Distribution and Change in Salinity in the Equus Beds Aquifer in the Burrton Intensive Groundwater Use Control Area

A report for
Kansas Department of Agriculture, Division of Water Resources

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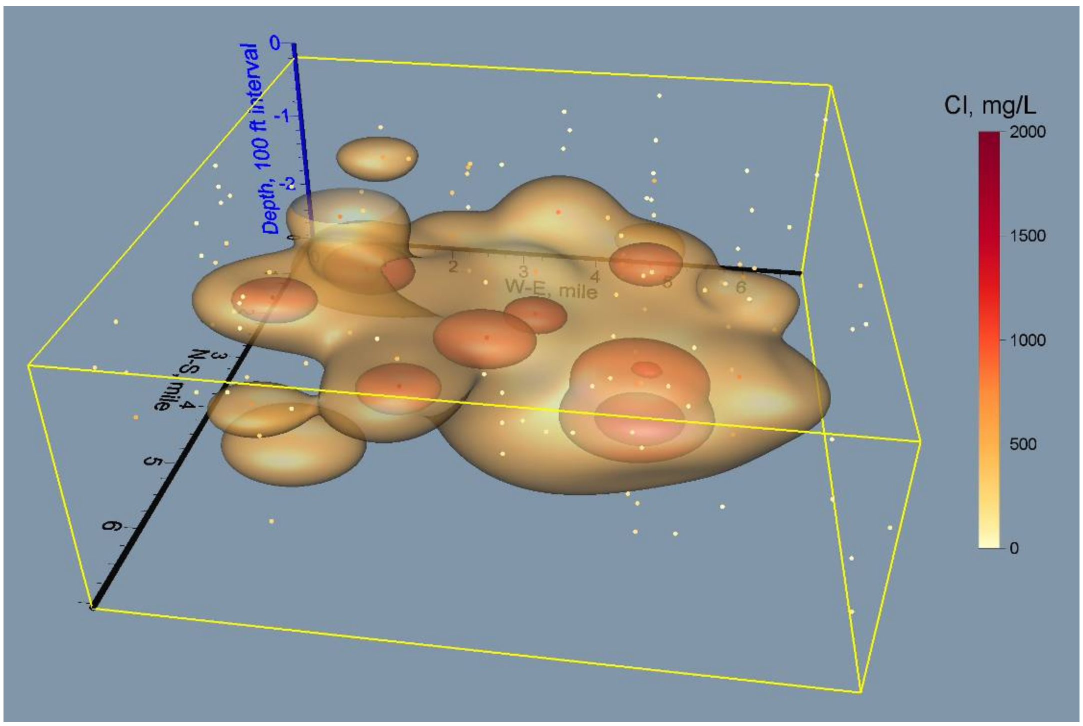

3D view of the saline water plume in the Burrton Intensive Groundwater Control Area

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ACKNOWLEDGMENTS

Much of this report was extracted from a report for Equus Beds Groundwater Management District No. 2 (GMD2) on a study that was partially funded by the District. John Woods and Michael Dealy of the Kansas Geological Survey contributed to some parts of the GMD2 report that are included in this report. GMD2 staff provided most of the chemical data for the area of the Burrton salinity plume; City of Wichita staff provided additional data. The Division of Water Resources in the Kansas Department of Agriculture (DWR) and Michael Dealy and James Butler, Jr. of the Kansas Geological Survey provided review comments on this report. The first version of the report produced at the end of December 2011 was later revised to expand discussion of the bedrock surface underlying the Burrton IGUCA in response to questions from the DWR.

EXECUTIVE SUMMARY

Past practices of saltwater disposal associated with the production of oil and gas in the Burrton area of west-central Harvey and east-central Reno counties contaminated fresh ground water in the Equus Beds area of the High Plains aquifer. Saltwater was disposed in surface ponds for about a decade following the discovery of the Burrton oil field in the early 1930s. During this period, a large percentage of the saltwater entered the ground water of the area.

The Burrton Intensive Groundwater Use Control Area (IGUCA) was established in 1984 as a result of concerns of Equus Beds Groundwater Management District No. 2 (GMD2) with the effect of irrigation development on accelerated movement of the saltwater plume. A recent Kansas Administrative Regulation requires that the Burrton IGUCA order be reviewed. The Kansas Department of Agriculture, Division of Water Resources (DWR) has begun the review. The Kansas Geological Survey is providing information on the Burrton saltwater plume in this report to assist the DWR in the technical part of the review process.

Water-quality data were assembled for GMD2 monitoring wells, irrigation wells, and municipal wells of the City of Wichita. Quality control methods were used to identify anomalous values in the data base and to correct them where possible. Graphical and statistical analyses of the data were used to characterize chloride concentration changes in the Burrton salinity plume.

The Burrton plume has migrated eastward and into the deeper portion of the aquifer with time. Substantial clay layers within the aquifer restricted the rate of vertical movement of saltwater and promoted a lateral and vertical “stair-stepping” migration of salinity. The front of the plume, as indicated by the 500 mg/L chloride isosurface, is about a mile away from the nearest municipal supply well in the Wichita well field. During 1982-2010, the plume front advanced at a rate of about 0.8-1.0 ft/day to the east, for a total migration of approximately 1.5 to over 2 miles.

An analysis of mean chloride concentration versus time in ground water sampled by the monitoring network indicates that no statistically significant trend has occurred in the Burrton plume area. This represents a conservation of chloride mass within the aquifer.

A total of 87 permitted points of diversion with active water use exist for supply wells within the IGUCA. The chloride concentration range and median for 35 of these wells (for which sample data exist) are 5-804 mg/L and 112 mg/L, respectively. Long-term changes in the chloride concentration of water pumped from these wells are generally consistent with the eastward and downward movement of saline ground water in the plume, along with dilution by fresh ground water and recharge. Some redistribution of the chloride mass occurs in the plume from the pumping of slightly saline water from within the aquifer to the surface by irrigation wells, followed by infiltration of saline soil moisture to the underlying shallow aquifer.

Based on this study, two additional monitoring wells are recommended for improving the detection of migrating salinity in the Burrton plume. One well is recommended for sampling the middle level of the aquifer near the edge of the advancing salinity plume. Another well is suggested for monitoring the salinity in the center of the Burrton plume where no monitoring site exists. An alternative to this monitoring well is sampling of a deep domestic well at this location.

INTRODUCTION

Past practices of saltwater disposal associated with the production of oil and gas in the Burrton area of west-central Harvey and east-central Reno counties contaminated fresh ground water in the Equus Beds area of the High Plains aquifer (Figure 1). Saltwater was disposed in surface ponds during about a decade following the discovery of the Burrton oil field. During this period, a large percentage of the estimated 1.9 million tons of salt associated with the produced brine entered the ground water of the area (Burrton Task Force, 1984). This type of disposal practice was later prohibited and replaced with regulated deep subsurface disposal of the brine.

The Burrton oil field was discovered in the early 1930s. As of April 2011, 1,271 total wells were in the field, which included 395 productive oil wells, 17 productive gas wells, and 141 abandoned wells (KGS online Digital Petroleum Atlas, http://chasm.kgs.ku.edu/pls/abyss/gemini.dpa_general_pkg.build_general_web_page?sFieldKID=1000148944). The field boundaries are shown in Figure 2 along with the locations of both current and past oil and gas wells.

Ground-water monitoring began in the Burrton area in the late 1930s by the City of Wichita to assess the brine contamination of the aquifer. After Equus Beds Groundwater Management District No. 2 (GMD2) was established in 1975, a well network was constructed for monitoring ground-water quality and water levels. The first monitoring wells in the network were installed and sampled in 1979 in the Burrton oil field area to improve both the areal and depth assessment of saltwater contamination (GMD2, 1995).

Substantial irrigation development occurred during the 1970s and early 1980s in the Equus Beds aquifer. GMD2 became concerned that increased pumping of ground water could accelerate movement of the Burrton saltwater plume into freshwater areas of the aquifer. After some initial study of the saltwater movement, GMD2 requested in 1982 that the Chief Engineer of the Division of Water Resources (DWR) initiate proceedings for the designation of an Intensive Groundwater Use Control Area (IGUCA) in a 36-square-mile area around Burrton (Burrton Task Force, 1984). After the Chief Engineer held a public hearing concerning an IGUCA in 1982, he appointed a task force to further study the area. The study included delineation of the salinity distribution, modeling of the plume migration, geochemical identification of saltwater, and assessment of oil- and gas-brine disposal practices. The geochemical identification determined that essentially all of the chloride above background concentration in the Burrton plume originated from oil brine rather than from natural saltwater in the Arkansas River corridor (Whittemore, 1982).

After an additional hearing in 1984, the Chief Engineer issued the order for the Burrton IGUCA. Provisions of the order include that all applications for a permit to appropriate water or to change an existing permit be approved on a case-by-case basis that considers the hydrology and water quality of the aquifer. The order also states that GMD2 annually review hydrologic data in the IGUCA.

The recent Kansas Administrative Regulation K.A.R. 5-20-2 requires that the Burrton IGUCA order be reviewed. The DWR has begun the review, which includes data gathering and analysis and at least one informal technical review meeting with the public (http://www.ksda.gov/appropriation/content/291/cid/1350). The Kansas Geological Survey (KGS) is providing information on the Burrton saltwater plume in this report to assist the DWR in the technical review process. The DWR will then hold a public hearing, followed by the Chief Engineer issuing findings and an order concerning the Burrton IGUCA.

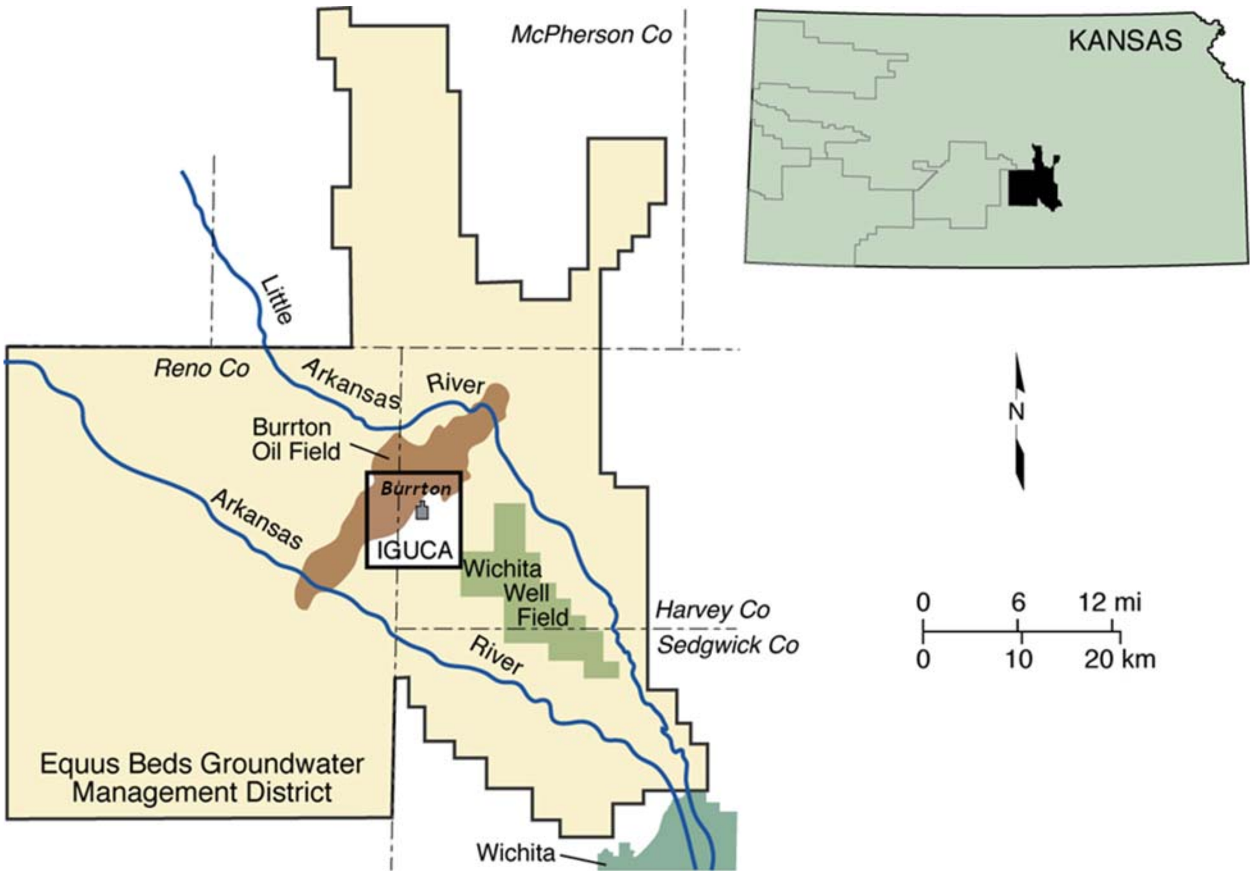

Figure 1. Location of Burrton Intensive Groundwater Control Area (IGUCA), Burrton oil field, and Wichita municipal well field in GMD2.

DATA SOURCES AND QUALITY CONTROL

GMD2 provided water-quality data for their monitoring network and supply wells (primarily irrigation use) in the Burrton area, along with location and depth information for the wells. Monitoring wells designated as EB in their site identification labels were constructed as a part of a GMD2 monitoring program. Other wells, which are designated as P wells, were installed in the Burrton area by the City of Wichita before GMD2 was formed. Most of the monitoring wells have screened intervals of 10 ft at the bottom of the well. Water-quality data records of the KGS and the U.S. Geological Survey (USGS) were searched for analyses of samples collected from GMD2 network wells (for wells designated as EB or P in their site identification) and added to the data base. Water-quality data were also obtained from Wichita and the USGS for municipal supply and observation wells in the Burrton area.

