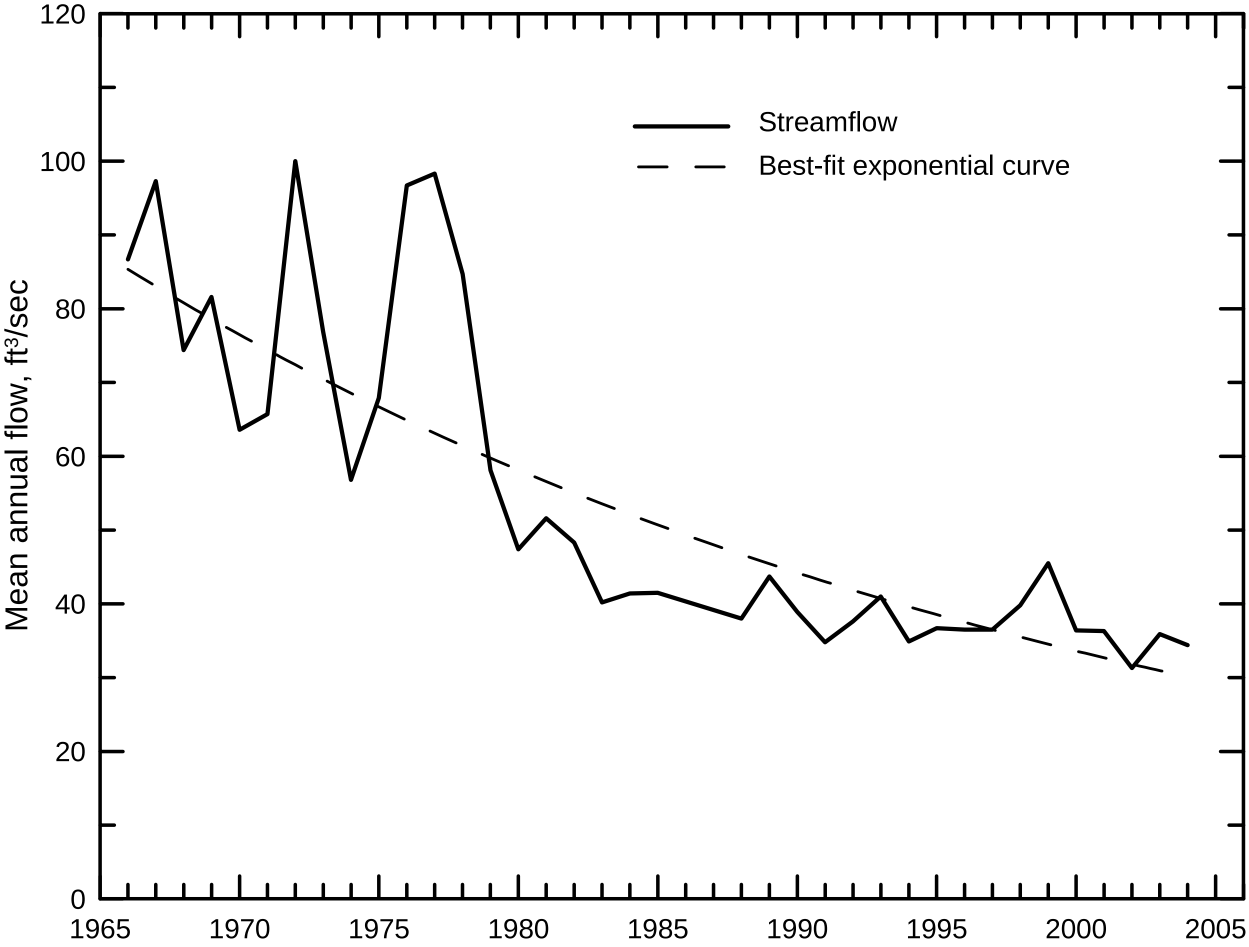


Figure 11. Mean annual flow versus time for the Cimarron River in southwest Meade County near Forgan, Oklahoma. Data are from the USGS.

intense that the flow rate in the river channel can exceed the infiltration into the alluvial sediments. In the present condition, most of the flow recorded in the river at the USGS gaging station near Forgan is expected to be sourced only from the portion of the watershed that extends upstream to the middle of Seward County.

The increase in the average chloride concentration of the Cimarron River near Forgan from the late 1960s to the period 2000-2004 is about a factor of two (from about 500 to 1,100 mg/L). The decrease in the mean daily flow for the collection date of the samples (Figure 13) in which the chloride was determined for the same period is also approximately a factor of two (from 70-80 ft^3/sec to 30-40 ft^3/sec). This implies that the chloride load in the river has remained constant as also indicated by Figure 14, which displays the chloride load in kg/sec (the product of the chloride concentration and river flow on the collection date.) The relatively constant load suggests that the intrusion of saline water from the High Plains aquifer (derived from the underlying Permian strata) into the Cimarron River has remained approximately constant with time during the flow decrease in the river. This is further corroborated by calculating the chloride load due to an assumed loss of fresh discharge from the High Plains aquifer into the

