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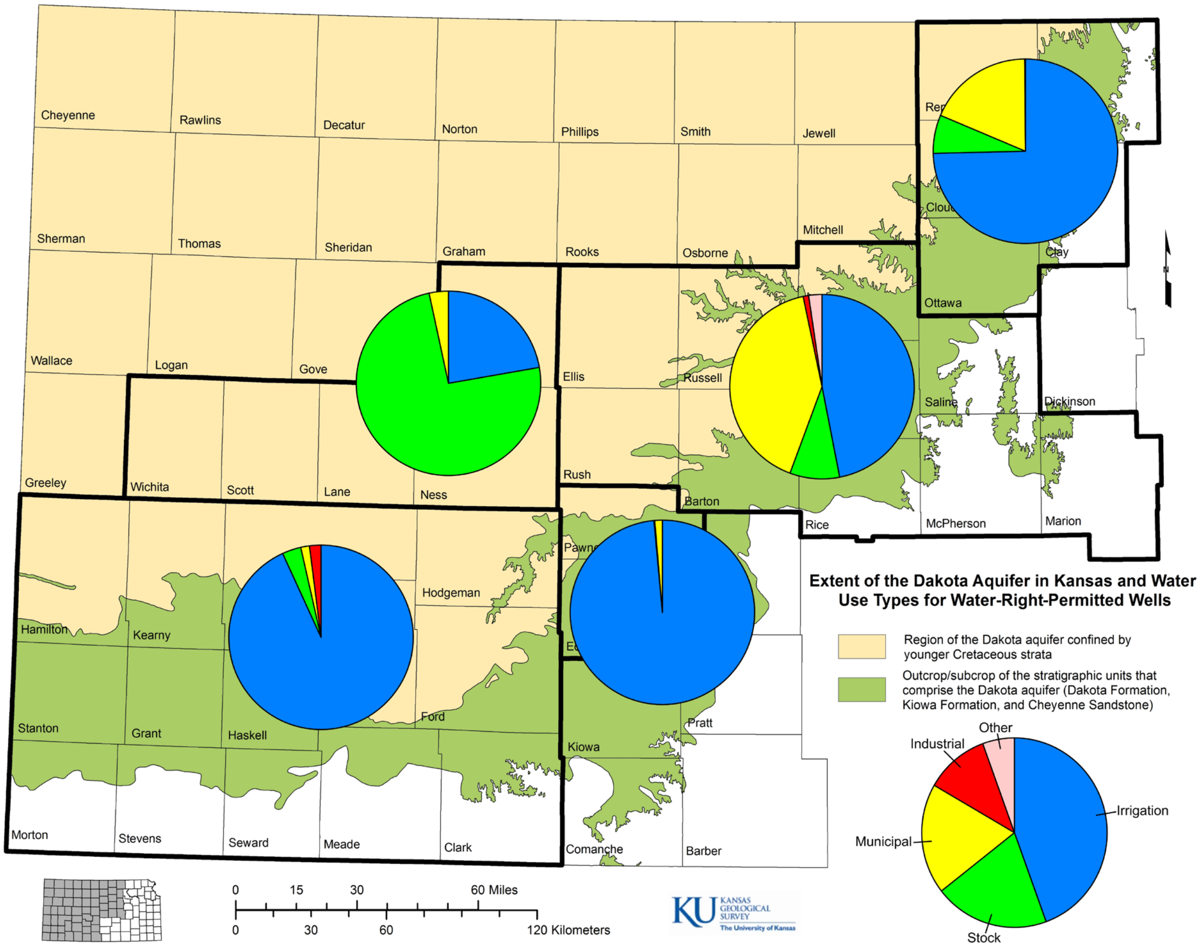

Extent of the Dakota Aquifer in Kansas and Water Use Types for Water-Right-Permitted Wells

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ABSTRACT

The Dakota aquifer system underlies most of the western two-thirds of Kansas and includes sandstone units in the Cretaceous Dakota, Kiowa, and Cheyenne Sandstone formations. The underlying Jurassic Morrison Formation in southwest Kansas is also considered by state statute to be part of the Dakota system. The Dakota aquifer has been developed as a water-supply source where the groundwater is fresh or only slightly saline and where other more easily obtained water supplies are not available. A total of 2,237 wells with active water rights and active uses made of water as of the end of 2011 were determined to produce greater than 5% of their total yield from the Dakota aquifer. Most of these wells are located where the Dakota aquifer underlies the High Plains aquifer (HPA) in southwest Kansas. In the 36 counties in which water-right-permitted wells pump partially or solely from the Dakota aquifer, the wells with Dakota yield are estimated to comprise 9% of the total of wells with water-right permits in all aquifers. Most (78%) of the water-right-permitted wells that draw part or all of their water from the Dakota aquifer are used for irrigation. Stock, municipal, and industrial wells comprise nearly all of the other uses (9.6%, 8.9%, and 2.2%, respectively, of the wells with some Dakota yield).

The mean annual volume of water used from the Dakota aquifer by water-right-permitted wells in Kansas is estimated to have been 117,000 acre-ft/yr (1.44 x 10^8 m^3/yr) from 2006 to 2010. The use was greatest in southwest Kansas (approximately 86% of the total Dakota use). The mean annual use for other regions ranged from approximately 0.5% of the total Dakota use for west-central Kansas, to 2.4% for central, 2.9% for south-central, and 8.1% for north-central Kansas. Although Dakota water use in north-central Kansas was much lower than in southwest Kansas, the percent Dakota use relative to total use from all aquifers was the highest (nearly 20%) of all the regions. The percent Dakota use compared to total use from all aquifers for the other regions is 5.2% for southwest, 2.5% for central, 2.0% for south-central, and 0.4% for west-central Kansas. About 90% of the mean annual use from the Dakota aquifer during 2006–2010 was for irrigation, most of which was in southwest Kansas. For stock and municipal purposes, water usage was nearly 4% each of the total volume pumped from the Dakota aquifer. However, municipal demands accounted for 41% and 18% of the total use from the Dakota in central and north-central Kansas, respectively.

The total number of "domestic" wells, defined as those for which water-right permits are not required, that currently produce most or all of their water from the Dakota aquifer in Kansas is estimated to be more than 11,000 (about 8,000 for north-central and central Kansas and nearly 3,200 for south-central, west-central, and southwest Kansas). Water use from the Dakota aquifer by "domestic" wells is estimated to be 4,800 acre-ft/yr (5.9 x 10^6 m^3/yr) in central Kansas, 1,500 acre-ft/yr (1.9 x 10^6 m^3/yr) in north-central Kansas, and a total of 1,700 acre-ft/yr (2.1 x 10^6 m^3/yr) in south-central, west-central, and southwest Kansas. The total "domestic" well use (about 8,000 acre-ft/yr) is about 6.4% of the approximately 125,000 acre-ft/yr (1.54 x 10^8 m^3/yr) pumped from the Dakota aquifer by both permitted and "domestic" wells in Kansas.

The processes of mixing, reactive cation exchange, and mineral dissolution and precipitation have produced a complex range of chemical characteristics for groundwater in the Dakota aquifer. Water quality in the aquifer ranges from very fresh (<300 mg/L total dissolved solids [TDS]) to saltwater (>10,000 mg/L TDS). Freshwaters in the outcrop and subcrop portions of the Dakota aquifer in north-central and central Kansas are usually calcium-bicarbonate type waters. Calcium-sulfate type water in some regions can result from one of two processes: (1) weathering of pyrite in shales in Dakota strata and concomitant dissolution of calcite or dolomite and (2) recharge from upper Cretaceous strata that was affected by the same processes or by dissolution of gypsum. Large areas of the Dakota aquifer contain saline water (sodium-chloride type water) that was derived from the upward intrusion of saltwater from underlying Permian units, especially the Cedar Hills Sandstone in central and north-central Kansas. The saltwater is derived from the dissolution of evaporite deposits containing rock salt (halite) in the Permian. The salinity of groundwater in the Dakota aquifer generally increases with depth, particularly across substantial shale units of appreciable lateral extent that confine or separate aquifer units. Sodium-bicarbonate type water, which exists in parts of the confined Dakota aquifer in central and west-central Kansas, is generated by the flushing of saline water from the aquifer by groundwater recharge of calcium-bicarbonate or calcium-sulfate types. During this process, calcium (and magnesium) in the freshwater is exchanged for sodium on clays in Dakota strata. Fluoride concentrations increase in the sodium-bicarbonate water as a result of dissolution of calcium-containing fluoride minerals during the decrease in calcium in the groundwater caused by the exchange process.

Fluoride concentrations exceed the maximum contaminant level (MCL) of 4 mg/L for public drinking water supply in some areas of the confined Dakota aquifer. About 10% of the sample records for the Dakota aquifer exceed the MCL for arsenic and the action level for lead, although some of the high lead values could be related to lead in plumbing systems. Uranium concentration and the radioactivity from radium isotopes and alpha particles exceed the MCL for public drinking waters in a small percentage of Dakota groundwaters. Many other natural constituents and properties in Dakota waters exceed recommended or suggested levels for drinking water, such as TDS, chloride, sulfate, iron, manganese, and ammonium ion concentrations, especially in saline water in the confined aquifer and in groundwaters that have chemically reducing conditions. The main contaminant from anthropogenic activities in Dakota groundwater is nitrate. Nitrate-nitrogen concentrations exceeding the MCL of 10 mg/L primarily occur in shallow wells in the unconfined aquifer in central and north-central Kansas. The expected sources are animal and human waste and fertilizer that enter groundwaters by shallow recharge or through the annular space of poorly constructed wells.

Development of the Dakota aquifer has been dependent on both the hydrogeologic properties of the aquifer and the salinity of the groundwater. The Kansas Geological Survey has identified an area of nearly fresh to slightly saline waters in upper Dakota strata that could be important for future water supplies. The area is triangular in shape, with its base along the south lines of Sheridan and Graham counties and its northern extent into south-central Norton County. Another factor in aquifer development is the decline in the water table in the HPA where it overlies and is hydraulically connected to the Dakota aquifer in southwest Kansas. Many new wells have been completed in both the HPA and underlying Dakota strata. In cases in which the new construction is a replacement well, the previous well was often only completed in the HPA. Thus, the percentage of wells completed in both aquifers is increasing. Continued assessment of the water resources potential of the Dakota aquifer is especially needed in southwest Kansas but is difficult due to the very limited data for depth-to-water measurements in the Dakota in that area. A selected group of wells across the Dakota in southwestern Kansas should be equipped with continuous monitoring equipment so that a better understanding of the relationship between the Dakota and the overlying HPA can be obtained.

INTRODUCTION

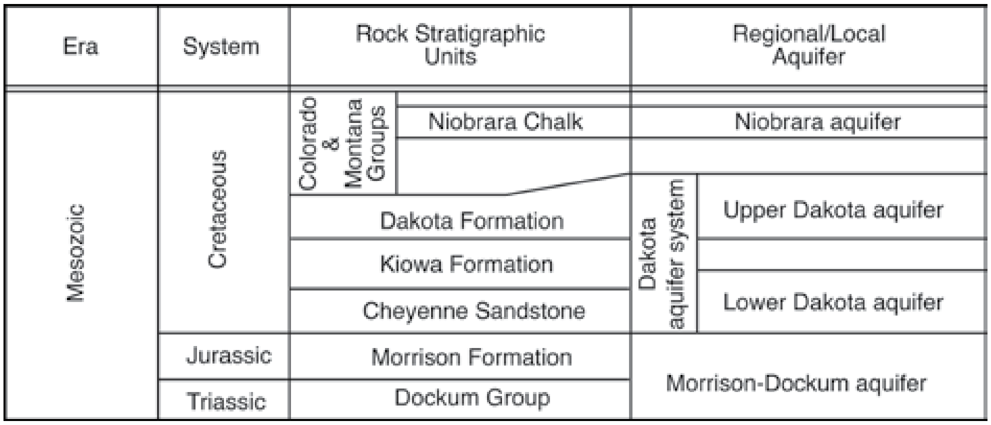
The Dakota aquifer is the most geographically extensive aquifer in Kansas, although the extent of freshwater is less than that of the High Plains aquifer (HPA). The Dakota has been used as a source of water in Kansas since before 1900. The aquifer system, which underlies most of the western two-thirds of Kansas, consists of the Cretaceous Dakota and Kiowa formations and Cheyenne Sandstone. The current and potential importance of the Dakota as a source of water in Kansas and the need to protect it from contamination by human activities have been of paramount importance to water planning and regulatory agencies. Although previous studies have improved the understanding of Dakota aquifer hydrology and water quality (Keene and Bayne, 1977; Lobmeyer and Weakly, 1979; Kume, 1984; Kume and Spinazola, 1982, 1985), a substantial amount of additional information was needed for management of the Dakota aquifer.

To address these issues, the Kansas Geological Survey (KGS) proposed and pursued an eight-year, multidisciplinary research effort, the Dakota Aquifer Program, to develop a better conceptual understanding of the geologic framework, flow systems, and aqueous geochemistry of the Dakota aquifer, including its confining layers and interactions with other aquifers. The objectives of the program included assessing the groundwater quality of the Dakota aquifer, contamination sources, and the impact of the quality on usable water resources. Publications derived from this program include a KGS technical series (Macfarlane, Doveton, and Whittemore, 1998) and *Current Research* paper (Macfarlane, 1995), KGS public information circulars (Macfarlane and Sawin, 1995; Macfarlane, 1997a, 1997b; Macfarlane, Whittemore, and Doveton,1998), journal papers (for example, Macfarlane, Doveton, et al., 1994; Macfarlane et al., 2000; Clark et al., 1998), and KGS open-file reports (for example, Macfarlane et al., 1988, 1990, 1991, 1992; Macfarlane, Whittemore, et al., 1994; Whittemore et al., 1993; Macfarlane and Whittemore, 1996). Web pages also provide information and data about the Dakota aquifer (http://www.kgs.ku.edu/Dakota/vol1/dakotaHome.html). Concurrent with the Dakota program of the KGS, the U.S. Geological Survey (USGS) conducted a regional investigation of the Great Plains aquifer system (which is equivalent to the Dakota aquifer in Kansas) primarily in Nebraska, Colorado, and Kansas (Helgeson et al., 1993).

After the Dakota program ended, development of online data bases for water-right and well log data, as well as development of user-friendly geographic information tools, facilitated locating and estimating yields for wells that draw water entirely or partially from the Dakota aquifer. This bulletin presents an overview of estimated recent water use from the Dakota aquifer; results of the Dakota program; results of later work on water-quality and geochemical studies; descriptions of suitability areas for water supply based on hydrogeology and water quality; and an assessment of other factors related to water-resource development and management. The bulletin consists of a main summary and an online appendix that contains more detailed descriptions of procedures and additional results and discussion (http://www.kgs.ku.edu/Publications/Bulletins/260/appendix.html).

DAKOTA AQUIFER SYSTEM

The Dakota aquifer has been defined by Macfarlane (2000) as the sandstone aquifers in the Lower Cretaceous Dakota and Kiowa formations and the Cheyenne Sandstone (fig. 1). Sandstones in the Cheyenne Sandstone, a valley-fill deposit at the base of the Lower Cretaceous Series, and in the overlying Kiowa Formation are thin and of limited extent. Thick, deltaic, and shoreline sandstones are locally developed in the Longford Member and Longford-equivalent strata in the Kiowa Formation in central Kansas. In contrast, sandstones in the Dakota Formation are widespread in Kansas because they were deposited on a broad, low-relief coastal plain adjacent to the developing Western Interior sea. In the rules and regulations of the Kansas Department of Agriculture, Division of Water Resources (DWR) (K.A.R. 5-1-1, 2011), the Dakota aquifer system is said to "include the Dakota formation, the Kiowa formation, the Cheyenne Sandstone, and, where hydraulically connected, the Morrison formation." The names of the Dakota and overlying and underlying Mesozoic Era aquifers and their rock stratigraphic equivalents in Kansas are shown in fig. 1. The Upper Dakota aquifer consists of sandstones in the Dakota Formation, and the Lower Dakota aquifer includes sandstones in the Longford Member of the Kiowa Formation and the Cheyenne Sandstone (Macfarlane, 2000). During the Regional Aquifer Systems Analysis of the USGS, most of the principal aquifers were renamed to reflect large-scale hydraulic continuity across state lines (Helgeson et al., 1993). The USGS used the names Maha aquifer, Apishapa confining unit, and Apishapa aquifer for the Upper Dakota aquifer, Kiowa Shale aquitard, and Lower Dakota aquifer, respectively.



Era	System	Rock Stratigraphic Units		Regional/Local Aquifer	
Mesozoic	Cretaceous	Colorado & Montana Groups			
			Niobrara Chalk	Niobrara aquifer	
		Dakota Formation		Dakota aquifer system	Upper Dakota aquifer
		Kiowa Formation			
		Cheyenne Sandstone			Lower Dakota aquifer
	Jurassic	Morrison Formation		Morrison-Dockum aquifer	
	Triassic	Dockum Group			

Figure 1. Nomenclature for aquifers of the Mesozoic era in Kansas. Modified from Macfarlane (2000).

The extent of the Dakota aquifer system in Kansas is shown in fig. 2. Not all of the geologic formations comprising the Dakota aquifer are present throughout the aquifer's extent (Macfarlane, 2000). In western and parts of central Kansas, the Dakota aquifer system is separated into upper and lower aquifers by an aquitard within the Kiowa Formation. Over much of central Kansas, the aquitard in the Kiowa is not present, and the upper and lower aquifer units cannot be differentiated.

Strata of the Dakota aquifer outcrop primarily in the eastern extent of the aquifer in Kansas, although small outcrop areas also exist in south-central Kansas (fig. 2). The aquifer is unconfined in this region as well as in areas where it is covered by alluvium (subcrop). It is also generally considered as unconfined where it is overlain by and hydraulically connected to the HPA in south-central and southwest Kansas. Most of the Dakota aquifer strata in Kansas are confined by overlying Upper Cretaceous shales and limestones. The Jurassic Morrison Formation underlies the aquifer in the northwest and westernmost parts of west-central and southwest Kansas (Merriam, 1963; Macfarlane, 2000). Elsewhere, the Dakota aquifer is underlain by Permian strata. Of particular significance is the Permian Cedar Hills Sandstone, which underlies the aquifer in parts of north-central and central Kansas (fig. 2). Saltwater in the Cedar Hills intrudes into the Dakota aquifer and substantially affects the water quality, as is described later in this bulletin.

Maps of the top and bottom configuration and of the potentiometric surface of the Dakota aquifer are available online at http://www.kgs.ku.edu/Dakota/vol3/bigmaps/index.htm. The combined thickness of Dakota, Kiowa, and Cheyenne units ranges up to more than 700 ft (210 m) in parts of west-central Kansas (Macfarlane, 1997a). More detailed maps of the top configuration and thickness of the upper Dakota aquifer, Kiowa Shale aquitard, lower Dakota aquifer, Morrison-Dockum aquifer (fig. 1), and overlying Upper Cretaceous and underlying Permian units are available in Macfarlane et al. (1993) (also available online at http://www.kgs.ku.edu/Hydro/Publications/1993/OFR93_1a/index.html).

The sandstone bodies that comprise the Dakota aquifer system are encapsulated in shales that are a part of the geologic units. Overall, less sandstone than shale exists in the system. The total thickness of sandstone in the Dakota aquifer ranges from less than 5% to more than 50% of the combined thickness of the Dakota and Kiowa formations and the Cheyenne Sandstone and varies dramatically even over distances of less than a few miles. The discontinuous sandstone bodies are generally lens shaped, rather than flat and continuous. Typically, the best sandstone aquifers are up to 100 ft (30 m) thick, 1.5 mi (2.4 km) wide, and 20 mi (32 km) or more long.

LOCATION AND AMOUNT OF WATER USE

Prior estimates of the total amount of recoverable water from the Dakota aquifer, irrespective of quality, range from 500 to 700 million acre-ft (6.2×10^{11} to 8.6×10^{11} m^3) (Crook, 1975; Helgeson et al., 1993). Keene and Bayne (1977) estimated that 70 to 80 million acre-ft (8.6×10^{10} to 9.9×10^{10} m^3) of water containing less than 1,000 mg/L total dissolved solids (TDS) concentration and an additional 10 million to 15 million acre-ft (1.2×10^{10} to 1.8×10^{10} m^3) containing 1,000 to 3,000 mg/L TDS could be obtained from this aquifer in Kansas. These estimates of recoverable groundwater in storage are based on limited information and regionalized estimates of drainable porosity and thickness of sandstone within the Dakota aquifer framework; they contain a wide range in uncertainty and may be substantially in error. Although sandstone porosity varies over a limited range and averages near 36%, total sandstone thickness ranges from less than 10% to more than 90% of the Dakota Formation thickness in Kansas. Furthermore, the amount of water

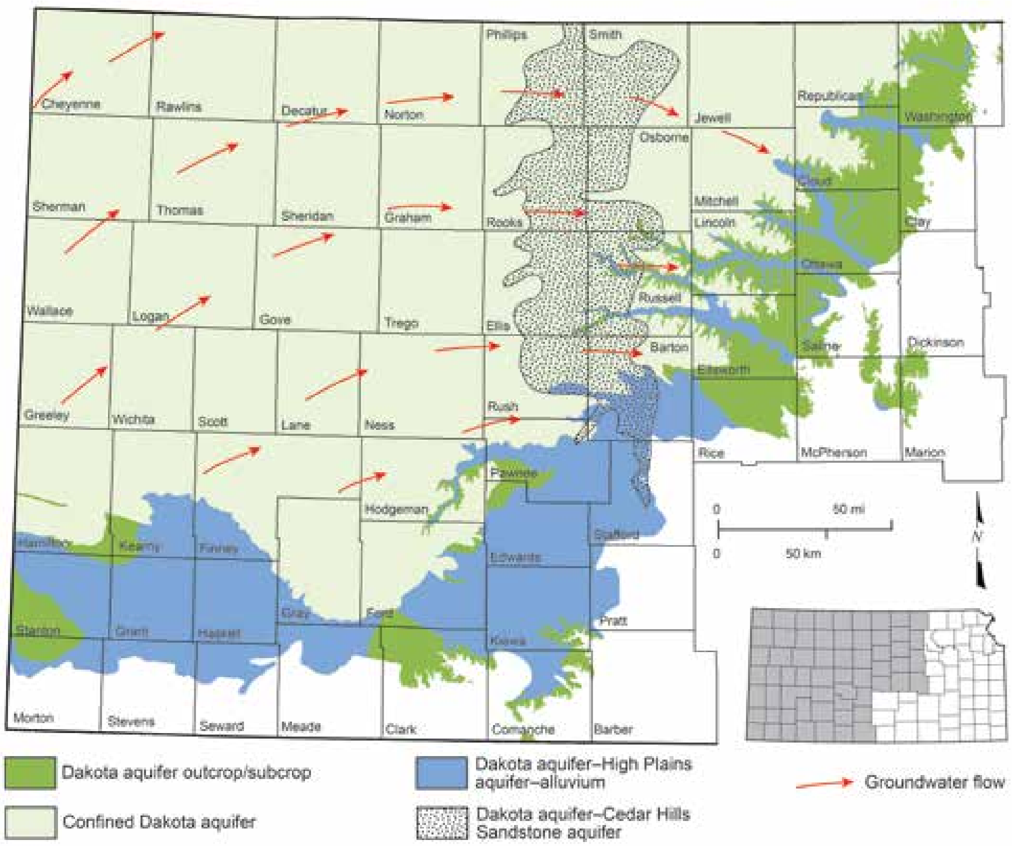


Figure 2. Extent of the Dakota aquifer system in Kansas. The aquifer is located in the western two-thirds of Kansas. Regions are shown where the Dakota aquifer is 1) a near-surface aquifer (outcrop/subcrop area) that either outcrops or is covered by thinly saturated Neogene or Quaternary sediments in southwest and south-central Kansas, 2) hydraulically connected to the overlying High Plains and alluvial valley aquifers, 3) hydraulically connected to the underlying Cedar Hills–upper Salt Plain aquifer, and 4) confined by overlying Upper Cretaceous strata. The arrows represent the generalized regional direction of groundwater flow.

released from the surrounding mudstones to the sandstones as leakage due to pumping is uncertain (Neuzil, 2002).

Groundwater from the Dakota aquifer is used for irrigation, stock, municipal, industrial, and domestic purposes. Development of the aquifer is limited primarily to areas where the groundwater is fresh or only slightly saline and where other more easily obtained water supplies, such as the High Plains and alluvial aquifers, are not available. Well yields depend on the ability of the aquifer to produce water as well as on the design and condition of the well and the pumping equipment. The most important hydrogeologic factors governing the potential yield are the thickness and lateral extent of the sandstone and its permeability, which depends on the properties of the sandstone matrix and the distribution of fractures. In general, because the sandstone is usually only fine- to medium-grained and cement (such as calcite and iron and manganese oxyhydroxides) may be present in pore spaces, the well yields are not as great as for the HPA. Reported well yields in the aquifer range widely from less than 10 to 2,000 gal/min (40 to 7,600 L/min) and are generally the highest in central and southwestern Kansas (Macfarlane, 1997a). In northern Ford and Hodgeman counties, yields reportedly exceed 1,000 gal/min (3,800 L/min) if the well is screened across thick intervals of permeable sandstone (Lobmeyer and Weakly, 1979). Farther north, where the aquifer strata outcrops in central and north-central Kansas, well yields generally range up to 600 gal/min (2,300 L/min). In northwest and west-central Kansas, use of the Dakota aquifer has been spotty or non-existent due to the more readily available and better quality near-surface water sources of the HPA.

Kansas statutes declare that all water within the state is "dedicated to the use of the people of the state, subject to the control and regulation of the state…" (Kansas State Statute 82a-702). Water may be appropriated for beneficial use subject to vested and existing senior water rights. These types of water appropriation or water rights are not required for "domestic" uses, although one can apply for a domestic-based water right. "Domestic" uses include household purposes, livestock as part of operating a farm (less than 1,000 confined head of cattle and less than 15 acre-ft [1,900 m^3] of use), or irrigation over less than 2 acres (0.8 ha) (Kansas Department of Agriculture, 2011). Wells with water-right permits are mainly for larger capacity production for irrigation, industrial, municipal, large feedlots, and other purposes. The distribution of wells that have a water-right appropriation and produce part or all of their supply from the Dakota aquifer in Kansas is a good indicator of where and how much groundwater is used from the aquifer. The DWR collects and checks data on the location and reported annual water use for wells with appropriation rights. The DWR stores its water-right data in an Oracle-based relational data-base management system called the Water Rights Information System (WRIS). The KGS, in cooperation with the DWR, developed an online interactive website, called the Water Information Management and Analysis System or WIMAS, to query and analyze WRIS-based data (http://hercules.kgs.ku.edu/geohydro/wimas/index.cfm).

The Kansas Department of Health and Environment (KDHE) has required well drillers to file water-well-completion records (WWC-5 form) for all types of constructed, reconstructed, and plugged wells since 1975. The lithologic logs associated with the drillers' records can allow determination of which wells are completed entirely or partially in the Dakota aquifer. The KGS stores the drillers' logs and has developed an online interactive data base of the log information (http://www.kgs.ku.edu/Magellan/WaterWell/index.html). The KGS developed the online system called the Kansas Master Ground-water Well Inventory (http://hercules.kgs.ku.edu/geohydro/master_well/index.cfm), which indexes the water rights, drillers' logs, and depth-to-water data together. This allows water usage along with water-level changes to be associated with geologic sources when the data records are available.

These recent data-base and online systems developments, coupled with the use of geographic information system (GIS) data layers generated with ArcGIS (http://www.esri.com/software/arcgis/index.html) and viewed in ArcGIS Explorer (http://www.esri.com/software/arcgis/explorer/index.html), greatly facilitated determining the wells with water rights and the percentage of their yield from the Dakota aquifer. "Domestic" wells, which do not require water rights, are greater in number but produce much smaller amounts of water from the Dakota aquifer. The number of these wells was estimated for different regions of the Dakota aquifer using WWC-5 records and selected KGS county bulletins. The general procedures used for determinations of well locations and estimations of water use are described in the next sections; more detailed descriptions of the methods are in the appendix (http://www.kgs.ku.edu/Publications/Bulletins/260/appendix.html).

Wells with Water-Right Permits

Determination of Well Location and Water Use

The WRIS includes aquifer codes for most wells (points of diversion) that have groundwater rights. Aquifer codes include those for the Dakota Formation, Kiowa Formation, Cheyenne Sandstone, confined or unconfined Dakota aquifer, and combinations of the Dakota aquifer with alluvial or Ogallala aquifers. However, aquifer codes for many points of diversion are unknown or yet to be established. During the investigation of permitted wells that could produce from the Dakota aquifer, many wells with other aquifer codes (such as the Ogallala aquifer, a commonly used name for the western portion of the HPA) were found to also be partially completed in the Dakota aquifer based on WWC-5 records or well depths from annual water-use reports.

Only water-right-permitted wells located within the extent of the Dakota aquifer (fig. 2) were considered for this bulletin. Wells with logs were examined to determine whether the well produced partially or solely from the Dakota aquifer. Wells without logs located outside of the extents of the HPA and alluvial aquifers, but within the area of freshwater in the Dakota aquifer and where other wells were known to be in Dakota strata based on well logs, were assumed to be completed in the Dakota aquifer. WRIS records for some points of diversion (locations of water withdrawal) include reported well depths. These were used within the HPA extent to determine which wells were substantially deeper (>50 ft [15 m]) than the bedrock surface of Dakota strata directly underlying the HPA, or even deeper where overlying Upper Cretaceous rocks confining the Dakota aquifer form the HPA bedrock surface. Water-right data were extracted from WRIS during December 2011 and January 2012, essentially representing conditions just prior to 2012.

Information from WWC-5 records for the water-right-permitted wells was examined to estimate the percentage of the yield for each well. This information included the completed well depth, depths of the screened intervals and of grout seal, the top depth of Dakota units below overlying strata based on the lithologic log, the static water level, water levels after a pumping test, the relative permeabilities and thicknesses of lithologic units acting as aquifer units (e.g., sand, gravel, sandstone), and any other relevant information such as whether Dakota sandstone took water during drilling. For wells located outside the HPA extent, the location relative to the extent of the Dakota aquifer confined by overlying upper Cretaceous strata and the salinity of water in the upper Dakota aquifer were also considered. For wells located within the HPA extent, an interpolated depth-to-bedrock surface (source data from Macfarlane and Wilson, 2006) at the well location was used to assist in interpretation of the lithologic log if the log description did not clearly indicate the HPA-Dakota strata contact. After determining whether a well was screened in both the Dakota aquifer and overlying unconsolidated sediment, the approximate depth of the static water level expected during the winters of the several years before 2012 was compared to that for the contact between Dakota and overlying strata. For those wells that were completed before this recent period, the static water level was estimated based on values for nearby wells with recent WWC-5 records or on depth-to-water measurements in the online KGS data base WIZARD (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html). The WWC-5 or WIZARD water level was used to determine the thickness of the saturated HPA contributing to the well yield relative to the sandstone thickness of the Dakota aquifer contributing to the yield.

Some of the wells with Dakota aquifer codes in WRIS records were found to have been drilled into but not screened in the Dakota aquifer. Many wells with only WRIS codes for other aquifers above the Dakota aquifer were found to be completed partially in Dakota strata. A few of these wells were determined to produce essentially all (>95%) of their yield from the Dakota aquifer because the recent static water level was near, at, or below the contact between the Dakota and overlying unconsolidated aquifer.

A percent yield from the Dakota aquifer was assigned to each well based on the estimated relative contribution of the Dakota strata to the total well yield. If the percentage was less than 5%, the contribution of the Dakota aquifer to the well yield was assumed to be insignificant and the well was not designated as producing from the Dakota. If the yield was estimated as >95%, the well was designated as producing entirely from the Dakota aquifer. The accuracy of the values depends on the quality of the lithologic logs, the interpretation of the logs and other data, and the assumption of relative hydraulic conductivities for the different strata. The estimated uncertainty in the percentages is probably ±10% for the 10–20% and 80–90% ranges and ±20% for the 30–70% range for most of the wells with logs.

Wells coded in WRIS as solely in Dakota units or in a combination of Dakota and other aquifers but without WWC-5 records were assigned a percent yield based on the percent yields of surrounding wells with well logs. Reported depths, if available, were used to assist in this estimation. Likewise, a percent yield from the Dakota aquifer was estimated for wells without logs that were coded as other aquifers or that had no aquifer code but that had depths greater than 50 ft (15 m) below the HPA bedrock surface, based on percentages from surrounding wells with logs. The uncertainty in the percent Dakota for these wells is expected to be substantially greater than that for the wells with well logs. Although some of the wells to which a portion of the yield was assigned to the Dakota may have substantially less or even no significant Dakota yield, this is probably offset by other wells that could have some yield from the Dakota but that were not identified based on the above procedure and available information. This would be the case for those wells that have reported depths less than 50 ft (15 m) below the actual bedrock surface but that are also screened in sandstone and for wells completed to a depth of greater than 50 ft (15 m) below the actual HPA bedrock surface in areas where local contours in the bedrock surface map of Macfarlane and Wilson (2006) are deeper than actual.

The procedure also would have missed wells that produce partially or solely from the Dakota aquifer within productive parts of the HPA if they had no well logs or reported well depths. USGS and KGS reports on sandstone aquifers in southwest Kansas and KGS bulletins on the geohydrology of selected counties, which were published during the mid-1960s to mid-1980s, were examined for records of wells producing primarily or partially from the Dakota aquifer. These records were compared to the list obtained by the above procedures and to WRIS and WWC-5 records; more than a dozen Dakota-producing wells were added to the list based on this additional review.

The water use from the Dakota aquifer for each year from 1990 to 2010 was then determined by multiplying the assigned Dakota yield percentage associated with each well by the water use reported for that year. This total Dakota water use is expected to be conservative given some use was probably missed for wells that produced from the Dakota aquifer but that were replaced, moved, or became inactive sometime during 1990–2010. Only wells with active, non-dismissed water rights at the time of the WRIS download were considered for this bulletin. In addition, only irrigation, stock, municipal, industrial, domestic, and recreational uses were considered; two dewatering wells in the Dakota aquifer in Ellsworth County were not included in the use totals.

Distribution of Wells

A total of 2,237 wells with active water rights and uses as of the end of 2011 were determined to produce greater than 5% of their total yield from the Dakota aquifer (table 1, fig. 3). This included about two dozen wells with pending water use; these wells are too new to have reported water use for 2010, the latest year of reported water use available to the public at the time of preparation of this bulletin. Most of the Dakota wells are located in southwest Kansas where the Dakota aquifer directly underlies the HPA. The remaining Dakota wells are distributed for the most part within the outcrop/subcrop area of the Dakota aquifer from north-central, through central, to south-central Kansas (fig. 3). Wells in west-central Kansas produce only from the confined Dakota aquifer.