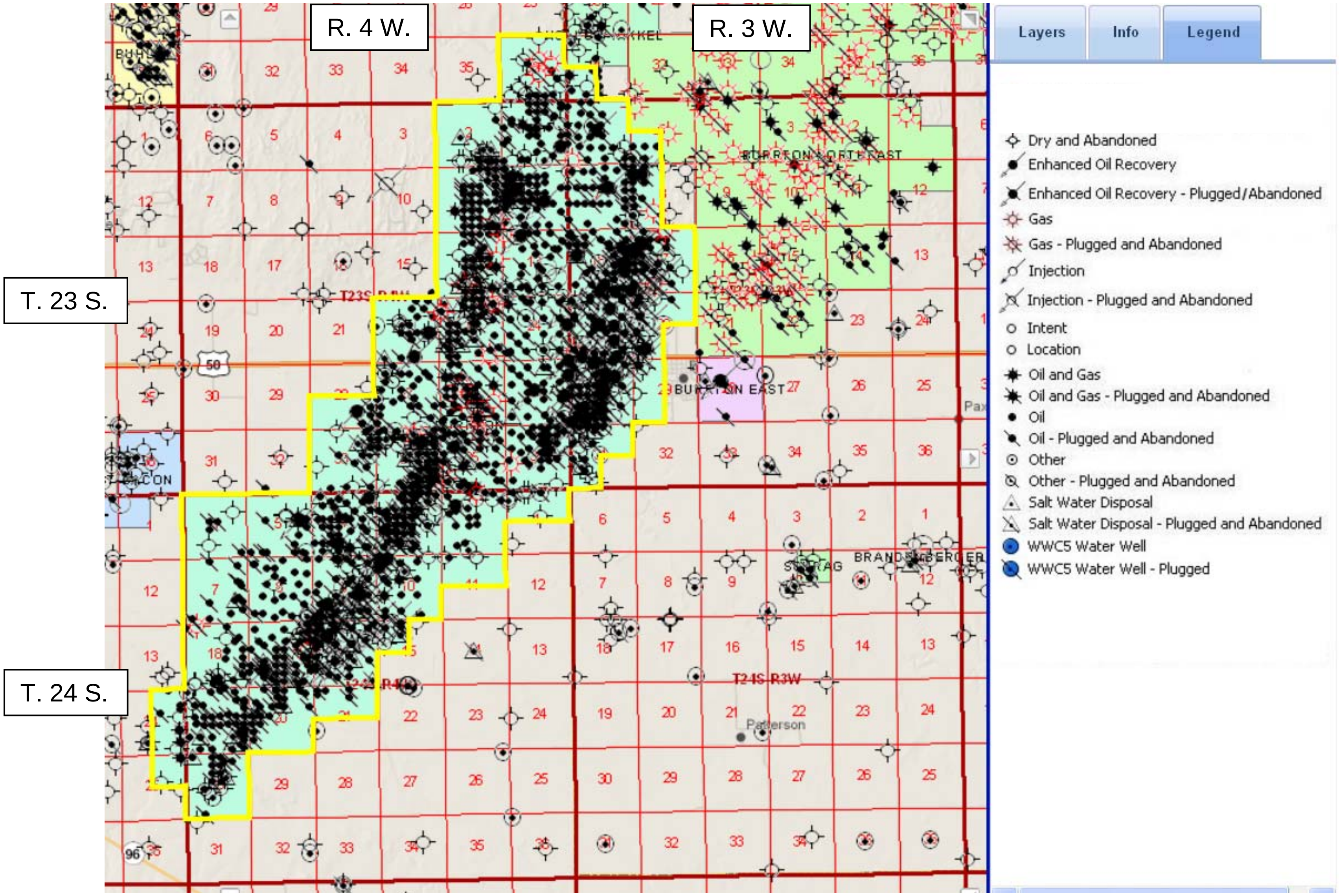

Figure 2. Burrton oil field (boundaries indicated by yellow line) and oil and gas well locations (from KGS online interactive Kansas oil and gas fields, http://maps.kgs.ku.edu/oilgas/index.cfm).

Quality control procedures were performed on the data, which involved steps such as ordering the records based on increasing numeric values of chloride concentration and examining all of the records at the low and high ends of the ordered spreadsheet. Anomalously low and high numeric values of chloride concentration were compared to the other chemical data for each record to determine whether they were in error. Obvious errors such as misplacement of a decimal point and an extra zero at the end of a value were reviewed and corrected. Anomalous data that could not be explained were deleted. The ordering procedure placed records with non-numeric chloride values at the end of the records with numeric values. This allowed correction or deletion of non-numeric values, for example, a letter or other non-numeric character instead of a number or a decimal point.

Comparisons of chemical data and depth information after ordering based on well identification and well number indicated labeling errors, which were corrected. Duplicate records were deleted. Plotting of chloride concentration with time for different P wells revealed that labels for a few samples from the shallow and deep wells at these locations had been switched, i.e., the expected chloride concentration for one well plotted on a graph where the other well should have plotted and vice versa. These were corrected where found.

BEDROCK SURFACE UNDERLYING THE HIGH PLAINS AQUFIER

The Permian Wellington Formation forms the bedrock surface underling the Equus Beds area of the High Plains aquifer where the Burrton IGUCA is located. The Wellington Formation consists primarily of shale, with some thin beds of argillaceous limestone and gypsum (Williams and Lohman, 1949). The Hutchinson Salt Member lies deeper in the Wellington strata below the IGUCA. Much of this subsurface salt member has been dissolved in the IGUCA area. Dissolution of the salt started during erosion of Cretaceous strata and the upper part of Permian rocks in the area, which allowed fresh ground water to penetrate to the salt body (Gogel, 1981). The erosion was substantial during the early Pliocene epoch when a deep incision produced the McPherson valley. The valley was subsequently filled with sediments during the late Pliocene and the Pleistocene (Stramel, 1966). These sediments formed the primary body of the Equus Beds aquifer. The main part of the McPherson valley is known as the McPherson channel, which cuts through the northeast portion of the IGUCA area. The greater depths of the bedrock surface in the northeast part of Figure 3 indicate where the channel is located.

The dissolution of the Hutchinson Salt underlying the IGUCA area was not even and resulted in subsidence and sinks, which produced an uneven surface over which sediments were deposited. The subsidence probably helped determine where the deeper parts of the McPherson channel are located. The thickness and amount of dissolution of the salt deposit and the location of the McPherson and Arkansas River channels were probably responsible for leaving the area of the bedrock high in the south-central portion of the IGUCA area (Figure 3).

Within the northeastern and eastern part of the IGUCA where the depth to bedrock exceeds 180 ft, permeable sediments (from fine sand to coarser deposits) lie on the bedrock surface. Monitoring well sites where this occurs include (from north to south) P32, EB56, EB10, EB17, P31, EB9, EB16, EB15, EB14, and EB13 (Figure 4). This area probably reflects the

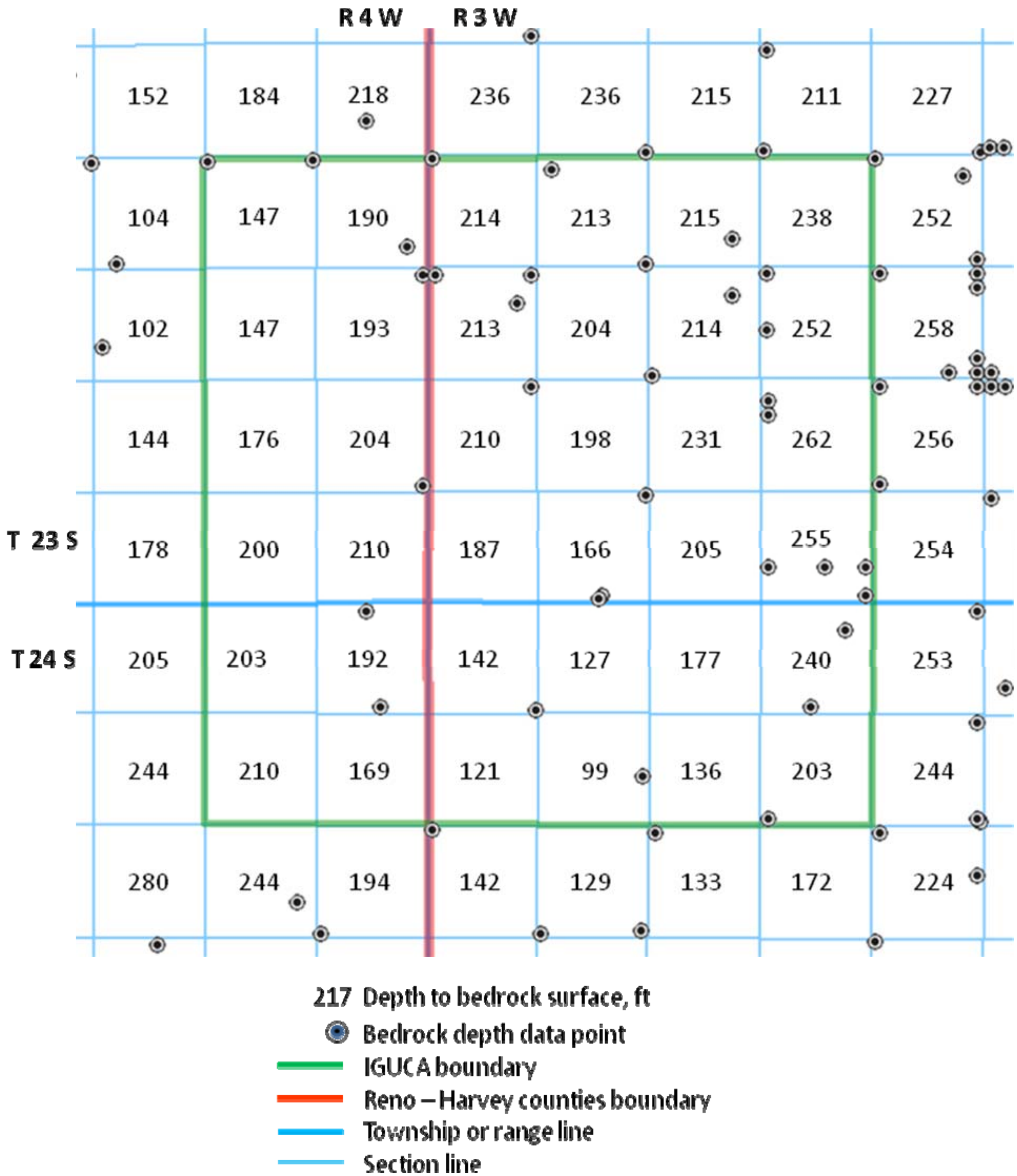

Figure 3. Depth to bedrock (ft) in the centers of sections in the Burrton IGUCA. The values were extracted from a smoothed bedrock surface coverage produced by the KGS using contours that were based on the depth data points shown.

western side of the McPherson channel. In the western and southernmost portions of the IGUCA, clay and silty clay overlie the bedrock surface where the depth to bedrock exceeds 130 ft. The thickness of the fine-grained deposits lying on bedrock is 50 ft or more in many of the wells in this area (from north to south: EB5, EB43, EB4, EB57, EB3, P30, and EB1 [Figure 4]). The clays overlying the bedrock surface may serve as the floor of the downward migration of saltwater just as the Wellington shale serves as the migration base where permeable aquifer sediments extend to the bedrock surface.

Partway through the Pleistocene epoch, deepening of stream channels in the upper Kansas River basin caused the lower Smoky Hill River to capture the drainage of the upper Smoky Hill River that had been flowing through to the McPherson valley (Bayne and Fent, 1963). Some of the last sediments deposited across parts of the Equus Beds area after the river capture were fine-grained and covered the coarser-grained deposits of the aquifer. During late Pleistocene time, the Little Arkansas River developed its drainage system, which includes the watershed of Kisiwa Creek that drains most of the IGUCA area.

CHLORIDE CONCENTRATION TRENDS IN MONITORING WELLS

Long-term trends in chloride concentration for five west-east cross sections (Figure 4) in the Burrton plume area are displayed in Figures 5-9 for individual EB and P monitoring wells from the late 1970s to 2010. The X and Y axes in Figures 5-9 have the same spacing per unit time and chloride concentration for easy visual comparison of relative differences. For these graphs, the upper aquifer is defined as extending down to 65 ft below land surface. The division between the middle and lower aquifers is defined as 60 ft above the bedrock surface or a depth halfway between 65 ft (the bottom of the upper aquifer) and the underlying bedrock surface, whichever is greater. The depth to the bedrock within the IGUCA ranges from a little less than 100 ft to 285 ft based on well data. Thus, the division between the middle and deep aquifers ranges from approximately 80 ft to 175 ft. If the screened interval of a well spans the division between two aquifer zones, the well was classified as in the upper of the two zones. Some multi-level well sites in Figures 5-9 have wells with depths within the same aquifer zone. The well depths increase at EB multi-level well sites in the order AA, A, B, and C. The A well at a P site is deeper than the well without the A designation.

Most of the wells in the upper and middle aquifer in the western part of the plume display a general decrease in chloride concentration with time (sites EB5 and EB56 in Figure 5, sites EB4 and EB57 in Figure 6, sites EB44 and EB3 in Figure 7, and site EB2 in Figure 8). The upper aquifer at site EB1 in the most southerly of the cross sections (E-E') first showed a small, gradual increase in chloride before starting a small, gradual decrease starting about 1994, while the middle aquifer has had both gradual increases and decreases depending on the wells. The chloride concentration in the lower aquifer at the western sites in the three most northerly of the cross sections has remained low, except for well EB43C, which has shown a steady decrease from several hundred mg/L. Well EB2C in the lower aquifer has been decreasing in chloride content after a more rapid rise from the mid-1980s to 1994.

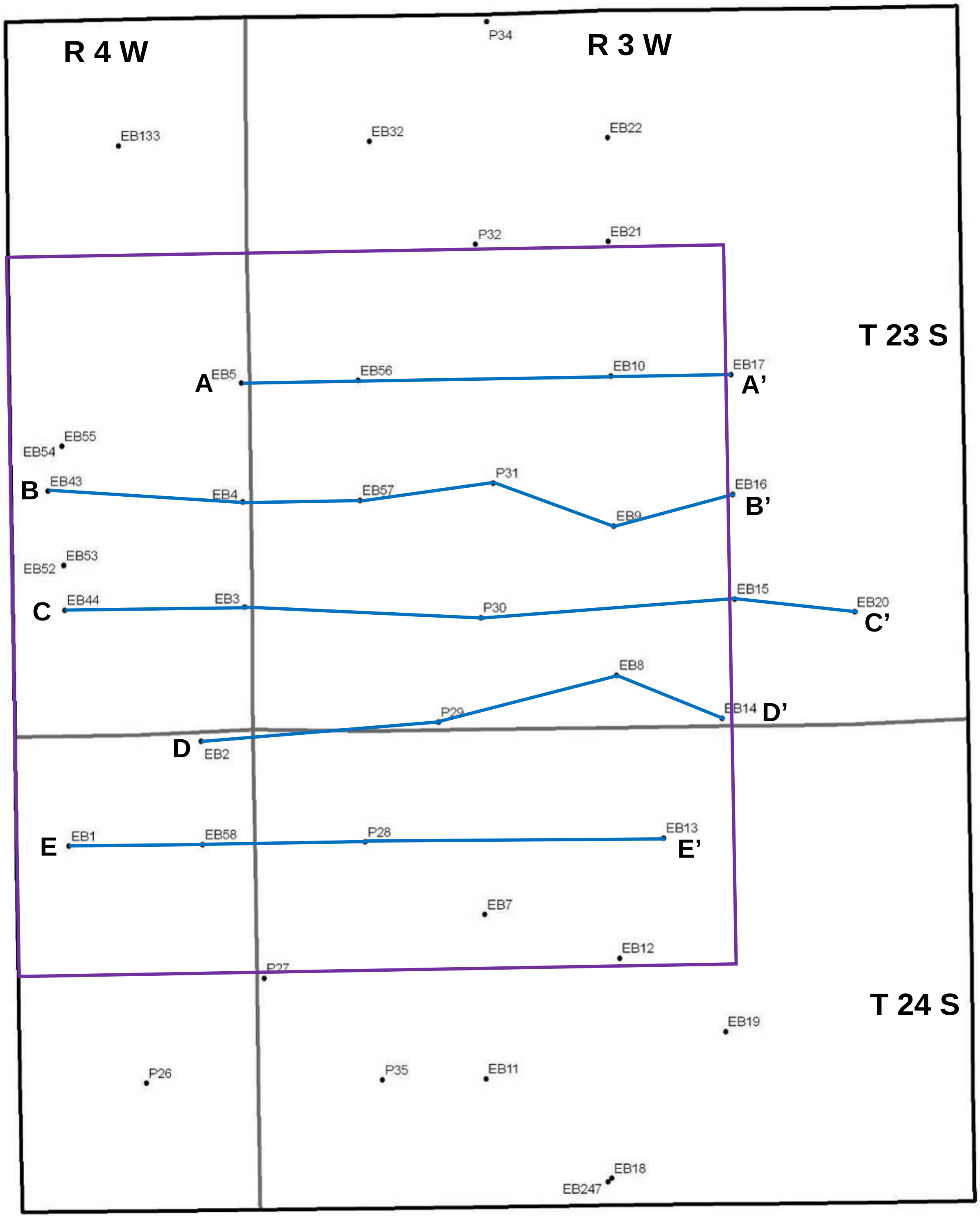

Figure 4. Location of west-east cross sections in Burrton plume area for which change in chloride concentration plots are shown in Figures 5-9. The Burrton IGUCA is the purple square.