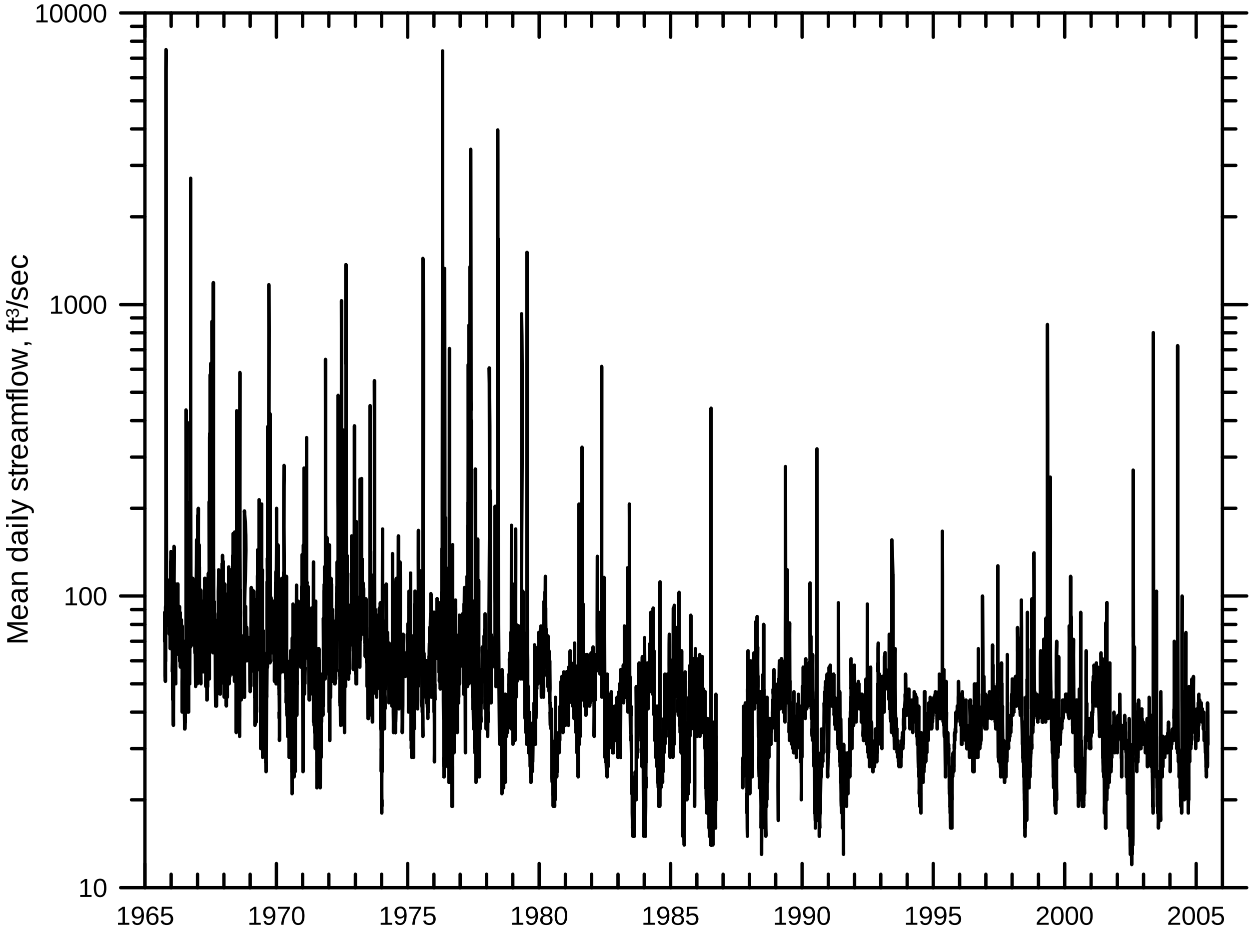


Figure 12. Mean daily flow versus time for the Cimarron River in southwest Meade County near Forgan, Oklahoma. Data are from the USGS.

alluvial aquifer and thence into the river upstream of the middle of Seward County. If the average concentration of chloride in the High Plains aquifer in the river corridor is 20 mg/L (Figure 3) and the loss in flow from the late 1960s to 2000-2004 is about 40 ft^3/sec, the loss in chloride load from fresh ground-water discharge is 0.0227 kg/sec. This is less than 3% of the approximate average of the total chloride load in the Cimarron River near Forgan during 1967-2004 (Figure 14). The value of 20 mg/L chloride content for ground-water discharge from the High Plains aquifer to the river upstream of the saline water intrusion fits the median chloride concentration of 20.5 mg/L for the Cimarron River northeast of Liberal based on 20 water-quality records of the USGS for the period 1962-1970.

The change in the river stage for the flow decrease from about 70-80 ft^3/sec to 30-40 ft^3/sec is <0.5 ft at the gaging station near Forgan based on USGS rating measurements. This difference is expected to be too small to significantly increase the amount of saline intrusion from the High Plains aquifer in the stretch of the river in southwest Meade County. The long-term water-level changes in the High Plains aquifer in or near the Cimarron River valley in southeast Seward County where the saline intrusion begins are relatively small. Therefore, little

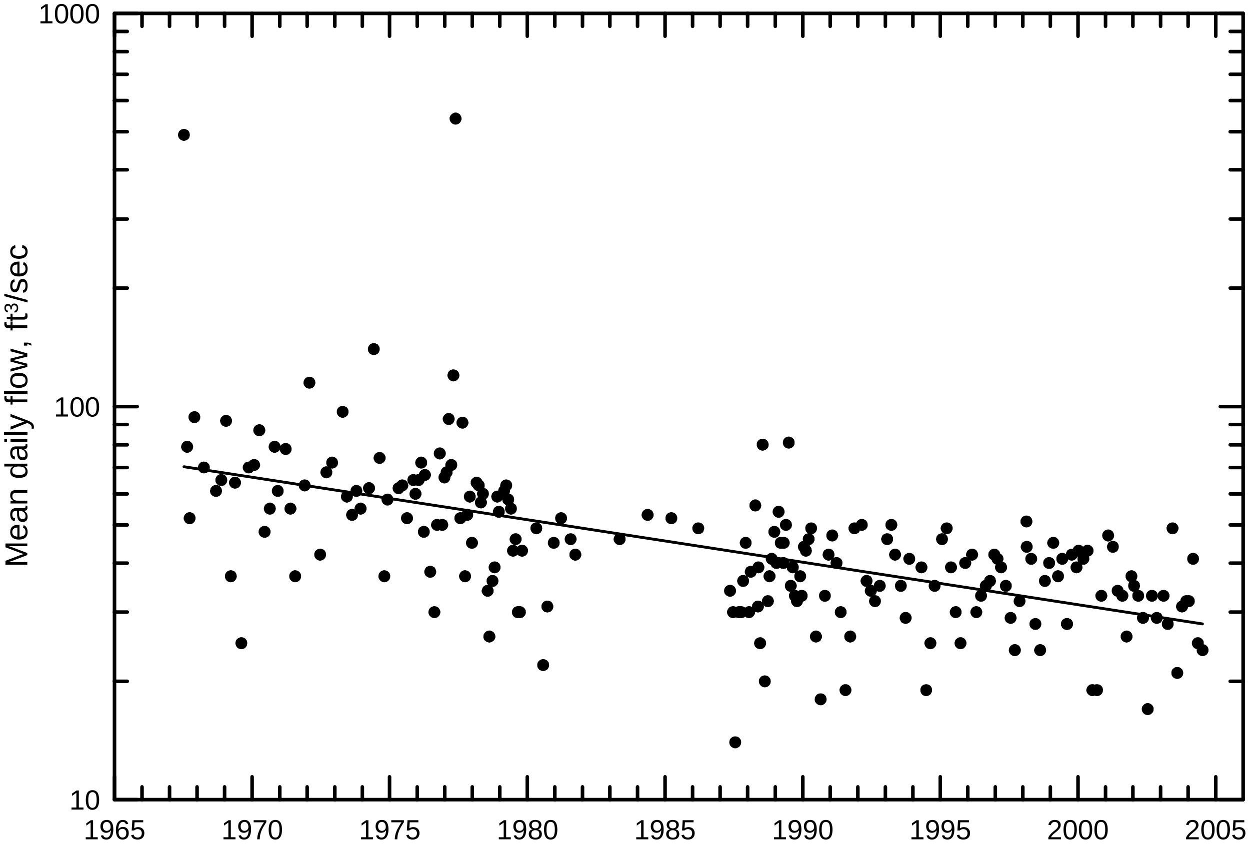


Figure 13. Mean daily flow versus date of water sample collection for the Cimarron River in southwest Meade County near Forgan, Oklahoma. The line is a best-fit exponential function. Data are from the USGS.