Of the 581 Dakota wells located in north-central and central Kansas, 538 (about 93%) produce all (or greater than 95%) of their yield from the Dakota aquifer (table 1). Washington and Cloud counties have the largest number of Dakota wells in these two regions. In Pawnee and Edwards counties, about 43% of the wells with Dakota production pump essentially only from the Dakota; the rest pump primarily from overlying alluvial aquifers. Only 19% of the wells that include the Dakota in southwest Kansas produce solely from the Dakota aquifer (and underlying Morrison-Dockum aquifer, if present); most of these are located in the three westernmost counties (Hamilton, Stanton, and Morton counties) and two of the easternmost counties (Ford and Hodgeman counties) in the region. A total of 609 (39%) of the 1,555 Dakota wells in southwest Kansas produce more than 50% of their yield from the Dakota aquifer; 946 wells pump 50% or more of their yield from other aquifers (nearly all of which is from the HPA). The average well that draws at least part of its water from the Dakota aquifer produces about half of its total yield from the Dakota in southwest Kansas in comparison with greater than 95% for the average Dakota well in north-central and central Kansas. In general, the greater the saturated thickness of the HPA in southwest Kansas, the smaller the percentage of the yield from the Dakota aquifer in those wells that obtain part of their supply from the Dakota (fig 3).

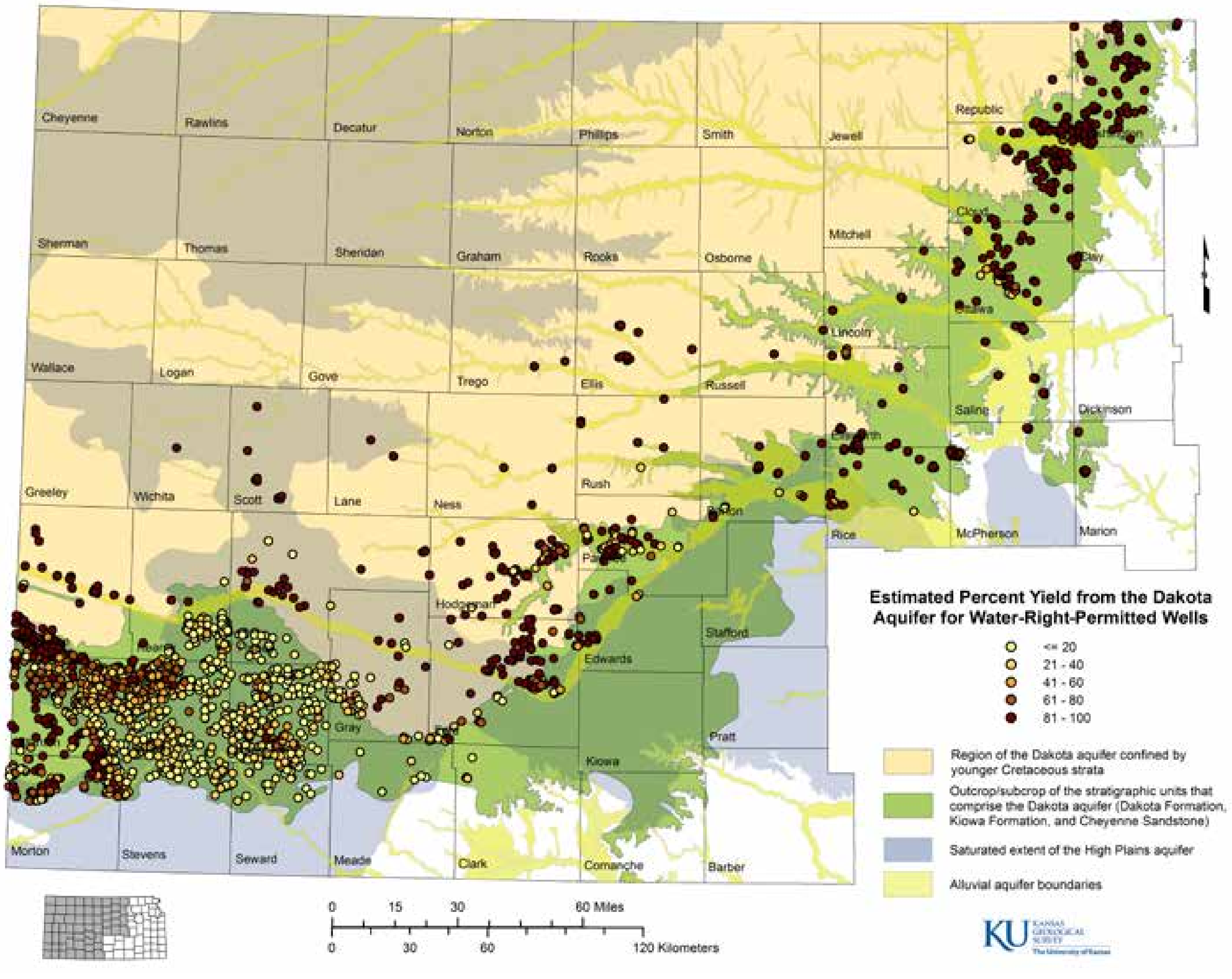


Figure 3. Distribution of wells producing partially or entirely from the Dakota aquifer according to percent of total yield that is from the Dakota system. The distribution is based on wells with active water rights and water use as of the end of 2011.

Table 1. Number of water-right-permitted wells that draw all or part of their yield from the Dakota aquifer and percent of total well yield from the Dakota aquifer.

County	Total wells	Estimated percentage of total well yield from Dakota aquifer										
		100%	90%	80%	70%	60%	50%	40%	30%	20%	10–15%	Mean %
North-central Kansas												
Clay	12	12										100
Cloud	110	108			1				1			99.1
Ottawa	63	51	1	4	2	1	2	1	3			91.9
Republic	13	13										100
Washington	173	173										100
Region total	**371**	**357**	**1**	**3**	**2**	**1**	**2**	**1**	**4**			**98.4**
Central Kansas												
Barton	21	17							1	2	1	84.8
Ellis	16	16										100
Ellsworth	42	30		12								94.3
Lincoln	6	6										100
Marion	10	10										100
McPherson	15	15										100
Rice	61	49	6	1		4			1			94.9
Rush	8	7							1			91.2
Russell	2	2										100
Saline	29	29										100
Region total	**210**	**181**	**6**	**13**		**4**			**3**	**2**	**1**	**95.5**
South-central Kansas												
Edwards	16	5	7		3	1						87.5
Pawnee	66	30	6	1	4				19	4	2	69.2
Region total	**82**	**35**	**13**	**1**	**7**	**1**			**19**	**4**	**2**	**72.8**
West-central Kansas												
Lane	3	3										100
Ness	4	4										100
Scott	8	8										100
Trego	3	3										100
Wichita	1	1										100
Region total	**19**	**19**										**100**
Southwest Kansas												
Clark	9								8		1	27.8
Finney	47	17	3	1				1	4	5	16	52.6
Ford	104	58	9	2	6	7	3	4	5	3	7	78.9
Grant	290	6	5	15	28	13	31	25	80	48	39	38.9
Gray	51	7	1	2	3	3	3	2	10	6	14	41.9
Hamilton	131	96	18	2	6		6		2		1	92.9
Haskell	230	1	1	1	7	4	10	17	68	58	63	25.9
Hodgeman	56	41	1		2	1	1		8	1	1	84.1
Kearny	84	4				5	6	8	20	20	21	30.3
Meade	7							1	1	2	3	20.0
Morton	138	31	8	8	21	3	21	5	13	10	18	58.9
Seward	30					1		2	2	5	20	17.3
Stanton	307	40	21	28	49	22	43	26	38	30	10	58.2
Stevens	71	1			1		3	8	19	19	20	25.2
Region total	**1,555**	**300**	**68**	**59**	**123**	**59**	**127**	**99**	**279**	**207**	**234**	**50.3**
Regions total	**2,237**	**893**	**87**	**76**	**132**	**65**	**129**	**100**	**305**	**213**	**237**	**63.8**

In the 36 counties in which water-right-permitted wells pump all or part of their supply from the Dakota aquifer, the Dakota wells are estimated to comprise 9% of the total wells with water-right permits that are completed in all aquifers (table 2). North-central Kansas has the greatest percentage of wells (about 22%) with Dakota production of any region in which water is pumped from the Dakota aquifer. Nearly two-thirds of all of the water-right-permitted wells in Washington County in this region draw water from the Dakota aquifer. Although only about 6% of all permitted wells in central Kansas pump water from the Dakota aquifer, more than half of the wells in Ellsworth County produce partially or solely from Dakota strata. The percentage of water-right-permitted wells that pump part or all of their water from the Dakota aquifer ranges substantially in southwest Kansas, from less than 1% in Meade County to more than 25% in Grant, Hamilton, Morton, and Stanton counties. The distribution of wells in fig. 3 shows that a major factor determining whether a county has a large percentage of wells pumping partially or solely from the Dakota is the proportion of the county that is underlain by the outcrop/subcrop extent of the aquifer.

Most (78%) of the water-right-permitted wells that draw part or all of their water from the Dakota aquifer are used for irrigation (table 2, fig. 4). The second most common use of water made from permitted wells in the Dakota aquifer is for stock (9.6% of the total Dakota wells) followed closely by municipal purposes (8.9% of Dakota wells). Industrial wells account for about 2.2% of water-right-permitted wells completed partially or solely in the Dakota, and domestic and recreational wells ("Other" in table 2) are only about 1% of the total. The percentage of the total number of partial or sole Dakota wells that are used for irrigation ranges from about 10% in west-central, to 28% in central, 63% in north-central, 89% in southwest, and 95% in south-central Kansas. Municipal wells comprise a larger percentage of the total number of partial or sole Dakota aquifer wells in central (42%), west-central (32%), and north-central (18%) Kansas than in south-central (2.4%) and southwest Kansas (2.3%).

Estimated Water Use

The average total volume of water used from the Dakota aquifer by water-right-permitted wells in Kansas is estimated to be 117,000 acre-ft/yr (1.44×10^8 m^3/yr) for the 5-yr period 2006–2010 (table 3). The estimated mean annual use is much greater in southwest Kansas (approximately 86% of the total Dakota aquifer use) than in the other regions. The mean annual use for the other regions ranges from approximately 0.5% of the total Dakota use for west-central Kansas to 2.4% for central, 2.9% for south-central, and 8.1% for north-central Kansas. The density of the mean annual use for 2006–2010 (fig. 5) indicates local areas of high use from southwest Hamilton through northern Stanton into northwest Grant counties. Other localities of high use are in northeast Morton, the southeast corner of Stanton, south-central Haskell, central Ford, southwest Pawnee, and southwest Washington counties. The county with the greatest estimated annual use from the Dakota aquifer is Stanton County, followed in order of decreasing use by Grant, Hamilton, and Haskell counties (table 3, fig. 6). The mean use density for 2006–2010 did not change substantially from earlier 5-yr averages (1990–1995, 1996–2000, 2001–2005; see online appendix, http://www.kgs.ku.edu/Publications/Bulletins/260/appendix.html). The main apparent differences are slightly larger or smaller areas of high use and the appearance or disappearance of individual wells in areas of few wells (mainly in the confined aquifer) from period to period.

Water pumped from the Dakota aquifer by water-right-permitted wells during 2006–2010 was about 5% of the total water pumped from all aquifers in the 36 counties with Dakota use (table 3). Percentage of Dakota use compared to total use from all aquifers is also displayed by county in fig. 7. Although Washington County has the ninth highest average use rate of the 36 counties that produce water from the Dakota aquifer, it has the highest percentage of estimated Dakota use compared to total groundwater use (approximately 84%). The county with the next highest percentage Dakota use relative to the total groundwater pumped is Ottawa (45%), followed by Hamilton (37%) and Cloud (32%) counties. The Dakota aquifer supplies more than 20% of the total groundwater used in Ellsworth and Stanton counties and more than 10% of the total groundwater used in Russell, Morton, Grant, and Marion counties (in decreasing order).

About 90% of the total mean annual use from the Dakota aquifer during 2006–2010 was for irrigation (table 3). The use ratios for stock and municipal purposes were about the same; each comprised nearly 4% of the total volume pumped from the Dakota aquifer. The mean annual use for industrial and other applications (domestic and recreational) accounted for less than 2% and 0.1% of the total Dakota water pumped, respectively. The mean percentage of annual water use during 2006–2010 for various purposes is shown in table 3 and fig. 8 for different regions of Kansas. Irrigation was the dominant use of water in south-central and southwest Kansas (99% and 93%, respectively)

Table 2. Number of water-right-permitted wells that draw all or part of their yield from the Dakota aquifer by water-use type and comparison to total number of water-right-permitted wells completed in all aquifers.

	Number of partial or sole Dakota wells							
County or region	**Irrigation**	**Stock**	**Municipal**	**Industrial**	**Other**	**Total**	**Total wells, all aquifers**	**% Dakota wells**
			North-central Kansas					
Clay			12			12	334	3.6
Cloud	95	2	10	2	1	110	446	24.7
Ottawa	39	10	12	2		63	178	35.4
Republic	7		6			13	439	3.0
Washington	92	45	27	6	3	173	268	64.6
Region total	**233**	**57**	**67**	**10**	**4**	**371**	**1,665**	**22.3**
			Central Kansas					
Barton	8		10	1	2	21	752	2.8
Ellis		6	6	3	1	17	307	5.2
Ellsworth	15	5	15	6	1	42	84	53.2
Lincoln	2	2	2			6	47	12.8
Marion			10			10	134	7.5
McPherson		4	3		8	15	673	2.2
Rice	30	13	10	7	1	61	618	10.0
Rush	1	1	6			8	447	1.8
Russell			2			2	51	3.9
Saline	2		25		2	29	273	10.6
Region total	**58**	**31**	**89**	**17**	**15**	**210**	**3,368**	**6.2**
			South-central Kansas					
Edwards	15	1				16	1,155	1.4
Pawnee	63	1	2			66	1,172	5.6
Region total	**78**	**2**	**2**	**0**	**0**	**82**	**2,327**	**3.5**
			West-central Kansas					
Lane	1	2				3	308	1.0
Ness	1		3			4	216	1.9
Scott		8				8	1,115	0.72
Trego			2		1	3	264	1.1
Wichita			1			1	1,149	0.09
Region total	**2**	**10**	**6**	**0**	**1**	**19**	**3,051**	**0.62**
			Southwest Kansas					
Clark	1	8				9	116	7.8
Finney	32	1	7	7		47	2,456	1.9
Ford	85	10	2	7		104	1,242	8.4
Grant	272	7	4	7		290	975	29.8
Gray	41	7	3			51	2,032	2.5
Hamilton	90	37	4			131	425	30.8
Haskell	209	14	7			230	1,392	16.5
Hodgeman	44	8	3		1	56	579	9.7
Kearny	76	4		2	2	84	1,166	7.2
Meade	7					7	818	0.86
Morton	131	7				138	540	25.6
Seward	30					30	861	3.5
Stanton	292	9	6			307	966	31.7
Stevens	69	2				71	1,122	6.3
Region total	**1,379**	**114**	**36**	**23**	**3**	**1,555**	**14,687**	**10.6**
Regions total	**1,750**	**214**	**200**	**50**	**23**	**2,237**	**25,098**	**8.9**

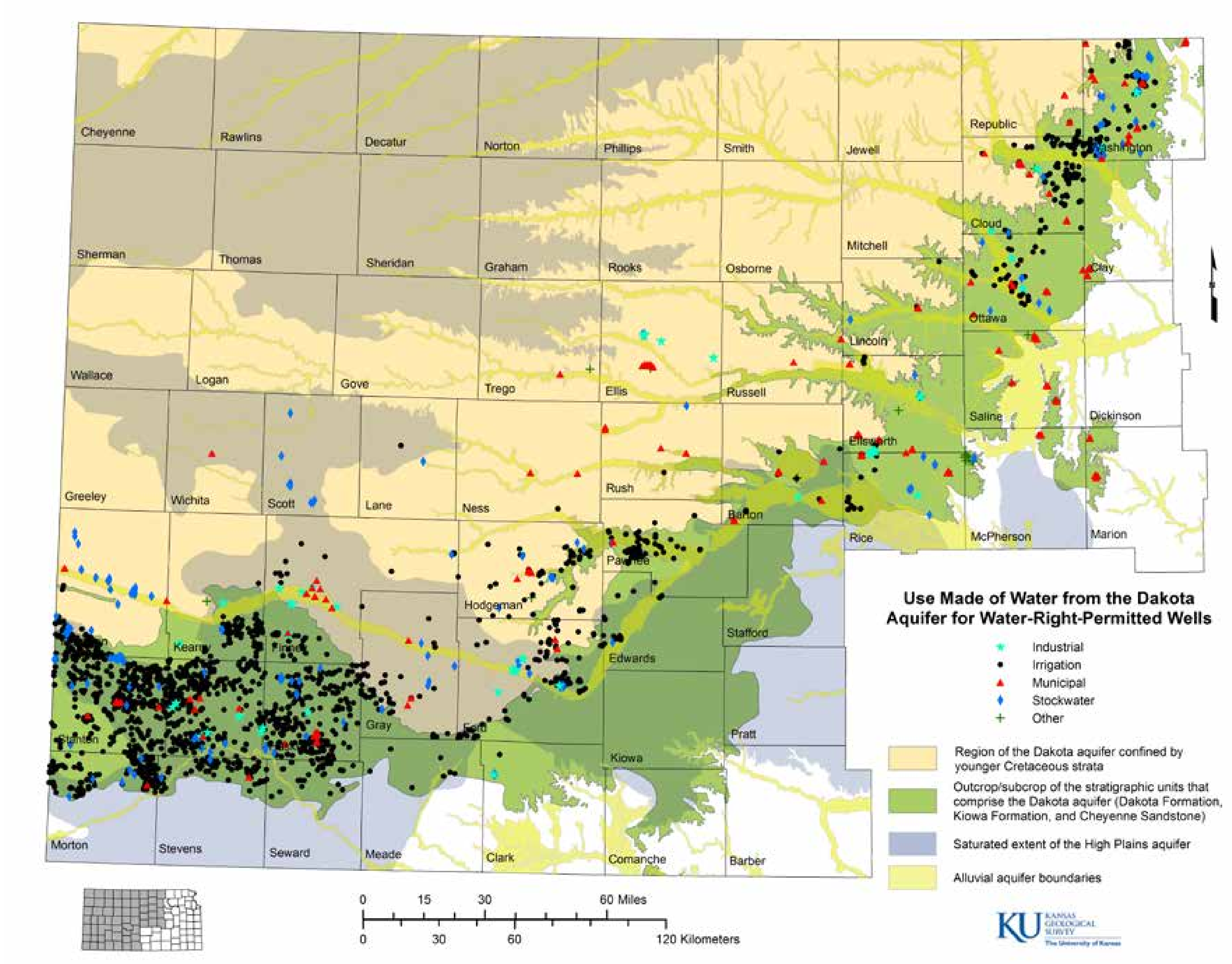


Figure 4. Distribution of water-right-permitted wells that draw part or all of their yield from the Dakota aquifer according to use type.

Table 3. Estimated mean annual water use during 2006–2010 from the Dakota aquifer by water-right-permitted wells for different use types, and total use from all aquifers. A blank cell indicates that no wells of that type were identified as producing from the Dakota aquifer in that county. Dakota use data are rounded to three significant figures or to 100, whichever is smaller.

	Mean annual water use during 2006–2010, acre-ft/yr							
	Use from Dakota aquifer						Total use all aquifers	% Dakota use
County or region	**Irrigation**	**Stock**	**Municipal**	**Industrial**	**Other**	**Total**		
			North-central Kansas					
Clay			163			163	10,950	1.5
Cloud	3,560	19.6	613	0.0	0.0	4,190	13,010	32.2
Ottawa	823	146	157	7.3		1,130	2,496	45.4
Republic	154		2.4			157	17,080	0.92
Washington	2,500	469	810	1.2	3.2	3,780	4,509	83.8
Region total	**7,030**	**634**	**1,740**	**8.5**	**3.2**	**9,420**	**48,050**	**19.6**
			Central Kansas					
Barton	52		75.1	0.0	64.8	192	36,640	0.52
Ellis		71.9	83.7	2.7	0.0	158	4,113	3.8
Ellsworth	365	14.4	215		0.0	594	2,571	23.1
Lincoln	0.23	14.4	27.8			42.4	544	7.8
Marion			133			133	999	13.3
McPherson		103	33.5		0.0	136	32,930	0.41
Rice	909	40.0	134	24.7	0.0	1,108	22,470	4.9
Rush	8.5	5.5	79.9			94	8,509	1.1
Russell			17.6			17.6	112	15.7
Saline	7.2		375		1.8	384	6,014	6.4
Region total	**1,340**	**249**	**1,170**	**27.4**	**66.6**	**2,860**	**114,900**	**2.5**
			South-central Kansas					
Edwards	616	3.0				619	105,700	0.59
Pawnee	2,780	1.9	45.6			2,820	66,670	4.2
Region total	**3,390**	**4.9**	**45.6**			**3,440**	**172,400**	**2.0**
			West-central Kansas					
Lane	101	35.8				136	17,140	0.80
Ness	29.4		16.2			45.6	3,770	1.2
Scott		399				399	51,800	0.77
Trego			3.6		0.0	3.6	5,959	0.06
Wichita			0.0			0.0	61,170	0.0
Region total	**130**	**435**	**19.8**		**0.0**	**585**	**139,800**	**0.42**
			Southwest Kansas					
Clark	18.2	32.2				50.4	5,591	0.90
Finney	828	4.0	615	722		2,170	302,700	0.72
Ford	6,840	528	41.4	1,240		8,660	106,300	8.1
Grant	18,000	48.0	94.4	34.0		18,200	133,400	13.6
Gray	1,810	333	260			2,400	213,100	1.1
Hamilton	13,100	1,340	41.7			14,400	38,940	37.1
Haskell	10,700	229	104	0.6		11,000	215,900	5.1
Hodgeman	1,960	183	110		2.9	2,260	23,770	9.5
Kearny	3,920	14.3		16.2	3.1	3,960	144,100	2.7
Meade	283					283	172,700	0.16
Morton	6,600	214				6,820	47,880	14.2
Seward	1,200					1,200	176,700	0.68
Stanton	25,100	374	267			25,800	127,100	20.3
Stevens	3,400	18.1				3,420	228,100	1.5
Region total	**93,700**	**3,320**	**1,530**	**2,020**	**5.9**	**100,600**	**1,936,300**	**5.2**
Regions total	**105,600**	**4,640**	**4,520**	**2,050**	**75.8**	**116,900**	**2,411,500**	**4.8**

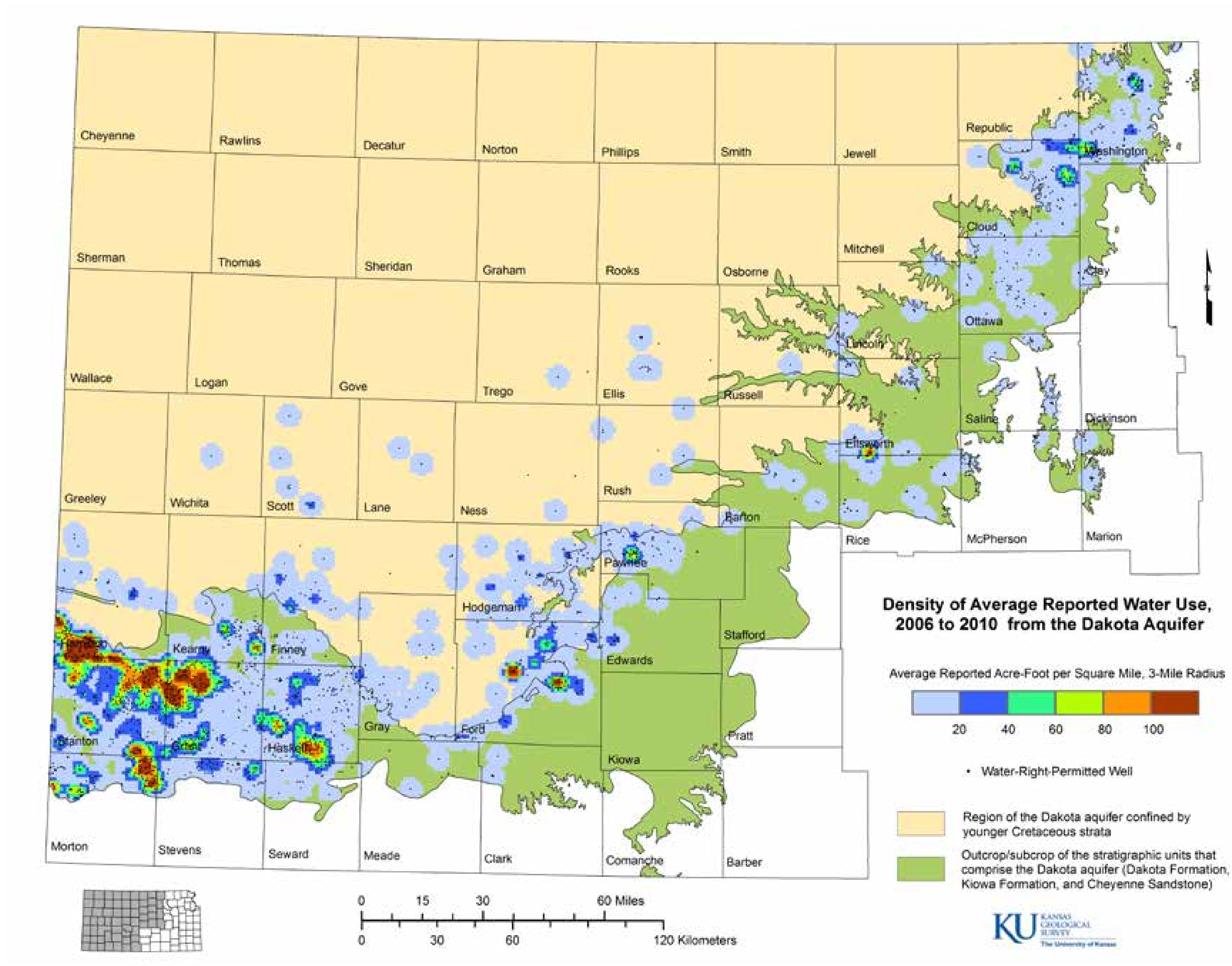


Figure 5. Density of estimated average annual use of groundwater from the Dakota aquifer in Kansas for 2006–2010.

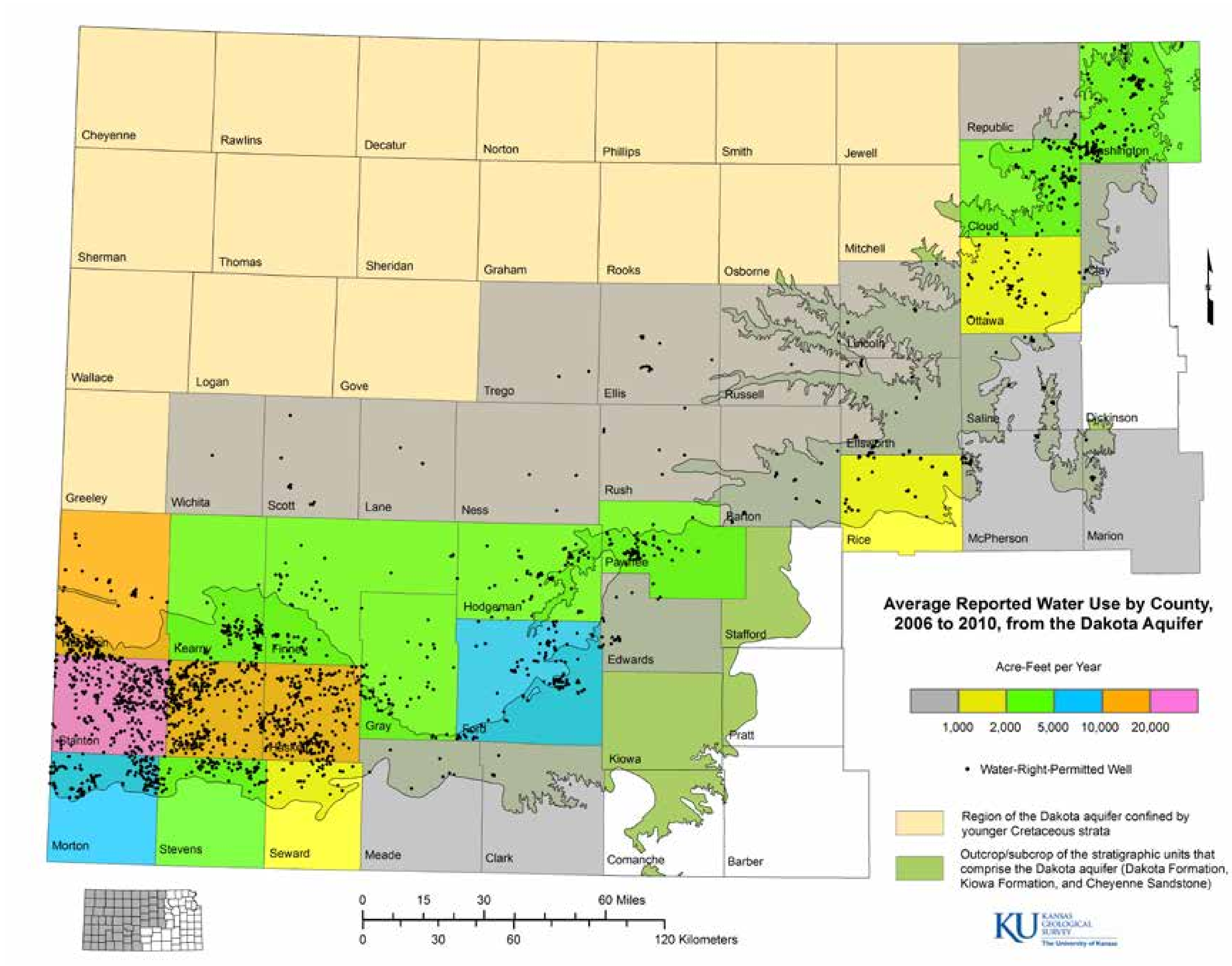


Figure 6. Estimated average annual use of groundwater from the Dakota aquifer by counties in Kansas for 2006–2010.

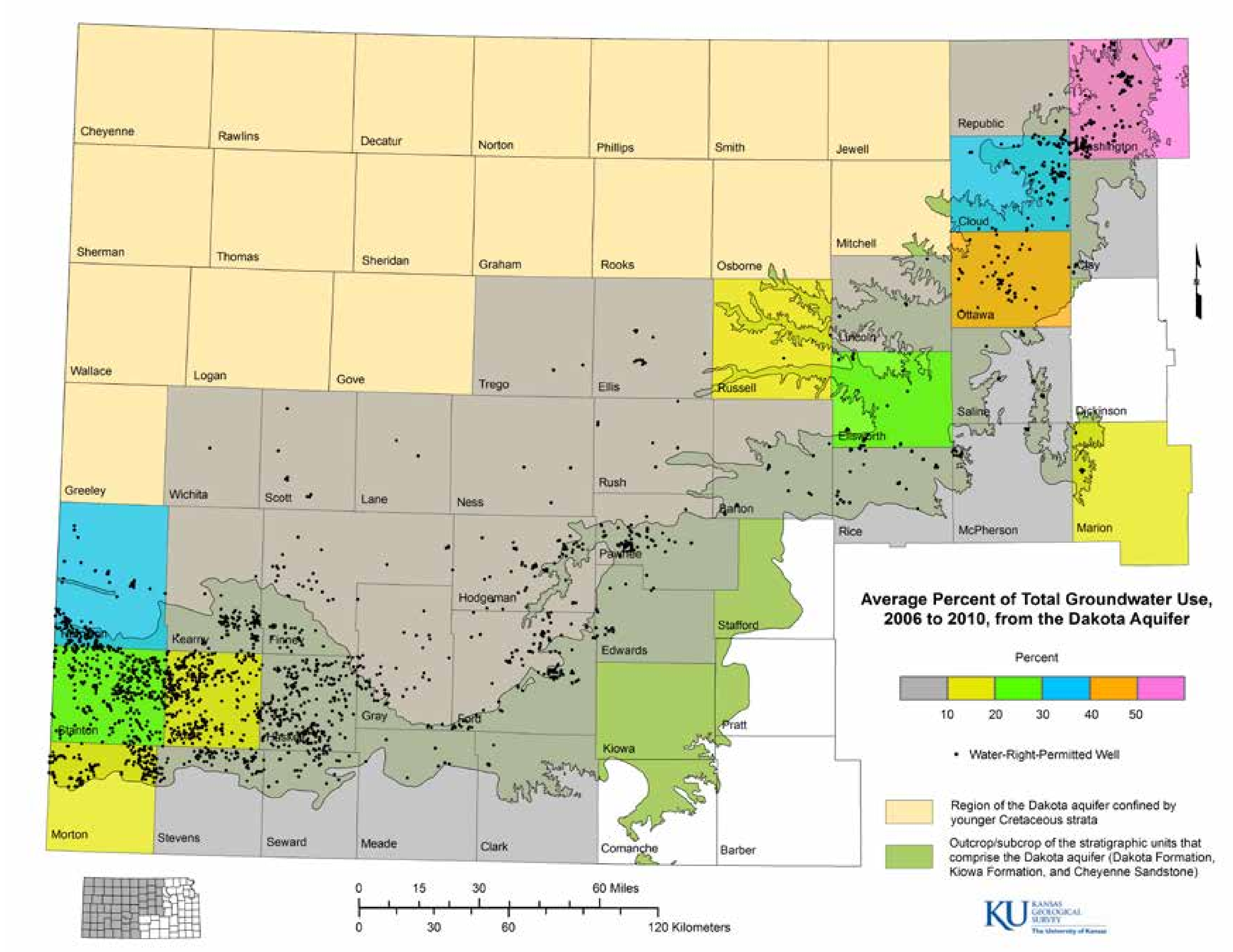


Figure 7. Average percent of total annual use of groundwater from all aquifers for 2006–2010 estimated to be from the Dakota aquifer.

