The Dakota Aquifer Program Annual Report, FY92

by
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Lawrence, Kansas
Kansas Geological Survey Open-File Report 93-1
January 1993

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Executive Summary

The Dakota aquifer system, which underlies much of western Kansas, is becoming an increasingly important water resource. Local depletion of shallower freshwater aquifers in central and western Kansas is creating a demand for water supplies from the underlying Dakota aquifer. Information on the ground-water quantity and quality, effects of withdrawals, and the impact of oil-brine disposal in shallow zones beneath the aquifer is needed by state and local agencies to evaluate the aquifer as a major water source for the future. Results of the Dakota program are providing technical guidance for policy decisions concerning the management of the aquifer and for predicting which undeveloped areas might contain a usable quantity and quality of water.

In recognition of the need for an integrated research program, the Kansas Geological Survey (KGS) began in FY89 to conduct and coordinate a long-term multi-agency program to assess the water-resources potential of the Dakota aquifer. Several water-quantity and water-quality issues associated with long-term development of the aquifer are being studied: (1) water availability, (2) sources and amounts of recharge and their effects on water quality, (3) impact of water withdrawals from the Ogallala and Dakota aquifers in southwestern Kansas on future water-supply availability, (4) effect of shallow disposal of oil brines in central Kansas, (5) delineation of usable zones in the aquifer, and (6) effect of saltwater discharge from the Dakota aquifer on water quality in central Kansas stream-aquifer systems.

For FY90–93 the overall objectives of the Dakota aquifer program are to characterize subregionally the water-resources potential of the Dakota aquifer where it is shallowest and is presently being used, to develop conceptual models of ground-water flow and chemistry, and to begin digital simulation of ground-water flow and quality. Results obtained in FY92 provide important advances in the understanding of the distribution of aquifer units, the ground-water flow system, and the water quality of the Dakota aquifer system. Although the focus of many of the diverse projects was on southwestern Kansas, other projects were conducted in central and north-central Kansas.

Work on the geologic framework of the Dakota system in FY92 focused on geologic maps and cross sections based largely on analysis of geophysical logs. A series of geologic maps nearing completion for southwestern Kansas comprise contoured surfaces and thicknesses for different stratigraphic units in the Upper Cretaceous aquitard overlying the Dakota aquifer, in the Dakota aquifer system, and in the Permian underlying the Dakota. A colored image for a cross section through southwestern to central Kansas was generated using computer analysis of geophysical logs to better illustrate distribution characteristics of aquifer sandstone units with distance and depth. Geostatistical analysis of sandstone and shale distributions was initiated in Hodgeman County where a high-density distribution of geophysical logs have been digitized.

Geohydrologic investigations included (1) determination of aquifer characteristics and aquifer interactions at monitoring sites in southwestern Kansas and (2) simulations of ground-water flow both aerially and vertically across the Dakota aquifer system at different scales and in different areas. New monitoring sites were constructed in Stanton and Gray counties. Hydrologic and/or water-quality tests were conducted at the Finney, Hodgeman, and Gray County monitoring sites. Ground-water flow simulations ranged from a regional steady-state model in western Kansas and southeastern Colorado to models for subregional and local areas. Extension of the Dakota study area into southeastern Colorado is important because the area is the source of much of the recharge for a substantial portion of the aquifer in Kansas. A report on the ground-water flow systems and water-resources potential of the Dakota aquifer in parts of Republic, Cloud, Clay, and Washington counties has been completed and is being reviewed. A steady-state model of ground-water flow in southeastern Colorado and southwestern Kansas is being developed in conjunction with the larger scale regional model but at a more detailed scale that will form the basis for a transient-flow model for assisting water-resources management in southwestern Kansas. A flow model completed along a cross section from southeastern Colorado to central Kansas shows the effect of hydrostratigraphy and topographic relief on the steady-state flow in the Dakota aquifer system. The model considers the interactions between geologic strata above, within, and below the Dakota aquifer and explains the generation of subnormal pressures in the aquifer. In addition, simulated flow in the cross section characterizes the water budget for local flow systems in the recharge and discharge areas of southwestern Colorado and the eastern outcrop belt of the Dakota system in central Kansas and the regional flow in the confined aquifer from western to central Kansas.

The geochemical framework of the saltwater-freshwater transition zone in the Dakota aquifer was characterized in north-central Kansas in preparation for simulating chemical changes during ground-water flow. Another geochemical project identified sources of salinity in ground waters within and discharging from the Dakota aquifer. No oil-field brine was found in the slightly saline ground waters from test wells drilled for the development of supplemental municipal water supplies for the city of Hays. Although no detectable oil brine was found in low flows of the Saline River where the Dakota aquifer discharges saline water, oil-brine contamination was found to contribute to natural saline discharge to the Smoky Hill River in southern Russell County. A study to geochemically characterize aquifer interactions and recharge to the Dakota aquifer from atmospheric precipitation and adjacent aquifers was begun in southwestern Kansas and southeastern Colorado. Water-quality distribution maps for the Dakota aquifer were modified to incorporate the new data, and maps of selected constituent concentrations were corrected for the effect of local nitrate contamination of the aquifer. A water-quality assessment based on drinking-water supply use was updated based on additional data and reassessment for selected constituents for which new state and federal standards took effect in 1992. The wide range in fluoride concentrations in Dakota ground waters is explained by water-rock interactions associated with natural softening, which in turn is related to differences in the chemistry and relative flow rates of recharge from the overlying Upper Cretaceous and underlying Permian rocks that mix with waters flowing through Dakota sediments.

In addition to the research just described, the KGS worked with and provided information on the Dakota aquifer to several federal, state, and local agencies and the public in FY92. Research was conducted with the U.S. Geological Survey through a cooperative arrangement between the two agencies, including working with Groundwater Management District No. 3 in southwestern Kansas. Lawrence Livermore National Laboratory and the Texas Bureau of Economic Geology cooperated with the KGS on research on the geochemistry of recharge and flow in the Dakota aquifer system and interactions with other aquifers. The KGS provided information on the Dakota aquifer to Hays as a part of the city's search for additional supplies of ground water for municipal use. Investigations for salinity source determination were conducted in cooperation with the Kansas Corporation Commission and the Kansas Water Office. Information transfer in FY92 included a symposium organized by the KGS and held at the University of Kansas to present results and plans of the Dakota program. The symposium provided a useful forum for communication of accomplishments and receipt of needs and suggestions for proposed work. Throughout FY92, program research staff answered questions and provided data in response to many requests for information on the Dakota aquifer. Other research communications included reports and presentations; the annual report of the FY91 Dakota aquifer was completed and published as KGS Open-File Report 92-1.

The primary emphases during FY93–95 in the Dakota program are (1) to integrate geologic, geohydrologic, and geochemical results to form conceptual models of the aquifer system and useful products for water-resource evaluation and (2) to develop three-dimensional digital models of the Dakota and adjacent aquifers that can be used to simulate the flow of water, transport of solutes, and chemical reactions along the flow path. Development and the use of the quasi-three-dimensional models to simulate the hydrology are being carried out in phases. Phase 1 work is reported in this FY92 report. Work on the regional and subregional steady-state simulations of the Dakota aquifer will continue through FY93. In the latter part of FY94 work will begin on developing a transient-flow model that will be completed in FY95 for southwestern Kansas to allow simulation of the effect of pumping. The models will be used to assess the effect of various water-management options in FY95. Late in FY94 research will also shift to the deeper subsurface of west-central, northwest, and north-central Kansas. In this area readily available data are sparse, the depth to the top of the Dakota aquifer is considerable, and salinities are commonly high. The main focus will be on the areas adjacent to the region under present development and on areas predicted to have usable water quality.

Introduction and Statement of the Problem

The Dakota aquifer is potentially an important water resource for central and western Kansas. This aquifer system underlies much of western Kansas and adjacent portions of Colorado and Nebraska (Figure 1). A lack of water resulting from local depletion of shallower freshwater aquifers in central and western Kansas will create a demand for water supplies from the underlying Dakota aquifer in the future. Those areas of the Dakota aquifer currently undergoing development are managed with little or no technical guidance for policy decisions because of a lack of data. In central Kansas oil-brine disposal in shallow zones beneath the Dakota aquifer may affect water quality in the Dakota aquifer, overlying aquifers, and surface waters by increasing the potential for upward migration of natural and disposed brines. No statewide assessment of these practices and their effect on the Dakota aquifer has been made to date. On the basis of work conducted by the Kansas Geological Survey (KGS) during the Dakota program, several water-quantity and water-quality problems associated with long-term development and management were identified. These problem areas relate to (1) water availability, (2) sources of recharge and their effects on water quality in the Dakota aquifer, (3) the impact of withdrawal of water from the Ogallala and Dakota aquifers in southwestern Kansas on future water-supply availability, (4) the definition of usable zones in the Dakota aquifer, (5) the effect of shallow disposal of produced oil brines on the Dakota aquifer in central Kansas, and (6) the effect of saltwater discharge from the Dakota aquifer on water quality in stream-aquifer systems of central Kansas.

Program Overview

In recognition of the need for an integrated program of research, the KGS has been carrying out and coordinating an eight-year-long multi-agency program to assess the water-resources potential of the Dakota aquifer since FY89. The program is conducted as integrated interdisciplinary research incorporating aspects of hydrology, structural geology, sequence stratigraphy, borehole and surface geophysics, geochemistry, and well

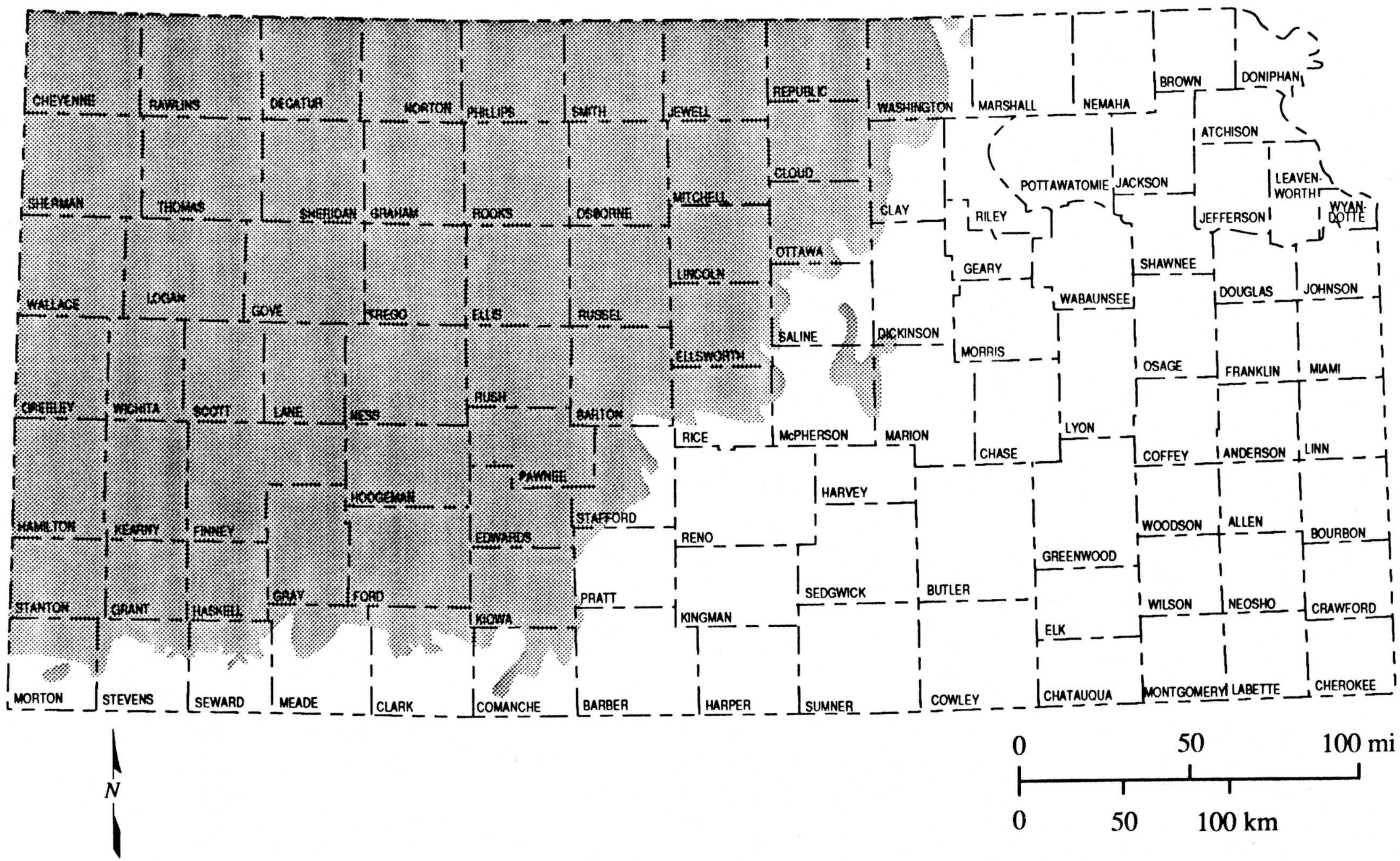


Figure 1. Extent of the Dakota aquifer in Kansas.

engineering. The overall objectives of the Dakota aquifer program (FY90–94) are (1) to characterize subregionally the water-resources potential of the areas where the Dakota aquifer is shallowest and is undergoing development in central and southwestern Kansas in FY90–91 and (2) to develop conceptual models of ground-water flow and assess water-planning and regulatory scenarios (FY92–94). The areas of investigation during the program are shown in Figure 2.

Work completed in the first three years of the program is described in the FY89, FY90, and FY91 annual reports and in additional reports on specific portions of the work and is displayed in maps. In FY92 research was conducted in areas not covered by the previous years in selected portions of the previous subareas for more detailed studies and across selected subareas to examine regional characteristics of the Dakota aquifer system. In addition, work has been directed toward further definition of the long-term research plans for the Dakota aquifer program.

Description and Use of the Aquifer

The Dakota and related aquifer systems are widely distributed geographically, covering much of the midcontinent of North America. The Dakota aquifer underlies most of the western two-thirds of Kansas and nearly all of Nebraska and eastern Colorado. Although the Dakota aquifer in Kansas is nearly as extensive as the High Plains aquifer (Ogallala Formation and associated alluvial deposits), generally lower well yields and greater depths across most of the aquifer and lower water quality in many areas have limited its use. However, good quality and well yields in large areas of the Dakota aquifer system have resulted in use for irrigation, public water supply, and industry in southwestern and central Kansas and southeastern Colorado.