impact from changes in hydraulic head in the aquifer relative to the river channel in this area is expected on the saline water intrusion to the river. Water-level declines in the High Plains aquifer in south-central and southeast Seward County might increase the upward movement of deeper saline waters. However, the water-level declines in the area of the High Plains aquifer with chloride >100 mg/L are generally within the range 0-20 ft (Schloss et al., 2000; Bohling and Wilson, 2005), which are not as great as elsewhere in the Cimarron River basin due to the smaller amount of water use in the aquifer relative to the rest of southwest Kansas. Although upconing of saline water under pumping wells could affect the aquifer salinity locally, the slow movement of water in the aquifer means that it would take many decades or hundreds of years for the saline water to reach the Cimarron River.

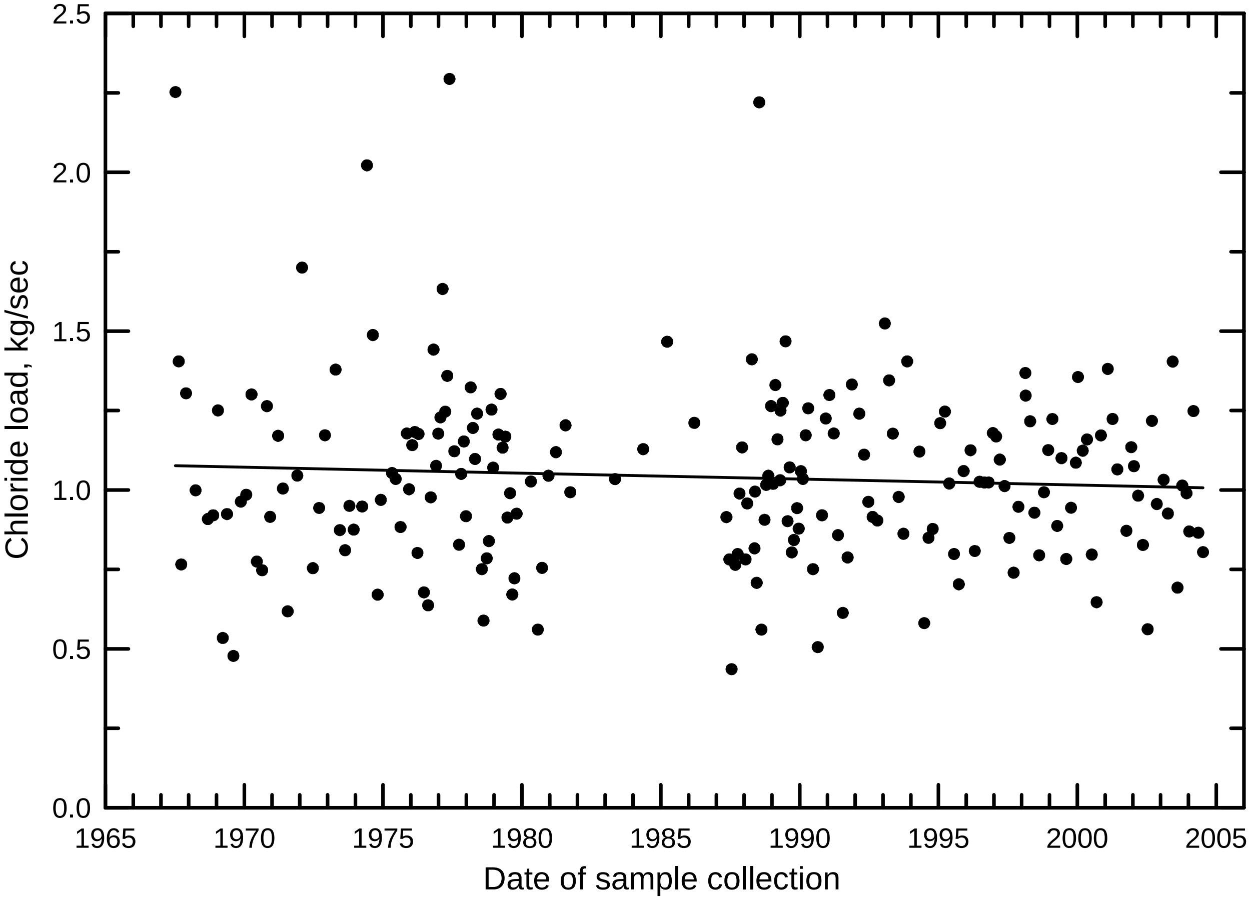


Figure 14. Chloride load versus date of water sample collection for the Cimarron River in southwest Meade County near Forgan, Oklahoma. The line is a best-fit linear regression. Data are from the USGS, KDHE, and Borell (1998).

CONCLUSIONS

Most of the ground water in the High Plains aquifer in Seward and Meade counties contains <500 mg/L TDS and <50 mg/L chloride concentration. The sulfate content of ground water in the aquifer in most of Meade County is lower (generally <100 mg/L) than in Seward County (usually 50-150 mg/L). Saline water (sodium-chloride chemical type) in the High Plains aquifer in southern Seward and Meade counties is derived from the intrusion of saline water from the underlying Permian strata. The saline water in the Permian rocks is from the dissolution of the evaporite minerals halite and anhydrite or gypsum. The chloride concentration at the base of the High Plains aquifer in southeastern Seward County can approach 2,000 mg/L at the base of the aquifer. Areas of the aquifer with a chloride concentration >150 mg/L extend from east of Liberal through southeast Seward County into southwest Meade County.

The saline ground water discharges into the alluvial aquifer and thence into the Cimarron River starting in southeast Seward County a few miles upstream of the Meade County border. The saline water intrusion increases substantially in southwest Meade County where the High Plains aquifer thins such that the chloride concentration can exceed 1,200 mg/L at low flow conditions. Although the sulfate content of the river water also increases in the stretch where the saline water intrudes, the chloride mass concentration is usually a few to several times greater than that of sulfate.