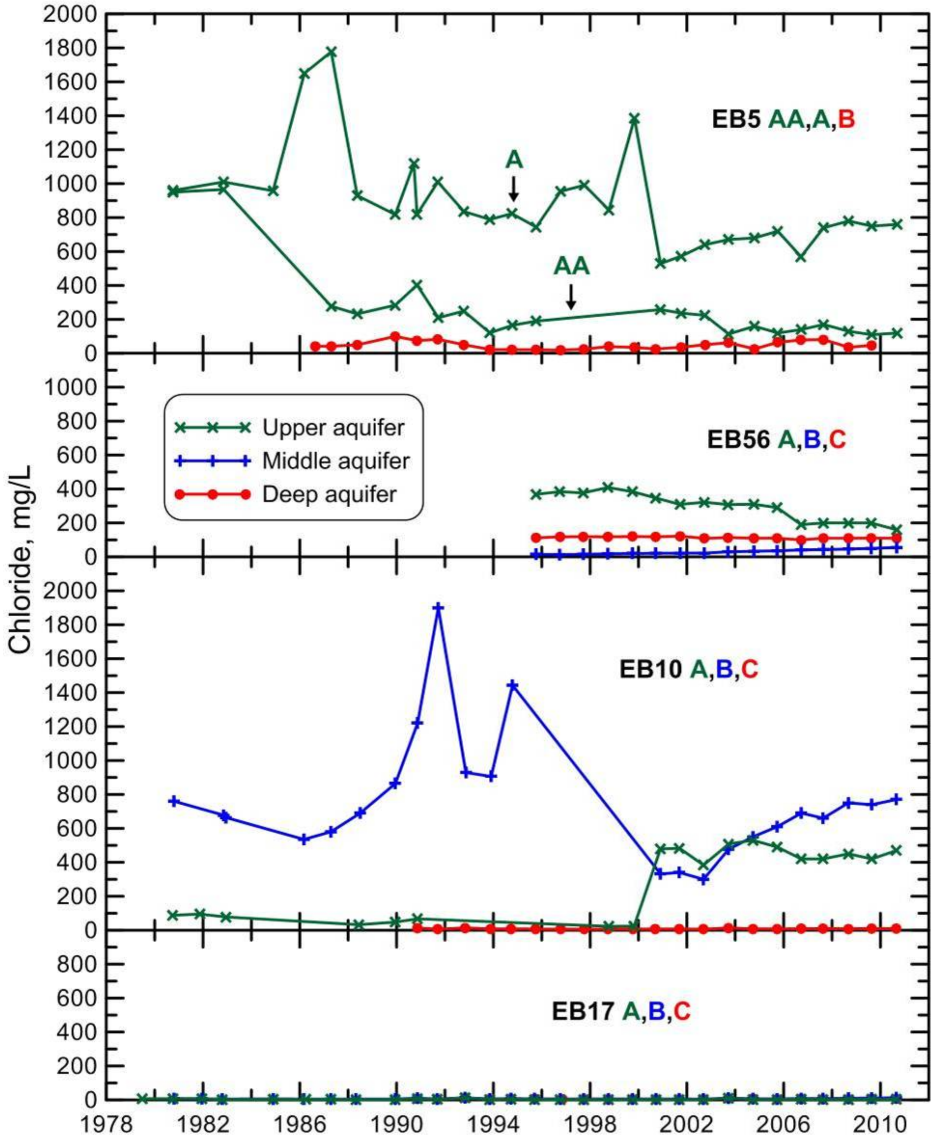

Figure 5. Change in chloride concentration for EB wells along west to east cross section A-A' (shown in Figure 4) in the northern part of the Burrton area plume. Well EB56A was designated as an upper aquifer well to distinguish it from EB56B because the middle of its screened interval is at 65 ft.

In the central part (from west to east) of the plume cross sections, the salinity is typically the highest in the middle aquifer (sites P29-P31 [well P31A is screened at the transition from the upper to middle aquifer] and EB8-EB10). Where two wells are in the upper or middle aquifer at a site (P30 and P31 wells), the chloride concentration is greater at the deeper of the two wells. Chloride concentration in the deep aquifer is usually low where the depth to bedrock exceeds 200 ft, except for well EB8, which shows a substantial increase in salinity to 2010. However, the clay deposits overlying the bedrock at sites EB57, P29, and P30, where the deeper of the two wells at each of these sites is screened to the top of this clay, may be the base of migration of the saltwater plume. Thus, the deeper wells at these three sites may effectively serve to monitor the

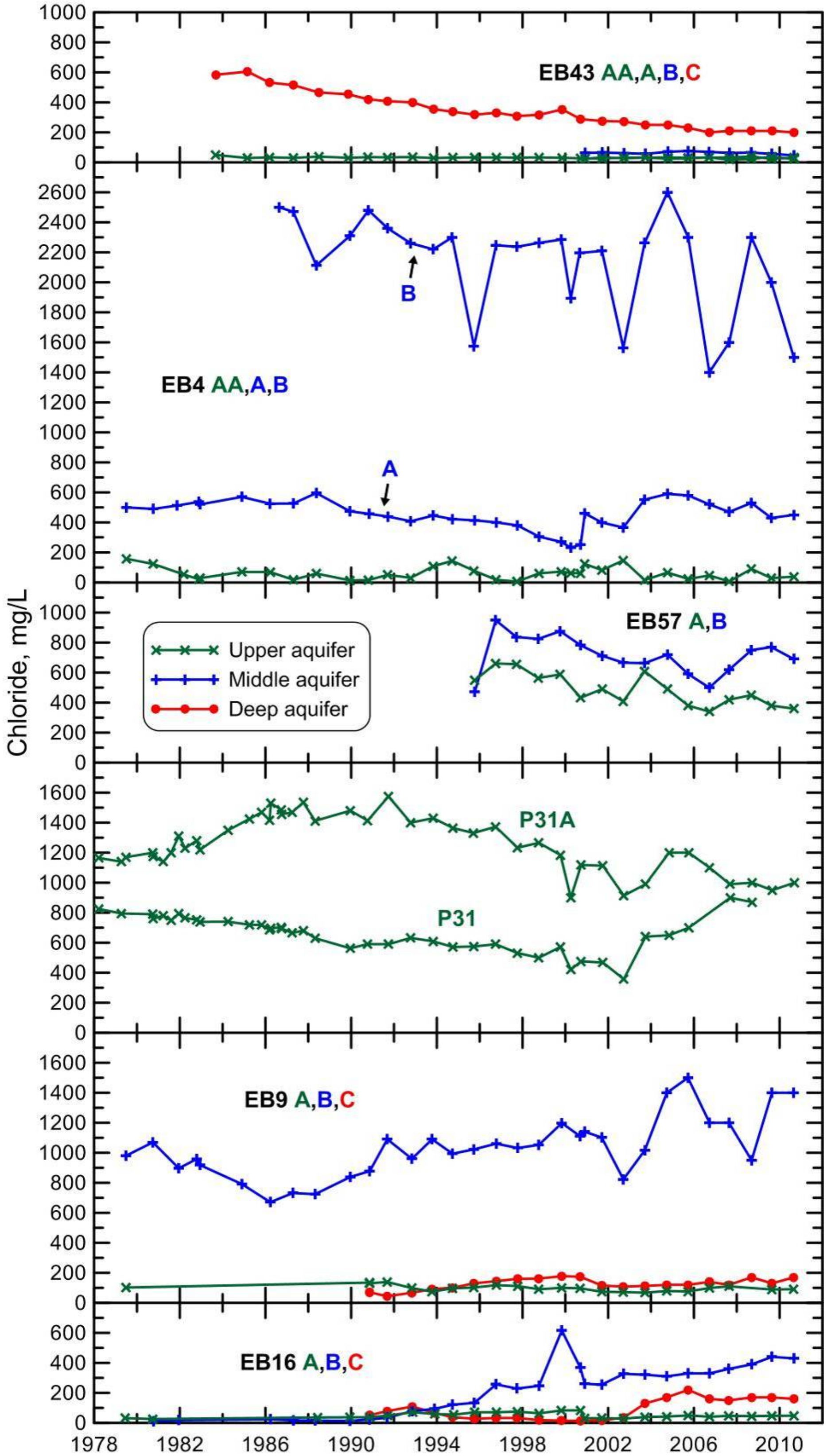

Figure 6. Change in chloride concentration for EB and P wells along west to east cross section B-B' (shown in Figure 4) in the northern/middle part of the Burrton area plume.

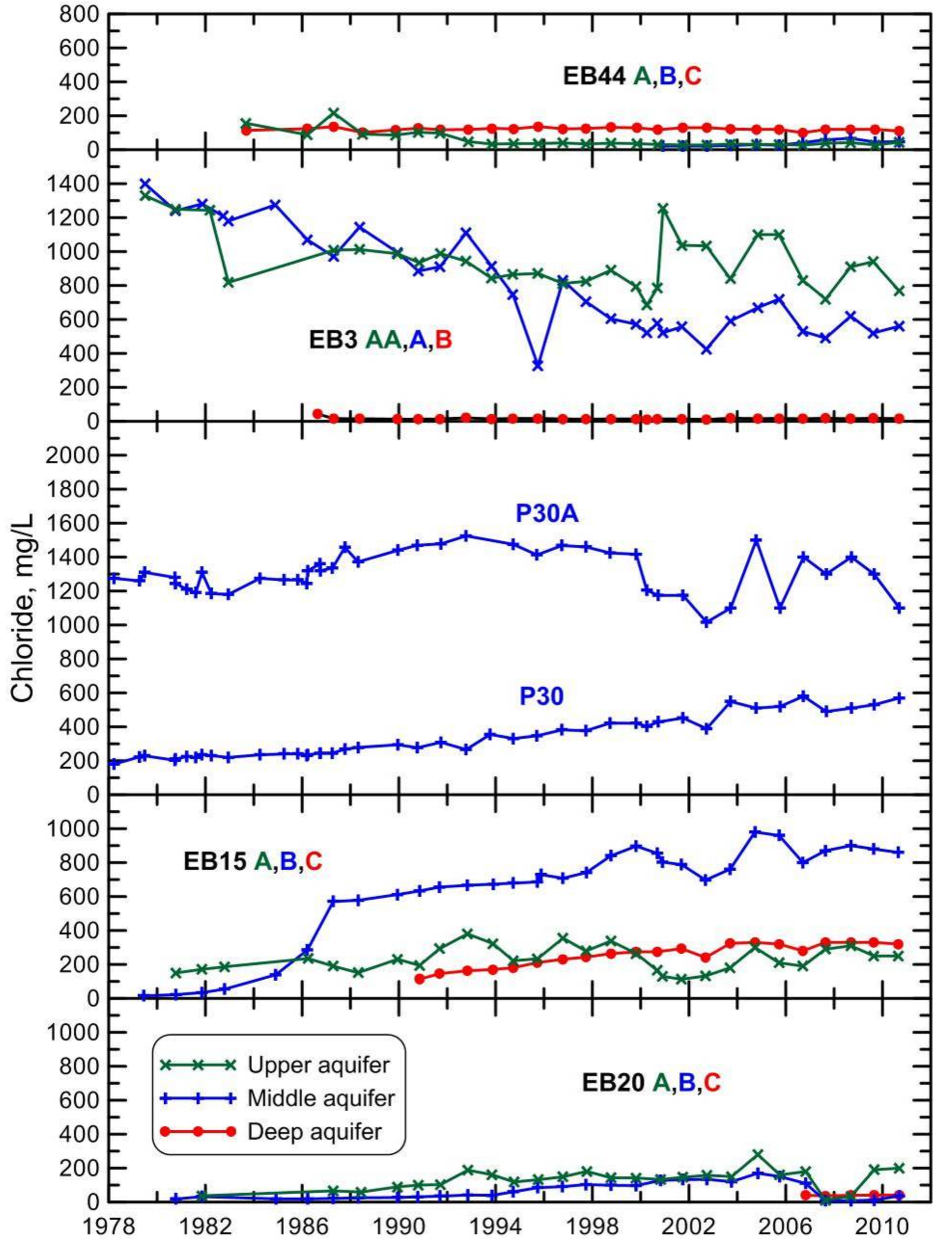

Figure 7. Change in chloride concentration for EB and P wells along west to east cross section C-C' (shown in Figure 4) in the middle part of the Burrton area plume.

base of the plume. The chloride concentration in these three deeper wells has always exceeded several hundred mg/L during the monitoring period and has exceeded 1,000 mg/L during the last two decades in wells P29A and P30A. No irrigation wells that are screened in the lower aquifer where the bedrock surface exceeds 160 ft, and that have been monitored for water-quality, are located in the central band (north-south strip with two-section width) of the IGUCA.

