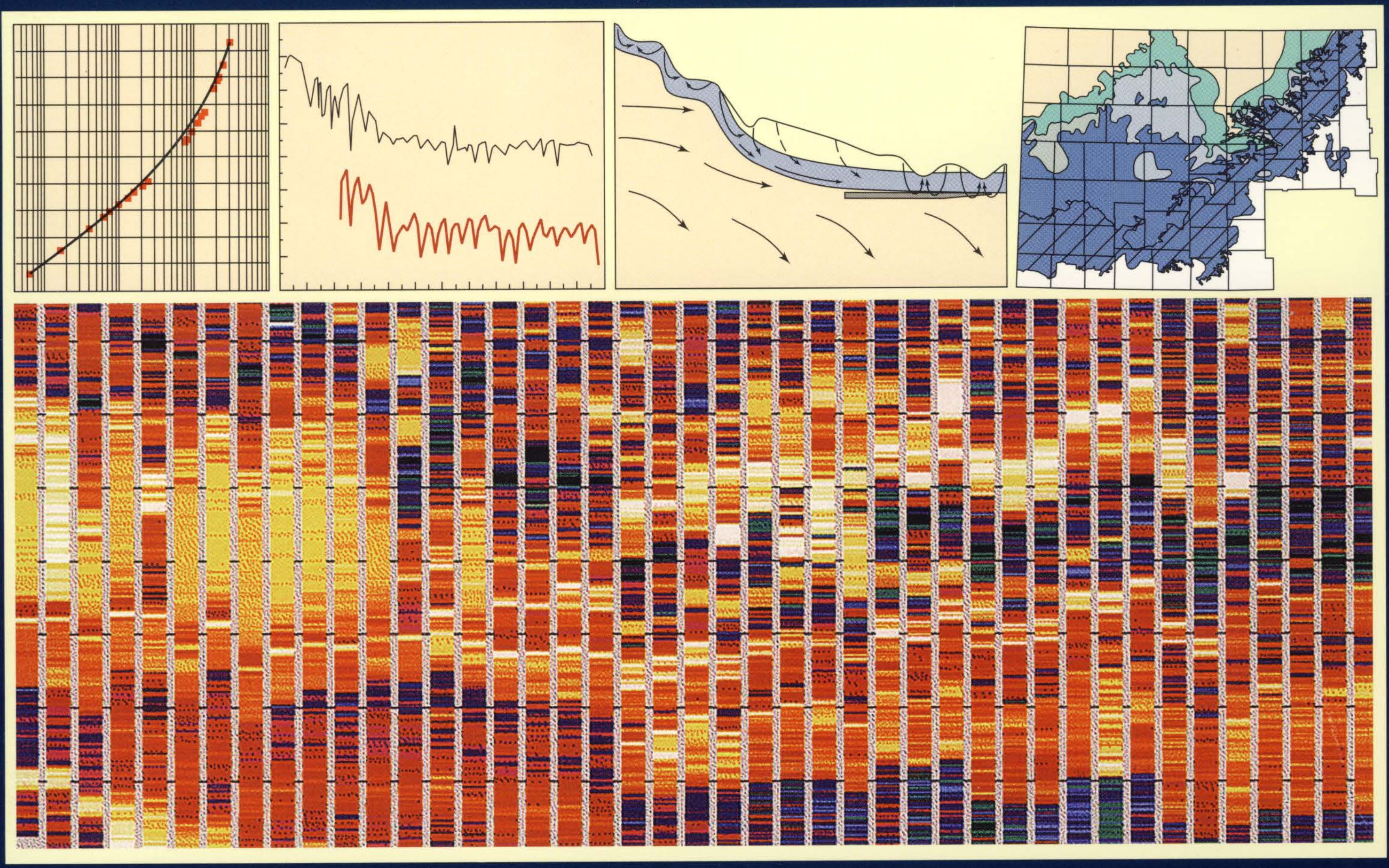
Kansas Geological Survey

Technical Series 2

User's Guide to the Dakota Aquifer in Kansas



P. Allen Macfarlane, John Doveton, and Donald O. Whittemore

Lawrence, Kansas 66047
1998

Kansas Geological Survey **Technical Series 2**

User's Guide to the Dakota Aquifer in Kansas

P. Allen Macfarlane, John H. Doveton, and Donald O. Whittemore

Lawrence, Kansas 66047

1998

COVER—The graphics displayed represent various aspects of Dakota hydrogeology and its complexity. The long strip is part of a vertical cross section through the Dakota aquifer framework constructed from gamma-ray logs that have been transformed to allow a more visual impression of the subsurface. Thus, the less radioactive rock units, the sandstones and limestones, are represented by the yellow and orange strips, and the darker shades represent the more radioactive shales and siltstones. Upon closer examinaton of this cross section, the viewer is struck by the extreme variability of the Dakota aquifer framework. The two panels above the cross section on the left show some of the tools traditionally used to analyze the Dakota aquifer hydrology, namely pumping-test results and well hydrographs. The third panel from the left is a vertical cross section from southeastern Colorado to central Kansas showing the interaction between local and regional flow systems conceptually. The panel on the far right shows the variation in total dissolved solids concentration in ground waters from the Dakota aquifer.

Editor: Marla D. Adkins–Heljeson
Designer: Jennifer Sims

Printed at The University of Kansas Printing Services
on recycled paper using soy-based ink

Contents

Tables

Figures

Introduction

The Dakota aquifer system and its equivalents extend across much of the central North American continent (fig. 1). The contiguous aquifer system extends northward from Kansas approximately to the Arctic Circle in Canada, southward into northeastern New Mexico and the Oklahoma panhandle, westward to the Rocky Mountain front, and eastward to western Iowa and Minnesota. Across the Continental Divide, the Dakota aquifer is present in many of the intermontane basins. Thus, the Dakota is an important source of water in many areas of the North American continent.

In Kansas, the Dakota is present in most of the western two-thirds of the state (fig. 2). The aquifer extends westward from Washington County along the Kansas–Nebraska border and northward from Morton County along the Kansas–Colorado border, and is present in 59 of the 105 Kansas counties.

Dakota Aquifer Program

Even though the Dakota has been used as a source of water for more than a century in Kansas, its hydrologic character has been poorly understood and the issues surrounding its use have been inadequately addressed. A decade ago, State and local agencies recognized the localized depletion of the High Plains (Ogallala) aquifer and stream-aquifer systems in western and central Kansas and the need to identify other sources that might replenish available supplies. Little was known about either the quantity or the quality of ground water or the impact of regional or local development on the Dakota that could be used to guide regional or local planning until recently. This focused the attention of the water agencies on the Dakota, a deeper and more complex sandstone aquifer system. Concerns related to human activity also were expressed, such as the potential hazards of disposing oil-brine in shallow zones beneath the Dakota in central Kansas and the protection of usable ground-water resources in the Dakota. Kansas has had oil-well surface casing and cementing standards for protecting shallow fresh ground water since the 1960's.

In response, the Kansas Geological Survey began an eight-year investigation into the hydrogeology and water quality of the Dakota in 1988. Goals of the program were to assess the water-resources potential of the Dakota aquifer and to assist the agencies in the development of appropriate management plans and policies. This program was unique because it was designed for proactive rather than reactive water-resources management of a regional aquifer system. The broad objectives of the program were to (1) characterize the geologic framework of the Dakota aquifer; (2) define the ground-water-flow system within the aquifer to identify sources of recharge, discharge, flow path, and areas of interaction with other aquifer systems; (3) assess the water quality of the Dakota aquifer; and (4) assess the impact of current and future development in the Dakota and interacting aquifer systems, including the impact of oil-field-brine disposal in the underlying Permian on the Dakota aquifer in the areas of aquifer interaction.

Purpose and Organization

Historically, the Dakota aquifer has generally been poorly understood in Kansas. Because of its complexity and limited use, our poorly documented experience with

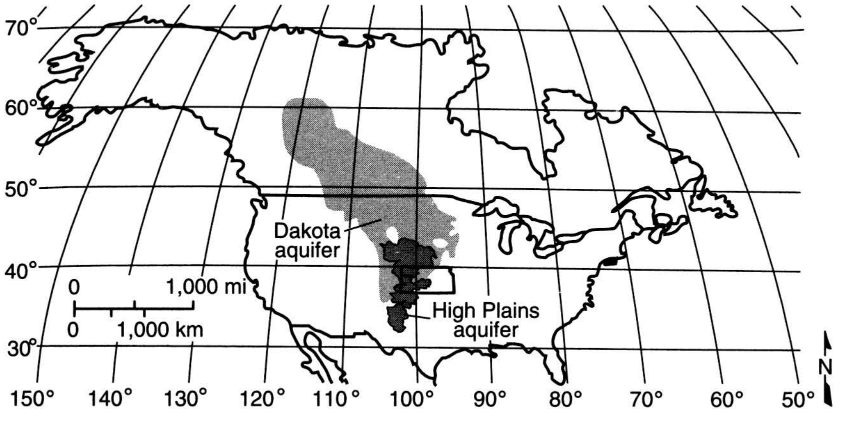


FIGURE 1—Limit of Dakota aquifer in North America.

this source of water contains some truths but many misconceptions about the Dakota that have continued to the present. The purpose of this book is to educate Kansans about the Dakota aquifer as we know it today. It is written primarily for a nontechnical to semi-technical audience and is designed to provide the reader with a basic understanding of the Dakota aquifer and the issues surrounding its use as a water resource. Where the discussion becomes more technical, every effort has been made to explain the concepts in less technical language. Also, a **Glossary** of the terms used in this report is contained in Appendix 1. During the initial stages of this project, it became obvious to us that the complexity of the Dakota warranted this type of publication to help guide those interested in the water resources of this aquifer system.

The user's guide contains two major sections. Part 1 describes the hydrogeology and water quality of the Dakota, and Part 2 is a discussion of its water resources. Because much of the information in Part 1 forms the background for the ensuing discussion in Part 2, readers are urged to read the sections in order of their presentation. The reader will also find a listing of agencies that will have information on the Dakota aquifer (Appendix 2) and the publications from the Dakota Aquifer Program (Appendix 3). Additional technical information on the Dakota aquifer can be found on the Kansas Geological Survey home page. The World Wide Web address is **http://www.kgs.ukans.edu/**. A bulletin on the Dakota also is planned and should provide considerable additional information to those seeking technical guidance. Some of the more general publications of the Dakota Aquifer Program are listed on the inside front cover of this publication.

Part 1: Hydrogeology and Water Quality

Regional Hydrostratigraphy of the Dakota Aquifer

All natural geologic materials are capable of transmitting and storing water to varying degrees. In a practical sense, **aquifers** are permeable and yield amounts of water to wells at rates that are suitable for human uses. On the other hand, an **aquitard** or a confining unit is sufficiently permeable to allow the slow transmission of significant amounts of water, but will not yield appreciable amounts to wells. Aquifers and aquitards are hydrostratigraphic units; they consist of a portion of a formation, a formation, or a group of formations. Aquifer and aquitard units are distinguished and characterized by their porosity and permeability or hydraulic conductivity. Thus, the distinction between these units is a relative one that depends on the contrast of properties between adjacent geologic units or rock types. In the case of the Dakota, a hydraulically connected network of sandstones forms the regional

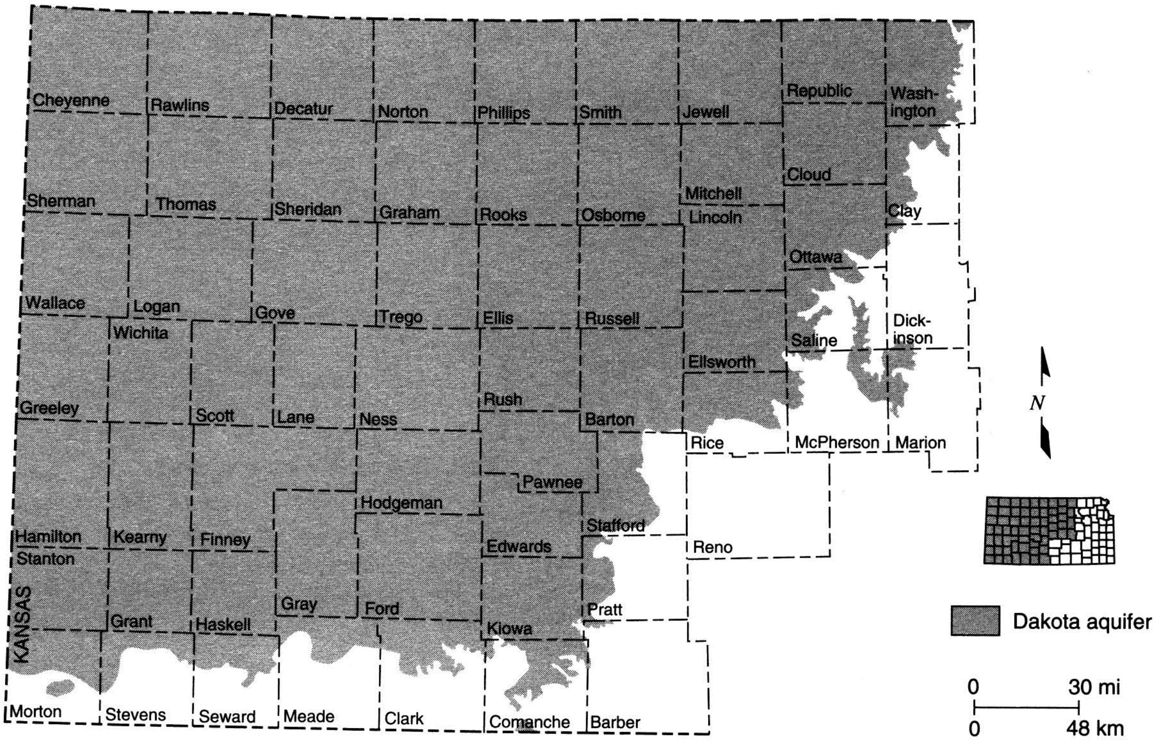


FIGURE 2—EXTENT OF DAKOTA AQUIFER IN KANSAS.

aquifer system, and the shaly geologic units form the regional aquitards.

The methodology used to define regional hydrostratigraphic units is discussed in detail in the papers and reports listed in Appendix 3. Table 1 shows the classification of regional aquifer units and its relation to the stratigraphic classification. Five aquifer and three aquitard units constitute the regional hydrostratigraphic framework of the upper 2,000 ft (600 m) of the western and central Kansas subsurface. All the regional aquitards consist largely of shale and are much less permeable than the regional aquifers by many orders of magnitude. As a result, the regional aquitards pose significant barriers to the vertical flow of ground water. In places, these regional aquitards have been eroded and two or more of the regional aquifers are in physical contact. Where these aquifers are in contact, they are considered to be hydraulically connected because there is no barrier to the flow of ground water between them.

The Dakota aquifer system is the most geographically extensive of all the aquifer systems in the upper 2,000 ft (600 m) of the subsurface of western and central Kansas. The geologic units that form the Dakota aquifer in Kansas are the Dakota Formation, the Kiowa Formation, and the Cheyenne Sandstone (table 1). These geologic units were deposited during the Cretaceous Period in alluvial valleys and in the coastal plain adjacent to the developing Western Interior seaway. Table 1 also shows the equivalent stratigraphic units in eastern Colorado. The combined thickness of these units can range up to more than 700 ft (210 m) in west-central parts of Kansas.

The Cheyenne Sandstone consists predominantly of crossbedded, fine- to medium-grained sandstone with lenses of shale and conglomerate (table 1). It was deposited in alluvial to deltaic environments and rests on an erosional surface that developed on underlying Permian and Jurassic rocks. Where it is present, the Cheyenne is variable in thickness, ranging up to 260 ft (78 m), but is typically less than 100 ft (30 m) thick, and tends to thicken into paleovalleys.

The Kiowa Formation overlies the Cheyenne Sandstone, and across much of Kansas it is primarily a marine shale that is typically 100–150 ft (30–45 m) thick (table 1). The Kiowa also contains interbedded sandstone, siltstone, and shale deposited in nearshore and shoreline and alluvial valley environments. These deposits belong to the Longford Member of the Kiowa Formation. In the subsurface, the transition from Cheyenne to Kiowa is commonly gradational with an upward increase in the proportion of shale, a decrease in sandstone-bed thickness, and an increase in bed continuity. The thickest Kiowa sandstones, as observed in core samples and on gamma-

TABLE 1—STRATIGRAPHY AND HYDROSTRATIGRAPHY OF THE SHALLOW SUBSURFACE IN SOUTHEASTERN COLORADO AND KANSAS.

ERA	SYSTEM	ROCK STRATIGRAPHIC UNITS				HYDROSTRATIGRAPHIC UNITS
		SE Colorado		**Kansas**		
Cenozoic	Quaternary		unconsolidated sediments		unconsolidated sediments	alluvial valley and High Plains aquifers
	Tertiary		Ogallala Formation		Ogallala Formation	
Mesozoic	Cretaceous	Colorado Gp.	Pierre Shale Niobrara Chalk Carlile Shale Greenhorn Limestone Graneros Shale	Colorado Gp.	Pierre Shale Niobrara Chalk Carlile Shale Greenhorn Limestone Graneros Shale	upper Cretaceous aquitard
			Dakota Sandstone		Dakota Formation	upper Dakota aquifer
		Purgatoire Fm.	Kiowa Shale Member	Kiowa Fm.	unnamed shale unit	Kiowa shale aquitard
					Longford Member	lower Dakota aquifer
			Cheyenne Sandstone Member		Cheyenne Sandstone	
	Jurassic/Triassic		Morrison Formation Dockum Group		Morrison Formation Dockum Group	Morrison–Dockum aquifer[1]
Paleozoic	Permian/ Pennsylvanian		Permian undiffer.		Permian undiffer.	Permian–Pennsylvanian aquitard
			Lyons Sandstone		Cedar Hills Sandstone	Cedar Hills Sandstone aquifer
			Permian/ Pennsylvanian undifferentiated		Permian/ Pennsylvanian undifferentiated	Permian–Pennsylvanian aquitard

[1] The Morrison–Dockum is considered an aquifer only in southeastern Colorado and adjacent southwestern Kansas. Elsewhere it is a part of the Permian–Pennsylvanian aquitard.

ray logs, occur near the base of the Kiowa in the Longford Member and are typically 30 ft (9 m) thick. The sandstone in these thick bodies is typically fine to medium grained and well sorted. Where the Cheyenne is absent, the Kiowa lies directly on Permian and Jurassic rocks.

The Dakota Formation lies between the Kiowa Formation below and Graneros Shale above (table 1). The Dakota is generally 200–300 ft (60–90 m) thick in Kansas and consists of fluvial and shoreline to nearshore sandstone bodies encased in a matrix of alluvial plain to shallow marine finer-grained mudstone. Across most of Kansas the Dakota was deposited on an erosional surface developed on the Kiowa Formation. However, in parts of Washington County, the underlying Kiowa Formation has been completely removed and the Dakota rests directly on eroded Permian rocks. Thick, crossbedded alluvial sandstone bodies up to 120 ft (36 m) thick may be present near the base of the formation. In outcrops, these thick, alluvial sandstone bodies form the bluffs and canyons along the north shore of Kanopolis Reservoir in Ellsworth County. Outcrops of sandstones can also be seen in roadcuts and on hilltops and in the sides of stream valleys in many other places in central Kansas. In cores and outcrops the sandstones are fine to medium grained, well sorted, and contain large-scale and small-scale crossbeds. These sandstone bodies are interpreted as river-channel deposits that generally trend west to southwest. Basal Dakota Formation sandstone bodies thicken appreciably into the paleovalleys cut into underlying rocks. In the lower half of the formation, sandstone beds are abruptly capped by fine-grained deposits or have a fining-upward succession. The Rocktown channel sandstone in the upper part of the Dakota Formation is a long-recognized outcrop expression of a channel sandstone in Russell County, Kansas. This channel contains crossbedded, fine to coarse, fluvial sandstone in a discontinuous, narrow (1–2 mi [1.6–3.2 km] wide or less), sinuous belt that has been traced along a straight-line distance of 27 mi (43 km). Sandstones near the top of the Dakota were deposited adjacent to the shoreline that was advancing from the west. These sandstones are thinner but more extensive than the alluvial sandstones and are elongated in a north-south direction, parallel to the orientation of the ancient Western Interior sea shoreline.

Regionally, the Dakota aquifer system consists of upper and lower units (table 1). The upper aquifer unit consists entirely of the Dakota Formation and the shoreline deposits at the top of the Kiowa Formation and is approximately 300 ft (90 m) thick. The lower aquifer unit consists of the Longford Member of the Kiowa Formation and the Cheyenne Sandstone and varies considerably in thickness up to 200 ft (60 m). These upper and lower regional aquifers are separated in western and parts of central Kansas by a thick, marine shale in the Kiowa Formation, which is referred to as the Kiowa shale aquitard (table 1). The thickness of the aquitard ranges up to more than 300 ft (90 m) in parts of west-central and southwestern Kansas. The Kiowa shale aquitard is not present in much of central Kansas where it has been removed by erosion or was not deposited. In these areas the upper and lower Dakota aquifers are considered to be in hydraulic connection, and the Dakota aquifer system is not differentiated into upper and lower units. Figure 3 shows the extent of the Kiowa shale aquitard in Kansas.

Local Aquifer and Aquitard Units within the Dakota Aquifer

The sandstone aquifers contained in these Cretaceous units occur as irregular, discontinuous bodies within the mudstone and generally occur in several, more or less distinct zones (fig. 4). The fluvial and distributary sandstone bodies are ribbon-shaped and follow the ancient drainage pattern that existed during this part of the Cretaceous. Continuity and thickness are greatest along the paleoflow directions, which vary locally, but trend generally to the west across the state. Upper Dakota Formation sandstone bodies deposited in deltas, estuaries, and beaches are generally tabular and trend parallel to the north-south paleoshoreline. Hydraulic connection between these sandstone bodies in this part of the section depends on the shifts in paleoenvironments that resulted from rising sea level along the eastern edge of the Western Interior sea and the proximity of these shallow sandstone bodies to underlying fluvial/distributary channel sandstones.

The proportion of sandstone to the total thickness of the stratigraphic units that constitute the Dakota aquifer is approximately 30% statewide. However, locally this proportion can vary widely from less than 5% to more than 50% over short distances. For example, 1,131 gamma-ray logs of oil wells were examined to determine the variation in the proportion of sandstone to total thickness of the Dakota Formation sampled by these boreholes in a 12-township area (432 mi^2 [1,123 km^2]) of western Ellis County. Figure 5 is a histogram showing the frequency of occurrence of sandstone in the Dakota Formation from the logs. The histogram shows that the amount of sandstone penetrated in the formation by boreholes drilled for oil and gas ranges widely from 3% to 78%. The average amount of sandstone penetrated was 29%. The average thickness of the Dakota Formation within the study area is 282 ft (85 m). This means the average total footage of sandstone encountered is approximately 82 ft (27 m). However, assuming an average formation thickness, slightly more than two-thirds of the 1,131 wells encountered between 16% and 42% sandstone or total thicknesses from 45 ft to 118 ft (15–39 m), respectively.

The high variability of the Dakota aquifer framework underscores the need to define hydostratigraphic units within the aquifer at both the local and regional scales (fig. 4). The aquifer/aquitard units defined at the regional scale would not be appropriate at the scale of the well field or well site, where the required level of detail is much higher. At the local scale, pumping causes transient-flow conditions in the vicinity of the well field or pumping well, and these propagate through the aquifer for some distance, mainly through the more permeable sandstones. Thus the local hydrostratigraphy consists of sandstone aquifers confined within mudstone aquitards within the Dakota and Kiowa formations and the Cheyenne Sandstone. The geometry of the sandstone bodies and their hydraulic properties become relatively important influences on ground-water flow that need to be evaluated at the local scale to resolve issues such as the effects of pumping or the transport of contaminants through the flow system.

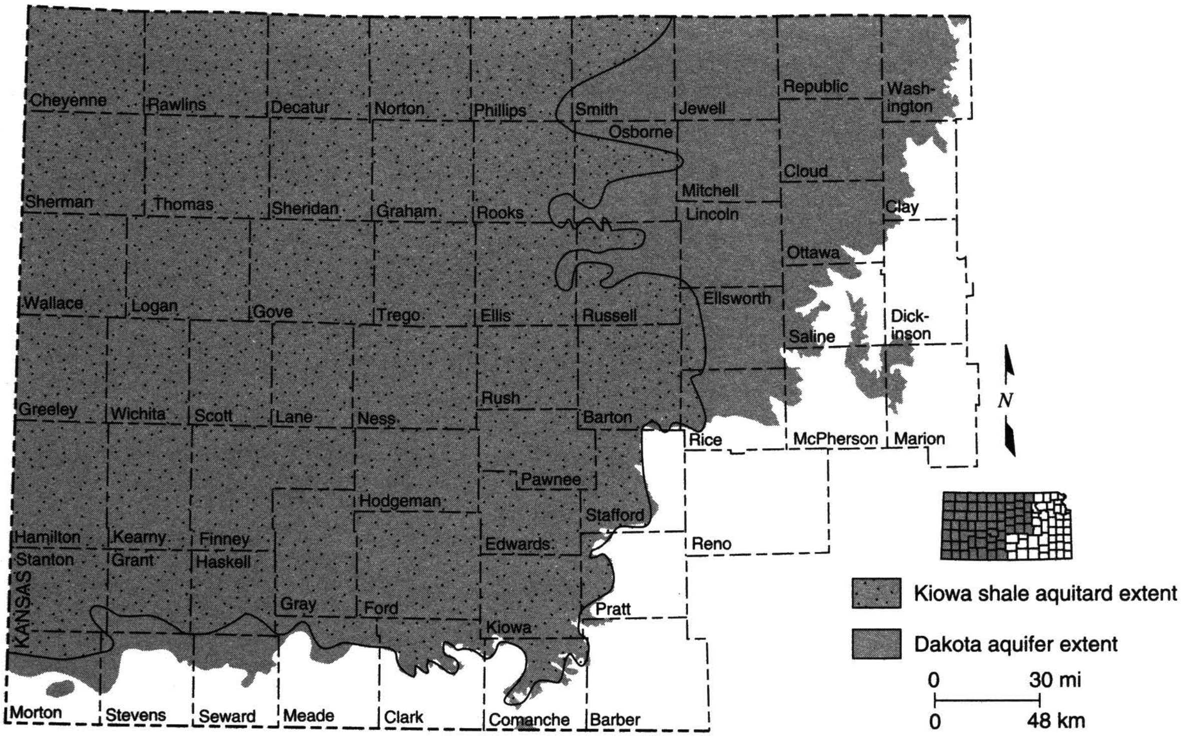


FIGURE 3—EXTENT OF KIOWA SHALE AQUITARD IN KANSAS.

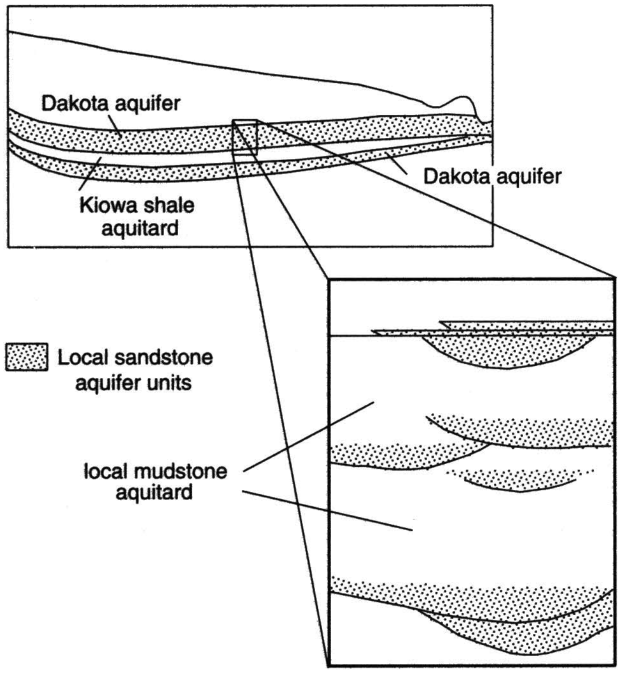


FIGURE 4—REGIONAL AND LOCAL AQUIFER/AQUITARD UNITS OF DAKOTA AQUIFER SYSTEM IN KANSAS.

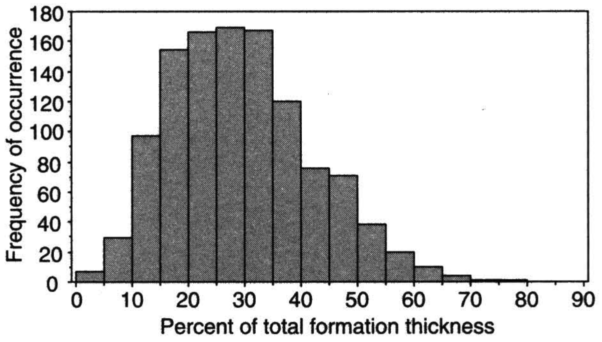


FIGURE 5—SANDSTONE PROPORTION TO TOTAL DAKOTA FORMATION THICKNESS ENCOUNTERED BY 1,131 OIL AND GAS WELLS IN SOUTHWESTERN ELLIS COUNTY, KANSAS.

Hydrologic Properties

In most hydrogeologic investigations, the permeable nature of a natural porous medium to the flow of water is indicated by its hydraulic conductivity, expressed in length per unit time (*L/T*) units. This parameter is a function of both the grain-size distribution of the porous medium and the viscosity and density of the invading fluid. In relatively freshwater, the variations of fluid properties are negligible. Thus hydraulic conductivity is a measure of the resistance to flow through the porous medium. Sandstone hydraulic conductivities are derived from the results of field tests involving either single or multiple wells and laboratory measurements of small samples from the outcrop or coring. Because of the variability of natural porous media, the hydraulic conductivity is a log-normally distributed parameter in most instances. The "average" value for the log-normal distribution is the geometric mean of the distribution.

Twenty-two reliable values of hydraulic conductivity from field hydraulic tests of wells in the upper Dakota aquifer of Kansas were found in the literature or were derived from field tests conducted for the Dakota Aquifer Program. Most of the values come from pumping tests where the Dakota aquifer is shallow in central and southwestern Kansas. The hydraulic conductivity data from the field hydraulic testing range from 3.6 to 88 ft (1.2–29.3 m)/day with a geometric mean value of 12.5 ft (4.2 m)/day (fig. 6A). The highest hydraulic conductivities are generally found in the outcrop or near the outcrop areas of the Dakota aquifer in central Kansas and the lowest values in southwestern Kansas. In fig. 7 similar trends can be observed in the results from lab tests on core samples of the sandstones from the Dakota aquifer in central and northwest Kansas. Core samples of sandstone from central Kansas appear to be more permeable than core samples of sandstone from northwest Kansas. The test results suggest that hydraulic conductivity is generally highest in the better-sorted and coarser sandstones. These sandstones are most common in the lower sections of thick, multi-story fluvial- and distributary-channel sandstone bodies found in central Kansas.

The transmissivity of a confined (or an unconfined) aquifer is the product of the hydraulic conductivity of the aquifer and its thickness:

$$T = Kb, \qquad \text{(eqn. 1)}$$

where *T* is the transmissivity (L^2/T), *K* is the hydraulic conductivity (*L/T*), and *b* is the aquifer thickness. The letters *L* and *T* refer to length and time, respectively. The hydraulic conductivity is a measure of the overall resistance of the aquifer framework to the flow of water per

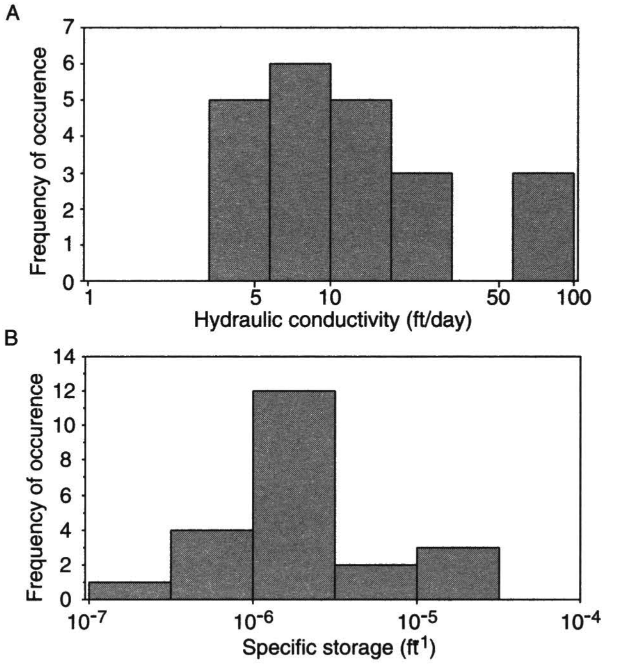


FIGURE 6—DISTRIBUTION OF HYDRAULIC CONDUCTIVITY (A) AND SPECIFIC STORAGE (B) VALUES FROM 22 PUMPING TESTS OF DAKOTA AQUIFER IN KANSAS.