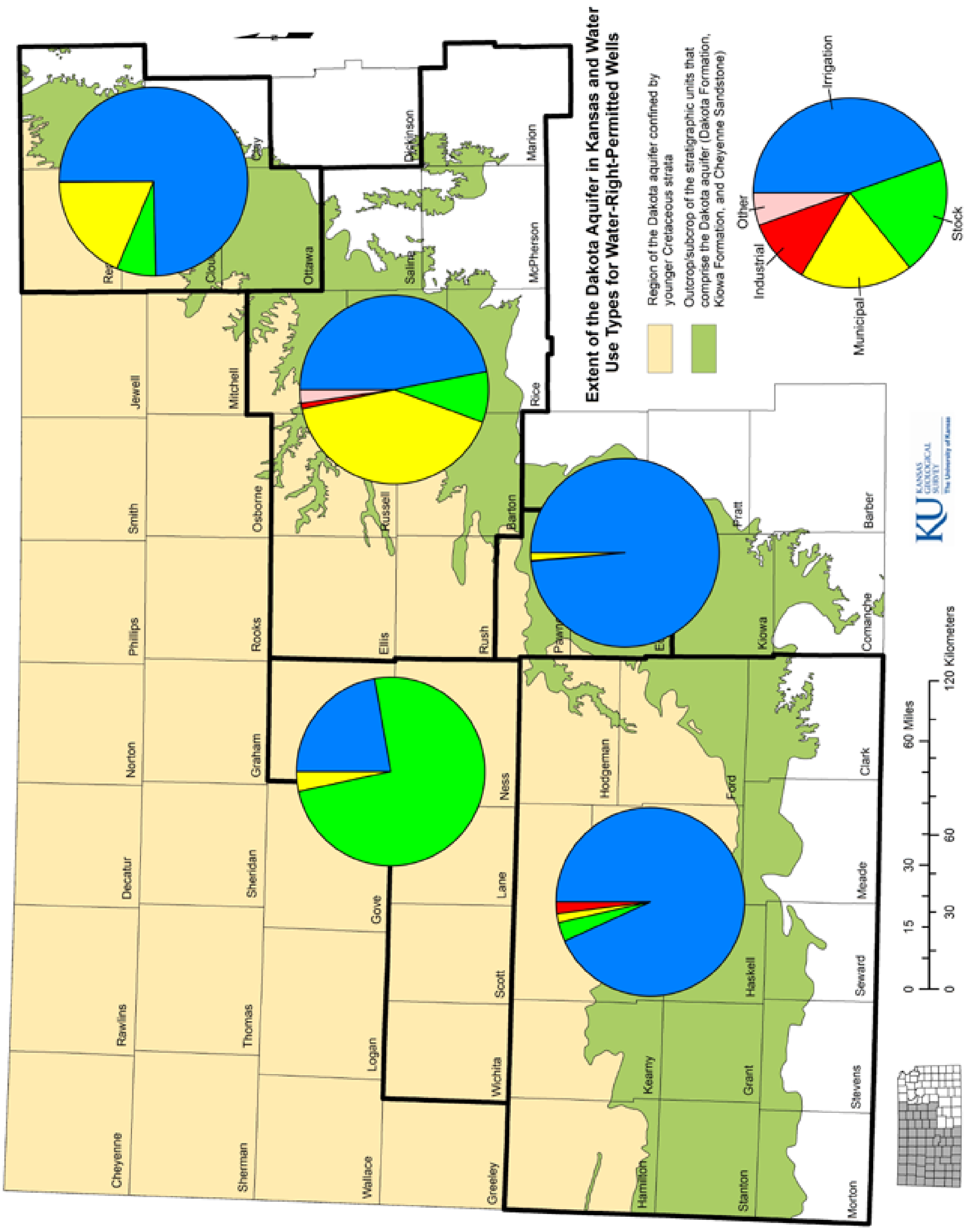


Figure 8. Mean 2006–2010 percentage of water use from the Dakota aquifer for different types of water-right-permitted wells drawing part or all of their supply from the Dakota aquifer in different regions of Kansas.

and was about 75% of the total annual use from the Dakota aquifer in north-central Kansas. The greatest percentage of municipal use occurred in central and north-central Kansas (41% and 18%, respectively, of the total annual use from the Dakota aquifer for these two regions). Stock use accounted for most (74%) of the Dakota water pumped annually from west-central Kansas.

The annual water use from the Dakota aquifer varied substantially across regions in Kansas during 1990–2010, the period for which water reports have been verified by state-sponsored programs for water-use quality control (fig. 9). The total change in the annual use for all regions parallels the use in southwest Kansas because water use from the Dakota aquifer in this region is approximately seven times the annual use for all of the other regions combined. The fluctuation in the total annual use from the Dakota aquifer in Kansas during 1990–2010 ranged from -22% to 26% (minimum to maximum, respectively, relative to the mean). The percent fluctuation was greatest in north-central Kansas (-75% to 92% of the mean) and the least in southwest Kansas (-29% to 28% of the mean). The use from the Dakota aquifer in north-central Kansas peaked in 2002 and has declined since then, which is in contrast with the other regions, where the use has generally been more stable, if not slightly increasing.

Irrigation is by far the dominant use made from the Dakota aquifer, accounting for the single largest use of water each year from 1990 to 2010 (fig. 10). Municipal use from the Dakota increased from 1990 to 2006 and has since declined somewhat in contrast to a general increase in irrigation use from 2006 to 2010. Stock water use shows an increasing trend during 1990–2010 and surpassed municipal use in 2010. Industrial use, which was greater than stock use from 1990 to 1996, has been relatively stable. Domestic and recreational uses with water-right permits have remained small and have generally fluctuated within ±30 acre-ft/yr (37,000 m^3/yr) of the average of 70 acre-ft/yr (86,000 m^3/yr) over the 1990–2010 period.

The variations in the annual rate of water use from the Dakota aquifer are related mainly to variations in climatic conditions for each year during 1990–2010, as indicated in figs. 11 and 12 for north-central and southwest Kansas, respectively. The Palmer drought severity index (PDSI) displayed in the upper portion of each graph represents the differences between wet (positive numbers) and dry (negative numbers) conditions in Kansas; it

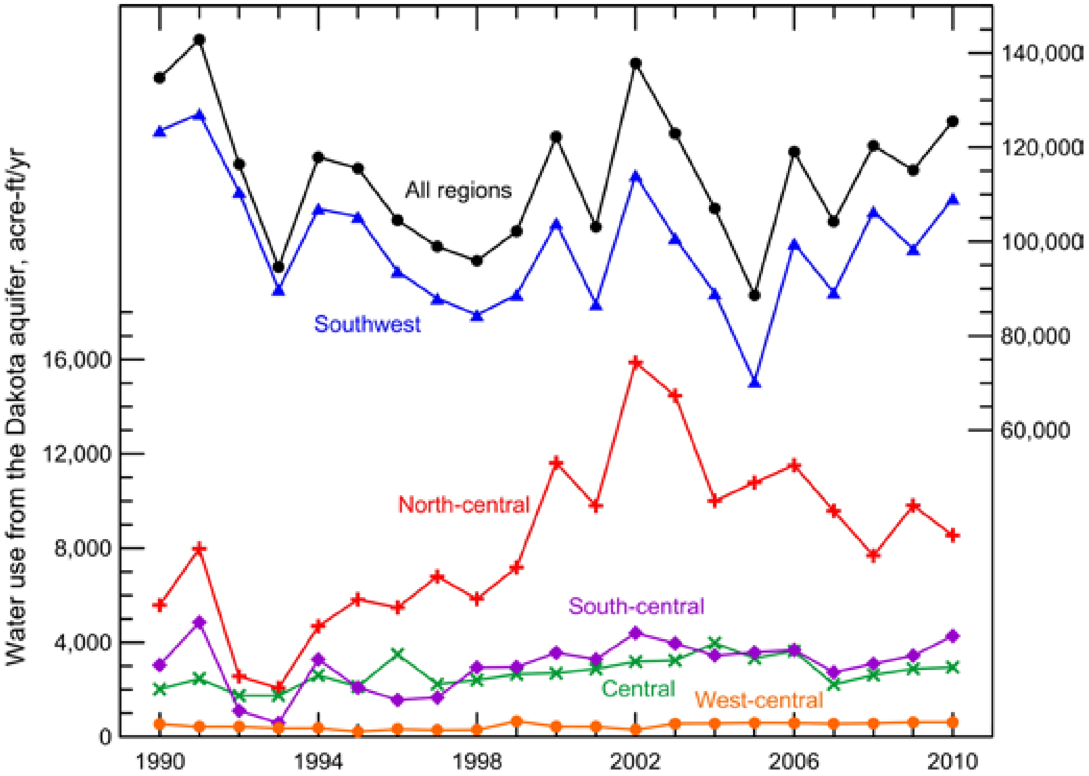


Figure 9. Estimated annual use of groundwater from the Dakota aquifer in Kansas and in different regions of Kansas from 1990 to 2010. The water-use values for the total of all regions and for southwest Kansas are represented on the right-hand y-axis, and the values for the other regions are on the left-hand y-axis, for which the units per axis length are expanded five times in comparison with the right-hand y-axis.

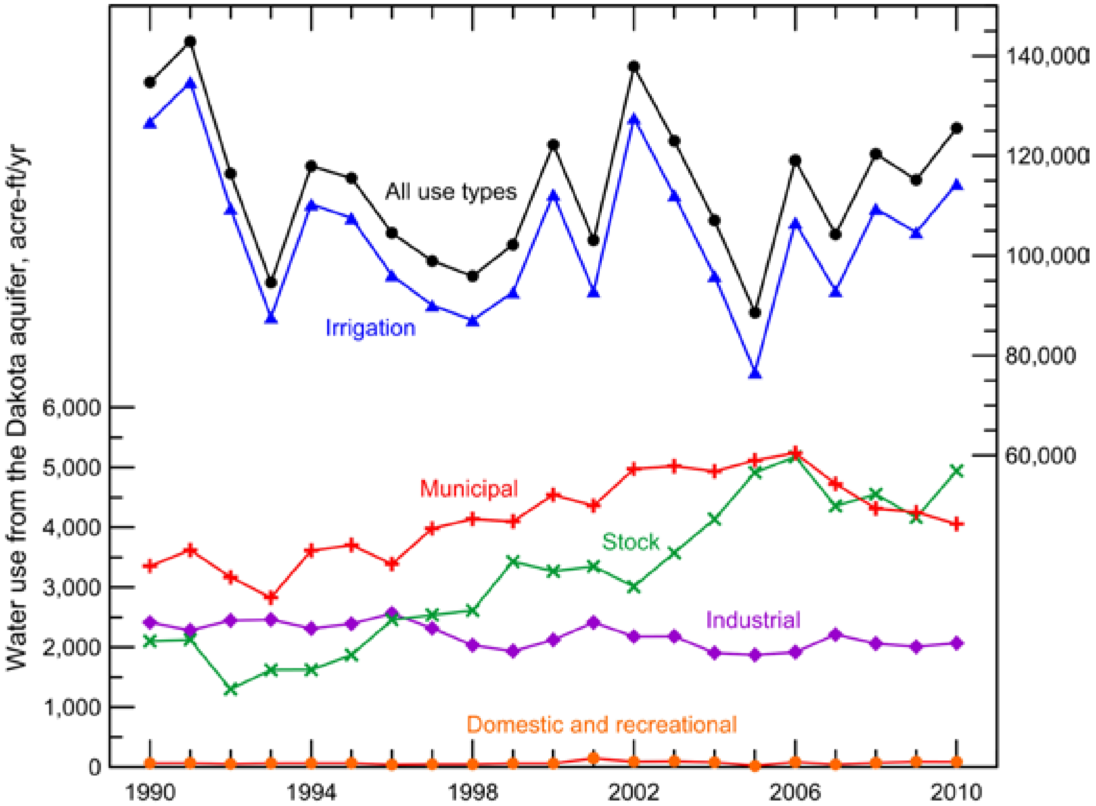


Figure 10. Estimated annual use of groundwater from the Dakota aquifer in Kansas according to different use types from 1990 to 2010. The water-use values for the total of all use types and for irrigation are represented on the right-hand y-axis, and the values for the other uses are on the left-hand y-axis, for which the units per axis length are expanded 12 times in comparison with the right-hand y-axis.

incorporates the factors that affect evapotranspiration over periods of months (precipitation, temperature, and soil characteristics). Irrigation, stock, and municipal use generally are substantially greater during droughts than wet periods. A general inverse relationship is apparent in the two Kansas regions, i.e., the positive peaks in PDSI (wetter years) match troughs in the estimated water-use rate, and the negative peaks in PDSI (drier years) coincide with positive peaks in estimated water use (figs. 11 and 12). In north-central Kansas, almost eight times as much water was used during the drought year of 2002 (15,900 acre-ft/yr [1.96 x 10^7 m^3/yr]) as during the very wet year of 1993 (2,070 acre-ft/yr [2.55 x 10^6 m^3/yr]). This relative range is greater than in southwest Kansas because during wet years in north-central Kansas, precipitation is completely or nearly sufficient for crop irrigation and lawn growth. In southwest Kansas, additional crop irrigation is often needed during short dry periods (a week or two) even in wet years due to the much greater rate of evapotranspiration that normally occurs relative to north-central Kansas. The decline in use from the Dakota aquifer in north-central Kansas from 2002 to 2010 fits the general increase in the PDSI during this period (fig. 11). The use in north-central Kansas is expected to increase in 2011 (annual PDSI of 1.9) and in 2012 (summer drought) in comparison with 2007–2010.

Watts (1989) estimated water use from the Dakota aquifer by water-right-permitted wells for five counties in southwest Kansas (Finney, Ford, Gray, Hodgeman, and Kearny) from 1975 to 1982. Comparison of the total mean annual water use for these counties during that period with the estimated total for 2006–2010 from this bulletin appears to indicate an insignificant change in the total (table 4). However, the values for Finney, Gray, and Kearny counties increased appreciably between the periods, while the use in Ford and Hodgeman counties decreased substantially. Part of the increases in Finney, Gray, and Kearny counties could reflect that Watts (1989) considered only those wells that obtained all or most of their water from the Dakota aquifer, whereas this study considered all wells with greater than 5% contribution from the Dakota. In addition, some of the increases represent additional wells in the Dakota, as well as the deepening of new or replacement wells screened in both the Dakota and HPA. The data in Watts (1989) show

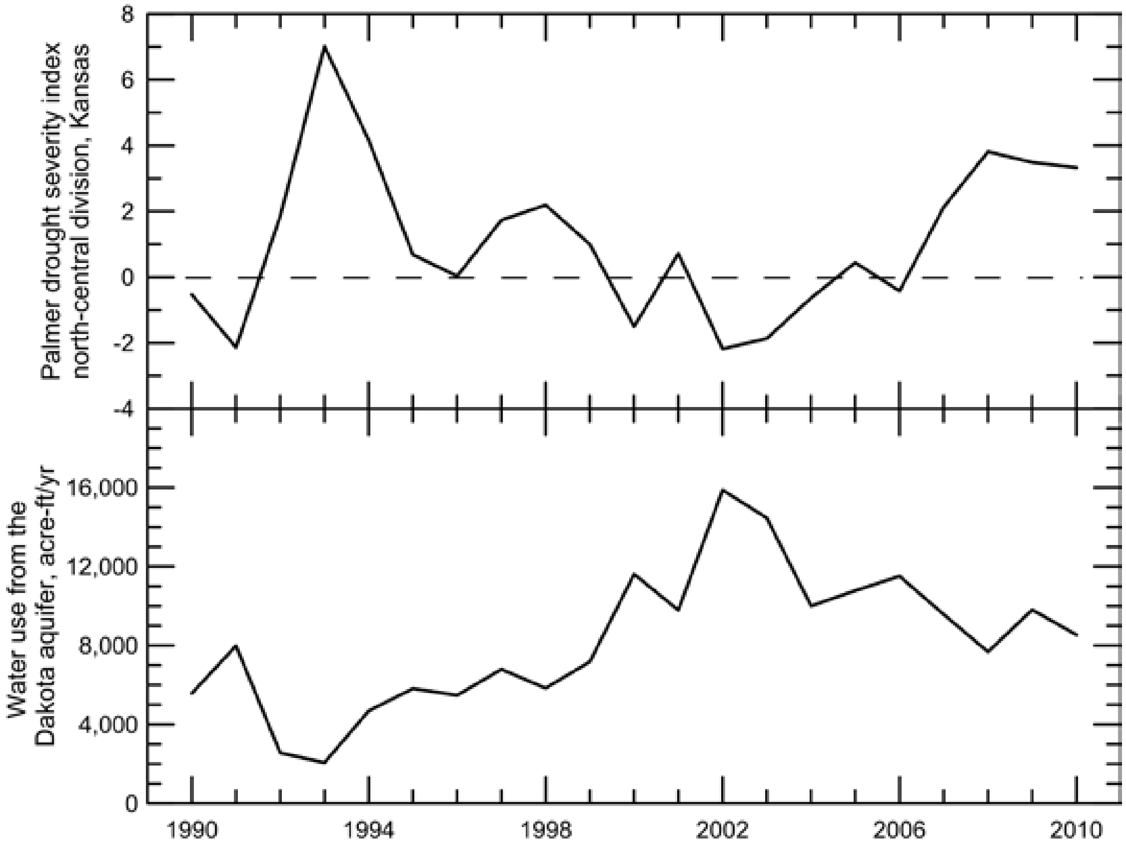


Figure 11. Palmer drought severity index and estimated annual use of groundwater from the Dakota aquifer in north-central Kansas from 1990 to 2010.

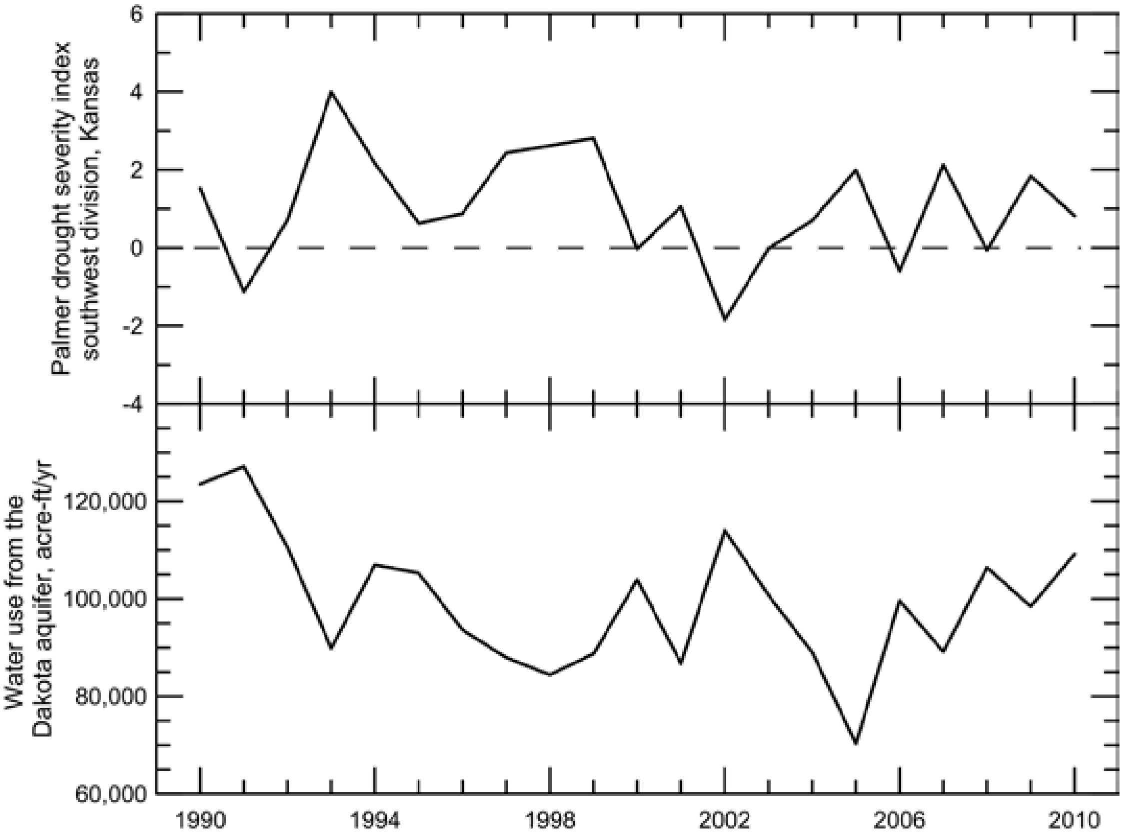


Figure 12. Palmer drought severity index and estimated annual use of groundwater from the Dakota aquifer in southwest Kansas from 1990 to 2010.

Table 4. Comparison of mean annual water use from the Dakota aquifer for water-right-permitted wells in Finney, Ford, Gray, Hodgeman, and Kearny counties from 1975–1982 to 2006–2010. The data for 1975–1982 are from Watts (1989) and for 2006–2010 from this report.

	Mean annual use, acre-ft/yr	
County	**1975–1982**	**2006–2010**
Finney	1,400	2,169
Ford	12,188	8,655
Gray	112	2,399
Hodgeman	5,888	2,255
Kearny	100	3,957
Total	19,688	19,435

an increase from 600 acre-ft/yr (7.4x10^5 m^3/yr) in 1975 to 4,100 acre-ft/yr (5.1x10^6 m^3/yr) in 1982 for Finney County and from 0 to 300 acre-ft/yr (0 to 3.7x10^5 m^3/yr) and 0 to 500 acre-ft/yr (0 to 6.2x10^5 m^3/yr) for Gray and Kearny counties, respectively, for the same period. From 1990 to 2010, a significant increase in Dakota water use occurred in Kearny County, a small increase occurred in Gray County, and no significant change took place in Finney County (fig. 13).

Although the water use values for the Dakota aquifer in Watts (1989) fluctuated for Ford and Hodgeman counties from 1975 to 1982, they did not show any significant trend. Water use in Ford County dropped substantially from a range of 10,500–12,400 acre-ft/yr (1.30 x 10^7–1.53 x 10^7 m^3/yr) in 1990 and 1991 to a range of 6,500–9,600 acre-ft/yr (0.80 x 10^7–1.18 x 10^7 m^3/yr) during 1992–2010 (fig. 13). Water use in Hodgeman County shows no significant trend and fluctuated between 1,400 and 3,300 acre-ft/yr (1.7 x 10^6–4.1 x 10^6 m^3/yr) during 1990–2010 (fig. 13).

Two main reasons explain the decreases in water use in Ford and Hodgeman counties from 1975–1982 to 2006–2010 (table 4), one based on data accuracy for 1975–1982 and the other reflecting actual decreases in water use. Reported water use values before 1990 are known to have been, in general, somewhat greater than the actual water use (based on comparison with data after 1990). The year 1990 was the first for which reported water use was examined by a state quality-control program (first undertaken by the KWO and today by the DWR) that checked water-use data. In addition, flow-rate meters were required for all pumping wells in Ford County from 1991 to 1996 as part of an order from Southwest Kansas Groundwater Management District No. 3 (GMD3), and starting in 1980 in Hodgeman County, flow-rate meters were required for all new or re-drilled water-right-permitted wells (Wilson, 2003). Water usage reports based on hours pumped times flow rates or on energy usage rates traditionally are higher than more accurate flow-rate meter readings.

Actual decreases in water use that occurred in Ford and Hodgeman counties also can be attributed to irrigators pumping less water from or no longer pumping, or not replacing, existing wells in the Dakota aquifer that had decreased in yield. A primary factor for this was probably greater maintenance costs for Dakota aquifer wells than typical for unconsolidated aquifer wells. Factors such as physical, biological, and chemical blockage of the well screen (Scherer, 2005) or well corrosion can result in

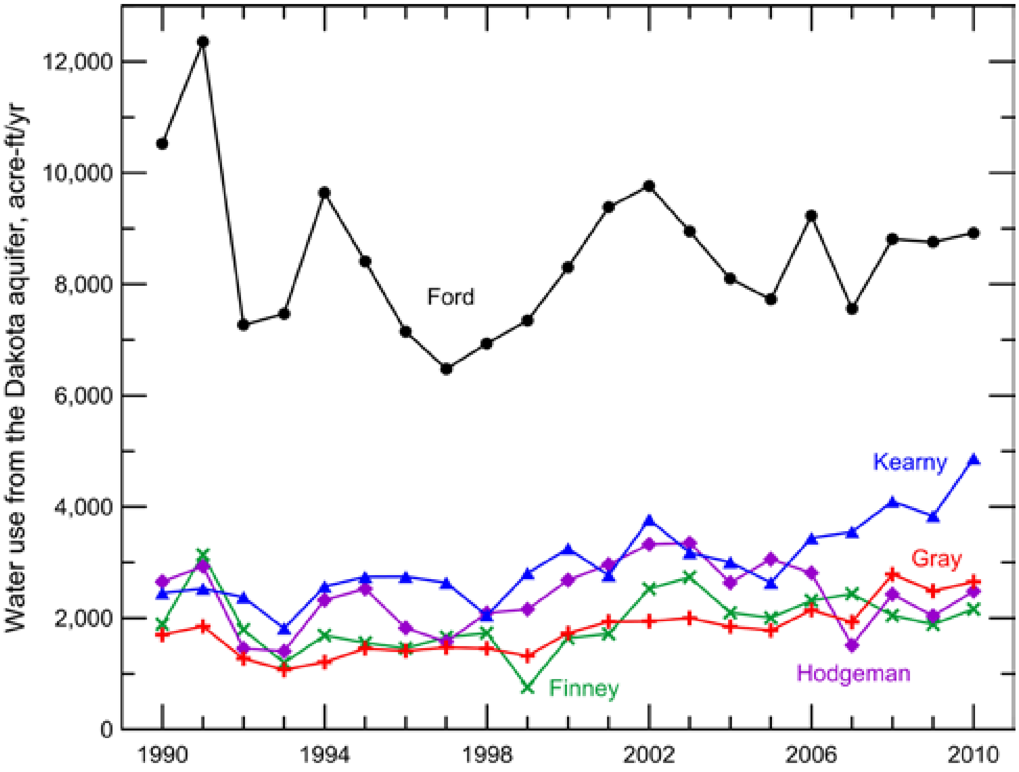


Figure 13. Estimated annual use of groundwater from the Dakota aquifer in Finney, Ford, Gray, Hodgeman, and Kearny counties from 1990 to 2010.

increased maintenance costs. The common occurrence of high iron and manganese concentrations in the Dakota wells (described in the geochemistry section of this bulletin) and a substantial drop in water level (allowing the introduction of more dissolved oxygen) could have resulted in oxyhydroxide precipitation and the formation of accompanying biological mats across the well screen. Also, corrosion of the well casing and screen by a chemically reducing environment sometimes encountered in the Dakota could have contributed to greater maintenance costs.

Wells without Water-Right Permits

Determination of Well Location

Estimating the number of "domestic" wells without water-right permits and their annual water usage is a challenge with a much higher level of uncertainty than well counts and water usage for wells with water-right permits. Wells that pump water primarily from the Dakota aquifer for "domestic" uses tend to be distributed mainly in areas outside the extents of alluvial aquifers and the HPA shown in fig. 3. The most recent KGS bulletins that describe the geohydrology of counties within the extent of the Dakota aquifer in north-central and central Kansas that also include lists of wells with information about water source and use type are for Ellsworth (Bayne et al., 1971), Ottawa (Mack, 1962), and Rush (McNellis, 1973). The numbers of domestic and stock wells listed in these publications that had a primary or sole water source from the Dakota aquifer were 136 in 1961 for Ellsworth County, 136 in 1957–1958 for Ottawa County, and 26 in 1959–1960 for Rush County.

Wells classified as "domestic" are not required to have quantified water rights by Kansas water law and include the use designations in WWC-5 records of domestic, lawn and garden, and feedlot/livestock/windmill. However, some of the feedlot wells and a few of the domestic and lawn-and-garden wells have water rights. Between 1975 (the start of the WWC-5 records) and early 2012, the number of "domestic" wells constructed in Ellsworth, Ottawa, and Rush counties, minus the number of plugged wells of this type and minus the number of permitted stock-watering and domestic use wells, totaled 348, 796, and 267, respectively. The sum for the three counties (1,411 wells) represents a net total of WWC-5 "domestic" wells for 1975–2012. The proportion of the 1975–2012 "domestic" wells that produce primarily or solely from the Dakota aquifer for each of the three counties was estimated from the ratio of Dakota domestic and stock wells to the total wells of these types in all aquifers in the list in the KGS bulletin for each county. The average annual rate of "domestic" Dakota well construction during 1975–2012 for each county was used to estimate the number of Dakota wells constructed between the date of the well list in each KGS bulletin and 1975. The total number of current Dakota wells with "domestic" uses was determined by summing the number in the KGS bulletin list, the estimated number between the bulletin list and 1975, and the estimated number during 1975–2012. These totals were further reduced by 5% to reflect wells that may have been plugged before 1975 or that are currently unused but not plugged. The numbers of wells currently producing primarily or solely from the Dakota aquifer for "domestic" uses were estimated to be 454 for Ellsworth, 910 for Ottawa, and 123 for Rush, giving a total of 1,487 for the three counties.

Ellsworth, Ottawa, and Rush counties are reasonably representative of the counties in the north-central and central regions where the Dakota aquifer is used for water supply (see table 1 for counties in named regions). The usable Dakota aquifer in these regions includes both confined and unconfined strata. Unconsolidated aquifers overlying part of the Dakota are mainly alluvial systems associated with stream and river valleys. The ratio of the estimated total of active "domestic" Dakota wells (1,487) divided by the net total (1,414) of wells constructed in 1975–2012 used for "domestic" purposes from all aquifer sources is 1.05 for these three counties. The total number of active Dakota wells used for "domestic" purposes in the north-central and central regions of Kansas was estimated by multiplying that ratio times the net total wells constructed during 1975–2012 in the counties in these regions. However, for this calculation, an adjustment must be made for the area for which "domestic" wells are summed from the WWC-5 data base because not all of the counties in these two regions are underlain by Dakota strata (fig. 3). Thus, no wells from Clay County were considered in the north-central region to approximately balance the area of Washington County that is not underlain by the Dakota aquifer. Similarly, no wells were considered in Saline, McPherson, and Marion counties to offset the area without underlying Dakota strata in Rice County and the part of Barton County south of the Arkansas River where the HPA is essentially the only aquifer used. The net total of "domestic" wells constructed during 1975 to early 2012 in the adjusted areas of north-central and central Kansas is 7,621. Application of the 1.05 ratio of active Dakota/net total wells gives an estimate of 8,000 "domestic" wells with a primary or sole water source from the Dakota aquifer for these two regions (table 5).

Table 5. Estimated number of "domestic" wells primarily or solely completed in the Dakota aquifer, mean annual water use from the Dakota by these wells compared to water-right-permitted wells that produced part or all of their yield from the Dakota aquifer during 2006–2010, and total mean annual use from the Dakota aquifer. Use values are rounded to three significant figures or to 100, whichever is smaller.

Region	Number of "domestic" wells in Dakota aquifer	Mean annual water use from Dakota aquifer, "domestic" wells, acre-ft/yr	Number of water-right-permitted wells in Dakota aquifer	Mean % of total yield that is from Dakota aquifer, water-right-permitted wells	Mean annual water use from Dakota aquifer, water-right-permitted wells, acre-ft/yr	Total mean annual water use from Dakota aquifer, all wells acre-ft/yr	Mean % of total Dakota use that is "domestic"
North-central	1,880	1,520	423	98.4	9,420	10,950	13.9
Central	6,120	4,810	236	95.5	2,860	7,670	62.7
South-central	345	212	82	72.8	3,440	3,660	5.8
West-central	696	573	21	100.0	585	1,160	49.5
Southwest	2,120	885	1,572	50.6	100,600	101,400	0.9
Total	**11,200**	**8,000**	**2,334**		**116,800**	**124,800**	**6.4**

The numbers of active "domestic" Dakota wells in south-central, west-central, and southwest Kansas (see table 1 for counties in named regions) were estimated based on WWC-5 records and modifications to the ratio used in the estimation for north-central and central Kansas. To estimate the number of active "domestic" Dakota wells in the south-central region of Kansas, the number of counties was first reduced to reflect areas where the Dakota aquifer is not used due to sole use of the HPA (fig. 3). Thus, WWC-5 records in Edwards County were not included and only wells in Pawnee County were considered. For the southwest Kansas region, WWC-5 records were not included in Clark, Meade, and Seward counties to offset the areas of Morton and Stevens counties that are not underlain by the Dakota aquifer in that region.

Major portions of the south-central, west-central, and southwest regions are underlain by the HPA, which is the primary source of water in these areas (fig. 2). The HPA is likely to be the only water source for "domestic" wells in these areas because the wells do not need the extra capacity that could be derived from completion in the underlying Dakota aquifer in addition to the HPA. However, in much of the area that either does not include the HPA or has only thinly saturated HPA, the Dakota aquifer (along with some underlying Morrison-Dockum aquifer in westernmost southwest Kansas) is the main water source. For example, Fader et al. (1964) list many wells completed in the Dakota Formation and several in the Cheyenne Sandstone and Dockum Group in Stanton County, especially in the southwest part of the county. These factors were considered in the reduction of the ratio of active Dakota wells/net total wells from the value of 1.05 for north-central and central Kansas to 0.5 for south-central, west-central, and southwest Kansas. This number was selected to be less than the ratio (0.65) of two fractions: the first (0.083) is the number of permitted water-right wells in the Dakota aquifer divided by the total permitted wells in all aquifers in south-central, west-central, and southwest Kansas; the second (0.129) is the analogous value for north-central and central Kansas. The net total of "domestic" wells constructed from 1975 to early 2012 in west-central Kansas and the adjusted areas of south-central and southwest Kansas is 6,346. Multiplying by the 0.5 ratio of active Dakota/net total wells gives an estimate of 3,160 "domestic" wells with a primary or sole water source from the Dakota aquifer for these three regions (table 5).

Based on the above computations, the total number of "domestic" wells that produce most or all of their water from the Dakota aquifer in Kansas is estimated to be 11,200 (8,000 in north-central and central Kansas and 3,160 in south-central, west-central, and southwest Kansas). Although "domestic" wells are generally much smaller in terms of overall pumping capacity than those requiring water rights, their estimated number is five times the estimated number (2,237) of water-right-permitted wells that obtain some or all of their source from the Dakota aquifer.