Samples from monitoring wells at all aquifer levels located just to the northeast (site EB17) and southeast (site EB 13) of the plume have had low chloride concentrations from the

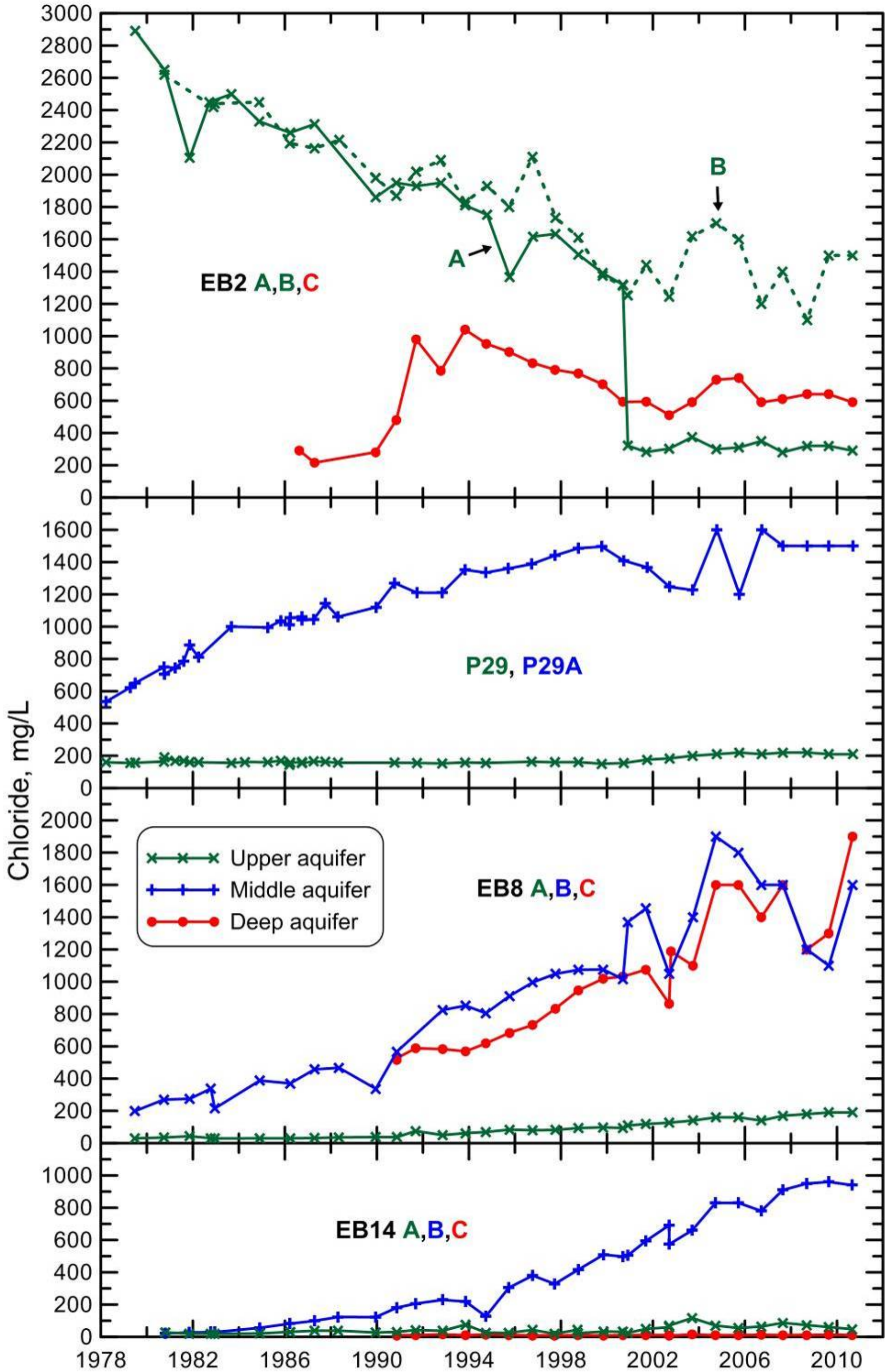

Figure 8. Change in chloride concentration for EB and P wells along west to east cross section D-D' (shown in Figure 4) in the middle/southern part of the Burrton area plume.

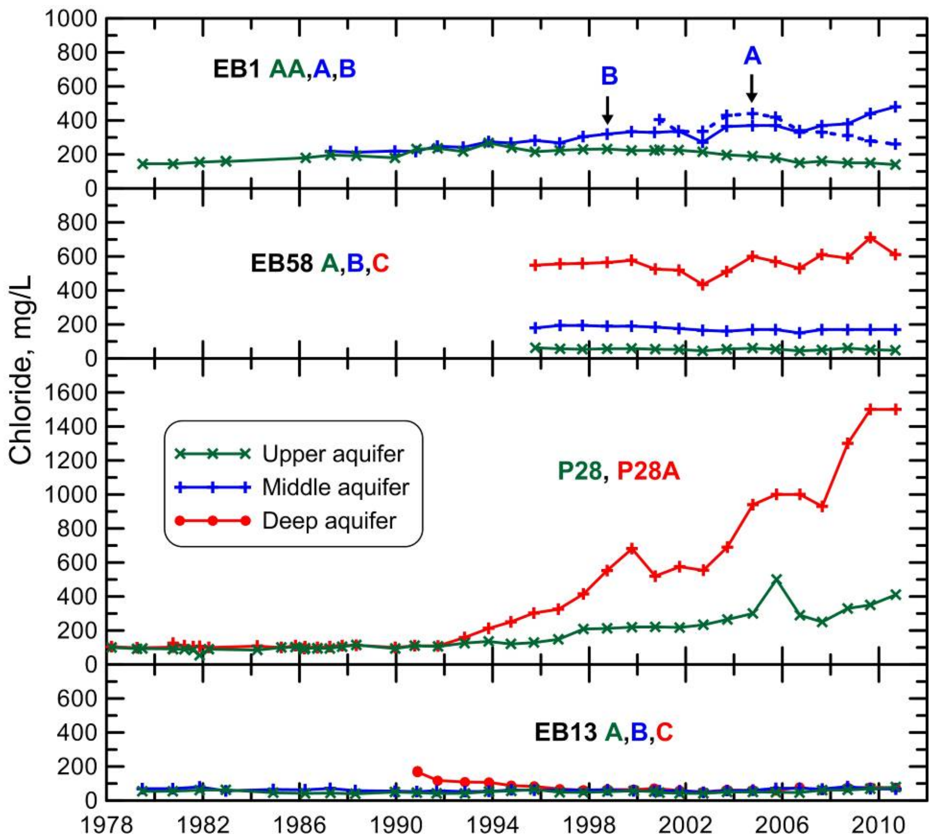

Figure 9. Change in chloride concentration for EB and P wells along west to east cross section E-E' (shown in Figure 4) in the southern part of the Burrton area plume.

late 1970s to 2010. Wells in the eastern front of the plume (sites EB14-EB16) have shown increases in salinity with time. These increases are greatest in the middle aquifer. Chloride concentration in the shallow and middle aquifer wells at site EB20 just east of the center of the plume front very slowly increased with time until about 2005. Since then the chloride level in well EB20A has decreased then increased back to about 200 mg/L, whereas the chloride concentration in well EB20B has decreased to less than 40 mg/L during 2007-2010.

CHLORIDE CONCENTRATION TRENDS IN WATER SUPPLY WELLS

A total of 87 unique points of diversion for water rights that were coded as active and for which the water use was also coded as active as of December 2011 (based on a WIMAS search) exist within the Burrton IGUCA (Table 1). Most of these wells are located in the southwest, south-central, and northeast parts of the IGUCA. The permitted water supply wells are used for irrigation, recreation, municipalities, or industry. The large number of points of diversion in secs. 1 and 2, T. 24 S., R. 4 W., result from several batteries of multiple wells used for irrigation.

GMD2 provided chloride concentration data for 35 of the 87 water supply wells in Table 1; the period of sample collection is 1984-2010, although the chloride data for most wells covers

Table 1. Number of unique points of diversion that were active and had active water use as of December 2011 within each section in the Burrton IGUCA.

Twn.-Rng.	Sec.	Irrigation	Recreation	Municipal	Industrial
23S-3W	15	1			
	16	2		1	
	17	1			
	18				
	19	1			
	20	3			1
	21	2			
	22	4			
	27	1	1		
	28	4			
	29			1	
	30				
	31				
	32				
	33	1			
	34	4			
23S-4W	13				
	14				
	23				
	24				
	25	1			
	26	2			
	35	1			
	36				
24S-3W	3	3			
	4	3			
	5	2	1		
	6	2	1		
	7	2			
	8	2			
	9	1	4		
	10				
24S-4W	1	11			
	2	16			
	11	3			
	12	4			
Totals		77	7	2	1

only the later part of this period. The range, mean, and median for the chloride data are 5-804 mg/L, 163 mg/L, and 112 mg/L, respectively, and for the depths of the sampled wells are 30-195 ft, 76 ft, and 54 ft, respectively. The concentration range for the well with the lowest chloride concentration was 5-53 mg/L for a 53-ft deep well in the northwest corner of sec. 16, T. 24 S., R. 4 W., which is located in the northeast part of the IGUCA to the north of the chloride plume. The range for the well with the highest chloride concentration was 696-804 mg/L for a 140-ft deep well in the SW NW NE sec. 34, T. 23 S., R. 3 W., which is located at the front of the advancing chloride plume.

Figures 10-12 display the trends in chloride concentration for 17 selected supply wells in the northern, middle, and southern strips (two sections north-south and six sections [full extent] west-east) across the 36 sections of the Burrton IGUCA (36 sections total). Figure 13 shows the locations of the supply wells for Figures 10-12. The X and Y axes in Figures 10-12 have the same spacing per unit time and chloride concentration. Well numbers (serial numbers used by GMD2) and depths are listed in the figures. The upper aquifer, middle, and deep aquifers are defined as before. The chloride concentration in some of the water supply wells has remained relatively constant, while increasing or decreasing substantially in others (Figures 10-12). The chloride values fluctuate appreciably in many of the wells from year to year, whether the long-term change is small or large.

Chloride concentration has usually remained either relatively constant or has decreased in supply wells screened in the shallow aquifer in the western and middle parts of the northern portion of the IGUCA as illustrated by GMD2 wells 655, 669, and 675 in Figure 10. In contrast, chloride concentration has slowly increased in the deep part of the aquifer in the eastern third of the northern strip of the IGUCA (GMD2 wells 667 and 675 in Figure 10).

In the western portion of the middle strip across the Burrton IGUCA, the chloride concentration has generally slowly decreased in supply wells screened in different levels of the aquifer (for example, GMD2 wells 644 and 646 in Figure 11). Except for a shallow municipal well of the City of Burrton, no water supply wells exist in the middle third of the middle strip of the IGUCA, probably because the chloride concentration is generally high in this part of the aquifer. In the eastern part of the middle strip, most of the supply wells (including those not shown in Figure 11) have yielded water in which the chloride concentration has either slowly increased (for example, well 645 in Figure 11) or remained roughly constant (well 628). Fluctuations have been particularly large in wells 670 and 628. In contrast, the chloride concentration in well 656 decreased for a few years and then remained constant.

The supply well that had the highest chloride concentration range was in the eastern part of the middle strip within the IGUCA (GMD2 well 681 located in sec. 34, T. 23 S., R. 3 W., an irrigation well with a depth of 140 ft for which the chloride concentration range during 1999-2001 was 696-804 mg/L). This point of diversion (PDiv ID 61403 in WIMAS) is no longer active. The point of diversion was changed to a shallow well (54 ft deep, GMD2 well 659, PDiv ID 67151 in WIMAS) installed within 20 ft of this location in 2002. The chloride concentration in the replacement well has fluctuated between 113 and 281 mg/L during 2002-2010. This location was the focus of a study on the effects of the saline water from the earlier irrigation well on the chloride content of the soil receiving the applied water (Whittemore, 2002).

In the western part of the southern third of the IGUCA, irrigation wells (including batteries of wells) are screened in the upper aquifer and have yielded water with chloride concentrations usually less than 200 mg/L. The chloride values have generally remained constant, although some decreases and increases have also occurred during the last two decades (for example, GMD2 wells 654 and 630 in Figure 12). Chloride concentrations in supply wells screened from the shallow to lower aquifer in the middle and eastern part of the southern strip of the IGUCA are commonly less than or slightly above 100 mg/L. Although the chloride concentration has remained relatively constant in some of these wells, it has slowly increased in other supply wells (for example, GMD2 wells 640 and 635 in Figure 12).

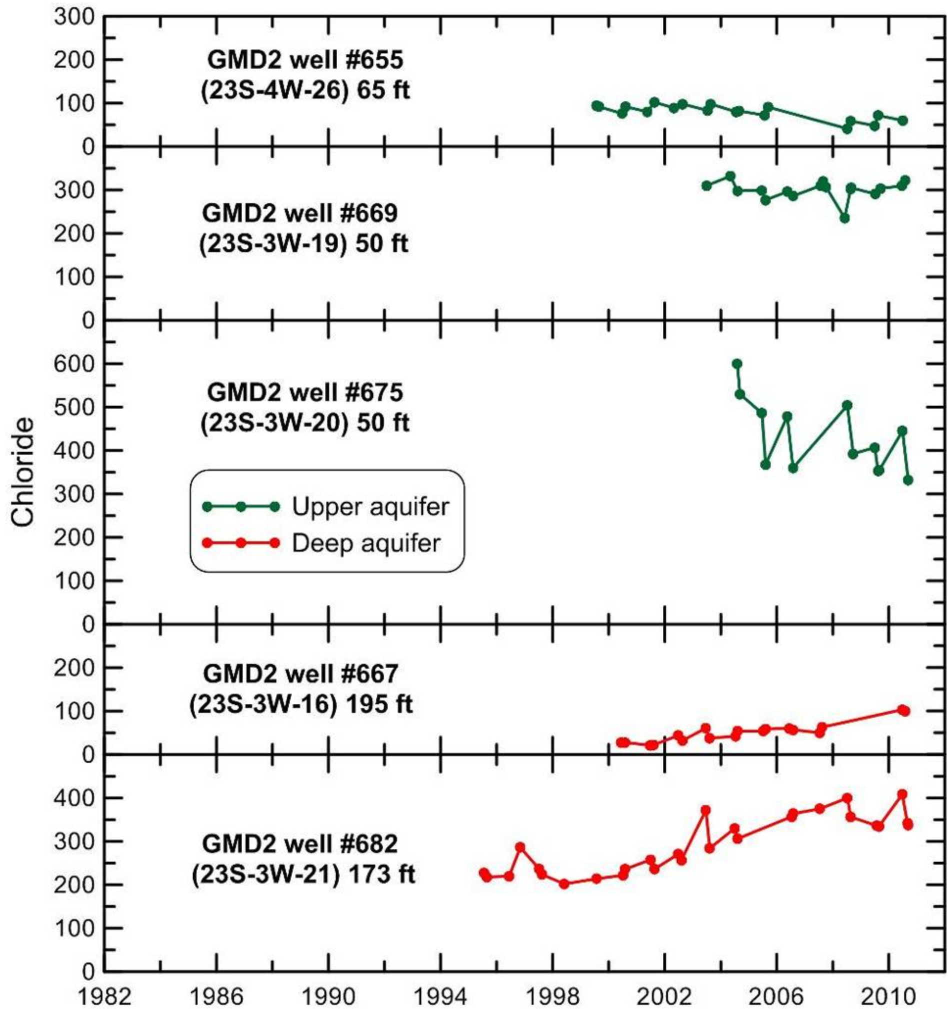

Figure 10. Change in chloride concentration for selected water supply wells within the northern third (a strip two sections north-south by six sections west-east) of the Burrton IGUCA.