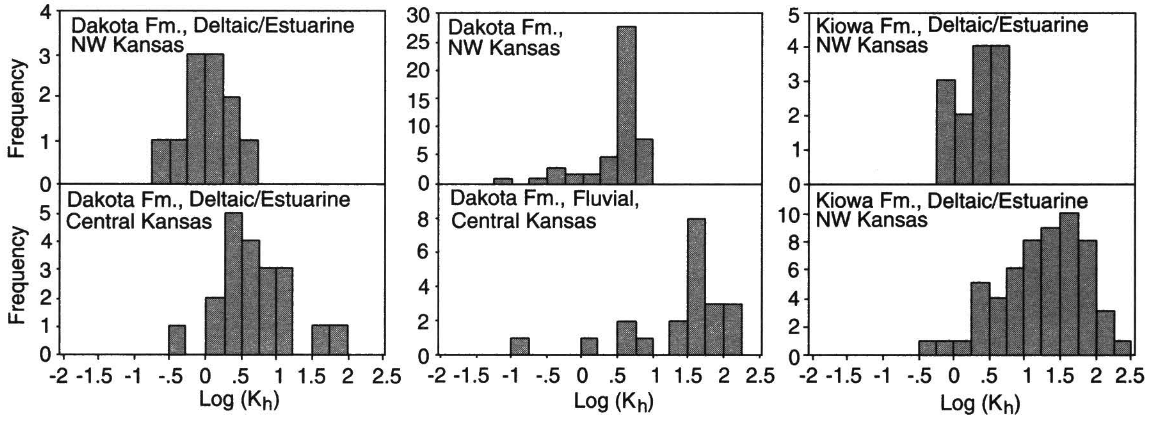


FIGURE 7—HISTOGRAMS OF HORIZONTAL HYDRAULIC CONDUCTIVITY OF FLUVIAL AND SHOREFACE SANDSTONES FROM DAKOTA AND KIOWA FORMATIONS IN KGS #1 JONES (CENTRAL KANSAS) AND #1 BEAUMEISTER (NORTHWESTERN KANSAS).

unit width. Hence, transmissivity is a measure of the ability of the aquifer to transmit water through its entire thickness.

For the upper Dakota aquifer, transmissivities vary widely and generally increase from west to east because of the eastward increase in hydraulic conductivities and net thickness of sandstone. The occurrence of thicker and more permeable units in central Kansas may result from the dominance of alluvially deposited sandstones in the upper Dakota. In southwestern Kansas, the reported transmissivities are less than 2,100 ft^2/day (189 m^2/day). In central Kansas, transmissivities of the thicker river-deposited sandstones range from 2,000 to more than 7,000 ft^2/day (630 m^2/day). In comparison, the transmissivities reported for pumping tests in High Plains and alluvial valley aquifers are generally higher, reflecting the more permeable nature of the aquifer. Reported values range from 1,400 to 62,000 ft^2/day (126–5,580 m^2/day) for the High Plains aquifer.

Direct field or laboratory tests on the mudstone matrix were not conducted in the Dakota Aquifer Program. However, a vertical hydraulic conductivity of 0.0022 ± 0.0006 ft (0.066 ± 0.018 cm)/day was calculated from a pumping test in Washington County. The analysis of other pumping test results from the confined Dakota near the outcrop in central Kansas reveals that the vertical hydraulic conductivity of the mudstone is considerably less than 0.001 ft (0.03 cm)/day, perhaps by several orders of magnitude.

The release of water from storage in confined aquifers is analogous to the process of consolidation in soil mechanics. Water is released from storage by (1) the expansion of water under confinement due to the decrease in fluid pressure to atmospheric pressure, and (2) the consolidation of the confined aquifer framework due to the release of water. These two phenomena are expressed jointly in the specific storage term:

$$S_s = \rho g \,(\alpha + n\beta) \qquad \text{(eqn. 2)}$$

where ρ is the water density mass (M) per unit volume (M/L^3), g is the acceleration of gravity (L/T^2), and α and β are the compressibilities of the aquifer framework and the water, respectively (LT^2/M). In eqn. 3, the compaction of the framework is reflected in α and that of the water is reflected in the $n\,\beta$ term. In most cases the consolidation of the aquifer framework is the most important influence on the specific storage. The storativity is the product of the specific storage and the thickness of the sandstone aquifer.

Twenty-two reliable values of specific storage from field hydraulic tests of wells in the Dakota aquifer of Kansas were found in the literature or were derived from field tests conducted for the Dakota Aquifer Program. Most of the values come from pumping tests where the Dakota aquifer is shallow in central and southwestern Kansas. Values of specific storage range from 1.5×10^{-7} ft^{-1} up to 2.9×10^{-5} ft^{-1}, which is within the expected range of values for confined sandstone aquifers. In fig. 6B, the data appear to be log-normally distributed with a geometric mean of 2.1×10^{-6} ft^{-1}.

Both the transmissivity and the storativity determine the effect of well pumping on aquifers as will be discussed in a later section. In general, the higher the transmissivity and storativity of the aquifer the greater the yield to a pumping well. Well yields typically range from less than 25 up to 750 gal/min (95–2,850 L/min).

Other Significant Aquifer and Aquitard Units Influencing the Dakota Aquifer

Over its extent in Kansas, the Dakota Formation is overlain by younger Upper Cretaceous bedrock units and Cenozoic unconsolidated deposits (table 1; fig. 8). The Upper Cretaceous sequence consists of shale, chalk, and limestone belonging to the Graneros Shale, the Greenhorn Limestone, the Carlile Shale, the Niobrara Chalk, and the Pierre Shale. In Kansas, the total thickness of this sequence generally increases to the west and north up to more than 2,000 ft (600 m) in the northwest corner of the state. These stratigraphic units form the Upper Cretaceous aquitard. The Dakota is considered a confined aquifer system where it is overlain by the Upper Cretaceous aquitard (fig. 8). In most of southwest and most of south-central Kansas and much of southeastern Colorado, the Upper Cretaceous aquitard has been eroded and the Dakota is overlain by and hydraulically connected to the High Plains aquifer (fig. 8). In the river valleys of the central part of the state, the Dakota aquifer is in hydraulic connection with the overlying saturated alluvial deposits which form the alluvial-valley aquifers (fig. 8).

Westward-dipping Jurassic and Permian rocks directly underlie the Dakota aquifer in Kansas. The subcrop of the Jurassic Morrison Formation beneath the Cretaceous is generally in the western part of the state, whereas the Permian subcrop is in the central part. In southwestern Kansas and southeastern Colorado, the Morrison and Dockum Groups form the Morrison–Dockum aquifer. The Morrison in southwestern Kansas consists mostly of sandstone and is a source of freshwater along with the Cheyenne Sandstone. Upper and lower Permian rocks consist of shale, siltstone, sandstone, and bedded salt with minor amounts of limestone and dolomite. Outside of southwestern Kansas, the Morrison, and the Permian and Pennsylvanian sequences form a thick regional aquitard. However, sandwiched within this aquitard is the Cedar Hills Sandstone aquifer which subcrops beneath the lower Dakota aquifer in central Kansas (table 1; fig. 8). The Cedar Hills Sandstone aquifer consists of the Permian Cedar Hills Sandstone and the sandstones and shaly sandstones at the top of the underlying Salt Plain Formation.

Steady-State Ground-water Flow System in the Dakota Aquifer

Without exception, ground water is constantly moving from points of recharge where it enters the subsurface hydrologic system to points of discharge where it exits back to the surface. The flowpaths taken by ground water are determined by the arrangement of aquifer and aquitard units and the land-surface topography. Some of the water only travels a short distance through the shallow subsurface from local recharge to local discharge areas. However, some water travels a much longer distance from regional recharge to discharge areas through the deeper subsurface. All the subsurface flowpaths from recharge to discharge areas taken together define a flow system that includes lateral flows within all the aquifer units and across all the aquitard units.

To define the pattern of moving ground water in a flow system, hydrogeologists use measurements of water-level elevation taken in wells distributed throughout all the regional aquifer in a ground-water basin. In most cases, the water-level elevation equals the hydraulic head in a well. The hydraulic head at any point in the flow system is a measure of the potential energy per unit weight of ground water at that point. The movement of ground water involves a loss of energy and is similar to the flow of water in river systems. Water naturally flows downhill from elevated regions of the continent (higher hydraulic head) to the sea (lower hydraulic head). In much the same way, but more slowly, ground water moves from points of higher hydraulic head to points of lower hydraulic head in a flow system. Most of the hydraulic-head data used to define the flow system come from the aquifer units. In wells tapping a confined aquifer, the water level is above the aquifer top whereas in an unconfined aquifer, the water-level (water-table) datum is the aquifer top. Hydraulic-head data are typically unavailable for the aquitard units. As a result, ground-water flow across the aquitards must be inferred from hydraulic-head measurements in the adjacent aquifer units.

Influences on the Flow System

In the central Great Plains, the ground-water flow system in the Dakota aquifer is influenced primarily by regional and local topography and the Upper Cretaceous aquitard. Hydrogeologists have long observed that the water table or the top of the saturated zone mimics the topography of the land surface. The land surface in the region slopes generally to the east and decreases in elevation from 5,000 ft (1,500 m) or more in eastern Colorado to 1,400 ft (420 m) or less in central Kansas (fig. 9). This decrease in elevation results in an easterly flow of ground water across the region in all the aquifer systems.

Due to its great thickness and extremely low permeability in the Denver basin of eastern Colorado, the Upper Cretaceous aquitard hydrologically isolates the flow system in the Dakota from the overlying water table. The aquitard is as much as 10,000 ft (3,000 m) thick in the

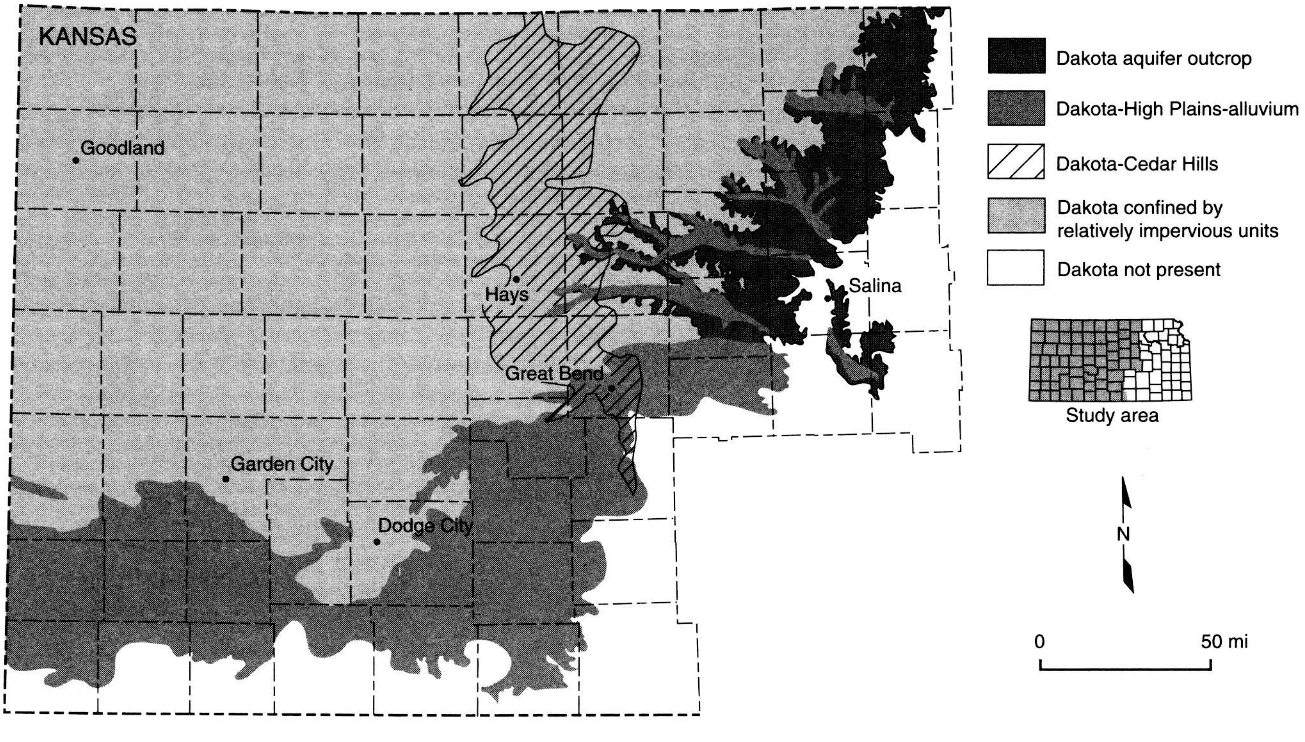


FIGURE 8—Extent of Dakota aquifer in Kansas showing regions of hydraulic connection to other aquifers, where Dakota is a near-surface aquifer, and where it is confined by relatively impervious units.

deepest part of the basin adjacent to the Front Range of the Rocky Mountains. Here, the hydraulic heads in the Dakota aquifer are more than 2,500 ft (750 m) lower than the elevation of the overlying water table (fig. 10). An aquifer is usually considered in good hydraulic communication with the overlying water table if there are only small head differences between them. The regional flow models have shown that the aquitard restricts the downward movement of recharge to the Dakota to near negligible levels.

However, away from the basin center in Kansas and southeastern Colorado, the Upper Cretaceous aquitard thins toward its extent in central and southwestern Kansas. As a result, its control on the flow system in the Dakota aquifer diminishes toward the outcrop/subcrop belt. Within the last 10 million years, differential uplift and intense local dissection of the High Plains surface have created considerable local and regional topographic relief. Incisement is a common feature of the drainage in the Arkansas River basin in southeastern Colorado and southern Kansas and in the Smoky Hill, Saline, and Solomon River systems in north-central Kansas. Many of these river systems have cut down through the aquitard and into the geologic units that constitute the Dakota aquifer system. Consequently, the head difference between the Dakota and the overlying water table is less than 1,000 ft (300 m) in most of western and central Kansas and southeastern Colorado where the confined aquifer is relatively shallow (figs. 9 and 10). Here, local topographic relief is an important influence on groundwater flow in the Dakota aquifer so that changes in water-table elevations across the area parallel the land-surface elevations (fig. 9).

Geologic processes also have played an active role in changing the boundary conditions of the flow field and the hydraulic properties and composition of the hydrostratigraphic framework. Periods of deposition, erosion, and tectonic activity associated with the Laramide Orogeny at the close of the Cretaceous Period and cycles of erosion and deposition that occurred in the Quaternary have undoubtedly induced significant changes in the flow system over time. Climatic change associated with the last glacial period may have increased or decreased recharge to the regional aquifers. These geologic processes and variations in recharge would have changed the elevation and configuration of the regional water table and pore pressures in low-permeability porous media. As a result, it is possible that an overprint of a more recent flow system on an older one is causing the regional system to adjust to a new steady-state condition. However, it is believed that if the flow system is still adjusting to a new equilibrium configuration, the changes in hydraulic head caused by the adjustments are relatively minor in comparison to the large hydraulic-head differences in the aquifer systems between eastern Colorado and central Kansas.

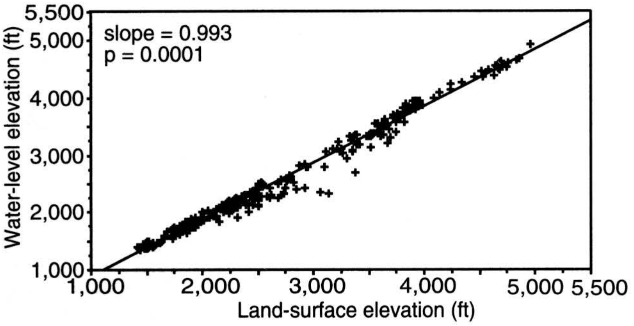


FIGURE 9—WATER-LEVEL ELEVATION VERSUS LAND-SURFACE ELEVATION IN THE CONFINED DAKOTA AQUIFER, SOUTHEASTERN COLORADO AND WESTERN AND CENTRAL KANSAS. The slope of the best-fit line from regression is 0.993, which is significant ($p = 0.001$). The larger negative deviations of data from the fitted line indicate the greater influence of the Upper Cretaceous aquitard on the flow system between 3,000-ft (900-m) and 3,700-ft (1,110-m) land-surface elevation.

Ground-water Flow Patterns in the Dakota Aquifer

Figure 11 is a potentiometric surface map of the upper Dakota aquifer in Kansas and extreme southeastern Colorado as it might have appeared in the early 1900's. The water-level data used to produce the map come from records of the earliest wells drilled in the region. Because the aquifer is shallower nearer the outcrop/subcrop region, the data are more numerous in this region than in areas to the north where the Dakota is much deeper and water-resources development of the aquifer has been minimal. As a result the map accuracy is much better in southwestern and central Kansas than it is in northwest Kansas where there are only a few scattered measurements. Another factor limiting map accuracy is that the data used to assemble the map are not all from the same time period. Many of the water-level measurements were made in wells that were installed in the 1940's through the 1960's. This is because development of water resources in the Dakota began at different times in different places. To limit the amount of introduced error, only the earliest measurements taken in any one area were used to generate the equipotentials on the potentiometric surface map. An insufficient number of measurements are available to define the regional potentiometric surface of the lower Dakota aquifer. The potentiometric surface of the lower Dakota is assumed to be similar to but not the same as the potentiometric surface of the upper Dakota at the regional scale.

The potentiometric-surface map in fig. 11 shows that the hydraulic head in the upper Dakota is higher to the south of the Arkansas River in southeastern Colorado than elsewhere to the north and east. On the map the equipotentials are arranged concentrically around a hydraulic-head maximum in this area and decrease rapidly to the north and east of this region. This indicates northeastward

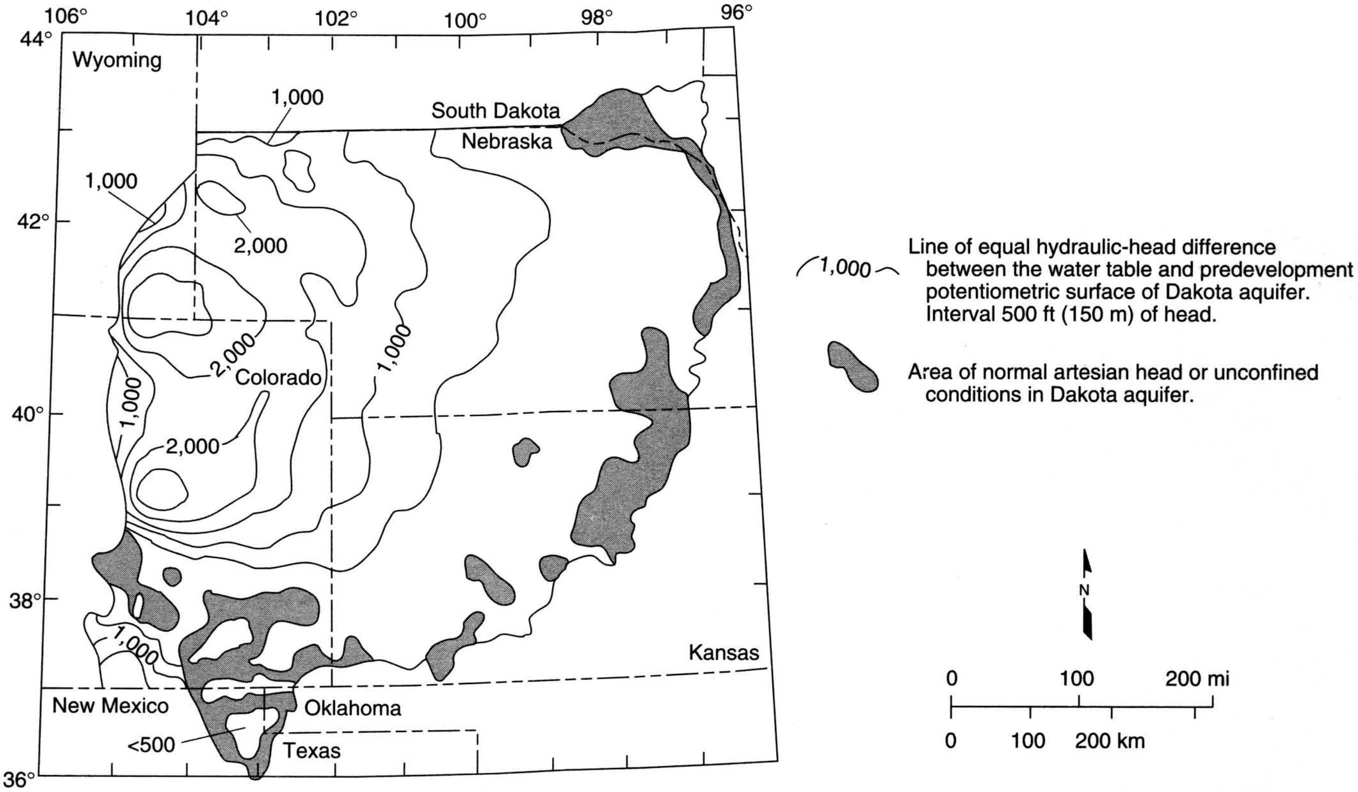


FIGURE 10—HYDRAULIC-HEAD DIFFERENCE BETWEEN DAKOTA AQUIFER AND OVERLYING WATER TABLE IN THE DENVER BASIN AND ADJACENT AREAS TO THE EAST. Modified from Helgesen et al. (1993).

flow away from an area of recharge in the upper Dakota. The total recharge from precipitation depends on the downward movement of water below the root zone to the water table or seepage into exposed bedrock outcrops. Within this recharge area in southeastern Colorado, a part of the upper Dakota underlies and is hydraulically connected to the High Plains aquifer. The total amount of seepage downward into the Dakota from the High Plains depends on the hydraulic connection between the two aquifers and the hydraulic-head gradient. As the conceptual model in fig. 12 shows, most of the recharge to the upper Dakota is intercepted by local shallow flow systems that discharge back to the surface drainage within the recharge area. Consequently, the age of ground water in this part of the system is generally less than 10,000 years.

Within the confined aquifer, the ground water moves slowly northeastward toward the regional discharge area in central Kansas due to low aquifer transmissivity (figs. 11 and 12). Over most of western Kansas, the vertical hydraulic conductivity of the overlying Upper Cretaceous aquitard is very low, on the order of 1×10^{-7} ft/day or less. Freshwater recharge to the confined Dakota is negligible, less than 0.1% of the lateral flow within the aquifer (fig. 13). Most of the freshwater recharge to the confined Dakota enters where the aquitard is relatively thin and dissected near the outcrop/subcrop areas. Here, the vertical hydraulic conductivity is two to three orders of magnitude higher, and recharge from overlying sources may amount to as much as 10% of the lateral flow within the aquifer. In central Kansas, an additional source of recharge to the Dakota comes from the underlying Cedar Hills Sandstone where both aquifers are hydraulically connected (fig. 12). The total recharge from this source amounts to less than 1% of the lateral flow in the upper Dakota aquifer.

The potentiometric-surface map in fig. 11 indicates that the hydraulic head in the Dakota aquifer is lower in north-central Kansas than elsewhere. Beneath most of the river valleys, the hydraulic head in the Dakota is higher than the water level in the streams and may be higher than the land-surface elevation. This suggests that ground water in the Dakota is moving toward these river valleys from elsewhere in the region and is discharging to streams or to the surface along the sloping valley sides in springs. In the outcrop areas, the flow system in the Dakota is influenced by both regional flow from the confined Dakota to the west and local flow systems that result from local topographic relief. These local systems are replenished by infiltration of local recharge that may be discharged from the aquifer at points up to a few tens of miles away. Also, pumping-test results suggest that the Dakota is generally more permeable in this region than it is to the west. Computer simulations of the steady-state-flow system indicate that the flux of freshwater through the outcrop/

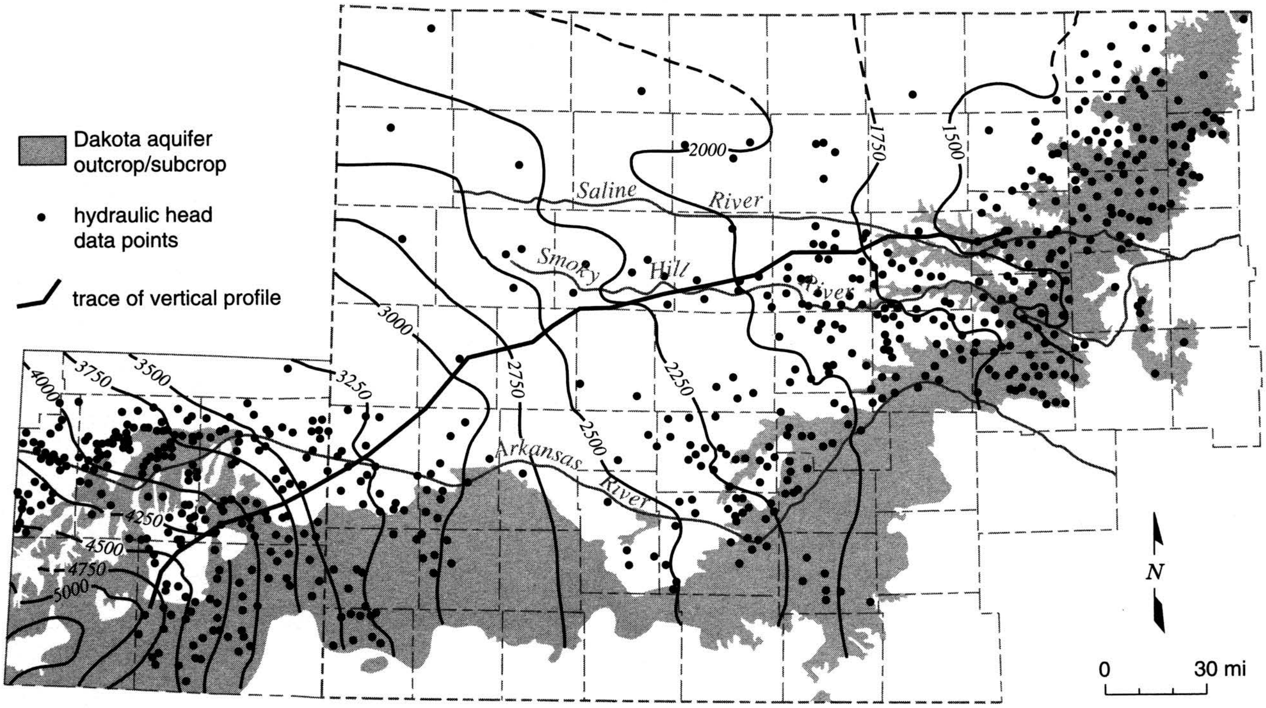


FIGURE 11—ELEVATION IN FEET ABOVE MEAN SEA LEVEL OF THE PREDEVELOPMENT POTENTIOMETRIC SURFACE OF THE DAKOTA AQUIFER IN SOUTHEASTERN COLORADO AND WESTERN KANSAS. The shaded area shows the area of outcrop, primarily in central Kansas, and subcrop beneath Pleistocene and Tertiary deposits in southwestern Kansas and southeastern Colorado. Hydraulic-head data are from the U.S. Geological Survey's Central Midwest Regional Analysis Program.

subcrop belt is several times higher than in the confined aquifer to the west. In the Washington County area, the annual recharge to the Dakota is estimated to be on the order of 0.25 inches (0.625 cm) where the aquifer is unconfined. As a result, fresh and saline water springs and seeps can be found in the river valleys. Salt marshes associated with saltwater discharge to surface water are common features in the Saline, Solomon, and Republican River valleys of north-central Kansas (fig. 14). During low-flow periods when baseflow constitutes the bulk of stream discharge, the chloride concentration of surface waters escalates rapidly (fig. 15). Elsewhere, freshwater is discharged from the upper Dakota to the Arkansas, Pawnee, and Wet Walnut River drainages.

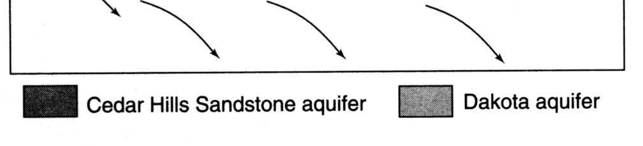


FIGURE 12—CONCEPTUAL MODEL OF GROUND-WATER FLOW THROUGH THE CONFINED DAKOTA AQUIFER FROM THE REGIONAL RECHARGE AREA IN SOUTHEASTERN COLORADO TO THE REGIONAL DISCHARGE AREA IN CENTRAL KANSAS. The trace of the cross section is shown on fig. 3. Most of the recharge to the Dakota aquifer is routed back to the surface by local flow systems in central Kansas and southeastern Colorado.

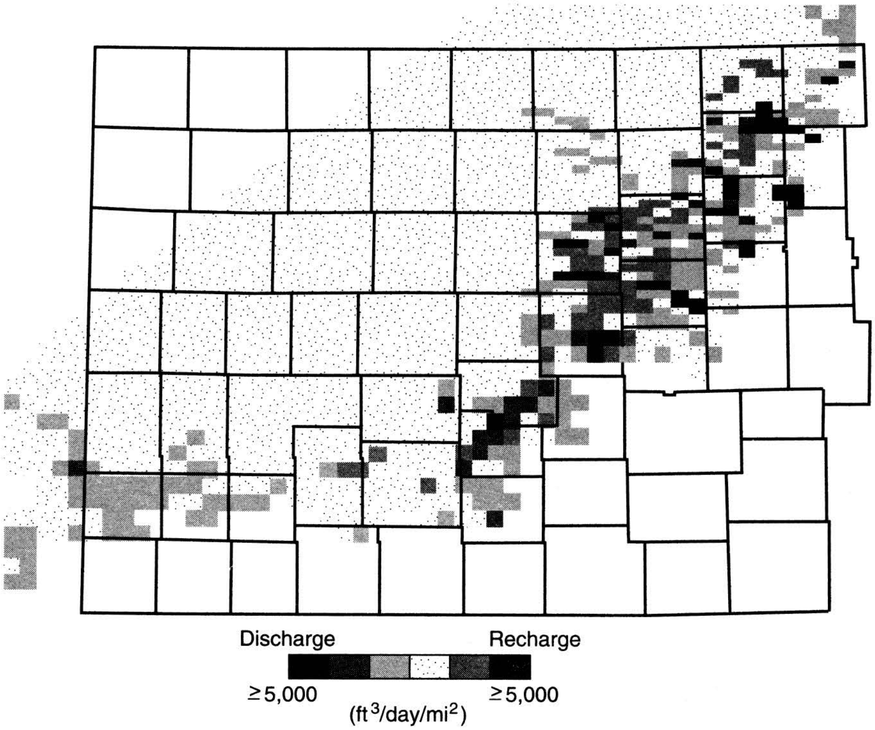


FIGURE 13—Recharge and discharge from the Dakota aquifer in units of $ft^3/day/mi^2$.

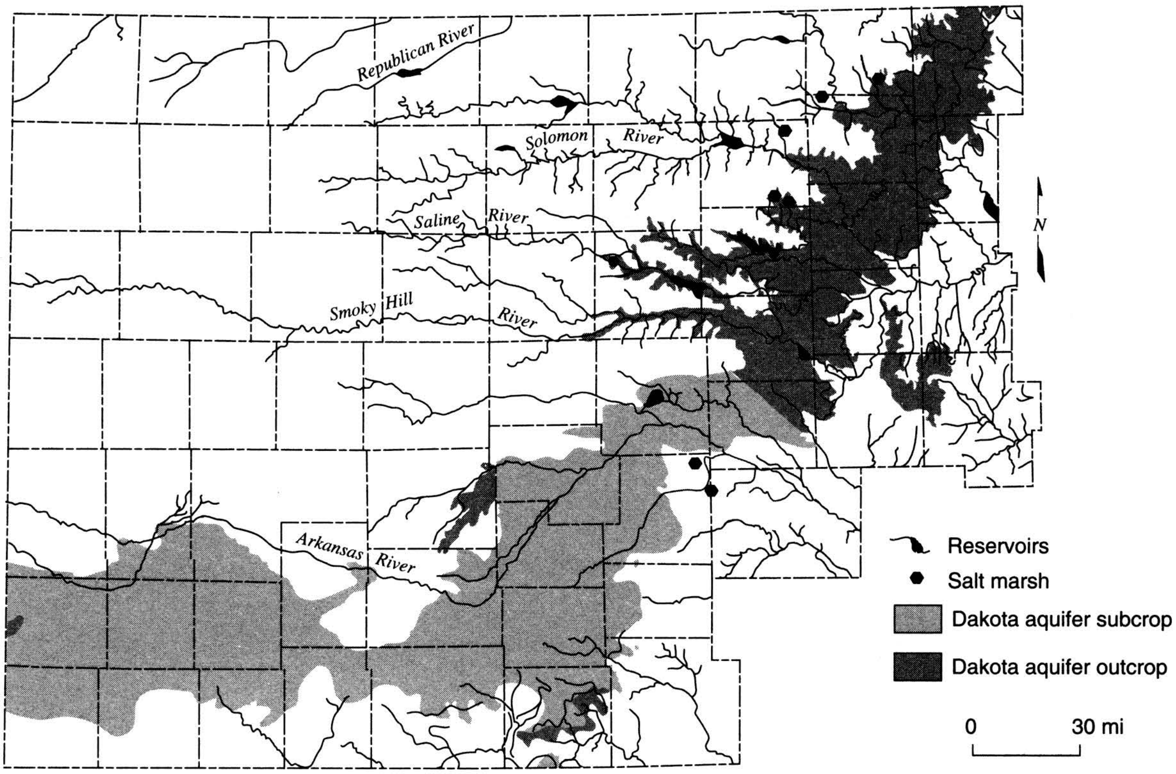


FIGURE 14—Location of salt marshes in central Kansas. Many of these features are associated with discharge from the Dakota aquifer.