The salinity of the Cimarron River in southwest Meade County has increased substantially and steadily since the late 1960s. The average chloride concentration of equivalent flows is now approximately twice that in the late 1960s. The cause of the salinity increase is attributed primarily to the decrease in the discharge of fresh ground water from the High Plains aquifer in Seward County. The decrease in ground-water discharge has been caused by substantial declines in the water levels of the High Plains aquifer from consumptive pumping. The water levels in the aquifer are now substantially below the riverbed in northwest and central Seward County, such that runoff to the river valley from substantial precipitation events in northwest and central Seward County can infiltrate within the dry riverbed, thereby not contributing substantially to flow farther downstream. The decrease in runoff and ground-water discharge has reduced the current mean annual flow in the Cimarron River in southwest Meade County to about half that during the late 1960s. The decrease in runoff has also reduced the magnitude of the annual and daily fluctuations of river flow since the late 1960s.

The long-term trends in the salinity increase and flow decrease in the Cimarron River are continuing, although at somewhat slower rates than in the 1970s. This is probably due to declines in ground-water levels that continue in the High Plains aquifer, but at a slower rate in southeast Seward and southwest Meade counties, where discharge of ground water still continues, than elsewhere in the counties.

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Appendix A. Data used in the generation of Figures 2-4.

Source	Co	Twn	Rng	Sec	Quar	Well No.	Sample	Depth, ft	Latitude	Longitude	Date	Cl	SO4	TDS
USGS	ME	30S	26W	3	BA	2	1				9/6/39	6	26	265
KGS irrigation	ME	30S	26W	4	CBB						7/27/76	6.9	28	274
USGS	ME	30S	26W	5	CBB	2	1				9/20/40	7.5	29	230
USGS	ME	30S	26W	7	BBB	1	3				7/16/80	50	81	425
USGS	ME	30S	26W	16	BC	1	1				9/6/39	7	33	251
GMD3	ME	30S	26W	17	BBCC	9	3	230			1993	53	45	444
USGS	ME	30S	26W	30	DAB	1	1	238			7/16/80	19	38	275
KGS irrigation	ME	30S	26W	31	CBC						7/27/76	42	156	511
KGS-KDA irrigation	ME	30S	26W	32	DDD			183*	37.3881	100.1808	7/26/94	9.2	14.5	304
USGS	ME	30S	26W	35	DC	1	1				9/7/39	14	19	272
KGS irrigation	ME	30S	27W	4	DBD						7/27/76	30	99	393
USGS	ME	30S	27W	8	DD	1	1				9/8/39	11	79	342
GMD3	ME	30S	27W	20	CBAD	16	1	300			1990	4	18	217
KGS irrigation	ME	30S	27W	23	ABB						7/27/76	12	49	276
USGS	ME	30S	27W	24	BB	1	1				9/7/39	22	54	419
USGS	ME	30S	27W	29	AA	1	1				9/6/39	6.5	14	200
USGS	ME	30S	27W	33	CD	1	1				9/6/39	7	20	213
GMD3	ME	30S	28W	2	BAA	33	2	270			1993	13	27	287
GMD3	ME	30S	28W	17	ABC	4	2	311			1988	20	21	282
KGS irrigation	ME	30S	28W	17	ABB						7/27/76	14	26	241
GMD3	ME	30S	28W	22	CBB	16.1	2				1993	4	18	223
USGS	ME	30S	28W	25	CC	1	1				9/6/39	6	28	219
GMD3	ME	30S	28W	32	BBB	20	1	309			1990	4	15	212
GMD3	ME	30S	28W	33	C	20.1	2				1993	13	21	256
KGS irrigation	ME	30S	29W	3	DCC						7/27/76	4.4	27	222
USGS	ME	30S	29W	3	ABB	1	1				9/14/40	2	10	190
GMD3	ME	30S	29W	5	ACC	13	2	426			1992	12	27	264
GMD3	ME	30S	29W	17	AAD	9.1	1				1993	31	30	335
GMD3	ME	30S	29W	20	CBB	23	2	375			1993	6	21	224
KGS irrigation	ME	30S	29W	23	CAD						7/27/76	4.7	18	229
KGS irrigation	ME	30S	29W	28	BBB						7/27/76	3.1	25	221
KGS irrigation	ME	30S	30W	12	CBB						7/27/76	6.6	28	218
USGS	ME	30S	30W	12	CCC	1	1				6/6/67	6	19	223
GMD3	ME	30S	30W	20	BCCC	12	2	442			1992	22	45	302
KGS irrigation	ME	30S	30W	28	ABB						7/27/76	8.8	40	235
USGS	ME	31S	26W	6	BA	1	1				11/23/54	5.5	30	274
USGS	ME	31S	26W	30	BBB	1	1				11/20/74	12	48	333
USGS	ME	31S	27W	11	DB	1	1				9/6/39	6	33	220
USGS	ME	31S	27W	14	AB	1	1				8/15/40	330	950	2170
USGS	ME	31S	27W	20	AAA	1	1				7/25/75	12	59	206