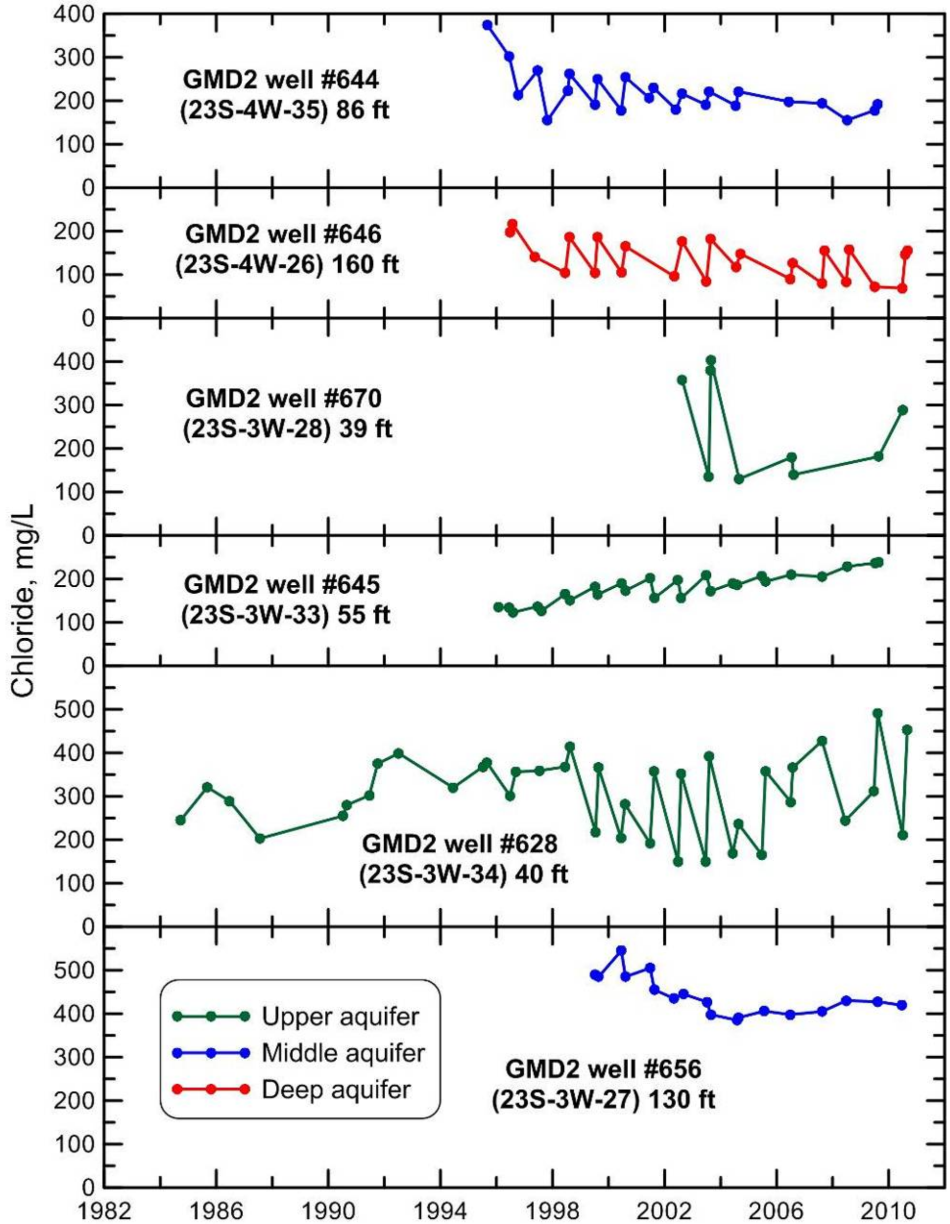

Figure 11. Change in chloride concentration for selected water supply wells within the middle third (a strip two sections north-south by six sections west-east) of the Burrton IGUCA.

THREE-DIMENSIONAL CHLORIDE DISTRIBUTION IN PLUME

Depths of the multi-level monitoring wells constructed in the Burrton area were chosen based on depth to bedrock and to clay layers that could affect the downward movement of dense saltwater. Contour maps displaying the areal chloride distribution for different monitoring well depths in effect average the chloride concentration across depth intervals. In order to discern more clearly the actual distribution of chloride concentration with depth as well as in areal extent, three-dimensional (3D) images of selected areas of the aquifer were produced using the program Voxler (Golden Software).

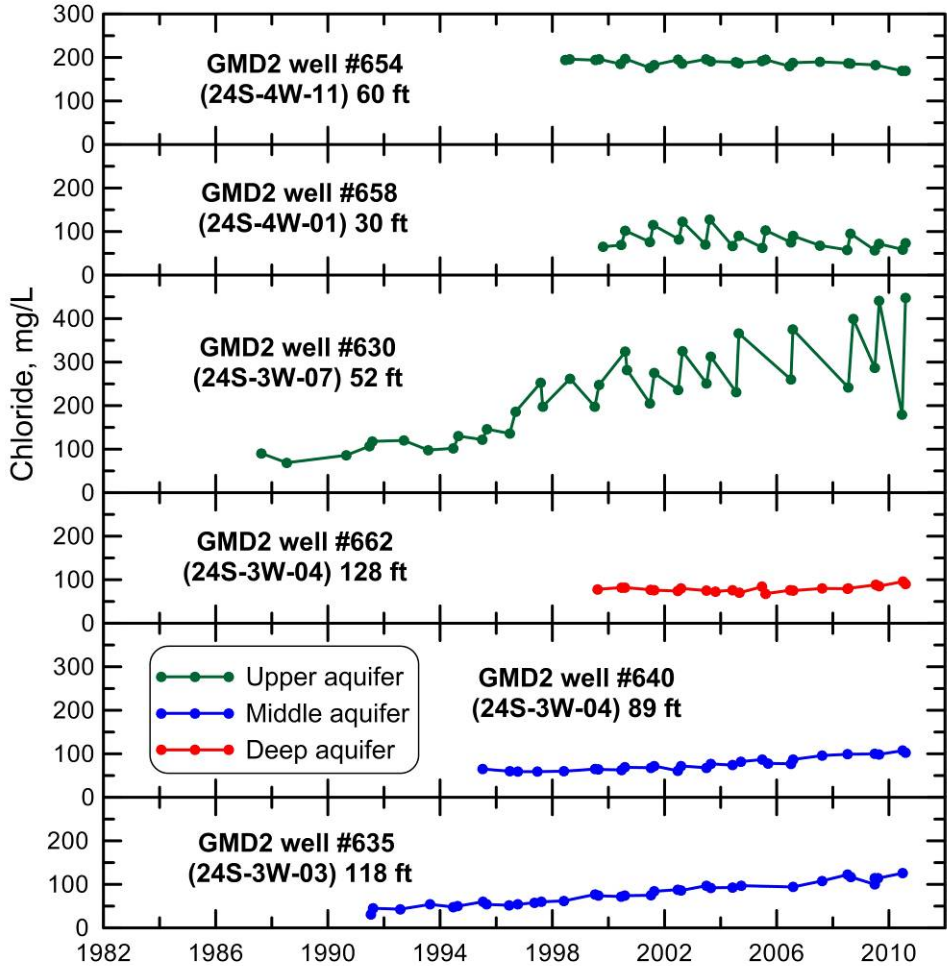

Figure 12. Change in chloride concentration for selected water supply wells within the southern third (a strip two sections north-south by six sections west-east) of the Burrton IGUCA.

The bounding box for a 3D Voxler image is dependent on the locations and depths of the wells for which data are used in the images. The areal (land surface) limits for the bounding box for the 3D image of the Burrton area plume extend from multi-level well site EB43 on the west, site EB22 on the north, site EB20 on the east, and site P27 on the south (Figure 13). The shallowest and deepest well depths serve as the vertical positions of the top and bottom faces of the bounding box.

A vertical exaggeration of 52.8 was selected for the images. The north-south and west-east directions in the Voxler images are represented in miles. In the Voxler program one unit in each axis direction is the same length. Thus, a unit of feet instead of a mile for well depths in the vertical axis is a multiplier of 5,280. In order to display an appropriate range for the vertical axis relative to the other two axes, the well depths were divided by 100 (5,280 divided by 100 gives 52.8).

The Voxler program grids the input data into a regular lattice before a 3D image is generated. An inverse distance approach was selected with anisotropic treatment (an elliptic

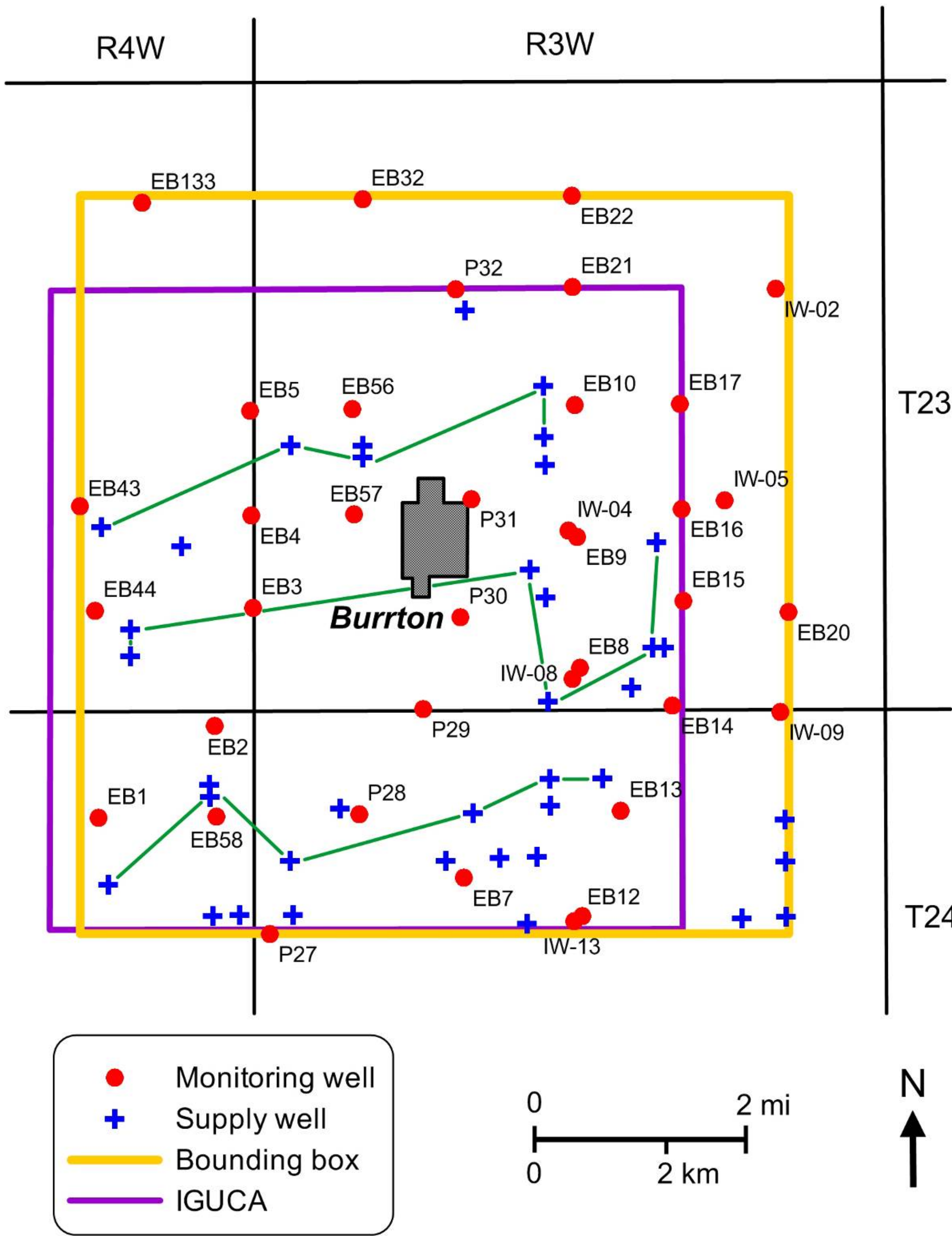

Figure 13. Location of wells and the areal extent of the top face of the 3D image bounding box for the Burrton area plume. Monitoring well sites are labeled. The supply wells with location symbols are for those with chloride concentration data. The green lines connect the locations for the northern, middle, and southern groups of wells in Figures 9-11.

search geometry). For the Burrton area, the north-south axis of the search ellipse was selected to be 0.75 of the west-east axis to recognize that ground-water flow was faster in the west-east direction than dispersive flow in the north-south direction. The vertical axis of the search ellipse was selected to be 0.5 of the west-east axis to represent slower downwards flow than lateral flow toward the east. The reduction of the vertical ellipse axis coupled with the 52.8 vertical exaggeration in effect resulted in a contrast of about 106 (52.8/0.5) for lateral west-east flow compared to vertical flow.

Data files and Voxler images were prepared for 1982, 1990, 2000, and 2010. Data additional to the EB and P monitoring wells for the 2010 image included six Wichita/USGS sites of IW multi-level observation wells (IW-02,-04,-05,-08, -09, and -13), three Wichita municipal wells (M41 through M43), and 34 wells monitored as a part of the Burrton IGUCA (30 irrigation wells, three recreational wells, and a Burrton municipal well). For the 2000 image, data were available for monitoring well P31 in addition to those GMD2 wells in the 2010 image, four Wichita municipal wells (M41 through M44), and, except for five fewer irrigation wells, the same supply wells monitored for the IGUCA. For the 1990 image, fewer data were available for EB wells and wells monitored for the IGUCA than in 2000 and 2010. Rather than use data for the EB and P wells, the four Wichita wells, and five irrigation wells for a 1980 image, 1982 was selected as the first year for a Voxler image because additional data were available for that year from the Burrton Task Force (1984) report for 18 domestic, oil well supply, and USGS observation wells in the Burrton area.

If a value was not available for the particular year, a value for a date within a couple years was used for an image, if available. Data for wells at sites EB52 through EB55 were not used because they represented very local conditions of old, leaky concrete pits storing oil brine. Table 2 summarizes the number and type of wells for each Voxler image prepared for the Burrton area.

Table 2. Number of different types of wells used in the 3D image of the Burrton area plume.

Type of well	Number of wells for year of 3D image			
	1982	1990	2000	2010
EB monitoring well	36	56	67	67
P monitoring well	12	12	12	11
Wichita/USGS IW monitoring well			12	12
Wichita well field ‘M’ well	4	4	4	3
Irrigation wells in Burrton IGUCA	5	4	25	30
Domestic, oil well supply, municipal, recreational, or other well	18	2	4	4
Total number of wells	75	78	124	127

The vertical extent of the top and bottom faces of the Voxler bounding box for the Burrton area were the minimum and maximum depths of the wells for which chloride data were used. The well depths used for the EB observation wells were the total well depths, which represent a value 5 ft greater than the middle of the 10-ft screened interval for all these wells. The total well depth was also used for P and IW observation wells, which either were known or assumed to have a 10-ft screened interval, and for the 18 wells for which data were taken from the Burrton Task Force (1984) report. Screened interval information for the Wichita municipal supply wells and irrigation wells in the Burrton IGUCA was obtained from Wichita and GMD2, respectively, or found in the WWC5 well log records. If a screened interval was not available from these sources for an irrigation well, an interval was estimated for the well based on WWC5 records for nearby irrigation wells. The well depth for the supply wells used in the 3D images was computed as the middle of the screened interval plus 5 ft to represent a sampled aquifer zone in a manner consistent with the observation well depths.