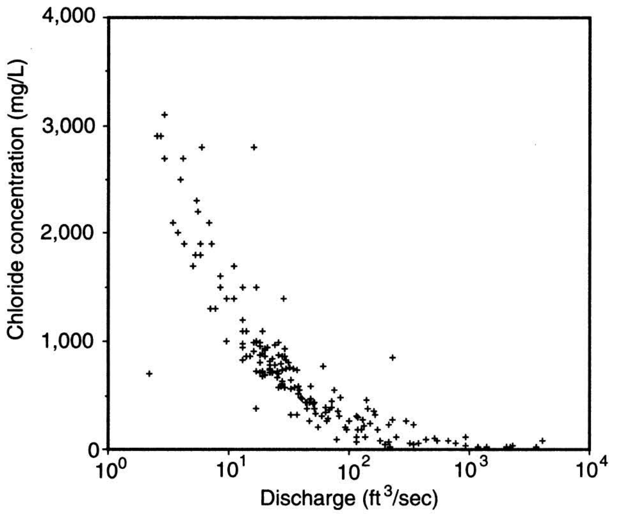


FIGURE 15—STREAM DISCHARGE VERSUS CHLORIDE CONCENTRATION AT THE SALINE RIVER GAGING STATIONS NORTH OF RUSSELL, KANSAS.

Ground-water Quality

Factors Controlling Water Quality

The quality of ground water depends primarily on the type and concentration of dissolved substances in the water. These substances can be dissolved gases and inorganic and organic solids. In addition, particulates that might accompany water flowing from a well may be of concern. These include sediment from the subsurface formation, microorganisms, and chemical precipitates that might form as a result of the disturbances brought about by the well. The concentrations of the dissolved and particulate substances are of interest because they can affect the water use or operation of the well. One of the most common considerations is whether the concentrations of constituents fall below levels mandated or recommended for drinking-water supply. Table 2 lists the maximum and recommended concentrations for common major, minor, and trace constituents naturally present in Dakota aquifer water. The concentrations are values listed by the Kansas Department of Health and Environment and were adopted mainly from the U.S. Environmental Protection Agency for implementation of the Safe Drinking Water Act.

Natural rainfall contains dissolved air and a very small amount of dissolved solids. During the travel of rainfall through soil, sediment, and rock to reach an aquifer, the water dissolves additional solids. Most of the soluble solids picked up by the water are inorganic because inorganic minerals are the main component of soils, sediments, and rocks; natural organic substances also tend to be less soluble than common mineral salts. Water flowing deeper into the subsurface may encounter very soluble minerals such as rock salt and produce saltwater after dissolving the salt. Other deep subsurface waters can be highly saline because they were originally trapped seawater that has been further altered through geologic time.

The **total dissolved solids** content (often abbreviated TDS) is a general measure of the salinity of a water. The most common substances contributing to the dissolved solids of most ground waters are the inorganic constituents calcium, magnesium, sodium (positively charged **cations**) and bicarbonate, chloride, and sulfate (negatively charged **anions**). Bicarbonate may also be represented as alkalinity in some water analyses. Inorganic constituents commonly contributing minor amounts to ground-water TDS are silica (uncharged), potassium (a cation), and nitrate and fluoride (anions). There are a large number of other individual and combined elements dissolved in water, including gases and metals. Table 2 lists the names, properties, and chemical symbols or representation for common major and minor dissolved inorganic substances, as well as several dissolved metals in Dakota aquifer waters. Concentrations of these dissolved substances are often reported as milligrams per liter (abbreviated mg/L). This concentration unit is essentially the same as a part per million (ppm) in freshwater, because the weight of a liter of water with dilute concentrations of dissolved constituents at ground-water temperatures is very close to 1,000 grams (one million milligrams). (In saltwater, a mg/L is a few percent different from a ppm because the density of the solution is greater than for freshwater.) Concentrations of trace amounts of dissolved constituents are often listed as micrograms per liter (μg/L), which is very close to parts per billion (ppb) in freshwater.

Freshwater is often defined as water containing less than 1,000 mg/L TDS. Freshwaters in the outcrop and subcrop portions of the upper and lower Dakota aquifers are usually calcium bicarbonate or calcium, magnesium 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 ($CaCO_3$). The calcite contains small amounts of magnesium and the mineral dolomite ($CaMg(CO_3)_2$) can also be present. During infiltration of rainfall, the carbonate minerals dissolve and add calcium, magnesium, and bicarbonate to the water. Small amounts of other inorganic constituents also are dissolved from soils and near-surface rocks. These substances are present in the main carbonate minerals and in the small amounts of other soluble minerals, are adsorbed on clays, or have been concentrated as salts in soils during dry periods. Typical ranges of major constituents and fluoride concentrations in the most common chemical types of Dakota waters are listed in table 3.

Fine-grained sediments in the upper and lower Dakota aquifers and overlying rocks often contain the mineral pyrite (FeS_2). The pyrite weathers to produce dissolved iron and sulfate. The iron can then oxidize and precipitate as iron oxide and oxyhydroxide (hydrous oxide), which

TABLE 2—Chemical properties, general concentration ranges, and water-quality criteria for dissolved inorganic substances and selected metals naturally occurring in Dakota aquifer waters. Natural values of the properties and concentrations can be less or greater than listed in the table but are usually within the general range.

Name	Chemical symbol or representation	General range, mg/L	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 0.05	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 Kansas Department of Health and Environment (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 range widely 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 either 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 of the alkalinity in ground water is bicarbonate. The bicarbonate can be calculated from the 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 often observed but are nearly always the result of human activities. Contaminated Dakota waters have been observed with nitrate.

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

[m] Concentration as ammonia-nitrogen.

[n] Lead concentrations >C.01 are occasionally observed in waters from water-supply wells. These are believed to be mainly related to lead in the piping system.

produces the red to orange coloration commonly occurring in Dakota strata. The solution from pyrite weathering is acidic and dissolves additional calcite in a natural neutralization process. These processes increase the calcium and sulfate concentrations dissolved in Dakota waters. Rocks overlying the Dakota aquifer such as the Graneros Shale often include gypsum ($CaSO_4 \cdot 2H_2O$), a very soluble mineral. Water infiltrating through these rocks can have relatively high concentrations of calcium and sulfate from dissolving gypsum. Recharge passing through rocks with gypsum and entering Dakota strata can substantially increase the calcium and sulfate content of waters in the upper aquifer. In some cases calcium sulfate waters may result, although this water type is not as common as other chemical types in ground water from the Dakota (table 3).

Large areas of the Dakota aquifer contain saltwater (primarily dissolved sodium and chloride). Concentrations of TDS can be in the tens of thousands of mg/L (table 2). Geochemical tests have identified the main source of this saltwater as dissolution of rock salt (NaCl) in Permian rocks underlying Dakota strata. Although most of the Dakota sediments probably contained seawater either during their deposition (the marine shales and sandstones) or after deposition when the sea covered these units, nearly all of the seawater has been flushed out by surface recharge. However, saltwater from the 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.

The past occurrence of saline water in Dakota aquifer strata resulted in the adsorption of large amounts of sodium on the clays in the shales, siltstones, and sandstones. As freshwater of calcium bicarbonate type slowly flushed the saline water from the aquifer, the process of natural softening of the water occurred as dissolved calcium and magnesium adsorbed on the clays and released sodium to solution. The decrease in calcium concentration allowed some calcite to dissolve where present in aquifer strata, thereby supplying additional calcium and bicarbonate to the water. The added calcium was then available for more cation exchange with sodium. Some additional bicarbonate may have been generated from slow oxidation of organic matter trapped in the aquifer framework. The combined effect of these processes increased dissolved sodium and bicarbonate concentrations while decreasing dissolved calcium, magnesium, and chloride concentrations in confined parts of the Dakota aquifer where the water is now fresh to slightly saline. The water types range from sodium bicarbonate to sodium chloride, bicarbonate to sodium chloride with excess sodium in the direction of increasing salinity. These waters are typically soft because the calcium and magnesium concentrations are relatively low. Typical ranges of major dissolved constituents in sodium bicarbonate waters in the Dakota aquifer are listed in table 3.

The pH of the sodium bicarbonate waters in the confined upper Dakota is alkaline and usually in the 7.5 to 8.5 range (pH is a measure of how acidic or alkaline a water is; a value of 7.0 units represents a neutral solution at room temperature). Elevated concentrations of dissolved fluoride also are usually associated with the sodium bicarbonate waters, ranging from over 1 mg/L to several or more mg/L in comparison with less than 1 mg/L for calcium bicarbonate type waters. The high fluoride levels derive from calcium minerals containing fluoride (probably mainly apatites). The low calcium concentration resulting from the cation exchange that produced the sodium bicarbonate water allowed the calcium minerals to dissolve. Some fluoride adsorbed or weakly attached to clays was released in the higher pH waters by exchange with hydroxyl ion (OH^-).

Other naturally occurring constituents of interest in upper Dakota waters are iron and manganese. Dissolved concentrations of iron range from less than a few µg/L to over 10 mg/L and manganese concentrations range from less than a µg/L to nearly a mg/L. The greater concentrations occur in two types of environments. One is in the outcrop or subcrop area of the Dakota aquifer where recharge containing dissolved oxygen reaches strata containing pyrite. Oxidation of pyrite was referred to earlier as a source of sulfate as well as dissolved iron in ground waters. Such waters can have a pH between 6 and 7 (very slightly acidic). The other type of environment exists where reactions with dissolved constituents and sediments have essentially completely consumed dissolved oxygen and produced a chemically reducing environment. This commonly occurs in the confined portion of the Dakota aquifer because the water is old, and no recent recharge with significant oxygen can enter. 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 be over a mg/L in the reducing environment (table 2).

Regional Water-quality Patterns

Figure 16 shows the distribution of total dissolved solids (TDS) concentrations in the upper Dakota aquifer. The present salinity pattern of Dakota waters is mainly dependent on the rate at which freshwater is able to enter from above and move along the long flow paths in the aquifer in comparison with the rate of saltwater intrusion from the 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. 8). In northwest Kansas the thickness of the confining units is great and the amount of freshwater throughflow 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 has also 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 rate of flushing is slow, such that substantial changes would take many thousands of years. In general, the greater the distance from the edge of the confining zone, the greater the salinity.

Ground water in the areas of the upper Dakota aquifer with high TDS or salinity (greater than 5,000 mg/L) shown in fig. 16 are of sodium chloride type. Waters in the area of the confined aquifer with 500-2,000 mg/L TDS are generally soft (low calcium and magnesium content), sodium bicarbonate in chemical type, and usually have elevated fluoride concentrations. Ground water with 2,000 to 5,000 mg/L TDS in the confined area is typically transitional between sodium bicarbonate and sodium chloride type. Waters in the outcrop and subcrop areas with less than 500 mg/L TDS usually are of calcium bicarbonate and sometimes of calcium, magnesium bicarbonate type. Concentrations of TDS between 500 and 2,000 mg/L in waters in the outcrop/subcrop areas are often due to high calcium and sulfate levels such that the waters can be calcium sulfate in type. Elevated sulfate concentrations can also produce sulfate type waters in less saline portions of the confined aquifer.

Figures 17 and 18 show the change in the relative concentrations of selected constituents in waters from supply wells along a traverse from the recharge area in southeastern Colorado, through the confined Dakota aquifer in western Kansas to the discharge area in central Kansas (see the cross section line on fig. 12). Although chloride is the predominant anion contributing to the large increase in TDS concentration in the Dakota aquifer in central Kansas (fig. 16), other anions are more important for TDS increases in western Kansas, as indicated by the relatively low chloride content (<100 mg/L) north to about R. 33 W. (fig. 17). Sulfate and chloride concentration of ground waters in the overlying High Plains aquifer and in the Dakota aquifer to the south near and within the unconfined areas tend to be substantially lower than in Dakota aquifer waters well within the confined-aquifer area.

Sodium concentration in Dakota waters (fig. 17) follows a similar pattern as TDS along the cross section. The increase in sodium concentration along the flow path is derived from both softening (cation exchange with calcium and magnesium) and increased intrusion of saltwater from the underlying Permian as the waters approach central Kansas. In contrast, dissolved calcium and magnesium concentrations decrease appreciably from the local flow area of southeastern Colorado to the confined Dakota aquifer in western and central Kansas (fig. 18). Ground waters in southeastern Colorado derive calcium and magnesium from leaching of carbonate minerals concentrated in soils in an environment of greater evapotranspiration than precipitation, and also from carbonate minerals in the aquifer rocks. The aquifer is well flushed in this area, thus any saline water has been essentially removed, and sodium and chloride concentrations in the ground water are low. The flushing in the Dakota aquifer in southeastern Colorado has been extensive enough to also remove high sodium contents adsorbed on clays deposited in brackish or marine environments or subjected to later saltwater intrusion from underlying Permian strata. Thus, any former capacity to soften recharge waters has been largely removed, and recharge retains its higher calcium plus magnesium than sodium content.

TABLE 3— TYPICAL RANGES OF MAJOR CONSTITUENT AND FLUORIDE CONCENTRATIONS IN THE MOST COMMON TYPES OF GROUND WATER IN THE DAKOTA AQUIFER. The water types are listed in order of generally increasing total dissolved solids (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

When the calcium bicarbonate to calcium sulfate type waters flowing deep enough in the system reach the confined portion of the Dakota aquifer in western Kansas, exchange of calcium and magnesium for sodium becomes important. The aquifer in the confined area has not been as well flushed as in the local flow areas, leaving high sodium concentrations on marine clays or on clays subjected to saline waters derived from Permian saltwater intrusion in earlier geologic time. The high exchange capacity of most aquifer clays acts as a reservoir that must be changed by large volumes of interacting waters before the adsorbed cation concentrations approach ratios that are near equilibrium with the recharge waters, and thus no longer appreciably change the inflow chemistry.

Calcium and magnesium concentrations can become as low as a few mg/L each in the confined Dakota aquifer along the cross section in western Kansas. In contrast, the calcium concentrations in overlying High Plains aquifer waters and in the Dakota water from the southern flow path are within the range of the Dakota aquifer waters in southeastern Colorado. The decrease in calcium and magnesium is abrupt near the state line. The calcium plus magnesium/sodium ratio remains low along the northern flow path until the confining layer thins in central Kansas. Flushing of the saline water that intrudes from the underlying Cedar Hills Sandstone and removal of the high adsorbed sodium content on clays by recharge in the local flow area in central Kansas allows the return of the water type to calcium bicarbonate. The calcium plus magnesium/sodium ratio in the High Plains and Dakota waters in the unconfined Dakota aquifer in southwestern Kansas is within the same range as for the Dakota ground waters in southeastern Colorado and in the local recharge-discharge area in central Kansas. Relative changes in fluoride concentrations along the flow path are generally inversely related to the calcium concentrations due to the dissolution of fluoride-containing calcium minerals (fig. 18).

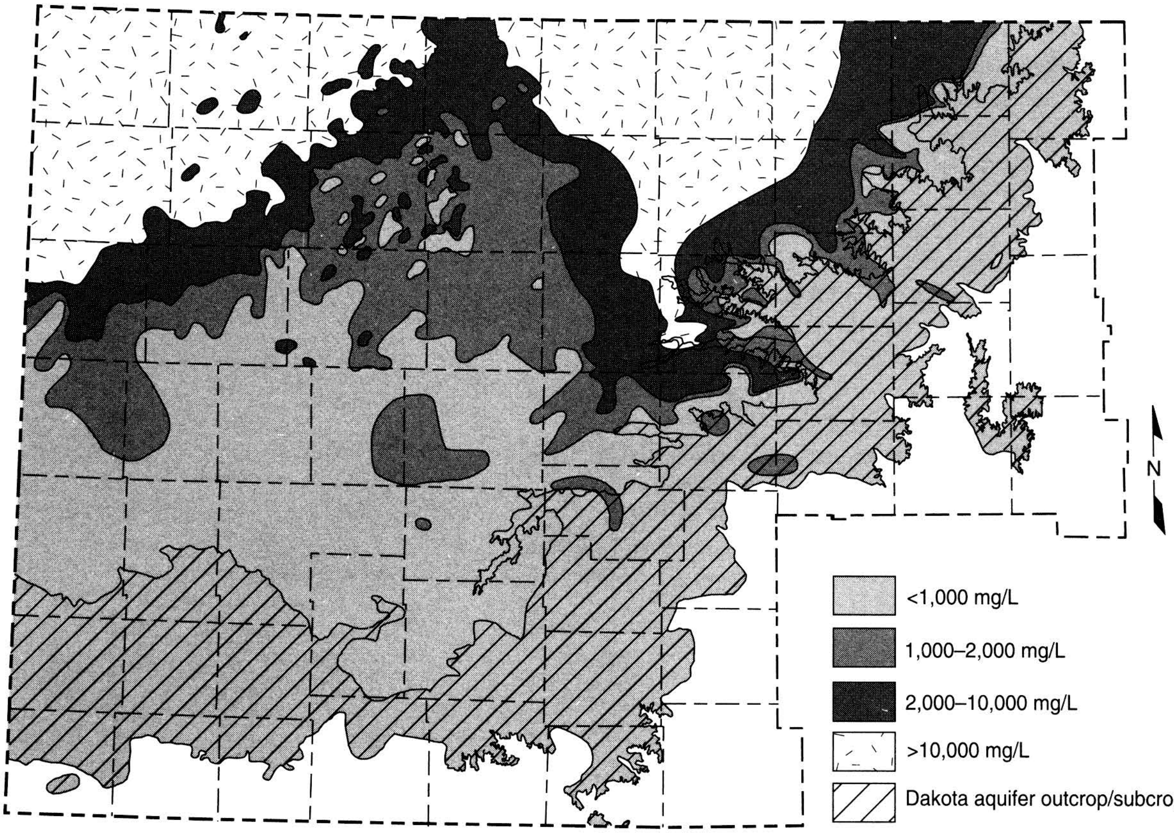


FIGURE 16—Distribution of total dissolved solids (TDS) concentrations in ground waters in the upper Dakota aquifer in western and central Kansas. Water less than 1,000 mg/L TDS is defined as fresh. Water with 1,000–2,000 mg/L TDS is usable for many purposes but is less desirable than freshwater. A concentration of 10,000 mg/L TDS is defined by State statute K.S.A. 55–150 (g) of the Kansas Corporation Commission as the upper limit of usable water; above 10,000 mg/L TDS, water is classified as unusable or mineralized.

Vertical Changes in Water Quality

Where saline waters exist in the Dakota aquifer or in underlying strata, salinity generally increases with depth. The rate of change with depth is seldom uniform; TDS is often substantially greater below local or regional low aquitard units that impede the upward movement of salinity. This is especially true where the Kiowa shale aquitard is present and separates saltwater in the lower Dakota aquifer from fresh or much less saline water in the upper Dakota. An example of this is shown in the change in TDS concentration with depth for a test hole in Ellis County (fig. 19). The depth interval for the Dakota Formation is 295–548 ft (98–183 m) in the test hole; the hole then penetrated the Kiowa Formation starting at 548 ft (183 m) before drilling was stopped at 595 ft (198 m). The TDS content generally increases in waters collected from silty sandstone and sandstone units in the test hole from 375 to 515 ft (125–213 m). The salinity appreciably increases in the test-hole waters sampled from the bottom of a sandstone just above siltstone and shale of the Kiowa Formation, and it continues to markedly increase within the Kiowa.

The substantially greater permeability of the sandstone units within the Dakota aquifer in comparison with the shales can allow a faster rate of flushing of salinity by fresher regional flow. The general inverse correlation of the particle size of the Dakota sediments with TDS concentrations in areas where some salinity exists, primarily in the confined aquifer, means that substantial local differences can occur in both the vertical and areal distribution of water quality depending on the particular sandstone-to-shale ratio. Consequently, often the better the water-yielding characteristics of the aquifer, the better the water quality within a given area. In some locations where a thick sandstone body is found below low-permeability rocks in the Dakota aquifer, the water can be fresher in the sandstone than in the overlying, less-permeable units.

In the confined aquifer, recharge passing through the overlying units can have appreciably higher calcium, magnesium, and sulfate concentrations than in the fresh to slightly saline portions of the upper Dakota aquifer. An example of the changes with depth in these dissolved constituents in the upper Dakota aquifer is illustrated in figs. 20 and 21 for the same test hole in Ellis County as for fig. 19. The decrease in calcium and magnesium and the increase in sodium content caused by the softening process is marked in the upper part of the aquifer. The increase in dissolved sodium with depth is greater than that of chloride in the upper part of the formation, whereas the increase in chloride is greater towards the bottom (fig. 20). The fluoride concentration 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. 20). Fluoride then decreases with depth at the bottom of the Dakota aquifer and into Permian strata where calcium concentrations are much greater in the saline water. Note the parallels of the constituent concentration changes with depth in figs. 20 and 21 to the changes along the cross section (figs. 17 and 18) from the recharge area in southwestern Kansas to the saline water in the confined aquifer in central Kansas.

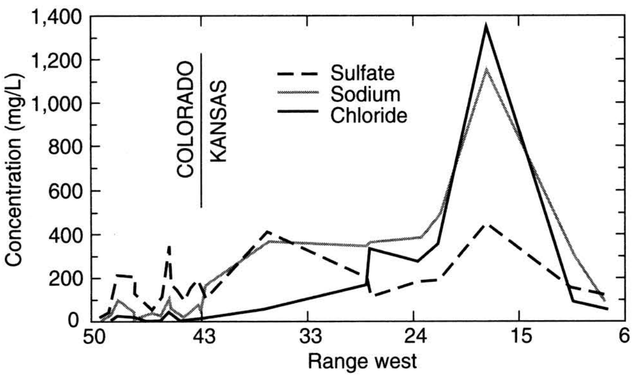


FIGURE 17—Regional profile of sodium, chloride, and sulfate concentrations in ground waters in the upper Dakota aquifer along a cross section from southeastern Colorado to central Kansas. The approximate trace of the profile is shown in fig. 11.

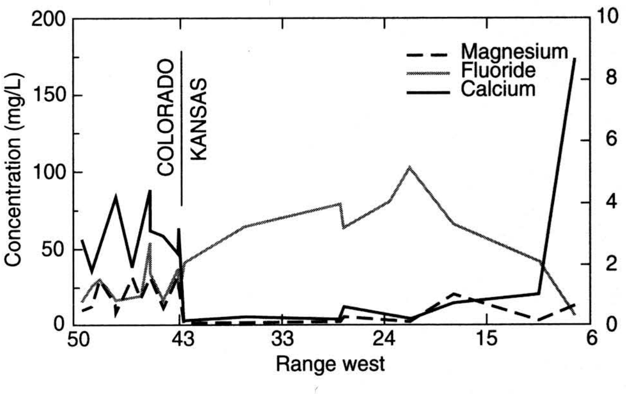


FIGURE 18—Regional profile of calcium, magnesium, and fluoride concentrations in ground waters in the upper Dakota aquifer along a cross section from southeastern Colorado to central Kansas. The approximate trace of the profile is shown in fig. 11.

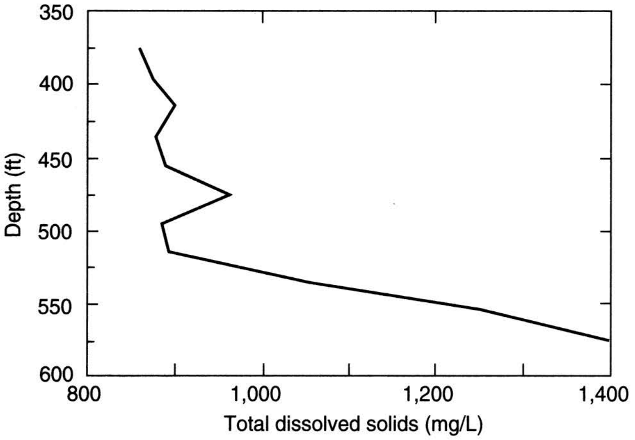


FIGURE 19—DEPTH PROFILE OF TOTAL DISSOLVED SOLIDS (TDS) CONCENTRATIONS IN THE DAKOTA AQUIFER based on data for a test hole in Ellis County, Kansas.

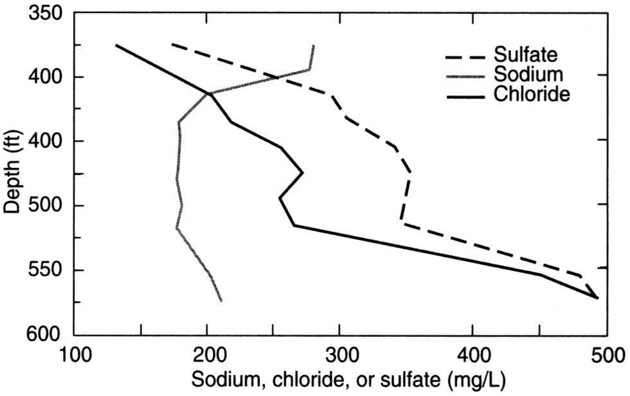


FIGURE 20—DEPTH PROFILE OF SODIUM, CHLORIDE, AND SULFATE CONCENTRATIONS IN DAKOTA AQUIFER WATERS from the same test hole in Ellis County as that of fig. 19.

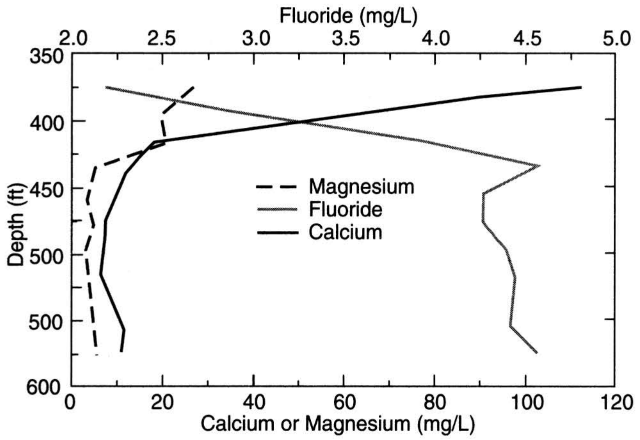


FIGURE 21—DEPTH PROFILE OF CALCIUM, MAGNESIUM, AND FLUORIDE CONCENTRATIONS IN DAKOTA AQUIFER WATERS from the same test hole in Ellis County as that of fig. 19.

Summary of Dakota Aquifer Hydrogeology and Water Quality

The local and regional complexity of the Dakota aquifer and its influence on ground-water flow and water quality can best be appreciated by viewing a subsurface cross section across central Kansas. Gamma-ray logs (and other log types) are routinely used for stratigraphic correlation of sandstones between wells. A stratigraphic framework can be drawn out by linking laterally continuous levels recognized on the logs. The conventional log is presented as a wiggle trace, but there are other graphic methods that can be used to present the same data. The best graphic technique is one that produces a plot with information content that can be easily understood by viewers. A display of many logs on a regional cross section can be both tiring and confusing to the eye as it tries to make sense of multiple curves.

Alternatively, a well-designed image transformation can be made to mimic subsurface geology in a compelling and direct manner. A gray-level scale is adequate to capture the variation of the gamma-ray log. Because the gamma-ray log is primarily sensitive to volumetric content of shale, the obvious choice of gray-scale is to equate the lowest readings with white, the highest with black. Using this convention, the gray-level image from a gamma-ray log will often show a striking mimicry of interbedded shale sequences as would be seen in an outcrop. The use of color can be made to accentuate shades and tones that may be too subtle for the human eye to differentiate in their gray form. Different lithologies therefore often have distinctive colors, while sharp contacts show as breaks in color and are contrasted with transitional blends of gradational sections. Ideally, the result of a regional cross section of transformed logs is a false-color image in which structure and stratigraphy are revealed automatically, as the eye interpolates lateral changes between the separate images at their point locations.

Gamma-ray logs of closely spaced wells along a lengthy east-west traverse across central Kansas at T. 16 S. were digitized from just below the Stone Corral (Lower Permian) to the Fort Hays Limestone Member of the Niobrara Chalk (Upper Cretaceous). Each digital gamma-ray log was transformed to a gray-level image strip, where the darkness intensity is a function of the natural gamma radioactivity of the logged formations. Under this system, sandstones and limestones appeared as white or pale gray, while shales registered as dark gray or black. As an enhancement of this method, the gray intensities were converted to an arbitrary color scale in order to accentuate differences between stratigraphic units. The use of color was then similar to that used on multicolor topographic-relief maps, where the single variable of elevation is color-coded as a visual aid. When hung together on a common stratigraphic horizon and arranged in correct geographic order, the result is a regional image of the subsurface geology of the Permian to Cretaceous sequence. The major advantage of this approach is that the information is coded in a visual form that is close to a simulation of how the geology would actually appear, when making allowance for the vertical exaggeration.

The resulting regional image is shown in fig. 22 with the colors indexed with some major subsurface units. All the transformed gamma-ray logs are referenced to a common stratigraphic datum, the top of the Graneros Shale (table 1), which is easily recognized on gamma-ray logs and is easily identified in the cross section (fig. 22). The regional strike of the top of the Graneros Shale is approximately parallel to the trace of the cross section.

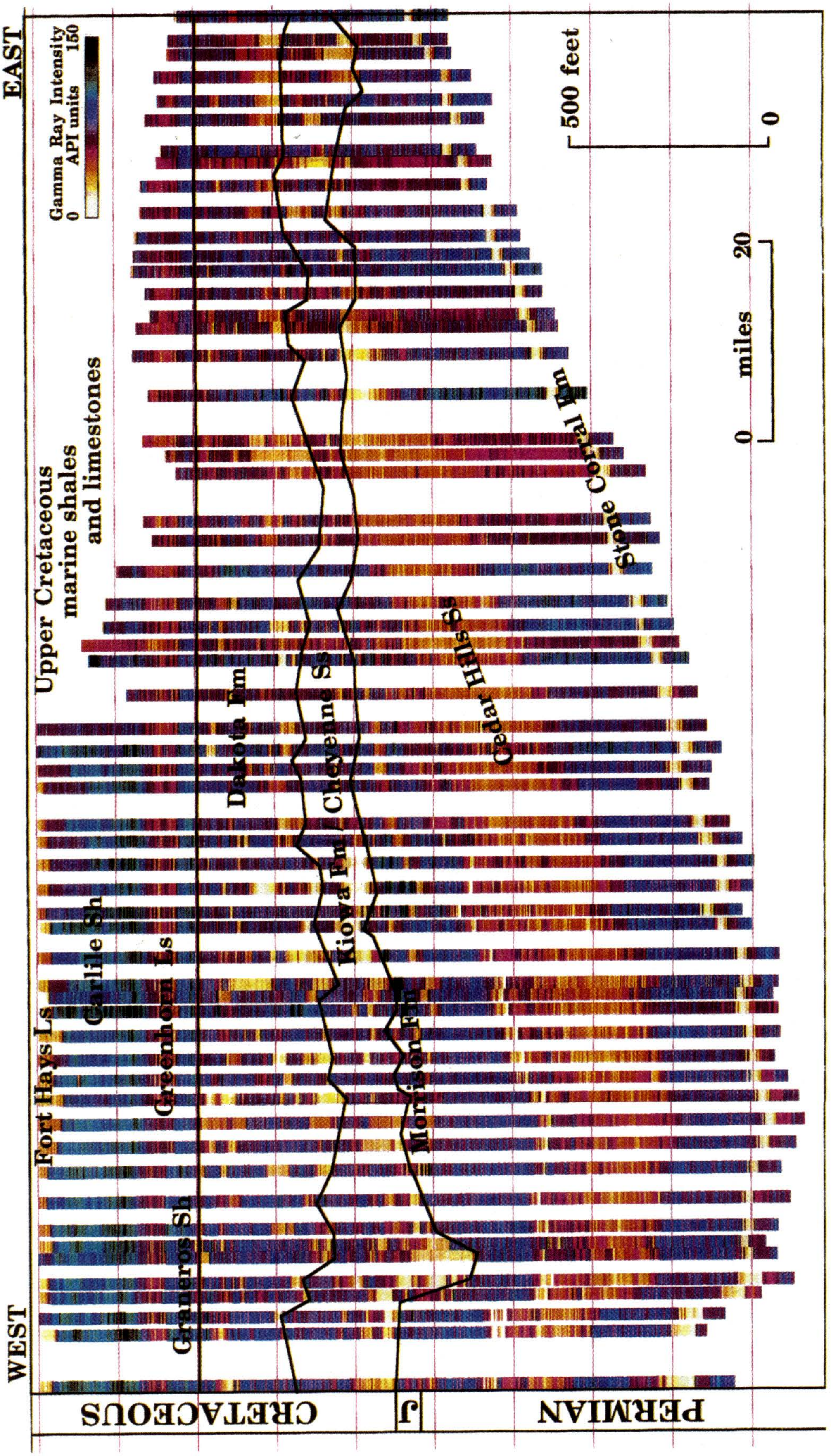
In fig. 22, the Permian units and the Jurassic Morrison Formation dip to the west in contrast to the nearly horizontal overlying Cretaceous sequence. The boundary between these two sequences is a regional angular unconformity that was produced by erosion prior to the deposition of Cretaceous deposits in Kansas and elsewhere. Within the Permian, the Stone Corral Formation forms a distinct and continuous band at the base of the cross section. The Cedar Hills Sandstone is the most obvious feature in the overlying Permian units as a thick continuous wedge that subcrops at the base of the Cretaceous to the east. The Cedar Hills Sandstone is an aquifer that contains natural halite-solution brine and is hydraulically connected to the overlying Dakota aquifer where they are in contact in central Kansas.