The Dakota aquifer has been used for water supply in Kansas and southeastern Colorado for nearly a century. In Kansas approximately 96% of the total volume of ground water withdrawn from the Dakota is from the southwestern and south-central parts of the state where irrigation wells pump from the Dakota alone or from wells screened in both the Dakota and High

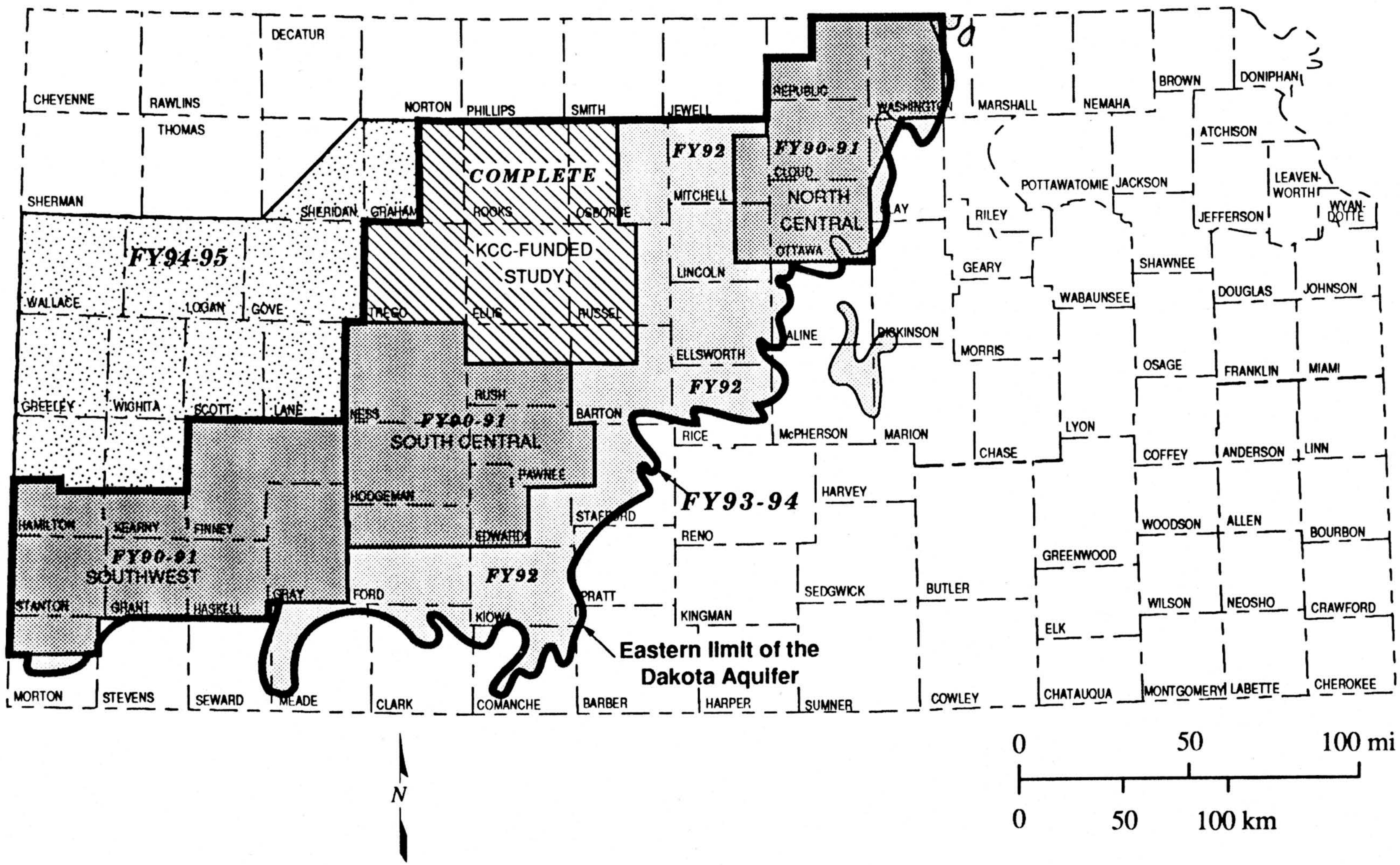


Figure 2. Subareas of investigation in the Dakota aquifer program.

Plains aquifers. However, irrigation use also occurs in the outcrop areas of the Dakota in central and north-central Kansas. What limited data exist suggest that long-term declines in water levels are greatest in southeastern Colorado and southwestern Kansas where flowing wells were once common in the Arkansas River. A figure showing the areas of artesian flow mapped for the Dakota aquifer in 1904 is included in the FY91 annual report (Macfarlane et al., 1992).

The Dakota aquifer system consists of interbedded lenses of sandstone and mudstones of Cretaceous age. The Dakota aquifer consists of three geologic formations: the Dakota Formation (the most important part of the aquifer relative to water use), the Kiowa Formation, and the Cheyenne Sandstone (Figure 3). The hydrostratigraphic classification developed for the Dakota aquifer divides the aquifer into the upper Dakota aquifer (the Dakota Formation), the lower Dakota aquifer (the sandy Longford Member of the Kiowa Formation and the Cheyenne Sandstone), and the Kiowa "Shale" aquitard (the shaly portion of the Kiowa Formation that restricts flow between the upper and lower Dakota aquifer).

The Dakota is a near-surface aquifer in southeastern Colorado and parts of southwestern and central Kansas. In most of southwestern Kansas and southeastern Colorado the aquifer underlies and is hydraulically connected to the overlying High Plains aquifer. Most of the Dakota aquifer in Kansas is overlain by younger shales, chalks, and limestones of Cretaceous age that form the upper Cretaceous aquitard that confines the aquifer (Figure 3). The Graneros Shale is the rock unit in the aquitard that immediately overlies the Dakota aquifer.

Rainfall recharge enters the Dakota aquifer in the outcrop areas in southeastern Colorado and southeastern and central Kansas. Freshwater also recharges the aquifer from the overlying High Plains aquifer in southeastern Colorado and southwestern Kansas. The main pattern of regional ground-water flow in the Dakota aquifer is from the recharge areas in southeastern Colorado and southwestern Kansas to discharge areas in the river valleys of central and north-central Kansas (Figure 4). Where freshwater recharge enters the Dakota, the water quality is good. However, recharge from underlying Permian rock units, especially the Cedar Hills

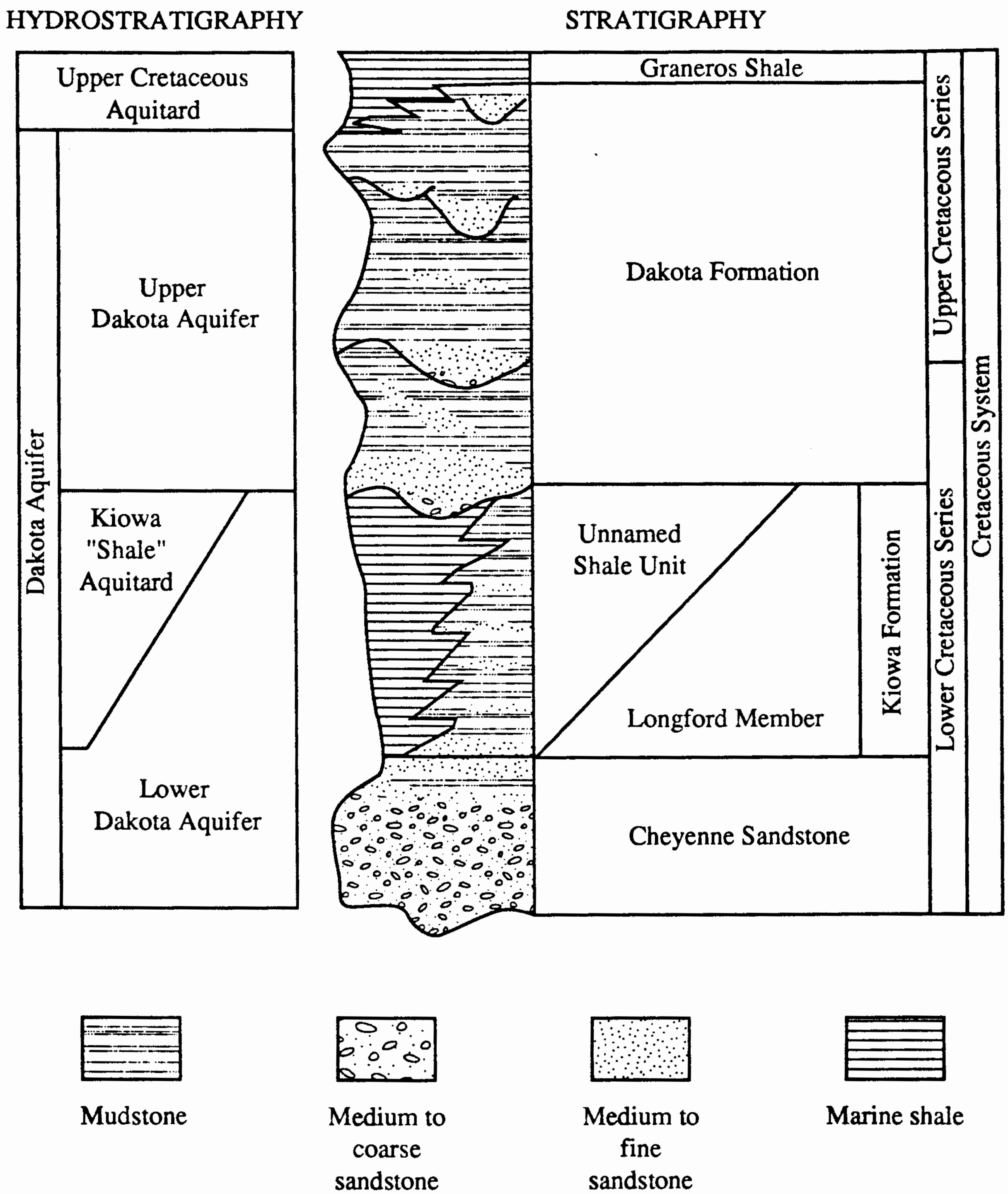


Figure 3. Stratigraphic and hydrostratigraphic classification of units that compose the Dakota aquifer in Kansas.

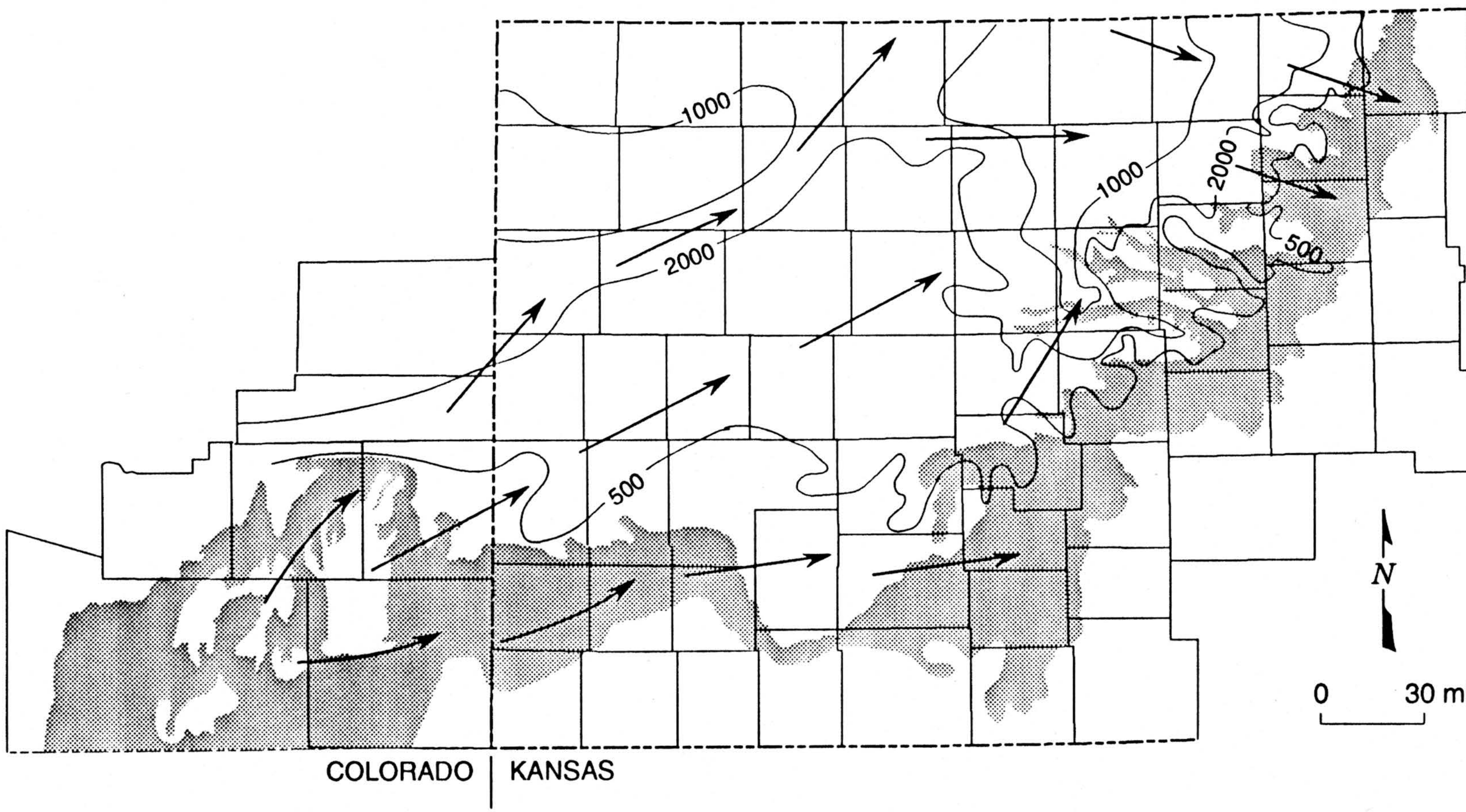


Figure 4. Direction of ground-water flow in the Dakota aquifer. Recharge enters the aquifer in southeastern Colorado and southwestern Kansas and then leaves the aquifer in central Kansas.

Sandstone in central Kansas, has increased the salinity of the aquifer waters in large areas of the aquifer covered by the upper Cretaceous aquitard.