Estimated Water Use

The annual water use for a domestic well in Kansas that serves a 2.5-person household (U.S. Census, http://quickfacts.census.gov/qfd/states/20000.html), uses 100 gal/day (380 L/day) per person (self-supplied use, Kenny et al., 2009), and waters a fifth of an acre of lawn and garden with 18 inches is estimated to be 0.6 acre-ft/yr (740 m^3/yr). A typical well dedicated to lawn and garden watering probably applies water to a larger area than watered by a typical domestic well; annual water use could average 0.5 acre-ft/yr (600 m^3/yr). Most stock wells are used to provide water for cattle. Beef cattle require an average of 8–12 gal/day (30–45 L/day) over a year (Blocksome and Powell, 2006). Wells that water fewer than 1,000 stock in a confined location do not require a permit. Thus, livestock wells that fall under the classification of "domestic uses" could pump from less than 1 to about 10 acre-ft/yr (1,200–12,000 m^3/yr), depending on the number of livestock at the facility.

Most of the wells used for "domestic" purposes (not requiring a water right) are recorded as domestic wells in the WWC-5 records for the regions in which the Dakota aquifer is used for supply. About one-sixth of the "domestic" wells are recorded as lawn and garden usage, and approximately one-tenth are recorded as feedlot and livestock usage. Based on this well distribution and average use rates of 0.6, 0.5, and 3 acre-ft/yr (740, 600, and 3,700 m^3/yr) for domestic, lawn and garden, and feedlot/livestock use, respectively, the use rate for an average "domestic" well is estimated as a little more than 0.8 acre-ft/yr (1,000 m^3/yr).

The total water use from the Dakota aquifer by wells that do not need a water right was determined by multiplying the estimated number of "domestic wells" by an average of 0.8 acre-ft/yr (1,000 m^3/yr) use and also by the mean percentage of total yield that is from the Dakota aquifer for water-right-permitted wells (table 5). This mean percentage (column three in table 5) is smaller for southwest and south-central Kansas than for the three other regions, indicating that a smaller proportion of the total pumping from a well partially completed in the Dakota aquifer is actually derived from Dakota strata.

The largest water use from the Dakota aquifer by "domestic" wells is expected to be from central Kansas (approximately 4,800 acre-ft/yr [5.9×10^6 m^3/yr]), followed by north-central Kansas (about 1,500 acre-ft/yr [1.9×10^6 m^3/yr]). Water pumped from the Dakota aquifer by "domestic" wells in the three other regions sums to approximately 1,700 acre-ft/yr (2.1×10^6 m^3/yr). The total use from the Dakota aquifer by wells that do not need a permit is estimated to be 8,000 acre-ft/yr (1.0×10^7 m^3/yr).

"Domestic" wells are estimated to pump more than 60% of the total water produced from the Dakota aquifer in central Kansas and half of the total Dakota water in west-central Kansas (table 5). Substantially smaller percentages of the total water use from the Dakota aquifer are pumped by "domestic" wells in the three other regions, with the "domestic" water use in southwest Kansas amounting to only about one percent of the total. The amount of water use from the Dakota aquifer by "domestic" wells in all Kansas regions is estimated to be 6.4% of the total of approximately 125,000 acre-ft/yr (1.54×10^8 m^3/yr) pumped from the aquifer by all wells.

GROUNDWATER GEOCHEMISTRY

Data about and interpretation of the geochemistry of groundwater in the Dakota aquifer is valuable for 1) determining and predicting where (including areal and vertical dimensions) water resources suitable for different uses are located, 2) understanding the origin of and factors that control individual constituents of concern for various water uses, and 3) differentiating between natural and contamination sources of constituents. During the Dakota Aquifer Program, the KGS assembled and reviewed existing water chemistry data for the Dakota aquifer. The KGS added substantial amounts of new data by sampling and analysis of groundwaters from observation and supply wells across the aquifer and by interpreting geophysical (resistivity) logs to estimate dissolved solids concentration. This section describes these data, factors that control the natural groundwater geochemistry in the aquifer, aquifer contaminants, and spatial variations (both regional patterns and vertical changes) in the groundwater chemistry. Coupled flow and geochemical modeling of freshwater to saltwater transition zones was used to help understand the evolution of chemical changes in the aquifer. Additional information about the geochemistry of groundwater in the Dakota aquifer is in the appendix for this bulletin (http://www.kgs.ku.edu/Publications/Bulletins/260/appendix.html).

Chemical Data for Groundwaters

Data for Water Samples

Water-quality data were assembled from several existing sources, including the USGS, the National Uranium Resource Evaluation program, the KDHE, and the KGS. Electronic data sets were found to contain many problems and errors. These were corrected to the extent possible by examining the original printed version of the data in KGS and USGS publications and by determining the consistency in terms of chemical characteristics such as charge balance. Missing values of major constituent concentrations for existing records in the data base were filled by referring to original data publications. Aquifer codes were assigned or revised based on examination of the well location and depth relative to the surface elevation and contour maps of stratigraphic tops and thicknesses. Records with substantial errors that could not be corrected were deleted.

The KGS collected and analyzed groundwater samples from domestic, stock, municipal, and observation wells during 1987–1988 as part of a Dakota aquifer study in central Kansas for the Kansas Corporation Commission (Macfarlane et al., 1988). The KGS collected and analyzed samples from domestic, municipal, stock, irrigation, and observation wells across most of the Dakota aquifer in Kansas during 1990–1997 as a part of the Dakota Aquifer Program. Sampling in 1992 included supply wells in southeast Colorado as part of a traverse from Colorado to central Kansas conducted in cooperation with the Lawrence Livermore National Laboratories. The KGS also cooperated with consulting companies investigating the water-supply potential of the Dakota aquifer in Ellis and Russell counties to obtain water samples that the KGS analyzed.

The KGS determined concentrations of dissolved major, minor, and selected trace inorganic constituents in 233 groundwater samples collected as part of the Dakota Aquifer Program. Selected samples were sent to USGS laboratories for determination of radionuclides. Kansas State University collected and analyzed 80 samples as part of a cooperative study for the Dakota program.

The chemical data were entered into a water-quality data base that is available on the KGS website for the Dakota Aquifer Program (http://www.kgs.ku.edu/Dakota/vol2/qualDB/quality.htm). As of late 2013, the data base contained 1,594 records for samples from wells that yielded water entirely or partly from the Dakota aquifer, 10 of which are in southeast Colorado and the rest of which are in Kansas. The data base also includes 10 records for wells in the Morrison Formation or Upper Jurassic Series. A total of 1,123 wells sampled only the Dakota aquifer (1,002 wells for samples entirely from the Dakota Formation or Lower Cretaceous Series, 81 wells for the Kiowa Formation, 38 for the Cheyenne Sandstone, and 2 for a combination of Dakota and Cheyenne or Kiowa and Cheyenne). The data base includes records for multiple samples (collected at different dates or times) from 121 of the wells completed entirely or partly in the Dakota aquifer.

Figure 14 displays the distribution of wells in Kansas from which groundwaters were analyzed and that obtained their water solely from the Dakota aquifer. Most of the sites are located where the water in the aquifer is of good enough quality to be used for water supply. The densest distribution of points is in a band along the eastern outcrop and subcrop of the Dakota Formation, with smaller numbers of points in southwest Kansas.

Water Quality from Geophysical Logs

Little water sample data are available for the Dakota aquifer in northwest Kansas. However, many oil and gas boreholes for which geophysical logs exist pass through Dakota strata in northwest Kansas. Water resistivities were estimated for groundwaters in Dakota strata from 977 geophysical logs that included spontaneous potential (SP) records in 11 counties in northwest Kansas. These values were used to estimate the TDS concentration using the relationship between conductivity (the inverse of resistivity) and TDS for Dakota aquifer samples within and surrounding northwest Kansas. Locations of logs, methodology, and results of the log analyses are in Boeken (1995). A general description of SP logs and the procedure for estimating water resistivities for the Dakota aquifer is in Macfarlane, Doveton, and Whittemore (1998).

Factors that Control Groundwater Chemistry

The chemistry of groundwater primarily refers to the type and concentration of dissolved substances in the water and properties such as specific conductance, pH, and hardness. The dissolved substances include gases and inorganic and organic constituents. An understanding of the water geochemistry coupled with information about the hydrogeologic properties of the aquifer aids in the delineation of regional and local flow systems.

Table 6 lists the chemical properties and major, minor, and trace constituents that are of value for determining the geochemical characteristics of waters in the Dakota aquifer system. The table also lists general ranges for the properties and constituent concentrations along with water-use criteria for public drinking water, livestock, and irrigation.

The most common substances dissolved in groundwaters in the Dakota aquifer are the inorganic constituents calcium, magnesium, and sodium (positively charged cations) and bicarbonate, chloride, and sulfate (negatively charged anions). Bicarbonate may also be represented as alkalinity in water analyses. Inorganic constituents that commonly

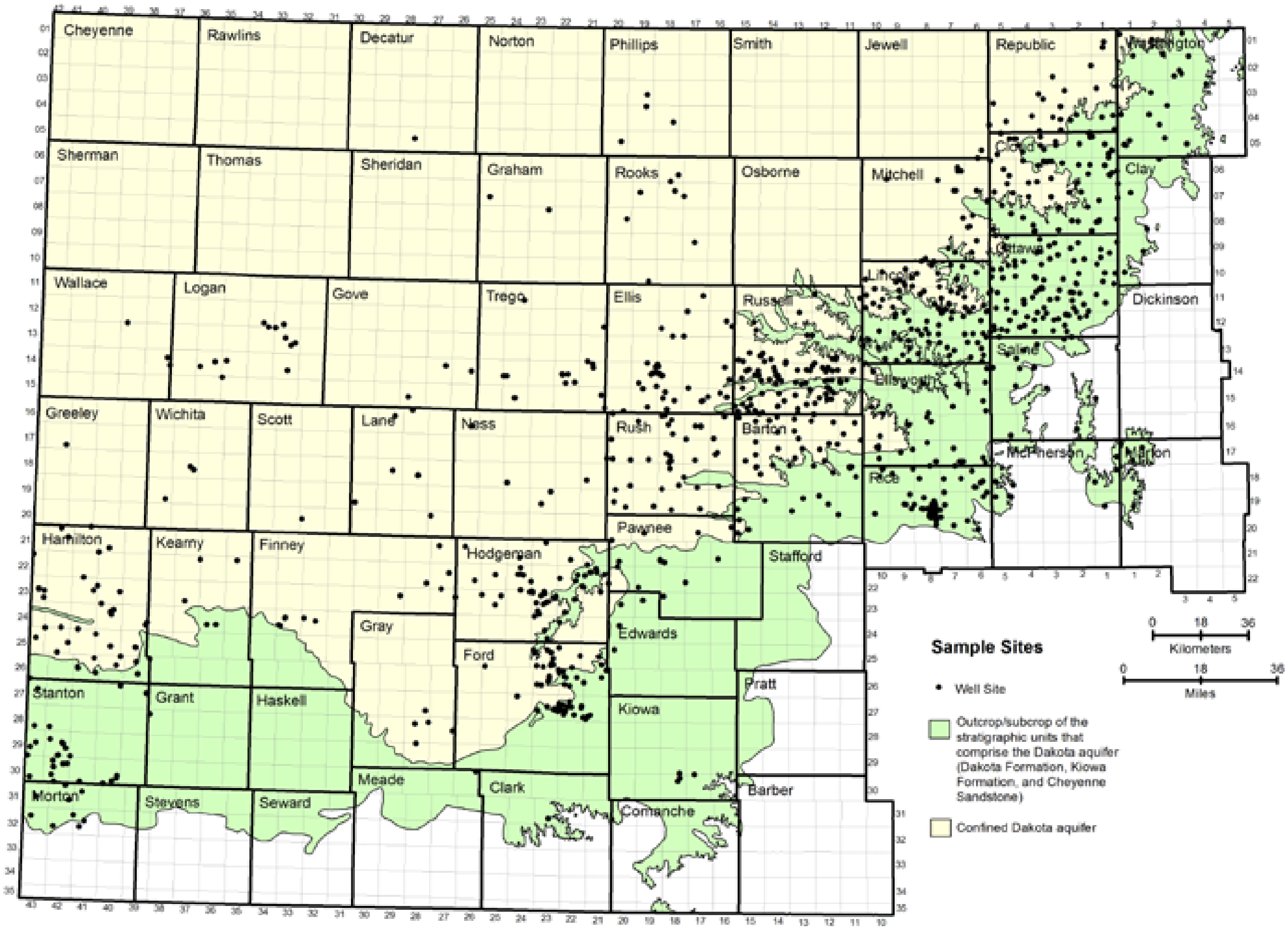


Figure 14. Distribution of water wells from which groundwater samples were collected from the Dakota aquifer.

contribute minor amounts to the dissolved solids in Dakota groundwater are silica (uncharged) and potassium (a cation), and nitrate and fluoride (anions). Trace to minor amounts of ammonium ion and strontium (cations) and bromide (an anion) in groundwaters are also of value for describing the geochemistry of groundwaters.

Major Dissolved Constituents and Chemical Water Types

Freshwater is often defined as water that contains less than 1,000 mg/L TDS concentration. The TDS of shallow groundwater in the Dakota aquifer can be as low as 100 mg/L. Saltwater sampled from the confined aquifer in parts of north-central Kansas where the Cedar Hills Sandstone directly underlies Dakota strata (fig. 2) can exceed a TDS of 50,000 mg/L.

Freshwaters in the outcrop and subcrop portions of the Dakota aquifer in north-central and central Kansas are usually calcium-bicarbonate type waters. Most soils and near-surface rocks in Kansas, including the Dakota aquifer, contain at least small amounts of calcium carbonate present as calcite ($CaCO_3$), which also contains small amounts of magnesium. The mineral dolomite ($CaMg(CO_3)_2$) can also be present in the rocks. During infiltration of rainfall, the carbonate minerals dissolve and add calcium, magnesium, and bicarbonate to the water. Table 7 lists the typical ranges of major constituent concentrations in calcium-bicarbonate type waters in the Dakota aquifer.

The weathering of pyrite in Upper Cretaceous shale has sometimes produced a high enough sulfate concentration and an acidic solution that dissolved enough calcium from calcite and dolomite that gypsum has precipitated in the shale. The Graneros Shale overlying the Dakota Formation often contains such secondary gypsum that occurs in the crystalline form selenite. Recharge infiltrating through Cretaceous strata that contains secondary gypsum can dissolve the gypsum, which, along with additional weathering of pyrite and dissolution of calcite, can produce relatively high concentrations of calcium and sulfate. Flow of this water into underlying Dakota strata or the weathering of pyrite and concomitant calcite dissolution within Dakota sediments can substantially increase the calcium and sulfate

Table 6. Chemical properties, general concentration ranges, and water-quality criteria for dissolved inorganic substances and selected metals naturally occurring in Dakota aquifer waters. Natural values can be less than or greater than listed in the table but are typically within the general range.

Name	**Chemical symbol or representation**	**General range in the Dakota aquifer, mg/L**	**Public drinking water criterion, mg/L[a]**	**Livestock water criterion, mg/L[b]**	**Irrigation water criterion, mg/L[bc]**
Properties					
Total dissolved solids	TDS[d]	100–60,000	R 500	5,000[e]	
Alkalinity[f]	Represented as $CaCO_3$	10–1,500	S 300		
Total hardness[g]	Represented as $CaCO_3$	10–9,000	S 400		
pH		6.3–8.8	R 6.5–8.5 units[h]		
Major constituents (usually or often greater than 5 mg/L)					
Calcium	Ca	2–2,000	S 200		
Magnesium	Mg	1–1,000	S 150		
Sodium	Na	3–22,000	S 100		
Bicarbonate[f]	HCO_3	12–1,800	S 120[i]		
Chloride	Cl	2–35,000	R 50		
Sulfate	SO_4	1–6,000	R 250	1,000[j]	
Silica	SiO_2	4–50	S 50		
Minor constituents (usually or often greater than 0.5 mg/L)					
Potassium	K	1–150	S 100		
Fluoride	F	0.2–8	R 2, M 4	2	1
Nitrate	NO_3	<0.01–3[k]	M 10	100	
Boron	B	0.03–2	H 0.6	5	1
Iron	Fe	<0.001–30	R 0.3		5
Trace constituents (usually or always less than 0.5 mg/L)					
Ammonia[l]	NH_4	<0.01–5[m]	S 0.1		
Arsenic	As	<0.001–0.05	M 0.01	0.2	0.1
Barium	Ba	0.005–0.5	M 2		
Cadmium	Cd	<0.0001–0.005	M 0.005	0.02	0.01
Chromium	Cr	<0.0001–0.002	M 0.1	1	0.1
Copper	Cu	<0.0001–0.02	T 1.3	0.5	0.2
Lead	Pb	<0.0001–0.01[n]	T 0.015	0.1	5
Manganese	Mn	<0.001–1	R 0.05		0.2
Mercury	Hg	<0.0001–0.002	M 0.002	0.01	
Selenium	Se	<0.001–0.05	M 0.05	0.05	0.02
Silver	Si	<0.0001–0.001	R 0.1		
Zinc	Zn	0.001–2	R 5	25	2

[a] Criteria from the KDHE. R = recommended (Federal Secondary Drinking Water Standard); S = suggested by KDHE; M = maximum contaminant level of U.S. EPA and KDHE; T = must be treated to below level for public supply; H = U.S. EPA health advisory.

[b] Values recommended by the National Academy of Sciences/National Academy of Engineering or U.S. EPA except for sulfate, which is recommended by Environment Canada.

[c] TDS and major constituent concentration limits vary depending on salinity tolerance of plants and sensitivity of soil to sodium hazard of water. TDS concentration greater than 500 mg/L can be detrimental to sensitive crops, whereas water with up to 5,000 mg/L TDS can be used for tolerant plants on permeable soils with careful management practices.

[d] TDS can be a measured value for evaporation to dryness or a sum of constituents in which bicarbonate is multiplied by 0.4917.

[e] A TDS of greater than 3,000 mg/L is not recommended for poultry. Adult cattle, sheep, swine, and horses can tolerate up to 7,000 mg/L if accustomed to elevated TDS.

[f] Nearly all alkalinity in groundwater is bicarbonate. Bicarbonate can be calculated from alkalinity by multiplying by 1.219.

[g] Total hardness is the sum of calcium and magnesium concentrations multiplied by 2.497 and 4.116, respectively, to represent conversion to $CaCO_3$.

[h] The unit of pH is dimensionless and represents the negative log of the activity of the hydrogen (hydronium) ion in water.

[i] The recommended limit for drinking water is based on conversion of the alkalinity value.

[j] Very young livestock are sensitive to sulfate and may not be able to tolerate above 400 mg/L.

[k] Concentration as nitrate-nitrogen. Values greater than 3 mg/L are nearly always the result of human activities.

[l] Ammonia is present in natural water primarily as ammonium ion (NH_4^+).

[m] Concentration as ammonia-nitrogen.

[n] Lead concentrations >0.01 that are observed in well waters are often related to lead in a piping system.

contents of groundwaters in the upper Dakota aquifer. In some cases, calcium-sulfate waters may result (table 7), although this water type is not as common as the other common types of Dakota groundwaters.

Large areas of the Dakota aquifer contain saltwater (sodium-chloride type water) in which the TDS concentration can exceed 10,000 mg/L (table 7). No known evaporite deposits occur in the Dakota aquifer in Kansas. Therefore, the saltwater could either have been derived from past seawater trapped in the Dakota sediments or saltwater that has flowed from other formations into the aquifer. Bromide and chloride relationships in Dakota groundwaters indicate that the main source of this saltwater is dissolution of rock salt in Permian rocks underlying Dakota strata. Although most of the Dakota sediments probably contained seawater either during their deposition or after deposition when the sea covered Dakota sediments, bromide/chloride ratios indicate that nearly all of the seawater in most of the Dakota aquifer in Kansas has been flushed out by freshwater recharge (see online appendix, http://www.kgs.ku.edu/Publications/Bulletins/260/appendix.html). However, saltwater from underlying Permian rocks has been slowly intruding into Dakota strata for millions of years. The salt-dissolution brine replaced the seawater source of salinity long ago. During more recent geologic time, freshwater recharge has been slowly flushing saltwater from the Dakota aquifer to reduce the constituent concentrations in sodium-chloride type waters.

The past occurrence of saline water in Dakota strata resulted in the adsorption of large amounts of sodium on the clays in the sediments. As freshwater of calcium-bicarbonate or calcium-sulfate type slowly flushed the saline water from the aquifer, natural softening of the water occurred as dissolved calcium and magnesium adsorbed on clays and adsorbed sodium desorbed and became dissolved in the water. The decrease in calcium and magnesium concentrations caused some calcite and dolomite in the aquifer strata to dissolve, thereby supplying additional calcium and magnesium to the pore water. Carbonate ions released during carbonate dissolution combined with hydrogen ions to form bicarbonate ions, thereby increasing the pH of the water. The added calcium and magnesium were then available for more cation exchange with sodium.

Some additional bicarbonate may have been generated from slow oxidation of organic matter trapped in Dakota sediments. The combined effect of this and the cation exchange process increased dissolved sodium and bicarbonate concentrations while decreasing dissolved calcium, magnesium, and chloride concentrations in confined parts of the Dakota aquifer. The water types created are, in order of increasing salinity, sodium-bicarbonate type; sodium-chloride, bicarbonate type; and sodium-chloride type with excess sodium. The bicarbonate and chloride-bicarbonate type waters are typically soft because the calcium and magnesium concentrations are relatively low and have alkaline pH as high as 9 units. Table 7 lists the typical ranges of major dissolved constituents in sodium-bicarbonate waters in the Dakota aquifer.

Chemical data for groundwater samples indicate that distinct water types occur in different regions of the Dakota

Table 7. Typical ranges of major constituent and fluoride concentrations in the most common types of groundwater in the Dakota aquifer. The water types are listed in order of generally increasing TDS concentration.

Constituent	Typical range, mg/L
Calcium-bicarbonate type	
Calcium	30–150
Magnesium	10–40
Sodium	10–60
Bicarbonate	150–400
Chloride	5–80
Sulfate	10–130
Fluoride	0.5–1.5
Sodium-bicarbonate type	
Calcium	3–50
Magnesium	1–20
Sodium	100–350
Bicarbonate	250–600
Chloride	20–200
Sulfate	20–200
Fluoride	1.5–5
Calcium-sulfate type	
Calcium	80–600
Magnesium	15–90
Sodium	30–400
Bicarbonate	200–400
Chloride	20–500
Sulfate	200–1,800
Fluoride	0.4–1.5
Sodium-chloride type	
Calcium	10–800
Magnesium	5–800
Sodium	300–15,000
Bicarbonate	200–1,300
Chloride	300–20,000
Sulfate	100–5,000
Fluoride	0.5–4

aquifer system. These water types have been generated by a combination of the mixing of groundwaters of different types and the chemical reactions that occur in response to rock-water interactions. As described above, cation exchange and concomitant mineral dissolution and precipitation are the main reactions that affect water chemistry. Mixing of fresh groundwater (from surface recharge) and saline groundwater (from the intrusion of saltwater from underlying Permian strata) in the Dakota aquifer is the main factor setting up conditions for substantial chemical changes in the aquifer.

The primary geochemical and mixing processes described above were simulated by numerical modeling to better understand the evolution of groundwater in the Dakota aquifer in central and north-central Kansas (Chu, 1995; see also online appendix, http://www.kgs.ku.edu/Publications/Bulletins/260/appendix.html). A model of one-dimensional (1-D) flow coupled with chemical reactions was developed to simulate the hydrogeochemical processes involved in cation exchange and calcite precipitation/dissolution along a hypothetical west-east flow path in the aquifer. A model of two-dimensional (2-D) flow coupled with chemical reactions was designed to simulate a chemical transition zone along a subregional lateral profile that incorporated geohydrologic complexities of the Dakota aquifer. Both the 1-D and 2-D models indicate that it takes much longer for the cation and bicarbonate chemistry of the water in the confined aquifer to become similar to that of the inflowing lateral recharge than it takes to flush the salinity (represented by the TDS and chloride concentrations) because of the large exchange capacity of the clays in the sediment. The results of the simulations improved the understanding of the spatial and temporal characteristics of the chemical transitions in the Dakota aquifer.

Table 6 lists recommended and suggested water-quality criteria for major dissolved constituents and properties of water for drinking, livestock, and irrigation use. Much of the groundwater in the Dakota aquifer has high concentrations of TDS and major dissolved constituents. Thus, depending largely on the salinity of the water, groundwater in the Dakota aquifer in many locations exceeds several of the recommended standards listed in table 6. Based on the water-quality data base assembled for the Dakota Program, TDS is the parameter that most often exceeds recommended or suggested public-drinking criteria, followed, in order of decreasing percentage of exceedance, by alkalinity, sodium, sulfate, chloride, calcium, and magnesium.

Relationships among Conductance and Major Dissolved Constituents

The electrical conductivity of water is a chemical property that is valuable for estimating the concentrations of TDS and most major and some minor dissolved constituents in water. Conductivity is one of the easiest measurements to make in the field or laboratory. The TDS concentration for Dakota groundwater is well correlated with specific conductance (fig. 15). The scatter of points in fig. 15 is usually somewhat greater at low conductances because the larger diversity of water types at lower TDS concentrations results in different relationships between TDS and major dissolved constituents

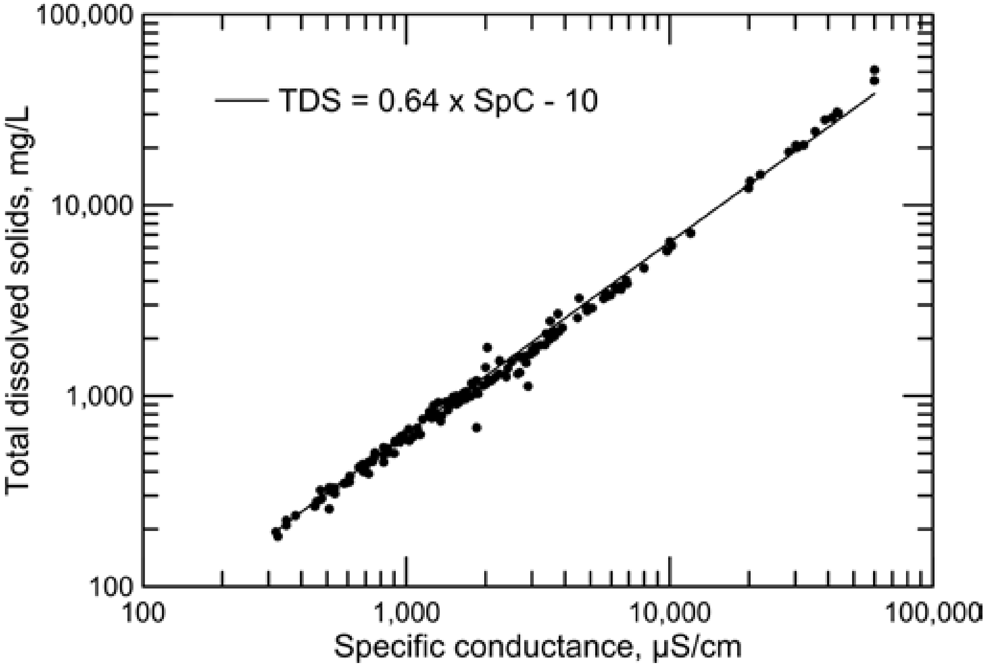


Figure 15. Total dissolved solids concentration versus specific conductance measured in the laboratory for Dakota aquifer waters. The line through the data is a visual fit, which is a better estimate of the relationship across the entire range of TDS and conductance than a linear regression. The R^2 for a linear regression is 0.989. A visual-fit line based on a second-degree polynomial function ($TDS = 0.6 \times SpC + 0.3 \times 10^{-6} \times SpC^2$) fits the data for the full conductance range better than the line shown.

and conductance. At high TDS concentration, the water type is sodium-chloride and the contributions of constituents other than sodium and chloride are relatively small.

Specific conductance also correlates well with concentrations of chloride (fig. 16) and other major constituents such as sodium. The correlation is much better at high than at low conductance values. In saline waters, the contribution of chloride to the total anion content is large and, along with sodium, predominantly controls the conductance value. As the conductance decreases below 4,000 µS/cm, the contributions of other major constituents (calcium, magnesium, sulfate, and bicarbonate), which have different concentration-conductance relationships, become an increasingly greater proportion of the TDS.

The correlation between sulfate and conductance is also high, although not as high as for sodium and chloride with conductance. Correlations between the other major constituents, calcium, magnesium, and bicarbonate, are statistically significant but not nearly as high as for sodium, chloride, and sulfate. Plots of major and minor constituent concentrations with conductance and TDS content are shown and described in the online appendix for this bulletin (http://www.kgs.ku.edu/Publications/Bulletins/260/appendix.html).

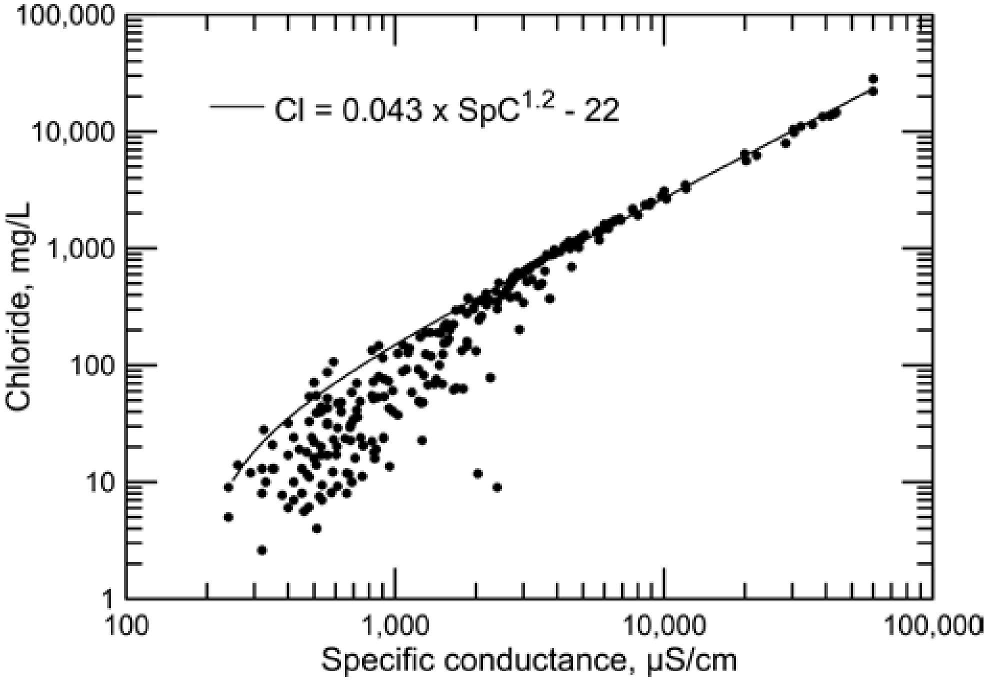


Figure 16. Chloride concentration versus laboratory specific conductance for Dakota aquifer waters. The curve is a function that best fits the upper limit of chloride concentration for lower conductance and best fits all chloride data for high conductance. The curve is also a better fit to the data for conductance greater than 4,000 µS/cm than a linear regression. The linear equation Cl = 0.34 x SpC - 500 also works well for estimating chloride concentration at conductance values greater than 4,000 µS/cm.

Minor and Trace Dissolved Constituents

Water in soils and the Dakota aquifer dissolves small amounts of minor and trace inorganic constituents. These substances are present in carbonate and clay minerals, coatings on quartz and other mineral grains, minor mineral grains, salts precipitated in soils during dry periods, and decomposing organic matter or are adsorbed on clays and other mineral surfaces. Infiltration of contaminants derived from anthropogenic activities can increase the concentrations of natural dissolved constituents (particularly nitrate) or add synthetic chemicals, such as pesticides and other dissolved organic compounds, to shallow Dakota waters. Table 6 lists typical ranges of minor and trace inorganic constituent concentrations in Dakota waters, and table 7 lists fluoride contents for different chemical water types.

Nitrate is a minor constituent in Dakota groundwaters free of significant anthropogenic contamination, although it can be a major constituent in some contaminated fresh groundwaters. Most Dakota groundwaters have a nitrate-nitrogen concentration between 0.1 and 100 mg/L. The primary standard for public drinking water, the maximum contaminant level (MCL), for nitrate-nitrogen (NO_3-N) is 10 mg/L. High nitrate contents (greater than 10 mg/L as nitrate-nitrogen) typically occur in Dakota groundwaters with a TDS content between 250 and 3,000 mg/L. These are usually from surface contamination and are commonly related to flow down poorly constructed wells. Nitrate is the dissolved constituent for which the largest number and percentage of Dakota aquifer water samples exceeded the MCL in the water-quality data base of the Dakota program. Of the 602 wells for which sample data include nitrate concentration, nearly 15% of the samples contained greater than 10 mg/L nitrate-nitrogen.

Fluoride concentrations range between 0.1 and 10 mg/L in Dakota groundwaters. Low fluoride concentrations (less than 1 mg/L) usually occur in freshwaters of calcium-bicarbonate chemical type. The greatest concentrations of fluoride occur in waters with a TDS content between 600 and 4,000 mg/L. Elevated concentrations of dissolved fluoride (greater than 1 mg/L) are usually associated with sodium-bicarbonate and mixed cation-anion type waters. The high fluoride concentration is primarily derived from the dissolution of calcium minerals that contain fluoride. The cation exchange process that decreases dissolved calcium concentration during the generation of sodium-bicarbonate type water allows these fluoride-containing minerals to dissolve. After nitrate, fluoride is the dissolved constituent with an MCL that is most frequently exceeded in groundwaters in the Dakota aquifer. The MCL for fluoride content in drinking water is 4 mg/L. In addition, a secondary MCL (SMCL) for fluoride of 2 mg/L requires public notification of customers who receive the public water supply. About 8% of the samples from the 768 wells for which fluoride data are available for the Dakota aquifer contain greater than 4 mg/L.

Chemically reducing environments occur where reactions of dissolved constituents and gases with other constituents and with the sediments have essentially completely consumed dissolved oxygen. This commonly occurs in the confined portion of the Dakota aquifer because the water is old and no recent recharge of water with significant oxygen has occurred. The reducing environment allows iron, manganese, and some other heavy metals to dissolve from the sediments. These waters can sometimes have a high enough hydrogen sulfide (H_2S) content to give a “rotten egg” odor. Ammonium ion (NH_4^+) levels can exceed 1 mg/L as ammonia-nitrogen in the reducing environment. Waters in the confined Dakota aquifer tend to have higher dissolved solids than in the unconfined, shallow portions of the aquifer. Thus, groundwater in which ammonium ion exceeds 1 mg/L tends to be slightly saline to saline. When ammonium ion concentration is definitely detectable (ammonia-nitrogen generally greater than 0.1 mg/L) in natural groundwaters with low oxidation-reduction potential, nitrate concentration is typically very low (nitrate-nitrogen less than 0.1 mg/L). Ammonia-nitrogen concentrations often exceed the suggested maximum of 0.1 mg/L for public drinking water in Dakota aquifer water.