Figure 14 is a Voxler image (areal view) displaying points that indicate the location and sampling depths of the water supply and multi-level monitoring wells appearing in the 2010 and 2000 images of the Burrton plume within the 3D bounding box. Figure 15 shows views of these well points toward the north, east, south, and west (south, west, north, and east faces of the bounding box, respectively) along with the bedrock surface underlying the aquifer. The bedrock surface was generated in Voxler using both the section center depths of the smoothed bedrock surface displayed in Figure 3 and the actual depths to bedrock at the monitoring well sites within the IGUCA. The areal extent of the Burrton IGUCA in the land surface plane is included in both figures for reference.

Isosurfaces of three different chloride concentrations (500, 1,000, and 1,500 mg/L) for the Burrton area plume are displayed in different 3D views for the years 1982, 1990, 2000, and 2010 in Figures 16-18. Figure 19 includes images for 1982 and 2010 along with the bedrock surface underlying the Equus Beds aquifer. An isosurface is similar to a contour or isoline except that it represents an equal concentration along its 3D surface rather than along a line as does a contour in a 2D view. The isosurfaces were made partially transparent to retain their color while allowing viewing of other isosurfaces and the dots for wells that are inside that isosurface. The well dots are also colored according to the color bar legend for chloride concentration.

The west-east axis in the images for 1990, 2000, and 2010 in Figures 16-19 extends from 0 mile on the west side of the 3D bounding box to 6.78 miles on the east side. The east end of this axis in the 1982 images is the same but the west end is -0.19 mile to allow incorporation of the chloride concentration for a well sampled in 1982 that was near the west edge of the 1990-2010 bounding box. The north-south axis for all images extends from 0 mile on the north side of the bounding box to 7.05 miles on the south side. The depth axis is shown as starting at 0 ft to represent the land surface (which assumes a flat plane). Each unit in the depth axis represents 100 ft and is shown as a negative number to indicate depth downwards. The maximum vertical extents of the top and bottom faces of the 3D bounding box (which represents the shallowest and deepest sample intervals for wells) are from either 17 ft or 18 ft to 285 ft for 1990, 2000, and 2010, and 17 ft to 259 ft for 1982.

Figures 16-19 show the general eastward migration of the plume with time. The front of the plume as represented by the 500 mg/L chloride isosurface advanced from about a mile and a half to over 2 miles to the east during 1982-2010, or approximately 280-380 ft/yr or 0.8-1.0 ft/day. Comparing Figures 2, 13, and 16 indicates that the front of the plume has moved nearly 5 miles beyond the eastern edge of oil wells in the Burrton oil field. Since the first substantial entrance of oil brine into the aquifer from surface brine ponds approximately 75 years ago, the rate of migration is consistent with the one and a half to 2 miles the plume moved for the 28 years between 1982 and 2010.

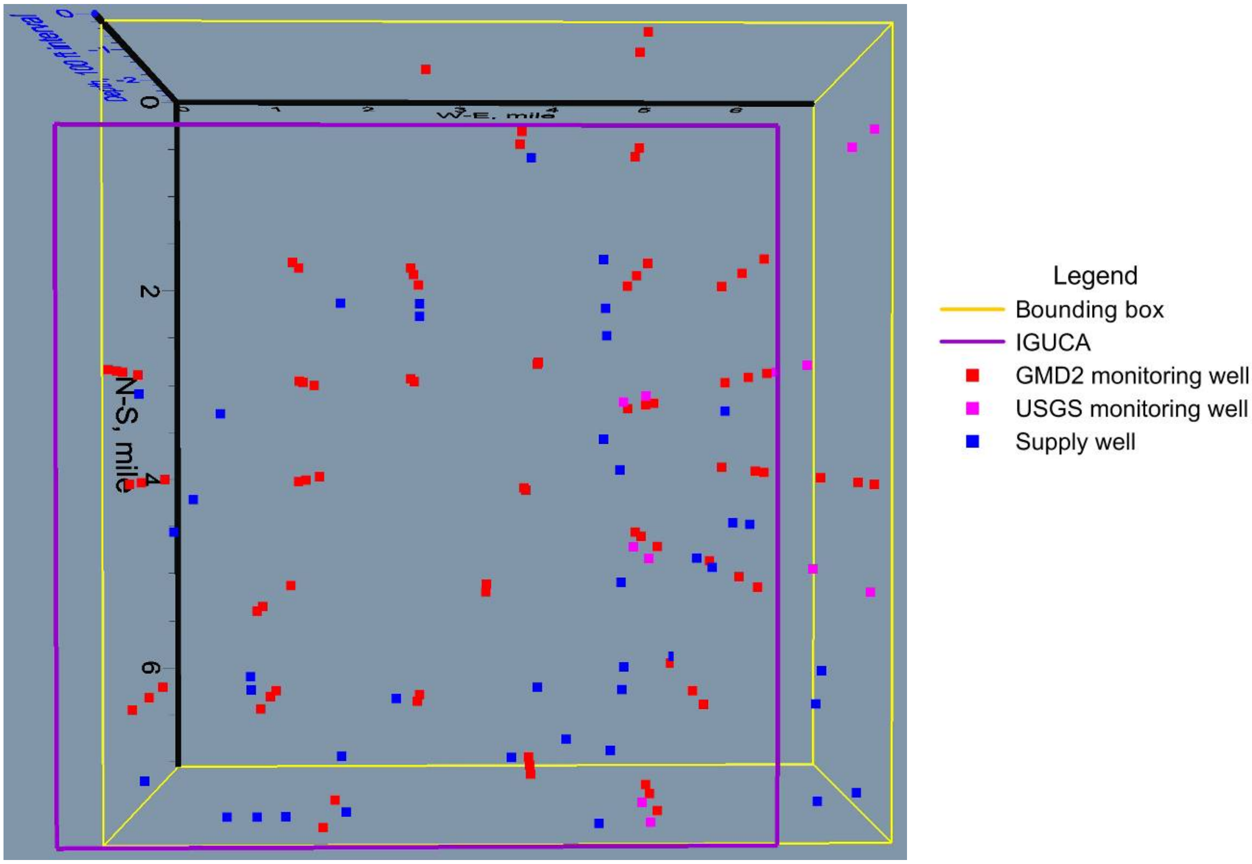

Figure 14. Distribution of points for well sampling depths with chloride concentration data within the bounding box for the Burrton plume viewed from above.

Figure 17 indicates that the plume has migrated to greater depths with time, which is expected because the saline water is denser than fresher ground water. The high concentration zones (>1,500 mg/L chloride concentration) that appear at shallow depths in 1982 and 1990 have shifted toward the east by 2010 and are generally smaller in size, reflecting not only migration but some dilution. The change in location of some of these high chloride zones appears to be farther than 2 miles during 1982-2010. It is possible that some of the high chloride zones in 2000 and 2010 represent more local downward migration of some high chloride ground water that was not sampled by the screened intervals of wells in earlier years. Figure 19, which includes an image of the bedrock surface topography, indicates that salinity in the upper aquifer zone has reached the aquifer base in the main part of the Burrton plume.

The distribution of clays within the Equus Beds aquifer has affected the migration of the saline water, as indicated by different studies of the plume (for example, the Burrton Task Force

a
b
c
d

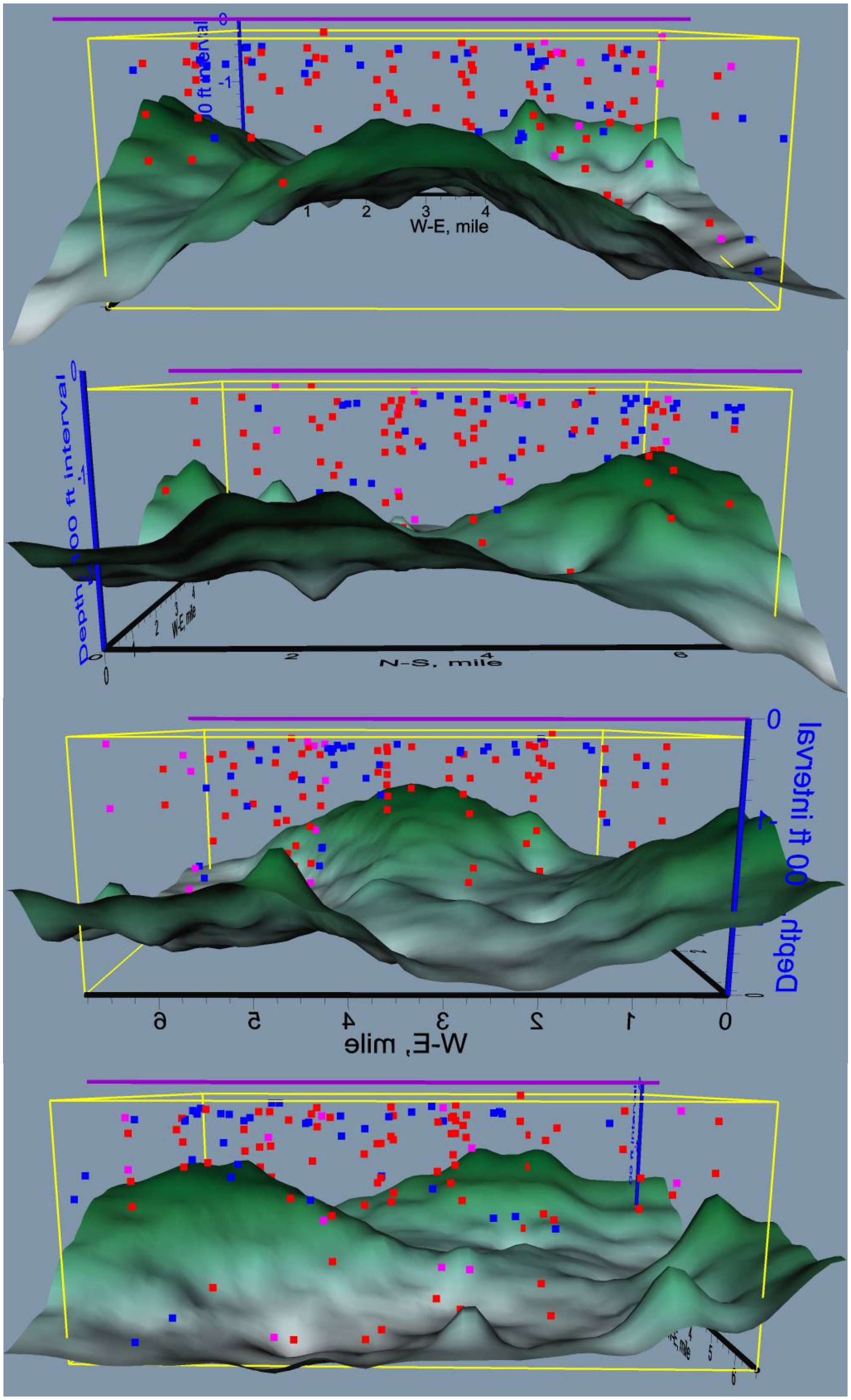

Figure 15. Well points in the bounding box for the Burrton plume viewed toward the north (a), east (b), south (c), and west (d), along with the bedrock surface. See Figure 14 for legend.

Report, 1984). The dense oil brine that was disposed in surface ponds or allowed to run over the surface would have initially migrated vertically if entering sand or sand and gravel deposits. When the saltwater generated by mixing of the brine and the fresh ground water encountered a low-permeability clay layer in the aquifer, the expected movement would be primarily in the direction of ground-water flow along the top of the clay. The clay layers in the aquifer are not

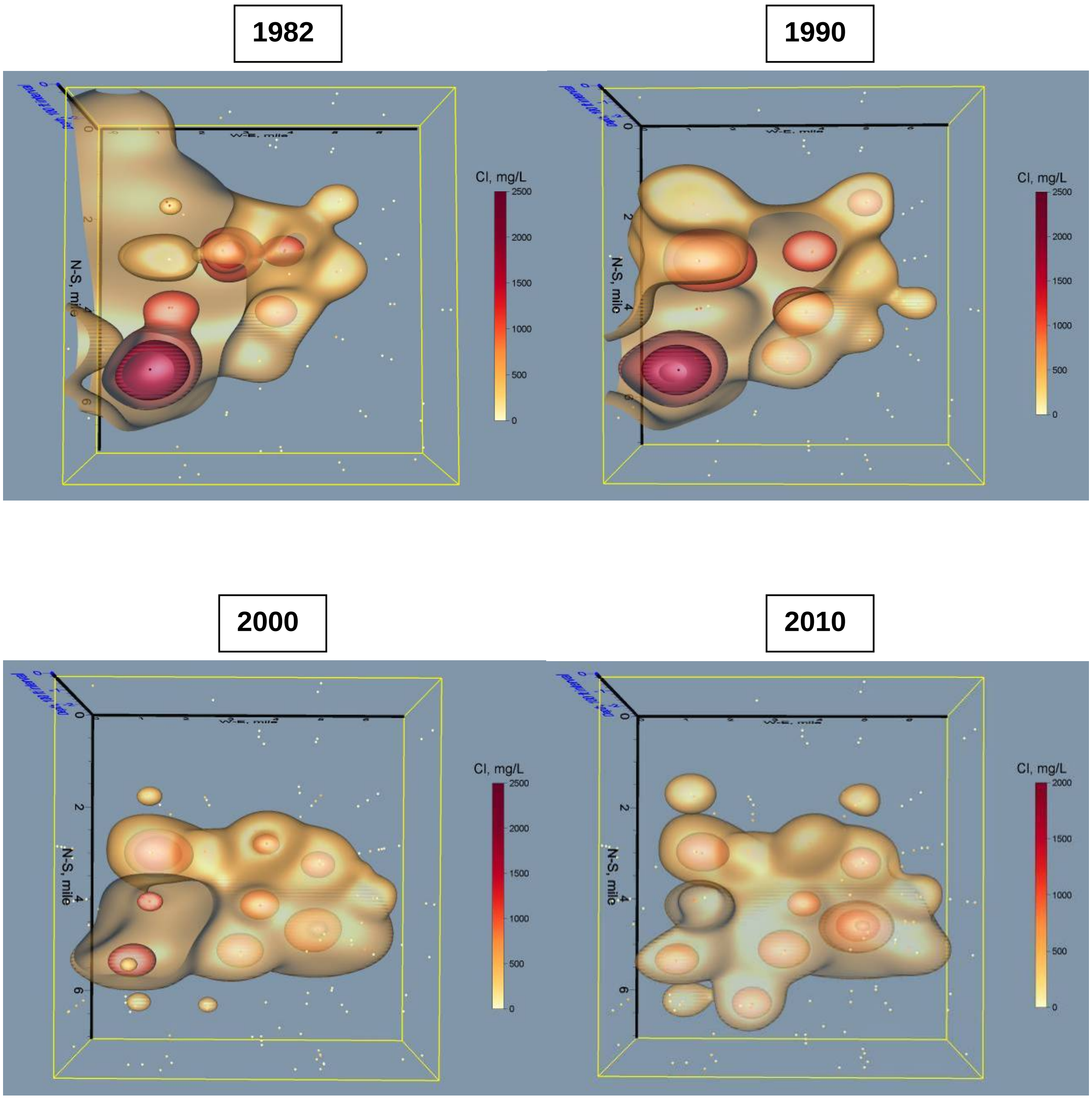

Figure 16. Chloride isosurfaces (500, 1,000, and 1,500 mg/L) for the Burrton area plume in 1982, 1990, 2000, and 2010, viewed from above. The dots represent the locations of the wells; the color of the dots and of the isosurfaces represents the chloride concentration as shown in the colored bar.