Source	Co	Twn	Rng	Sec	Quar	Well No.	Sample	Depth, ft	Latitude	Longitude	Date	Cl	SO4	TDS
GMD3	ME	31S	27W	21	BBB	5	2	360			1991	10	45	257
GMD3	ME	31S	28W	8	ABB	15	2				1992	8	15	201
KGS irrigation	ME	31S	28W	10	BCB						7/27/76	12	23	244
USGS	ME	31S	28W	12	AA	1	1				9/6/39	8	18	218
USGS	ME	31S	28W	23	AC	1	1				9/10/64	9	30	271
USGS	ME	31S	28W	24	BA	1	1				9/6/39	5	18	205
GMD3	ME	31S	28W	27	DDD	14	2	200			1992	5	57	255
GMD3	ME	31S	28W	30	BAB	21.1	2				1993	36	39	375
USGS	ME	31S	28W	35	CA	1	1	150			9/6/39	4.5	17	201
GMD3	ME	31S	29W	4	ADCC	11	2	400			1992	10	24	251
USGS	ME	31S	29W	6	DD	1	1				8/20/40	7	33	221
USGS	ME	31S	29W	25	AAA	1	1	250			7/28/79	17	33	291
GMD3	ME	31S	29W	36	ACC	21	1				1990	6	24	236
KGS-KDA irrigation	ME	31S	30W	2	CDC				37.3730	100.5615	1996	4.4	36.5	241
GMD3	ME	31S	30W	3	CAA	18	2				1993	20	39	316
USGS	ME	31S	30W	4	CB	1	1				8/30/40	8.5	38	219
USGS	ME	31S	30W	16	BBC	1	3				7/14/80	14	40	271
GMD3	ME	31S	30W	34	BDD	10	2	382			1992	11	39	269
GMD3	SW	31S	31W	1	CBCB	11.1	2	513?			1993	11	54	265
KGS irrigation	SW	31S	31W	8	BCC						7/27/76	60	83	391
USGS	SW	31S	31W	12	CCB	1	1				4/26/66	8	52	276
KGS irrigation	SW	31S	31W	13	BCB						7/27/76	10	60	272
GMD3	SW	31S	31W	25	CBB	28	2	425			1993	14	108	332
GMD3	SW	31S	31W	29	CCBD	6	2	498			1991	15	93	330
USGS	SW	31S	31W	29	CCA	1	1				4/26/66	12	77	323
USGS	SW	31S	32W	3	DAD	1	10				8/3/89	26.3	88	424
GMD3	SW	31S	32W	4	CCC	23	1	555			1990	28	159	431
USGS	SW	31S	32W	4	AB	1	1				8/18/40	9.5	82	304
USGS	SW	31S	32W	5	CB	1	1				7/4/64	18	130	433
GMD3	SW	31S	32W	21	ABC	24	2	546			1993	39	204	510
KGS irrigation	SW	31S	32W	21	CBA						7/27/76	30	177	491
KGS irrigation	SW	31S	32W	34	CBB						7/27/76	20	168	466
KGS irrigation	SW	31S	33W	6	CBD						7/27/76	33	116	410
GMD3	SW	31S	33W	10	BBB	14	2	405			1992	26	159	433
GMD3	SW	31S	33W	29	DBB	26	2	590			1993	18	108	389
USGS	SW	31S	34W	5	AAA	1	1				8/18/40	11	110	385
USGS	SW	31S	34W	6	DA	1	1				8/18/40	11	45	288
USGS	SW	31S	34W	14	AB	1	1				8/17/40	9.5	84	328
KGS irrigation	SW	31S	34W	18	BBB						7/27/76	16	153	458
GMD3	SW	31S	34W	21	CBA	1	2	198			1991	25	150	443

Source	Co	Twn	Rng	Sec	Quar	Well No.	Sample	Depth, ft	Latitude	Longitude	Date	Cl	SO4	TDS
USGS	ME	32S	26W	2	DCA	1	1				4/22/71	20	23	340
USGS	ME	32S	26W	3	CD	1	1	36			9/7/39	19	29	282
USGS	ME	32S	26W	25	BB	1	1				9/11/40	5	5.1	254
USGS	ME	32S	27W	5	AD	1	1				9/11/39	51	65	361
USGS	ME	32S	27W	12	DDD	1	1				6/7/67	18	76	371
USGS	ME	32S	28W	2	CBB	1	3				6/19/68	9	23	228
USGS	ME	32S	28W	4	ABB	1	2				9/18/79	7	20	228
USGS	ME	32S	28W	6	BAB	1	1				5/11/66	5	23	227
USGS	ME	32S	28W	11	AB	1	2				1/9/41	31	35	258
USGS	ME	32S	28W	11	ABA	2	3				7/26/67	47	35	304
USGS	ME	32S	28W	11	ACB	1	1				6/8/64	18	24	245
USGS	ME	32S	28W	11	BA	1	7				8/3/89	8.1	26	245
GMD3	ME	32S	28W	12	DDD	26	1	120			1990	3	18	210
USGS	ME	32S	28W	13	BB	1	1				9/8/39	6	16	194
USGS	ME	32S	28W	14	AC	1	1				9/7/39	6	27	224
USGS	ME	32S	28W	14	DD	1	1				9/6/40	30	6	211
KGS irrigation	ME	32S	29W	5	CC						7/27/76	8.7	50	261
GMD3	ME	32S	29W	6	AAA	1	2				1991	6	36	240
GMD3	ME	32S	29W	7	BBB	31	1	372			1991	9	42	256
USGS	ME	32S	29W	10	BA	1	1				9/9/39	7.5	28	250
USGS	ME	32S	29W	12	DD	1	1				8/8/75	13	59	
USGS	ME	32S	29W	15	DC	1	1				9/6/40	4.5	39	235
USGS	ME	32S	29W	27	AAB	2	1	468			11/22/74	18	73	319
GMD3	ME	32S	29W	28	DAD	32	2	270			1993	15	48	297
KGS irrigation	ME	32S	30W	9	CCC						7/27/76	22	66	317
USGS	ME	32S	30W	16	CA	1	2				2/5/41	7	57	252
KGS-NAWQA	ME	32S	30W	21	BCC			350*			1999	19.0	78.6	348
KGS irrigation	ME	32S	30W	28	BBC						7/27/76	15	69	298
KGS irrigation	ME	32S	30W	35	CAA						7/27/76	13	73	309
USGS	ME	32S	30W	35	CDA	1	1				5/11/66	11	59	287
KGS irrigation	SW	32S	31W	8	BBB						7/27/76	13	78	334
USGS	SW	32S	31W	12	DA	1	1				8/18/40	9	57	258
GMD3	SW	32S	31W	22	BBC	29	2	480			1993	17	90	324
KGS-NAWQA	SW	32S	31W	25	BAA						1999	15.1	98.5	365
KGS irrigation	SW	32S	31W	26	CAA						7/27/76	22	91	362
KGS irrigation	SW	32S	31W	31	ACC						7/27/76	19	173	466
GMD3	SW	32S	32W	6	BCD	5	2	450			1991	63	144	579
USGS	SW	32S	32W	6	BCC	1	1				4/29/66	24	140	433
GMD3	SW	32S	32W	11	CAA	27	2	402			1993	21	132	391
USGS	SW	32S	32W	14	BBB	1	3				7/13/80	19	140	440