Dissolved concentrations of iron range from less than a few μg/L to more than 10 mg/L and of manganese range from less than 1 μg/L to nearly 1 mg/L. The greater concentrations occur in two types of environments. One occurrence is the chemically reducing environment described above. The other environment is in the outcrop or subcrop area of the Dakota aquifer where recharge with dissolved oxygen reaches strata containing pyrite. Oxidation of pyrite and other sulfides, which was discussed earlier as a source of sulfate, is also a source of dissolved iron and manganese in groundwaters. The dissolved iron and manganese released from sulfide weathering oxidizes and precipitates as oxides and oxyhydroxides that produce the red to orange to brown coloration that commonly occurs in Dakota strata. Dissolved iron and manganese in Dakota groundwaters often exceed the recommended criteria of 0.3 mg/L and 0.05 mg/L, respectively, for public drinking use; 59% of the samples from the 691 wells with iron data and 45% of the samples from the 295 wells with manganese data exceeded these criteria. These percentages are substantially greater than for the HPA; only a little more than 1% of about 450 samples from HPA irrigation wells in west-central and southwest Kansas exceeded the iron and manganese criteria (based on data in Hathaway et al., 1977, 1978).

Although trace metals are contained in a variety of minerals, the main substances that control the concentrations of heavy metals (e.g., cadmium, chromium, copper, lead, mercury, nickel, and zinc) and semimetals (e.g., arsenic and selenium) in Dakota groundwaters are probably sulfides, oxides, and oxyhydroxides. Oxidation of sulfides and reduction of oxides and oxyhydroxides can release metals and semimetals within the minerals to the groundwater. Precipitation of these minerals and adsorption on their surfaces, especially on oxides and oxyhydroxides, remove trace and semimetals from solution. Adsorption on clays also can control the amount of trace ionic species in solution. Table 6 lists the general concentration ranges in Dakota groundwaters and the criteria for public drinking water for selected heavy metals and semimetals. Nearly 10% of the Dakota wells for which sample data exist yielded water that exceeded the MCL for arsenic of 0.01 mg/L and the action level for lead of 0.015 mg/L in public drinking water. Some of the lead values could be related to lead in the plumbing system from which the sample was collected. A few to several percent of the sample records exceed the MCLs for cadmium and mercury of 0.005 mg/L and 0.002 mg/L, respectively. No samples were found to have exceeded the MCLs or recommended criteria for public drinking water for chromium, copper, selenium, silver, or zinc.

Uranium and Radionuclides

Uranium occurs naturally in a wide range of rocks and sediments and is weakly radioactive. The three natural uranium isotopes found in the environment undergo radioactive decay by emission of an alpha particle accompanied by weak gamma radiation. Radium is a naturally occurring radioactive constituent that is dissolved in water as a doubly charged cation. It is a radionuclide formed by the decay of uranium and thorium in the environment. Its most common isotopes are radium-226, radium-224, and radium-228. The radioactive decay of radium-226 emits alpha particles and gamma radiation, whereas the decay of radium-228 emits primarily beta particles. Radon is a naturally occurring radioactive gas that has no color, odor, or taste. It is soluble in water and easily leaves water that is exposed to the atmosphere, especially if the water is agitated. Radon has numerous different isotopes; radon-220 and -222 are the most common and are produced by the radioactive decay of radium and thorium, respectively. Table 8 lists the current MCL values for uranium and radionuclides in drinking water. The MCL for uranium is based on the toxicity of the element and not its radioactivity. The MCLs for the other parameters in table 8 are based on radioactivity.

Uranium concentrations are generally low in groundwaters in the Dakota aquifer (table 8). However, a few percent of the well waters sampled exceeded the MCL for drinking water. A few percent of the sampled well waters also exceeded the MCL for gross alpha radioactivity, whereas none of the samples collected from the Dakota aquifer had gross beta radioactivity greater than the MCL. Several percent of the sampled Dakota waters contained combined radium-226 and -228 radioactivity greater than the MCL. Nearly half of the groundwaters sampled for radon-222 radioactivity exceeded the proposed MCL. However, the MCL of 300 pCi/L for dissolved radon proposed by the federal government is quite low and corresponds to less than 10% of the natural radon content in outdoor air. None of the Dakota waters sampled for radon contained close to the alternate MCL (table 8).

Characteristics of Contaminated Groundwater

The main constituent in Dakota groundwater that has been increased substantially in concentration by human activities is nitrate. Nitrate-nitrogen concentration greater than 3 mg/L is generally considered to be above that originally present in uncontaminated Kansas groundwater. Human sources of nitrate include fertilizer and animal and human waste. Dissolved species of nitrogen from these sources can enter groundwaters by infiltration of water through the unsaturated zone to the water table or by water flowing down the boreholes of wells, especially if the annular space between the well casing and borehole is poorly sealed or not sealed. If the contaminated water that reaches the water table contains a high concentration of dissolved nitrogen species in the form of ammonium ion or nitrogen-containing organic compounds, oxidation to nitrate in the groundwater system could occur if there were enough dissolved oxygen or other dissolved species that could oxidize the nitrogen.

The occurrence of most high-nitrate waters (greater than several mg/L nitrate-nitrogen) at shallow depths in the unconfined portion of the Dakota aquifer is consistent

Table 8. Assessment of water-quality data for the Dakota aquifer based on public-drinking-water limits for uranium and radiochemical constituents and properties. Criteria are maximum contaminant levels used by the KDHE and the U.S. EPA.

Property or constituent	Number of sites	Range	Drinking-water criterion	Percent exceeding criterion	Limit of detection	Number of < values[a]
Uranium, µg/L	77	<0.01–41	30	2.6	0.01–0.2	15
Gross alpha radioactivity (minus uranium), pCi/L	40	0–29	15	5.1	0.4–1	6
Gross beta radioactivity, pCi/L	40	2.4–29.9	50	0	1	0
Radium-226/228 (combined), pCi/L	40	0.1–10.8	5	7.5	0.1	0
Radon-222, pCi/L	29	<40–1,200	300[b] 4,000[c]	48.3 0	40	2

[a] Number of values reported as less than the detection limit of the analytical method used.

[b] Maximum contaminant level proposed by U.S. EPA if a state chooses not to develop a Multimedia Mitigation program.

[c] Alternative maximum contaminant level proposed by U.S. EPA if a state chooses to develop a Multimedia Mitigation program.

with a surface source of nitrate contamination. All waters with records in the Dakota water-quality data base that were sampled from wells with depths greater than 300 ft (91 m) in the unconfined aquifer contained nitrate-nitrogen less than several mg/L. Several samples of groundwaters from the confined aquifer contained high nitrate content. It is probable, especially for wells with depths greater than 100 ft (30 m), that some water from the surface or shallow depths entered the aquifer through poorly constructed wells, because the confining stratum immediately above the Dakota aquifer (Graneros Shale) should have a low enough permeability to substantially retard downward movement of contaminated water.

Another constituent elevated in some Kansas groundwater by human activities is chloride. The determination of the amount of chloride from anthropogenic sources in Dakota aquifer water is often difficult due to the large concentration that can come from natural sources. Use of bromide, chloride, and sulfate concentration relationships is generally the best approach for geochemical differentiation of anthropogenic sources of chloride contamination, such as oil-field brine, from natural salinity. Evaluation of chemical data for the Dakota aquifer indicates that substantial contamination of the Dakota aquifer by oil-brine contamination occurs only at a few locations. In comparison, nitrate contamination of the aquifer is much more common.

Regional Groundwater Geochemistry

Areal Geochemical Patterns

The TDS and chloride concentrations of Dakota groundwaters are the most useful parameters for characterization of the salinity. The regional distributions of TDS and chloride concentrations in groundwaters in the upper Dakota aquifer are shown in figs. 17 and 18. The maps represent only the upper part of the Dakota aquifer in each region because the shallower portion of the aquifer at a given location generally contains the least saline water, which would be the most usable in that area. In most regions, the maps represent the quality of water in the Dakota Formation, but in the outcrop and subcrop areas where the Dakota Formation has been removed by erosion, the upper Dakota aquifer in the maps can be the Kiowa Formation or Cheyenne Sandstone. The TDS and chloride maps are based on chemical analyses of samples from supply wells in the area where water is used, analyses of samples from observation wells, and interpretation of geophysical logs from many oil and gas boreholes in the area of saline water without supply wells in northwest Kansas.

Groundwater in the Dakota aquifer is usually fresh (TDS content less than 1,000 mg/L) in the outcrop area and where the aquifer subcrops beneath unconsolidated deposits of alluvium in central and north-central Kansas and the HPA in south-central and southwest Kansas (fig. 17). The freshest water (TDS content less than 250 mg/L) occurs in parts of Washington, Cloud, Clay, Ottawa, Ellsworth, and Saline counties in the central to eastern part of the outcrop belt from central to north-central Kansas. The less than 250 mg/L TDS water typically contains less than 50 mg/L chloride (fig. 18) and less than 50 mg/L sulfate concentrations. Groundwater with 250–1,000 mg/L TDS content in the outcrop and subcrop belt in central and north-central Kansas usually has a greater sulfate than chloride level.

Freshwater occurs in the subcrop area of the Dakota aquifer underlying the HPA in south-central and southwest Kansas. However, Dakota strata in western Stafford County, the southernmost part of Barton County south of the Arkansas River, southeast Pawnee County, easternmost Edwards County, and northwest Pratt County where the Dakota occurs are expected to contain saline water even though no sample data are available. Saltwater intrudes upwards from the Cedar Hills Sandstone and other Permian units underlying Dakota strata to affect the HPA in that area. The TDS, chloride, and sulfate concentration isolines for that area in figs. 17–19 are estimates based on data from observation wells screened at the base of the HPA and in the Permian bedrock (Whittemore, 1993). The salinity could range substantially with depth in the Dakota in parts of this area, from higher concentrations just above the Permian to lower values just below the HPA.

Almost no chemical data exist for groundwater in the unconfined part of the Dakota aquifer in Grant, Haskell, southern Kearny, southern Finney, northern Stevens, northern Seward, northern Meade, and southwestern Gray counties. In October 2013, the KGS analyzed a sample of water pumped from 700–780 ft in a test well in the Cheyenne Sandstone in northwest Haskell County. The water was fresh, with TDS, chloride, and sulfate concentrations of 520 mg/L, 9 mg/L, and 219 mg/L, respectively. These data suggest that not only can freshwater be obtained from the upper Dakota aquifer in the unconfined region of southwest Kansas but also from the lower Dakota aquifer.

Freshwater extends into the confined portions of the aquifer in southwest Kansas and parts of south-central and

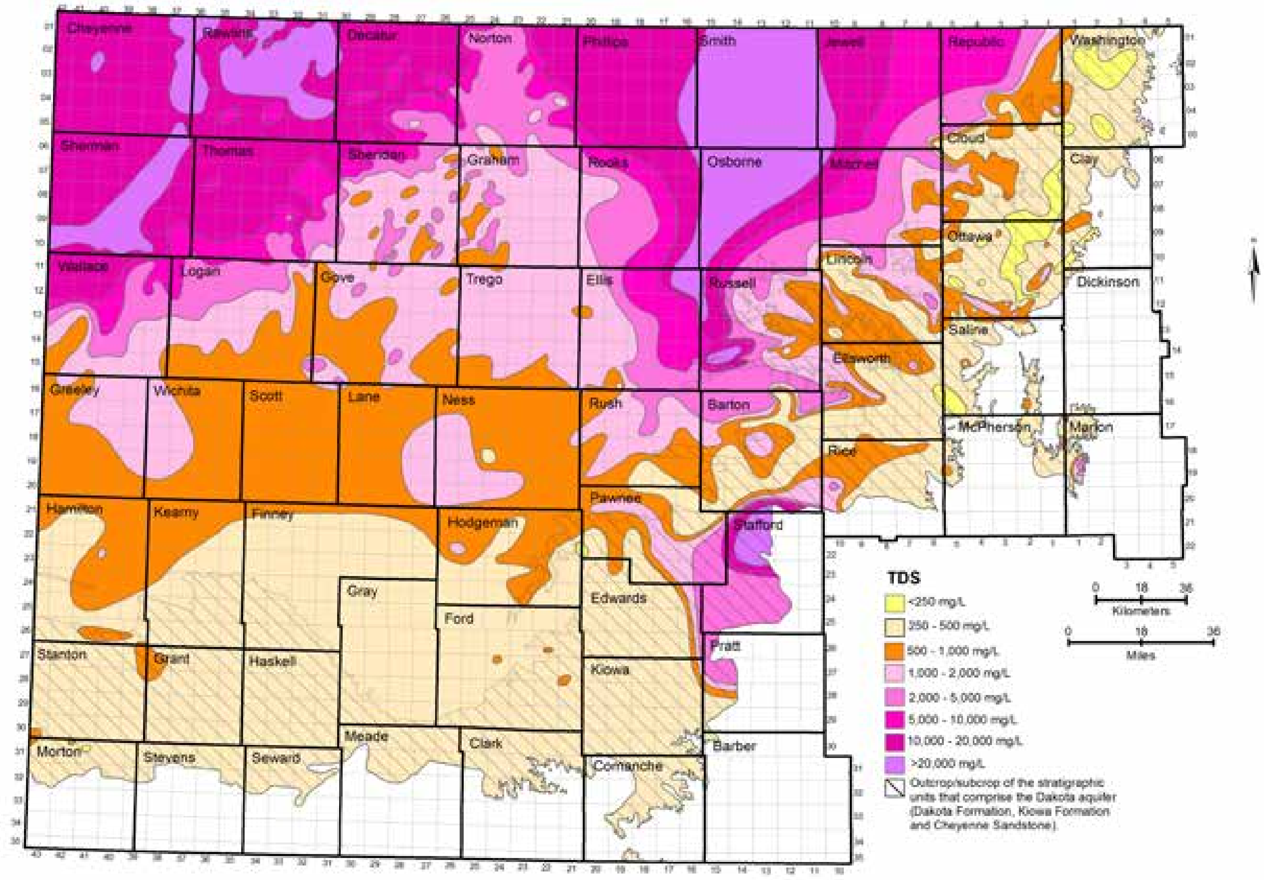


Figure 17. Distribution of total dissolved solids concentration in groundwaters in the upper Dakota aquifer.

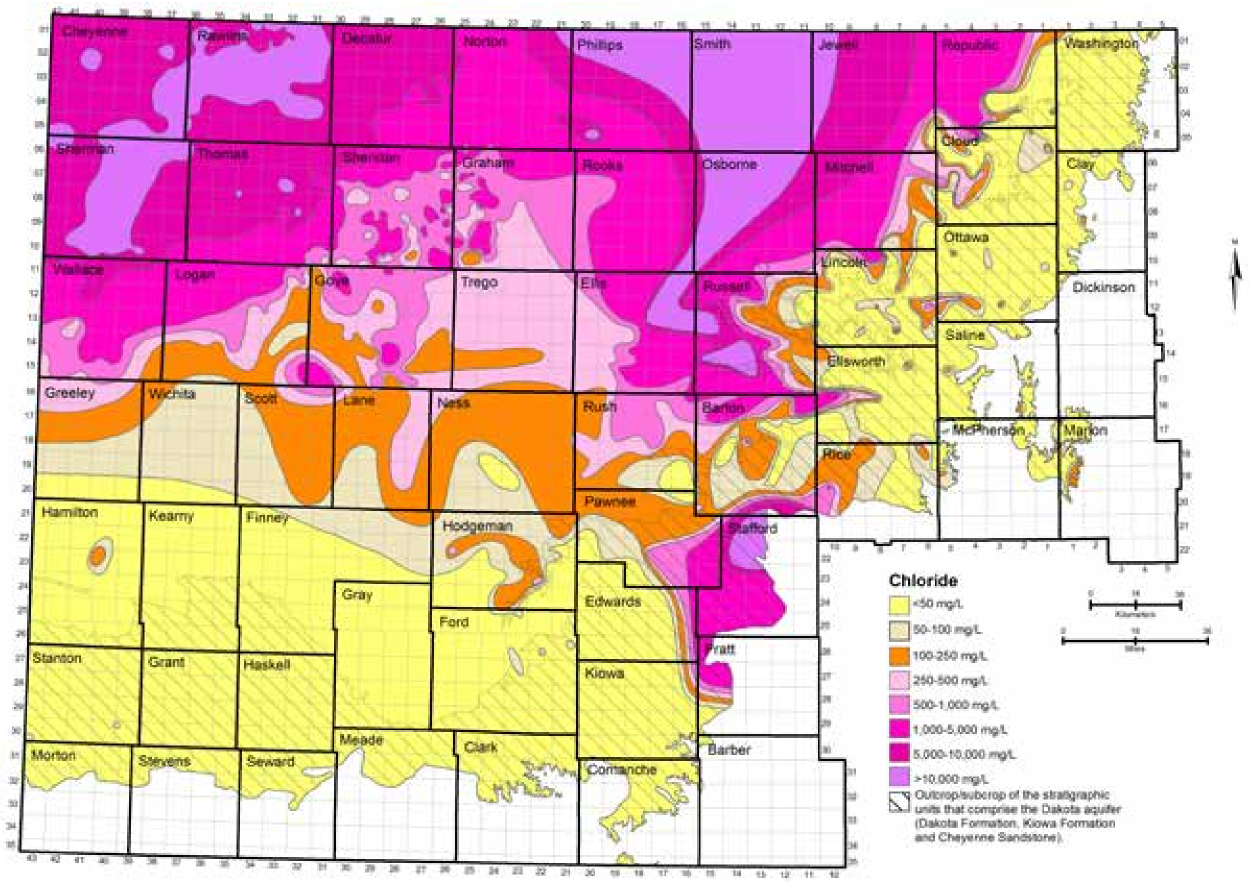


Figure 18. Distribution of chloride concentration in groundwaters in the upper Dakota aquifer.

west-central Kansas (fig. 17). Data from the interpretation of geophysical logs suggests that there could be fingers of fresh to nearly fresh water (near 1,000 mg/L TDS) in the confined aquifer as far north as southeast Sheridan and southwest Graham counties. As is the case in the outcrop area, the sulfate concentration is usually greater than the chloride content for these freshwaters.

The transition of freshwater to saline water (TDS content greater than 1,000 mg/L) in the Dakota aquifer in central and north-central Kansas generally occurs near the outcrop/subcrop boundary (fig. 17). The shape of the transition near this boundary is irregular because of the convolutions in the boundary caused by the erosion of major valleys into the confining layer. The salinity of the groundwater increases substantially in a westerly direction from the outcrop/subcrop belt to a TDS level that exceeds 20,000 mg/L in most of Smith County, more than half of Osborne County, and parts of eastern Phillips, western Jewell, northwest Mitchell, eastern Rooks, northeast Ellis, and western Russell counties. The chloride concentration in these areas is close to or greater than 10,000 mg/L (fig. 18). West of this saltwater zone is a well-defined wedge of slightly to moderately saline groundwater (1,000–5,000 mg/L TDS) that points northward to the Nebraska border. The southern part of the wedge extends from Logan County on the west through Gove and Trego counties to Ellis County on the east. The center of the wedge occurs from southeast Thomas County through Sheridan and Graham counties to western Rooks County. The top of the wedge is located in southeast Decatur County and much of Norton County. Groundwater in the confined Dakota aquifer increases in salinity into northwest Kansas. In parts of northwest Kansas, primarily parts of Cheyenne, Rawlins, and Sherman counties, the TDS concentration of the groundwater exceeds 20,000 mg/L.

The regional salinity pattern of Dakota groundwaters is mainly dependent on the rate at which freshwater is able to enter from above and along the long flow paths in the aquifer in comparison with the rate of saltwater intrusion from underlying Permian rocks. In some regions, the saltwater is able to more rapidly intrude into the bottom of the Dakota, such as in parts of central to north-central Kansas where the Dakota directly overlies the Cedar Hills Sandstone (fig. 2). In northwest Kansas, the thickness of the confining units is great and the rate at which freshwater flows through is low. The Dakota rocks contain saltwater in both of these regions.

Surface recharge along the outcrop belt of the Dakota aquifer in southeast Colorado and central Kansas occurs at a much greater rate than underlying saltwater intrusion, resulting in essentially complete flushing of any previous saltwater. Fresh recharge flowing through the Dakota sandstones in southwest Kansas also has removed nearly all salinity. The freshwater flowing through sandstones in the confined aquifer between northwest and central Kansas has removed much of the saltwater, but enough dissolved salt remains to make much of the water slightly to moderately saline. The western side of the wedge of Dakota groundwater with TDS less than 5,000 mg/L between northwest and north-central Kansas reflects where the flushing rate has been greater than the saltwater intrusion rate; on the eastern side, the transition is to where the saltwater intrusion rate is greater than that of the flushing. The rate of any flushing is slow, such that substantial changes over regional distances take many thousands of years. In general, the greater the distance from the edge of the confining zone, the greater the salinity.

Although sulfate concentration generally increases along with chloride concentration in the saline waters in the Dakota aquifer that intrude from underlying Permian strata, sulfate can also independently vary spatially (fig. 19). For example, fig. 19 indicates that sulfate concentration can be greater than 250 mg/L (the recommended limit for drinking water) in areas where the chloride concentration is less than 50 mg/L. In this case, the sulfate is either derived internally in Dakota strata from the oxidation of pyrite or introduced by high-sulfate recharge into the aquifer from overlying Upper Cretaceous rocks. In both cases, the continual introduction of sulfate can be at a rate that negates the flushing by local and regional flow that dilutes the chloride concentration. Although sulfate contours in most of the map area of fig. 19 are based on sample data for the Dakota aquifer, the area of high sulfate concentration centered on western Stafford County was inferred from observation wells in underlying Permian strata and at the base of the overlying HPA (as was the case for the distribution of TDS and chloride shown in figs. 17 and 18, too).

Groundwater in the areas of the upper Dakota aquifer with high TDS content (greater than 5,000 mg/L) shown in fig. 17 is of sodium-chloride chemical type. Water in the area of the confined aquifer in fig. 17 with 500–2,000 mg/L TDS is generally soft (low calcium and magnesium content) and sodium-bicarbonate in chemical type. Groundwater with 2,000–5,000 mg/L TDS in the confined area is typically transitional between sodium-bicarbonate and sodium-chloride type. Groundwater in the outcrop and subcrop areas with less than 500 mg/L TDS content is usually of calcium

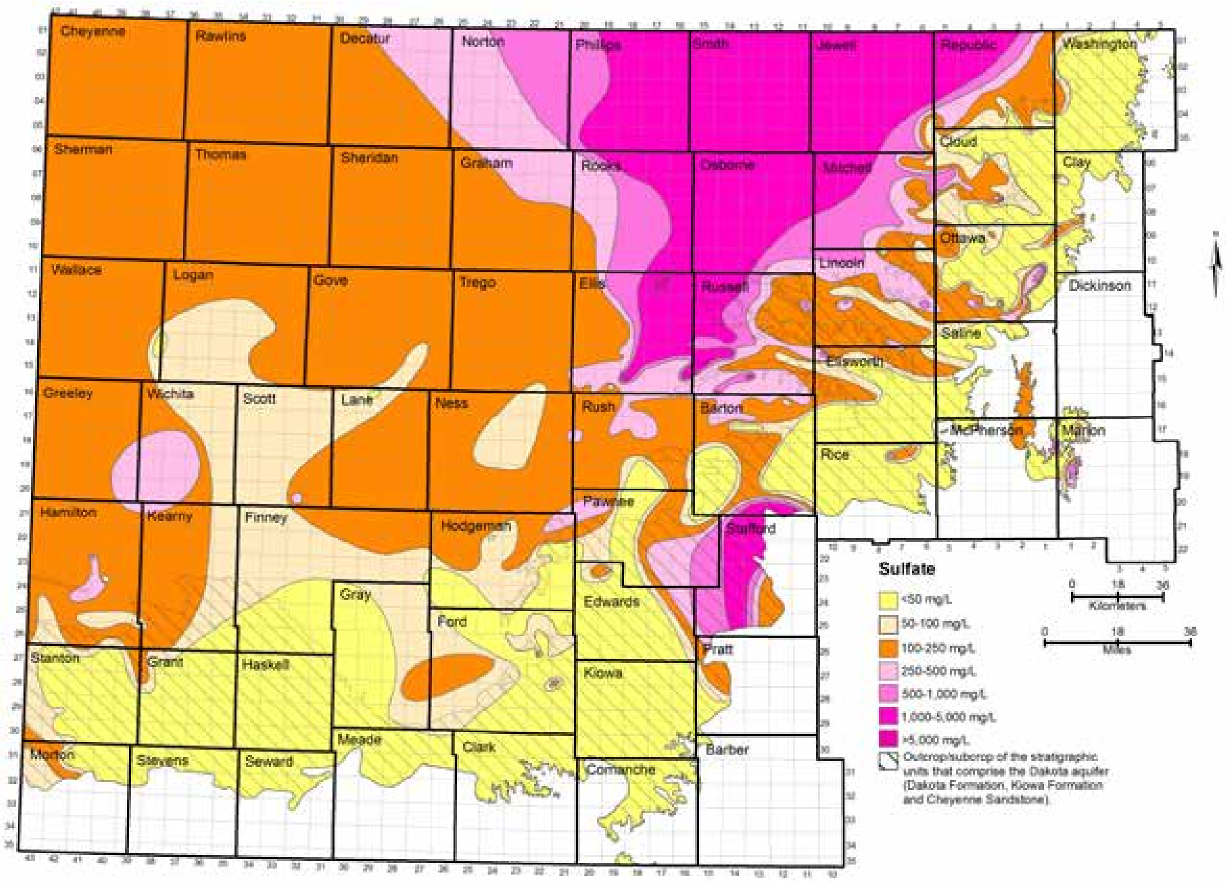


Figure 19. Distribution of sulfate concentration in groundwaters in the upper Dakota aquifer. Some isolated locations within the areas of <50 and 50–100 mg/L may contain higher sulfate concentration depending on the local composition of Dakota sediments.

bicarbonate type. Concentrations of TDS between 500 and 2,000 mg/L in water in the outcrop/subcrop areas are often due primarily to dissolved calcium and sulfate contents that make the waters calcium-sulfate in type. Elevated sulfate concentration with substantially lower chloride content can produce sulfate-type water in less saline portions of the confined aquifer.

Groundwater in the Dakota aquifer typically contains a low fluoride concentration (less than 1 mg/L) in the outcrop and subcrop areas where calcium-bicarbonate type water is the common chemical type (fig. 20). Low fluoride water also occurs in parts of the confined aquifer near the outcrop/subcrop boundary. Fluoride concentrations are usually 1–3 mg/L in the Dakota aquifer in most of the region where the Dakota directly underlies the HPA in southwest Kansas. Fluoride levels generally increase from about 1 mg/L near the outcrop/subcrop boundary to greater than 4 mg/L where greater thicknesses of Upper Cretaceous rocks confine the Dakota aquifer. Higher fluoride concentration is generally associated with sodium-bicarbonate or mixed cation-anion type waters in the confined aquifer. Water in the area of the confined aquifer with a TDS content in the range of 500–2,000 mg/L that is soft (low calcium and magnesium content) often has relatively high fluoride concentration (greater than 4 mg/L). This type water occurs in the confined aquifer from west-central Kansas toward central Kansas. It is unknown as to whether the fluoride content of the highly saline water in northwest Kansas also exceeds 4 mg/L. However, the high calcium concentration in the saline water is generally expected to limit the fluoride content to below a few to several mg/L.

Natural nitrate concentration in Dakota groundwater is usually less than 2 mg/L as nitrate-nitrogen. The low nitrate water occurs both in the unconfined and confined portions of the aquifer (fig. 21). Contaminated groundwaters are mainly distributed in the area of the unconfined aquifer but also occur in the confined aquifer, especially near the confined-unconfined boundary in central and north-central Kansas. Many of the wells in north-central and central Kansas have yielded water with greater than the MCL for nitrate-nitrogen of 10 mg/L; most of these are for domestic and stock wells. As described in the previous section on contamination

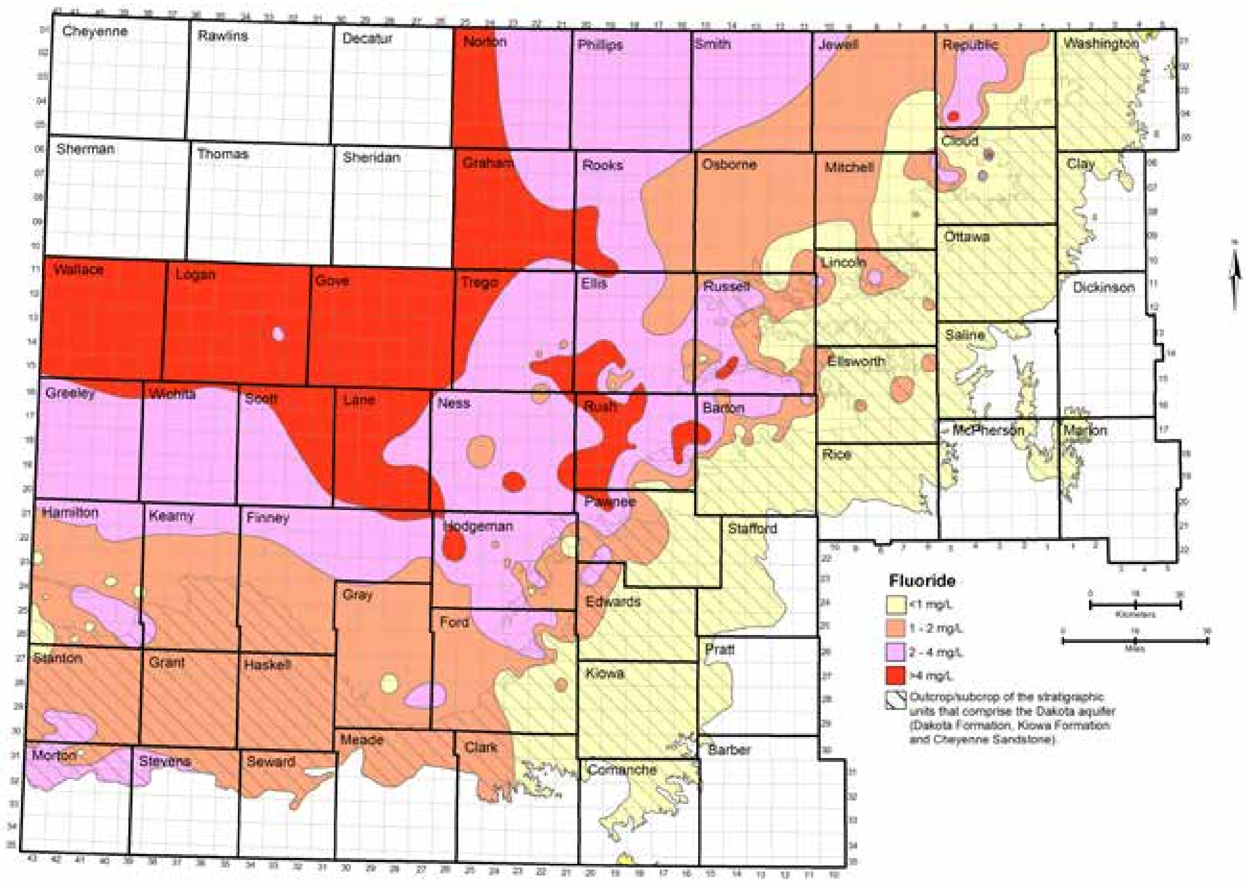


Figure 20. Distribution of fluoride concentration in groundwaters in the upper Dakota aquifer. The six counties in northwest Kansas are not shaded because no data for fluoride are available in that area.

characterization, nitrate contamination of the confined aquifer probably occurs mainly from the flow of water from the surface or near surface down an unsealed or poorly sealed annulus in a well borehole. Most of the water produced from wells in the confined aquifer in western Kansas has not been contaminated by nitrate, indicating protection by the confining zone as well as implying better well construction. Data for all well locations in the chemical data base for the Dakota aquifer were used to prepare fig. 21. Some of the older wells with contamination in north-central and central Kansas are probably no longer used. Thus, dilution of past contamination and better well construction could result in a map with fewer locations showing greater than 10 mg/L nitrate-nitrogen if only more recent data were used.

Geochemical Profiles across an Aquifer Flow Path

A cross section of the chemical characteristics in the Dakota aquifer from southeast Colorado to central Kansas illustrates the chemical transitions along a major regional path of groundwater flow in the aquifer (see fig. 2 for generalized regional flow patterns). The geochemical profiles are based on data collected during the Dakota Aquifer Program. Figure 22 is a cross section depicting the elevations of the land surface and of the middle of the screened interval of the wells sampled. A general decrease in land surface slope is apparent near the boundary between Colorado and Kansas. The groundwater flow in the Colorado subregion of the cross section is primarily within a local flow system. The flow path in Kansas is confined until the farthest eastern well, although the confining strata are thin enough at the next to most eastern well that vertical recharge through the confining unit is sufficient to appreciably change the water chemistry. The most eastern well is in the local recharge and discharge flow system of the outcropping Dakota aquifer. The cross section graphically illustrates that the wells in the Dakota aquifer are generally shallower in the western and eastern local flow areas and deeper in the confined portion of the aquifer in western Kansas.