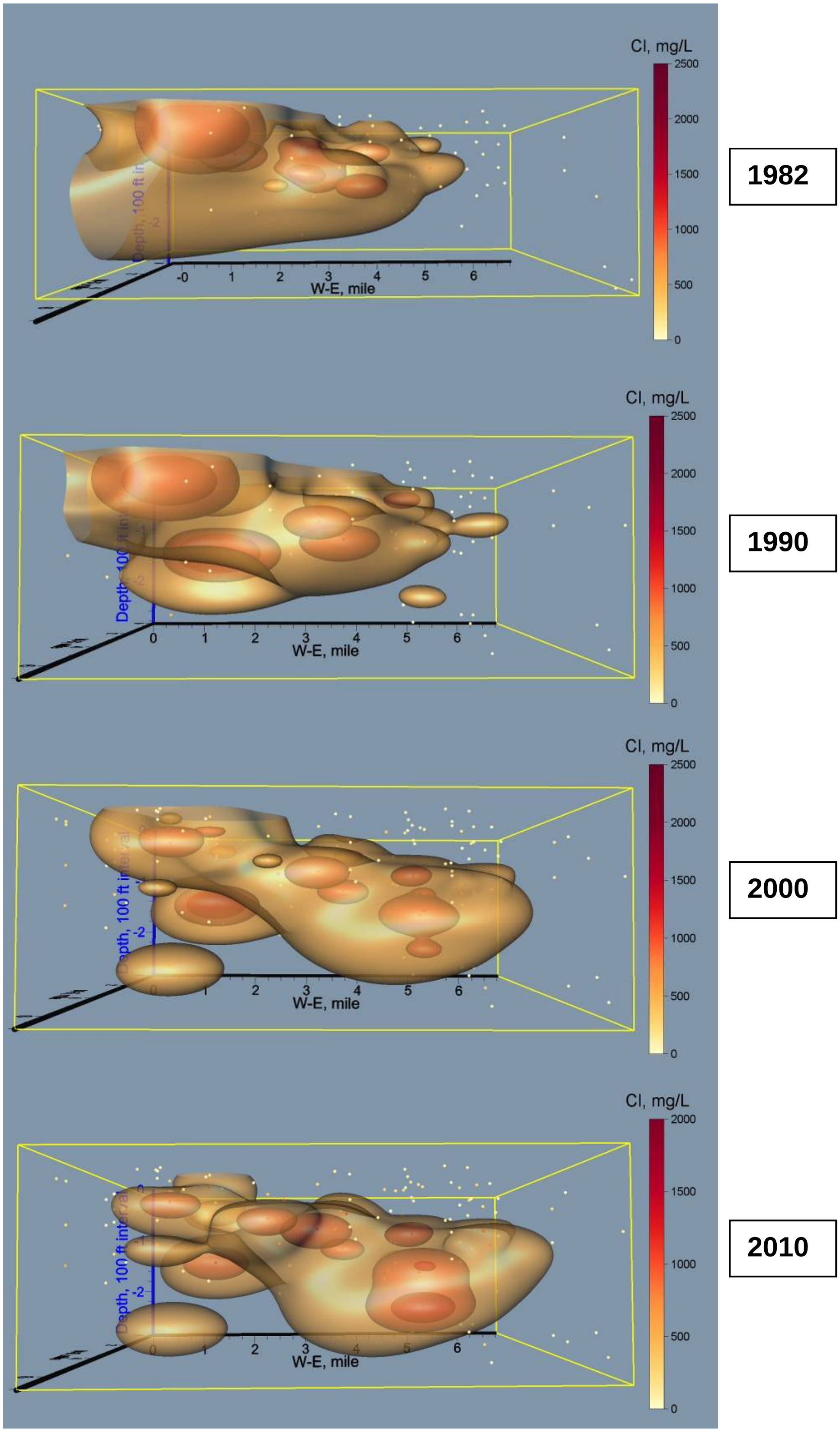

Figure 17. Chloride isosurfaces (500, 1,000, and 1,500 mg/L) for the Burrton area plume in 1982, 1990, 2000, and 2010. The view direction is toward the north for each image.

continuous in extent and can allow downward movement of dense saltwater at their edge in coarser unconsolidated deposits. The saline water migration can therefore be pictured as "stair-stepping" down through portions of the aquifer. As the saline water is diluted, the density contrast with freshwater decreases to the point where lateral migration with the direction of ground-water flow becomes prevalent. The clay layers, along with the multiple locations of the source brine ponds, could also help explain the "pocket-like" distribution of the salinity in the plume seen in Figures 16-19.

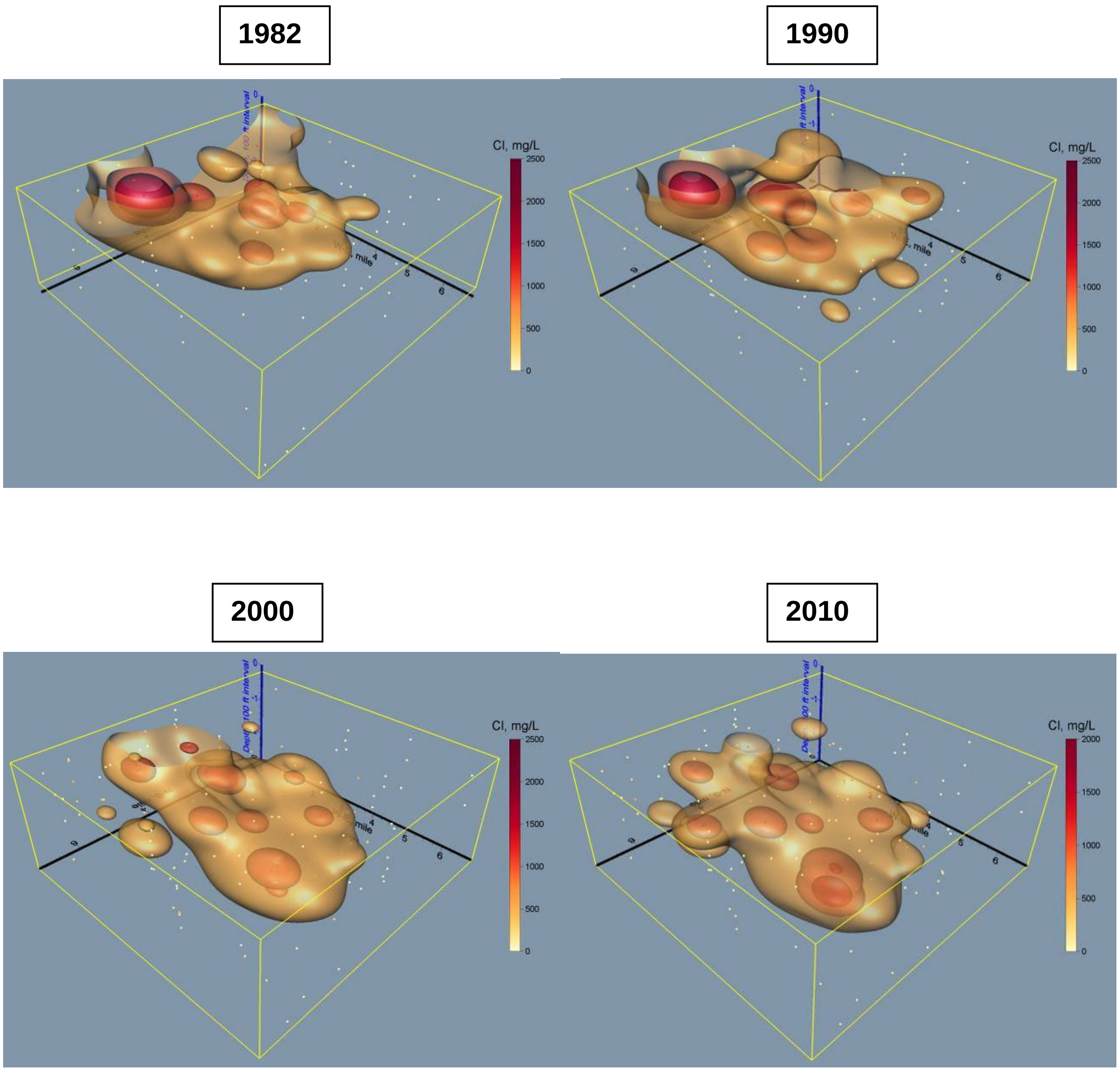

Figure 18. Chloride isosurfaces (500, 1,000, and 1,500 mg/L) for the Burrton area plume in 1982, 1990, 2000, and 2010. The view direction is toward the northwest for each image.

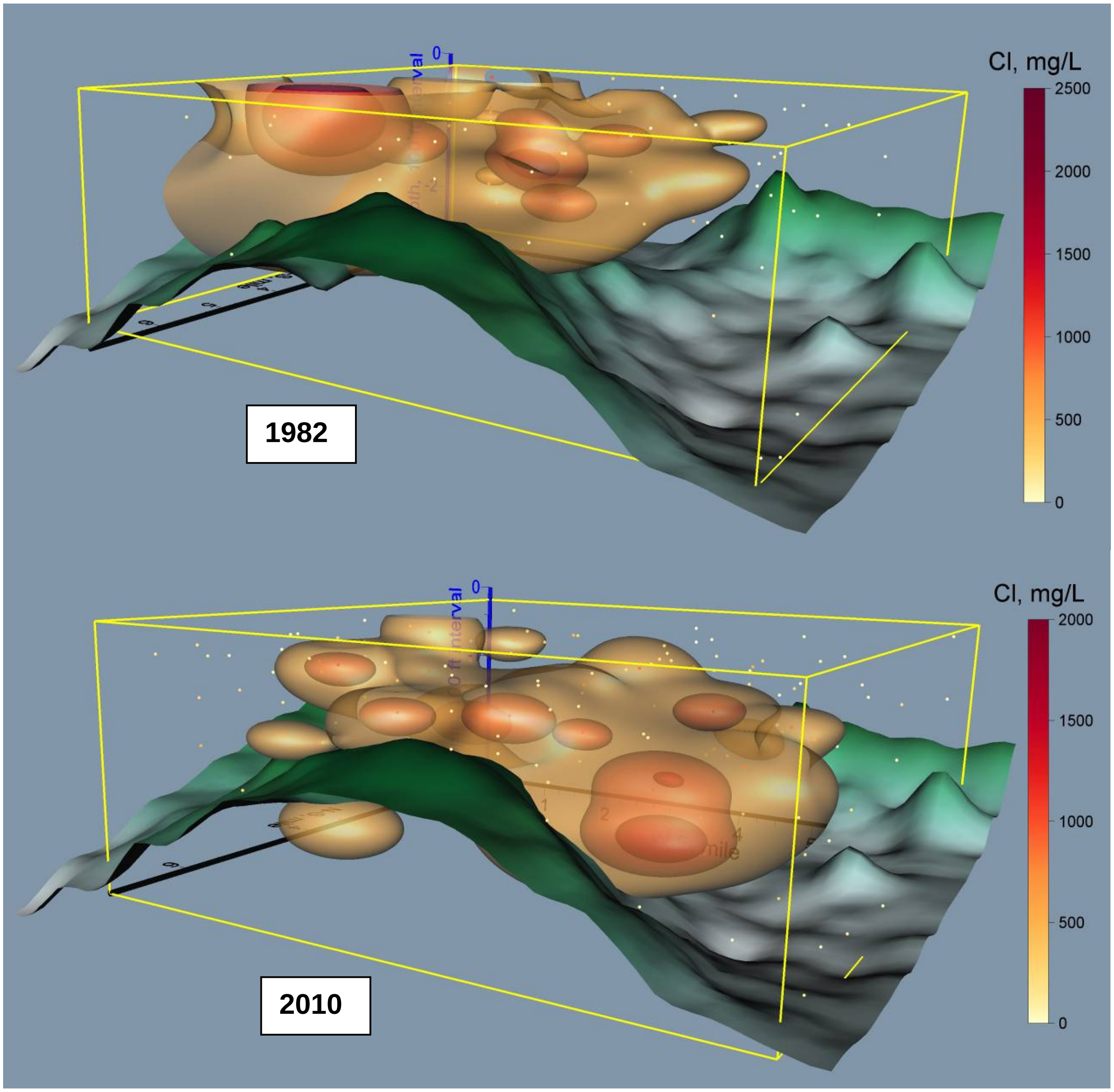

Figure 19. Chloride isosurfaces (500, 1,000, and 1,500 mg/L) for the Burrton area plume in 1982 and 2010, and the bedrock surface (in green shades). The view direction is toward the north-northwest for each image.

STATISTICAL TREND IN CHLORIDE CONCENTRATION

The overall statistical trend in the mean chloride concentration for the Burrton plume was determined by selecting data for wells that have a long-term record (the EB and P monitoring well data). Only those wells were selected that are located either within the area of elevated chloride concentration or immediately adjacent to the plume boundaries. The period of record used for 48 wells in the Burrton area is 1980 to 2010. If a chloride value for a well was missing for a year, an average of the values for the years immediately before and after the missing year was used. If more than one year was missing, a prorated change was calculated depending on the year in between the years with values. Thus, the data set for the statistical trend analysis was not biased by the presence of missing values. The mean of the chloride values for each year for all wells was computed for the trend analysis.

The data for the Burrton area were examined for the presence of a normal distribution. The data distribution is almost normal as shown by the histogram in Figure 20.