FY92 Activities and Results

Results presented in this annual report provide important advances in the understanding of the distribution of aquifer units, the ground-water flow system, and the water quality of the Dakota aquifer system. Research activities initiated earlier in the program continued, and new projects were started on the geologic framework, geohydrology, and geochemistry of the aquifer areas currently being developed. Although the focus of many of the diverse projects was on southwestern Kansas, other projects were conducted in central and north-central Kansas.

The FY92 activities in the program area involving the geologic framework of the Dakota aquifer were (1) geologic mapping in southwestern Kansas, (2) analysis of geophysical logs for producing geologic cross-section images and monitoring site characterization, and (3) geostatistical analysis of sandstone and shale distributions. The geologic mapping focused on southwestern Kansas and was based on interpretation of information from geophysical logs. A colored image for a geologic cross section from southwestern to central Kansas was generated using computer analysis of geophysical logs to better illustrate aquifer unit characteristics. The geostatistical research was initiated in Hodgeman County where a high-density distribution of geophysical logs have been digitized.

The geohydrologic work concentrated on (1) determining aquifer characteristics and aquifer interactions at monitoring sites in southwestern Kansas and (2) simulating ground-water flow aerially and vertically across the Dakota aquifer system at different scales and in different areas. A monitoring site was constructed in Stanton County, and slug and pumping tests were conducted at the Finney and Hodgeman County monitoring sites. The water levels and chemical quality were measured for assessing the interaction between the Ogallala and Dakota aquifers at a monitoring site in Gray County as part of a cooperative project with Groundwater Management District No. 3. Ground-water flow simulations ranged from a regional steady-state model in western Kansas and southeastern Colorado to smaller-scale models in subregional and local areas. A report on the subregional study of the ground-water flow systems and water-resources potential of the Dakota aquifer in parts of Republic, Cloud, Clay, and Washington counties has been completed and is being reviewed. The steady-state model of ground-water flow in southeastern Colorado and southwestern Kansas is being developed in conjunction with the larger-scale regional model but at a more detailed scale that will form the basis for a transient-flow model for assisting water-resources management in southwestern Kansas. A flow model completed along a cross section from southeastern Colorado to central Kansas shows the effect of hydrostratigraphy and topographic relief on the steady-state flow in the Dakota aquifer system. The model considers the interactions between geologic strata above, within, and below the Dakota aquifer and explains the generation of subnormal pressures in the aquifer. In addition, simulated flow in the cross section characterizes the water budget for local flow systems in the recharge and discharge areas of southwestern Colorado and the eastern outcrop belt of the Dakota system in central Kansas and the regional flow in the confined aquifer from western to central Kansas.

Geochemical activities for FY92 consisted of (1) determining water quality at monitoring sites, (2) characterizing the geochemistry of aquifer interactions and recharge, (3) modeling ground-water flow and geochemistry in north-central Kansas, (4) identifying sources of salinity in ground waters in and discharging from the Dakota aquifer, (5) determining the hydrogeochemistry of fluoride in the aquifer, and (6) updating water-quality distribution maps and assessing water quality for water supplies. Water quality was examined during the pumping tests at Finney and Hodgeman counties. Ground waters were sampled and analyzed as part of cooperative studies with the Texas Bureau of Economic Geology and the Lawrence Livermore National Laboratory to characterize recharge to the Dakota aquifer from atmospheric precipitation and adjacent aquifers and to date flow in the aquifer. Work in north-central Kansas focused on determining a conceptual geochemical model before using a coupled geochemical and mass transport model for flow and chemical simulation. Salinity identification studies determined that no oil-field brine was found in the slightly saline ground waters from test wells drilled for the development of supplemental municipal water supplies for the city of Hays. No detectable oil brine was found in low flows of the Saline River where the Dakota aquifer discharges saline water, but oil-brine contamination was found to contribute to the natural saline discharge to the Smoky Hill River in southern Russell County. The wide range in fluoride concentrations in Dakota ground waters is explained as the solution of fluoride-containing minerals and desorption of fluoride from some mineral surfaces. The processes of cation exchange and carbonate mineral dissolution, which are related to differences in the chemistry of recharge from the overlying Upper Cretaceous and underlying Permian rocks, are responsible for chemical changes that lead to increased dissolved fluoride in the Dakota aquifer. Water-quality distribution maps for the Dakota aquifer were modified to include new data, and maps of selected constituent concentrations were corrected for the effect of local nitrate contamination of the aquifer. The update of the water-quality assessment based on drinking-water supply use involved additional data and reassessment for selected constituents for which new state and federal standards took effect in 1992.

Geologic Framework

Geologic Mapping of the Shallow Subsurface in Southwestern Kansas

All the regional geologic mapping efforts were focused on southwestern Kansas south of T. 14 S. and west of R. 10 W. The data used in the mapping are formation tops picked from API-calibrated, gamma-ray logs of oil and gas production and exploration boreholes. Eight-hundred ten logs were selected for subsurface mapping in southwestern Kansas. Over much of the eastern part of the region, in the vicinity of the Central Kansas uplift and the Pratt anticline, the data density is approximately four logs per township, except in a nine-township area of Hodgeman County. In this smaller area 317 logs were selected. To the west of the Central Kansas uplift and the Pratt anticline and near the Hugoton embayment, the log density declines to less than one log per township for many of the formation tops. To the north of this sparsely populated region the log density approaches one per township for all the stratigraphic horizons mapped.

Hand-contoured maps of the top of the following stratigraphic units were produced: Carlile Shale, Greenhorn Limestone, Graneros Shale, Dakota Formation, Kiowa Formation, Longford Member (Kiowa Formation) or Cheyenne Sandstone, Morrison formation, Permian System, Cedar Hills Sandstone, Salt Plains Formation, and Stone Corral Formation. Using the formation tops, thicknesses were computed and mapped for the following geologic units: Carlile Shale, Greenhorn Limestone, Graneros Shale, Dakota Formation, Kiowa Formation undifferentiated marine shale, Longford Member (Kiowa Formation) or Cheyenne Sandstone, Morrison formation and other undifferentiated Jurassic and Triassic deposits, Permian strata above the Cedar Hills Sandstone, the Cedar Hills Sandstone, Salt Plains Formation, and Harper Sandstone.

The hand-drawing of the isoelevation and isopach contours has been completed, and the contours and the points are in the process of being digitized into the ARC/INFO geographic information system, where they will be used to create coverages for map production. The finished maps will be assembled into a geologic atlas of southwestern Kansas, which should be ready for publication during the early part of FY94. The maps will also be used later in the flow modeling of the shallow part of the regional system to delineate regional hydrostratigraphic units, the aquifer, and aquitard units.

Work in the future will be directed toward using the digital gamma-ray data to generate sandstone/shale ratios in the stratigraphic units that constitute the upper and lower Dakota aquifer units across southwestern Kansas. The ratios will be contoured to produce isolith maps for each sequence-stratigraphic subdivision to identify the dominant sandstone-body trends in the Dakota and to map three-dimensionally the distribution of sandstone. This is an important first step in the process of defining the complicated plumbing system of interconnected sandstone bodies in the Dakota.

Regional Gamma-Ray Gray-Level Intensity Cross-Section Images of the Permian-Cretaceous Sequence

The provisional profile described and shown as Figure 18 in the annual report for FY91 (Macfarlane et al., 1992) has been revised and completed. The image was converted from gray-level representation as illustrated in the FY91 report to a colored image based on the application of color information theory to the log interpretation. The colored image (Figure 5) improves the visual conceptualization of the aquifer and aquitard units in the Dakota aquifer and the overlying and underlying rock units. The work was presented as a poster at the SEPM 1992 Theme Meeting in Fort Collins, Colorado, in August 1993 ["Regional gamma-ray gray-tone intensity images of the Permian-Cretaceous sequence of western Kansas" by D. R. Collins, J. H. Doveton, and P. A. Macfarlane (see list of Dakota program publications at end of this report)]. Interpretive work will be continued on both this and other regional cross sections for a variety of applications, ranging from improvements in the characterization of the regional geology to incorporation into the modeling phase of the Dakota program.

Geophysical Log Analysis of the Gray County Site

Spectral gamma-ray, lithodensity-neutron, acoustic velocity, and resistivity logs were run in the Gray County well drilled in March 1993 in sec. 26, T. 27 S., R. 28 W. The stratigraphy differs from other wells of the Dakota program series in that it has an interval of the Ogallala Formation above the Cretaceous section. A major point of interest in this logging run was whether the Ogallala can be distinguished from the Dakota sandstones on the basis of geophysical logs alone. If so, then what are the petrophysical properties that make this distinction possible? Some conclusions are discussed in this summary with reference to the resistivity (Figure 6), lithodensity-neutron (Figure 7), acoustic velocity (Figure 8), and spectral gamma-ray logs (Figure 9) from this well.

Some geophysical log comparisons between the Ogallala and the Dakota were easier than others because most of the Ogallala section was above the water level in the well. As a result,

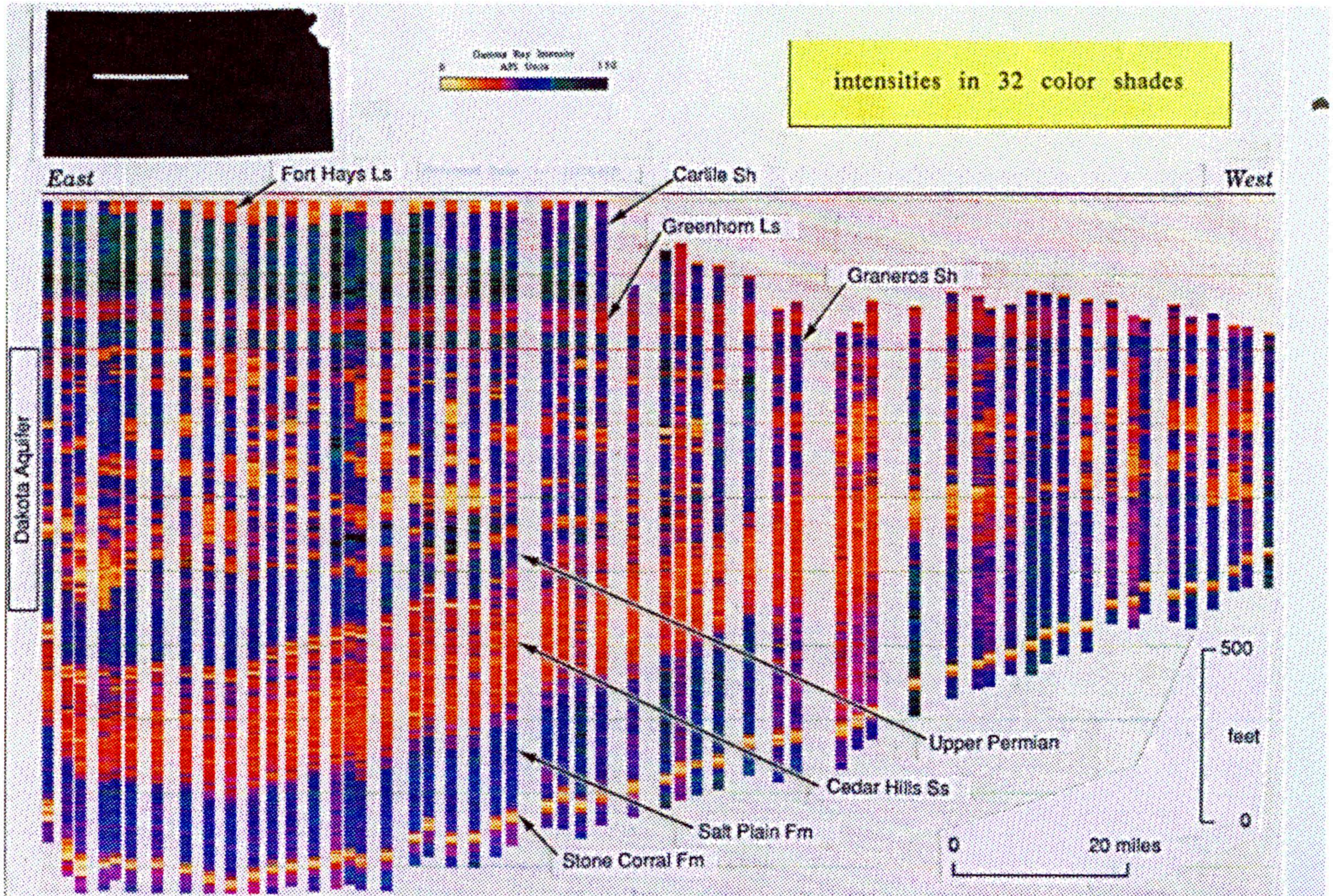


Figure 5. Reduced color image of gamma-ray log intensity of the Permian to Upper Cretaceous strata in western Kansas along T.16.S. from R.31.W. to R.9.W.