Groundwater in the Dakota aquifer is fresh and the chloride concentration generally less than 50 mg/L in the recharge and local flow area of southeast Colorado (fig. 23). The TDS concentration increases to about 1,000 mg/L in water in the confined aquifer in western Kansas and then increases substantially in the zone of Permian saltwater

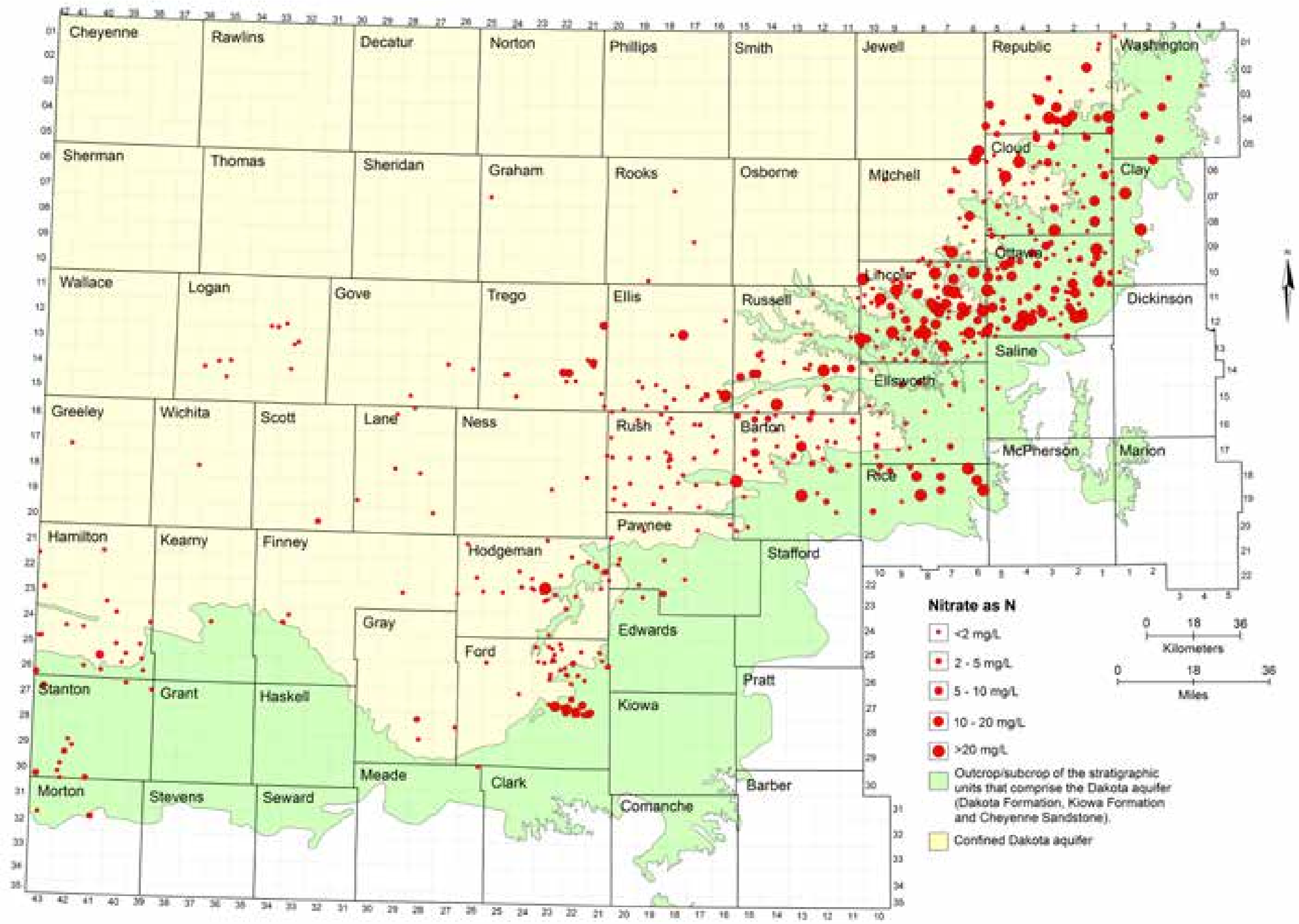


Figure 21. Nitrate concentration in groundwaters at well locations in the upper Dakota aquifer.

intrusion in the confined aquifer in central Kansas. The chloride concentration increases steadily in the confined part of the profile and becomes a greater percentage of the TDS content. The TDS and chloride concentrations then decrease farther to the east in the discharge and local flow system of the outcrop/subcrop belt where freshwater recharge flushes and dilutes saline water in the Dakota aquifer. Sulfate concentration ranges relatively widely across the profile; the ranges for the samples collected in Colorado at the well locations displayed in fig. 22 and for samples collected farther down the flow path substantially overlap (17–358 mg/L for the western recharge zone and 113–457 mg/L for the confined zone). The easternmost groundwater at the discharge end of the profile contained 128 mg/L of dissolved sulfate. Bicarbonate concentration generally increases from west to east along the profile, from the range 136–269 mg/L in the western recharge zone, to 268–442 mg/L in the central part of the confined zone, to 379–547 mg/L in the easternmost two wells.

The patterns for sodium and calcium concentrations along the profile differ substantially (fig. 24). The change in sodium is somewhat similar to that for chloride. Although the concentration increase from the recharge zone to the location with the highest concentration (saline intrusion from the Permian) is substantial, it is not as steady as for chloride. The reason is that cation exchange of calcium and magnesium (in the recharge) for sodium on clays in the aquifer increases the sodium concentration from what would be expected from the simple mixture of freshwater flowing along the profile with saltwater intrusion from the underlying Permian strata. Therefore, the increase in sodium concentration along the flow path is derived from both the cation exchange process and an increasing amount of saline water from Permian intrusion.

The pattern in the calcium concentration (fig. 24) illustrates the onset of the cation exchange process once the flow path leaves the recharge zone in Colorado and enters the confined aquifer in western Kansas. The pattern in the magnesium profile is similar to that for calcium. Groundwaters in southeast Colorado derive calcium and magnesium from leaching carbonate minerals in the aquifer rocks as well as from recharge that leaches carbonate minerals in soils in an environment of greater

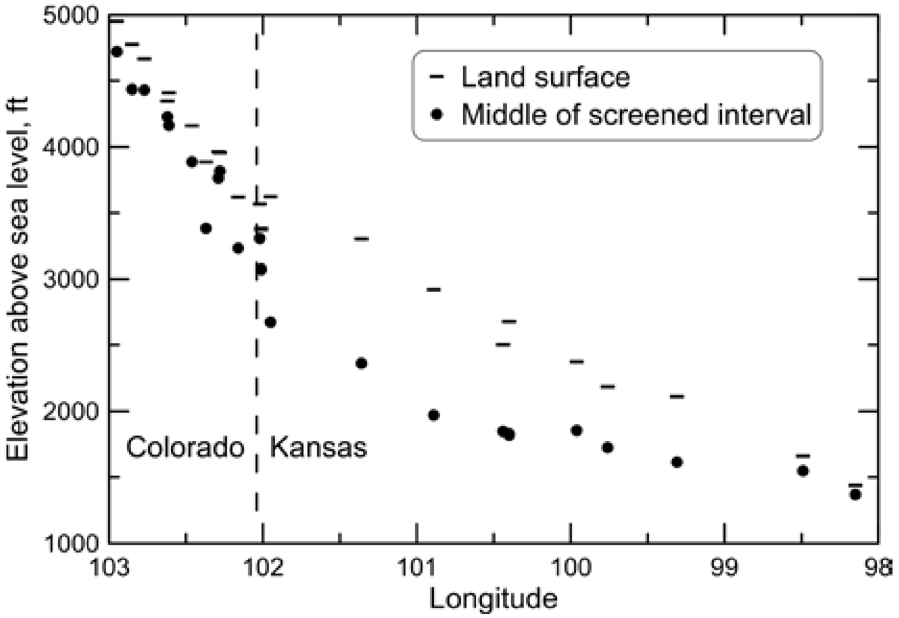


Figure 22. Elevation of the land surface and the middle of the screened interval for wells sampled along a regional flow path of the Dakota aquifer from southeast Colorado to central Kansas.

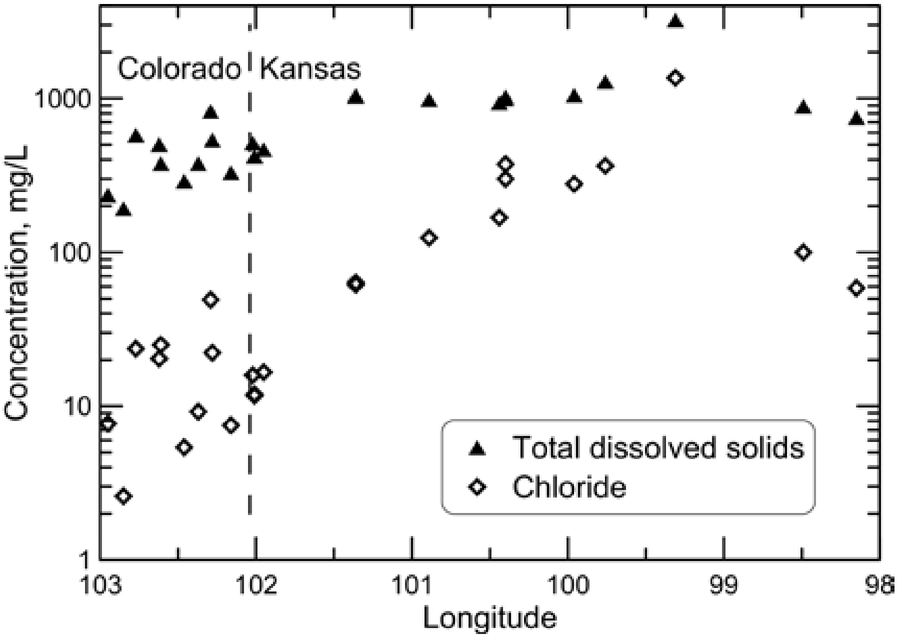


Figure 23. Total dissolved solids and chloride concentrations for wells sampled along a regional flow path of the Dakota aquifer from southeast Colorado to central Kansas.

evapotranspiration than precipitation. The aquifer is well flushed in this area. Thus, any saline water has been essentially removed, and sodium and chloride concentrations in the groundwater are low. When the flow path enters the westernmost part of the confined zone in western Kansas, both calcium and magnesium concentrations drop sharply as a result of the cation exchange process. The aquifer in the confined area has not been as well flushed of saline water as in the local flow and recharge area of southeast Colorado, leaving a high sodium content on the clays. The high exchange capacity of most aquifer clays requires interactions with large volumes of inflowing water before the adsorbed cation concentrations approach ratios that are in near equilibrium with the inflows, and thus no longer appreciably change the inflow chemistry. The calcium and magnesium concentrations generally increase across the confined portion of the aquifer in Kansas as the TDS content rises. The local flow and discharge zone at the eastern end of the profile contains groundwater with calcium and magnesium contents either similar to or higher than in the recharge zone in Colorado.

The change in the ratio (calcium + magnesium)/sodium along the flow path illustrates the effects of the exchange process (fig. 25). The ratio decreases by an average of about two orders of magnitude from the recharge area in southeast Colorado to the western part of the confined zone

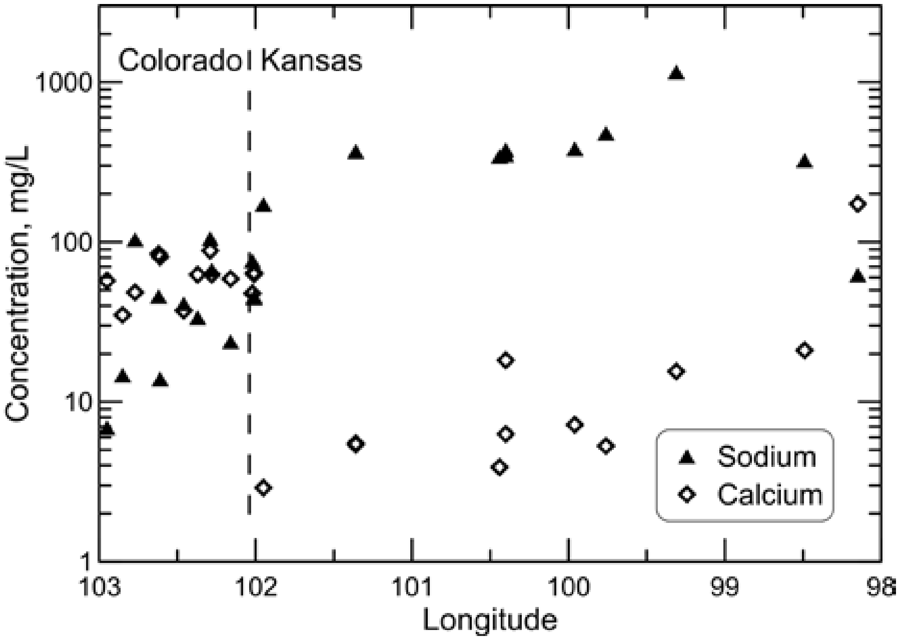


Figure 24. Sodium and calcium concentrations for wells sampled along a regional flow path of the Dakota aquifer from southeast Colorado to central Kansas.

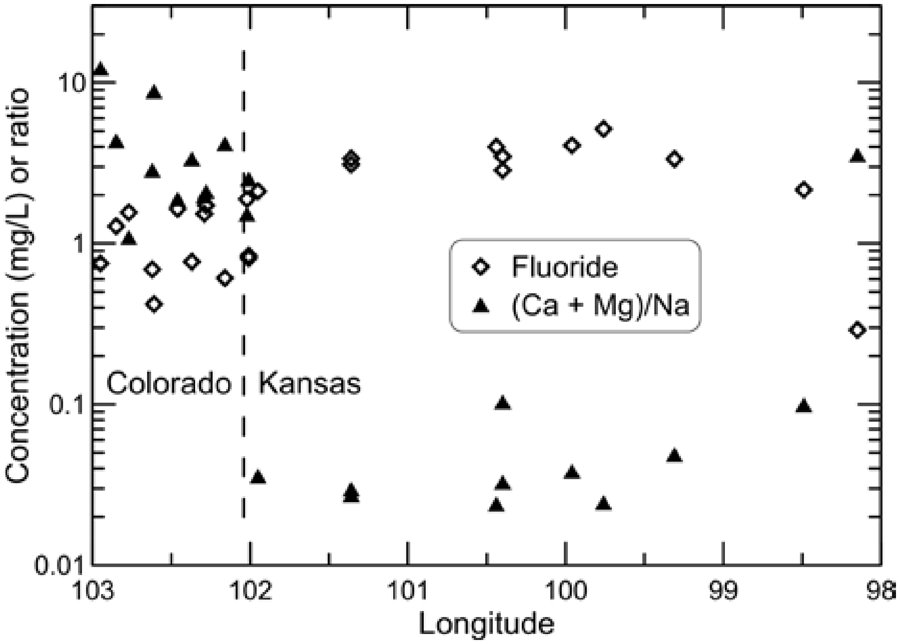


Figure 25. Fluoride concentration and (calcium + magnesium)/ sodium equivalent ratio for wells sampled along a regional flow path of the Dakota aquifer from southeast Colorado to central Kansas.

in western Kansas. The ratio remains relatively low in the confined aquifer and then increases substantially in the local recharge and discharge zone to a value within the range of that for the recharge zone in southeast Colorado. The relative change in dissolved fluoride concentration in the Dakota aquifer water along the flow path from southeast Colorado to central Kansas (fig. 25) is generally inversely related to the calcium concentration (fig. 24) because of the dissolution of fluoride-containing calcium minerals as described earlier. The fluoride concentration is greatest in the main part of the confined flow path in Kansas where the water has low calcium concentrations from cation exchange.

Vertical Geochemical Changes

Saltwater occurs in the Permian rocks underlying the Dakota aquifer in much of Kansas. The saltwater intruded into Dakota aquifer strata in the geologic past and continues to intrude at varying rates into the aquifer where the Permian contains saltwater. Freshwater recharge from the surface and lateral flow of that recharge has been diluting and flushing the saline water from the aquifer at a faster rate than upward intrusion of the saltwater. Thus, the salinity in the Dakota aquifer generally increases with depth. The rate of salinity change with depth is seldom uniform; the TDS concentration is usually substantially greater below low-permeability layers that impede either the upper transport of saline water or the downward movement of fresh groundwater recharge, depending on the local hydraulic gradient. Salinity can also increase with depth within a thick sandstone if saltwater occurs in underlying units.

In the western areas of the outcrop/subcrop belt in south-central to north-central Kansas and the parts of the confined aquifer near the boundary with the outcrop/subcrop belt, the topography varies because of the incision of streams and rivers. The lowland areas along streams can serve as locations of regional and local saline discharge. As a result, deeper, saline water in the Dakota aquifer can discharge to the alluvial aquifer and streams, creating saline water springs and seeps and increasing the salinity of streams and rivers. Salt marshes associated with this saline discharge occur in the Saline, Solomon, and Republican river valleys of central and north-central Kansas (see fig. 14 in Macfarlane, Doveton, and Whittemore, 1998). Discharge of the saline water to the alluvial aquifers and thence to streams and rivers just to the east of the boundary of the confined zone increases the salinity of the Saline, Smoky Hill, Solomon, and Republican rivers. Surface recharge of freshwater to the Dakota aquifer in the upland areas creates local hydraulic heads that are higher than the water levels in the stream valleys. This causes downward flow of the freshwater along curved flow lines from the uplands to the valleys and mixing with the regional discharge. In general, greater salinity increases in a river are related to a greater salinity and volume of saline groundwater discharge, a smaller amount of fresh groundwater recharge mixing with the deeper, discharging saline groundwater, and a smaller flow of fresh river water entering the area where the saline groundwater discharge occurs. Such conditions explain why the salinity increase in the Saline River is greater than in other rivers in central and north-central Kansas.

An example of the effect on groundwater quality of increasing salinity with depth and upward flow of saline water in valleys near the confined zone is shown by the increase in specific conductance during pumping of a well drilled for irrigation use in northwest Washington County during 2011 (fig. 26). The well was 200 ft (61 m) deep with a screened interval of 140–200 ft (43–61 m) and a casing diameter of 16 in (41 cm). A fine sandstone in the Dakota Formation extends between shale from 115 to 197 ft (35 to 60 m) (with shale strips at 120–140 ft [37–43 m]). The location is a few miles southeast of the extent of the confined Dakota aquifer and several miles southeast of the 500 mg/L TDS and 50 mg/L chloride concentration isolines for the upper Dakota aquifer (figs. 17 and 18). The well is sited approximately 200 ft (61 m) from a stream at an elevation of 10–15 ft (3–5 m) above the stream channel. The drawdown after two hours of pumping at 800 gpm (3.0 m^3/min) was to a depth of 148 ft (45 m) below land surface from a static water level of 50 ft (15 m). The well was then pumped at 350 gpm (1.3 m^3/min) for 6.3 hours and the conductivity of the water periodically measured (fig. 26). For the first three hours of pumping, the specific conductance remained below 1,000 µS/cm, indicating a very fresh water with about 300 mg/L TDS (fig. 15). After four hours of pumping, the conductance rapidly rose to more than 3,100 µS/cm (fig. 26). The KGS analyzed a sample collected at the end of the pumping; the conductance was 3,410 µS/cm, and the chloride and sulfate concentrations were 823 and 191 mg/L, respectively. Both the bromide/chloride and sodium/chloride ratios of this water indicate a natural saltwater source. The initial freshwater pumped by the well probably represented extraction of freshwater in the shallower portions of the sandstone interval in the Dakota. As the water level dropped in the well, a greater amount of groundwater was withdrawn from deeper in the sandstone interval, which contained saline water and increased the salinity of the mixture pumped from the well. The increase in salinity with depth in the Dakota at the location fits the mixing of subregional discharge of saline water in the stream valley with local recharge from precipitation. A 200 ft (61 m) borehole was drilled about 550 ft (170 m) to

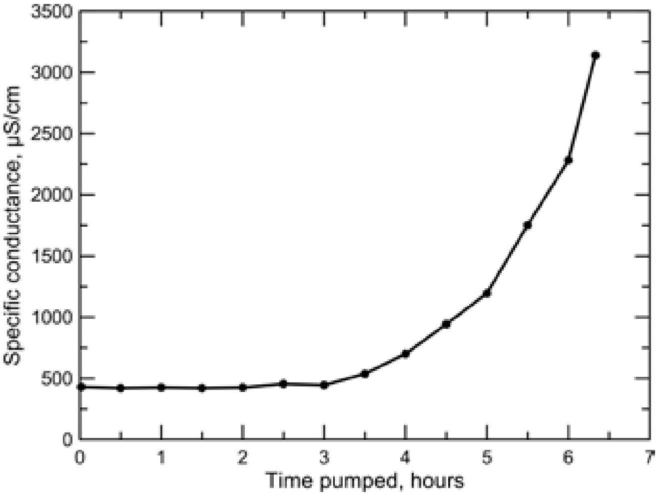


Figure 26. Increase in salinity over time pumped of a 200 ft (61 m) deep well in the Dakota aquifer in northwest Washington County. The well was pumped for 6.3 hours at 350 gpm (1.3 m3/min).

the east-southeast of the original well. A resistivity log in this borehole indicated increasing salinity of water starting about 120 ft (37 m). The borehole was plugged up to 140 ft and the well was completed with a screened interval of 60–140 ft (18–43 m). The original well was subsequently plugged up to a depth of 170 ft (52 m). Pumping of the original well at 150 gpm (0.57 m^3/min) and the newer well at 600 gpm (2.3 m^3/min) produced a sufficient quantity of freshwater for irrigation (E. Simms, personal communication).

The substantially greater permeability of sandstone units within the Dakota aquifer in comparison with the shales can allow a faster rate of flushing of salinity by fresher regional flow. A general inverse correlation of the particle size of the Dakota sediments with TDS concentration in areas where some salinity exists, primarily in the confined aquifer (such as found in the test drilling of several wells near the City of Hays in Ellis County), means that substantial local differences can exist in both the vertical and areal distribution of water quality depending on the particular sandstone-to-shale ratio. Consequently, often the zones of higher permeability in the aquifer yield better quality water. In some locations where a thick and permeable sandstone receiving regional flow lies below low-permeability rocks in the Dakota aquifer, the water can be fresher in the sandstone than in the overlying, less-permeable units.

Although a general increase in salinity with depth occurs within subregions of the Dakota aquifer, differences in the geohydrology among subregions result in a wide-range of TDS concentrations with depth across the aquifer in Kansas. This is also true for concentrations of the major constituents, such as chloride and sulfate. However, a general decreasing trend in the (calcium + magnesium)/sodium ratio occurs with depth. This reflects higher values of the ratio for shallow groundwaters, which are often calcium, magnesium-bicarbonate in chemical type, in comparison with deeper waters that have undergone cation exchange of calcium and magnesium for sodium on clays during recharge and saltwater flushing by the fresher waters. The chemical signature of waters affected by the exchange process tends to occur more commonly in the confined aquifer. Recharge by freshwater occurs more easily in the unconfined aquifer, where substantial flows of recharge water have largely flushed out waters with a low (calcium + magnesium)/sodium ratio as the clays have lost their water softening capacity.

The greatest salinity changes with depth occur across substantial shale units with appreciable lateral extent that confine or separate aquifer units. Where the Graneros Shale is laterally continuous over miles (not isolated strata separated by multiple valleys), it can separate fresh or slightly saline water in the Greenhorn Limestone from very saline water (greater than 10,000 mg/L TDS) in the Dakota aquifer. Shales with a continuous lateral extent within the Dakota can also produce confined conditions in which saline waters are shielded from significant flushing by fresh recharge. Where the Kiowa Formation is mainly shale, it can separate saltwater in the Cheyenne Sandstone derived from underlying Permian strata from substantially less saline water in the overlying Dakota Formation.

In the confined aquifer, recharge passing through the overlying upper Cretaceous limestones and shales can have appreciably higher calcium, magnesium, and sulfate concentrations than in fresh to slightly saline portions of the upper Dakota aquifer. The water chemistry of samples collected during drilling of a test hole by the City of Hays in 1992 to explore water resources in the Dakota aquifer illustrates the changes with depth in these dissolved constituents as well as in the TDS, sodium, chloride, and fluoride concentrations in the aquifer groundwater (figs. 27–29). The test hole was located in southwest Ellis County above the western edge of where the Cedar Hills Sandstone directly underlies the Dakota aquifer and allows a greater rate of saltwater intrusion from the Permian to the Dakota aquifer base than where shales separate the strata. The depth interval for the Dakota Formation was 295–548 ft (90–167 m) in the test hole; the hole then penetrated the Kiowa Formation starting at 548 ft (167 m) before drilling was stopped at 595 ft (181 m). The lithology of the Dakota interval at the location is mainly siltstone and sandstone and that of the Kiowa Formation is siltstone and shale.

The TDS concentration of groundwater at the test-hole location generally increases by a relatively small amount in the upper to middle part of the siltstone and sandstone interval of the Dakota Formation, then increases markedly beginning just above the Kiowa Formation and continuing into the Kiowa (fig. 27). The sulfate content decreases in the uppermost part of the interval and then does not change substantially, whereas both the sodium and chloride concentrations increase in the upper portion, stabilize in the middle, and appreciably increase across the lower part of the interval (fig. 28). The calcium concentration decreases greatly and the magnesium content declines more moderately in the uppermost part of the Dakota Formation, followed by relatively small changes in the rest of the interval (fig. 29).

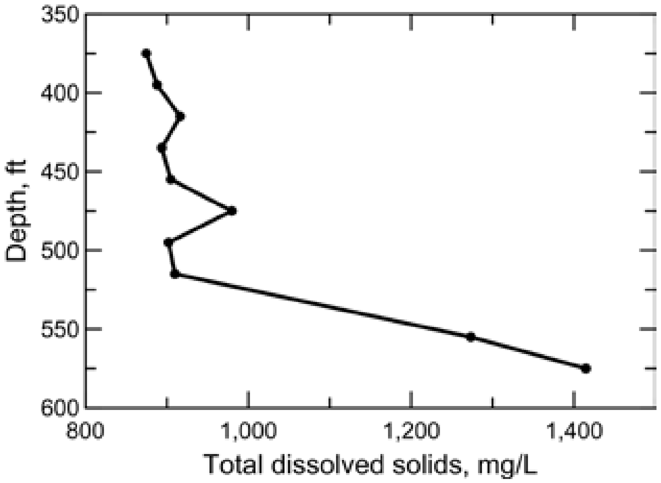


Figure 27. Depth profile of total dissolved solids concentration in the Dakota aquifer for samples collected during drilling of a test hole in Ellis County, Kansas.

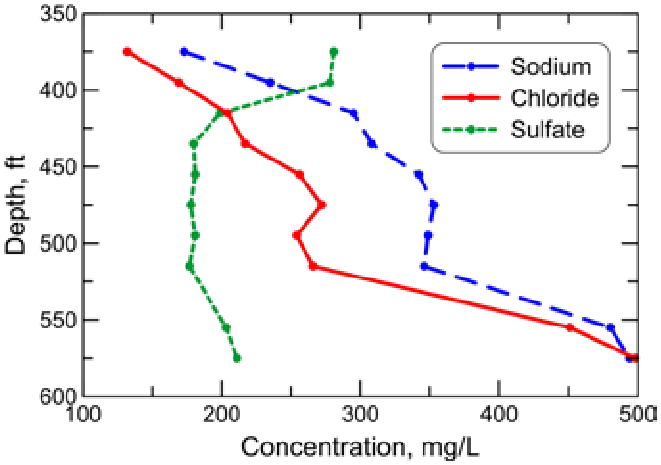


Figure 28. Depth profile of dissolved sodium, chloride, and sulfate concentrations in the Dakota aquifer for the same test hole in Ellis County as in fig. 27.

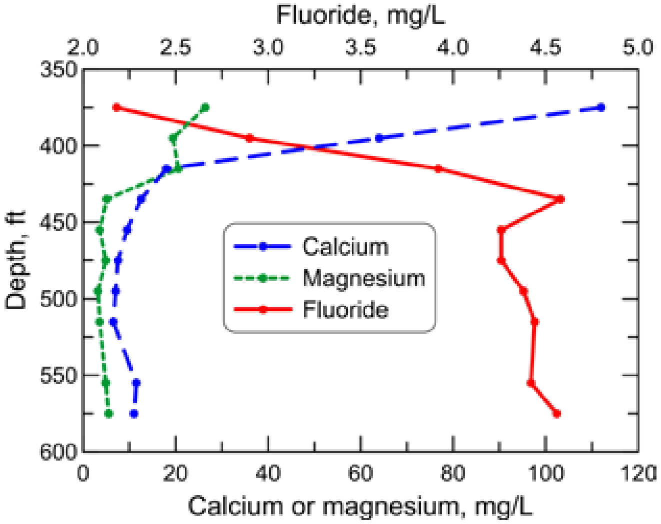


Figure 29. Depth profile of dissolved calcium, magnesium, and fluoride concentrations in the Dakota aquifer for the same test hole in Ellis County as in fig. 27.

The fluoride concentration in the groundwater at the test-hole site follows a pattern with depth opposite to that of the calcium because the low calcium concentration within the aquifer waters allows fluoride-containing calcium minerals to dissolve (fig. 29). Fluoride is then expected to decrease with depth at the bottom of the Dakota aquifer and into Permian strata (below the interval shown in fig. 29) where calcium concentrations are much greater in more saline water, as indicated by data for saltwater-containing strata of the Dakota and Permian. The vertical changes in the constituent concentrations with depth in figs. 27–29 parallel the changes along the regional flow-path in the Dakota aquifer (figs. 24–25) from the recharge area near the southeast Colorado–southwest Kansas border to the saline water in the confined aquifer in central Kansas.

DEVELOPMENT OF THE AQUIFER

Water-Supply Suitability Areas

Development of the Dakota aquifer has been dependent on both the physical characteristics of the aquifer (transmissivity of and depth to the aquifer, confined versus unconfined nature) and the chemical characteristics of the groundwater (primarily TDS concentration). The substantial variability in both the physical characteristics and water quality of the aquifer across Kansas strongly influences the suitability of the aquifer as a source for water supply. Five types of water-supply suitability areas have been defined primarily on the basis of their physical hydrogeologic characteristics and, secondarily, on their water-quality characteristics (fig. 30). One of these areas is subdivided according to the salinity of the groundwater. The five suitability areas are a modification of the six areas originally described in Macfarlane (1997b).

Suitability Area I

Suitability Area I (fig. 30) encompasses the region where the Dakota aquifer is hydraulically connected to the overlying High Plains or alluvial aquifers in southwestern and south-central Kansas (fig. 2). The southwest Kansas part of this suitability area contains the greatest number of water-right-permitted wells completed partially or solely in the Dakota aquifer (fig. 3). Only the western reaches of the south-central part of Suitability Area I are used for water supply (fig. 3). The HPA is thick enough and water tables have been stable enough in most of south-central Kansas that the Dakota aquifer is not used. Dakota strata also thin across south-central Kansas toward the eastern extent of the Dakota aquifer and could contain saline water from the underlying Permian strata in this area. Where the HPA is thickest in southwest Kansas, the depth to the top of the Dakota aquifer is more than 500 ft (152 m). In western Stanton, western Morton, and southern Hamilton counties, the HPA is absent or is very thinly saturated and the Dakota aquifer (with some Morrison-Dockum strata contributing in Stanton and Morton counties) is the primary shallow aquifer.

Groundwater in the upper Dakota aquifer is fresh throughout nearly all of Suitability Area I (fig. 30). In this suitability area, the Dakota is used for irrigation, municipal purposes, stock, and industry (fig. 4), with the greatest use volume for irrigation (fig. 8). However, groundwater chemical quality is variable in the lower Dakota aquifer because of the small amount of freshwater recharge that passes through the Kiowa shale aquitard. The TDS and chloride concentrations can exceed 2,000 mg/L and 500 mg/L, respectively, in some parts of the lower Dakota (levels too high for irrigation and human consumption but usable for livestock). Nearer the Kansas-Colorado border and the southern extent of the Dakota aquifer in southwestern Kansas, the lower Dakota contains freshwater because of its proximity to the regional recharge area in southeastern Colorado and local recharge from the HPA.

Pre-development conditions indicate that the HPA was naturally recharged by the Dakota aquifer in Stanton, Morton, and Grant counties. To the east, the Dakota was recharged by the HPA under pre-development conditions. Water-level declines in the Dakota aquifer from development are generally less than 50 ft (15 m) but can be greater in portions of Suitability Area I. The Dakota and High Plains aquifers are generally hydraulically connected, so they largely behave as a single system over extended time in this area. Thus, water levels might be expected to drop in the future where both the HPA and Dakota aquifer are heavily

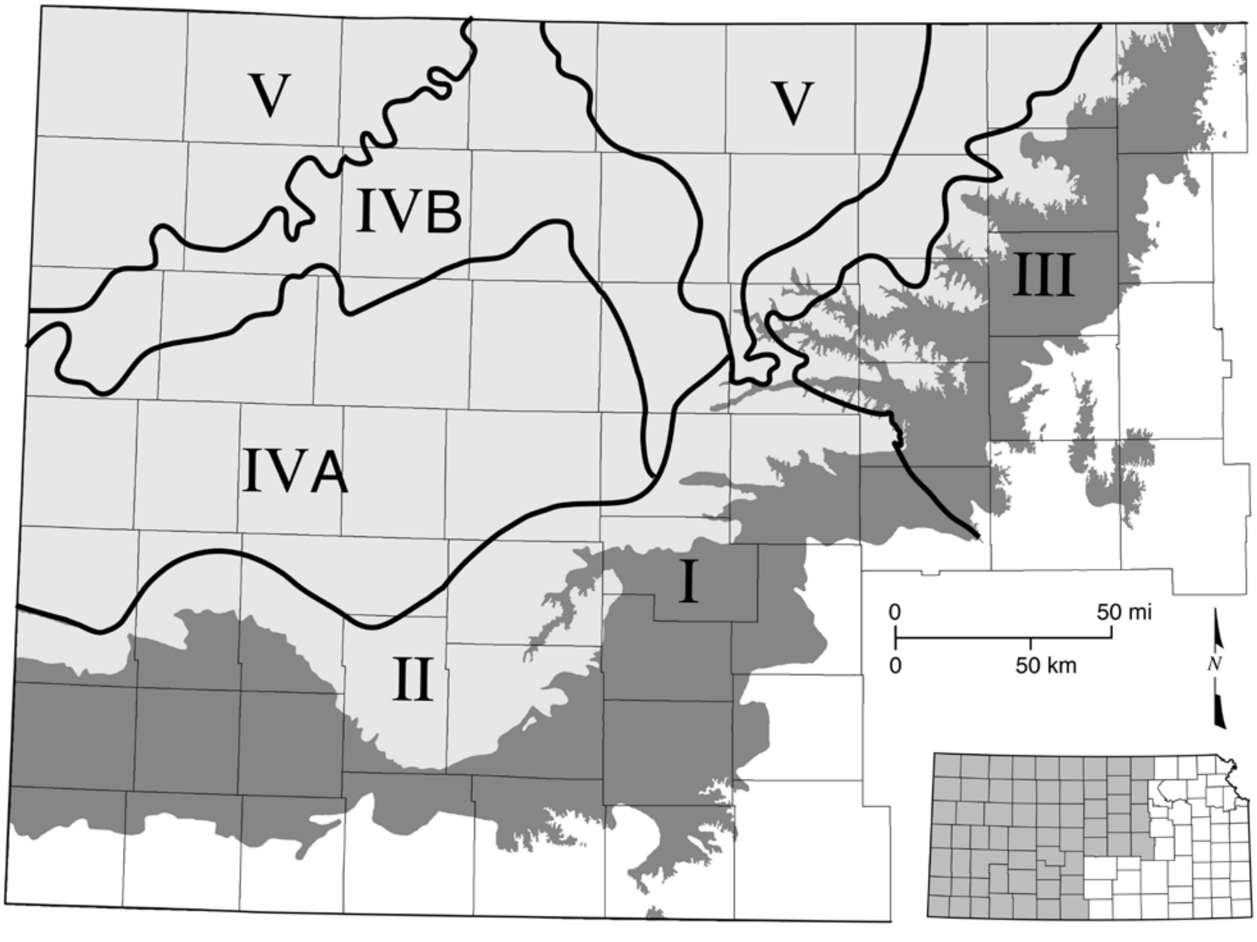


Figure 30. Map of the five water-supply suitability areas of the Dakota aquifer in Kansas. The light gray area is the confined region of the aquifer, and the dark gray area is the outcrop/subcrop region. Suitability Area I is within the outcrop/subcrop region and Suitability Area II is within the confined region. Suitability Area III is primarily within the outcrop/subcrop region but includes part of the confined region. The separation between Suitability Areas IVA and IVB generally represents the 1,500 mg/L isoline for TDS concentration, with fresher groundwaters in IVA and more saline groundwaters in IVB.

used (fig. 3). Water-management policies developed for one of the aquifers will eventually have an impact on the other. Consequently, it is appropriate to consider both aquifer systems together in policy development.