Most of the ground-water flow in the Dakota aquifer is through the thicker, and more extensive, sandstones that form a hydraulically continuous network. The sandstones of the Dakota Formation constitute the bulk of the upper Dakota aquifer. In the cross section, the sandstones in the lower part of the upper Dakota seem to be more continuous than overlying sandstones, perhaps because the east-west orientation of the cross section follows the trend of the paleodrainage at the time of their deposition. These overlying sandstones were deposited in environments that were closer to the north-south shoreline of the Western Interior sea and thus appear to be more patchy and discontinuous. This is the expected outcome of viewing the complex, three-dimensional mosiac of deposits that are typically found in river valleys and coastal plains in a single east-west cross section.

Beneath the upper Dakota aquifer, the thick blue bands in the western two-thirds of the cross section represent thick shales deposited offshore in a marine environment in the Kiowa Formation (fig. 22). The thick marine shales form the Kiowa shale aquitard. Thick, light-yellow bands just above the regional angular unconformity are the channel sandstone bodies in the lower Dakota aquifer (Cheyenne Sandstone) that rest on the regional unconformity that marks the base of the Cretaceous. These were deposited in river valleys like the one shown near the west edge of the cross section. To the east, the thinner blue bands alternating with red and orange bands in the Kiowa in the eastern third of the cross section represent the interbedded sandstones and shales of the lower Dakota aquifer (Longford Member [Kiowa Formation]). In central Kansas at the east end of the cross section, the thicker yellow bands represent sandstone bodies that were deposited in deltaic environments during Longford deposition. Along the cross section (T. 16 S.), ground-water within the lower Dakota is believed to be at least brackish in quality. Where the Kiowa shale aquitard is absent in central Kansas, brines from the Cedar Hills Sandstone aquifer and brackish ground waters from the lower Dakota aquifer move upward into the upper Dakota aquifer. These saline ground waters are eventually discharged to streams crossing the Dakota aquifer outcrop.

The marine transgressive sequence of the Upper Cretaceous above the Dakota Formation (Graneros Shale, Greenhorn Limestone, Carlile Shale, and Niobrara Chalk) shows as broad regional bands at the top of the section. The limestones and chalks show as orange and yellow and the shales and siltstones as green and red. These units form the Upper Cretaceous aquitard along the cross section and restrict the vertical movement of recharge to lower aquifers from overlying sources.

FIGURE 22 (right)—COLORIZED GAMMA-RAY LOG INTENSITY IMAGE OF THE PERMIAN–CRETACEOUS SECTION IN WESTERN KANSAS ALONG T. 16 S. Each strip is a false-color rendition of a gray-level transformation of a gamma-ray log. Datum is the top of the Graneros Shale.


WEST
EAST
Gamma Ray Intensity
API units
0
150
Upper Cretaceous marine shales and limestones
Fort Hays Ls
Carlile Sh
Greenhorn Ls
Graneros Sh
Dakota Fm
Kiowa Fm / Cheyenne Ss
Morrison Fm
Cedar Hills Ss
Stone Corral Fm
500 feet
0
0
miles
20
CRETACEOUS
J
PERMIAN

PART 2: Water Resources

Development of Water Resources in the Dakota Aquifer

Brief History of Water-resources Development

In his reconnaissance of the Great Plains in the early 1900's, N. H. Darton found widespread use of the Dakota for drinking water, steam locomotives, and non-irrigated agriculture. Flowing wells were very common in the Arkansas River valley of southeastern Colorado, in much of South Dakota, and parts of southeastern North Dakota and northeastern Nebraska in the Missouri River valley. The artesian pressure within the aquifer in these areas was sufficient that many of the wells produced an adequate supply of freshwater without a pump.

In the Arkansas River valley of southeastern Colorado, the depths of these flowing wells ranged from more than 1,000 ft (300 m) at Pueblo and Fowler, Colorado, to 300 ft (90 m) at Coolidge, Kansas. Darton found considerable artesian pressure in many of the wells he visited. He estimated that in some cases if the well casing were extended up into the air, water levels would rise from a few feet up to 150 ft (45 m) above land surface. Flow rates ranged from less than one up to more than 100 gallons (3.8–380 L) per minute.

Figure 23 shows one of the flowing artesian wells visited by Darton in the early 1900's. The water levels in the first flowing artesian Dakota wells at Coolidge, Kansas, in 1885, were estimated to be almost 20 ft (6 m) above land surface. At the time of Darton's survey, flowing artesian wells in the Arkansas River valley between Coolidge and Syracuse produced 25 to 75 gallons (95–285 L) of water per minute. By the 1930's and early 1940's, the flow rates from these wells decreased to 30 gal (114 L)/min or less in this same stretch of the valley.

In the 1940's, flowing wells were commonly found in an area of the Bear Creek drainage north of Walsh, Colorado, and referred to as the Walsh artesian area. The flowing wells were 200–250 ft (60–75 m) deep and the static water levels were estimated to be 12–31 ft (3.6–9 m) above land surface. Flow rates from these wells ranged from a trickle up to an estimated 100 gallons (380 L) per minute during this time.

Many of the wells inventoried by Darton in the Arkansas River valley did not flow naturally to the surface. Water levels were generally 75 ft (22.5 m) or less below land surface eastward of Lamar, Colorado. Darton reported that some of the artesian pressure had been lost due to pumping and unregulated, year-round discharge from the flowing wells. Steam- or wind-power was needed to bring water to the surface at rates that ranged from 25 to 80 gal (95–304 L)/min. In 1913, the Kansas

FIGURE 23—Flowing wells in the Dakota aquifer in southeastern Colorado.

Geological Survey produced a map that outlined an area where the Dakota could be practically used for water supply. This area included most of the Arkansas River drainage above Great Bend, Kansas, and a portion of the Cimarron River basin. The extent of the area outlined was determined on the basis of only a few scattered reports of Dakota wells in Kansas. The early Survey scientists observed freshwater springs emanating from the hillsides in central Kansas. They reported that these springs were fed locally by the Dakota aquifer, but did not mention the springs' use by the local population for water supply.

Since the 1930's, the attention of users has been largely focused on the shallower and more prolific sources of water in the High Plains aquifer and in the river valleys of Kansas. In the last few decades, these shallower sources of water have been under intense development primarily from irrigated agriculture, especially in western Kansas. As a result, water levels in these shallow aquifer systems have declined significantly, and in several instances these sources now are insufficient to meet existing demand in local areas. During this period, the competition for water stimulated interest in tapping deeper sources in the Dakota aquifer in western Kansas to supplement yields from the dwindling shallower sources.

In the late 1970's, a regional study of the Dakota aquifer was conducted by K. M. Keene and C. K. Bayne of the Kansas Geological Survey, and their results were reported in the Survey's Chemical Quality Series 5, *Ground Water from Lower Cretaceous Rocks in Kansas*. They estimated that 80–95 million acre-ft of water with a total dissolved solids concentration of less than 3,000 mg/L could potentially be withdrawn from the Dakota. However, they recognized that development of water resources for irrigation of crops could be limited due to the complexity and highly variable water quality of the Dakota.

In southwestern Kansas, the institution of new management policies for the High Plains aquifer sparked interest in the Dakota as a source of water for irrigating crops. New management policies and regulations were developed and instituted by Southwest Groundwater Management District 3 that applied to both the High Plains and the Dakota aquifers. These policies and regulations were based on a limited quantitative understanding of the hydrologic interactions between the Dakota and the overlying High Plains aquifer in the District. The new regulations featured a graduated well spacing based on the yearly withdrawal of ground water from the well to be installed.

In north-central Kansas in the early 1970's, limited use of the Dakota aquifer for irrigating crops in southwestern Washington and adjacent Cloud and Republic counties also began and has continued to the present. The only guidelines applied to this development stipulated a well spacing of 1 mile (1.6 km) between the higher-yielding (greater than 150 gal [570 L]/min) irrigation and municipal wells.

Potential Areas for Water-resources Development

Initial development of water resources in an aquifer depends on the quantity and quality of water available for particular uses and the economic costs to obtain the supply. After initial development, further water production also depends on the aquifer's ability to sustain additional withdrawals. At least moderate quantities of water can be found in the Dakota aquifer, where thicker sandstones have been identified locally by previous investigations or test drilling. Thus, the current level of development of the Dakota aquifer has been largely driven by the need for freshwater supplies where surface waters or more economically obtainable ground water are not present from the alluvial valley and High Plains aquifers. In addition, where available surface and ground waters have already been appropriated, wells have been drilled into the Dakota aquifer for supplies. Most of the development in the Dakota aquifer also has occurred where the depths to substantial sandstones are shallow to moderate (less than about 750 ft [225 m]), keeping well-construction costs within reason. Thus, most of the wells are located in the outcrop/subcrop area and the margin of the confined aquifer where the thickness of overlying rocks is not great. A past economic incentive that drove development in southeastern Colorado and the westernmost part of southwest Kansas was the artesian nature of the aquifer which caused wells to flow or nearly flow. Declines in the potentiometric surface in these areas have removed much of this incentive.

Additional development of water resources in the Dakota aquifer will be determined largely by the needs of users, the availability of water from the Dakota and other aquifers, and the management goals and the planning horizons established by state and local water planning and regulatory agencies in Kansas. Management options, including issues related to long-term sustainability, are discussed more fully in the "Sustainability of the Dakota Aquifer" section of this report.

In general, the closer potential well sites are to the northwest corner of Kansas, the greater the depth to the top of the Dakota aquifer. This makes well construction and pumping more expensive. Where the depth to the top of the confined aquifer approaches 1,000 ft (300 m) or more, the depth to water from land surface approaches 300 to 350 ft (90–105 m). Uses that are more water intensive, such as irrigated agriculture, are not practical because of the high energy costs associated with production relative to well yield. As a result, the Dakota is currently an underutilized resource in most of western Kansas because of the availability of shallower, more prolific supplies in the High Plains aquifer. However, as these supplies continue to become scarcer and more valuable, exploration for usable waters in the confined aquifer will increase for other uses, such as public water supply, stock watering, and domestic purposes. The salinity of Dakota aquifer waters is one of the most important factors limiting current exploration in the confined aquifer. Water availability and economics have caused the City of Hays to develop slightly saline waters in the Dakota in west-central Ellis County. 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 Dakota Aquifer Program has discovered a substantial area of additional waters that are nearly fresh to slightly saline that could be important for future supplies. The aquifer area is roughly shaped as a triangle with its base along the south lines of Sheridan and Graham counties and extending into south-central Norton County (fig. 16). Most of this area was previously believed to have waters of substantially greater salinity. Regional flow of fresher ground water through the Dakota aquifer from the southwest is believed to have flushed salinity to the present levels. Some waters may even be slightly less than the TDS classification for fresh (less than 1,000 mg/L) in thick and wide sandstones in the south-central portion of this triangle where greater permeability could have allowed more extensive flushing. Parts of western Gove County may also have more freshwater than earlier thought.

Partially developed areas where additional withdrawals could occur are mainly (1) underneath greater saturated thicknesses of the High Plains aquifer in southwest Kansas, (2) in the portions of the aquifer not currently greatly stressed in the eastern outcrop/subcrop area, and (3) in the zone of the confined aquifer nearest the outcrop/subcrop belt. In the confined aquifer the sandstones in the upper Dakota aquifer will be the primary targets for new exploration because of their greater thickness and permeability and lower levels of salinity. 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, in the lower Dakota will be likely targets of exploration for new water supplies.

Ground-water Exploration Techniques

The search for suitable freshwater-bearing sandstones can be frustrating and costly if users rely only on random test-hole drilling. In most cases exploration efforts must be made in an organized manner, starting with a review of the available information from Federal, State, and local agencies, water-well drillers, and other users of the Dakota aquifer in each local community. Appendix 2 is a listing of the various sources of information on the Dakota aquifer by agency, a synopsis of the information they can provide to users in Kansas, and their phone numbers and addresses. Appendix 3 is a short bibliography of reports that provide helpful background information on the Dakota aquifer and ground water in Kansas in more detail than is discussed in this publication. The remainder of this section of the user's guide is devoted to the use of geophysical logs in the exploration for freshwater in the Dakota aquifer and other major aspects of the exploration program leading to the installation of a well in the aquifer.

DELINEATION OF LOCAL AQUIFER ZONES—The geology of the shallow subsurface in the western and central parts of Kansas is complex, because of periods of uplift, erosion, and deposition in the geologic past. This has resulted in complicated geologic relationships between rock units and created considerable variation in thickness and lithology within these units. Because of this complexity, the search for water supplies within the Dakota usually requires a test-hole drilling program to locate suitable aquifer zones. This can be expensive if a preliminary analysis of the available subsurface information is not performed to limit the scope of exploration. The information needed for this preliminary analysis is collected by technically trained people and contained in the geophysical logs of wells drilled for oil and gas and the logs of the cuttings produced during the drilling of boreholes for wells (a driller's log). The objective of this analysis is to identify the target stratigraphic units likely to contain sandstones sufficient for water production. To do this, well-site geologists or drillers must be able to locate formation boundaries from the logs of their test holes and integrate the results with the available information from surrounding boreholes. This is accomplished using geologic-correlation techniques. The correlation or extension of formation boundaries from the logs of one borehole to the logs of another must be done in a manner that is consistent with the subsurface stratigraphy. In this regard, geophysical logs provide a more accurate and objective location of formation and lithologic boundaries in the Dakota than is possible with a driller's log.

The critical stratigraphic boundaries relevant to the Dakota aquifer are (1) the base of the Cheyenne Sandstone or the Kiowa Formation, (2) the base of the Dakota Formation, and (3) the top of the Dakota Formation. These boundaries define the base of the Dakota aquifer system, the base of the upper Dakota aquifer, and the top of the Dakota aquifer system, respectively (table 1). In some areas, recognition of stratigraphic boundaries is straightforward; however, in other areas the boundaries are not easily located from a driller's log. New information from the Dakota Aquifer Program by the Kansas Geological Survey has provided the most precise information ever available to recognize these boundaries based on available subsurface gamma-ray logs of wells drilled for hydrocarbons and as test holes by the Survey. The Survey is publishing a set of type logs online for each township in central and western Kansas for which suitable logs are available. It will also be possible to output this information on compact disks as desired. Included with the logs in digital form on the Survey web site will be a table containing formation tops of these type logs, including the depth to the tops of the Dakota Formation, Kiowa Formation, Morrison Formation, and the underlying Permian. An understanding of the origin of the stratigraphic boundaries in the Dakota aquifer is useful in their identification on gamma-ray logs. More detailed information on the depositional history of these units and geologic correlation techniques can be found using the reference resource list at the back of this publication in Appendix 3.

GEOPHYSICAL LOG ANALYSIS OF THE DAKOTA AQUIFER— Geophysical logs are records of physical properties of rocks in boreholes drilled for hydrocarbons, minerals, or water. Logs are made by electrical, acoustic, and nuclear tools suspended on a wireline and winched up through formations penetrated by the borehole (fig. 24). A logging tool may be about 50 ft (15 m) in length and its measurements are recorded as traces on a graphic chart of depth—a "log." Most tools are run by logging service companies for the oil industry in both exploration holes and producing wells. Fortunately, many of the rock properties used to locate and describe oil and gas reservoirs also are useful in the search for aquifer beds with usable water.

The long history of oil exploration in Kansas has resulted in the recording of hundreds of thousands of logs across the state. These are filed with the Kansas Corporation Commission and then archived at both the Kansas Geological Survey in Lawrence and the Kansas Geological Society in Wichita, where copies are available for purchase by the public. The main use of logs is for the identification of the depths of stratigraphic formation boundaries ("tops") and their correlation between wells. The maps of correlated tops are similar in style to topographic maps. However, underground surfaces cannot be seen, but must be estimated between the available well control.

Logs also provide valuable information on the Dakota aquifer because they can be used for

1) rock-type recognition: Sandstones (aquifers) can usually be distinguished easily from shales (aquitards) in the Dakota on most logs. This information can be used to give both depth and footage of sandstones at the well location, as well as trace them between wells.
2) sandstone storage-capacity determination: Some logging tools (the density, neutron, and acoustic velocity or sonic) make measurements that can be used to calculate the volumetric proportion of the water in the saturated sandstone.
3) water-quality estimation: The electrical logging measurements of spontaneous potential (SP) and resistivity can be used to estimate the salinity of water within Dakota sandstones.

These three applications are explored in more detail in the following pages, where the properties and uses of the common logs are described. All the logs illustrated have been taken from a single well, so that the properties and interrelationships can be understood more easily.

The gamma-ray log: The gamma-ray log is widely used as a record to locate the depth of key stratigraphic formations (fig. 25) and to subdivide the Dakota into units of sandstone and shale (fig. 26). The gamma-ray tool measures natural radioactivity of rocks in a similar way to a Geiger counter. The sources of radiation are almost entirely from isotopes of thorium, uranium, and potassium. Although the radioactivity of most rocks is fairly low, it is sufficient to make a clear distinction between sandstones (low radioactivity) and shales (higher radioactivity) (fig. 26). Older gamma-ray logs are recorded in "counts," the numbers of which vary according to the tool design. Almost all modern gamma-ray logs are recorded in API (American Petroleum Institute) units, which makes a common standard for log comparison. The scale was chosen so that a value of zero would mean no radioactivity and a value of 100 would match a typical midcontinent shale. In practice, shales can be somewhat variable in their radioactivity according to their silt content, types of clay mineral, and the occurrence of small amounts of uranium.

Once the stratigraphic boundaries of the Dakota aquifer are located (fig. 25), the gamma-ray log can be used to mark off depth intervals of sandstones and shales. As a rule-of-thumb, experience has shown that a value of 60 API units is a satisfactory boundary to differentiate sandstones (below 60) and shales (above 60). An example of using this procedure is shown in fig. 26. The subdivision of a Dakota aquifer section into sandstones and shales reveals the structure of aquifer and aquitard layers.

The "porosity" logs: Three types of logging tools are used to estimate the amount of pore space in a rock: the neutron, density, and acoustic velocity (or sonic) tool. Although either one or several of these types of logs are commonly run in oil-exploration holes that penetrate the Dakota, they are not always recorded in the Dakota interval. Commonly, a full suite of logs is recorded in the deeper section, where there is a potential for oil and gas up to the level of the Permian Stone Corral. Above the Stone Corral, a more restricted suite may be run for correlation purposes and typically consists of the gamma-ray, SP, and resistivity logs.

The neutron log records the number of collisions between neutrons that radiate from a tool source and hydrogen atoms within the rock of the borehole wall. So, the log is mainly a measure of hydrogen concentration (mostly contained by the pore fluids of the formation). Older neutron logs are recorded in numbers that require conversion to porosity units either by calibration to units of known porosity within the logged section or by reconciliation with cored samples from the same well. Newer neutron logs are scaled directly in units of porosity (fig. 27). Shales appear to have high porosities on the neutron log, mostly because of bound water, rather than effective porosity. However, porosities recorded in shale-free

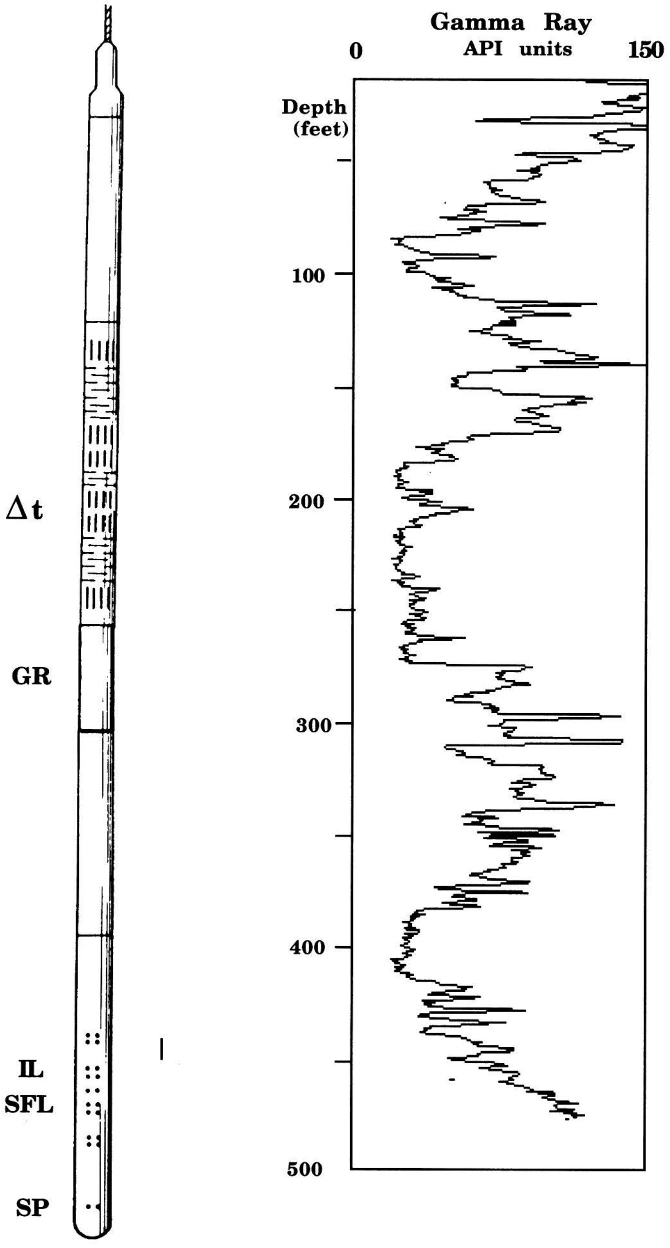


FIGURE 24—Combination logging tool for measuring acoustic travel time (Δt), natural gamma radiation (GR), shallow-focused (SFL) and deep-focused (IL) electrical conductivity, and spontaneous electrical potential (SP) of rock formations in a borehole, together with a typical gamma-ray log of a Dakota aquifer section. The tool shown is 55 ft, 7 inches (16.9 m) long.

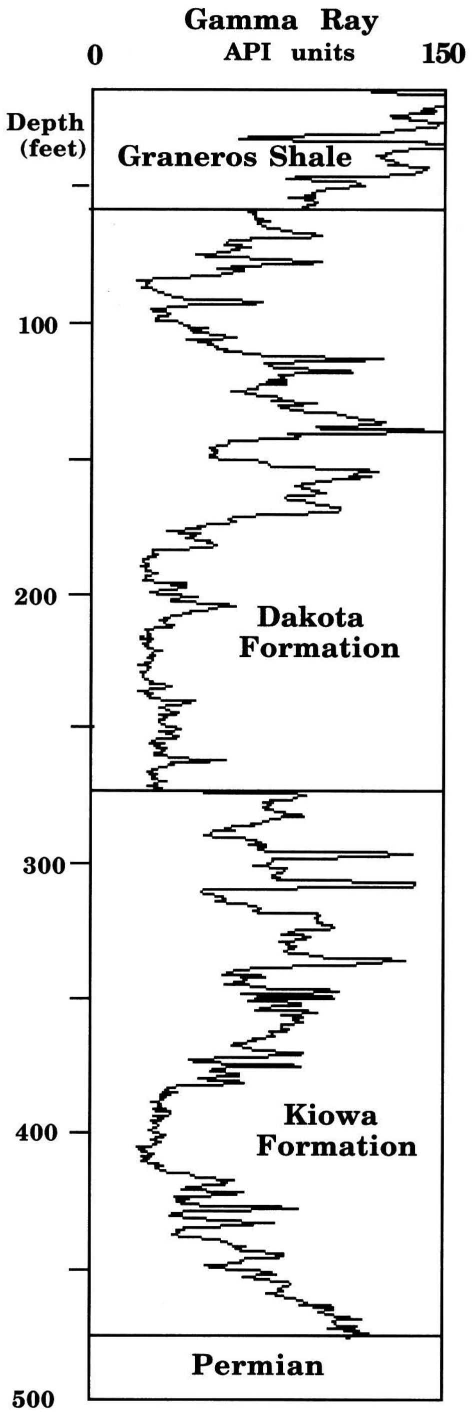


FIGURE 25—Use of a gamma-ray log for stratigraphic subdivision of the Dakota aquifer in KGS Jones #1, NE NE NE sec. 2, T. 10 S., R. 8 W., Lincoln County, Kansas.

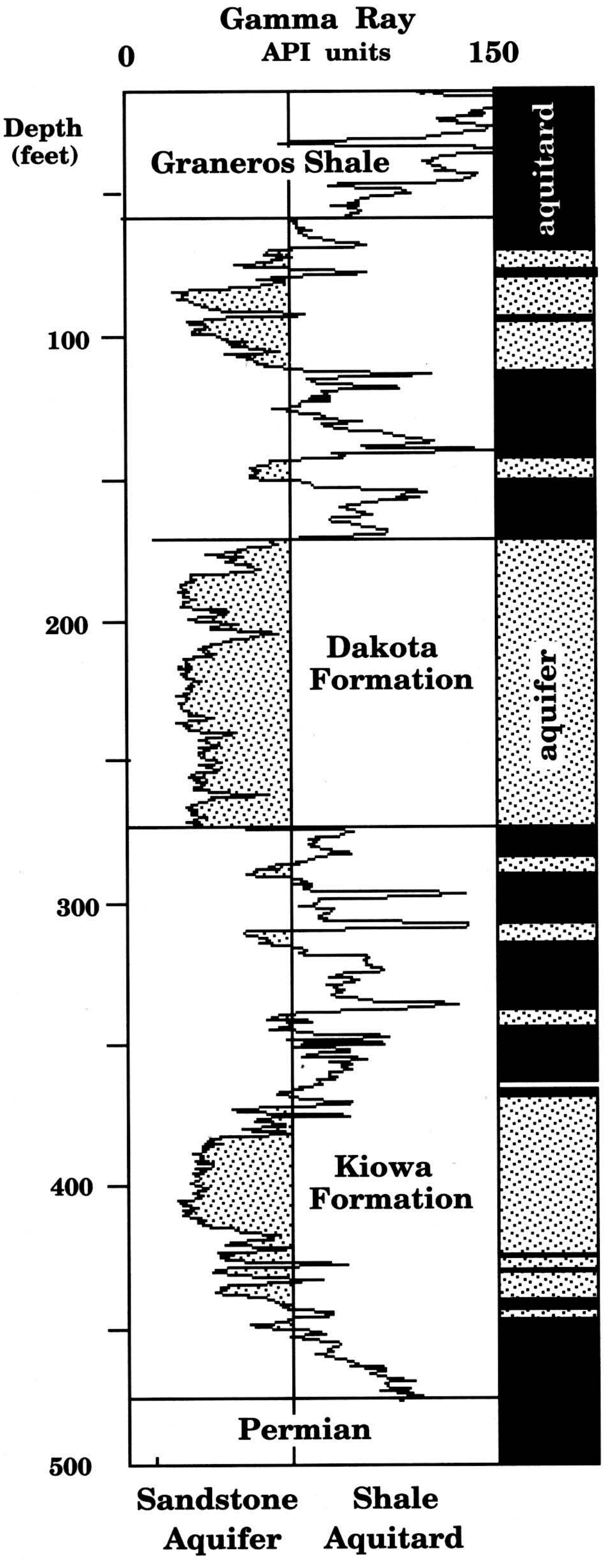


FIGURE 26—Use of a gamma-ray log to subdivide the Dakota aquifer in KGS Jones #1, NE NE NE sec. 2, T. 10 S., R. 8 W., Lincoln County, Kansas, between sandstone-aquifer zones and shale-aquitard zones through the use of a gamma-ray cut-off value.

sandstones are a reasonable estimate of pore spaces containing water that can be produced in a well.

The density log is a measure of apparent density of the rock and is computed from the absorption of gamma rays by the formation upon exposure to a radioactive source. An example of a density log run in the Dakota is shown in fig. 28. The density of quartz is about 2.65 grams per cubic centimeter, and that of water is approximately 1.0. These two values correspond to the density of a sandstone with zero porosity and a hypothetical sandstone with a porosity of 100%. The two limits can be used to convert the density scale to values of equivalent porosity units. On more recent density logs, a supplementary curve of the photoelectric factor also is recorded, and is a useful measure of formation mineralogy.

Both the neutron and density logs are commonly recorded on the same logging run and shown as an "overlay" on a common scale of equivalent limestone porosity units (see fig. 29). The overlay allows shales, sandstones, and other lithologies to be distinguished and a better estimate to be made of the true porosity of the formation at any depth. The log overlay has sufficient information to be converted to a profile that graphically shows shale content and volume of effective pore space (fig. 30). Notice that the overall shale composition estimated from the density-neutron log combination is similar to shale indicated by the gamma-ray log, but there are also systematic differences. That is because both measurements are sensitive to shale content, but the gamma-ray log responds to the natural radioactivity of the shale, while the neutron-density logs are influenced by the bound water and density of the shales.

The third type of porosity estimate is computed from measurements of the speed of ultrasonic sound through the formation. The sonic tool has a mechanical source of compressional energy that radiates sound through the rock formation in the borehole wall. The log records the acoustic velocity of the rocks as a trace that is shown as a continuous function of depth. The log is measured as transit time in units of microseconds per foot. Sound travels faster in rocks with low amounts of contained fluids than those with higher fluid contents. This physical relationship can be used to compute the porosity of a sandstone at any depth, by interpolating the measured value at any depth between the expected value of quartz (55.5 microseconds per foot) and that of water (189 microseconds per foot) as extremes of a porosity scale of zero to 100% porosity.

The spontaneous potential (SP) log: The spontaneous potential tool measures natural electrical potentials that occur in boreholes and generally distinguishes porous, permeable sandstones from intervening shales. The "natural battery" is caused when the use of drilling mud with a different salinity from the formation waters causes two solutions with different ion concentrations to be in contact. Ions diffuse from the more concentrated solution (typically formation water) to the more dilute. The ion

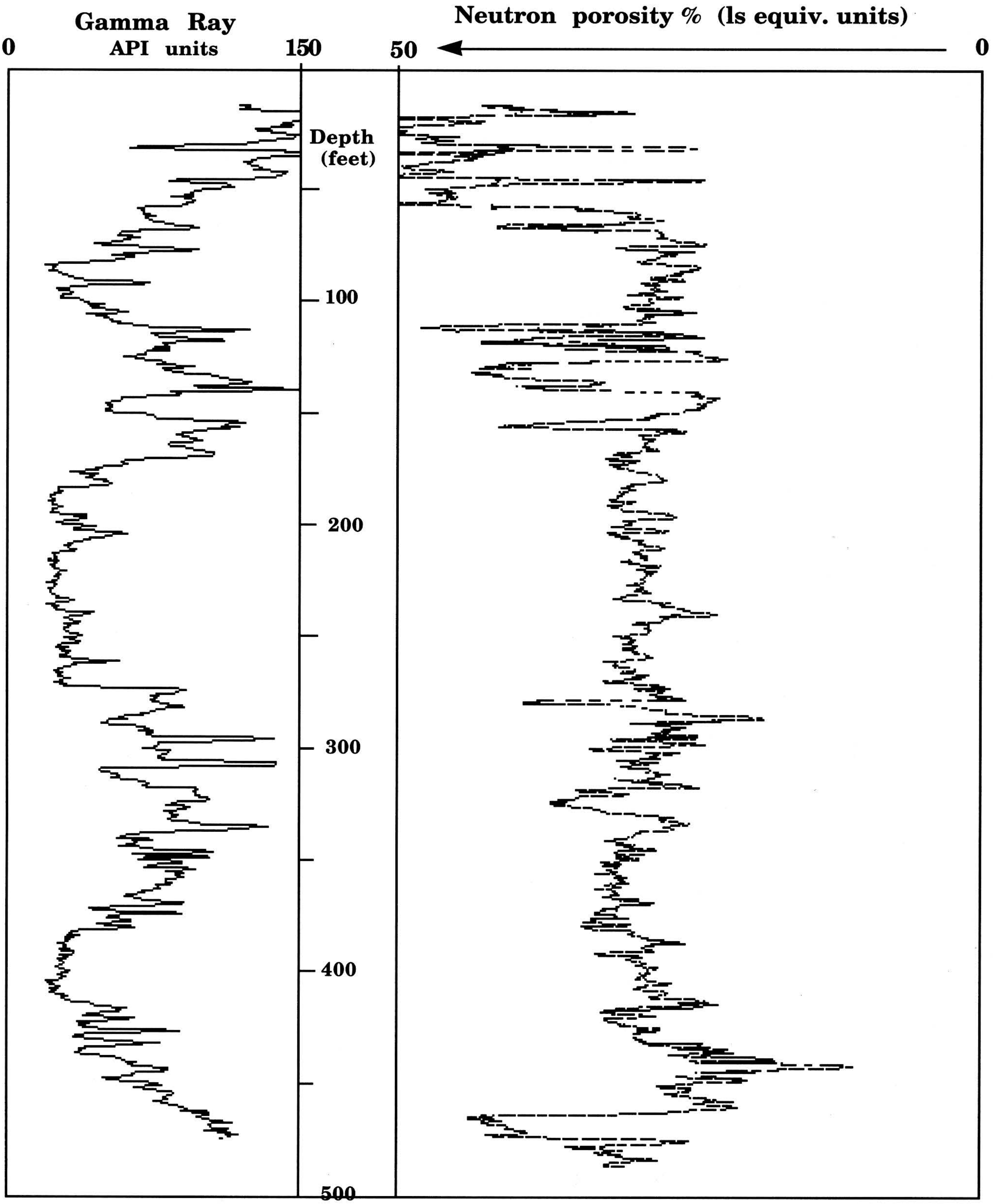


FIGURE 27—NEUTRON-POROSITY LOG FROM KGS JONES #1, NE NE NE SEC. 2, T. 10 S., R. 8 W., LINCOLN COUNTY, KANSAS. Note that porosity increases from right to left. A "limestone scale" is normally recorded, because oil-exploration targets below the Dakota are usually limestone. Actual porosities in the sandstones will be about 3% higher. The porosity reflects "free" water in the sandstones, but bound water in the shales.