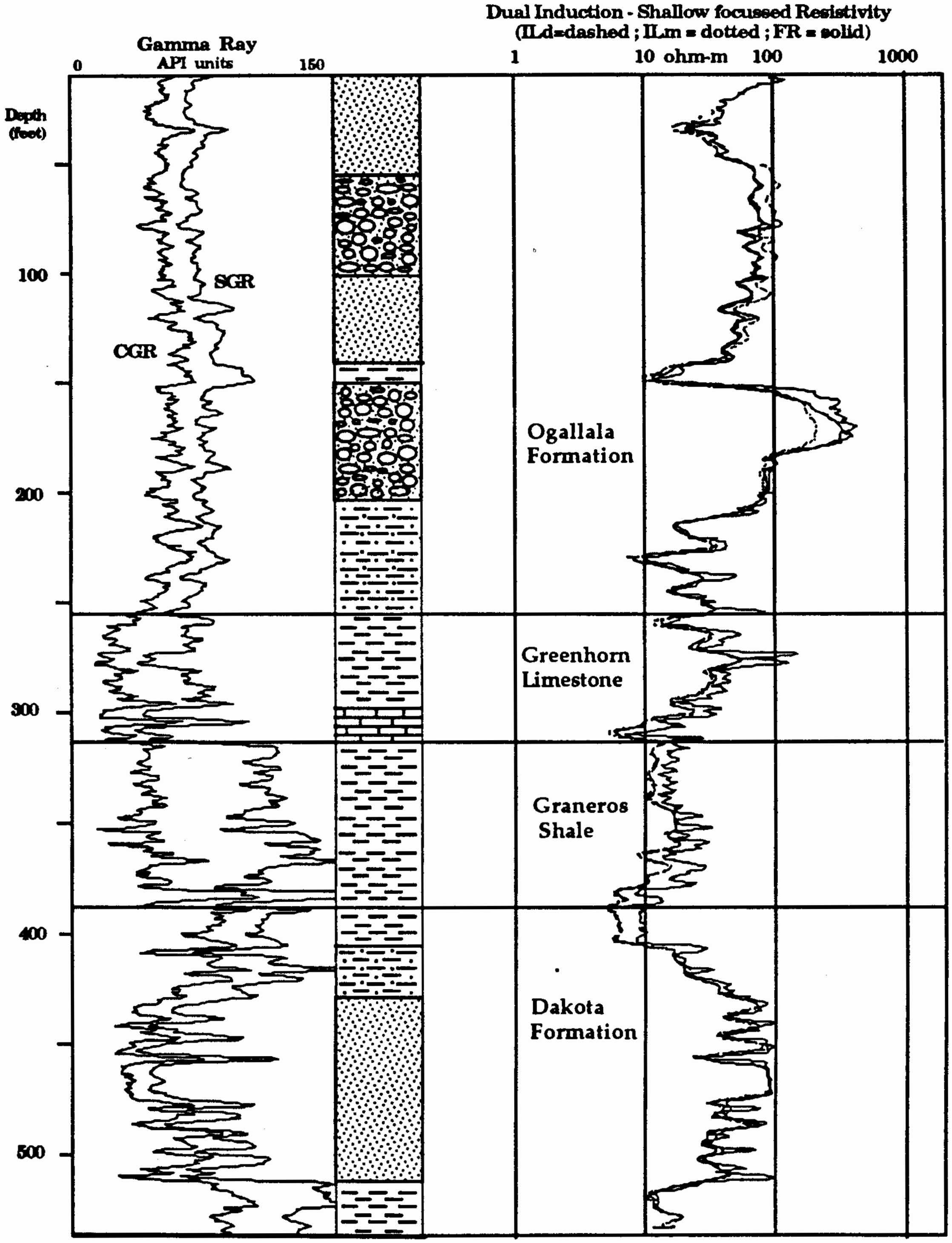


Figure 6. Resistivity logs from KGS Gray County Feed Yard 1, SENE sec. 26, T. 27 S., R. 28 W., Gray County, Kansas.

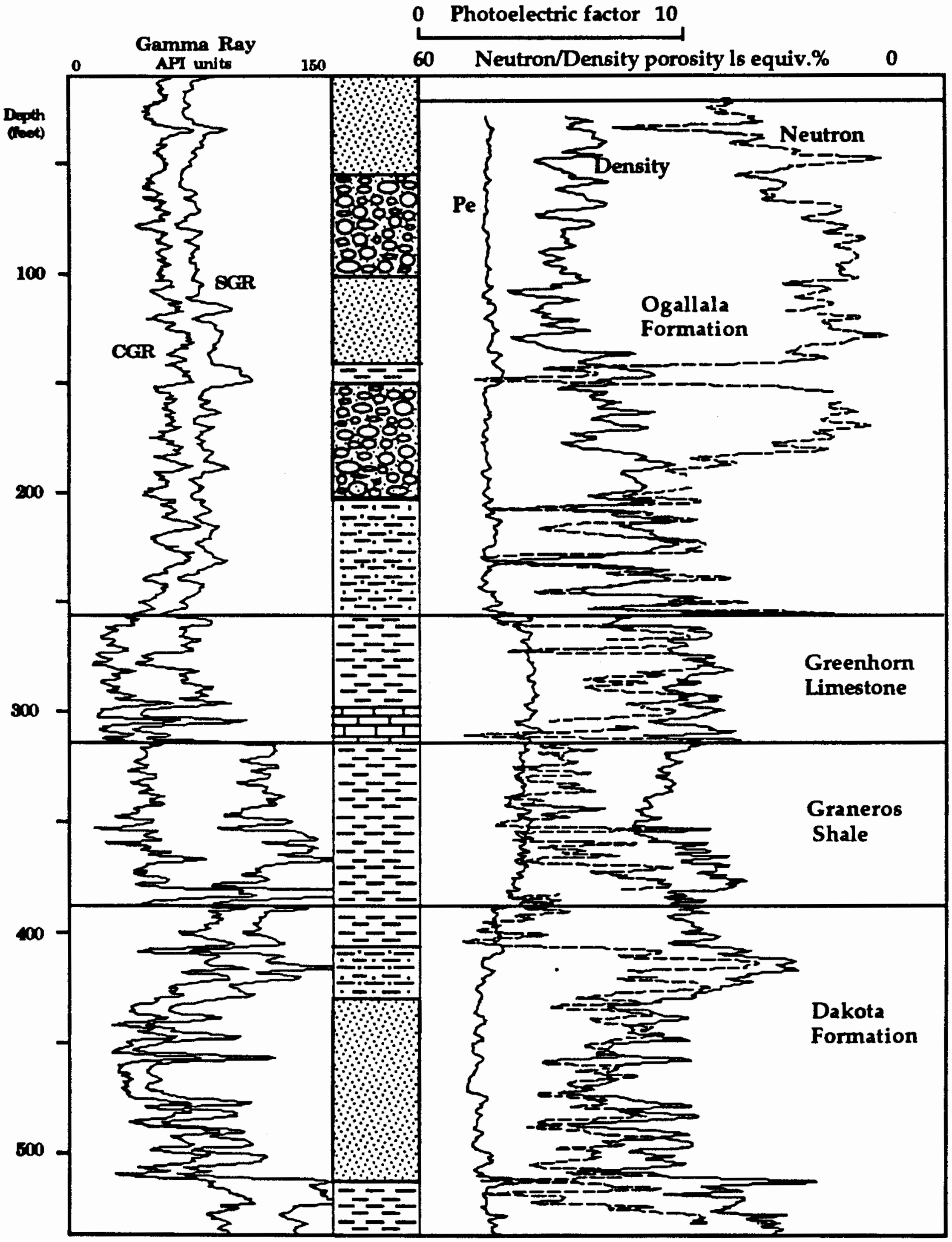


Figure 7. Lithodensity-neutron logs from KGS Gray County Feed Yard 1, SENE sec. 26, T. 27 S., R. 28 W., Gray County, Kansas.

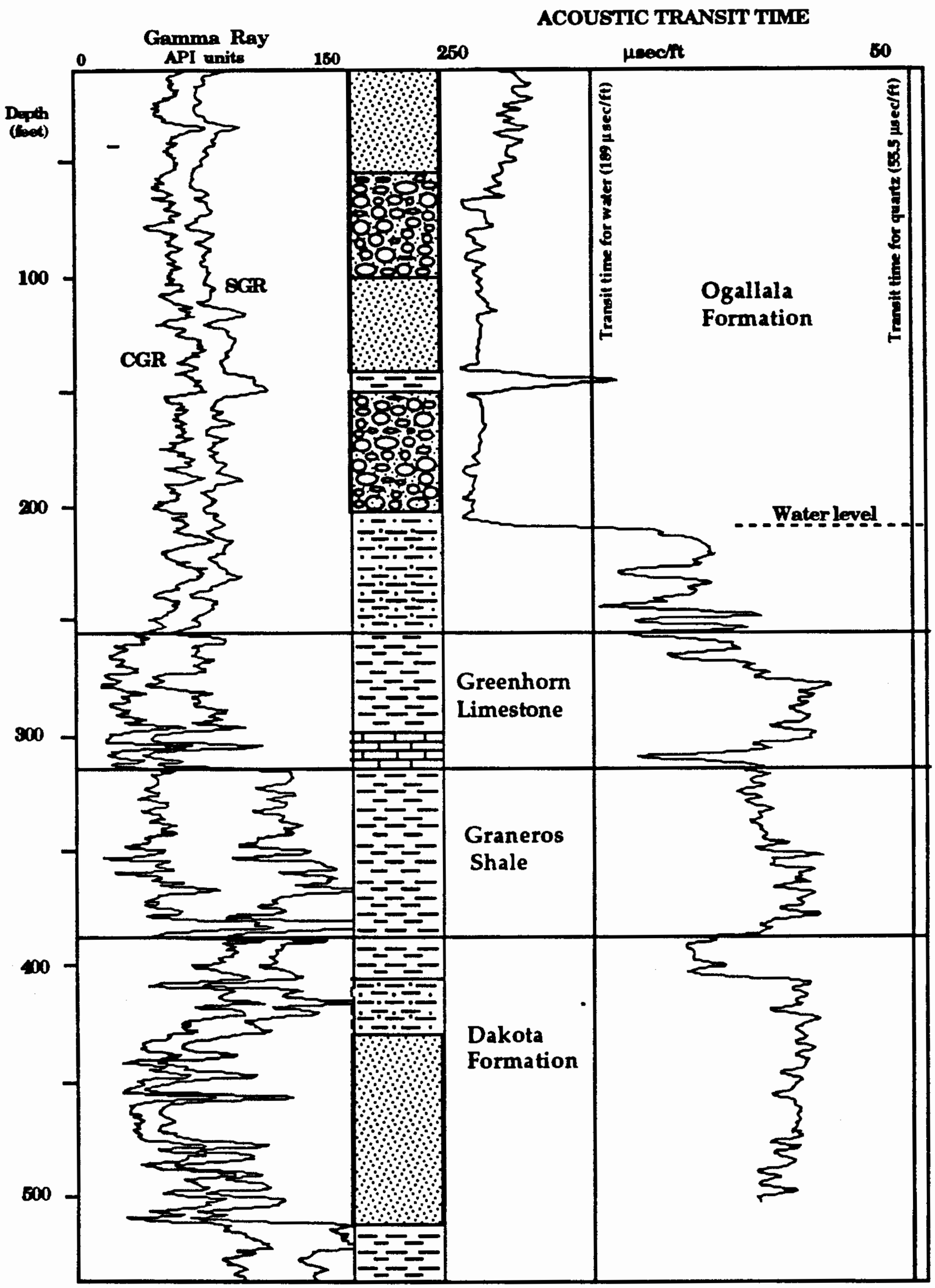


Figure 8. Acoustic velocity log from KGS Gray County Feed Yard 1, SENE sec. 26, T. 27 S., R. 28 W., Gray County, Kansas.

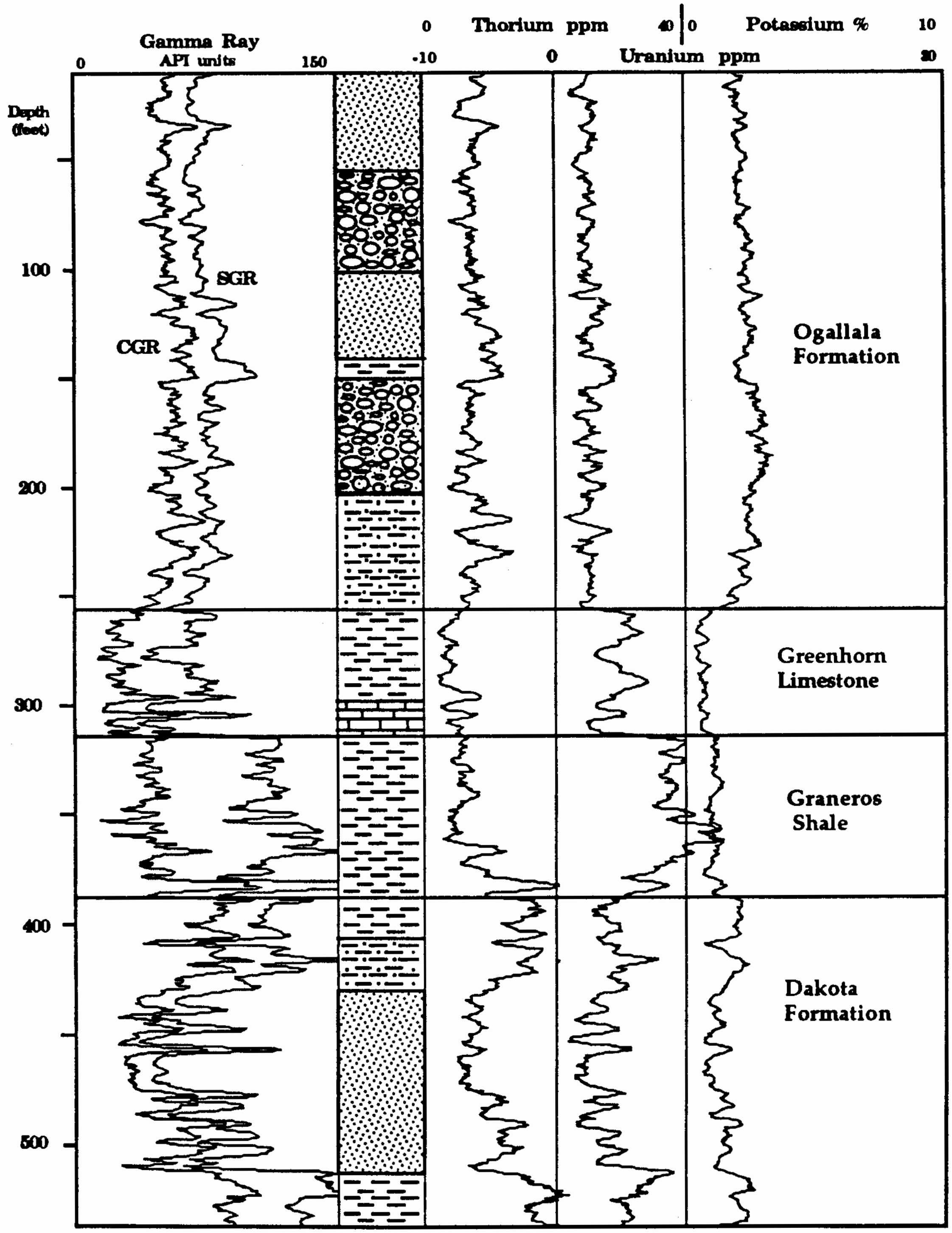


Figure 9. Spectral gamma-ray logs from KGS Gray County Feed Yard 1, SENE sec. 26, T. 27 S., R. 28 W., Gray County, Kansas.

the pore space in the Ogallala sands and gravels was only partially saturated with water. The high air content of the pore space can be seen readily on several logs, particularly those from tools with relatively shallow depth of investigation beyond the borehole wall. The relatively high-density porosity and low neutron porosity readings in the Ogallala (Figure 7) would be recognized immediately by most petroleum geologists as a gas effect. In this instance the gas is not a hydrocarbon but natural air. However, the effect is the same because of the low density and low hydrogen content of air compared with water. The effect of the air phase is also evident in the acoustic velocity log. Above the water level there is a marked increase in transit time (Figure 8), because the speed of sound is much slower in gas than in aqueous media.