Suitability Area II

In Suitability Area II (fig. 30), the Dakota aquifer is confined (or partially confined immediately adjacent to the outcrop/subcrop belt) by the Upper Cretaceous aquitard. This area is adjacent to Suitability Areas I and III. Recharge from overlying sources can be a significant component of the flow in the Dakota where the confining layer is thin and relatively permeable. However, in southwest and south-central Kansas near the edge of the confined boundary, the primary source of recharge to this part of the Dakota under pumping conditions is from the High Plains or alluvial aquifers where the Dakota is hydraulically connected to one of these aquifers.

Many wells tap the Dakota aquifer for a variety of uses in the part of Suitability Area II in southwest Kansas and part of south-central Kansas (fig. 4) that contains freshwater. Use of the Dakota for irrigation is more common in Hodgeman and northern Ford counties than in other counties in this area. The wells in the western part of Suitability Area II tend to be completed only in the Dakota aquifer rather than both the HPA and Dakota as in much of the southwest Kansas portion of Suitability Area I. The depth below the surface to the top of the Dakota aquifer is less than 400 ft (120 m) over most of Suitability Area II. Water-level declines from development are generally less than 50 ft (15 m).

Groundwater in the upper Dakota aquifer is fresh (TDS less than 1,000 mg/L, chloride less than 250 mg/L) over the southwest Kansas portion of the region (figs. 17 and 18). However, the central and north-central parts of this subunit are located near the regional discharge area of the Dakota and the Cedar Hills Sandstone–Upper Salt Plain aquifers (fig. 2) and the Lower Dakota confining layer is not present. Saltwater intrusion into the lower and then the upper Dakota aquifer is widespread. Groundwater salinity increases substantially with depth and little groundwater is used. Groundwater salinity in the lower Dakota in the western part of Suitability Area II is estimated to be less than 5,000 mg/L and in the eastern half to be substantially greater than 5,000 mg/L.

Suitability Area III

In the eastern part of Suitability Area III (the main portion of the area), the Dakota is a shallow unconfined aquifer or is in contact with stream-aquifer systems (figs. 2 and 30). In the westernmost part of the area, the Dakota is confined and the Upper Cretaceous aquitard is thin and relatively permeable. In the confined part of this area, the depth below the surface to the top of the Dakota aquifer is generally less than 150 ft (46 m). Where the Dakota is unconfined, recharge has been estimated at a few tenths of an inch per year (Wade, 1992). The aquifer is used for a variety of water-right-permitted purposes and is also usually the main water source for domestic wells. Irrigation use is concentrated primarily in southwestern Washington, eastern Cloud, and northern and central Ottawa counties where the thickness and permeability of sandstone units are generally greater than in other portions of the unconfined aquifer in this suitability area (figs. 4 and 8).

Groundwater quality in the upper part of the Dakota aquifer is locally variable throughout Suitability Area III, although fresh over most of the unconfined upper Dakota (fig. 17). In some areas, especially the confined parts, not all of the high chloride water has been flushed from the aquifer by freshwater recharge (fig. 18). Salinity generally increases with depth into the lower aquifer in the confined portions and increases in the unconfined aquifer near some of the larger streams that cross the area as a result of groundwater discharge of deeper saline water in the Dakota. Water-level declines from development in Suitability Area III are believed to be less than 20 ft (6 m). Continued declines from further development could reduce discharge from the Dakota aquifer to streams and increase lateral movement of groundwater from the confined to the unconfined Dakota aquifer from west to east.

Suitability Area IV

In Suitability Area IV (fig. 30), the thickness of the Upper Dakota confining layer ranges from less than 200 ft (61 m) in southeast Ellis County up to 600 ft (180 m) in Hamilton County along its south boundary. Along the northern boundary with Suitability Area V, the confining layer thickness ranges from approximately 600 ft (183 m) in southeastern Rooks County to 2,000 ft (610 m) along the Kansas-Colorado border in Wallace County. The confined Dakota aquifer in this area receives negligible freshwater recharge from overlying sources. The major source of freshwater is flow from the regional recharge area in southeastern Colorado.

TDS concentration in the upper Dakota aquifer generally increases northeastward from less than 500 mg/L to 1,500 mg/L in Suitability Area IVA and from 1,500 mg/L to 10,000 mg/L in Suitability Area IVB (fig. 17). In general, the upper Dakota is more saline with depth to the north and east. TDS concentration in the lower Dakota aquifer is probably greater than 2,000 mg/L and could exceed 10,000 mg/L in the far northern and eastern parts of the suitability area.

Although water quality in Suitability Area IVA is acceptable for most uses, the number of water-right-permitted wells is regionally sparse (fig. 4) because of the greater depth to and lower permeability of sandstone units in the Dakota aquifer than in Suitability Areas I–III. Most of the water use from water-right-permitted wells in the Dakota is for livestock, followed by municipal purposes (fig 8). Water-level declines from development are probably less than 50 ft (15 m) in Suitability Area IVA due to its limited use. However, pumping rates are expected to greatly exceed recharge from overlying sources. As a result, pumping may locally deplete the aquifer if wells and wellfields are spaced too closely together. In Suitability Area IVB, the water quality is too saline for direct use. However, Hays has six municipal supply wells in the Dakota aquifer that produce saline water (chloride concentration generally in the range of 570–700 mg/L) that is mixed with freshwater sources from alluvial aquifers.

Suitability Area V

In Suitability Area V (fig. 30), the Dakota aquifer is confined by a substantial thickness of Upper Cretaceous strata and contains saline or “mineralized” groundwater, defined by state statute as water containing more than 5,000 mg/L chloride or more than 10,000 mg/L TDS. Mineralized groundwater is considered unusable or undesirable for most uses except oil and gas operations (such as secondary recovery) and is not protected by state and local regulations. In the northwest Kansas part of Suitability Area V, the Dakota receives negligible freshwater recharge from overlying sources, flow rates are very low, and the depth to the top of the Dakota exceeds 1,500 ft (460 m). In the eastern part (between Suitability areas IVB and II), vertical and lateral flow rates through the aquifer are higher than in northwestern Kansas and the top of the aquifer is fewer than 500 ft (150 m) below the surface. However, the flow of freshwater through the aquifer has been insufficient to flush the saltwater from the aquifer where it is hydraulically connected to the Cedar Hills Sandstone.

Recent Development Trends

One approach to characterizing recent development of the Dakota aquifer is to determine the temporal trend in the number of new water-right-permitted wells estimated to be completed partially or solely in the aquifer. This was done using the approach described in the Location and Amount of Water Use section of this bulletin. For the five counties in the north-central Kansas region, 191 well logs (51%) were found for the 371 active points of diversion (active water rights and water use). Information in WIMAS for many of the permitted wells without logs indicates that they were probably drilled before 1975 (the year when well-log records were required of all completed wells in Kansas) and, thus, would not be expected to have a well log. Many other permitted wells with active water rights but without logs have dates for a change in the point of diversion or are water rights with priority dates after 1975. Some of the wells for these water rights might have existed before 1975 because, although Kansas law allowed the filing for water rights in 1945, water rights were not required until January 1, 1978. It would be expected that all groundwater rights with priority dates at least a few to several years after this date and changed points of diversions for groundwater appropriation after 1975 should have a WWC-5 record (well log). However, no well-log records could be found for many of the points of diversion falling in these categories. Either the missing logs were prepared but then not sent to KDHE, were misplaced somewhere along the line, or were never completed.

To add to the number of wells with completion dates and with active water rights for north-central Kansas, well completion dates were estimated for water-right priority dates and point-of-diversion changes from the mid-1980s to 2011 using two data components associated with water rights. The history (action trail) of a water right was reviewed for dates related to entries for “completed pending inspection” for new water rights or the date of “change approved” for an existing water right to change its point of diversion. A secondary approach was to base the well completion on the first year of reported water use. Using these methods, dates of well completion were estimated for 78 water-right-permitted wells without well logs in north-central Kansas, bringing the total number of water-right-permitted wells with completion dates to 73% of the total active points of diversion in this region.

The number of wells with active water rights and water use completed after 1975 in north-central Kansas shows a declining trend from 1975 to the middle 1980s, followed by a general peak during the mid-1990s to early 2000s (fig. 31). Approximately 46% of the wells for which completion dates were determined in the region are for

Washington County, which shows a similar pattern to that for all the five counties in the region. Some of the general variations in the numbers of completed wells for particular years may be related to periods of wet or dry conditions. For example, during 1982–1987, the Palmer drought severity index (PDSI) for north-central Kansas was positive, with values indicating slightly wet conditions for 1983 and 1985, moderately wet for 1982 and 1986, and very wet for 1987. This coincides with the generally low values for drilling activity in the Dakota aquifer. The PDSI values during 1988–1991 were negative, with mild drought approaching moderate drought in 1988, severe drought in 1989, and moderate drought in 1991. The drought conditions may be responsible for the general rise in completed wells that started about 1988.

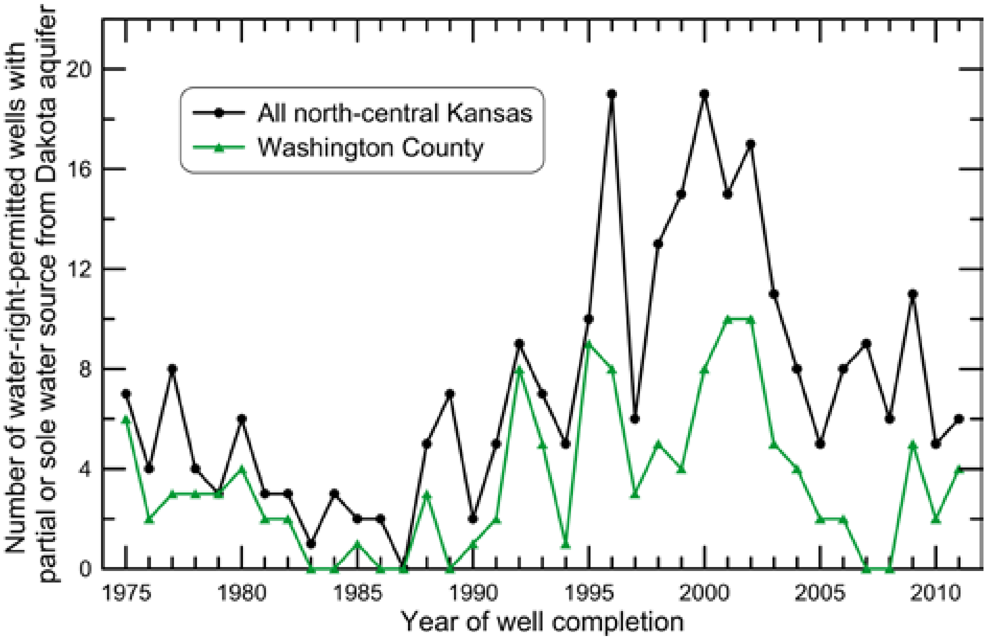


Figure 31. Trend in the number of new wells with active water rights and water use completed in north-central Kansas since 1975. The number of wells is based on points of diversion with well logs plus wells without well logs for which completion dates were estimated using the water-right history for the permitted well.

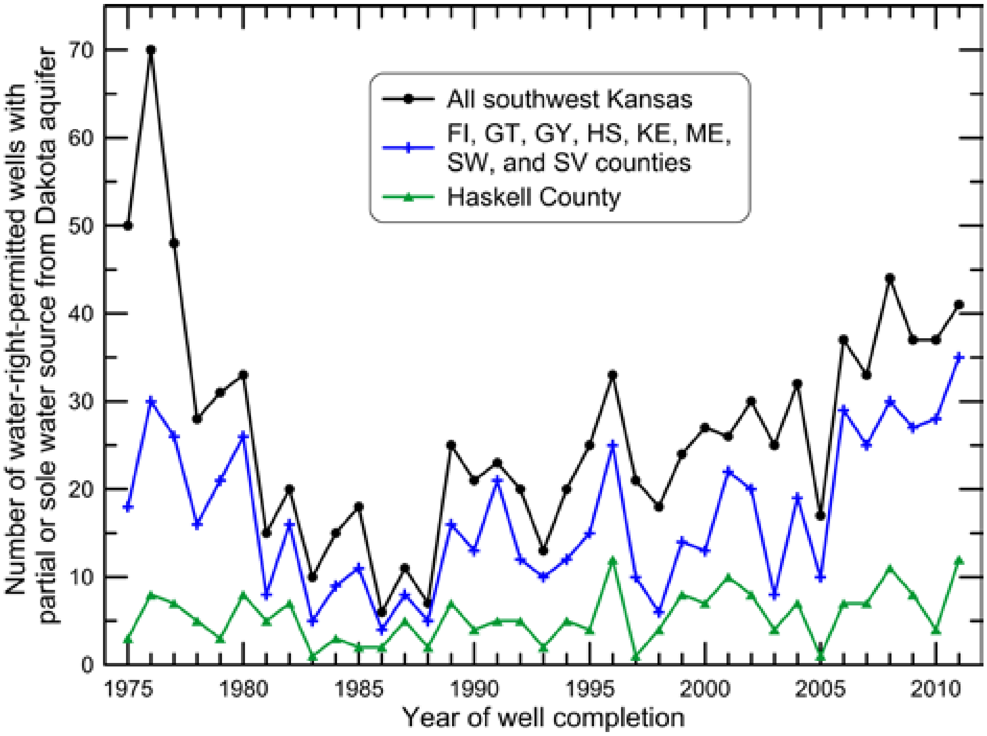


Figure 32. Trend in the number of new or replacement wells each year with active water rights and water use completed partially or solely in the Dakota aquifer in southwest Kansas since 1975. The number of wells is based on points of diversion with well logs.

The much greater number of wells estimated to be completed partially or solely in the Dakota aquifer in southwest Kansas (1,554) resulted in a larger number of active points of diversion with well logs (993, or 64% of the wells). These data were used to generate the trends in drilled wells shown in fig. 32 for southwest Kansas without estimating well completion dates for recent points of diversion missing logs. Figure 32 displays the annual number of new wells completed partially or solely in the Dakota aquifer for all of southwest Kansas, the central block of eight counties in southwest Kansas, and Haskell County in the middle of this block.

All three plots in fig. 32 show a similar pattern: a decline in the number of new wells completed partially or solely in the Dakota aquifer during the late 1970s to the middle 1980s, followed by an increasing trend from the late 1980s to 2011. The decline in the number of wells completed from the late 1970s to the mid-1980s in fig. 32 is related to the substantial slowing of the development of water rights and points of diversion for groundwater sources in all the aquifers in southwest Kansas (fig. 33). The growth in the cumulative number of active water-right-permitted wells for all aquifers grew rapidly from the middle 1950s until the late 1970s when the development rate substantially slowed. Figure 33 shows that the number of points of diversion associated with new water rights and their priority dates (not replacement wells) has essentially plateaued since 2004; only 23 new points of diversion for new water rights were added in all of southwest Kansas from 2004 to 2011 and only four were added from 2009 to 2011. The plateau is primarily related to four administrative actions from 1991 to 2002 that closed more than 90% of the area within GMD3 to new applications for water rights (Southwest Kansas Groundwater Management District No. 3, 2004).

The general shape of the curves for the estimated cumulative number of wells determined to derive part or all of their source from the Dakota aquifer in southwest Kansas (fig. 34) are similar to those for wells in all aquifers (fig.

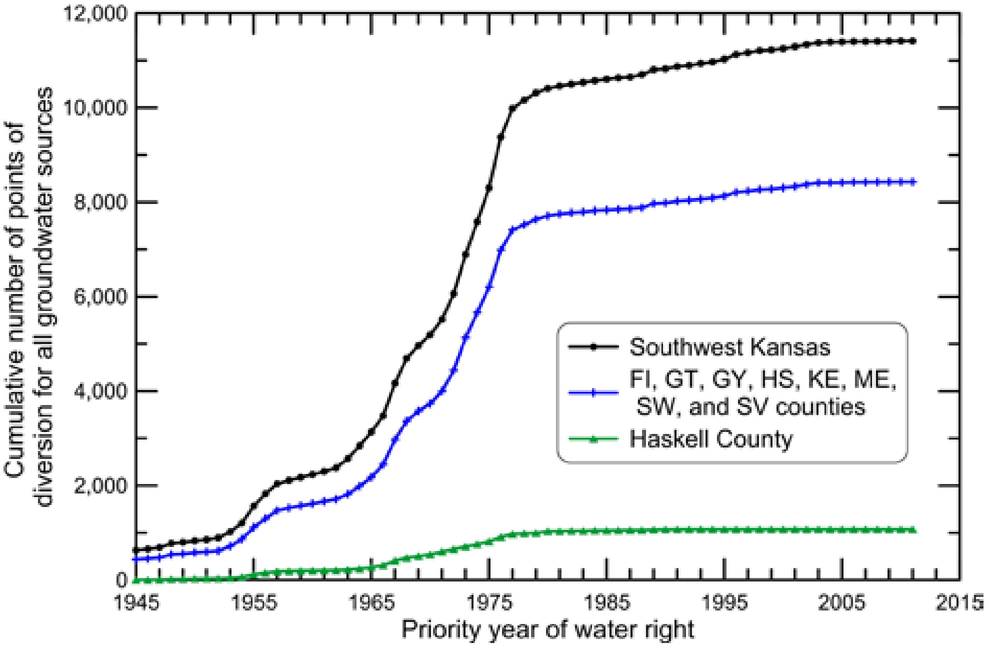


Figure 33. Cumulative number of active points of diversion for all aquifers in southwest Kansas during 1945–2011 based on the priority date of the water right.

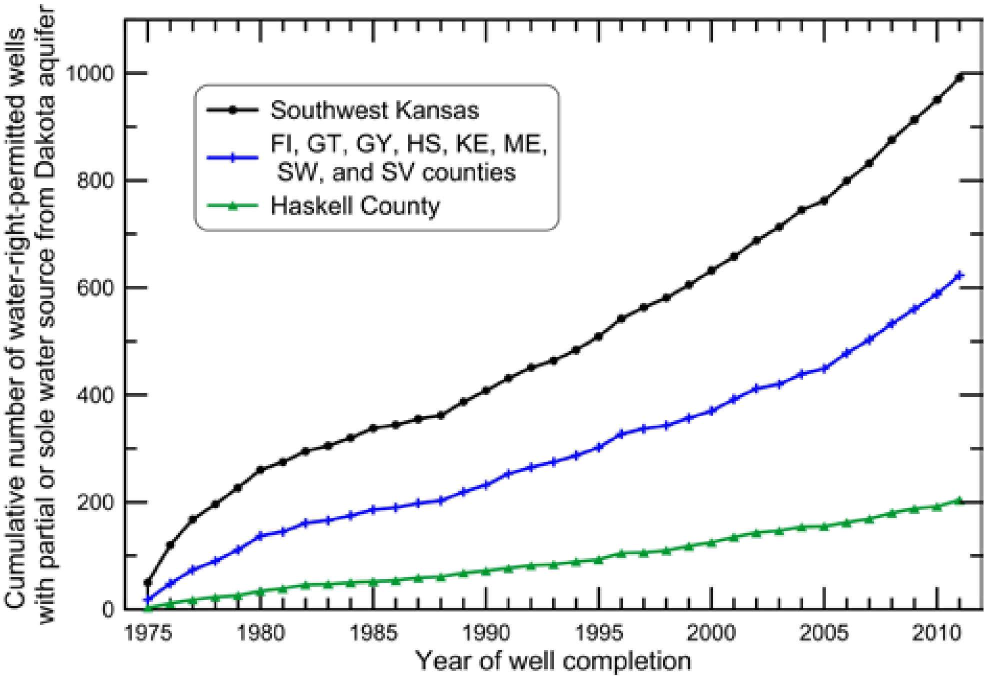


Figure 34. Trend in the cumulative number of wells with active water rights and water use completed partially or solely in the Dakota aquifer in southwest Kansas since 1975. Data are the same as for fig. 32 except for representation as cumulative totals.

33) for the period from 1975 to the mid-1980s. However, the curves in fig. 34 display an increasing upward slope starting in the late 1980s in comparison with a generally linear, increasing trend for the late 1980s to 2003 for all aquifers. The increasing trend continued through 2011 for Dakota wells in comparison with very little increase during 2003–2011 for all aquifers. The percentage increase for the Dakota wells is also substantially greater than for new water right/points of diversion for all aquifers. The substantial number of replacement wells (involved with a change in the point of diversion associated with a water right) that include the Dakota aquifer explains most of the difference between figs. 33 and 34 for the late 1980s to 2011. Many wells drilled to replace permitted wells that were completed only in the HPA were completed in both the HPA and underlying Dakota strata, thereby increasing the percentage of wells completed in both aquifers. A relatively small number of other wells were drilled solely into the Dakota aquifer in areas where the saturated thickness of the HPA was or was becoming thin or insignificant. Although the replacement wells may be newly tapping the Dakota aquifer, this is allowed in GMD3, where the Dakota and High Plains aquifers are considered to be hydraulically connected because the definition of the HPA includes “deeper aquifers that are in vertical or horizontal hydraulic contact with the Ogallala formation” (Kansas Administrative Regulation [K.A.R.] 5-23-1[b].

Current Guidelines for Development

The water resources of Kansas are managed by the DWR using the concept of safe yield. Safe yield is the long-term sustainable yield of the water supply, which, for groundwater resources, includes hydraulically connected surface water and adjacent aquifers. Thus, the total amount of water pumped from an aquifer should be equal to or less than the decrease in discharge resulting from the water-level decline caused by pumping, and not equal to the recharge, so as to not deplete the aquifer. Well-spacing requirements are in place to ensure that new wells do not impair the supply of water to existing wells.

The Dakota aquifer is susceptible to over-development unless the spacing between wells is large enough to avoid well interference (overlap of the cones of depression produced by pumping wells). If wells are too close together, they may exacerbate water-level declines and lead to more rapid depletion of the aquifer. This is most likely where the Dakota aquifer is overlain by thick, relatively impervious strata such as in Suitability Area IV and the parts of Suitability Area II away from the confined edge. Local freshwater recharge to this part of the aquifer is expected to be insignificant relative to the typical pumping rate of large-capacity supply wells. Consequently, water must come from other parts of the aquifer not affected by pumping. This represents a net loss of water from the aquifer and will lead to water-level declines. In areas where the Dakota aquifer is at the surface or is overlain by shallow aquifers, local recharge to the Dakota aquifer from precipitation or from the overlying aquifer is sufficient to justify a denser well spacing. A denser well spacing for domestic wells is appropriate because they typically operate at low pumping rates and often for shorter periods of time than high-capacity supply wells, thereby causing less impact on the aquifer.

Sandstones in the Dakota aquifer are usually substantially less permeable than the sands and gravels forming the HPA and alluvial aquifers. The permeability difference means that a pumping well in the Dakota aquifer will produce significantly greater drawdown than would a well in the HPA or many alluvial aquifers being pumped at the same rate. The sandstone units in the Dakota are also typically smaller in extent and thickness than most sand and gravel zones in the HPA. Therefore, the spacing between high-capacity wells in the Dakota aquifer must generally be much greater than that in the HPA to avoid significant amounts of well interference (overlapping cones of depression).

In 1994, the DWR modified the existing well-spacing requirements for the Dakota aquifer based on research results from the Dakota Aquifer Program (Macfarlane and Sawin, 1995). The well-spacing requirements are founded on the general character of recharge to and groundwater flow rates within the Dakota aquifer. The current Rules and Regulations of the Kansas Water Appropriation Act (Kansas Department of Agriculture, 2011) specify the minimum distance from a well that is the subject of a water appropriation application to other wells in the Dakota aquifer system as follows (K.A.R. 5-4-4):

- Where the Dakota aquifer is unconfined (at the surface or beneath the HPA or alluvial aquifers—generally areas of significant surface or inter-aquifer recharge), the minimum well spacing is 0.5 mile (0.8 km) to other senior authorized non-domestic and non-temporary wells and 1,320 feet (396 m) to domestic wells, whose common source of supply is the Dakota aquifer.
- Where the Dakota aquifer is confined (overlain by relatively impervious rock units—generally very slow recharge), the minimum well spacing is 4 miles (6.4

km) to other senior authorized non-domestic and non-temporary wells and 0.5 mile (0.8 km) for domestic wells, whose common source of supply is the Dakota aquifer.

In comparison, the minimum spacing for wells in aquifers other than the Dakota is 1,320 ft (400 m) to other senior authorized non-domestic and non-temporary wells, and 660 ft (200 m) to domestic wells. A Dakota aquifer system well is defined in the Rules and Regulations (Kansas Department of Agriculture, 2011) as a well screened in whole or in part in the Dakota aquifer system, which includes the Dakota Formation, Kiowa Formation, Cheyenne Sandstone, and, where hydraulically connected, the Morrison Formation (K.A.R. 5-1-1). This definition implies that the spacing for wells screened in both the HPA and Dakota would be the 0.5 mi (0.8 km) and 1,320 ft (400 m) distance for senior authorized and domestic wells, respectively, if the common source for both were the Dakota aquifer. However, the spacing requirements are regulations; if both the proposed and existing wells only yielded a minor amount from the Dakota, the chief engineer of the DWR could determine whether the spacing regulations were not necessary to prevent direct impairment. These regulations apply to the areas of the Dakota aquifer outside of groundwater management districts (GMDs). The chief engineer has adopted the regulations for well spacing that are specific to each of GMDs Nos. 1, 3, and 4. The Dakota aquifer does not exist within GMD No. 2. The rules and regulations for Northwest Kansas GMD No. 4 include the same well-spacing guidelines for wells in the Dakota aquifer system (K.A.R. 5-24-3) as in the DWR rules and regulations.

The Dakota aquifer is confined in all of Western Kansas GMD No. 1 (GMD1), which covers parts of Suitability Area IV. The well-spacing requirements of GMD1 are a minimum of 0.5 mi (0.8 km) between a well for which water is proposed to be withdrawn from the Dakota for non-domestic use and any other well constructed into the same Dakota aquifer (K.A.R. 5-21-3).

Southwest Kansas GMD No. 3 (GMD3) specifies spacing requirements for the HPA, which also apply to wells screened in both the HPA and Dakota aquifer where they are hydraulically connected (Suitability Area I within GMD3), and for confined aquifers, which apply to the Dakota aquifer within the GMD3 portion of Suitability Area II. The well-spacing requirements are dependent on the quantity of water per well proposed for a water-right permit. The minimum horizontal spacing between each proposed well and all other senior non-temporary, non-domestic wells in the HPA ranges from 660 ft (201 m) for a quantity of 15 acre-ft/yr or less per well to 2,300 ft (700 m) for more than 500 acre-ft/yr per well (K.A.R. 5-23-3). The minimum spacing between each proposed well and all other senior non-temporary, non-domestic wells in a confined aquifer ranges from 660 ft (201 m) for a quantity of 15 acre-ft/yr or less per well to 2 miles (3.2 km) for more than 100 acre-ft/yr per well (K.A.R. 5-23-3). In addition, for a Dakota well to be defined as within the confined portion of the aquifer, the GMD3 rules include a distance from the edge of the confined boundary (called the hydraulic contact point), which is also dependent on the proposed quantity of annual use and ranges from 0.5 to 5 mi (0.8 to 8 km).

Within the boundaries of Big Bend Prairie GMD No. 5 (GMD5), the Dakota aquifer is unconfined in Suitability Area 1 and confined in Suitability Area II. The well-spacing requirement of GMD5 is a minimum of 1 mi (1.6 km) between a well for which water is proposed to be withdrawn from the Dakota aquifer for non-domestic use and all other wells withdrawing water from the same formation, including domestic wells, except for those domestic wells owned by the applicant (K.A.R. 5-25-2).

The regulations of GMDs 1, 3, and 4 also require that a well penetrating the Dakota aquifer and any other aquifers be constructed to prevent migration of water between the aquifers.

Water-Level Declines Since Pre-development

Long-term depth-to-water measurements, especially in the same wells, are valuable for assessing the amount of water in storage within an aquifer. The KGS and the DWR have routinely measured water levels for many years as part of the Kansas Annual Cooperative Water-Level Measurement Program, but in only a limited number of Dakota wells. Continuous water-level records from wells drilled at the time development began in the Dakota aquifer are unavailable.

Development of water resources in the Dakota aquifer started in the latter part of the 19th century, primarily in north-central, central, and southwestern Kansas where the aquifer is shallow. Darton (1905) used water-level measurements from these wells to construct the first potentiometric surface map of the Dakota aquifer. After that time, development slowly expanded into areas where the Dakota is deeper. Water levels in the first flowing artesian wells at Coolidge, Kansas, in 1885, were estimated to be almost 20 ft (6.1 m) above land surface. At the time of Darton's (1905) survey, flowing artesian wells in the Arkansas River valley between

Coolidge and Syracuse produced 25–75 gal/min (95–285 L/min) of water (Haworth, 1913). In the 1930s and early 1940s, the maximum flow rate from these wells reportedly decreased to 30 gal/min (114 L/min) or less and water levels in these wells were only a few feet (1 m) above land surface (McLaughlin, 1943).

Annual winter water levels are shown in figs. 35–38 for wells in the Dakota aquifer and overlying alluvial and High Plains aquifers in southwest Kansas; the time axis and the scale of the depth axis are the same in all three figures to allow comparison of the hydrographs. The water-level data are available online through the water well levels data base (WIZARD) of the KGS.

Hydrographs for a nest of observation wells screened in the alluvial, High Plains, and Dakota aquifers east of Holcomb in the Arkansas River valley, Finney County, show fluctuating levels from 1981 to 2002 followed by a general decline after 2002 (fig. 35). At this location, the Dakota aquifer is confined by the Upper Dakota confining layer. However, within 2–3 mi (3.2–5 km) south of the monitoring site, the confining layer is absent and the aquifers are hydraulically connected. Two supply wells (one for industrial and one for municipal use) are completed solely in the Dakota aquifer within 3 mi (5 km) of the observation well nest. Water levels were measured quarterly in the observation wells up until 1990 and since then at a semi-annual or annual interval. Detailed hydrographs incorporating all of the measurements (not shown in fig. 35) show the response of both aquifers to seasonal pumpage and recovery. The annual winter measurements indicate that until 1985, the seasonally recovered water levels in the Dakota were about the same as those in the HPA. After 1985, the recovered water levels in the Dakota have been lower than those in the HPA. This suggests a change in the hydrologic relationship between the aquifers. From 1981 to 1985, no substantial hydraulic head gradient existed. After 1985, the flow direction between aquifers appears to be more variable with upward flow of water from the Dakota to the High Plains during periods of more intense pumpage (generally summer months) and downward flow during times of recovery (usually winter months).

Except for the last several years, the pattern in the variations of the annual winter water levels in the High Plains and Dakota aquifers at the Finney County observation well nest have reflected changes in the shallow alluvial aquifer (fig. 35) as it responds to rapid recharge from and discharge to the Arkansas River. River flow entering Kansas was below the long-term mean during the 1970s to 1982. The flow at Garden

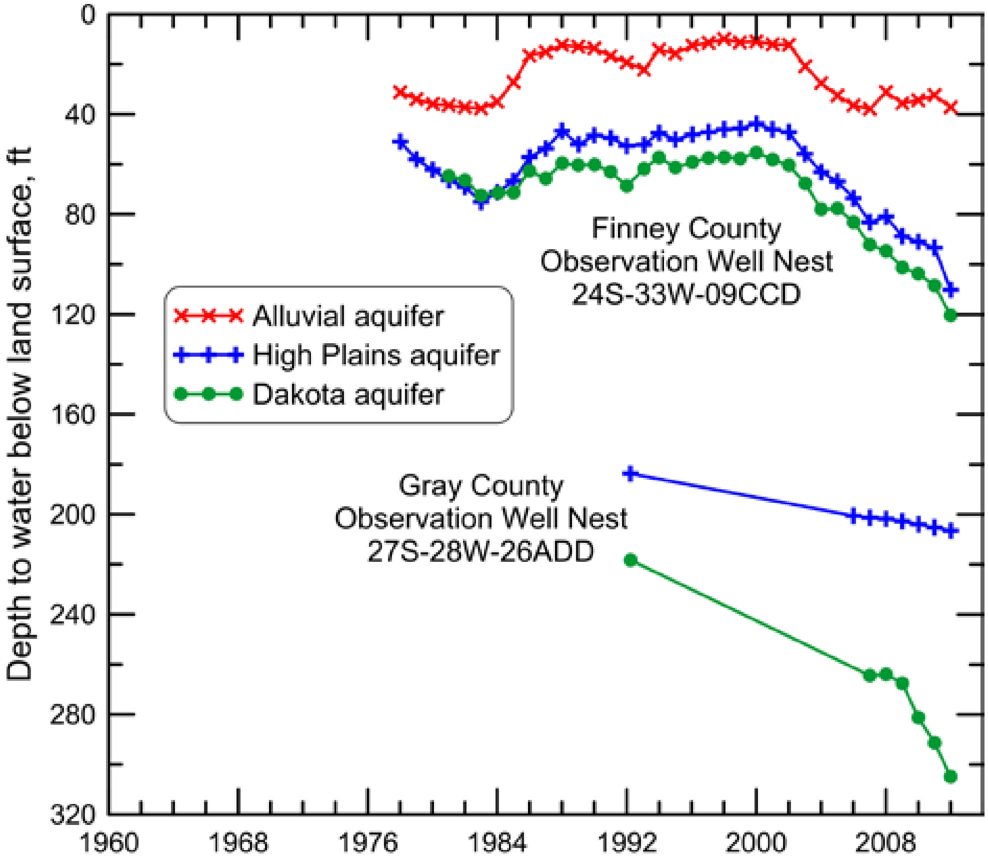


Figure 35. Annual winter water levels in observation wells in the Dakota and overlying aquifers in southwest Kansas. The depths of the Finney County wells are 55 ft, 210 ft, and 560 ft for the alluvial aquifer, HPA, and Dakota aquifer, respectively. The screened intervals of the Gray County wells are 205–235 ft and 490–510 ft for the HPA and Dakota aquifer, respectively. All measurements are for January except the first Gray County measurement, which was March 26, 1992.