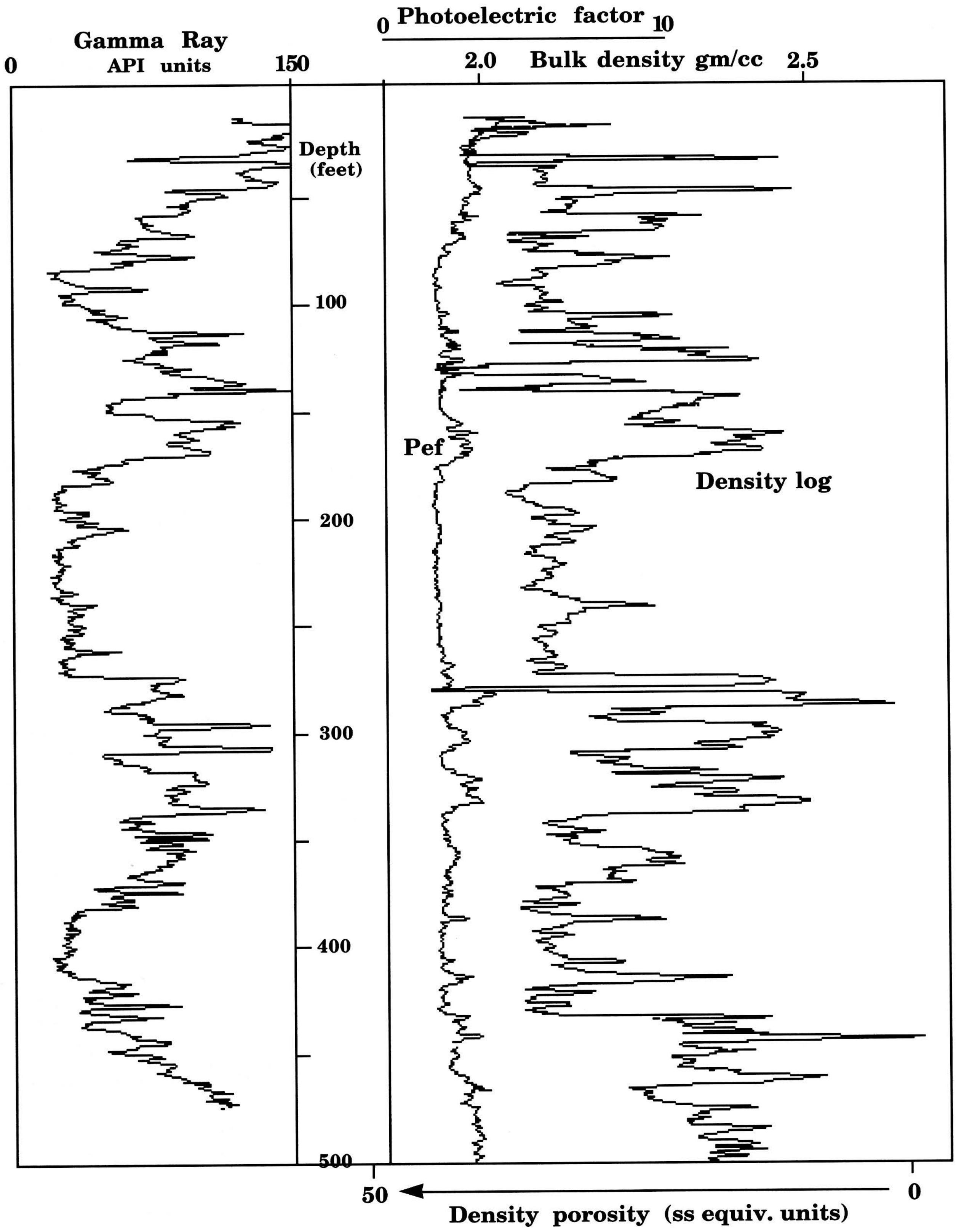


FIGURE 28—Density log from KGS Jones #1, NE NE NE sec. 2, T. 10 S., R. 8 W., Lincoln County, Kansas, recorded in grams per cm^3 (above) and an equivalent sandstone porosity scale (below). Newer density logs commonly have a photoelectric factor curve which is a useful lithology discriminator.

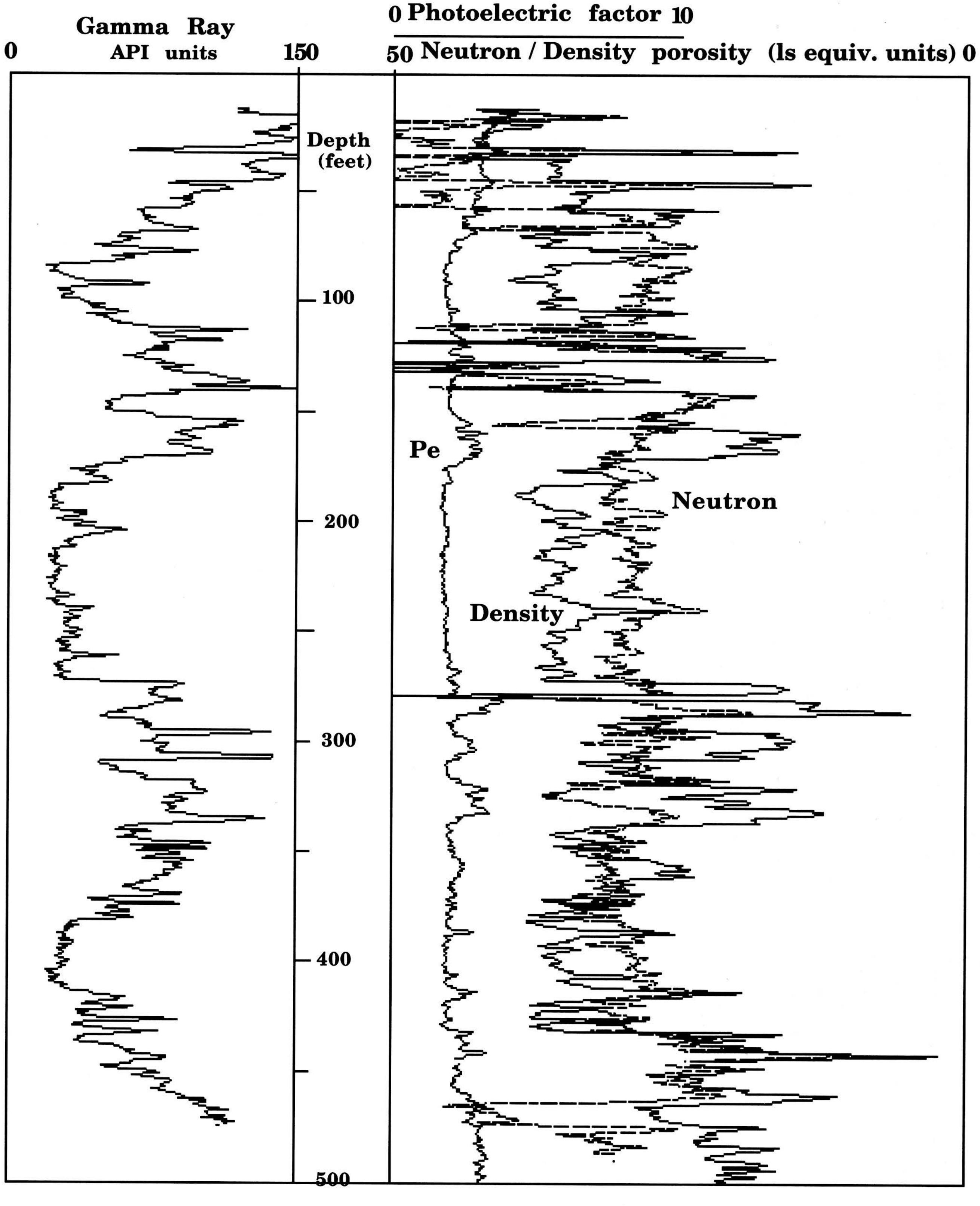


FIGURE 29—Neutron and density logs from KGS Jones #1, NE NE NE sec. 2, T. 10 S., R. 8 W., Lincoln County, Kansas, overlaid on a common equivalent limestone-porosity scale. The overlay allows the log analyst to recognize lithologies and read values of true porosity in zones of interest.

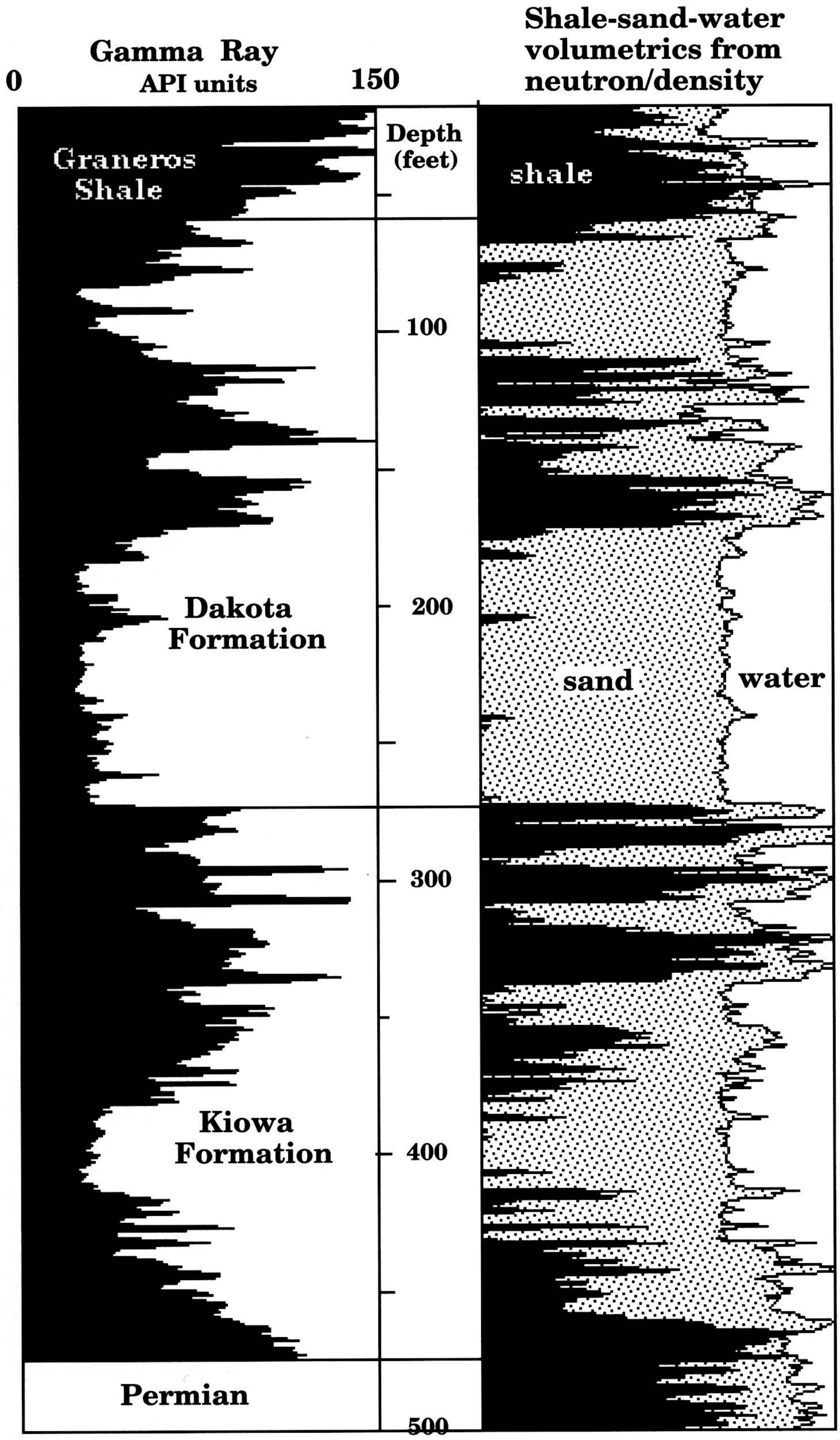


FIGURE 30—Volumetric summary of shale, quartz, and pore space indicated by gamma-ray and lithodensity-neutron logs from KGS Jones #1, NE NE NE sec. 2, T. 10 S., R. 8 W., Lincoln County, Kansas. Note that shale estimation by the gamma-ray log is based on natural radioactivity and shows slight differences with shales from the lithodensity and neutron logs which are based on shale-bound water and density characteristics.

flow constitutes electrical current, which generates a small natural potential measured by the SP tool in millivolts.

When the salinities of mud filtrate and formation water are the same, the potential is zero and the SP log should be a featureless line. With a fresher mud filtrate (and thus, more saline formation water), a sandstone will show a deflection in a negative potential direction (to the left) from a "shale base line" (fig. 31). The amount of the deflection is controlled by the salinity contrast between the mud filtrate and the formation water. Clean (shale-free) sandstone units with the same water salinity should show a common value, the "sand line." In practice, drift will occur with depth because of the changing salinity of formation waters. The displacement on the log between the shale and sand lines is the "static self-potential" (SSP).

The SP log in fig. 31 is an example taken from a shallow section of the Dakota. Notice how the shale baseline shows a distinctive drift with depth. This characteristic is commonly observed in shallow sections and may be caused by increases in relative oxidation of the rocks that are close to the land surface. The highest sandstone in the well has a muted deflection on the SP log as compared with the lower sandstones. This contrast is an immediate indication that water in the upper sandstone may be significantly fresher than waters of the lower sandstone. In other wells it is not uncommon to see sandstone units where the SP deflection goes to the right of the shale baseline. In these instances, the drilling mud filtrate is saltier than the formation water. A good example of this phenomenon is shown in fig. 32 from a well in northwest Kansas. In the upper sandstone, "U," the SP log shows a deflection to the right, indicating formation water to be fresher than the drilling mud, while in the lower sandstone, "L," the deflection is to the left, showing the formation water to be more saline.

The conductivity of the drilling-mud filtrate is measured by engineers at the well-site and recorded on the "header" of the log. This information combined with the SSP "battery effect" shown on the log can be used to estimate the conductivity of the formation water. The calculation is made commonly by petroleum-log analysts as an important variable in the search for potential oil or gas zones (see fig. 33). When used to evaluate the quality of aquifer waters, care must be taken to ensure realistic conclusions. Although formation-water compositions at greater depths tend to be mostly sodium and chloride (monovalent ions), the divalent ions of calcium, magnesium, bicarbonate, and sulfate become more important in shallow, fresher aquifer waters. As a result, the equations used by petroleum-log analysts are only approximate and must be adjusted to consider the ionic mix of the local aquifer water. In general, the divalent ions of shallow waters tend to make them appear slightly more saline than they actually are when computed from the SP log.

An empirical chart was developed as part of the research in the Dakota to correct apparent water resistivities calculated from standard equations to estimates of real resistivities measured in Dakota aquifer water samples (fig. 34). The corrected resistivities were then transformed to estimates of total dissolved solids concentrations. The method is particularly useful in Dakota aquifer studies because it allows water-quality studies to be extended beyond wells from which Dakota water samples were taken to wells that were unsampled but logged with an SP device. This procedure was used to estimate the TDS concentrations in the upper Dakota aquifer in northwest Kansas (fig. 16).

The resistivity log: Resistivity logs measure the ability of rocks to conduct electrical current and are scaled in units of ohm-meters. There are many resistivity-tool designs, but a major difference between them lies in their "depth of investigation" (how far does the measurement extend beyond the borehole wall?) and their "vertical resolution" (what is the thinnest bed that can be seen?). These characteristics become important because of the process of formation "invasion" that occurs at the time of drilling. In addition to its other functions, drilling mud forms a mudcake seal on the borehole wall of permeable formations. However, in doing this, some mud filtrate penetrates the formation, displacing formation water. This is called "invasion." The replacement of formation water by mud filtrate involves a change of pore-water resistivity.

The difference between the resistivity-log measurements and the invasion process can be seen on fig. 35, where separation between the curves can be seen in the more porous and permeable sandstones, but minimal separation is seen in the shales, which are effectively impermeable. From a hydrologic perspective, the multiple-resistivity curves are therefore excellent discriminators of aquifer and aquitard units. The mud used in the example well was less saline than formation waters in the deeper units, as is common in many drilling operations. The shallowest reading resistivity device (in this case, the spherically focused log) therefore records the highest resistivity because it responds mostly to the formation being invaded by the higher-resistivity mud filtrate. The two induction logs draw their responses from deeper in the formation, so that the deep induction log (ILD) probably records a reading close to the true resistivity of the undisturbed formation. Notice that the resistivities in the uppermost sandstone (depth, 100 ft [30 m]) are less separated than those in the lower sandstones. As observed already, the dampened deflection of this sandstone on the SP log shows that its contained water is only slightly more saline than the drilling mud and much less saline than the lower sandstones. Therefore, invading mud filtrate is only slightly fresher than the formation water, so that invasion effects on the resistivity logs are masked.

The sensitivity of resistivity logs to water salinity can be used in an alternative method to SP-log estimates of water quality. In a sandstone-shale sequence, resistivity variation is controlled by a variety of phenomena, including cation-exchange mechanisms of clay minerals within the shalier zones, conduction by metallic minerals, and the

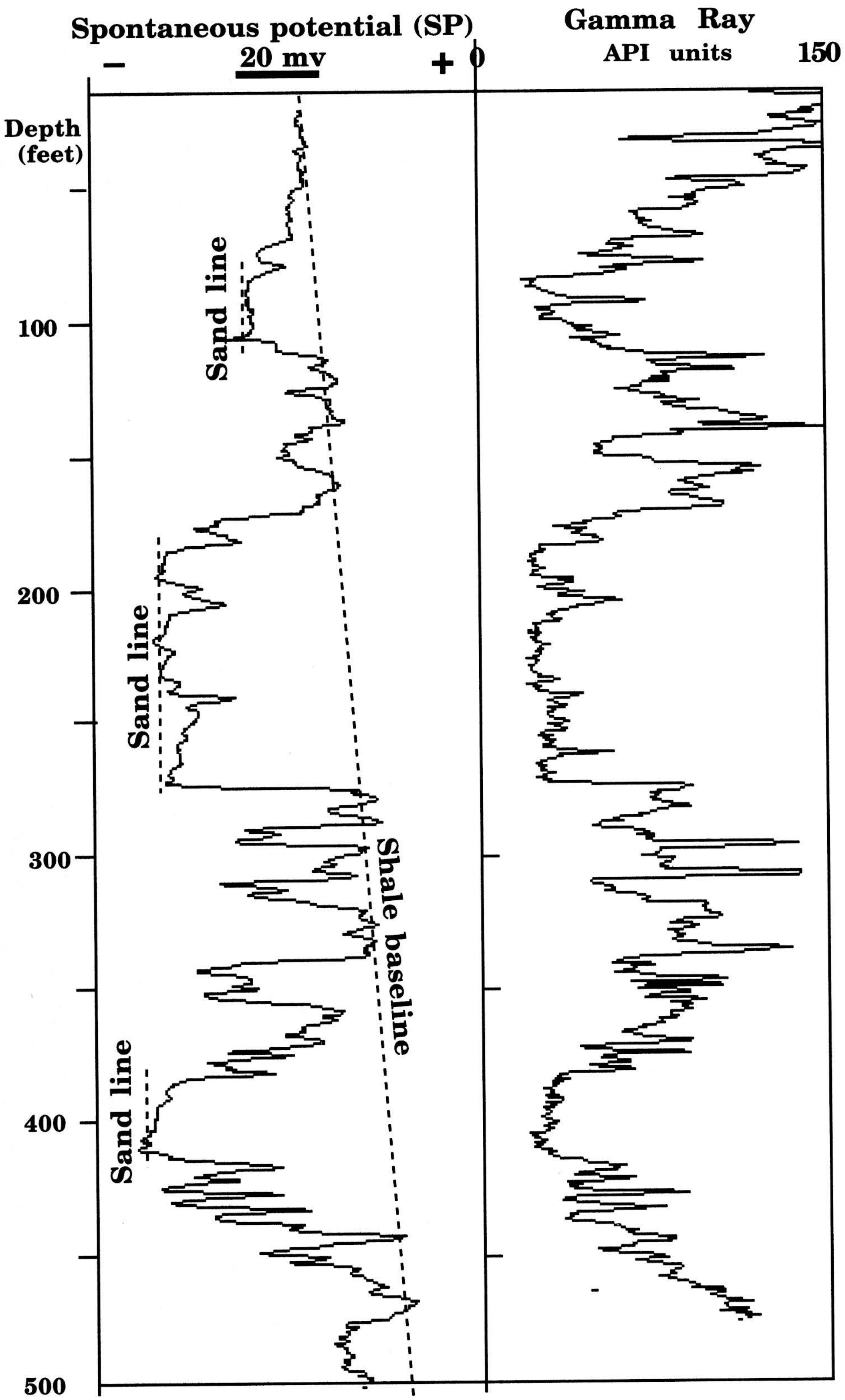


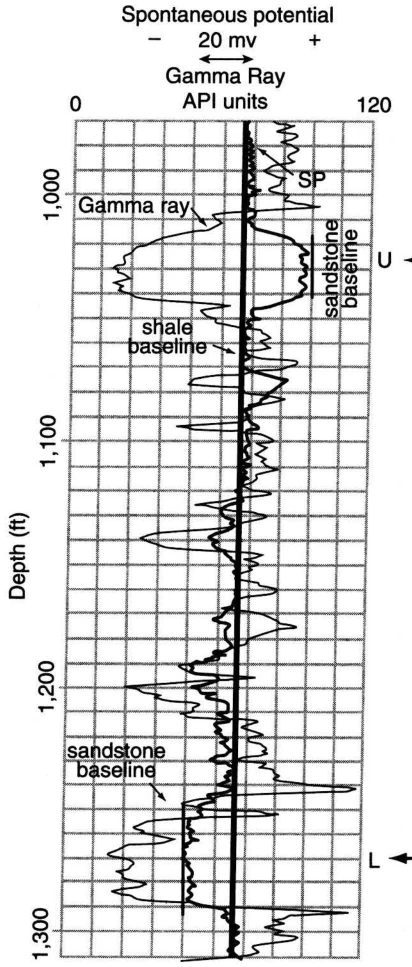
FIGURE 31—SPONTANEOUS POTENTIAL (SP) AND GAMMA-RAY LOG FROM KGS JONES #1, NE NE NE SEC. 2, T. 10 S., R. 8 W., LINCOLN COUNTY, KANSAS. Although they record different physical properties, the two logs are comparable because of their sensitivities to shale and so both can be used to differentiate between sandstones and shales. The stronger sandstone differentiation at greater depths on the SP log is caused by greater salinities in the deeper sandstones.

dissolved ions within the pore water of the sandstones. However, formation water resistivity may be calculated in shale-free sandstone zones that are logged by resistivity and porosity tools. The water resistivity (R_w) is calculated from the resistivity and porosity log readings by the Archie equation that incorporates a "cementation factor" (m), expressing the tortuosity of the pore network as a modifier to the fractional volume of pore space (Φ):

$$R_W = R_O \Phi^m , \qquad \text{(eqn. 3)}$$

where R_O is the resistivity reading of the zone when it is completely saturated with water whose resistivity is R_w. The method is widely used by log analysts in the oil industry and generally gives good estimates of water resistivity in deeper (more saline) formation waters. Results are less reliable in aquifers because of clay-mineral effects as well as surface conduction on quartz-grain surfaces.

A water-resistivity/specific-conductance curve was computed for the Dakota aquifer in the Jones well using the Archie equation with a cementation exponent (m) of



Calculations of total dissolved solids (TDS) concentration from the log header:
R_{mf} = 1.08 @ 75°F

SSP = 40 mv
Formation temperature = 70°F
K = 69.3 @ 70°F
R_{mfe} = 0.92 @ 75°F
R_{mfe}/R_{we} = 0.27
R_{we} = 3.38 @ 77°F
TDS = 550 mg/L

SSP = 36 mv
Formation temperature = 74°F
K = 68.8 @ 70°F
R_{mfe} = 0.92 @ 75°F
R_{mfe}/R_{we} = 3.36
R_{we} = 0.27 @ 77°F
TDS = 23,172 mg/L

FIGURE 32—Spontaneous potential (SP) and gamma-ray logs of the upper Dakota from Cities Service Montgomery #2, center NE NW sec. 7, T. 8 S., R. 23 W., Gorham County, Kansas. Note the SP deflects to the right in the upper sandstone (U) but to the left in the lower sandstone (L). This "reversal" occurs because the formation water in the upper sandstone is fresher than the drilling mud, but saltier than the drilling in the lower sandstone. The calculations of total dissolved solids (TDS) concentration (mg/L) in the two sandstones were made using the flow chart in fig. 33 and the correction chart in fig. 34. See Boeken (1995) listed in Appendix 3 for more details.

1.6 (an appropriate value for a slightly cemented sandstone). The water-resistivity curve is shown in fig. 36 and is indexed with two water-sample measurements and a reference value for a low-flow sample of water from Rattlesnake Creek, in a valley in northern Lincoln County near the Jones well in NE NE NE sec 2, T. 10 S., R. 8 W. The saltwater sample from Rattlesnake Creek is believed to be a good representative of the saltwater discharging from the lower stratigraphic interval of the Jones well into the creek bottom. The curve is shown only for zones of sandstone that are relatively low in clay content as indicated by the gamma-ray log. The estimated specific-conductance trace is a highly acceptable match with sample measurements and appears to show a transition zone between the fresher water of the upper sandstone and the more saline waters of the lower sandstones.

Again, it must be emphasized that log estimates of water quality should only be used (and then with caution) where no samples are available for direct analysis. In each case, the log property is an *indirect* measure, because it records a physically dependent property, rather than water salinity itself. In addition, rock properties other than water salinity may contribute to overall conductivity effects. The accuracy of the estimates degrades as water salinity decreases, generally overpredicting salinity in fresher waters. However, when used judiciously with water-

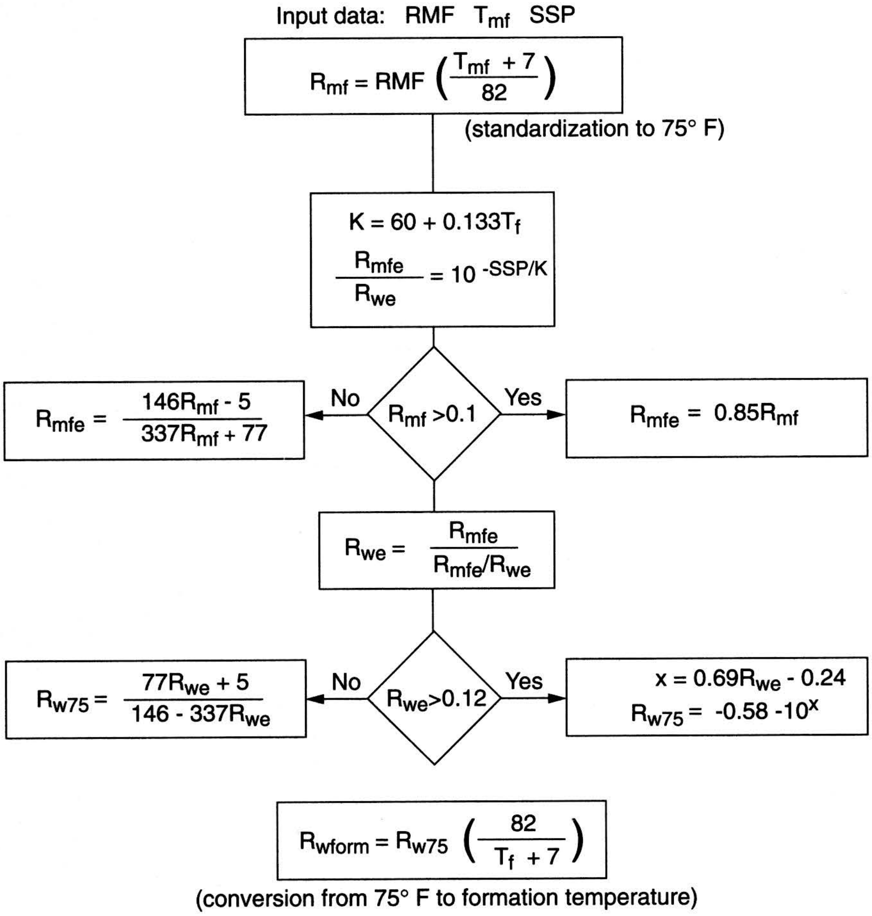


FIGURE 33—FLOW CHART FROM OIL-INDUSTRY LOG ANALYSIS TO ESTIMATE FORMATION-WATER RESISTIVITY, RW, IN DEEP FORMATIONS FROM THE SP LOG (Bateman and Konen, 1977). RMF is mud-filtrate resistivity measured at temperature Tmf and recorded on the log header; Tf is the temperature of the formation, generally estimated by interpolating between the bottom-hole temperature (BHT) at total depth (TD) and mean annual temperature at the surface; SSP is the static self-potential measured on the log between the "clean line" and "shale line" in millivolts (mv) AND with associated sign (positive or negative).

chemical measurements, log-data estimates are valuable in extending knowledge of Dakota aquifer water quality over larger geographic areas and greater depth ranges.

Pumping of Test Holes—When suitable aquifer zones have been located through test-hole drilling, a temporary casing and well screen may be installed, creating a test well. The test well can then be pumped to obtain preliminary estimates of well yield, water quality, and aquifer characteristics. Final site selection and well design are determined on the basis of these preliminary tests and an analysis of the cuttings produced from drilling the borehole.

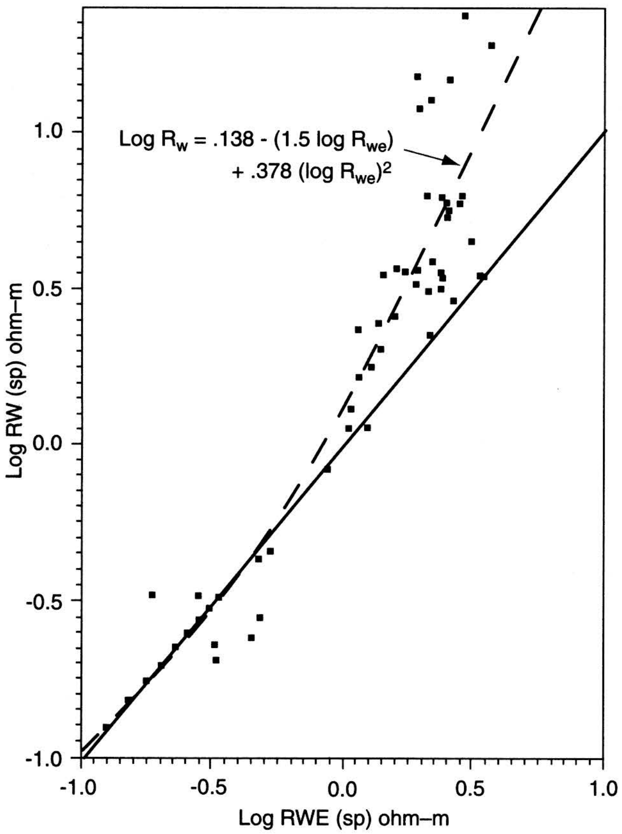


FIGURE 34—Custom-designed chart and function to convert apparent water resistivity (Rwe) calculated from oil-industry algorithms to actual resistivity (Rw) of Dakota aquifer waters. The correction is necessary because Rwe is calculated with the assumption that the dissolved solids in the water are from a single salt; actual Rw's will be controlled by the ionic mix of natural waters, and discrepancies with Rwe will be particularly noticeable in the relatively fresher waters of shallow formations. From Boeken (1995).