Source	Co	Twn	Rng	Sec	Quar	Well No.	Sample	Depth, ft	Latitude	Longitude	Date	Cl	SO4	TDS
USGS	SW	32S	32W	18	AB	1	1				4/24/64	17	120	397
KGS irrigation	SW	32S	32W	19	BAB						7/27/76	14	75	333
GMD3	SW	32S	32W	20	BBA	39.1	2				1993	24	117	398
USGS	SW	32S	32W	20	BBB	1	1				10/28/77	21	120	414
USGS	SW	32S	32W	22	ABB	1	1				4/26/66	17	160	469
Borell thesis	SW	32S	32W	30	AAD	QT-i					3/27/97	15.0	130	519
GMD3	SW	32S	32W	34	BAA	21	3				1993	14	123	361
KGS irrigation	SW	32S	33W	12	BCC						7/27/76	15	89	358
GMD3	SW	32S	33W	18	ACB	36	1	200			1991	13	105	353
GMD3	SW	32S	33W	21	CCD	10	2	100			1992	14	102	342
USGS	SW	32S	33W	21	CCA	1	1				11/14/74	23	140	566
USGS	SW	32S	33W	21	CDB	1	1				8/20/40	14	140	407
GMD3	SW	32S	33W	25	CA	39	1				1991	14	99	347
KGS-KDA irrigation	SW	32S	33W	25	CCA				37.2311	100.8648	6/13/94	11.8	107	384
KGS-KDA irrigation	SW	32S	33W	32	B				37.2135	100.9408	1996	13.1	118	401
Borell thesis	SW	32S	33W	35	DBA	T-f		280			10/3/97	15.5	160	610
USGS	SW	32S	33W	36	CDA	1	1				11/14/74	19	120	452
GMD3	SW	32S	34W	7	DC	25	1	460			1990	20	132	387
KGS irrigation	SW	32S	34W	10	DA						7/27/76	12	99	350
USGS	SW	32S	34W	11	CBC	1	1				4/26/66	13	110	388
USGS	SW	32S	34W	17	DCC	1	1				5/7/74	23	120	411
KGS-KDA irrigation	SW	32S	34W	21	DBD				37.2472	101.0188	7/20/94	21.4	107	412
USGS	SW	32S	34W	22	CA	1	1				4/23/64	17	120	400
KGS irrigation	SW	32S	34W	32	BBB						7/27/76	19	122	406
GMD3	SW	32S	34W	33	DAA	15	2	520			1992	34	141	468
USGS	ME	33S	26W	16	DA	1	1				9/11/40	220	60	702
USGS	ME	33S	27W	4	BB	1	1				9/11/39	11	26	280
USGS	ME	33S	27W	26	CDD	1	1				6/6/67	220	73	695
GMD3	ME	33S	28W	4	AAC	30	1	150			1990	13	33	268
USGS	ME	33S	28W	4	AA	1	1	75			9/9/39	10	31	222
USGS	ME	33S	28W	8	ABB	1	1	340			7/16/80	16	50	278
USGS	ME	33S	28W	14	DD	1	1				9/8/39	290	85	816
KGS irrigation	ME	33S	28W	29	BC						7/27/76	118	60	471
USGS	ME	33S	28W	29	CBC	1	1	120			7/15/80	270	77	785
USGS	ME	33S	28W	31	AD	1	1				9/6/39	320	84	827
GMD3	ME	33S	29W	1	BAA	19	2				1993	28	54	342
USGS	ME	33S	29W	15	DC	1	1				8/16/40	10	46	243
USGS	ME	33S	29W	15	DDA	1	1	300			7/28/79	10	61	304
USGS	ME	33S	29W	15	DDD	1	1				4/7/70	14	56	296
USGS	ME	33S	29W	19	BCC	1	1				6/6/67	9	56	297

Source	Co	Twn	Rng	Sec	Quar	Well No.	Sample	Depth, ft	Latitude	Longitude	Date	Cl	SO4	TDS
USGS	ME	33S	29W	24	BB	1	1				8/15/40	8.5	28	226
GMD3	ME	33S	29W	32	ADB	8	2	445			1992	13	48	296
USGS	ME	33S	29W	32	AAD	1	3				7/13/80	13	60	290
KGS irrigation	ME	33S	29W	36	AAB						7/27/76	445	108	1097
GMD3	ME	33S	30W	8	BBAA	7	2				1992	23	81	361
USGS	ME	33S	30W	18	DBA	1	1	425			7/14/80	13	220	522
USGS	ME	33S	30W	31	CA	1	1				8/27/40	8	53	291
GMD3	ME	33S	30W	32	C	24	1	376			1990	8	66	297
GMD3	ME	33S	30W	35	D	6	2	396			1991	9	63	277
KGS irrigation	ME	33S	30W	35	CB						7/27/76	11	74	298
USGS	SW	33S	31W	4	CAA	1	2				4/11/67	17	130	427
USGS	SW	33S	31W	4	CBA	1	1				4/25/66	13	110	392
USGS	SW	33S	31W	4	CD	1	1				2/13/39	13	99	389
USGS	SW	33S	31W	4	CDA	1	4				7/16/62	17	120	402
GMD3	SW	33S	31W	7	A	3	2				1991	15	135	376
KGS-KDA irrigation	SW	33S	31W	16	BCC				37.1778	100.7063	7/28/94	16.2	156	460
Borell thesis	SW	33S	31W	19	ABB	QT-l		300			8/30/97	18.6	148	551
GMD3	SW	33S	31W	21	D	20	2	452			1992	16	141	400
USGS	SW	33S	31W	23	DD	1	2				8/18/64	13	130	386
Borell thesis	SW	33S	31W	30	CAB	QT-f					8/30/97	19.6	128	478
Borell thesis	SW	33S	31W	31	BBA	QT-n		78			10/3/97	15.5	160	575
KGS-KDA irrigation	SW	33S	32W	1	DAA				37.1988	100.7601	1997	41.0	127	478
Borell thesis	SW	33S	32W	17	BD	QT-o		200			10/3/97	18.7	140	597
GMD3	SW	33S	32W	20	BCC	32	1				1990	23	168	464
USGS	SW	33S	32W	20	ACD	1	1				11/14/74	21	140	461
USGS	SW	33S	32W	23	ADA	1	1	232			7/27/79	12	130	430
USGS	SW	33S	32W	25	ACC	1	1				11/14/74	40	150	492
Borell thesis	SW	33S	32W	26	DDD	T-h		171			10/3/97	52.8	155	641
USGS	SW	33S	32W	28	CDD	2	1				10/10/74	96	150	577
GMD3	SW	33S	32W	32		34	1				1990	19	72	362
Borell thesis	SW	33S	32W	35	CAC	QT-u	4				10/3/97	277.0	180	987
Borell thesis	SW	33S	32W	36	BCD	QT-k					8/30/97	83.5	60	534
Borell thesis	SW	33S	33W	1	DCD	QT-p		220			10/3/97	17.6	170	599
USGS	SW	33S	33W	2	A	1	3				7/16/80	24	110	413
GMD3	SW	33S	33W	4	C	35	1	330			1990	18	123	409
USGS	SW	33S	33W	11	CAD	1	1	360			7/27/79	13	140	450
KGS irrigation	SW	33S	33W	12	AAD						7/27/76	14	109	407
Borell thesis	SW	33S	33W	25	DCCC	QT-j					7/4/97	25.2	115	532
KGS-KDA irrigation	SW	33S	33W	30	AAA				37.1412	100.9581	1997	28.3	150	472
GMD3	SW	33S	33W	33	CAAD	16	2	500			1992	15	87	355