The spectral gamma-ray logs (Figure 9) proved to be a valuable aid in the interpretation of rock types and units from drill cuttings. In particular, the feldspar content of the Ogallala gives a useful signature on the potassium curve of the spectral log, differentiating the Ogallala from the Dakota rocks. The discrimination is best made by the computation of a Th/K ratio log (Figure 10), so that the effects of potassium-feldspar (high potassium and moderate thorium) can be accentuated relative to those of illitic shales (high potassium and high thorium). Note that the distinction of the Ogallala from the Dakota in this well is quite clear-cut when using the Th/K ratio as a criterion.

The Th/U ratio values of the Ogallala and the Dakota are similar (Figure 10), and their range indicates fairly neutral redox conditions in their formation. However, both units differ drastically from the intervening Graneros Shale and Greenhorn Limestone, where a consistently low Th/U ratio reflects enhanced uranium concentrations. The uranium was probably fixed by organic matter by the reducing conditions that prevailed during the marine deposition of these units.

Collectively, the gamma-ray spectral ratio signatures are valid and useful measures for distinguishing the Ogallala and Dakota Formations and for recognizing the Graneros Shale and Greenhorn Limestone. The discrimination criteria are also likely to be of regional rather than localized significance. The Miocene Ogallala Formation represents clastic deposits derived from

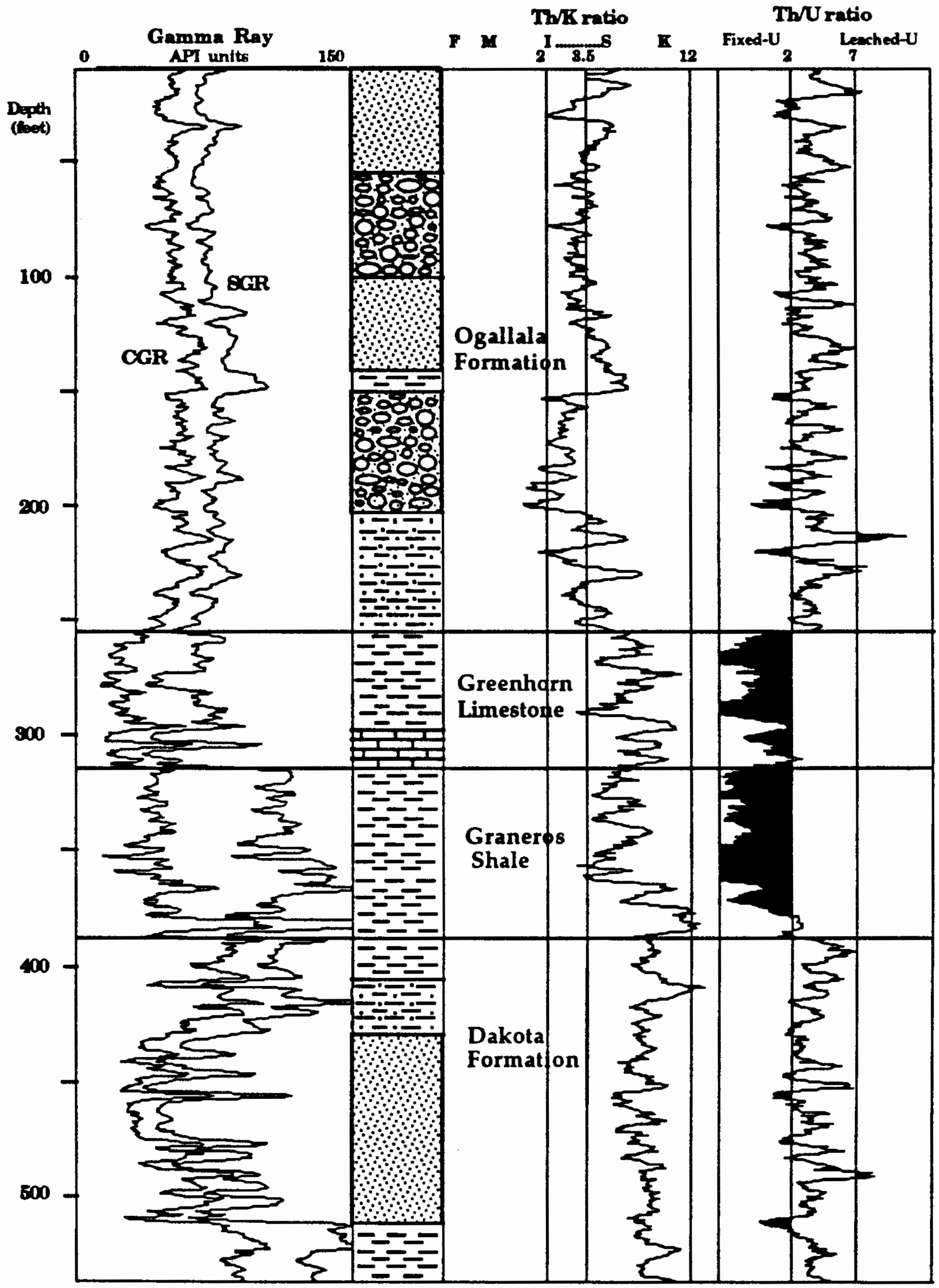


Figure 10. Gamma-ray spectral ratio logs from KGS Gray County Feed Yard 1, SENE sec. 26, T. 27 S., R. 28 W., Gray County, Kansas.

the uplift of the Rocky Mountains to the west, with feldspar supplied from fresh granitic material. These sediments contrast with the more mature clastics of the Dakota Formation, which originated from more distant sources to the east. The relative increase of uranium concentration in the Graneros Shale is well known across Kansas and is a typical phenomenon in regional marine shales of this type, where the seafloor was under reducing conditions. Enhanced uranium contents are less common and much more localized in the fluvial and deltaic deposits of the Dakota and Ogallala Formations, where neutral or mildly oxidizing conditions appear to have been the rule in either the original deposition or subsequent diagenesis.

Spectral gamma-ray logs are more expensive to run than conventional gamma-ray logs. However, their use can be justified on occasions where the aquifer stratigraphy is poorly understood and where distinctions between the Ogallala and Dakota Formations are needed. Alternatively, they could be run as reference logs (i.e., as a stratigraphic standard) at selected locations for the correlation of conventional gamma-ray logs run in wells in the surrounding area.

Geostatistical Analysis of Sandstone and Shale Distribution in Hodgeman County

Approximately 360 gamma-ray logs of the Dakota aquifer have been digitized in a nine-township area of Hodgeman County (Figure 11). These logs provide an extremely high density of control compared with the average state coverage of the Dakota (one well per township). At each well location stratigraphic tops have been picked as lithostratigraphic subdivisions of the Lower Cretaceous section. These tops and their codes are shown in Figure 12, where they are matched with their corresponding Dakota aquifer subdivisions. The data set will be analyzed with respect to vertical, lateral, and directional change in the distribution of sandstones and shales. The initial phase of the project should be completed by the fall of 1993. The database construction is almost complete, and the analytical strategy has been determined. The data will be analyzed by Ling Bian (Geography Department, University of Kansas) using geostatistical methods to determine the degree of lateral continuity and orientation in the Dakota aquifer units.

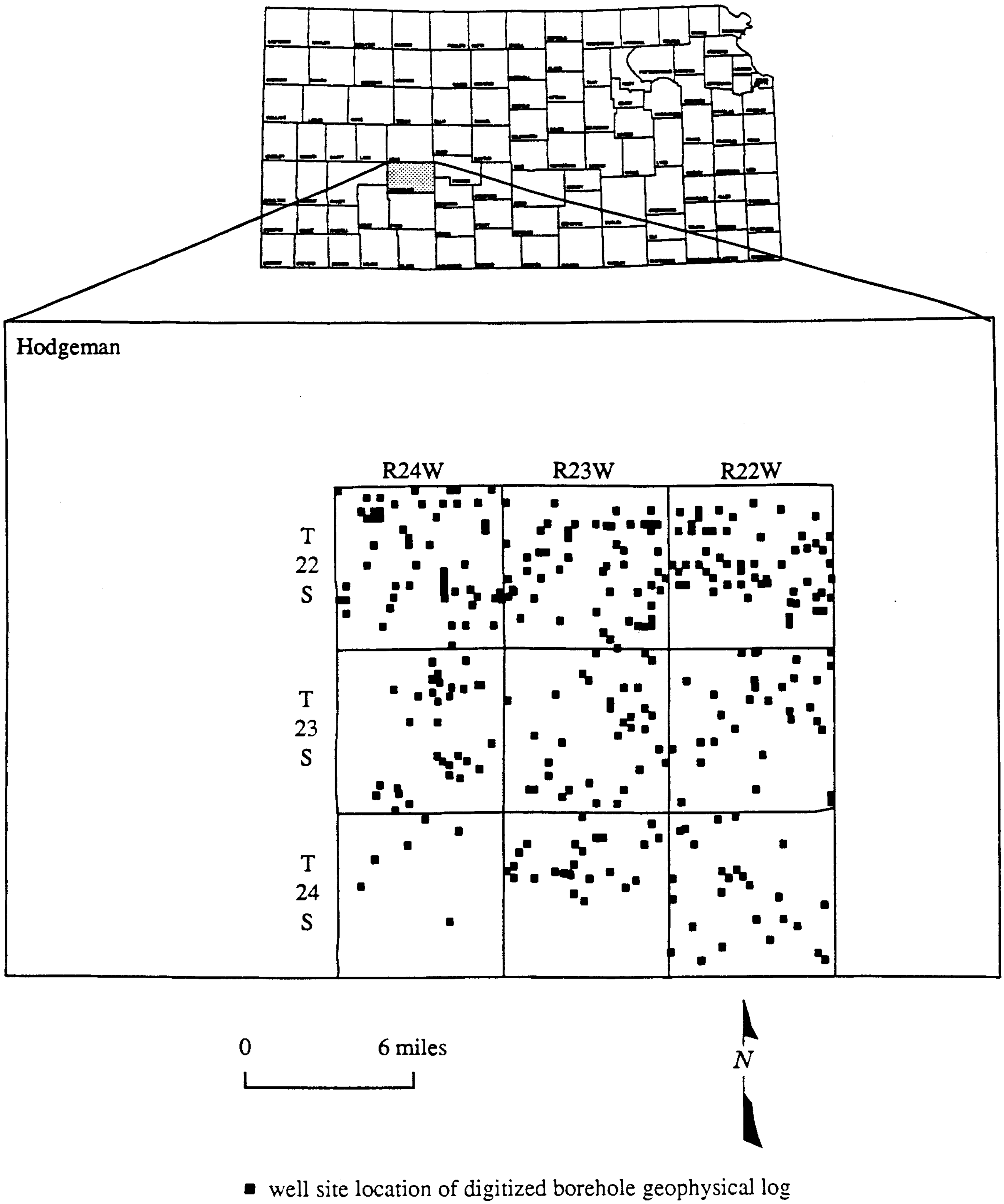


Figure 11. Distribution of digitized gamma-ray logs in the Hodgeman County intensive study area.

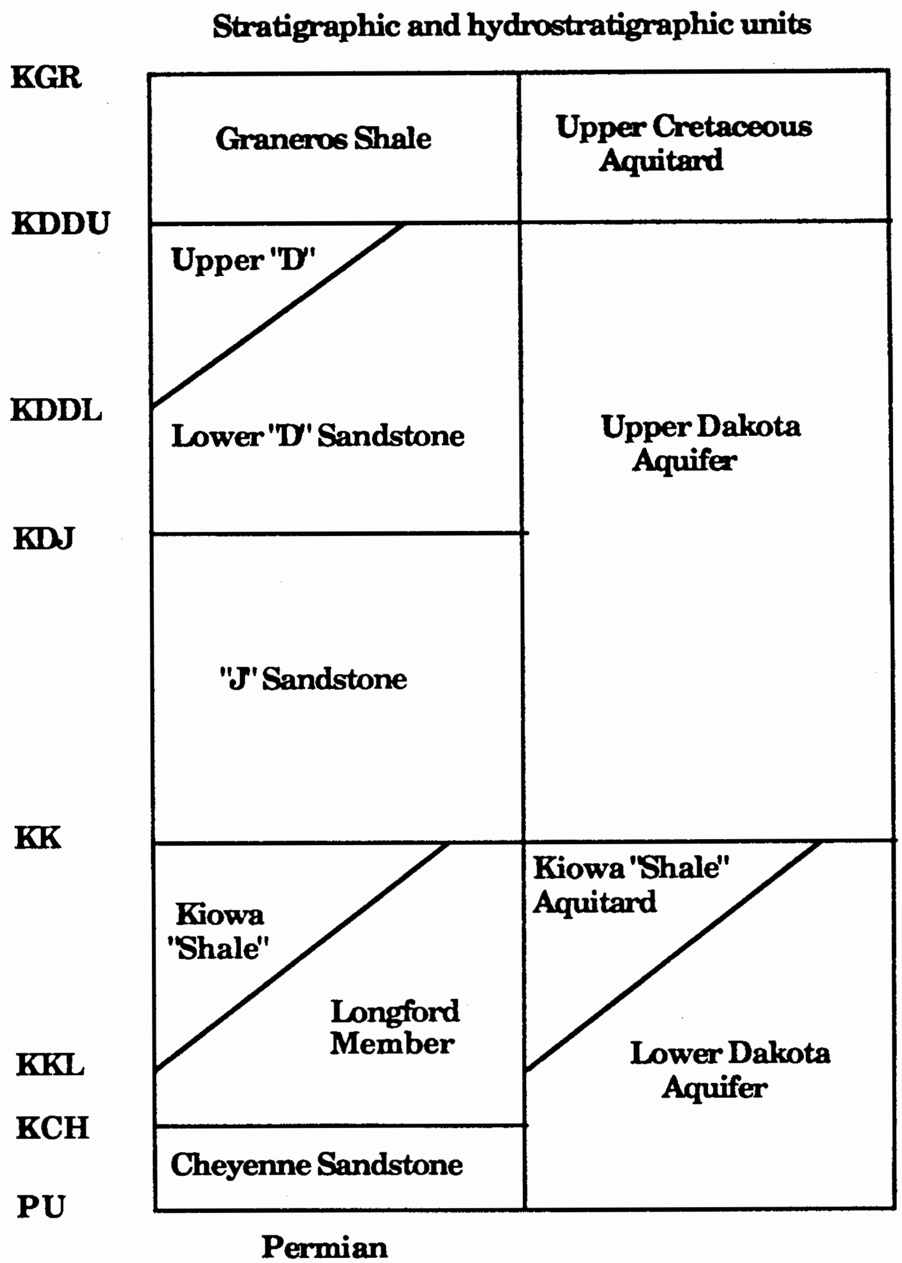


Figure 12. Formation elevations in Hodgeman County data set referenced with lithostratigraphy and aquifer subdivisions.