The change in the mean chloride concentration with time for the Burrton plume is shown in Figure 21 along with the linear regression calculated for the data. The linear regression has a very low coefficient of determination (R^2) and correlation coefficient ($R = 0.21$). Although the line appears to show a slight increase in chloride concentration with time, it is not statistically significant. This approximately constant chloride concentration is expected if the monitoring well samples effectively represent the complete distribution of chloride in the plume. The saltwater that entered the aquifer has migrated within the total past and present area of the plume but has not discharged from that area. Any slightly saline water withdrawn by irrigation would

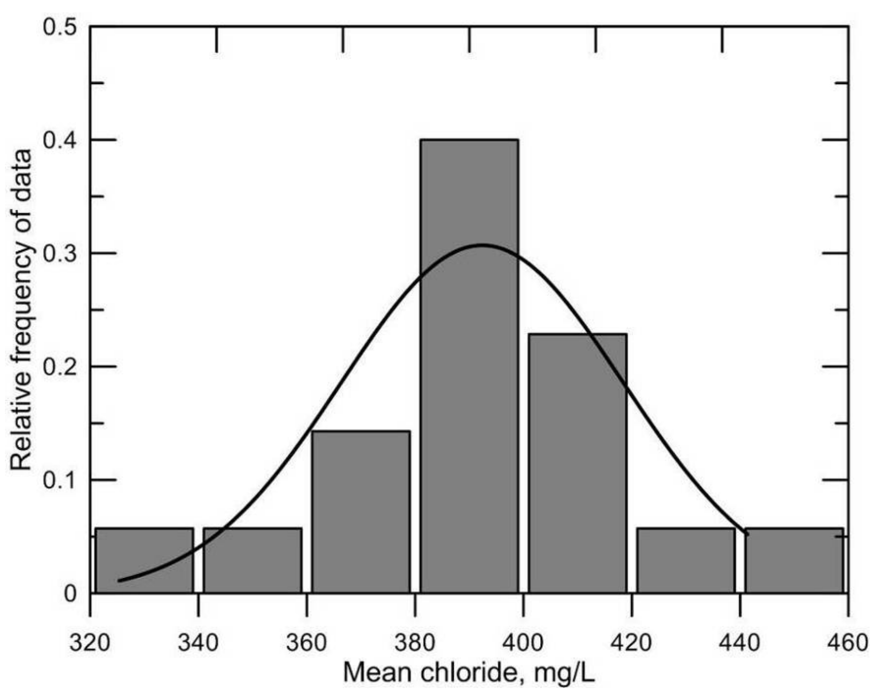

Figure 20. Histogram of data used for trend analysis of mean chloride concentration in the Burrton area plume. The solid line is the fit calculated for a normal distribution.

be returned to the aquifer as return flow. Thus, the results indicate a conservation of chloride mass within the aquifer.

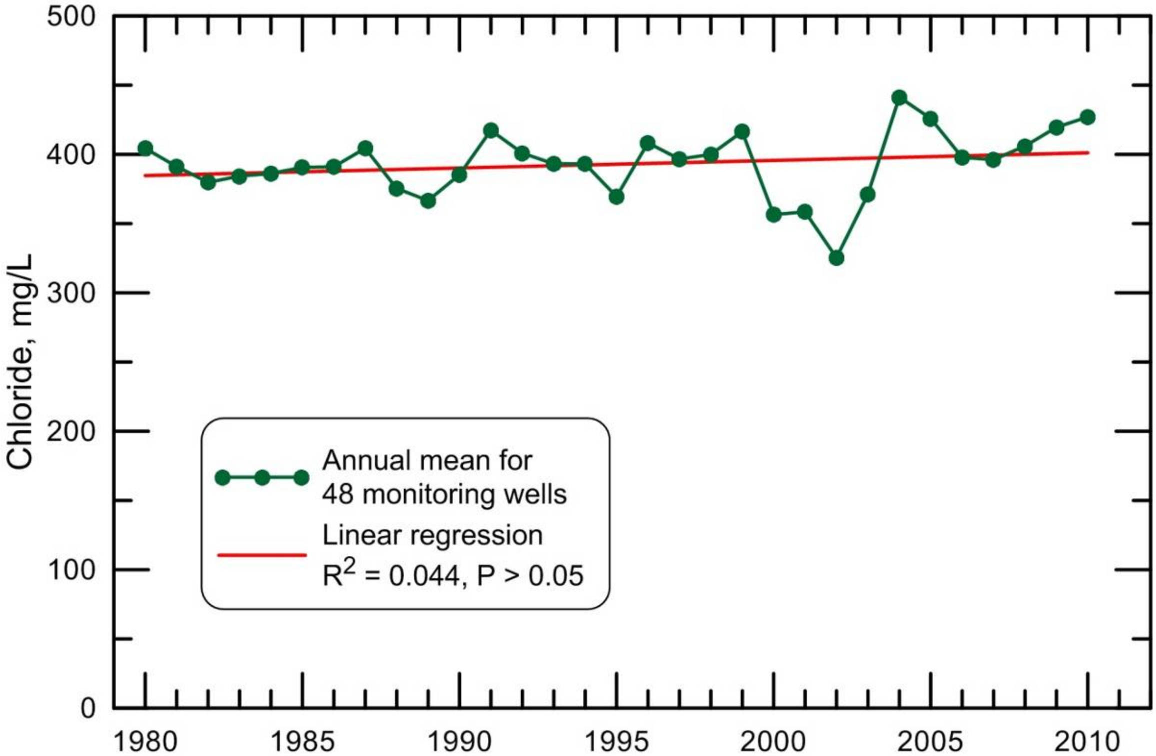

Figure 21. Change in the mean chloride concentration for 48 monitoring wells within and immediately adjacent to the Burrton salinity plume.

ASSESSMENT OF FUTURE CHANGES

The trend in decreasing chloride concentration in the western part of the Burrton plume area should continue as the saline ground water migrates to the east and is diluted by fresh ground-water recharge. Areas that contained water unusable for irrigation, stock, and drinking will improve and become available for most uses. The slow migration of ground water with elevated chloride concentration to the east along the front of the plume and into the lower aquifer will degrade the quality of ground water along the southeastern part of T. 23 S., R. 3 W., and the northeast corner of T. 24 S., R. 3 W., and make it unusable for most uses. Assuming no new saltwater is introduced into the plume, the chloride level is not expected to reach the concentration levels recorded in the monitoring well data for the early 1980s to early 1990s in the western and central parts of the plume.

Although dilution will continue to decrease the overall chloride concentration in the plume, the total volume of the water affected by the salinity will increase as the plume spreads because the chloride mass is conservative. Some of the chloride mass is also being redistributed by the pumping of slightly saline water from within the aquifer to the surface by irrigation wells. The application of this water to the surface can increase the chloride content of the soil, as shown by a study in the east-central part of the Burrton IGUCA (Whittemore, 2002). Soil water with higher chloride concentration can then infiltrate to the underlying water table during wetter conditions. Thus, dilution of chloride concentration in the shallow aquifer by fresh recharge can be partially offset by redistribution by irrigation pumping of saline ground water.

Elevated chloride concentration in the Burrton plume will eventually reach the cluster of wells M41-M44 in the Wichita well field (the four southeasternmost supply wells in Figure 13) but should be diluted to a few hundred mg/L upon arrival. The chloride concentration increase in monitoring well EB14B appears to be reaching a peak of about 960 mg/L based on the shape of the line in a time versus chloride plot. A chloride concentration increase will probably occur in the two most northerly (M41 and M42) of the four Wichita water-supply wells. However, the protruding nose of the plume is in the middle aquifer level to the east of monitoring well site EB14. If the plume nose continued to migrate to the east, the higher chloride concentration would first pass to the north of the four Wichita supply wells before spreading to the four supply wells.

ASSESSMENT OF GMD2 MONITORING WELL NETWORK

The areal location of monitoring wells in the GMD2 network is relatively well distributed to capture salinity trends in the Burrton area. Also, the screened interval depths of the monitoring wells are reasonably well distributed to allow examination of water-quality changes at different levels of the aquifer. Based on this study, two additional monitoring wells are recommended to improve the discernment of migrating salinity in the area of the Burrton plume.

The 3D visualization of the Burrton plume shows where the front of the saline water is migrating within the aquifer. The nose of the plume in the 3D image extends within the middle level of the aquifer past well EB14B to near the location of Wichita/USGS monitoring well site IW-09. Two monitoring wells located at site IW-09 include a shallow well screened at 33-53 ft and a deep well screened at 233-253 ft. Well EB14B, which has shown an increasing chloride concentration to 960 mg/L in 2010 in the middle level of the aquifer, is screened at 115-125 ft. The migrating chloride plume could potentially pass through the gap between the shallow and deep IW-09 wells without being detected. Wichita supply well M41 is about a mile to the south of site IW-09. The WWC-5 well log for the deep well at IW-09 indicates a relatively thick clay zone at 128-163 ft below land surface, which is overlain by sand from 84 to 128 ft. A 13-ft thick clay layer overlies this sand, and a sand and gravel layer at a depth of 41-61 ft overlies this clay. The shallow well at site IW-09 appears to sample ground water from this 20-ft thick sand and gravel zone. A new monitoring well screened at a depth of 118-128 ft is recommended for installation at the IW-09 site.

WWC-5 well log records indicate that the City of Wichita has eight other monitoring wells (RB 1 MN S, RB 1 MN D, RB 1 MS S, RB 1 MS D, RB 1 PZ S, RB 1 PZ D, RR 05 S, and RR 05 D) in the northeast 10-acre tract of sec. 2, T. 23 S., R. 3 W., the area where site IW-09 is located. The deepest ‘S’ or shallow well of these eight wells extends to 65 ft and the shallowest ‘D’ or deep well is at 253 ft. Thus, none of these wells samples the zone where the chloride plume nose could potentially extend in the future. Wichita also has a high capacity supply well

(RR05) in the northeast corner of the same 10-acre tract that has screened intervals from 80-100 ft, 120-132 ft, 183-222 ft, and 240-264 ft below land surface. The lithologic log for this well indicates that the only clay stringers were found in tight medium sand at 140-160 ft, a depth approximately equivalent to the clay zone at 128-163 ft at site IW-09. Although this well would not be a good indicator for detecting salinity in the middle aquifer level, it would be expected to draw ground water from the different screened intervals and be subject to expected elevated chloride concentration at the plume front.

Although no monitoring wells extend to the base of the aquifer in the central part of the Burrton plume in the vicinity of well sites EB57, P29, P30, and P31, the lower of the two wells at sites EB57, P29, and P30 monitors the deepest permeable (aquifer) sediments at these locations. Clay and silty clay overlies the bedrock below the screened intervals of these three wells. Thus, the aquifer portion of most of the central part of the plume is effectively monitored.

The area missing a monitoring well site in the plume center is at the geographic center of the IGUCA (the intersection of sections 29-32, T. 23 S., R. 3 W.) in the middle of the space surrounded by sites EB2, EB3, EB57, P29, and P30. No supply wells are currently monitored in this area. In order to determine the chloride distribution in this area and assess whether the water is usable for supply, a monitoring well screened at the base of the deepest (permeable) aquifer is recommended. As an alternative, one of two existing domestic wells could be monitored. Two domestic wells have been drilled at this location since 1996. One is located at the NW NE NE sec. 31, T. 23 S., R. 3 W. and was drilled to a depth of 211 ft, which is probably at or close to the depth to bedrock based on Figure 3. The well has a screened interval of 145-185 ft that crosses zones of fine sand at 140-152 ft, 158-163 ft, and 167-179 ft. The lithology between 179 and 211 ft was recorded as clay. The other domestic well is located at the SW NW NW sec. 32, T. 23 S., R. 3 W. and was drilled to a depth of 179 ft. The well has a screened interval of 154-164 ft across a zone of fine sand at 155-165 ft. The lithology between 165 and 179 ft was recorded as clay. The annular space in these wells is grouted through the shallow and middle parts of the aquifer to a depth of 140 ft in the first well and to 145 ft in the second well. If one of these wells could be sampled, it would provide a reasonably representative characterization of the salinity of the lower part of the aquifer in this area.

CONCLUSIONS AND RECOMMENDATIONS

The water-quality monitoring programs of GMD2 and the City of Wichita in the Equus Beds aquifer in the Burrton area have provided a substantial amount of data for assessing the distribution of salinity in the ground water. The monitoring programs have been particularly valuable in allowing determination of long-term trends in water quality in the aquifer.

Graphs for individual wells and three-dimensional imaging of the chloride concentration in the aquifer assisted in characterizing changes in the Burrton salinity plume. The saltwater plume has migrated primarily toward the east and has also moved deeper in the aquifer with time. Substantial clay layers within the aquifer have restricted the rate of vertical movement of salinity and promoted a lateral and vertical “stair-stepping” migration. The front of the plume, as indicated by the 500 mg/L chloride isosurface, is now about a mile away from the nearest municipal supply well in the Wichita well field. The plume front has advanced from about a mile and a half to over 2 miles to the east during 1982-2010 (about 0.8-1.0 ft/day).

A total of 87 unique, active points of diversion with active water use exist for supply wells with water rights within the Burrton IGUCA. GMD2 has chloride concentration data for selected periods for 35 of these wells. The chloride concentration range and median for these wells is 5-804 mg/L and 112 mg/L, respectively. The depths of the wells range from 30 ft to 195 ft, although most of the wells are shallow as indicated by the median depth of 54 ft. Substantial fluctuations in chloride concentration have occurred in some wells within a year that are probably related to stratification of saline water in the aquifer relative to the well screen intervals. The longer term trend in chloride concentration is generally a decrease for supply wells screened in the shallow and middle levels of the aquifer in the western part of the IGUCA. However, the chloride concentration has increased in some supply wells in the deep part of the aquifer in the western IGUCA area. In the middle and eastern parts of the IGUCA, the chloride concentration of water sampled from the supply wells screened in the middle and deep parts of the aquifer has generally either remained roughly constant or has increased.

An analysis of mean chloride concentration versus time in ground water sampled by the GMD2 monitoring network indicates that no statistically significant trend has occurred in the area of the saline plume. This is not unexpected if the monitoring well samples accurately represent the complete distribution of chloride concentration in the plume. The saltwater that entered the plume has migrated within the total past and present area of the plume but has not discharged from that area. This represents a conservation of chloride mass within the aquifer.

Some redistribution of the chloride mass occurs in the plume from the pumping of slightly saline water from within the aquifer to the surface by irrigation wells. The saline irrigation water can then increase the chloride content of the soil, especially during dry periods. Saline soil moisture can then infiltrate to the underlying water table during wetter conditions to increase the chloride concentration of the underlying shallow aquifer.

The areal distribution of monitoring well sites in the GMD2 network and their vertical sampling distribution is good for capturing salinity trends in the Burrton area, especially considering the effective base of saltwater migration where either shale of the Wellington Formation underlies the aquifer or clay at the bottom of the Equus Beds overlies the bedrock. Based on this study, two additional monitoring wells are recommended for improving the detection of migrating salinity in the area of the Burrton plume. One well is recommended at Wichita/USGS monitoring well site IW-09 for sampling the middle level of the aquifer near the nose of the advancing salinity plume. The leading edge of the plume will most likely migrate through the middle level of the aquifer between the two wells at site IW-09, which are screened only in the shallow and deep levels of the aquifer.

Another well is recommended to monitor the salinity in the center of the Burrton plume where no monitoring well exists. An alternative to this well is utilization of one of the two domestic wells located near the geographic center of the Burrton IGUCA, drilled since 1996, screened in the lower aquifer, and grouted through the upper and middle aquifer, as a monitoring location for an assessment of the salinity.

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