Source	Co	Twn	Rng	Sec	Quar	Well No.	Sample	Depth, ft	Latitude	Longitude	Date	Cl	SO4	TDS
Borell thesis	SW	33S	33W	36	CBB	QT-g		280			3/27/97	23.2	80	496
GMD3	SW	33S	34W	20	BBB	30	1	560			1990	16	180	413
KGS-KDA irrigation	SW	33S	34W	21	DBB				37.1554	101.0308	1997	14.5	184	505
USGS	ME	34S	26W	24	CB	1	1				8/19/40	22	51	300
USGS	ME	34S	27W	7	DC	1	1				9/11/40	92	45	430
USGS	ME	34S	27W	23	BAD	1	1				9/11/40	10	15	224
USGS	ME	34S	27W	33	CC	1	1				9/4/40	27	260	697
GMD3	ME	34S	28W	5	B	3	2	250			1991	369	78	1627
USGS	ME	34S	28W	19	BD	1	1				8/31/40	53	160	493
GMD3	ME	34S	28W	31	AAA	27	1	160			1990	65	102	555
USGS	ME	34S	28W	34	AA	1	2				8/15/40	25	30	422
Borell thesis	ME	34S	29W	1	B	QT-t		330			3/28/97	131.3	235	847
KGS-NAWQA	ME	34S	29W	3	BBC			210			4/23/99	119	151	583
Borell thesis	ME	34S	29W	6	ADB	QT-b		275			10/24/97	11.4	72	415
Borell thesis	ME	34S	29W	17	ADB	QT-c		300			10/24/97	11.4	72	421
GMD3	ME	34S	29W	32	AAA	28	1	280			1990	14	171	490
Borell thesis	ME	34S	30W	2	A	QT-d					3/28/97	28.3	65	437
Borell thesis	ME	34S	30W	12	BCA	QT-e					3/28/97	18.2	78	460
GMD3	ME	34S	30W	22	CCBB	34	1				1991	10	57	302
USGS	ME	34S	30W	22	CBC	1	1	280			7/15/80	13	68	319
USGS	ME	34S	30W	26	AA	1	1				8/29/40	10	61	271
USGS	ME	34S	30W	27	BBB	2	1				11/20/74	21	200	494
Borell thesis	ME	34S	30W	29	BA	T-c		270			10/5/97	11.4	120	508
GMD3	ME	34S	30W	31	DC	25	1				1990	18	66	324
USGS	ME	34S	30W	31	BBC	1	1				11/14/74	190	150	739
Borell thesis	ME	34S	30W	31	ABB	T-i	2	340			2/20/98	1002	290	2309
Borell thesis	ME	34S	30W	32	ADD	T-b	2	360			2/20/98	37.8	65	459
GMD3	SW	34S	31W	5	C	31	1				1990	14	147	379
Borell thesis	SW	34S	31W	13	BB	QT-h					8/30/97	16.5	96	516
Borell thesis	SW	34S	31W	13	BC	QT-m		280			10/3/97	16.6	135	564
USGS	SW	34S	31W	15	CBA	1	1				11/14/74	98	150	608
KGS83361	SW	34S	31W	22	DBD	1					7/27/83	170	86	
Borell thesis	SW	34S	31W	23	DB	Al-b		60			2/20/98	36.8	130	578
Borell thesis	SW	34S	31W	24	BC	T-g		220			10/3/97	37.3	175	623
Borell thesis	SW	34S	31W	27	ACC	T-e		112			7/4/97	116.0	67	587
USGS	SW	34S	31W	30	BBB	2	1				10/22/74	1270	200	2420
USGS	SW	34S	31W	30	BBB	3	1				7/22/75	100	77	403
KGS920155	SW	34S	31W	32	CAD		Irrigation well				1992	351	88	
GMD3	SW	34S	31W	34	CCCB	33	1	440			1990	144	54	788

Source	Co	Twn	Rng	Sec	Quar	Well No.	Sample	Depth, ft	Latitude	Longitude	Date	Cl	SO4	TDS
KGS83363	SW	34S	32W	5	DDC	1	AMIGO CIR#1				7/27/83	23	54	
KDHE162	SW	34S	32W	6	BAC	1	AMIGO RANCH				7/27/83	27	113	412
USGS	SW	34S	32W	8	AAB	1	1	360			7/27/79	19	59	353
GMD3	SW	34S	32W	9	D	2	2	300			1991	32	75	374
KGS-KDA irrigation	SW	34S	32W	10	CBB				37.0973	100.7958	1997	563	153	1317
Borell thesis	SW	34S	32W	12	AD	QT-q		186			10/3/97	40.0	143	609
KGS83366	SW	34S	32W	17	BAB	1	COPE				7/27/83	173	125	
KGS83362	SW	34S	32W	23	DDB	1					7/27/83	266	89	
KGS83354	SW	34S	32W	27	CBD	1	Public W.S.				7/27/83	72	60	
GMD3	SW	34S	32W	28	BBB	17	2	430			1992	401	129	1655
KDHE161	SW	34S	32W	28	BAA	1					7/27/83	603	120	1333
KGS83355	SW	34S	32W	29	BAA	1	Cope #2				7/27/83	89	72	
KDHE168	SW	34S	32W	31	BDD	1					7/27/83	48	49	371
KGS-NAWQA	SW	34S	32W	32	DBD						1999	216	86	698
GMD3	SW	34S	32W	35	AAD	18	2	285			1992	86	45	593
KGS irrigation	SW	34S	32W	35	ADA						7/27/76	170	74	614
KGS-NAWQA	SW	34S	33W	25	AA			265			4/15/99	19.6	57.6	335
GMD3	SW	34S	33W	26	CCC	13	2	215			1992	415	21	1832
USGS	SW	34S	33W	32	AA	3	3				6/17/85	13	65	329
USGS	SW	34S	33W	32	AAA	1	1				7/1/64	19	76	362
USGS	SW	34S	33W	32	AAC	1	1				6/14/88	8.3	75	335
USGS	SW	34S	33W	32	ADB	1	5				8/12/87	14.2	75	342
GMD3	SW	34S	33W	34	BAA	9	3				1991	571	45	2399
GMD3	SW	34S	34W	4	DBBC	38	1				1991	13	126	344
GMD3	SW	34S	34W	16	BDD	38.1	2				1993	53	57	403
USGS	SW	34S	34W	16	DAA	1	2				9/6/78	17	120	371
GMD3	SW	34S	34W	26	B	12	2	462			1992	14	93	309
GMD3	SW	34S	34W	30	BBB	7	2	518			1991	32	27	337
USGS	ME	35S	27W	1	B	1	1				3/10/72	1000	160	2080
USGS	ME	35S	28W	18	DAD	1	1				11/21/74	670	180	1530
Borell thesis	ME	35S	29W	2	ABD	QP		156			7/26/97	1666	160	3137
Borell thesis	ME	35S	29W	3	DD	AP-g		155			2/20/98	5410	415	9022
USGS	ME	35S	29W	8	DDC	1	1				11/14/74	620	180	1460
Borell thesis	ME	35S	29W	8	DCA	AP-d	1	260			1/7/97	2035	260	4113
GMD3	ME	35S	29W	9	CCC	29	1				1990	98	90	664
Borell thesis	ME	35S	29W	9	BAB	AP-f		80			7/26/97	3228	260	5746
USGS	ME	35S	29W	10	BCD	1	1				11/14/74	650	180	1520
Borell thesis	ME	35S	29W	10	ADA	AP-h		40			7/26/97	5206	1200	10280