The results will have important implications regarding the design and performance of the dynamic models that will be applied to simulate flow in the Dakota.

Geohydrology

Monitoring Sites

Construction of the Monitoring Site in Stanton County

The U.S. Geological Survey completed the drilling of the pumping-test well and one observation well in the Cheyenne Sandstone in the lower part of the Dakota aquifer and one deeper observation well in the Permian Morrison formation. The wells are located in SESESW SE sec. 21, T. 29 S., R. 43 W., in southwest Stanton County, about 3 mi (5 km) north-northeast of Saunders. The location is in the valley of Bear Creek and several hundred feet to the east of the creek. The three wells have been assigned well identification numbers 372024102012001 through 372024102012003 in the USGS GWSI (Ground-Water Site Inventory) database. The observation wells are located 12 ft (3.7 m) and 30 ft (9.1 m) from the pumping-test well in a general east-west orientation.

The pumping-test well (372024102012001) was installed at a finished depth of 280 ft (85.3 m) after the hole was backfilled with bentonite from the drilled total depth of 582 ft (177 m). The well has a 5-in. (13-cm) diameter PVC casing and 40 ft (12 m) of 0.020-in. (0.5 mm) mill-cut slotted PVC screen and is filter-packed with medium sand from 294 ft to 235 ft (89.6–71.6 m). The annular space above the filter pack is sealed with a mixture of polymer gel and bentonite up to 80 ft (24 m) depth and with bentonite up to the land surface.

The deeper observation well (372024102012002) in the Morrison formation was installed at a finished depth of 415 ft (126 m) after the hole was backfilled from the drilled depth of 422 ft (129 m). The observation well is a 2-in. (5-cm) diameter PVC-cased well with 20 ft (6.1 m) of 0.020-in. (0.5-mm) mill-cut slotted PVC screen and is filter-packed with medium sand from 422 ft to 382 ft (124–116 m). The annular space above the filter pack is sealed with a grout mixture of polymer gel and bentonite up to 120 ft and with bentonite up to the land surface.

The second observation well (372024102012003) in the lower Dakota aquifer was installed at a finished depth of 270 ft (82.3 m) after the hole was backfilled from the drilled depth of 282 ft (86.0 m). The observation well is a 2-in. (5-cm) diameter PVC-cased well with 20 ft (6.1 m) of 0.020-in. (0.5-mm) mill-cut slotted PVC screen and is filter packed with medium sand from 282 ft to 242 ft (86.0–73.8 m). The annular space above the filter pack is sealed with a grout mixture of polymer gel and bentonite up to within a few feet of the land surface and with bentonite up to the land surface.

Slug and Pumping Tests Conducted at the Finney and Hodgeman County Monitoring Sites

In FY92 the KGS continued a program of well testing directed at gathering more information about the storage and transmissive properties of the Dakota aquifer system in central and southwestern Kansas. Field testing was completed at two sites in Hodgeman and Finney counties in late FY92. Testing at the remaining site in Stanton County will be completed by early FY93. Analysis of all the test results will be included in the FY93 report.

The field testing program at both sites lasted about one month. The general procedure was to begin monitoring at a site 10 days to 2 weeks before a planned pumping test. Ground-water levels were monitored with electronic pressure transducers, and atmospheric pressure was monitored with an electronic barometer. Both the transducers and the barometer were connected to a data logger so that data could be recorded without the need for human intervention. Before placement at the site, the transducers and barometer were calibrated at the KGS.

This initial period of monitoring was designed to gather information about background water levels at the site and to help define the relationship between barometric pressure variations and water-level fluctuations. An understanding of the relationship between barometric pressure and water levels is necessary to correct the drawdown data measured during the pumping test for any changes in atmospheric pressure that might occur during the test.

A series of slug tests was performed at each site before the pumping test. These slug tests allowed some preliminary estimates of the subsurface flow properties at the site to be determined. These preliminary estimates were then used to plan the mechanics of the pumping test. Without the information from the slug tests, it would be difficult to estimate a pumping rate that would produce measurable drawdown at the observation wells but not be great enough to cause water levels at the pumping well to fall beneath the intake screen of the pump.

After a 10-day to 2-week period of background monitoring, a pumping test lasting approximately 24 hours was performed at each site. During this test, the well was pumped at a constant rate and drawdown was measured in both the pumping and observation wells. In addition to the transducers and the barometer, an electronic flowmeter was employed to closely monitor the rate of pumping throughout the test. As with the other equipment, the flowmeter was calibrated at the KGS before use in the field. Note that manual readings of water levels using an electric tape and flow rate measurement using a calibrated bucket were taken frequently during the test to supplement the electronically gathered data.

A final 10-day to 2-week period of monitoring followed the pumping test. The purpose of this monitoring was to assess the recovery of water levels after the period of pumping and to gather further information about the relationship between water-level fluctuations and atmospheric pressure changes. At the end of this period a final series of slug tests was performed to assess how the 24 hours of pumping had changed the estimates of flow properties obtained from the earlier slug tests.

The program of slug tests carried out at each site was based on methods recently developed at the KGS. The slug tests were performed using the KGS packer-based slug test system (Butler et al., 1990). In this system an inflatable rubber packer is lowered into the well on 3/8-in. pump rods. The packer is placed below the static water level in the well but above the well screen. It is then inflated from the surface using nitrogen gas, closing off the annular space between the inner diameter of the well and the original outer diameter of the uninflated rubber packer. The central pipe on which the packer is mounted is the only connection between the screened and cased portions of the well. This pipe can be opened and closed using a brass plug that is attached to the pump rods. A slug test is initiated by closing off the central pipe and adding water above the packer. This slug of water is then instantaneously introduced into the well screen by opening the central pipe. The water-level response to the introduced slug is measured with a pressure transducer placed above the packer.

After completion of a slug test, the data are analyzed with SUPRPUMP, an automated well-test analysis package that was recently developed at the KGS (Bohling and McElwee, 1992; Bohling et al., 1990), to obtain estimates of the transmissivity and storativity of the formation in the vicinity of the well. Figure 13 displays the results of such an analysis for a Dakota well at the Hodgeman County test site, and Figure 14 displays the results of such an analysis for a Dakota well at the Finney County site. Note that at both sites multiwell slug tests (McElwee et al., 1991) were also attempted. As described in the FY91 report (Macfarlane et al., 1992), the multiwell slug test can provide parameter estimates of much greater reliability than conventional single-well slug tests. Unfortunately, because of the nature of the well construction at the Hodgeman and Finney County sites, the multiwell slug tests met with only limited success.

Cooperative Monitoring Site in Gray County with Southwestern Kansas Groundwater Management District No. 3

Concerns about the degree of hydraulic connection between the Dakota and the overlying High Plains aquifer in southwestern Kansas Groundwater Management District No. 3 (GMD3) are being addressed in a cooperative project between the GMD3 and the Kansas Geological Survey. Monitoring well sites are being established that consist of two wells, one screened in the Dakota aquifer and the other in the High Plains aquifer. It is anticipated that the monitoring sites will be used for short-term hydrologic testing and monitoring conducted by the KGS and longer-term monitoring by the GMD3.

The first monitoring site was established in Gray County (SESENE sec. 26, T. 27 S, R. 28 W.) in FY92. Wells were drilled and constructed by Don Fulton with the assistance and

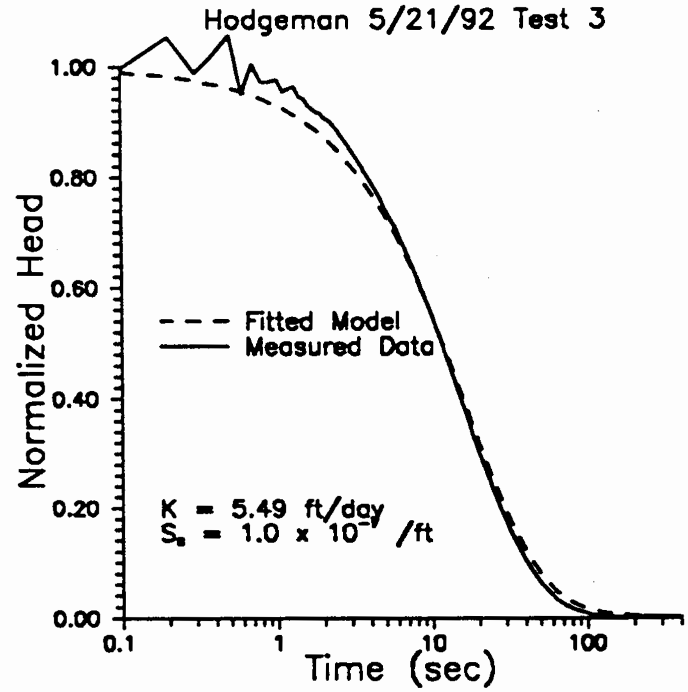


Figure 13. Data and fitted model results for a slug test performed in the Dakota observation well at the Hodgeman County site.

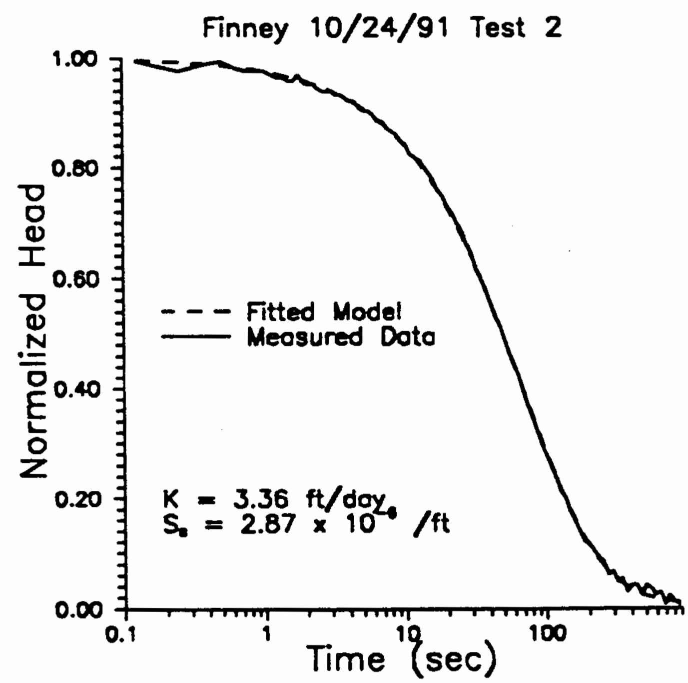


Figure 14. Data and fitted model results for a slug test performed in the Dakota pumping well at the Finney County site.

guidance of Alan Wade of the Kansas Geological Survey during March 5–12, 1992. Each well is a standpipe piezometer cased with 2-in. (5-cm) diameter PVC. The KGS developed the wells during March 25–26, 1992, by pumping 1,700 gal (6,435 l) from well 1 and 2,200 gal (8,329 l) from well 2; samples were collected at the end of each well development. The samples were taken to the KGS laboratories for analysis. Well construction and water-level information are listed in Table 1.

The Gray County monitoring site is located at the Gray County Feeders stockyard, near Montezuma, Kansas, near an erosional re-entrant in the Upper Cretaceous aquitard. The total thickness of the Ogallala Formation and Pleistocene deposits at the site is approximately 260 ft (79 m). However, the saturated thickness is only about 70 ft (21 m). The High Plains aquifer monitoring well is approximately 230 ft deep and is screened near the bottom of the aquifer in a silty sand and gravel. The upper Dakota aquifer is separated from the overlying Ogallala by approximately 140 ft (43 m) of Greenhorn Limestone and Graneros Shale, which constitutes the Upper Cretaceous aquitard at this site. The upper Dakota monitoring well is approximately 475 ft (145 m) deep and is screened in a sandstone of probable deltaic origin in the upper part of the D sandstone, Dakota Formation. At this site the difference in water levels between the Dakota and the overlying High Plains is approximately 33 ft (10 m), indicating a significant tendency for downward flow between aquifers under natural conditions.

Table 1. Well-Construction Information and Water Levels during Period of Development of the Gray County Monitoring Well.

Well	Aquifer	Screened interval (ft)	Gravel-pack interval (ft)	Water level before development 3-25-92 (ft)	Water level after development 3-26-92 (ft)
2	Ogallala	210–230	200–232	185.9	185.7
1	Dakota	455–475	439–500	219.0	220.3

Well construction values are depths below land surface. Water levels are depths below the top of the casing, which is 1.9 ft above the well pad.

The quality of the water samples collected from both wells is fresh (Table 2). Comparison of the water chemistry for the two wells suggests that some recharge from the Ogallala Formation may be entering the underlying Dakota aquifer. Water is fresh in the Dakota aquifer all along the flow path from the west through Stanton, Grant, and Haskell counties to the Gray County monitoring site. Thus it is difficult to estimate the amount of recharge from the overlying Ogallala relative to the recharge from the west that combines in the Dakota at this location. Although the chloride concentrations are low and nearly the same in the two aquifers, the sulfate concentration is substantially higher in the Dakota. The higher sulfate content might be from oxidation of pyrite (iron sulfide) in finer-grained sediments in the Dakota system. The lower calcium and higher sodium concentrations in the Dakota compared with the Ogallala suggest that cation exchange may have altered the water chemistry in the Dakota aquifer. Recharge from the Ogallala containing higher calcium concentration could be the main drive for the ion exchange. The lower calcium content in the Dakota water has allowed calcium minerals containing fluoride to dissolve, producing a higher fluoride content. (See also the section on the hydrogeochemistry of fluoride in this report.) The greater nitrate concentration in the Ogallala, although well below the drinking water standard, is most probably from an agricultural source, such as the stockyard area.

Table 2. Dissolved Constituent Concentrations in Water Samples Collected from the Gray County Monitoring Wells on March 26, 1992 after Well Development.