City was zero or near zero during much of 1975 to 1983. Flow at the Colorado-Kansas state line began to increase during 1984 and was high in 1987. River flow was low during 1989 to 1994 and then changed to a sustained period of substantially greater than mean annual flow from 1995 through 2000. Since April 2002, annual flow in the Arkansas River at Garden City has been zero or near zero. Although the winter water levels in the alluvial aquifer have not changed substantially since 2005, the levels in the High Plains and Dakota aquifers have continued to decline at about the same rate as during 2002 to 2005. The HPA and Dakota aquifers now appear to be disconnected from the alluvial aquifer.

Observation wells were installed in the confined Dakota aquifer and underlying HPA about 8 mi (13 km) south of the Arkansas River in east-central Gray County in 1992 during the Dakota Program (Gray County observation well nest shown in fig. 35). The site is approximately 12 mi (19 km) north of the edge of the confined aquifer. Thus, at this site, the Dakota aquifer is confined and not hydraulically connected to the HPA. Two feedlot wells pump water from the Dakota aquifer within 1 mi (1.6 km) of the observation well nest; one feedlot well is screened solely in the Dakota, the other obtains an estimated 80% of its yield from the Dakota (and the remainder from the HPA). An irrigation well, which pumps about 70% of its supply from the Dakota aquifer (with the remainder from the HPA), is a little more than 1 mi (1.6 km) from the well nest. The water level in the Dakota aquifer at the time of observation well installation in 1992 was 34.6 ft (10.5 m) below that in the HPA well (fig. 35). Since then the water level in the Dakota well has declined at a greater rate than in the HPA well; the water-level separation between the two units was more than 94 ft (28.7 m) in January 2012.

Changes in water levels for a Dakota aquifer well and nearby wells in the HPA along the margin of the substantial saturated thickness of the HPA in northwest Grant County are displayed in fig. 36. The wells are located along an edge of the regional subsidence from dissolution of salt in Permian strata in southwest Kansas that led to greater deposition of sediments forming the HPA; the prominent edge of subsidence in the northwest part of southwest Kansas is known as the Bear Creek fault zone. The bedrock surface along the zone deepens rapidly towards the south-southeast in the northwest corner of Grant County. The well in the Dakota aquifer, which is the only Dakota well with long-term water-level data in Grant County, was located a little over 1 mi (1.6 km) farther to the northwest (in the direction of the shallowing bedrock surface) than a line between the two wells in the HPA in fig. 36. The bedrock surface is 155 ft (47 m) below land surface at the Dakota well (Watts, 1989) in comparison with about 300 and 325 ft (91 and 99 m) at the HPA wells in Sec. 12 and 22, respectively (which places the bedrock surface at the HPA wells below the extent of the y-axis in fig. 36). No lithologic log is available for the Dakota well, so it is unknown whether it is also partially screened in the HPA. Some connection with the HPA could have existed (before the water level dropped below the HPA base) through the gravel pack, which is usually installed to near land surface.

Annual winter water levels for all wells in fig. 36 generally declined from 1960 to the end of the records. The water level in the Dakota well dropped below the base of the HPA in the late 1960s. The continued declines after 1963, the year of last irrigation water use from the well, could represent withdrawals from the Dakota aquifer in the general area, but they could also be in response to the declines in the HPA to the southeast (direction of HPA thickening). The water levels in the HPA at substantially lower elevations than at the Dakota well location have created a lateral hydraulic gradient from Dakota sandstones into the HPA towards the south-southeast. The subsidence from Permian salt dissolution along the Bear Creek fault zone could have created normal faults exposing Dakota sandstones to the HPA as well as fractures that increased hydraulic connection between the Dakota and the HPA. Thus, groundwater could be flowing from the Dakota aquifer to the overlying HPA in both vertical and lateral directions.

Winter water levels in irrigation and unused wells in southwest Stanton and northwest Morton counties, where the Dakota aquifer mainly underlies unsaturated or thinly saturated Neogene or Quaternary sediments but also outcrops (see fig. 2), have remained either nearly constant or have slowly declined (fig. 37). The well showing the greatest decline (29S-43W-33CDB) has reported irrigation water use for all except one year during 2001–2010. The hydrographs imply that the Dakota aquifer is not substantially used or stressed in this area.

In Hodgeman and northern Ford counties, where the Dakota aquifer is primarily confined and not overlain by a significant saturated thickness of the HPA (fig. 2), water levels in the Dakota have either remained relatively constant or have slowly declined. This is illustrated by hydrographs in fig. 38 for an east-west transect across central Hodgeman

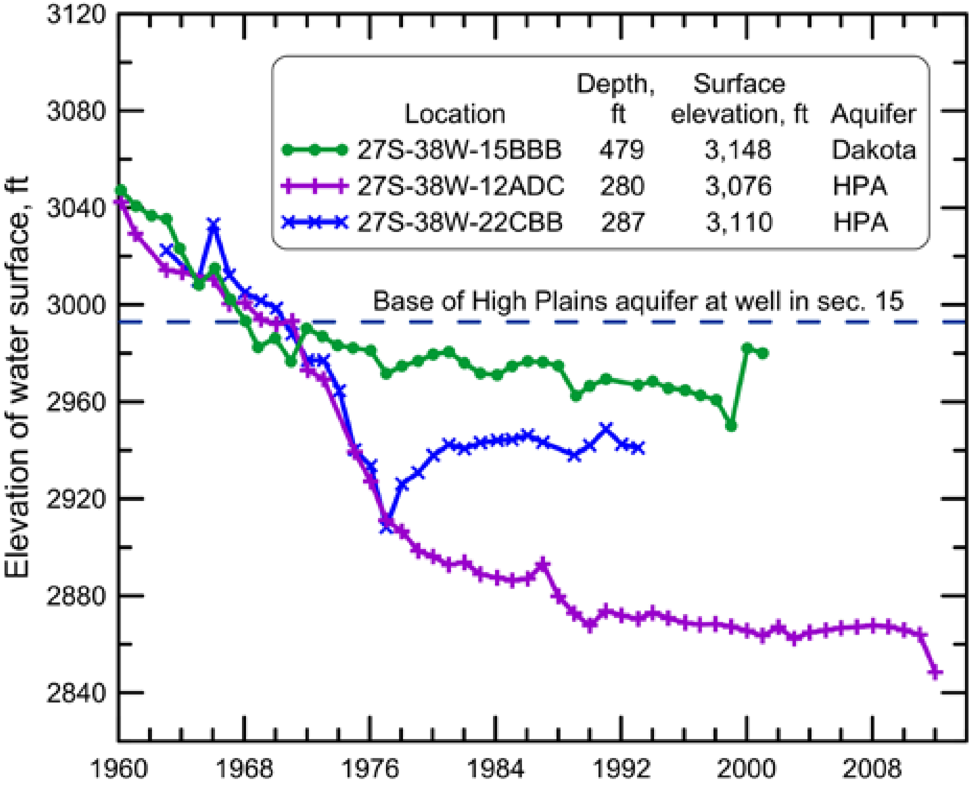


Figure 36. Annual winter water levels in wells in the Dakota and High Plains aquifers in northwest Grant County. The 479-ft-deep well in the Dakota aquifer was used for irrigation; no water has been pumped since 1963. The HPA well in sec. 12 is also for irrigation; no water has been used since 2004. The HPA well in sec. 22 was formerly an irrigation well that is now plugged; water use probably stopped after 1977. Measurements are predominantly for January; of those measurements not taken in January, most are for December and February.

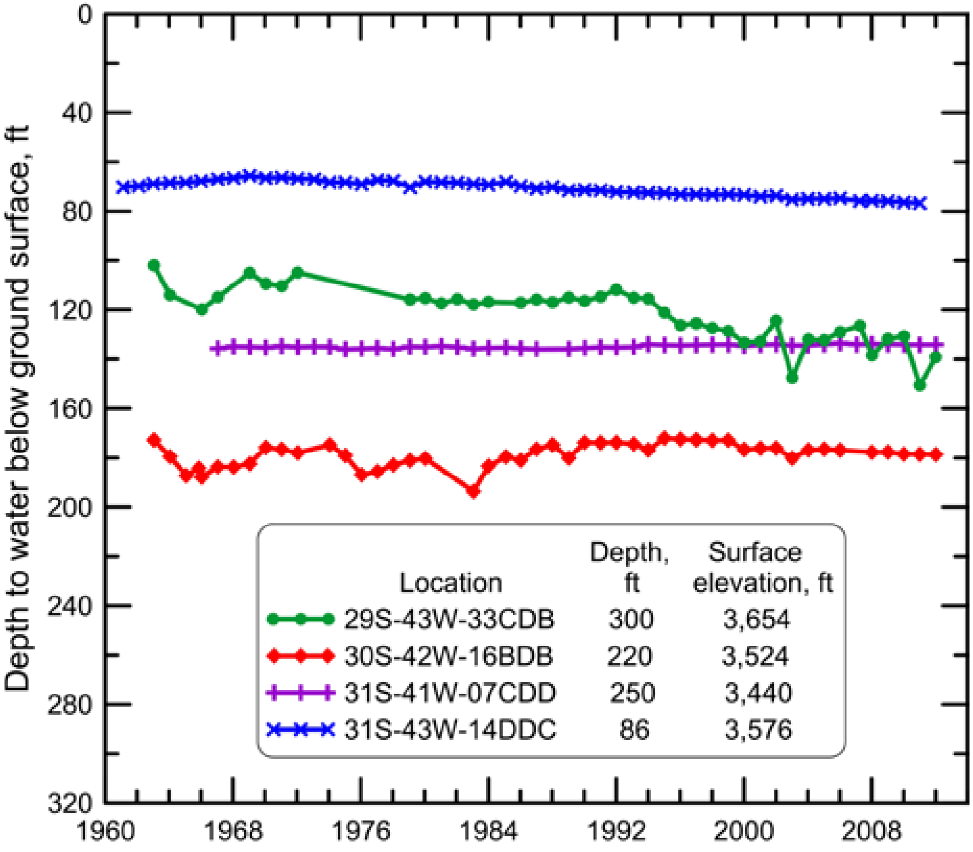


Figure 37. Annual winter water levels in wells in the Dakota aquifer in southwest Stanton and northwest Morton counties with thinly saturated or no HPA. The two wells in T. 29 S. and T. 30 S. are in Stanton County and are used for irrigation; the two in T. 31 S. are in Morton County and are unused. Water use has been reported for all except one year during 2001–2010 for the irrigation well in T. 29 S. but has not been reported since 1986 for the irrigation well in T. 30 S. The measurements are predominantly for January; of the measurements not taken in January, most are for December or February except for a few that are for November, March, or early April.

County of four irrigation wells that tap the confined Dakota aquifer. Thus, just as in the Dakota outcrop/subcrop area in southwest Stanton and northwest Morton counties, the Dakota aquifer does not appear to be appreciably stressed. In these wells, and also farther east and northeast in central and north-central Kansas where development has been less intense or began more recently, water levels decline during seasonal periods of intense pumping but typically recover when pumping is reduced or stopped.

The area where a substantial saturated thickness of the HPA is hydraulically connected to the Dakota (within Suitability Area I in southwest Kansas) does not contain an observation well sealed exclusively in the Dakota aquifer. From 2009 to 2012, January water levels were measured in a 782-ft (238-m) deep irrigation well in northwest Haskell County, for which the lithologic log indicates two screened intervals that are deeper than the bedrock depth of about 520 ft (158 m) (based on lithologic logs for the area; the log for this well is not distinctive enough to allow determination of the HPA base). However, this well is gravel packed from 20 ft (6 m) to the bottom of the well, which could allow some communication of water between the HPA and Dakota aquifer. The static water level was 374 ft (114 m) below land surface when the well was completed in December 1989. January measurements in 2009 and 2012 were 397.7 ft and 414.6 ft (121.1 m and 126.4 m), respectively, indicating an average annual decline in water level of 5.6 ft (1.7 m). Water levels in HPA wells in the area have also declined substantially during the last several years.

It is not known whether the annual water-level measurements in the HPA area of southwest Kansas are indicative of a truly interconnected system of the HPA and the unconfined Dakota aquifer. The possibility exists in some areas of Suitability Area I in southwest Kansas that shale layers are thick enough to isolate individual Dakota sandstone units in which the wells are completed; in that case, water levels could change in the Dakota at a different rate from that in the HPA, as shown in fig. 35 for the observation well nest in the confined region of the Dakota aquifer in Gray County. Further work is needed to assess the nature of the interconnection between the HPA and unconfined Dakota aquifer.

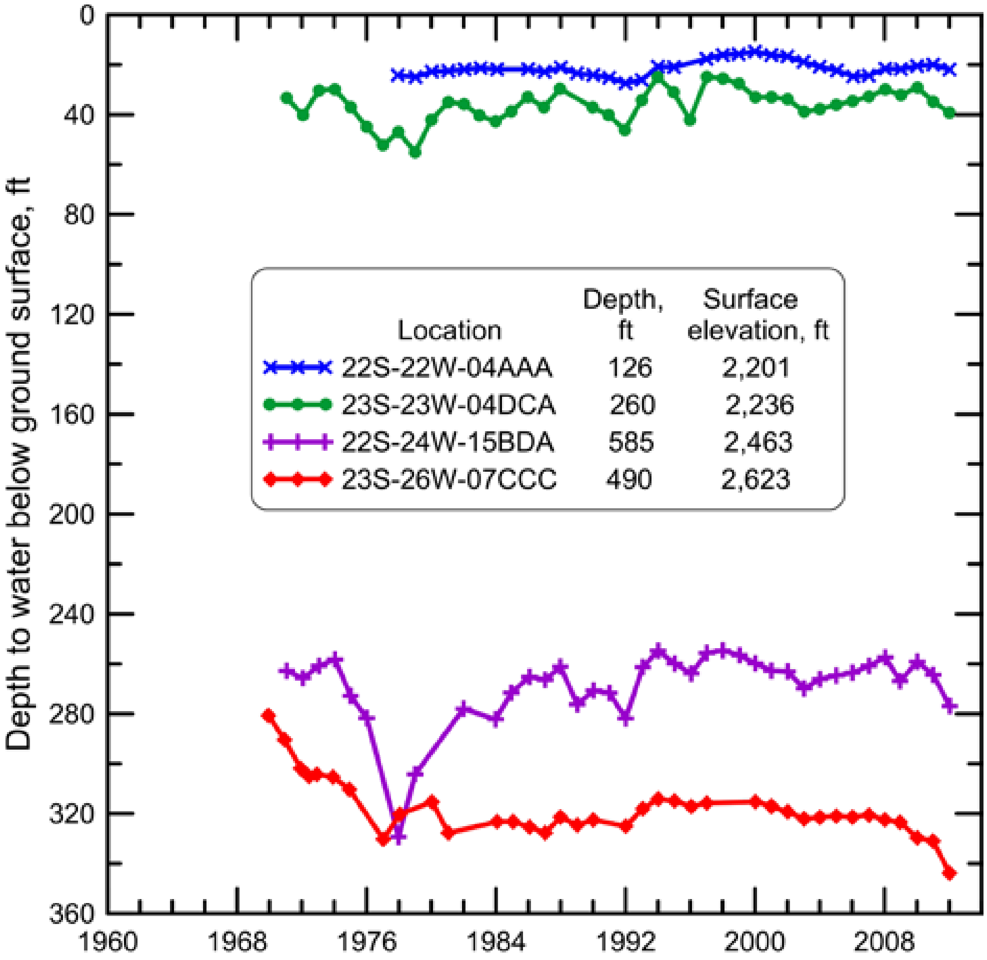


Figure 38. Annual winter water levels in irrigation wells in the Dakota aquifer in Hodgeman County. The well list in the legend is ordered from top to bottom to represent an east-to-west direction across the central part of the county. Water use has been reported for nearly all years during the last two decades for the wells in R. 22 and 23 W. but not since 1999 for the well in R. 24 W. and not since 2001 for the well in R. 26 W. Measurements are for December or January.

Future Development

Additional development of the water resources in the Dakota aquifer will be determined by the needs of users, the availability of water from the Dakota and other aquifers, and the management goals established by state and local water planning and regulatory agencies in Kansas. The increasing number of wells completed in both the HPA and the underlying Dakota aquifer in southwest Kansas indicates that as water levels decline in the HPA, more and more users are looking at the Dakota aquifer as an additional water source. New, high-capacity wells are also being completed solely in the Dakota aquifer in other regions where the HPA is absent, such as north-central Kansas. These trends are expected to continue in southwest Kansas as the saturated thickness of the HPA decreases and in other areas where additional water supplies are needed for municipal and agricultural demands, especially during drought periods.

The Dakota Aquifer Program identified a substantial area of additional nearly fresh to slightly saline waters in upper Dakota strata that could be important for future supplies. This aquifer area is triangular in shape with its base along the south lines of Sheridan and Graham counties and extending northward into the south-central portion of Norton County, where it is bounded by the 2,000 mg/L isocon for TDS concentration (fig. 17). Most of this area was previously believed to have waters of greater salinity (Keene and Bayne, 1977). Regional flow of fresher groundwater through the Dakota aquifer from the southwest is believed to have reduced the groundwater salinity to its present level. Some waters may even be slightly less than the TDS classification for freshwater (less than 1,000 mg/L) in thicker sandstones in the south-central portion of this triangle where greater permeability might have allowed more extensive flushing. Parts of western Gove County may also have more freshwater than previously thought.

Partially developed areas where additional withdrawals could be made are mainly in southwest Kansas (Suitability Area I), the portions of the aquifer not currently greatly stressed in the eastern outcrop/subcrop area (Suitability Area III), and the zone of the confined aquifer nearest the outcrop/subcrop belt (Suitability Area II) (fig. 30). In the confined aquifer, the thicker sandstones in the Upper Dakota aquifer will be the primary targets for possible new development because of their greater permeability and lower levels of salinity. Development in the fresh to slightly saline area in parts of Graham and Sheridan counties, as well as those areas in the undeveloped and very limited development region of Greeley, Wichita, Scott, Lane, Ness, Rush, Wallace, Logan, Gove, Trego, and Ellis counties will depend on the extent to which current water supplies can no longer meet future demands. Disadvantages of the Dakota aquifer in this region include the limited distribution of sandstones thick enough and of enough lateral extent to yield adequate amounts of water, the generally fine-grained nature of these sandstones, and the greater depth (and, thus, expense) of wells required to reach and extend through sufficient thickness of sandstone units for a viable well. In central Kansas, exploration for usable groundwater will be mainly limited to sandstones of the uppermost Upper Dakota aquifer in areas where the Upper Dakota confining layer is present and has slowed upward intrusion of saltwater into the Dakota aquifer from the underlying Cedar Hills Sandstone–upper Salt Plain aquifer. In southwest Kansas, the primary targets for exploration will be the sandstones in both the upper and lower Dakota aquifers and in the Morrison-Dockum aquifer. In the outcrop areas of central Kansas, the sandstones in the Upper Dakota and, near the eastern margin, the lower Dakota will be likely targets of exploration for new water supplies.

As shallower water supplies continue to become scarce, exploration for deeper usable waters in the confined Dakota aquifer will increase. Although the salinity of Dakota aquifer waters in much of the confined region is one of the most important factors limiting its use, the cost of desalinization methods is decreasing with time as more efficient systems are developed. Water availability and economic considerations caused the City of Hays to develop brackish water sources in the Dakota in west central Ellis County to mix with other freshwater sources. For a short time, Hays also experimented with advanced treatment technologies to reduce the level of salinity in the water coming from its new well field. The urgent need for water supplies in some areas of Kansas where supplies could become scarce may cause further consideration of treatment of brackish water from the Dakota aquifer.

SUMMARY AND CONCLUSIONS

The Dakota aquifer system underlies most of the western two-thirds of Kansas and includes sandstone units in the Cretaceous Dakota and Kiowa formations and Cheyenne Sandstone. In southwesternmost Kansas, the underlying Jurassic Morrison Formation, where hydraulically connected, is also considered by state statute to be part of the Dakota system. The Dakota aquifer is unconfined where the aquifer strata outcrop in the eastern portions of the aquifer and where these strata are overlain by alluvial aquifers. The aquifer is also considered to be unconfined where it is overlain by and hydraulically connected to the HPA in south-central and southwest Kansas. Most of the Dakota system in Kansas is overlain by Upper Cretaceous shales and limestones and is considered to be confined.

The Dakota aquifer has been developed as a water-supply source in areas where the groundwater is fresh or only slightly saline and where other more easily obtained water supplies are not available. A total of 2,237 wells with active water rights and active use as of the end of 2011 were determined to produce greater than 5% of their total yield from the Dakota aquifer. Most of these wells are located where the Dakota aquifer directly underlies the HPA in southwest Kansas. Most of the other wells are distributed within the outcrop/subcrop area of the Dakota aquifer from north-central, through central, to south-central Kansas. A much smaller number of wells produce from the confined Dakota aquifer in west-central Kansas. Thirty-nine percent of the 1,555 Dakota wells with water rights in southwest Kansas produce more than 50% of their yield from the Dakota aquifer. About 93% of the 581 Dakota wells in north-central and central Kansas produce all (or greater than 95%) of their yield from the Dakota aquifer. In the 36 counties in which water-right-permitted wells pump all or part of their supply from the Dakota aquifer, the Dakota wells are estimated to comprise 9% of the total of wells with water-right permits in all aquifers. Most (78%) of the water-right-permitted wells that draw part or all of their water from the Dakota aquifer are used for irrigation. Stock, municipal, and industrial wells comprise nearly all of the other uses (9.6%, 8.9%, and 2.2%, respectively) of the Dakota wells.

The mean annual volume of water used from the Dakota aquifer by permitted wells in Kansas is estimated to have been 117,000 acre-ft/yr (1.44 x 10^8 m^3/yr) for the 5-yr period 2006–2010. The use was greatest in southwest Kansas (approximately 86% of the total Dakota aquifer use). The mean annual use for the other regions ranged from approximately 0.5% of the total Dakota use for west-central Kansas, to 2.4% for central, 2.9% for south-central, and 8.1% for north-central Kansas. The county with the greatest estimated annual use from the Dakota aquifer is Stanton County, followed in order of decreasing use by Grant, Hamilton, and Haskell counties, all of which use more than 10,000 acre-ft/yr (1.2 x 10^7 m^3/yr). Counties in southwest Kansas with between 3,000 and 9,000 acre-ft/yr (3.7 x 10^6 and 1.1 x 10^7 m^3/yr) of Dakota use are Ford, Morton, Kearny, and Stevens counties (in decreasing order). The only counties in the other regions of the Dakota aquifer that exceed 3,000 acre-ft/yr (3.7 x 10^7 m^3/yr) of permitted use are Cloud (4,200 acre-ft/yr [5.2 x 10^6 m^3/yr]) and Washington (3,800 acre-ft/yr [4.7 x 10^6 m^3/yr]) counties. Although water use from the Dakota in north-central Kansas is much lower than in southwest Kansas, the percentage of Dakota use relative to total use from all aquifers is the highest (nearly 20%) of all regions. The percent Dakota use compared to total use from all aquifers for the other regions ranges from 5.2% for southwest, to 2.5% for central, to 2.0% for south-central, and to 0.4% for west-central Kansas.

About 90% of the mean annual use from the Dakota aquifer during 2006–2010 was for irrigation. Most of this use was in southwest Kansas. The use rates for stock and municipal purposes were each nearly 4% of the total volume pumped from the Dakota aquifer. However, municipal use accounted for 41% and 18% of the total use from the Dakota in central and north-central Kansas, respectively.

Variations in the annual rate of water use from the Dakota aquifer are related mainly to climatic conditions because irrigation, stock, and municipal use generally are substantially greater during droughts than during wet periods. For example, in north-central Kansas, almost eight times as much water was used during the drought year of 2002 (15,900 acre-ft/yr [1.96 x 10^7 m^3/yr) than during the very wet year of 1993 (2,070 acre-ft/yr [2.55 x 10^6 m^3/yr]). The relative range between dry and wet years is greater in north-central than in southwest Kansas because during wet years in north-central Kansas, precipitation is completely or nearly sufficient for crop irrigation and lawn growth.

Water use was also estimated for "domestic" wells, which are not required to obtain a permit. The total number of "domestic" wells currently producing most or all of their water from the Dakota aquifer in Kansas is estimated to be more than 11,000 (8,000 for north-central and central Kansas and 3,200 for south-central, west-central, and southwest Kansas). This is about 4.7 times the estimated number of permitted wells that obtain some or all of their source from the Dakota aquifer.

Water use from the Dakota aquifer by "domestic" wells is estimated to be 4,800 acre-ft/yr (5.9 x 10^6 m^3/yr) in central Kansas, 1,500 acre-ft/yr (1.9 x 10^6 m^3/yr) in north-central Kansas, and a combined total of 1,700 acre-ft/yr (2.1 x 10^6 m^3/yr) for south-central, west-central, and southwest Kansas.

The estimated use by "domestic" wells ranges from nearly two-thirds of the total water (both permitted and domestic uses) pumped from the Dakota aquifer in central Kansas to only 1% in southwest Kansas. The total "domestic" use (about 8,000 acre-ft/yr [1.0 x 10^7 m^3/yr]) is 6% of the approximately 125,000 acre-ft/yr (1.54 x 10^8 m^3/yr) pumped from the Dakota aquifer by both permitted and domestic wells in Kansas.

The processes of mixing, reactive cation exchange, and mineral dissolution and precipitation have produced a complex range of chemical characteristics for groundwater in the Dakota aquifer. Water quality in the aquifer ranges from very fresh (less than 300 mg/L TDS) to saltwater (greater than 10,000 mg/L TDS). Freshwaters in the outcrop and subcrop portions of the Dakota aquifer in north-central and central Kansas are usually calcium-bicarbonate type waters. Weathering of pyrite in shales in Dakota system strata and concomitant dissolution of any calcite or dolomite present can cause local increases in sulfate, calcium, and magnesium concentrations in Dakota groundwater. Recharge to the Dakota aquifer of groundwater in upper Cretaceous confining strata that was affected by these same processes or by dissolution of gypsum can increase the sulfate, calcium, and magnesium contents of Dakota groundwater. Calcium-sulfate type water can result.

Large areas of the Dakota aquifer contain saline water that is derived from the upward intrusion of saltwater from underlying Permian units, especially the Cedar Hills Sandstone in central and north-central Kansas. Geochemical data indicate that past seawater incorporated in the Dakota sediments has been flushed by groundwater flow. The saltwater intrusion from Permian units is derived from the dissolution of evaporite deposits containing rock salt (halite). Sodium and chloride are the main components of saline water in the Dakota aquifer.

Flushing of saline water from the Dakota aquifer is accompanied by the generation of sodium-bicarbonate groundwater. As freshwater of calcium-bicarbonate or calcium-sulfate types replaces the saline water, exchange of the calcium (and magnesium) in the freshwater for sodium on clays in Dakota strata decreases the calcium (and magnesium) concentration and increases the sodium concentration in the aquifer water. The decrease in calcium and magnesium is accompanied by the dissolution of calcite and dolomite in the sediments, resulting in the increase in bicarbonate that is formed from the dissolved carbonate. Natural softening of the groundwater occurs and sodium-bicarbonate groundwater can be formed in the Dakota aquifer. An increase in the pH of the water is associated with this process.

Fluoride concentrations exceed the secondary MCL for public drinking water (2 mg/L) in parts of the confined and small portions of the unconfined Dakota aquifer and exceed the MCL (4 mg/L) in some areas of the confined aquifer. The high fluoride is derived primarily from the dissolution of calcium minerals that contain fluoride during the generation of sodium-bicarbonate type water. About 10% of the sample records for the Dakota aquifer exceed the MCL for arsenic and the action level for lead; some of the high lead values could be related to lead in plumbing systems and not to natural levels in the Dakota aquifer. Uranium concentration and the radioactivity from radium isotopes and alpha particles exceed the MCL for public drinking waters in a small percentage of Dakota groundwaters. Many other natural constituents and properties in Dakota waters exceed recommended or suggested levels for drinking water, such as TDS, chloride, sulfate, iron, manganese, and ammonium ion concentrations, especially in saline water in the confined aquifer and in groundwaters that have chemically reducing conditions.

The main contaminant from anthropogenic activities in Dakota groundwater is nitrate. Nitrate-nitrogen concentrations exceeding the MCL of 10 mg/L primarily occur in shallow wells in the unconfined aquifer in central and north-central Kansas. Human sources of nitrogen include fertilizer and animal and human waste. Nitrate in or generated from the oxidation of nitrogen in these sources can enter groundwaters by infiltration of water through the unsaturated zone to the water table or by water flowing down the boreholes of wells, especially if the annular space between the well casing and borehole is not sealed or is poorly sealed.

The salinity of groundwater in the Dakota aquifer generally increases with depth. In the western areas of the outcrop/subcrop belt in south-central to north-central Kansas and the parts of the confined aquifer near the boundary with the outcrop/subcrop belt, topographic variations create local hydraulic heads in the Dakota aquifer that are higher than the water levels in the streams in the valleys. This can cause discharge of saline water from the regional flow system deeper in the Dakota aquifer to the stream valleys, creating saline water springs and seeps and increasing the salinity of streams and rivers. Steep salinity gradients can be present in the valleys adjacent to the streams. Thus, care must be taken when drilling wells too deep; shallow freshwater in the Dakota aquifer derived from surface recharge can be underlain by saline groundwater. The greatest salinity changes with depth occur across substantial shale units with appreciable lateral extent that confine or separate aquifer units.

Development of the Dakota aquifer has been dependent on both the hydrogeologic characteristics of the aquifer and the salinity of the groundwater. The substantial variability in both the hydrogeologic characteristics and water quality of the aquifer across Kansas strongly influences the suitability of the aquifer as a source for water supply. Another, more recent factor in the development of the Dakota is the decline in the water table in the HPA where it overlies the Dakota aquifer. Many new wells and wells drilled to replace permitted wells that were completed only in the HPA have been completed in both the HPA and underlying Dakota strata, thereby increasing the percentage of wells completed in both aquifers. An increasing trend has occurred since the latter 1980s in the number of wells with active water rights that have been completed partially or solely in the Dakota aquifer in southwest Kansas. Development is also continuing in the eastern outcrop/subcrop zone of the aquifer.

The KGS, as part of its work on the Dakota Aquifer Program, identified an area of additional nearly fresh to slightly saline waters in upper Dakota strata that could be important for future supplies. The aquifer area is triangular in shape with its base along the south lines of Sheridan and Graham counties and extending into south-central Norton County. Most of this area was previously believed to have waters of greater salinity. Development of this area, as well as other confined regions of the aquifer with greater depths to aquifer units and more saline water than in other parts of the aquifer, could occur in the future depending on water demands for agriculture, municipalities, and industry. Decreases in the cost of desalinization processes could make water use more possible from these areas of the aquifer for municipal and industrial uses.

Water-level data for the confined Dakota aquifer that underlies the HPA near where it is hydraulically connected to the HPA, suggest that water levels in the Dakota, which may have been either slightly above or below those in the HPA during pre-development, are now lower than in the HPA and may be declining at a greater rate than in the HPA. Water levels in the outcrop/subcrop belt of the Dakota, which drop during seasonal pumping, generally recover during the winter, and long-term levels have been relatively stable. Long-term water-level measurements in the Dakota are very limited in the region where it is hydraulically connected to the HPA.

Installation of a well screened solely in the Dakota aquifer and equipped with a continuously recording pressure transducer would be especially valuable for assessing conditions at and future prospects for the index/calibration well site in Haskell County (Butler et al., 2012). Characterization of water levels in the HPA at this site has improved understanding of aquifer responses to pumping and the HPA zones that contribute water to that pumping. For example, a leaky aquifer response has been observed in confined sands and gravels at the base of the HPA at this site (Butler et al., 2013). Continuously monitored water levels from a Dakota observation well would help determine whether most of the leakage to the HPA confined zone is from overlying HPA sediments or underlying Dakota strata. In addition, such water-level data could indicate whether leakage was currently occurring from the HPA to the Dakota or whether that leakage could start as more pumping stress was placed on the Dakota aquifer in the future. Similar monitoring of water levels in the Dakota aquifer elsewhere in southwestern Kansas would be extremely helpful in assessing the Dakota-HPA relationship.

Part of the water use decrease in the Dakota aquifer in Ford and Hodgeman counties from 1975–1982 to 2006–2010 was from decreased yield or abandonment of wells even though long-term water levels appear to have been generally stable across these periods. A probable, important contributing factor was greater maintenance costs for Dakota aquifer wells than for the typical unconsolidated aquifer wells due to the often high iron and manganese concentrations and sometimes corrosive characteristic of Dakota groundwater. As the value of water increases with increasing prices for agricultural products, thereby allowing for greater well maintenance costs, the potential exists for redevelopment of the Dakota in parts of Ford and Hodgeman counties.

This bulletin represents an important step for the assessment of the water resources of the Dakota aquifer in Kansas. Additional efforts recommended for assessment of the future potential of the aquifer include improved determination of the percentage of the Dakota water in mixed aquifer completions for existing wells, updating the percentages for new and replacement wells with water-right permits, and continued estimation of water use based on these percentages and reported water use from the DWR. Further work is needed to determine the depths to which the Dakota aquifer system is usable in southwest and west-central Kansas. Some deep wells in southwest Kansas where the Dakota and High Plains aquifers are hydraulically connected have depths that indicate they penetrate though the entire Dakota system at those locations. This implies that the water in the lower Dakota at those sites is not so saline as to render the well water unusable. However, this is based on water use from the well and not analyses of water samples. Sampling of selected deep wells that obtain a substantial percentage of their yield from the Dakota aquifer in Suitability Area I in southwest Kansas is recommended for further addressing this question. Finally, a selected group of wells across the Dakota in southwestern Kansas should be equipped with continuous monitoring equipment so that a better understanding of the relationship between the Dakota and the overlying HPA can be obtained.

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