Well yields in the Dakota aquifer of Kansas range widely from less than 25 up to more than 750 gal/min (95–2,850 L/min). The highest reported yields come from near the central Kansas outcrop belt. Lobmeyer and Weakly (1979) reported well yields up to more than 1,000 gal/min (3,800 L/min) for wells in the Dakota of Hodgeman and northern Ford counties. Wade (1991) reported the results of a pumping test on a well used for crop irrigation in a part of southwestern Washington County where high-capacity wells in the Dakota are common. The rate of production during the test was approximately 592 gal/min (2,250 L/min). Watts (1989) reported the results of a pumping test on a Dakota well near Garden City. For the duration of the test, the production rate was more than 1,000 gal/min (3,800 L/min). To the north in Ellis County, pairs of wells in the Dakota installed by the City of Hays were pumped at a rate of 75 gal/min (285 L/min) during the summer of 1994. Farther west, wells in the Dakota are primarily for low-demand domestic and stock use. These wells yield up to 100 gal/min (380 L/min) in some cases.

Well yield is partly a function of the aquifer's ability to produce water. For the Dakota aquifer, the most important factors governing this ability are the total thickness and hydraulic conductivity (transmissivity) of the sandstone. In general, the greater the accumulated thickness of sandstone adjacent to the well screen, the greater the yield because more of the aquifer is available to the well for water production. The hydraulic conductivity of a material is a measure of its resistance to flow. The larger the value, the easier it is for the well to produce water. From the set of pumping-test results available for the Dakota, the aquifer appears to be much more permeable near the central Kansas outcrop belt than in western Kansas. This generally coincides with the area of the state where high-yielding wells in the Dakota are more common. However, even in this part of the state, the Dakota is less permeable than the High Plains aquifer.

Another important factor is the aquifer extent in the vicinity of the well. The aquifer extent refers here not only to size and shape of the individual sandstone body adjacent to the screened well, but also to the degree of interconnection with other nearby sandstone bodies. In general, the greater the net thickness of sandstone adjacent to the well screen, the greater the likelihood of the well penetrating one or more sandstone bodies that are part of a network of aquifer units. Tapping into the network of hydraulically connected sandstones helps to ensure that well yield will be maintained over the long term.

Figure 16 can be used as a general guide as to whether the waters in the upper part of the Dakota aquifer at a given location will be fresh or saline. The great range in TDS concentration that can be encountered in the Dakota aquifer shows the need for careful monitoring of salinity during test drilling in those areas near or within regions of saline water, especially if deeper wells are drilled. The specific conductance of a water is a very easy measurement to make; relatively inexpensive, hand-held meters are now available for determining conductances of sufficient accuracy for salinity estimation. The specific-conductance reading in µmho/cm or µS/cm can be multiplied by 0.63 for an estimate of the TDS in mg/L (nearly the same as ppm) of most Dakota aquifer waters. Freshwaters are classified as containing less than 1,000 mg/L. Field tests of chloride concentration can also be made in the field with simple test kits.

Monitoring of salinity during drilling could be particularly valuable when passing below shale units into lower sandstones in areas of potential salinity. The wide range in the rate of salinity increase with depth, for example in fig. 19, shows that waters of acceptable quality in an upper sandstone may lie above a sandstone with saline water. Frequent measurement of the conductance of drilling fluids could aid in early determination of how deep the zone of usable water extends. The presence of drilling mud will somewhat affect the conductance reading of the water. Thus, measurement of the difference in specific conductance between the drilling water before and after drilling mud or rock cuttings are mixed is useful for approximate adjustment of readings to values representative of the true conductance of the aquifer water.

Water samples should be collected from the test hole and submitted for analysis in a chemical laboratory. If the waters are to be used for drinking, the analysis should be examined for constituent concentrations relative to recommended levels and maximum contaminant limits (MCL). Some of the contaminant limits are listed in table 2; the complete list is available from the Kansas Department of Health and Environment. In addition to major constituents contributing to the salinity of the water, fluoride, iron, and manganese contents of the water may be of particular interest because they are often high in the confined portion of the upper Dakota aquifer as indicated in the previous section on water quality. Hydrogen sulfide may be present in ground waters in some locations, particularly in the confined aquifer; the dissolved gas will be apparent as a "rotten egg" odor. Natural contents of nitrate and heavy metals are nearly always below MCL's in uncontaminated Dakota waters, although nitrate contamination might be present in shallow waters in the outcrop zone. Consideration should be given to determining the presence of arsenic, mercury, and lead in an assessment for drinking-water use because these have been observed to be somewhat above MCL's in a very few locations. However, the observed lead values may be related to the presence of lead solder in the piping or electrical systems, and care must be taken to avoid these materials in test and constructed wells and distribution systems. Waters in the confined aquifer can be corrosive due to higher dissolved solids contents and dissolved hydrogen sulfide. The sodium bicarbonate waters in the confined aquifer have high sodium-adsorption ratios and should be used carefully as irrigation waters to prevent reduction of soil permeability.

Water-resources Management Issues in the Dakota Aquifer

Effect of Well Pumping on the Dakota Aquifer

Ground water from the surrounding aquifer must move toward the well for it to produce; this happens when the pump is turned on. As water is removed from the well by pumping, the hydraulic head in the well and in the aquifer adjacent to the well screen is decreased. This causes ground water in the aquifer to move laterally toward the well. The drawdown is the decline of water level (or hydraulic head) observed in wells screened in the aquifer being pumped. Under ideal conditions of a relatively uniform regional aquifer, such as the High Plains aquifer, the area experiencing drawdown around the pumping well is nearly circular in plan view. The amount of drawdown is a maximum at the pumping well and diminishes to zero some distance away. The region affected by drawdown from pumping is referred to as the cone of depression (fig. 37). The size of the cone of depression and the drawdown will increase until there is a balance between the pumping rate and the flow in the aquifer moving radially toward the well from all directions. If the rate of water production greatly exceeds the radial flow moving toward the well, the cone of depression will grow continuously and the aquifer around the well will eventually be depleted. The movement of water toward the well is governed by the aquifer permeability and thickness.

As discussed earlier, the Dakota is not a uniform regional aquifer; it consists of hydraulically connected and isolated permeable sandstone bodies that are finite in size and encased in relatively impervious mudstone. Because the mudstones effectively do not yield water, the edges of these sandstone bodies are hydrologic barriers to flow depending on the rate and duration of pumping. This reduces the rate of recharge moving laterally toward the developing cone of depression or zone of influence. As a result, the zone of influence can extend out from the well along the length of these elongated sandstone bodies for several miles or more and may extend into other hydraulically connected sandstone bodies. However, in the direction perpendicular to the long axis of the sandstone body, this zone may only extend to the edge of the aquifer. In some cases this may be less than a mile away (fig. 38). These boundaries affect the well by accelerating the rate of drawdown with time. The lower water levels may necessitate lowering the pump in the well, which increases energy costs associated with water production.

If two pumping wells in the Dakota aquifer are spaced even a few miles apart and are withdrawing water from the same sandstone body, their zones of influence will likely overlap and coalesce (fig. 39). When this occurs, the total recharge moving laterally into each well's zone of influence from the adjacent aquifer is reduced, creating an

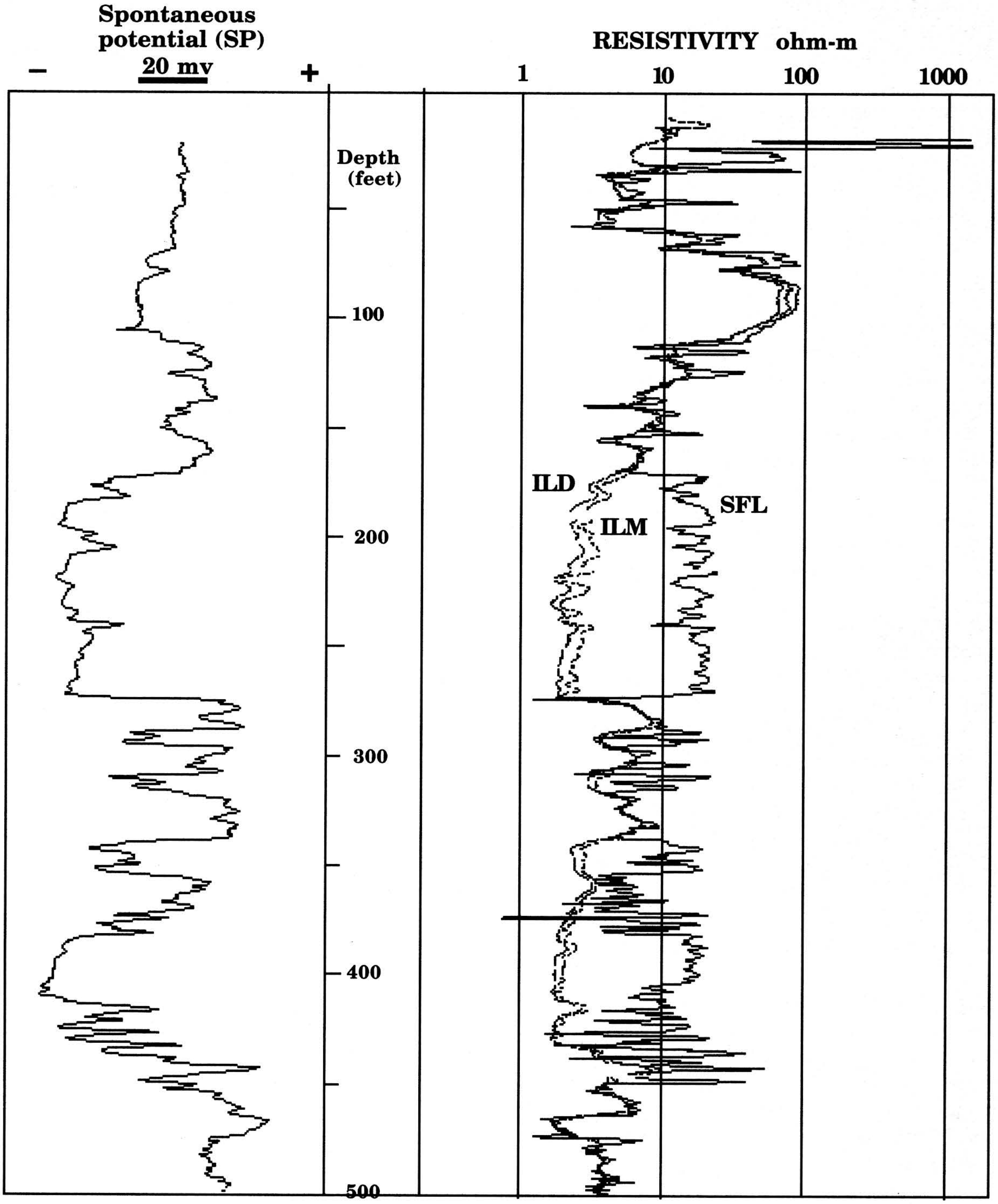


FIGURE 35—SPONTANEOUS POTENTIAL (SP), SPHERICALLY FOCUSED (SFL), MEDIUM- (ILM) AND DEEP- (ILD) INDUCTION RESISTIVITY LOGS FROM KGS JONES #1, NE NE NE SEC. 2, T. 10 S., R. 8 W., LINCOLN COUNTY, KANSAS.

impairment. Impairment results when one well diminishes the supply of water available to another nearby well. The immediate impact of this impairment is to increase the drawdown in both wells. If both wells continue pumping for longer periods of time, it may cause local depletion of the aquifer. This is most likely to happen where the pumping wells are located far away from sources of recharge or a discharge area.

The pumping effect on hydraulic head is transmitted through an aquifer much faster than the actual movement of water. However, pumping does move water and can induce the movement of saline water in the aquifer into a supply well. Figure 19 shows the great increase in salinity at the bottom of a sandstone into the underlying shale. Water withdrawn from a well will be preferentially derived laterally from the most permeable layers in a sandstone. Some water also may be derived vertically as leakage from overlying units. However, if pumping occurs at a great enough rate or over a long enough period of time, the

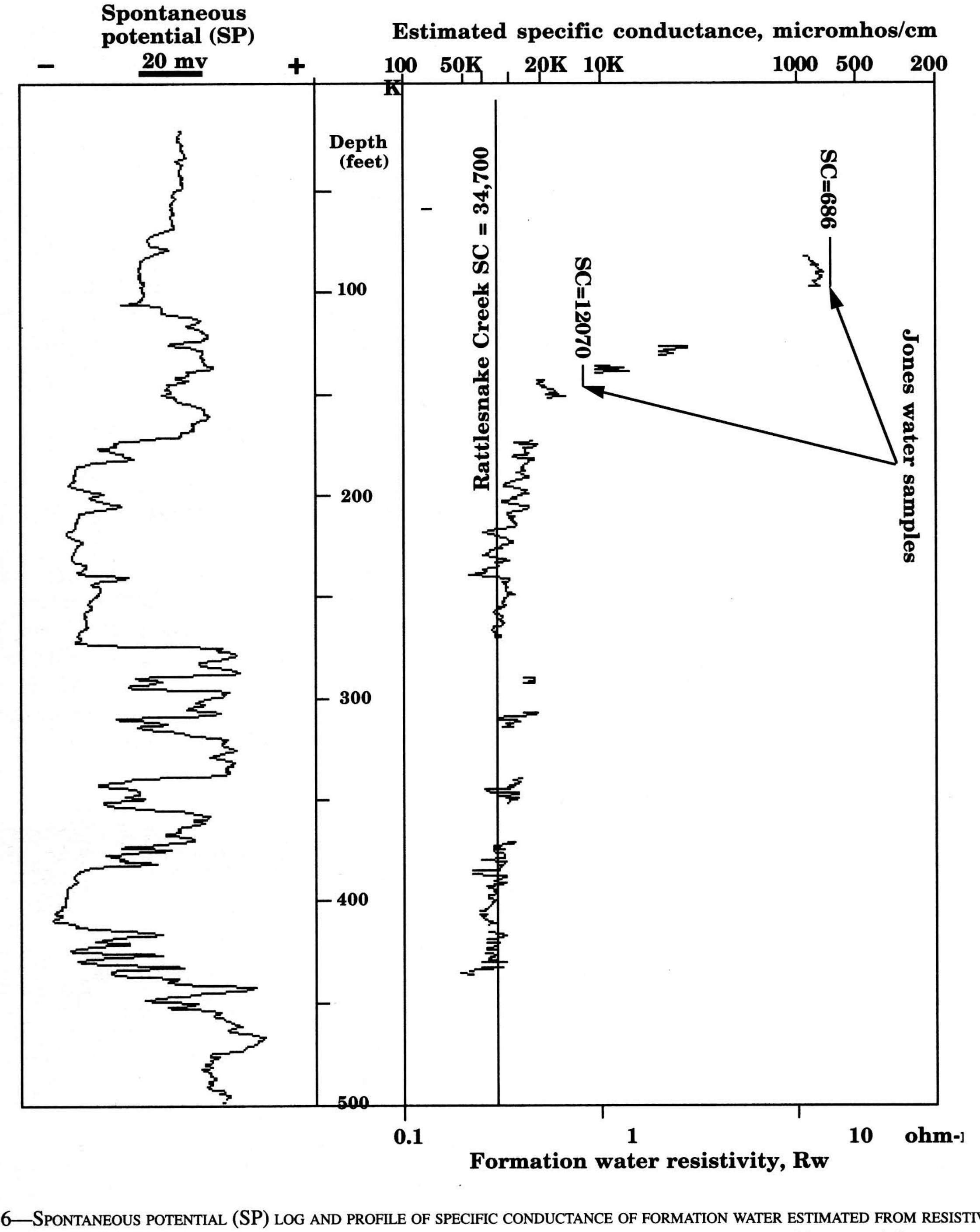


FIGURE 36—Spontaneous potential (SP) log and profile of specific conductance of formation water estimated from resistivity and porosity logs in KGS Jones #1, NE NE NE sec. 2, T. 10 S., R. 8 W., Lincoln County, Kansas. Note match between profile and conductances measured from well-water samples.

stress may be sufficient to cause upward movement of saline water from the bottom of a sandstone below which there is a great salinity increase. Pumping stress can also move water laterally from near the edge of sandstone bodies where water in the confined aquifer can be more saline in finer-grained sediments. In addition, long-term pumping near lateral zones of freshwater to saltwater transition could obtain higher-salinity water from the transition zone. Decreasing the rate of withdrawal could decrease the amount of saline water drawn from below and laterally if leakage from above the sandstone is relatively important. However, upconing and lateral movement of salinity from nearby sandstone boundaries and saltwater-transition zones could eventually cause slow increases in TDS concentrations if the leakage rate from above is relatively low.

Well-spacing Regulations

The Chief Engineer, Division of Water Resources (DWR), and the groundwater management districts (GMDs) have each formulated regulations that address the minimum spacing between pumping wells in the Dakota. The purpose of well-spacing requirements is to ensure that there is no direct impairment between wells using the Dakota as a source of supply. The regulations take into account either the rate of withdrawal or the local hydrogeologic setting or both. The DWR well-spacing for the Dakota where the Dakota is confined by the Upper Cretaceous aquitard is 4 mi (6.4 km) for all wells other than domestic, and 0.5 mi (0.8 km) for domestic wells because the local recharge to the Dakota is negligible. Where the Dakota aquifer is at the surface or is beneath the alluvial valley or High Plains aquifer, the new well spacing is 0.5 mi (0.8 km) for all wells other than domestic and 1,320 ft (0.25 mi [0.4 km]) for domestic wells. Computer simulations indicate that there is sufficient local recharge to the aquifer from infiltrating precipitation or from overlying shallow aquifers to justify the smaller well spacing. In Great Bend GMD 5, West-central Kansas GMD 1, and Northwest Kansas GMD 4, the spacing between Dakota wells other than domestic is 1 mi (1.6 km).

In Southwest Kansas GMD 3, the hydrogeology and use of the Dakota are sufficiently diverse across the District that a variable well spacing is appropriate. Figure 40 shows the generalized hydrogeology of the District in cross section. Beneath the unconsolidated High Plains aquifer, the bedrock units are slightly tilted to the north. In the northern part of the District, the Upper Cretaceous aquitard is present and the Dakota and High Plains aquifers are separate systems. In the southern part of the District where the Upper Cretaceous aquitard is not present, the Dakota thins to the south due to erosion and is hydraulically connected to the overlying High Plains aquifer. As a result, the boundary separating the High Plains from the Dakota is an irregular surface. Within this part, the upper Dakota aquifer is not present near the southern extent of the Dakota aquifer system. In this part of the District, the Kiowa Shale aquitard provides a local separation between the lower Dakota and the High Plains aquifers, or the lower Dakota is hydraulically connected to the overlying High Plains aquifer. Where both aquifer systems are hydraulically connected, the spacing for wells in the Dakota withdrawing more than 500 acre-ft/yr is 2,300 ft (690 m), the same as it is for High Plains aquifer wells. Wells withdrawing less water can be placed more closely together.

Sustainability of the Dakota Aquifer System

The major ground-water management issue that will affect the long-term viability of the Dakota as a major resource is its sustainability under development. As it is defined here, sustainability is the ability of the aquifer to supply water to users without being depleted during the planning period. As a practical matter, we arbitrarily set the planning horizon to be 20 years.

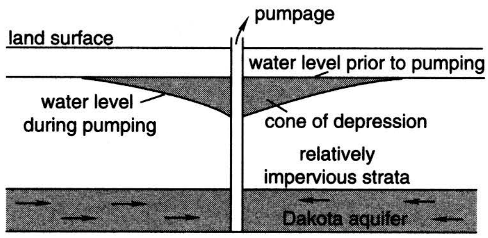


FIGURE 37—THE CONE OF DEPRESSION THAT RESULTS FROM PUMPING WATER FROM A CONFINED AQUIFER. Pumping decreases the fluid pressure in the confined aquifer, thereby also decreasing the hydraulic head in the aquifer.

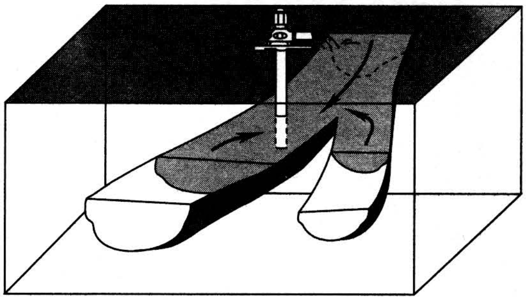


FIGURE 38—GROUND-WATER FLOW TO A PUMPING WELL IN A RIVER-DEPOSITED SANDSTONE AQUIFER. Ground-water flow follows the axis of the channel. The effects of ground-water withdrawals may be felt a long distance from the pumping, depending on the geometry of the sandstone body and its hydraulic diffusivity.

Sustainability implies the attainment of a new dynamic equilibrium under conditions of widespread development. For equilibrium to occur, withdrawals from the aquifer must either induce additional recharge to the aquifer, reduce discharge from the aquifer, or both. This occurs by increasing the hydraulic gradient in the aquifer when the hydraulic head within the aquifer is decreased. These decreases will continue until changes in recharge and discharge balance withdrawals from the aquifer. The most direct evidence of this new balance is long-term stability of hydraulic heads in the aquifer. The sustained yield depends on the rate at which the hydraulic-head decreases propagate through the aquifer to the recharge or discharge area. The closer the pumping centers are placed to either the recharge or discharge areas, the more likely it is that additional recharge or reduced discharge can be realized by withdrawals. The rate of propagation is a function of aquifer diffusivity (the ratio of the hydraulic conductivity to the specific storage). The higher the diffusivity, the faster the rate of propagation of the cone of depression. It is likely that pumping centers located farther away from either the recharge or the discharge areas will influence the amount of recharge to and discharge from the aquifer only if the diffusivity is high.

Water budgets are useful for examining the flow of water between the various compartments within the hydrologic cycle or a ground-water-flow system. Under predevelopment conditions within an aquifer, there is a dynamic equilibrium between recharge and the discharge or outflow from an aquifer (fig. 41A). Water also is in storage within the pores of the aquifer framework, and under these conditions, the total volume in storage remains relatively constant.

With the introduction of pumping wells, the volume of water in each of these three categories changes depending on the location of the pumping wells in the aquifer with respect to sources of recharge and discharge, rates of withdrawal, and aquifer hydraulic diffusivity. All the water withdrawn by a pumping well in a confined aquifer comes either from storage or capture (fig. 41B). Initially, all the water produced by the well comes from storage in the aquifer adjacent to the well. As the well continues to pump, more and more of the aquifer experiences water-level declines. The higher the hydraulic diffusivity, the faster these water-level declines propagate through the aquifer system. Given enough time, these declines will propagate to either the recharge or the discharge area, or both, producing "capture" (fig. 41C). When this happens, additional recharge enters or discharge from the aquifer system is decreased, resulting in an additional source of water added to the aquifer to balance the withdrawal. Capture is the sum of the increase in recharge and the decrease in discharge that results from pumping. As the well continues to pump, more and more of the water produced by the well is replaced by capture. The additional recharge coming from the recharge area may result from reduced local discharge to streams in the recharge area or from another hydraulically connnected aquifer. The generation of capture by pumping does not create any "new" water but is merely a reallocation of the amounts in the total hydrologic budget for a region. All other things being equal, the proportion of the capture that comes from added recharge or decreased discharge will depend on whether the well is located closer to the source of the recharge or the discharge area. Eventually, a new dynamic equilibrium occurs when the amount of water withdrawn is balanced by capture. At this point, the hydraulic heads in the aquifer approach stability at levels that are lower than they were during predevelopment (fig. 42).

In the confined part of the Dakota aquifer, the effects of development will be pronounced. The distance from recharge to discharge areas is up to several hundred miles away in the Dakota in northwest Kansas. If the production wells are more than approximately 20 mi (32 km) away from sources of recharge or discharge, the generation of capture is unlikely within a 20-year time frame. Even where the High Plains aquifer is present, significant amounts of additional freshwater recharge to the confined

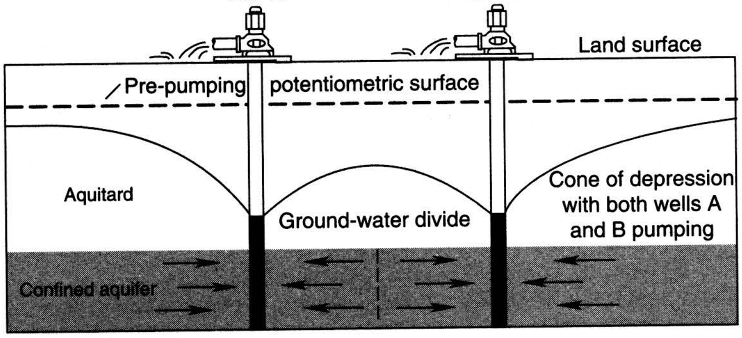


FIGURE 39—The mutual interference developed from wells spaced too closely together in a confined aquifer. Note how the drawdown in the coalescing cones of depression is greater than for the drawdown produced by a single pumping well.

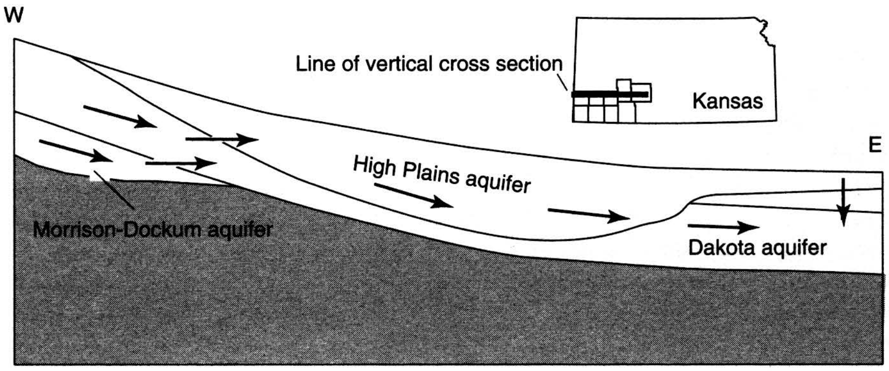


FIGURE 40—GROUND-WATER FLOW IN THE DAKOTA, MORRISON–DOCKUM, AND HIGH PLAINS AQUIFERS IN SOUTHWESTERN KANSAS.

Dakota are unlikely because of the low vertical hydraulic conductivity and thickness of the overlying aquitard. Hence, all the water withdrawn from the aquifer will come from storage. Meaningful management plans in this part of the system should be premised on an acceptable rate of water-level decline within the planning period and not on the premise of sustained yield.

Depletion of the confined aquifer is likely if production wells are spaced too closely together and the rates of withdrawal from the aquifer are unregulated. Computer simulations to assess the effects of pumping have demonstrated that in the confined upper Dakota aquifer, coalescing cones of depression from multiple pumping wells spaced from 1 to 4 mi (1.6–6.4 km) apart form quickly after pumping begins. After 10 years, larger drawdowns than would be expected from a single pumping well are produced and a much larger area of the aquifer is affected by the withdrawals. Taking into account the heterogeneity of the Dakota, a well spacing of 20 mi (32 km) in an east-west direction and 5 mi (8 km) in a north-south direction is recommended to avoid mutual interference problems. A 20-mi (32-km) spacing between well fields with multiple wells also is recommended where only one or two wells are pumped at a time.

The steps taken to prevent depletion clearly depend on the total intensity of development. At low intensities (average spacing of major centers of withdrawal of 20 mi [32 km] or more), well spacing and control of pumping rates should be adequate. Under higher-intensity development, prevention of depletion is only possible by maintaining the points of withdrawal in proximity to sources of recharge or the discharge areas from the aquifer, if capture from these sources is allowed in the management scheme.

Where wells are located within the confined part of the aquifer and a few miles from the confined-unconfined boundary, the loss of storage will continue until the cone of depression, due to pumping, reaches a source of recharge, such as an overlying aquifer. At this point, additional recharge will be induced to enter the unconfined Dakota and the loss of water from storage will diminish and water levels in the aquifer will begin to stabilize. The time it will take to attain this new equilibrium depends on the distance from the source of recharge or discharge and the properties of the aquifer. In the more permeable part of the aquifer, this may take up to 10 years or more to accomplish. Management on the basis of sustained yield may be more realistic in this part of the confined system.

However, not all of the consequences of managing these systems on the basis of sustained yield are necessarily positive. The generation of capture may create saltwater-intrusion problems if the points of withdrawal from the aquifer are located too closely to water-quality transitions, or sources of saltwater recharge, as in the case of the Dakota aquifer in central and northwest Kansas.

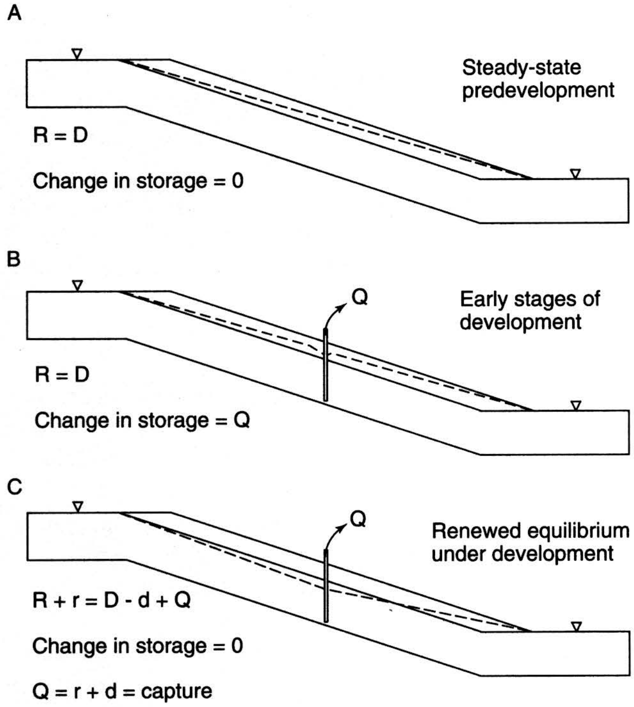


FIGURE 41—Changes in the water budget of a confined aquifer caused by water-resources development. The dashed line represents the trace of the potentiometric surface in the cross section. Under the steady-state, predevelopment phase, recharge (*R*) is balanced by discharge (*D*) from the aquifer with no change in storage. In the early stages of development, the water produced by wells comes entirely from storage. Once the potentiometric surface has been lowered sufficiently to increase the hydraulic gradient near the recharge or discharge area, additional recharge (*r*) or reduced discharge (*d*) or both may occur, generating capture. In this later stage of development, the water produced by wells comes entirely from capture, and there is no further loss of storage; a new equilibrium condition is created. The time required to generate significant capture depends on the diffusivity (the ratio of hydraulic conductivity to specific storage) of the aquifer.

From an overall management perspective, capture may not be beneficial if the additional recharge moving into the confined aquifer is coming from an already overappropriated, hydraulically connected aquifer system such as the High Plains. In the 1970's, Southwest Kansas GMD 3 declared that high-capacity wells (withdrawal rates of greater than 100 acre-ft/ yr) in the confined Dakota aquifer could not be located closer than 5 mi (8 km) from the confined/unconfined boundary of the Dakota within the district. Wells pumping at lower rates can be located closer to the confined/unconfined boundary. The purpose of this regulation is to prevent induced recharge to the confined aquifer from the hydraulically connected High Plains/Dakota aquifer system by pumpage in the confined part of the Dakota.

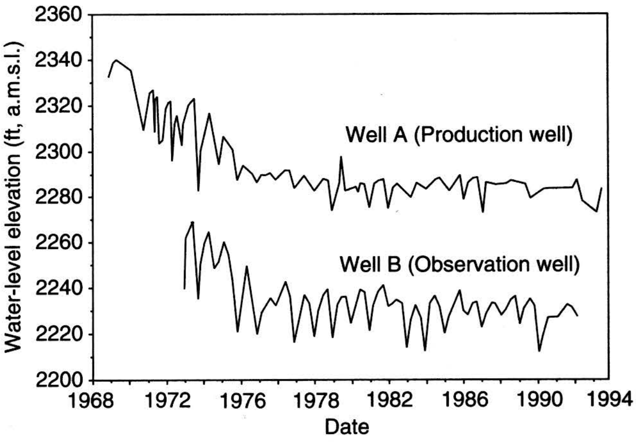


FIGURE 42—Hydrographs of a production well and an observation well in the upper Dakota aquifer of Ford County, Kansas. The wells are approximately 6 mi (9.6 km) apart. Water-level declines during the early phase of development induce flow into the Dakota aquifer from the High Plains aquifer, eventually creating a new equilibrium within the aquifer.