Well and aquifer	Sp.C. (µS/cm)	TDS	Ca	Mg	Na	K	Sr	HCO_3	SO_4	Cl	F	NO_3-N
2-Ogallala	425	264	59.8	8.6	18.6	3.7	0.47	218	19.5	7.1	0.45	4.2
1-Dakota	450	283	39.8	8.3	47.4	3.8	0.59	205	53.9	8.0	1.06	1.0

Sp.C. and TDS refer to specific conductance in microsiemen/cm (µS/cm) and total dissolved solids (in mg/L), respectively. All other concentrations are in mg/L. The total dissolved solids was calculated from the sum of the constituents after converting bicarbonate (HCO_3) to evaporated carbonate and assuming silica (SiO_2) concentrations of 15 and 20 mg/L for wells 1 and 2, respectively, based on data for other Dakota and Ogallala well waters.

In the near future the owners of the stockyard plan to drill and construct at least one high-capacity production well in the upper Dakota. This will provide an opportunity to monitor changes in the flow system and the water chemistry in both aquifers during development. It is anticipated that KGS will be working closely with the GMD3 to gather the necessary hydrologic and geochemical data to document these changes through time. A second monitoring site has been discussed with the GMD3 for southern Haskell County but has not been scheduled.

Ground-Water Flow Simulation

Large-Scale Steady-State Modeling of the Regional Flow System in Southeastern Colorado and Western Kansas

The primary result of the FY92 work on the regional model was the development of an interface between the KGS geographic information system (GIS), ARC/INFO, and the ground-water flow model, MODFLOW, that will be used to simulate the regional flow system. All of the research effort was put into modifying an existing interface designed by the U.S. Geological Survey. Unfortunately, no work could be completed on assembly of the regional model because of the time required for putting the geologic and hydrologic databases into a format that could be accepted by the ARC/INFO-MODFLOW interface.

The advantage of linking the GIS to MODFLOW is the pre- and postprocessing capability that allows for easier input of data, evaluation of model results during calibration and simulation of hydrologic processes, and dissemination of model results to users. The linkage of ARC/INFO with the MODFLOW ground-water model is intended to facilitate movement of information in the Dakota Aquifer Program databases from the GIS to the model and subsequently to return the output in a form that allows for easy postprocessing. Output can result in tabular data sets or maps, either of which can be created quickly and distributed to users for evaluation of model runs. With the interface it is possible to automate many aspects of the modeling process, which will make the process of constructing model runs more efficient. This aspect becomes important, especially when modeling a system as large and complex as the Dakota aquifer. It also allows for interactive editing of parameters at the nodes in the model cells, either visually by plotting the grid on the screen or by modifying the relational database of INFO. The post-processing capability of the GIS also makes it convenient to create maps of the input and output. The interface itself does not transform or manipulate the data and is used only for the storage and movement of the data into and out of the GIS.

The U.S. Geological Survey interface was designed for a Prime computer system and was primarily based on the Prime Control Program Language, INFO, and Fortran programs. A considerable effort was invested in the conversion of the interface to the KGS Data General computer system. Four features of the U.S. Geological Survey interface make it attractive: (1) there is no need for changes to the ground-water model code; (2) the data structure is designed within the GIS to match MODFLOW; (3) the interface is flexible enough to allow for all the options available in MODFLOW; and (4) the interface is efficient in terms of computer time and space. The first feature proved to be the most difficult in the conversion process. In the converted version of the interface, changes in the way that the model opens data files passed on from the GIS through the interface were made in the MODFLOW code. As written, files for input and output were opened before entry into the MODFLOW program. However, the Data General operating system requires that the opening of files take place within the program itself. In the Data General version this does not cause any change in the model output. However, this may cause an inconvenience whenever the interface and the MODFLOW program are moved to another platform. Steps are now underway to make the interface query the user for file locations and then to make the necessary modifications based on the response(s) given by the user. The other three features have been retained in the Data General version of the interface. To test the performance of the interface, a simple hypothetical example including a small grid and sample data set was set up. The results indicate that the interface properly converts GIS input into data files that can be used by MODFLOW.

Five sequential operations occur in the interface program to translate the GIS input into a form that can be used by MODFLOW. The interface (1) queries INFO to determine which packages are in use and which parameters are required for the model run, (2) runs the INFO package output program using the control files containing the parameters and outputs system files for the model run, (3) executes MODFLOW, which opens and uses the system files that were output in the previous step, (4) executes a Fortran program that opens selected output files and reformats the records for input back into INFO, and (5) executes one of two programs that allows the user to produce GIS coverages of either heads and drawdowns or flow terms. Between steps 4 and 5 the user can view the output files to determine whether the results are reasonable. If the desired results are not obtained, the user can interactively correct the input controls or values and re-execute the interface and model. If, however, the results appear to be satisfactory, one or both of the final programs can be executed to produce GIS coverages (which can then be used to produce maps). A simplified flow chart of the processes and options of the interface appears in the section on Geographic Information Systems and data-base management activities for FY92. The interface allows input of data in several forms, including the GIS databases, and also the original file format that MODFLOW was initially designed to handle. Output can either consist of ARC/INFO databases in the form of coverages or the original MODFLOW output file in an ASCII format.

Ground-Water Flow Systems and Water-Resources Potential of the Dakota Aquifer in Parts of Republic, Cloud, Clay, and Washington Counties

The results of this research are described in detail in a recently completed report that is under review and is expected to be released for publication early in FY94 (Wade, 1993). Below is a summary of the research findings from this report.

The Dakota aquifer in Republic, Washington, and northern Cloud and Clay counties is approximately 40% sandstone and 60% mudstone and is composed mainly of the Dakota Formation. Test holes reveal that the sandstones are largely isolated from each other by mudstone with the exception of a sheetlike amalgamated fluvial channel sandstone at the base of the Dakota Formation, which is the most important conduit of lateral flow in the aquifer.

Field measurements of water levels, depths to water from driller's logs, ground-water quality, and surface features of ground-water discharge show that flow systems in the aquifer are both regional and local. The regional system is driven by the topographic slope of the Great Plains toward the east. This system brings halite-solution brine, originally derived from Permian strata, into the area from the west. The incised watersheds of Salt Creek in Republic County and Mill Creek in Washington County drain the regional flow system, creating local flow systems that are recharged in the outcrop area. The local systems have potentiometric surfaces that are subdued forms of the local relief.

Ground water in local flow systems is pumped for domestic, irrigation, stock, and municipal use. A steady-state flow model indicates that the recharge to local flow systems in southwestern Washington County is 0.25 in./yr (0.6 cm/yr). Simulations incorporating pumping suggest that water quality and availability have not been significantly affected by pumping in this area and that the aquifer probably could sustain an increase in pumping to double the current level without drawing in water of inferior quality. This is in agreement with limited long-term monitoring data. Mean drawdowns estimated for this pumping rate are between 3 ft and 6 ft (1–1.8 m).

Steady-State Modeling of Ground-Water Flow in Southeastern Colorado and Southwestern Kansas

The U.S. Geological Survey is developing a simulation of the flow system in a subarea of the regional Dakota aquifer system. The project involves modeling on a smaller scale in southeastern Colorado and southwestern Kansas, thereby allowing more detail in the area where the largest amount of water is currently withdrawn from the Dakota aquifer. The study includes development of a conceptual model of the aquifer and its relation to the overlying High Plains aquifer, underlying Permian units, and stream-aquifer interaction in the Arkansas River valley. From the conceptual model of the aquifer system, a three-dimensional finite-difference multilayer digital simulation is being formulated. The geologic and hydrologic information compiled for the subarea, including test-hole drilling and hydrologic testing during FY90–92 are being used in the construction of the model. The computer model is based on the program MODFLOW.

A model grid has been created that is a subdivision of the 6-mi node spacing grid being developed for the large-scale regional model. The grid spacing selected, 1.5 mi, will provide the detail for answering questions concerning well spacing and well interference for ground-water management of the Dakota aquifer. Smaller grid spacing was found to produce such a large number of nodes that computer processing would be too complex and time-consuming to be practical. Updated GIS coverages of the Dakota aquifer, adjacent formation tops and thicknesses, and predevelopment water levels were provided by the KGS so that input data for both the large-scale regional and smaller-scale subregional models would agree. Preliminary boundary conditions and hydraulic parameters have been assigned to the several aquifer and adjacent layers, based on the conceptual model of the aquifer system.

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

The Dakota aquifer is widely known as a dependable source of freshwater over much of the Great Plains of North America. In the Arkansas River valley of southeastern Colorado and adjacent parts of southwestern Kansas, the Dakota was probably one of the first sources of water used by the early settlers and railroads because of its flowing well conditions and its shallow depth.

Darton (1905, 1906) describes the results of the earliest regional reconnaissance investigations into the hydrogeology of the Dakota aquifer in southeastern Colorado and adjacent parts of western and central Kansas. Darton reported numerous flowing wells in the Arkansas River valley and its tributaries in southeastern Colorado and in parts of central Kansas. He demonstrated that water enters the Dakota where it crops out at the surface south of the river, flows northeastward, and eventually discharges in central Kansas, where again the aquifer crops out at the surface (Figure 15). Using Chamberlin's (1885) concept of artesian aquifers, Darton believed that ground-water flow was controlled mostly by the head difference between recharge

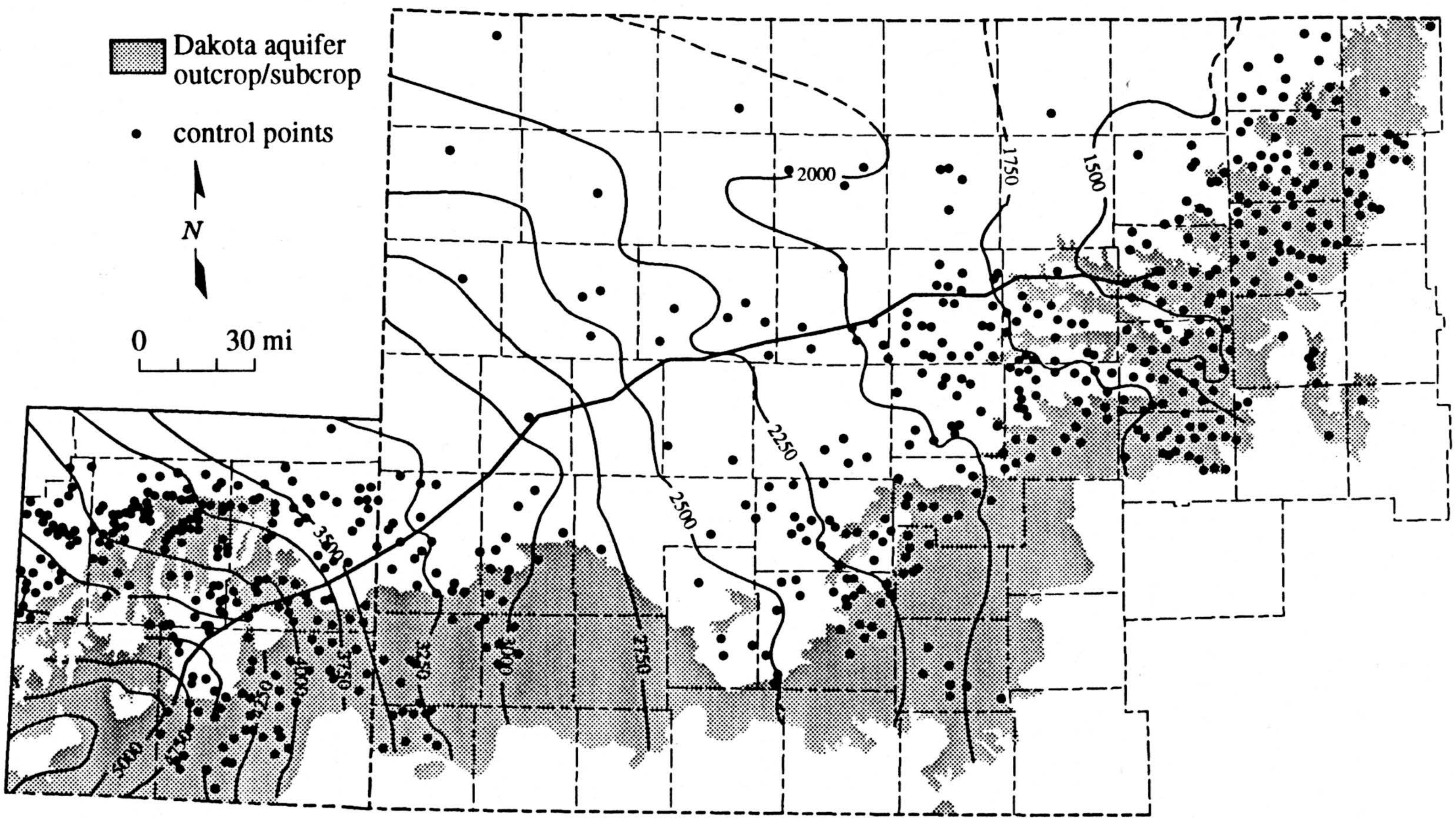


Figure 15. Elevation in feet above mean sea level of the predevelopment potentiometric surface of the Dakota aquifer in southeastern Colorado and western Kansas.

and discharge areas. Darton reasoned that the flowing wells in the Arkansas River valley and elsewhere in central Kansas could be accounted for only by (1) the elevated recharge areas south of the river and (2) the maintenance of artesian pressure in the Dakota from recharge to discharge areas by overlying Upper Cretaceous shales, referred to here as the Upper Cretaceous aquitard. Thus Darton described the Dakota as a classic example of an artesian aquifer.

More recent detailed hydrogeologic investigations have not supported Darton's conceptualization of flow in the Dakota. In a review of the literature, Helgeson et al. (1982) questioned the applicability of Chamberlin's (1885) concept to the Dakota on the basis of aquifer geometry and lateral hydraulic continuity. Others have found from regional flow models that factors other than the head difference between the recharge and discharge areas may influence ground-water flow in the Dakota and underlying aquifers. An aquifer is usually considered to be in good hydraulic communication with the overlying water table if there are only small head differences between them. In the Denver basin the Dakota is overlain by the Upper Cretaceous aquitard, which is as much as 10,000 ft (3,050 m) thick. In the basin and adjacent areas of eastern Colorado and western and central Kansas, Belitz (1985), Belitz and Bredehoeft (1988), and Helgeson et al. (1993) reported that heads in the Dakota and the deeper aquifers are in some cases more than 2,500 ft (760 m) lower than the head on the overlying water table. From regional flow models, they concluded that thick aquitards consisting of Upper Cretaceous shale and chalk severely restrict recharge to deeper parts of the flow system. Because of this, it appears that the head in the Dakota and the deeper aquifers is more responsive to the elevation of discharge areas to the east than to the head of the overlying water table in the basin.