Source	Co	Twn	Rng	Sec	Quar	Well No.	Sample	Depth, ft	Latitude	Longitude	Date	Cl	SO4	TDS
Borell thesis	ME	35S	29W	11	BBB	AP-e		155			7/26/97	2603	160	4517
Borell thesis	ME	35S	29W	13	A	AP-b		100			1/7/97	913	260	2142
Borell thesis	ME	35S	29W	15	ABB	QT-a		210			7/26/97	7.2	24	403
Borell thesis	ME	35S	29W	15	DBB	QT-s		305			7/26/97	83.3	140	813
USGS	ME	35S	30W	4	CCA	1	1	100			7/29/79	44	91	398
Borell thesis	ME	35S	30W	6	AA	Al-a		200			2/20/98	35.8	97	509
USGS	ME	35S	30W	9	CCB	1	1				11/14/74	220	150	772
Borell thesis	ME	35S	30W	9		Al-c	1	140			3/28/97	207	88	781
GMD3	ME	35S	30W	10	C	2	2	120			1991	15	48	316
USGS	ME	35S	30W	10	CDB	1	7				7/28/88	498	104	1150
USGS	ME	35S	30W	13	BBB	1	1				11/14/74	580	170	1400
Borell thesis	ME	35S	30W	13	AAA	Al-e		80			2/20/98	1132	120	2385
Borell thesis	SW	35S	31W	1	CAB	T-a					7/4/97	18.2	23	356
KDHE167	SW	35S	31W	4	BDB	1	Frantz	300			7/27/83	110	48	486
KDHE449	SW	35S	31W	4	BDD	1	Frantz				8/18/82	121	47	517
KDHE2114	SW	35S	31W	4	CDB	1	Frantz	300			4/22/82	108	34	456
KGS83359	SW	35S	31W	4	DDB	1	Frantz	415			7/27/83	162	47	
KDHE165	SW	35S	31W	5	ABD	1	Frantz				7/27/83	203	59	639
KDHE1570	SW	35S	31W	5	BAB	1	Holmes				2/19/82	155	47	538
KDHE166	SW	35S	31W	5	DBD	1	Frantz	400			7/27/83	428	92	1033
KGS920156	SW	35S	31W	5	CAA		House well	200			1992	98.5	41	
KDHE447	SW	35S	31W	7	DCC	1					8/18/82	112	48	480
KDHE2116	SW	35S	31W	10	ACA	1	Lauderback				4/22/82	99	46	465
KGS83364	SW	35S	31W	18	ADD	1	Dip samp, OWS				7/27/83	48	36	
KDHE508	SW	35S	32W	1	CDB	1					8/29/83	49	31	349
KDHE164	SW	35S	32W	2	AAA	1	PE Compr Plt				7/27/83	201	65	640
KDHE507	SW	35S	32W	2	DAD	1	Abandoned				8/29/83	814	126	1650
GMD3	SW	35S	32W	5	ABB	19	2	260			1992	79	21	570
KGS-NAWQA	SW	35S	32W	6	CBB						1999	270	115	842
KDHE160	SW	35S	32W	12	ADB	1					7/27/83	206	65	646
GMD3	SW	35S	33W	10	BCDD	4	2	190			1991	17	39	282
KGS irrigation	SW	35S	33W	16	BCA						7/27/76	15	72	312
GMD3	SW	35S	34W	10	CBB	37	1	360			1991	73	51	525
USGS	SW	35S	34W	10	BBB	1	5				7/17/80	180	120	696
KDHE PWS	ME					5	7		37.27839	100.34357	8/28/93	7.1	25.0	226
KDHE PWS	ME					3	1		37.26452	100.59424	5/12/88	14.6	57.0	293
KDHE PWS	ME					4	1		37.26187	100.58596	5/12/88	12.7	71.0	305
KDHE PWS	ME					5	1		37.27091	100.58925	5/12/88	12.4	63.0	292

Source	Co	Twn	Rng	Sec	Quar	Well No.	Sample	Depth, ft	Latitude	Longitude	Date	Cl	SO4	TDS
KDHE PWS	SW					1	1		37.14591	100.76312	8/8/91	24.6	128	416
KDHE PWS	SW					6	6		37.05222	100.92529	8/16/93	19.4	74.0	339
KDHE PWS	SW					22	1		37.02379	100.93049	12/15/88	11.6	60.0	
KDHE PWS	SW					2	1		37.00728	100.97821	3/4/92	11.6	34.0	
KDHE PWS	SW					1	1		37.09259	100.79065	7/18/94	64.9	74.0	
USGS-NAWQA	SW					4		160	370033	1005342	8/27/99	20.0	21.4	331
USGS-NAWQA	SW					3		319	370033	1005342	8/27/99	9.2	61.0	311
USGS-NAWQA	SW					2		436	370033	1005342	8/26/99	9.8	59.5	309
USGS-NAWQA	SW					1		570	370033	1005342	8/26/99	12.7	87.4	364
Average for 4 wells	SW					Ave.						13	573	329
USGS-NAWQA	SW	34S	31W	22	BDD	4		65	370434	1004052	9/1/99	71.4	36.7	370
USGS-NAWQA	SW	34S	31W	22	BDD	3		210	370434	1004052	8/31/99	52.5	76.5	414
USGS-NAWQA	SW	34S	31W	22	BDD	2		336	370434	1004052	9/1/99	1861	261	4030
Weighted ave. for 3 wells	SW	34S	31W	22	BDD	Ave.						418	105	1128