Where the Dakota is unconfined, the effects of development will be less dramatic than in the confined part of the aquifer because pumping will be located near local recharge and discharge areas where the aquifers are more permeable. In the outcrop areas, local recharge areas for the Dakota coincide with the upland areas and are near the drainage divides, and local discharge zones are along the drainage network. The distance from local recharge to local discharge areas is relatively short (on the order of a few tens of miles or less). As a result, the potential for a well to generate capture and produce a new dynamic equilibrium is very much enhanced. The high probability of occurrence of sandstones with higher than average hydraulic conductivity in the outcrop belt indicates that capture can be quickly generated by pumping. This will most likely result by reduction in discharge from the aquifer to streams in central Kansas and to the High Plains and Arkansas River alluvial aquifer in parts of Stanton, Morton, and Hamilton counties. The long-term hydrographs of high-capacity wells tapping ground-water supplies in this part of the aquifer do not show a pattern of decline.

In much of southwestern Kansas, the Dakota is hydraulically connected to the overlying High Plains aquifer. Computer simulations demonstrate that capture is produced in the Dakota due to an increase in downward leakage from the High Plains aquifer and reduced down-gradient flow of water to the east. The model results also show that the High Plains–Dakota aquifer system is sensitive to the nature of the coupling between both aquifers. This suggests that the proportion of increased leakage to capture generated by pumpage also depends on this coupling. Hence, the more hydraulically connected the Dakota is to the High Plains aquifer, the more easily leakage (or flow) will transfer from one aquifer to the other in response to pumping.

Protection of Water Resources from Contamination by Human Activities

PROTECTION FROM SURFACE SOURCES OF CONTAMINATION—Most of the contamination observed in Dakota aquifer waters involves elevated concentrations of nitrate and other constituents associated with nitrate sources. Nitrate occurs naturally at low concentrations (usually below a couple mg/L) in Dakota ground waters. High nitrate concentrations are derived from anthropogenic sources and are generally local. The number of wells yielding high nitrate content is appreciably greater in the eastern outcrop area than in the confined aquifer and the subcrop area overlain by the High Plains aquifer.

Although some infiltration of surface sources of nitrate could pass through soils and rock to reach shallow water tables in the outcrop area, most of the nitrate contamination of Dakota ground waters is probably related to old or poor well construction. Most of the wells in the outcrop and subcrop area are used for domestic and stock purposes. Many of the wells yielding water with elevated nitrate were installed before the State required construction methods that increased protection from surface contamination. Irrigation wells and newer domestic and stock wells tend to yield water with substantially lower nitrate concentrations in the outcrop area. Older wells were constructed without adequately thick surface seals around the well casing; this can allow surface or near-surface drainage to enter well water in the borehole along the outside of the casing (pipe lining the borehole). Another avenue of contamination is through unplugged, abandoned wells, especially those that were poorly constructed or have deteriorated. Several older wells in the confined Dakota aquifer near the eastern outcrop/subcrop belt yield waters with high nitrate content, definitely indicating well construction or abandoned, unplugged wells as the problem, because recharge could not penetrate to the confined Dakota aquifer in the time since settlement of the area. Newer well-construction methods, well rehabilitation, and active programs to plug old abandoned wells are an important approach to protecting the aquifer from surface contamination.

The sources of the high nitrate at the surface are primarily animal and human wastes and fertilizer, although oxidation of nitrogen in soil organic matter can contribute as well. Domestic and stock wells in rural areas are often in or near barnyards and may be relatively close to septic tanks and drainage lines. Domestic wells in towns can also be close to human-waste discharges and lawn and garden chemicals and could be susceptible to contamination if not properly constructed or if close to abandoned, unplugged wells. Other inorganic constituents associated with high nitrate concentrations, in order of average decreasing importance, are chloride, calcium, sodium, and magnesium. Thus, ground waters in the Dakota aquifer with nitrate contamination usually have elevated TDS content. Other chemicals associated with agricultural activities and lawn maintenance such as pesticides, and organic compounds used in commerce such as degreasing solvents could accompany inorganic constituents in water draining through poorly constructed or deteriorated used and unused water wells.

Although direct entrance of surface or near-surface waters through boreholes and improperly plugged testholes and wells is probably the main avenue of contamination of the Dakota aquifer, pollutant chemicals could also infiltrate through soil and shallow thicknesses of the Dakota aquifer to reach ground waters in the outcrop area. Well-head protection is an important method of keeping potential sources of contaminants at a distance from wells. The approach involves delineating an area on the ground surface around a water-supply well and disallowing or removing activities or materials that could lead to the release of contaminants. Thus, gasoline stations, pesticide and fertilizer distribution, and waste sites, for example, should not be placed within the protection area. The simplest area boundary is a circle of a fixed radius such as a quarter mile, although better well-head protection areas are based on the zone under the surface within which water would be pumped or "captured" by a supply well over a given time period such as 50 years.

PROTECTION FROM SUBSURFACE CONTAMINATION BY FORMATION BRINES—Oil and gas is produced from rock formations underlying much of the region of the Dakota aquifer. The oil or gas pumped by production wells is accompanied by varying amounts of saltwater from the deep formations containing the petroleum. The saltwater must be disposed in subsurface formations containing saltwater at depths that will not lead to contamination of overlying aquifers. Current Kansas regulations establish minimum depths for disposal of oil and gas brines (Table II of the General Rules and Regulations for the Conservation of Oil and Natural Gas of the Kansas Corporation Commission [KCC]). However, some disposal of formation brine took place in the early 1940's into zones in the lower part of the upper Dakota aquifer already containing saline water in Russell County and in the lower Dakota aquifer in central Kansas until 1970.

Oil brine has been and is disposed into the Cedar Hills Sandstone underlying the Dakota aquifer. A concern has been whether the additional pressures in the Cedar Hills could allow upward movement of saltwater into the Dakota aquifer through abandoned oil and gas boreholes that were improperly sealed or plugged or not plugged. Consequently, the eastern limit of the area where brine disposal was allowed in the Cedar Hills Sandstone was moved to the west by a moratorium regulation to better protect water quality in the High Plains and the Dakota aquifers (fig. 43). The south-central Kansas moratorium passed by the KCC in 1987 prohibits Cedar Hills disposal in (1) all of Pratt, Stafford, Barton, Comanche, and Kiowa counties; (2) the eastern half of R. 18 W. and all of R. 16–17 W. in Rush, Pawnee, and Edwards counties; and (3) all of T. 27–29 S., R. 21–22 W. in Ford County. The north-central Kansas moratorium passed by the KCC in 1990 prohibits Cedar Hills disposal in all of Russell and Osborne counties, and established a buffer zone in T. 7–15 S., R. 16 W.; T. 7–11 and 15 S., R. 17 W.; T. 7–8 and 15 S., R. 18 W.; and T. 15 S., R. 19 W., in Ellis and Rooks counties.

Kansas regulations also require the petroleum industry to protect fresh and usable aquifers from contamination by establishing minimum depths for surface casing in an oil or gas borehole (Table I of the General Rules and Regulations for the Conservation of Oil and Natural Gas of the KCC). The surface casing is a pipe that is inserted into the borehole being drilled during oil or gas exploration and sealed by injecting cement under pressure to fill the space between the casing and the borehole. The primary function of the surface casing in the petroleum industry is to prevent saltwater from entering a usable aquifer from lower zones intersected by the borehole. Although the static fluid level in some of the formations underlying the Dakota aquifer can be below the bottom of the aquifer, the fluid level can often be above the aquifer base in some areas such as where saltwater intrudes from the Cedar Hills Sandstone into the base of the Dakota in central Kansas. In other areas, pressures have been increased in the petroleum-bearing strata by the injection of secondary or waterflood waters or in brine-disposal zones by disposed saltwater. The greater pressures could also lead to flow of saltwater into overlying aquifers if the aquifer sediments were not sealed along the borehole. The cemented surface casing has the added advantage of protecting fresh and usable aquifers from surface contamination and from loss of water resources by drainage down boreholes where fluid levels in deeper formations are below the aquifer.

State statutes define the classifications for the fresh and usable aquifer waters that must be protected:

Class I—Fresh ground water contains not more than 500 mg/L chloride or 1,000 mg/L of total dissolved solids.

Class II—Usable ground water contains more than 500 mg/L but not more than 5,000 mg/L chloride, or more than 1,000 mg/L but not more than 10,000 mg/L total dissolved solids.

Class III—Mineralized ground water contains more than 5,000 mg/L chloride or more than 10,000 mg/L total dissolved solids.

The map of total dissolved solids (fig. 16) includes contour lines for both the 1,000 mg/L and 10,000 mg/L TDS values for the limits of fresh and usable waters. Figure 16 was produced to generally display the freshest water within the aquifer and can serve as a conservative estimate of what waters should be protected. The data for this figure are based on analyses of water samples primarily in the fresh

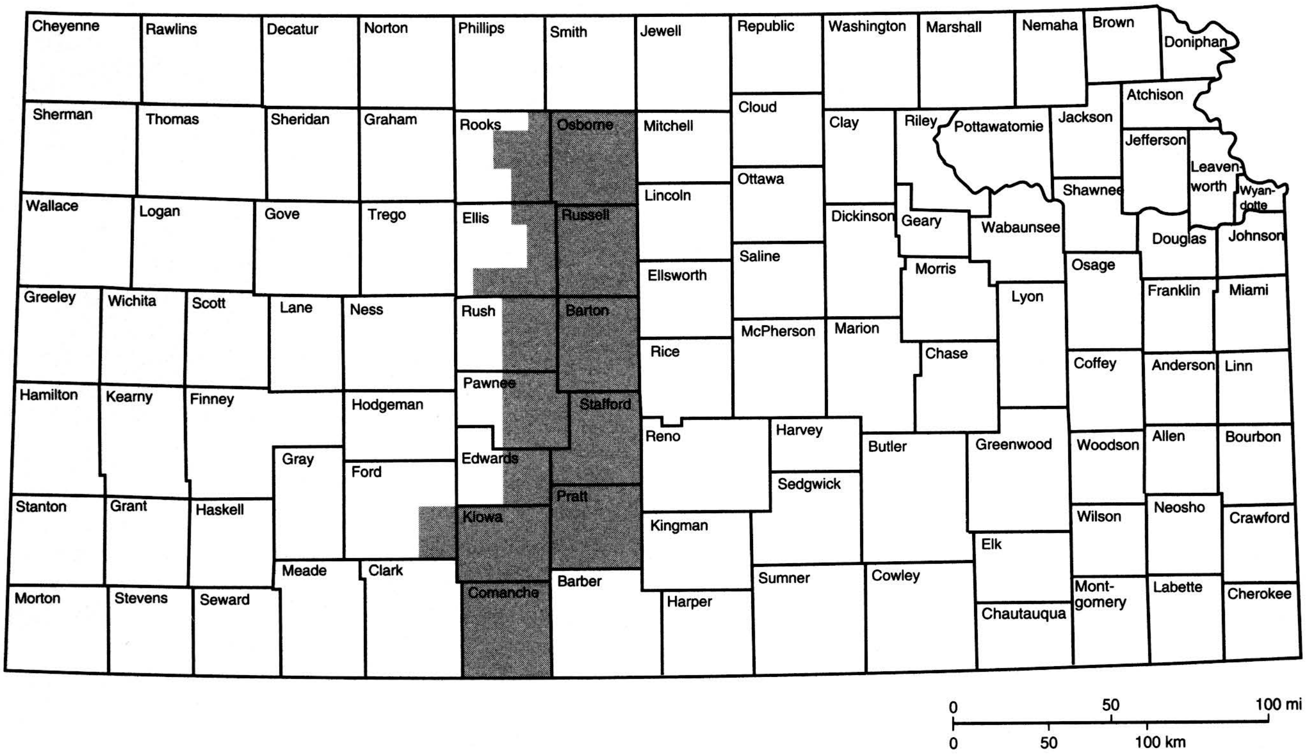


FIGURE 43—CEDAR HILLS DISPOSAL MORATORIUM AREAS ESTABLISHED BY THE KANSAS CORPORATION COMMISSION FOR CENTRAL KANSAS.

to usable water areas and on interpretation of geophysical logs in northwest Kansas. Table I of the KCC includes some of the regulations for minimum surface-casing requirements that were established using data preceding the Dakota Aquifer Program. Figure 16 provides improved information on which future revisions of Table I could be based.

The chloride distribution in Dakota aquifer waters is similar to the pattern shown in fig. 16. However, the area of ground water with chloride concentrations less than or equal to 500 mg/L is larger than for the area of TDS concentrations of 1,000 mg/L or less (freshwater). The main dissolved constituents in saltwater in Dakota aquifer waters are sodium and chloride, with lesser concentrations of calcium, magnesium, and sulfate. Fresh or slightly saline water contains appreciable amounts of dissolved constituents other than sodium and chloride, including bicarbonate. Thus, Dakota water with a TDS of 1,000 mg/L has a chloride content of from about 70 to 270 mg/L, values substantially less than 500 mg/L. In contrast, the average chloride concentration of Dakota aquifer water with a TDS content of 10,000 mg/L is very close to 5,000 mg/L; therefore, the chloride and TDS classification values agree well for the limit of usable water. Chloride concentration can be approximately estimated from TDS values greater than 1,350 mg/L using the following equation:

$$\text{Chloride (mg/L)} = 0.5441\ (\text{TDS [mg/L]}) - 381. \qquad \text{(eqn. 4)}$$

For example, if the TDS equals 5,000 mg/L, the approximate chloride content would be 5,060 mg/L, or about 50% of the TDS. The other 4,940 mg/L of dissolved solids would primarily be sodium, sulfate, bicarbonate, calcium, and magnesium. The higher the TDS content, the better the estimate. Chloride concentration cannot be estimated very accurately from TDS values less than 1,350 mg/L, although the following relationship will at least give a rough approximation of chloride usually within ±50% of the true value:

$$\text{Chloride (mg/L)} = 0.3815\ (\text{TDS [mg/L]}) - 163. \qquad \text{(eqn. 5)}$$

Based on this equation, a water with a TDS concentration of 1,000 mg/L would contain a chloride content of about 220 mg/L. The other dissolved constituents would account for approximately 80% of the total TDS, in comparison with the example above in which a water with 10,000 mg/L TDS would contain about 50% chloride.

Water-supply Suitability Areas of the Dakota Aquifer in Kansas

From Part 1, it is clear that the regional hydrogeologic setting, including sources of recharge, discharge, ground-water-flow paths, and water quality are highly variable in the Dakota aquifer of Kansas. Locally, the heterogeneity in the aquifer framework strongly influences ground-water availability and the potential for inducing water-quality problems. Development in some areas may also induce capture (the increase in recharge and the decrease in discharge that results from pumping near recharge or discharge areas). In other areas, development may only result in the loss of water from storage in the aquifer.

This variability strongly indicates that management of water resources in the Dakota aquifer is best undertaken at the subregional level by defining water-supply suitability areas. Within each suitability area, the hydrogeologic and water-quality characteristics are similar within a certain range of possible states and parameter values. Each suitability area has its own set of factors to consider in developing appropriate policies and plans for development. Hence, the constraints on water-resources development will vary from one suitability area to another. A similar basis was used to define the boundaries of the groundwater management districts (subregions of the High Plains aquifer). However, for the Dakota, it is not appropriate to establish groundwater management districts because the boundary locations between suitability areas are not well known and may change. The rate and intensity of development may necessitate the adjustment of these boundaries. We have partially addressed these factors by arbitrarily selecting a 20-year planning horizon. More importantly, the Dakota remains a relatively unknown aquifer system in Kansas in comparison to the High Plains aquifer. It is expected that as development of the Dakota proceeds, the boundaries defining these suitability areas will be refined as more information becomes available.

The following is a description of these water-supply suitability areas, which we believe adequately capture the variable nature of the Dakota aquifer in Kansas. Figure 44 shows the approximate extent of each of the suitability areas. They are defined primarily on the basis of their hydrogeologic and secondarily on their water-quality characteristics.

Suitability Area I: This suitability area encompasses the region where the Dakota and the High Plains aquifers are hydraulically connected in southwestern and south-central Kansas. Where the High Plains aquifer's saturated thickness is greatest, the depth below the surface to the top of the Dakota aquifer is more than 500 ft (150 m). In western Stanton, western Morton, and southern Hamilton counties, the High Plains aquifer is absent or is very thin and the Dakota aquifer is the primary shallow aquifer. Ground water in the upper Dakota aquifer is fresh throughout this suitability area. However, ground-water chemical quality is variable in the lower Dakota aquifer because of the small amount of freshwater recharge that passes through the Kiowa shale aquitard. Ground-water salinities may exceed 2,000 mg/L (a value too high for human consumption but usable for livestock) in these parts of the suitability area. Nearer the Kansas–Colorado border and the Dakota's southern extent 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 High Plains aquifer. In this suitability area, the Dakota is used for drinking, industry, and agriculture, including irrigation. Water-level declines in the Dakota from previous development are less than 50 ft (15 m) in Suitability Area I.

Because the Dakota and the High Plains aquifers are hydraulically connected, they behave as a single system in this suitability area. The 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 in policy development.

Suitability Area II: In this area, the Dakota aquifer is confined by the Upper Cretaceous aquitard and is adjacent to the area where the Dakota is hydraulically connected to the High Plains aquifer in 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 this suitability area. Because the aquitard is thin, recharge from overlying sources contributes significantly to the upper Dakota aquifer but is less than the amount being withdrawn by pumping. Ground water in the upper Dakota is fresh (TDS of less than 1,000 mg/L) over most of the region. Ground-water salinity in the lower Dakota is believed to be less than 5,000 mg/L in the western half and more than 5,000 mg/L in the eastern half of the area. The upper Dakota is used for drinking water, industry, and agriculture, including irrigation. Use of the Dakota for irrigation is more common in Hodgeman and Ford counties. Water-level declines from previous water-resources development are generally less than 50 ft (15 m). Pumping wells in the Dakota aquifer in Suitability Area II may increase recharge from the High Plains aquifer into the Dakota aquifer in Suitability Area I.

Suitability Area III: In the eastern part of Suitability Area III, the Dakota is a shallow unconfined aquifer or is in contact with stream/aquifer systems. In the western part of the suitability area, the Dakota is poorly confined because the Upper Cretaceous aquitard is thin and relatively pervious. The depth below the surface to the top of the Dakota aquifer in the western part of this suitability area is generally less than 150 ft (45 m). The maximum recharge rates are on the order of a few tenths of an inch per year where the Dakota is unconfined. Ground-water quality in the upper part of the Dakota is locally variable where the salinity has not been flushed from the aquifer by freshwater recharge. In the unconfined regions, ground water in the upper part of the Dakota is mostly fresh. Salinity generally increases with depth in the lower part of the aquifer where the Dakota is confined and near some of the major streams that cross central Kansas. In this suitability area, the Dakota is used for drinking water, industry, and agriculture, including irrigation. Irrigation use is concentrated primarily in southwestern Washington, southeastern Republic, and northern Cloud counties. Water-level

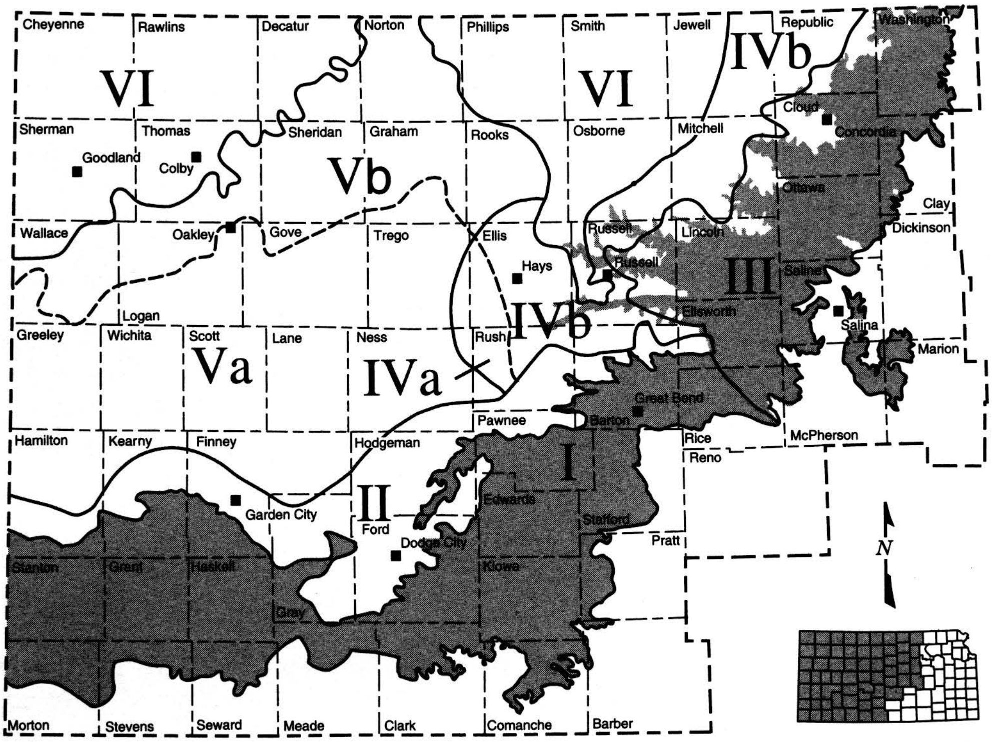


FIGURE 44—The water-supply suitability areas of the Dakota aquifer in Kansas. The boundaries of these areas are defined by their hydrogeologic and water-quality characteristics.

declines from development in Suitability Area III are believed to be less than 20 ft (6 m).

According to computer simulations, the primary impact of water-resources development in Suitability Area III is a reduction in discharge from the Dakota aquifer to streams, and the lateral movement of water from the confined to the unconfined Dakota aquifer from west to east. Further increases in development may only slightly increase water-level declines where the Dakota is a shallow aquifer.

Suitability Area IV: This suitability area includes that part of the confined Dakota aquifer located west of its regional discharge areas in north-central Kansas. Depth below the surface to the top of the Dakota aquifer is generally less than 400 ft (120 m). Freshwater recharge from overlying sources is variable locally and may have flushed some of the salinity from the upper part of the aquifer. However, natural saltwater in the lower part of the Dakota from the Cedar Hills Sandstone is widespread in this suitability area. Consequently, ground-water salinity generally increases with depth. In Suitability Area IVa, the salinity in the upper Dakota is less than 1,500 mg/L, whereas in Suitability Area IVb the salinity ranges from 1,500 mg/L to 10,000 mg/L. In Suitability Area IVa, water quality is acceptable for most uses, but in Suitability Area IVb, the aquifer is marginally usable. Ground-water salinities in the lower part of the Dakota aquifer probably exceed 10,000 mg/L over the entire suitability area. Water-level declines from development are believed to be less than 10 ft (3 m). In this suitability area, the upper Dakota is used primarily for drinking water and stock water. In Suitability Area IVb, the Dakota's use is limited and may require advanced treatment technologies to reduce ground-water salinity.

Wells in the upper part of the Dakota aquifer near the eastern edge of Suitability Area IV may reduce the eastward flow of fresher ground waters into the regional discharge areas. This may allow deeper, more saline ground water to move into the upper part of the Dakota and may increase the salinity of ground-water discharge to streams.

Suitability Area V: The confined Dakota aquifer receives negligible freshwater recharge from overlying sources. Depth below the surface to the top of the aquifer ranges from 400 ft to more than 1,500 ft (120–450 m) along the shared boundary with Suitability Area VI in northwest Kansas. The major source of freshwater is from the regional recharge area in southeastern Colorado. Ground-water salinites in the upper Dakota aquifer generally increase northeastward from less than 500 up to 1,500 mg/L in Suitability Area Va, and from 1,500 mg/L to 10,000 mg/L in Suitability Area Vb. Ground-water salinities in the lower Dakota aquifer are greater than 2,000 mg/L and may locally exceed 10,000 mg/L in the far northern and eastern parts of the Suitability Area V. In Suitability Area Va, water quality is acceptable for most uses and the Dakota is used primarily for drinking and livestock, but in Suitability Area Vb the water quality is marginal. In general, the farther to the north and east, the greater the increase in salinity with depth in the upper Dakota. Water-level declines from development are believed to be less than 50 ft (15 m) in this suitability area due to its limited use.

Water-resources development in this part of the aquifer is not likely to induce additional freshwater recharge from the High Plains aquifer into the unconfined Dakota aquifer in Suitability Area I. Pumping rates greatly exceed recharge from overlying sources. As a result, pumping may locally deplete the aquifer if wells and well fields are spaced too closely together.

Suitability Area VI: The Dakota is a confined aquifer and contains saline or "mineralized" ground water as defined by State statute, where mineralized ground water is defined as water containing more than 5,000 mg/L chloride or more than 10,000 mg/L total dissolved solids. Mineralized ground water is considered 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 part of Suitability Area VI, 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 (450 m). In the central part, vertical and lateral flow rates through the aquifer are higher and the top of the aquifer is less than 500 ft (150 m) deep. However, the flow of freshwater through the aquifer has been insufficient to flush the salinity from the aquifer where it is hydraulically connected to the Cedar Hills Sandstone.

Summary

The High Plains aquifer and the saturated alluvium adjacent to the streams that cross western and central Kansas have been major sources of water for agriculture, drinking water, and industrial use. Withdrawal of water from these shallow sources in some areas has resulted in substantial decreases in saturated thickness indicating overdevelopment. To control further development, more stringent management policies were applied by the Division of Water Resources (DWR), Kansas Department of Agriculture, and the groundwater management districts. These policies effectively eliminated new appropriations of water from these sources to users. However, even with more stringent policies in place, these once prolific sources of water may become insufficient to meet existing demand in the next few decades. These factors have combined to create interest in using a deeper source, the Dakota aquifer, to supplement or replace the dwindling shallower sources.

The Dakota aquifer covers approximately 40,000 mi^2 (104,000 km^2) of western and central Kansas and is more extensive than the shallower High Plains aquifer. The geologic units that form the Dakota aquifer in Kansas are the Dakota Formation, the Kiowa Formation, and the Cheyenne Sandstone. The Dakota has been used as a source of water for more than a century in the central Great Plains region that includes Kansas. Flowing wells tapping the Dakota were common in the Arkansas River valley of southeastern Colorado and southwestern Kansas in the late 1800's and early 1900's.

Unlike development in the High Plains aquifer, development in the Dakota is minimal even where the aquifer is relatively shallow in southwestern and central parts of the state. Until recently, the Dakota was less well understood than other aquifers because of its geologic complexity and, in some parts of the state, its great depth. Uncertainties with respect to (1) the quantity and quality of ground waters available, (2) the effects of withdrawals, and (3) the potential impact of oil-brine disposal on Dakota water quality have significantly impeded development of appropriate management policies by State and local agencies. Past management decisions were often made with little or no technical guidance. Well yield, water quality, and the considerable depth to the top of the aquifer are major factors contributing to the minimal use of this aquifer system in Kansas.

The major ground-water management issue that will affect the long-term viability of the Dakota as a major resource is its sustainability under increased development. Research results indicate that the Dakota will not produce water at the same rate as the High Plains aquifer on a sustained basis. The high variability of the deposits that constitute this aquifer system and the distances to recharge and discharge areas strongly indicate a potential for depletion due to overdevelopment in most of the confined aquifer. Also, pumping in areas of marginal water quality near saltwater-freshwater transition zones will need to be at rates that do not induce substantial encroachment of saline water. Because of these factors, the goal of managing for sustainability as it it is currently understood is untenable in this part of the aquifer. Controls on the spacing between pumping wells and rates of withdrawal are likely to be the most successful management tools. This will reduce the likelihood of water-rights impairment and large-scale depletion as long as the intensity of development is low. Where the Dakota is a near-surface aquifer in central Kansas, increased development will result in fewer long-term impacts than in the confined area because the potential for generating induced recharge is much higher. In southwestern Kansas, the hydraulic connection between the Dakota and the overlying High Plains aquifer suggests that both aquifers should be managed as a single system.

Appendix 1

Glossary

Alluvial environment: In general, a nonmarine environment dominated by the geologic processes associated with rivers and streams.

Aquifer: A part of a geologic formation (or one or more geologic formations) that is porous and permeable enough to transmit water at a rate sufficient to feed a spring or for economic extraction by a well. An aquifer transmits more water than an aquitard.

Aquitard (Confining unit): A part of a geologic formation (or one or more geologic formations) of much lower permeability than an aquifer (generally two or more orders of magnitude less) that will not transmit water at a rate sufficient to feed a spring or for economic extraction by a well.

Artesian pressure: The fluid pressure of the water in a confined aquifer indicated by the height of water above the top of the overlying aquitard in wells.

Boundary conditions: A mathematical expression of a state of a physical system that constrains the equations of a mathematical model of the system.

Capture: Water withdrawn artificially from an aquifer is derived from a decrease in storage in the aquifer, a reduction in the previous discharge from the aquifer, and increase in recharge, or a combination of these changes. The decrease in discharge plus the increase in recharge is termed capture. Capture generally results in reduced surface flows.

Cation exchange: The uptake of cations from solution by and the subsequent release of bound cations from the aquifer framework. This commonly occurs in fine-grained sediments containing clays. The individual clay particles often contain loosely bound ions (such as sodium) in their crystal lattice and adsorbed on the surface to reduce an overall charge imbalance. When ground water containing calcium ions passes through a clayey, porous medium containing adsorbed sodium ions, the clays preferentially replace the sodium for the calcium ions and release sodium to the ground water.

Cenozoic Era: The interval of geologic time that extends from approximately 66.4 million years ago up to the present.

Cone of depression: A cone-shaped lowering of the water table (or potentiometric surface) around a pumping well due to the temporary reduction in hydraulic head due to pumping.

Confined aquifer: An aquifer that is bounded above and below by aquitard units; water levels in wells screened in the confined aquifer are higher than the top of the aquifer.

Consolidation: In soil mechanics, the gradual reduction in volume and increase in density of unconsolidated sediments in response to loading or a compressive stress.

Cretaceous (Series): Rocks that were deposited during the interval between 144 and 66.4 million years ago.

Deltaic environment: In general, a nonmarine to marine environment dominated by the geologic processes associated with deltas.

Diffusivity: The ratio of the hydraulic conductivity to the specific storage of an aquifer. Diffusivity is a measure of the sensitivity of the aquifer to changes in hydraulic head. The higher the diffusivity, the more quickly changes in hydraulic head due to pumping will propagate through the aquifer to either the recharge or the discharge area or both.

Discharge area: An area where ground water is lost naturally from an aquifer through springs, seeps, or hydraulic connection to other aquifers.

Distributary channel: One of the many divergent stream or river channels carrying water and sediment across a delta to a sea or lake.

Drawdown: The lowering of hydraulic head in an aquifer that results from pumping.

Equipotential: A line of equal hydraulic head drawn on a map or on a vertical cross section. The direction of ground-water flow is generally taken to be perpendicular to the equipotential and opposite to the direction of the hydraulic gradient.

Era: A unit of geologic time next in order of magnitude below an eon and containing two or more periods.

Fluvial: Of or pertaining to a river or stream.

Formation water: The ground water contained within a porous medium, which may be fresh or saline.

Gamma-ray log: A record of the natural radioactivity emanating from the rocks with depth along the wall of a borehole.

Ground water: Subsurface water beneath the top of the zone of saturation or the water table. Ground water flows naturally from areas of recharge to areas of discharge.

Ground-water basin: A geologically and hydrologically defined region bounded by regional surface or ground-water divides or both.

Ground-water-flow system: The subsurface part of the hydrologic cycle that includes areas of recharge and discharge and the paths traveled by ground water in between these areas within a ground-water basin. The ground-water-flow system includes the flows across all aquifer and aquitard units below the top of the zone of saturation. Flow systems are dependent on both the arrangement and properties of aquifer and aquitard units and the nature of the topography within the basin. Areas of gently sloping topography with low local relief tend to be dominated by regional flow systems. Discharge areas in regional flow systems are often hundreds of miles away from areas of recharge. Areas of steep or undulating (hummocky) topography tend to be dominated by local flow systems. Local flow systems are much smaller in scale (on the order of 10 mi [16 km] or less) and may only involve a single aquifer.

Ground-water storage: 1) The quantity of water in the saturated zone, or 2) water available to wells from the aquifer, excluding capture.

Heterogeneity: A property that varies with location in the porous medium.

Hydraulic conductivity: A property that depends on the intrinsic permeability of the porous medium and the viscosity and density of the invading fluid.

Hydraulic head: The height that water in an aquifer can raise itself above an arbitrary reference level or datum (commonly mean sea level) measured in feet. When a borehole is drilled, the elevation of the water level in the borehole is for all practical purposes the hydraulic head of the aquifer at that point. The hydraulic head defines how much potential energy is possessed by the water at a point in the ground-water-flow system. Ground water possesses energy by virtue of its position (elevation head) and its pressure (pressure head). In a ground-water-flow system, the movement of water is accompanied by a reduction in hydraulic head.

Hydraulic-head gradient: The change in hydraulic head per unit distance in a specific direction indicated by the slope of the water table or the potentiometric surface. The maximum hydraulic gradient is opposite to the direction of ground-water flow.

Hydraulically connected: A condition where two or more adjacent aquifers are in physical contact so that there are no intervening aquitard units to restrict the flow of ground water between them. As a result, a change in hydraulic head in one aquifer where they are hydraulically connected is readily transmitted to the other aquifers.

Hydrogeology: The study of ground water with particular emphasis given to its chemistry, the influences on its flow, and its relationship to the geologic environment.

Hydrograph: A graph showing the fluctuations in water level or hydraulic head in a well over time.

Hydrostratigraphic unit: Portions of a geologic unit or one or more adjacent geologic units distinguished by their porosity and permeability (hydraulic-conductivity) characteristics.

Impairment: In a hydrogeologic sense, the reduction in flow to a well that occurs when its cone of depression overlaps with the cone of depression of a nearby well. In the area of overlap, the drawdown from simultaneously pumping both wells is the sum of the drawdowns that would occur if each well were being pumped singly.

Intrinsic permeability: A quantitative measure of the fluid-transmitting ability of the porous medium that is related to the size and interconnectedness of its void spaces. For a granular porous medium, this property depends on the grain-size distribution.

Jurassic (Series): Rocks that were deposited during the interval between 208 and 144 million years ago.

Laramide Orogeny: An episode of regional uplift resulting in the formation of the Rocky Mountains that began near the end of the Cretaceous Period and extended into the Tertiary Period.

Lithology: The description of rocks or sediments on the basis of such characteristics as color, structure, mineralogic composition, and grain size.

Major constituent: Dissolved ionic constituents usually present in amounts greater than a few mg/L, including calcium, magnesium, sodium, bicarbonate, sulfate, and chloride.

Mesozoic Era: The geologic time interval between the Cenozoic and Paleozoic Eras from 245 to 66.4 million years ago.

Minor constituent: Dissolved ionic constituents usually present in amounts greater than 0.1 mg/L and less than 10 mg/L. This usually includes potassium, nitrate, iron, fluoride, strontium, and boron.

Mudcake: During drilling, a layer of cuttings and drilling mud that builds up on the wall of the borehole uphole from the drill bit.

Mud filtrate: The invading fluid that flows outward from the borehole during drilling and into the surrounding porous medium. The depth of invasion depends on the porosity and permeability of the host rock as well as the amount of time available during invasion.

Mudstone: A general term that includes claystone, siltstone, and shale.

Multi-story: A vertical sequence of channel sandstone bodies that often appear as locally amalgamated bodies of sandstone where cut and fill has removed intervening fine-grained floodplain deposits.

Nearshore environment: In general the region where marine processes dominate seaward of the shoreface and shoreward of the open marine environment.

Outcrop/subcrop belt: A belt where the combined Dakota Formation, Kiowa Formation, and Cheyenne Sandstone crop out at the surface or beneath younger Cenozoic deposits near their eastern and southern extents in Kansas. The younger Cretaceous units all have been removed by erosion within this belt.

Quaternary (Series): Strata deposited during the Quaternary Period from 1.59 million years up to approximately 10,000 years ago.

Paleoshoreline: An ancient shoreline whose location has been inferred from its associated deposits.

Paleovalleys: An ancient buried valley whose location has been inferred from its associated deposits.

Paleozoic Era: The interval of geologic time that extends from approximately 570 to 245 million years ago.

Pennsylvanian (Series): Rocks that were deposited during the interval between 320 and 286 million years ago.

Permian (Series): Rocks that were deposited during the interval between 286 and 245 million years ago.

Porosity: A quantitative measure of the void space in relation to the bulk volume of a porous medium.

Potentiometric surface map: A contoured map showing the variation in hydraulic head within an aquifer. The contours drawn on the map are lines of equal hydraulic head, or equipotentials. Hydrogeologists use these maps to discern the flows of ground water between recharge and discharge areas and for other purposes.

Recharge area: A geographic area where water enters a ground-water flow system or an aquifer. Recharge areas usually coincide with topographically elevated regions where aquifer units crop out at the surface. In these areas, infiltrated precipitation is the primary source of recharge. The recharge area may also coincide with the area of hydraulic connection where one aquifer receives flow from another adjacent aquifer.

Rock stratigraphic unit: A mappable geologic unit distinguished by its lithologic characteristics and relative lithologic homogeneity.

Shoreline environment: In general, an environment dominated by the geologic processes associated with a shoreline, including supratidal, tidal, and subtidal environments.

Series: All of the rocks that were deposited during a specific interval of geologic time, such as the Permian or Cretaceous Periods.

Specific conductance: A measure of the ability of water to conduct an electrical current, expressed in microsiemens or micromhos per centimeter (µs/cm or µmho/cm) at 25° C. Specific conductance is related to the type and concentration of ions in solution and can be used for approximating the dissolved solids content of the water. Commonly, the concentration of dissolved solids (in milligrams per liter) is about 65% of the specific conductance (in micromhos per centimeter). This relation is not constant from supply to supply, and it may even vary in the same source with changes in composition of the dissolved-solids load in the water.

Specific storage: The volume of water released from or taken into storage per unit volume of the confined aquifer per unit change in hydraulic head.

Steady state: A ground-water-flow system condition in which recharge is balanced by discharge from the system and there is no change in the amount of water in storage with time.

Storativity: The volume of water released from storage per unit area of confined aquifer and per unit drop in hydraulic head. The storativity is a function of the compressive qualities of the aquifer framework and the water in the aquifer.

Surface casing: An outer well casing installed to protect fresh ground water from contamination by saltwater moving upward from deeper aquifers along the annular space of the borehole.

Sustainability: The ability of the aquifer to supply water to users without being depleted during the planning period.

Tectonic activity: Processes involving crustal movements, resulting in episodes of subsidence and uplift.

Total dissolved solids concentration: The concentration of all of the dissolved ionic constituents in water, usually expressed in milligrams per liter (mg/L).

Trace constituent: Dissolved ionic constituents usually present in amounts less than 0.5 mg/L.

Transient: In ground water, a state of the flow system in which the hydraulic head changes with time.

Transmissivity: A quantitative measure of the capacity of an aquifer to transmit flow through a given cross sectional area, expressed as volume per unit time per unit surface area. Transmissivity is the product of the aquifer hydraulic conductivity and thickness.

Unconfined (water-table) aquifer: An aquifer bounded above by the water table.

Unconsolidated: Loosely arranged, uncemented.

Water budget: A method of tracking the flows of water through all or parts of the subsurface hydrologic cycle in a particular geographic area, including recharge, storage within the aquifer or the flow system, and discharge. Discharge includes natural discharge, ground-water withdrawals, evapotranspiration losses, and flows to streams or other hydraulically connected aquifers. Recharge includes infiltrated precipitation that enters the flow system in recharge areas and flows from other aquifers.

Water quality: The physical, chemical, and biological characteristics of water and how they relate to particular uses.

Water table: The approximate upper boundary of the ground-water-flow system.

Well-head protection: A means of protecting the ground-water supply of a well field from contamination due to human activity. To initiate well-head-protection efforts, potential contamination sources must be identified, and the ground-water-flow patterns and time of travel of dissolved contaminants from a point of introduction to the well field must be delineated. Zoning and other land-use controls are typically used to eliminate sources of contamination and protect the ground-water supply.

Western Interior seaway: An asymmetrical basin that extended from the Gulf Coast to the Arctic Circle in North America during the Cretaceous Period.

Appendix 2

Sources of Information to Guide the Exploration for Water in the Dakota Aquifer

Is the Dakota aquifer present in a specific area? Are the quality and quantity of the water suitable for your particular water use? How expensive will it be to utilize the Dakota? These are questions that can be addressed by incurring only the expenses from a few phone calls, some postage, and publications such as this user's guide. An initial evaluation of the Dakota aquifer can answer these questions. Several sources of information are available to anyone interested in investigating or utilizing ground-water resources, either for irrigation or personal use. Often, the best source of information is local people who are familiar with well drilling or local ground-water resources. This is usually a good place to start because they may know local areas better than the State agencies that have to cover the entire state. If local water-resource people cannot answer specific questions, they often know who to contact. Several State and Federal water-related agencies also offer assistance and information to anyone interested in the Dakota aquifer as a source of water. The following is a summary of the functions of and information available from the various Federal, State, and local agencies.

LOCAL AGENCIES AND OTHER LOCAL SOURCES OF INFORMATION

Groundwater Management Districts. Some areas of Kansas are represented at the local level by groundwater management districts (GMDs), entities governed by local boards who are authorized under State law to manage water resources in their districts. The four GMDs that are underlain by the Dakota aquifer are outlined in fig. A2.1.

County Health Departments. County Health Departments are concerned with drinking-water quality. Usually for a nominal fee, they will provide sample bottles and instructions for individuals to take their own samples. You will need to send the sample to the Kansas Department of Health and Environment for analysis at nominal cost. The analysis examines concentrations of basic bacteriological and chemical components for safe drinking water.

Cooperative Extension Service. Kansas State University's Cooperative Extension Service has offices in every county in Kansas. County extension agents can provide information and educational programs in water quality and soil and water conservation. Educational efforts involve irrigation and water-use efficiency; natural resource, energy, and environmental stewardship; non-point pollution prevention and abatement; and safe use of chemicals. County agents and specialists work with farmers, irrigators, and groundwater management, watershed, and conservation districts to manage and conserve the state's soil and water resources.

Water-well Drillers. Water-well drillers are another source of local information. A list of local drillers can be found in telephone directories. Water-well drillers usually have several years of practical experience in local areas and can often provide general information about drilling a well at a specific site. They sometimes have records of other wells drilled in the area. More information on water-well drillers and drilling techniques can be obtained by contacting the Kansas Ground Water Association directly.

INFORMATION MAINTAINED AT THE KANSAS GEOLOGICAL SURVEY TO ASSIST PUBLIC INQUIRIES

The Kansas Geological Survey (KGS) conducts geological studies and research and maintains information about water quality and quantity and other earth resources in Kansas. Available from the Survey are water-well records, maps, publications, and other water-related information. Additional information on the Dakota aquifer can be found on the Kansas Geological Survey (KGS) home page on the World Wide Web at http://www.kgs.ukans.edu.

Water-well Records. Commonly referred to as the "WWC- 5" records, this form is required by the State of anyone drilling a water well. Examining these records for wells drilled in the area of interest can provide information on drilling depths, flow rates, and water quality. The WWC-5 form includes information on location of the water well; the well owner; depth of the well, depth to water, and the estimated yield; casing, perforation, and completion information; and a lithologic log. Figure A2.2 is a reproduction of a Water Well Record (form WWC-5). The Water-well Records are maintained by the Geoscience Data Library at the KGS.

Electric Logs. Many wells have been drilled through the Dakota aquifer in search of oil and gas. Electric and radioactivity logs were run on most wells, and these records are available at the Survey. In addition, the Survey has other oil and gas well-drilling information that may be useful for Dakota aquifer evaluation or exploration.

Kansas Water Levels. Water-level measurements in Kansas are reported each year and compared to long-term water-level changes. Information on well locations and characteristics, past and present water-level measurements, water resources, and trends in the measurements are presented in this annual KGS publication. Copies of this report can be obtained from Publications Sales at the KGS. Water-level data also can be obtained on the KGS World Wide Web pages.

Publications and Maps. The KGS has numerous publications and maps that may be useful in ground-water exploration. Topographic (with contours) and planimetric (without contours) maps are available for the entire state at scales ranging from the detailed 1:24,000-scale series (7.5-minute quadrangle) to generalized 1:500,000-scale maps of the state. Technical and non-technical publications related to ground-water occurrence, chemical quality, irrigation, and many other topics are available at the KGS. Contact Publications Sales at 785/864-3965.

INFORMATION AVAILABLE FROM OTHER STATE AND FEDERAL WATER-RELATED AGENCIES

Numerous State and Federal agencies have regulatory and non-regulatory responsibilities involving Kansas water. Listed below are some of the principal agencies that could be helpful in exploring for water in the Dakota aquifer.

State Agencies

Division of Water Resources
Kansas Department of Agriculture
109 SW 9th Street, Suite 202
Topeka, Kansas 66612-1283 785/296-3717

The Division of Water Resources (DWR) is the primary State agency regulating the appropriation of surface and ground water for beneficial use in Kansas. Through the Groundwater Management District Act of 1972, the DWR works with local groundwater management districts in the management of ground-water resources within each district's boundaries. The DWR is involved in intensive ground-water use control areas (IGUCA)—areas experiencing unusual declines or areas that require special management considerations. The DWR also measures water levels in many wells as part of the State water-level program.

Kansas Corporation Commission
Oil and Gas Conservation Division
130 South Market Street, Suite 2078
Wichita , Kansas 67202-3810 316/337-6200

The Oil and Gas Conservation Division of the Kansas Corporation Commission (KCC) has regulatory responsibility for permitting the location and construction (including surface-casing requirements) of oil and gas wells in Kansas and for the proper plugging or temporary abandonment of these wells. The Division's mandate is to protect fresh and usable water resources. The Division also has responsibility for implementing the Underground Injection Control program for Class II (oil and gas) wells in Kansas. States are required to meet EPA standards for regulating underground injection of fluids. Injection applications are technically reviewed by the Division to ensure that fresh and usable water, hydrocarbons, and correlative rights will be protected.

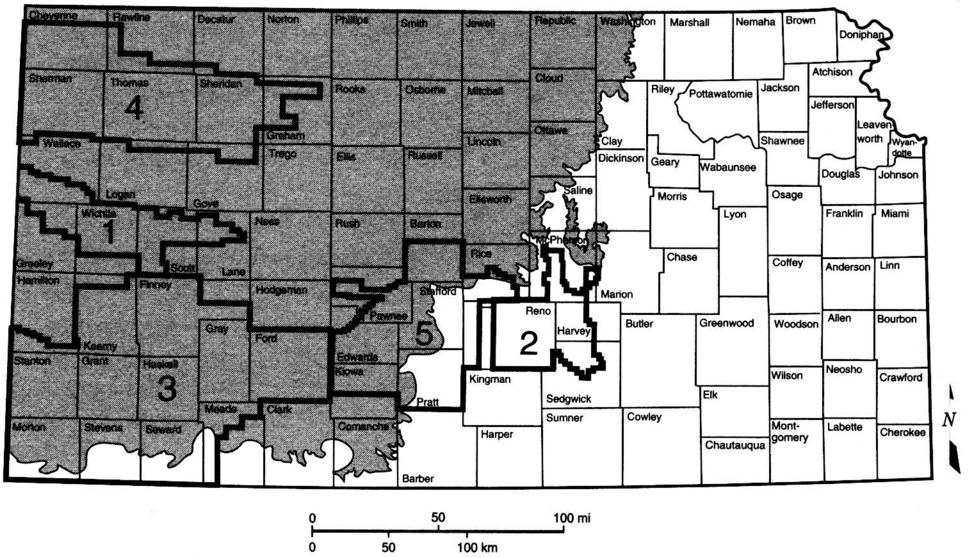


FIGURE A.2.1—GROUNDWATER MANAGEMENT DISTRICTS UNDERLAIN BY THE DAKOTA AQUIFER IN KANSAS.

Kansas Department of Health and Environment
Division of Environment
Building 704, Forbes Field
Topeka, Kansas 66620 785/296-1535

The Division of Environment in the Kansas Department of Health and Environment (KDHE) is responsible for identifying water-quality and water-pollution problems and recommending appropriate remediation. The Division also regulates coal mining and reclamation, non-point source pollution, hazardous-waste facilities, livestock feedlots, wastewater-treatment facilities, public-water supplies, and solid-waste landfills. Since 1975 the Division has been responsible for managing water-well records submitted to the agency by drillers (WWC-5 form) and has maintained a State licensing program for water-well drillers. The Division is a source of information concerning water quality, water wells drilled and plugged in the state since 1975, and regulations on well construction.

Kansas Water Office
109 SW 9th Street, Suite 200
Topeka, Kansas 66612-1215 785/296-3185

The Kansas Water Office formulates, on a continuous basis, a comprehensive Kansas Water Plan for the management, conservation, and development of the water resources of the state. The Water Plan provides for the establishment of basin advisory committees — groups of citizen volunteers in each river basin — that provide advice on the formulation and implementation of the Kansas Water Plan. The Water Office oversees the State's water-marketing and water-assurance programs, monitors water research by governmental agencies, develops water-supply and demand estimates for Kansas, issues licenses and permits for weather-modification activities, and establishes and monitors minimum desirable streamflows.

Federal Agencies

Environmental Protection Agency
726 Minnesota Avenue
Kansas City, Kansas 66101 913/236-2815

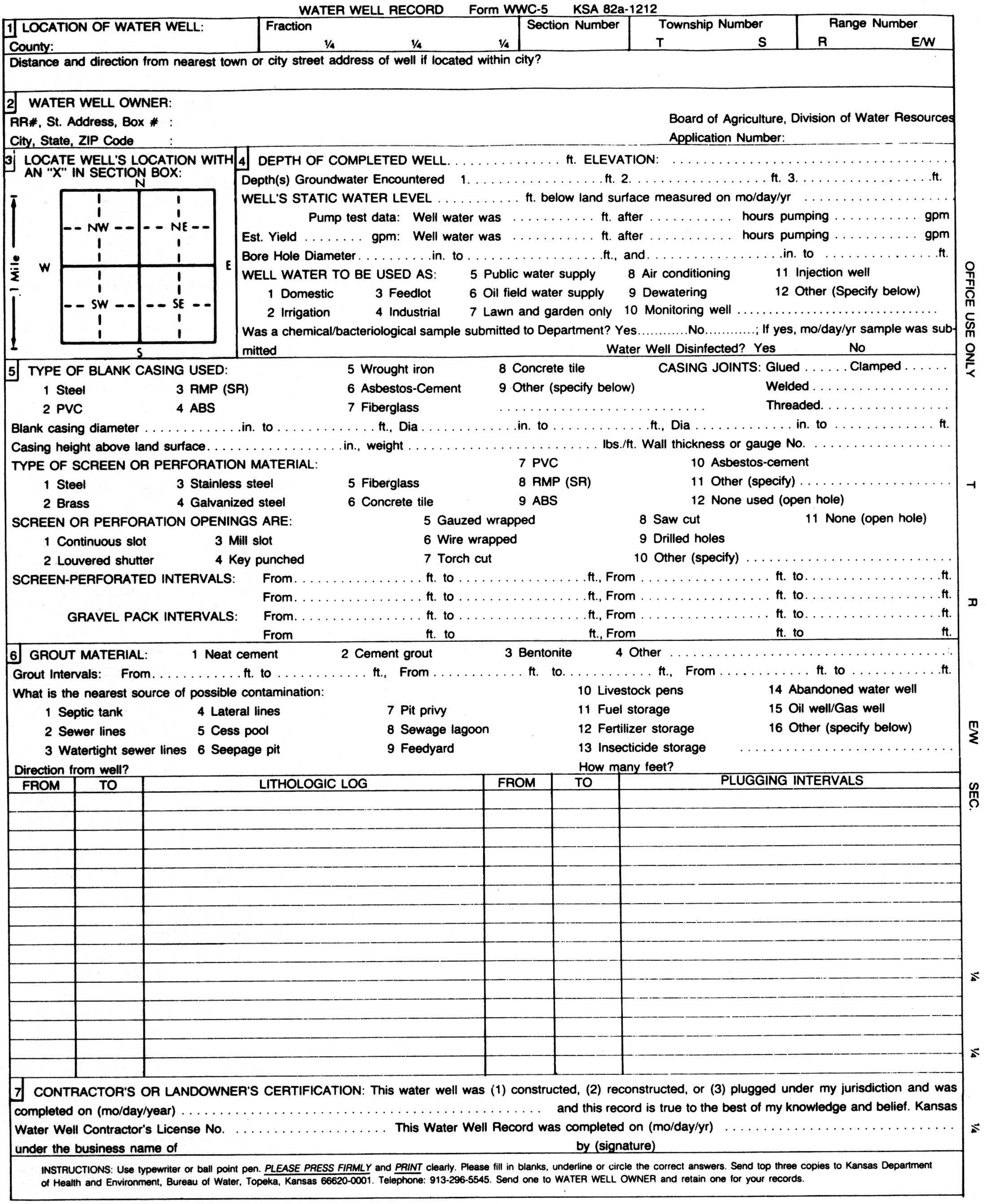
The Region VII office in Kansas City is responsible for Federal environmental regulations in Kansas and provides support for the State ground-water program, wastewater-treatment facilities, and other pollution-control activities through grants and loans. The EPA oversees the Safe Drinking Water Act, has a wellhead-protection program for wells that produce drinking water, regulates permits for pollution discharges, administers a nonpoint source pollution-control program (with KDHE), sets water-quality standards for state surface waters, and is responsible for underground injection control (with KDHE and KCC).

U.S. Geological Survey, Water Resources Division
4821 Quail Crest Place
Lawrence, Kansas 66049 785/842-9909

In Kansas, this Federal agency conducts regional hydrologic studies, undertakes research in geochemistry, and conducts studies in water quality in Kansas and adjacent states. This agency also has developed and maintains a statewide network for collecting water-resource data. Numerous publications and maps on ground water are available from the U.S. Geological Survey.

Local Soil and Water Conservation District Offices
Natural Resources Conservation Service (NCRS)
U.S. Department of Agriculture

Formerly the Soil Conservation Service, the NRCS provides technical assistance to farmers and ranchers to develop and apply soil- and water-conservation plans for their land. Assistance is provided through the state's 105 local conservation districts.



WATER WELL RECORD Form WWC-5 KSA 82a-1212

1 LOCATION OF WATER WELL: County:	Fraction ¼ ¼ ¼	Section Number	Township Number T S	Range Number R E/W

Distance and direction from nearest town or city street address of well if located within city?

2 WATER WELL OWNER:
RR#, St. Address, Box # :
City, State, ZIP Code :
Board of Agriculture, Division of Water Resources
Application Number:

3 LOCATE WELL'S LOCATION WITH AN "X" IN SECTION BOX:
N
NW NE
W E
SW SE
S
1 Mile

4 DEPTH OF COMPLETED WELL. . . . . ft. ELEVATION: . . . .
Depth(s) Groundwater Encountered 1. . . . . . . .ft. 2. . . . . ft. 3. . . . . . . .ft.
WELL'S STATIC WATER LEVEL . . . . . . ft. below land surface measured on mo/day/yr . . . .
Pump test data: Well water was . . . . . . ft. after . . . . . . hours pumping . . . . . . gpm
Est. Yield . . . . . . gpm: Well water was . . . . . . ft. after . . . . . . hours pumping . . . . . . gpm
Bore Hole Diameter. . . . . .in. to . . . . .ft., and. . . . . . . .in. to . . . . .ft.
WELL WATER TO BE USED AS: 5 Public water supply 8 Air conditioning 11 Injection well
1 Domestic 3 Feedlot 6 Oil field water supply 9 Dewatering 12 Other (Specify below)
2 Irrigation 4 Industrial 7 Lawn and garden only 10 Monitoring well . . . .
Was a chemical/bacteriological sample submitted to Department? Yes. . . . . .No. . . . . .; If yes, mo/day/yr sample was submitted Water Well Disinfected? Yes No

5 TYPE OF BLANK CASING USED: 5 Wrought iron 8 Concrete tile CASING JOINTS: Glued . . . . . Clamped . . . . .
1 Steel 3 RMP (SR) 6 Asbestos-Cement 9 Other (specify below) Welded . . . .
2 PVC 4 ABS 7 Fiberglass . . . . Threaded. . . . .
Blank casing diameter . . . . . . .in. to . . . . ft., Dia . . . . . . .in. to . . . . . . .ft., Dia . . . . in. to . . . . ft.
Casing height above land surface. . . . . .in., weight . . . . lbs./ft. Wall thickness or gauge No. . . . .
TYPE OF SCREEN OR PERFORATION MATERIAL: 7 PVC 10 Asbestos-cement
1 Steel 3 Stainless steel 5 Fiberglass 8 RMP (SR) 11 Other (specify) . . . .
2 Brass 4 Galvanized steel 6 Concrete tile 9 ABS 12 None used (open hole)
SCREEN OR PERFORATION OPENINGS ARE: 5 Gauzed wrapped 8 Saw cut 11 None (open hole)
1 Continuous slot 3 Mill slot 6 Wire wrapped 9 Drilled holes
2 Louvered shutter 4 Key punched 7 Torch cut 10 Other (specify) . . . .
SCREEN-PERFORATED INTERVALS: From. . . . . ft. to . . . . .ft., From . . . . ft. to. . . . . . . .ft.
From. . . . . ft. to . . . . .ft., From . . . . ft. to. . . . . . . .ft.
GRAVEL PACK INTERVALS: From. . . . . ft. to . . . . .ft., From . . . . ft. to. . . . . . . .ft.
From ft. to ft., From ft. to ft.

6 GROUT MATERIAL: 1 Neat cement 2 Cement grout 3 Bentonite 4 Other . . . .
Grout Intervals: From. . . . . . .ft. to . . . . . . ft., From . . . . . . ft. to. . . . . . ft., From . . . . . . ft. to . . . . . .ft.
What is the nearest source of possible contamination: 10 Livestock pens 14 Abandoned water well
1 Septic tank 4 Lateral lines 7 Pit privy 11 Fuel storage 15 Oil well/Gas well
2 Sewer lines 5 Cess pool 8 Sewage lagoon 12 Fertilizer storage 16 Other (specify below)
3 Watertight sewer lines 6 Seepage pit 9 Feedyard 13 Insecticide storage . . . .
Direction from well? How many feet?

FROM	TO	LITHOLOGIC LOG	FROM	TO	PLUGGING INTERVALS

7 CONTRACTOR'S OR LANDOWNER'S CERTIFICATION: This water well was (1) constructed, (2) reconstructed, or (3) plugged under my jurisdiction and was completed on (mo/day/year) . . . . and this record is true to the best of my knowledge and belief. Kansas Water Well Contractor's License No. . . . . This Water Well Record was completed on (mo/day/yr) . . . . under the business name of by (signature)

INSTRUCTIONS: Use typewriter or ball point pen. *PLEASE PRESS FIRMLY* and *PRINT* clearly. Please fill in blanks, underline or circle the correct answers. Send top three copies to Kansas Department of Health and Environment, Bureau of Water, Topeka, Kansas 66620-0001. Telephone: 913-296-5545. Send one to WATER WELL OWNER and retain one for your records.

OFFICE USE ONLY
T
R
E/W
SEC.
¼
¼
¼

FIGURE A.2.2—Reproduction of a Water Well Record (form WWC-5).

Appendix 3

Further Reading and Other Educational Materials from the Dakota Aquifer Program

Belitz, K., and Bredehoeft, J. D., 1988, Hydrodynamics of the Denver basin—Explanation of fluid subnormal pressures: American Association of Petroleum Geologists, Bulletin 72, no. 11, p. 1,334–1,359

Boeken, R., 1995, Estimate of water quality in the Dakota aquifer of northwest Kansas using self potential readings of downhole geophysical logs: Kansas Geological Survey, Open-file Report 95–1a, 93 p.

Darton, N. H., 1905, Preliminary report on the geology and underground water resources of the central Great Plains: U.S. Geological Survey, Professional Paper 32, 433 p.

Franks, P. C., 1979, Paralic to fluvial record of an Early Cretaceous marine transgression—Longford Member, Kiowa Formation, north-central Kansas: Kansas Geological Survey, Bulletin 219, 55 p.

Hamilton, V. J., 1994, Sequence stratigraphy of Cretaceous Albian and Cenomanian strata in Kansas; *in,* Perspectives on the Eastern Margin of the Cretaceous Western Interior Basin, G. W. Shurr, G. A. Ludvigsen, and R. H. Hammond, eds.: Geological Society of America, Special Paper 287, p. 79–96

Hattin, D. E., and Siemers, C. T., 1987, Guidebook—Upper Cretaceous stratigraphy and depositional environments of western Kansas (with modifications): Kansas Geological Survey, Guidebook Series 3, 55 p.

Helgesen, J. O., Leonard, R. B., and Wolf, R. J., 1993, Aquifer systems underlying Kansas, Nebraska, and parts of Arkansas, Colorado, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming—Hydrology of the Great Plains aquifer system in Nebraska, Colorado, Kansas, and adjacent areas: U.S. Geological Survey, Professional Paper 1414–E, 161 p.

Keene, K. M., and Bayne, C. K., 1977, Ground water from lower Cretaceous rocks in Kansas: Kansas Geological Survey, Chemical Quality Series 5, 18 p.

Lobmeyer, D. H., and Weakly, E. C., 1979, Water in the Dakota formation, Hodgeman and Ford counties, southwestern Kansas: Kansas Geological Survey, Irrigation Series 5, 41 p.

Macfarlane, P. A., 1995, The effect of river valleys and the upper Cretaceous aquitard on regional flow in the Dakota aquifer in the central Great Plains of Kansas and southeastern Colorado; *in,* Current Research in Earth Sciences: Kansas Geological Survey, Bulletin 238, p. 11–30

Macfarlane, P. A., and Sawin, R. S., 1995, A user's guide to well-spacing requirements for the Dakota aquifer in Kansas: Kansas Geological Survey, Public Information Circular 1, 4 p.

Macfarlane, P. A., Combes, J., Turbek, S., and Kirshen, D., 1993, Shallow subsurface bedrock geology and hydrostratigraphy of southwestern Kansas: Kansas Geological Survey, Open-file Report 93–1a, 13 p. and 18 maps

Macfarlane, P. A., Doveton, J. H., and Coble, G., 1989, Interpretation of lithologies and depositional environments of Cretaceous and Lower Permian rocks using a diverse suite of logs from a borehole in central Kansas: Geology, v. 17, p. 303–306

Macfarlane, P. A., Doveton, J. H., Feldman, H. R., Butler, J. J., Jr., Combes, J. M., and Collins, D. R., 1994, Aquifer/aquitard units of the Dakota aquifer system in Kansas—Methods of delineation and sedimentary architecture effects on ground-water flow and flow properties: Journal of Sedimentary Research, v. 64, no. 4, p. 464–480

Macfarlane, P. A., Townsend, M. A., Whitemore, D. O., Doveton, J. H., and Staton, M., 1988, Hydrogeology and water chemistry of the Great Plains (Dakota, Kiowa, and Cheyenne) and Cedar Hills aquifers in central Kansas—End of contract report: Kansas Geological Survey, Open-file Report 88–39, 184 p.

Macfarlane, P. A., Wade, A., Doveton, J. H., and Hamilton, V. J., 1991, Revised stratigraphic interpretation and implications for pre-Graneros paleogeography from test-hole drilling in central Kansas: Kansas Geological Survey, Open-file Report 91–1A, 73 p.

Macfarlane, P. A., Whittemore, D. O., Chu, T., Butler, J. J., Jr., Wade, A., Coleman, J., Doveton, J. H., Mitchell, J. E., and Kay, S., 1991, The Dakota Aquifer Program—Annual report, FY91: Kansas Geological Survey, Open-file Report 92–1, 93 p.

Macfarlane, P. A., Whittemore, D. O., Doveton, J. H., Chu, T., Smith, M., Feldman, H., Myers, N. C., and Gillespie, J. B., 1994, The Dakota Aquifer Program—Annual report, FY93: Kansas Geological Survey, Open-file Report 94–1, 115 p.

Macfarlane, P. A., Whittemore, D. O., Townsend, M. A., Butler, J. J., Jr., Doveton, J. H., Hamilton, V. J., Coleman, J., Chu, T., and Wade, A., 1991, The Dakota Aquifer Program—Annual report, FY90: Kansas Geological Survey, Open-file Report 91–1, 42 p.

Macfarlane, P. A., Whittemore, D. O., Townsend, M. A., Doveton, J. H., Hamilton, V. J., Coyle, W. G., III, Wade, A., Macpherson, G. L., and Black, R. D., 1990, The Dakota Aquifer Program—Annual report, FY89: Kansas Geological Survey, Open-file Report 90–1, 301 p.

Wade, A., 1991, Determination of aquifer properties of the Dakota aquifer in Washington County, Kansas, from a pumping test: Kansas Geological Survey, Open-file Report 91–1c, 62 p.

Watts, K. R., 1989, Potential hydrologic effects of ground-water withdrawals from the Dakota aquifer, southwestern Kansas: U.S. Geological Survey, Water-supply Paper 2304, 47 p.

Whittemore, D. O., Macfarlane, P. A., Doveton, J. H., Butler, J. J., Jr., Chu, T., Bassler, R., Smith, M., Mitchell, J. E., and Wade, A., 1993, The Dakota Aquifer Program—Annual report, FY92: Kansas Geological Survey, Open-file Report 93–1, 170 p.

Macfarlane et al. USER'S GUIDE TO THE DAKOTA AQUIFER IN KANSAS Technical Series 2 KGS 1998

Kansas Geological Survey
1930 Constant Avenue
The University of Kansas
Lawrence, Kansas 66047–3726