In southeastern Colorado and in most of western Kansas the Dakota is within 1,000 ft (300 m) of land surface and the head difference between the water table and the Dakota is less than 500 ft (150 m) (Helgeson et al., 1993). Thus heads in the Dakota are subhydrostatic because they are significantly less than that of the overlying water table in both the Denver basin and adjacent western Kansas. Heads in the deeper aquifers below the Pennsylvanian are more than 2,000–3,000 ft (600–900 m) lower than heads in the Dakota aquifer (Belitz and Bredehoeft, 1988; Jorgensen et al., 1993). This suggests (1) that thick aquitards below the Dakota continue to restrict recharge to these deeper aquifers eastward of the Denver basin and (2) that the Dakota aquifer hydrogeology changes significantly between the basin and this part of the central Great Plains because of the thinning of the Upper Cretaceous aquitard.

Revised Conceptualization of the Flow System

In this research, it is hypothesized that in this part of the central Great Plains steady-state ground-water flow in the upper part of the regional system, including the Dakota aquifer, is influenced primarily by (1) the Upper Cretaceous aquitard, (2) the Arkansas River, and (3) the proximity of the confined Dakota to discharge areas in central Kansas. The Dakota is an important component of the regional flow system because it is hydraulically connected to all the major overlying and underlying aquifer systems and with the overlying water table where it crops out at the surface in southeastern Colorado and central Kansas. The Upper Cretaceous aquitard continues to restrict recharge to the Dakota and underlying aquifers in western Kansas because of its thickness and low permeability. In southeastern Colorado the Arkansas River valley is located downgradient of the primary Dakota aquifer recharge area and removes some of the underflow that otherwise would move into western Kansas. The loss of underflow diminishes recharge to downgradient portions of the flow system in western Kansas and contributes to subhydrostatic heads in the Dakota and other shallow aquifers below the Upper Cretaceous aquitard. The Saline and Smoky Hill rivers have eroded through the Upper Cretaceous aquitard westward of the main outcrop belt of the Dakota aquifer in central Kansas. This has effectively moved the discharge area closer to the confined Dakota aquifer in western Kansas and thus contributes to the observed subhydrostatic conditions (Belitz, 1985; Belitz and Bredehoeft, 1988).

The control exerted by the Upper Cretaceous aquitard on flow systems in the Dakota and underlying shallow aquifers is much less than in the Denver basin due to its reduced thickness. Within the last 10 million years differential uplift and intense local dissection of the High Plains surface by erosion have created considerable local and regional topographic relief (Gable and Hatton, 1983; Trimble, 1980; Osterkamp et al., 1987). Many of the rivers that cross the central Great Plains, such as the Arkansas, the Saline, and the Smoky Hill, have cut down through the aquitard and into the Dakota aquifer. High local relief favors the subdivision of the regional flow system into smaller subsystems, especially near river valleys (Toth, 1962, 1963; Freeze and Witherspoon, 1967). Consequently, the head difference between the Dakota aquifer and the overlying water table is reduced because of the proximity of the aquifer to the near-surface hydrologic environment. Helgeson et al. (1993) and Leonard et al. (1983) recognized a separate stronger flow component in the Dakota aquifer in this region that is not present in the Denver basin and emphasized the importance of cross-formational flow.

Regional investigations into the hydrogeology of the Dakota aquifer since Darton's time have shown that the head difference between regional recharge and discharge areas does not explain most of the observed head distribution in the aquifer. Darton (1906) believed that the only significant source of recharge was infiltrated precipitation entering the Dakota directly in southeastern Colorado. He did not recognize that the Upper Cretaceous aquitard could induce head losses in the underlying Dakota by restricting recharge. Neither Darton's work nor the later modeling studies reported by Belitz (1985), Belitz and Bredehoeft (1988), and Helgeson et al. (1993) address the influence of the Arkansas River and the Smoky Hill and Saline rivers on the flow system in the Dakota aquifer in western Kansas.

Approach

Two of the primary uses of computer simulation in hydrogeology are (1) to evaluate conceptualizations of ground-water flow system dynamics and (2) make inferences on system dynamics based on these conceptualizations. Anderson and Woessner (1992) refer to these uses collectively as the interpretive application of computer simulation. Simulation in this research is used only in the interpretive sense to assess the relative importance of the Upper Cretaceous aquitard and the Saline and Arkansas rivers to the flow system in the Dakota aquifer. To achieve this, we focus our discussion on a vertical profile model of ground-water flow in the upper part of the regional flow system in southeastern Colorado and western and central Kansas. The vertical profile extends from the Baca–Las Animas county line in southeastern Colorado to western Lincoln County in central Kansas and is parallel to the flow directions in all the major aquifers in the upper part of the regional flow system.

A significant drawback to the formulation of a fully calibrated model of the flow system in this research is that most of the available hydrologic properties and head data come from the upper part of the Dakota and other shallow aquifers and from much deeper hydrocarbon reservoirs in Permian and Pennsylvanian rocks. Because of this, the nature of the flow system below the Dakota and above these hydrocarbon reservoirs can only be surmised, and hence there is less information by which to calibrate the model. Fortunately, a fully calibrated model is not required when the purpose of the simulation is interpretive (Anderson and Woessner, 1992).

Accordingly, the objectives here are (1) to characterize the regional hydrogeology of the upper part of the regional flow system in southeastern Colorado and western and central Kansas, (2) to describe the construction of a vertical profile model of the upper part of the flow system, (3) to discuss the flow patterns in the partially calibrated steady-state model and the water budget, and (4) to present the results of sensitivity analyses that show the effect of the hydrostratigraphy and the river valleys on the flow system.

Regional Setting

The vertical profile that is the subject of this report extends from the Baca–Las Animas county line in southeastern Colorado to western Lincoln County in central Kansas (Figure 16). The vertical profile is parallel to a flow line in the Dakota aquifer. It traverses portions of Baca and Prowers counties in Colorado and Hamilton, Kearny, Wichita, Scott, Gove, Trego, Ellis, Russell, and Lincoln counties in Kansas.

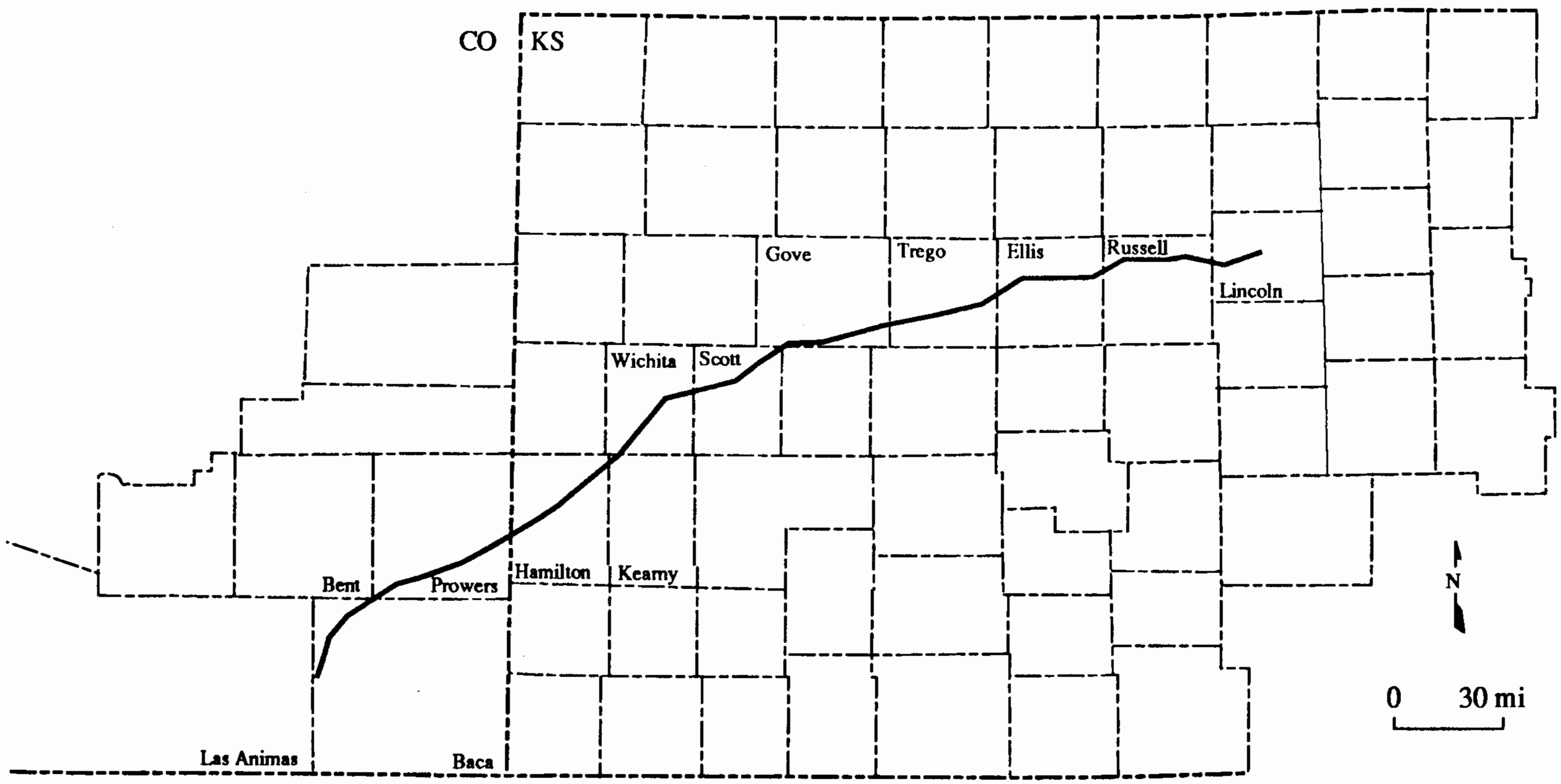


Figure 16. Location of the vertical profile in southeastern Colorado and western and central Kansas.

Physiography

Southeastern Colorado and southwestern and central Kansas are located in the Raton Section, Colorado Piedmont, High Plains, and Plains Border sections of the Great Plains physiographic province (Fenneman, 1946). The land surface slopes to the east and decreases in elevation from slightly more than 5,000 ft (1,500 m) near the Baca–Las Animas County line, Colorado, to slightly more than 1,400 ft (430 m) in western Lincoln County, Kansas (Figure 17). The regional land-surface slope ranges from 26.7 ft/mi (5.06 m/km) in southeastern Colorado to 10.6 ft/mi (2.01 m/km) in western Kansas to 6.7 ft/mi (1.3 m/km) in central Kansas in the vertical profile. The vertical profile traverses the Arkansas, Smoky Hill, and Saline River drainage basins (Figure 18). The valleys cut by these river systems into unconsolidated Cenozoic deposits and Cretaceous bedrock locally increase the topographic relief significantly. In the Arkansas River valley in southeastern Colorado and southwestern Kansas and in the Saline River valley in central Kansas the local relief commonly exceeds 200 ft/mi (37.9 m/km).

Climate

The climate of the region is warm, continental semiarid in all except the eastern portions of the study area in central Kansas, where the climate is subhumid continental (Dugan and Peckanpaugh, 1985). The mean annual temperature is approximately 54°F across the study area. Mean annual rainfall for the period 1951–1980 ranges from 15 in. (38 cm) in southeastern Colorado to 28.5 in. (72.4 cm) in central Kansas. Approximately 75% of the precipitation falls mainly during the warm season months of the year. Because of the low relative humidity, high average wind velocities, and abundant sunshine, the potential evaporation exceeds the average annual precipitation over most of the region. Dugan and Peckanpaugh (1985) calculated that the potential mean annual recharge to ground water from precipitation ranges from less than 0.1 in. (0.2 cm) in southeastern Colorado to 1–2 in. (5 cm) in central Kansas.

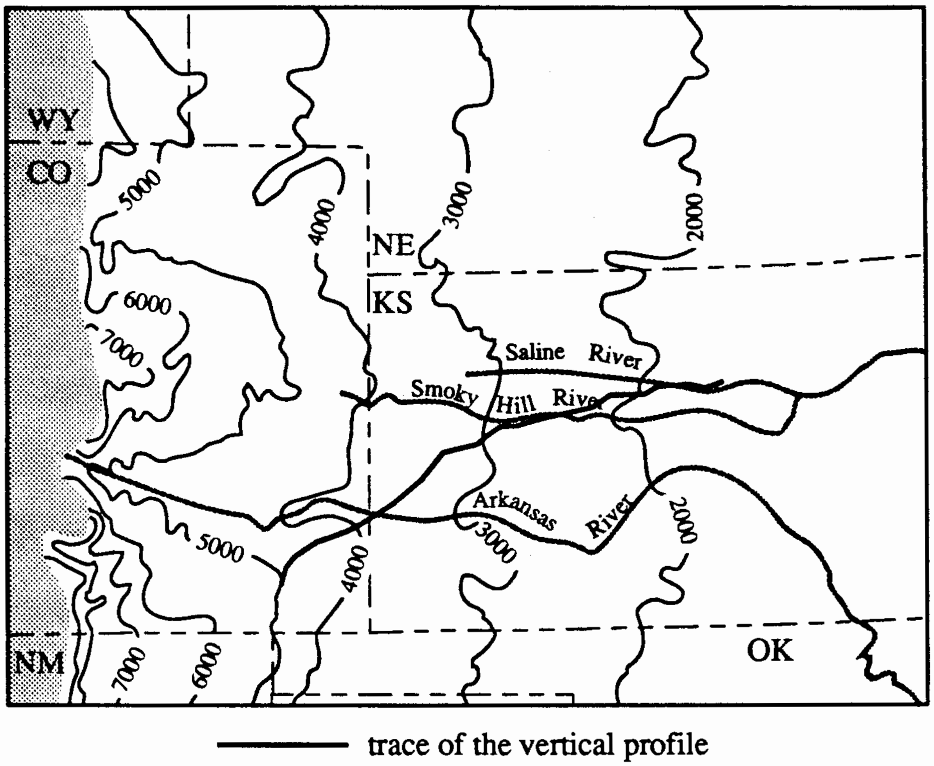


Figure 17. Generalized land-surface topography and the major streams traversed by the vertical profile in eastern Colorado and western and central Kansas and adjacent areas.

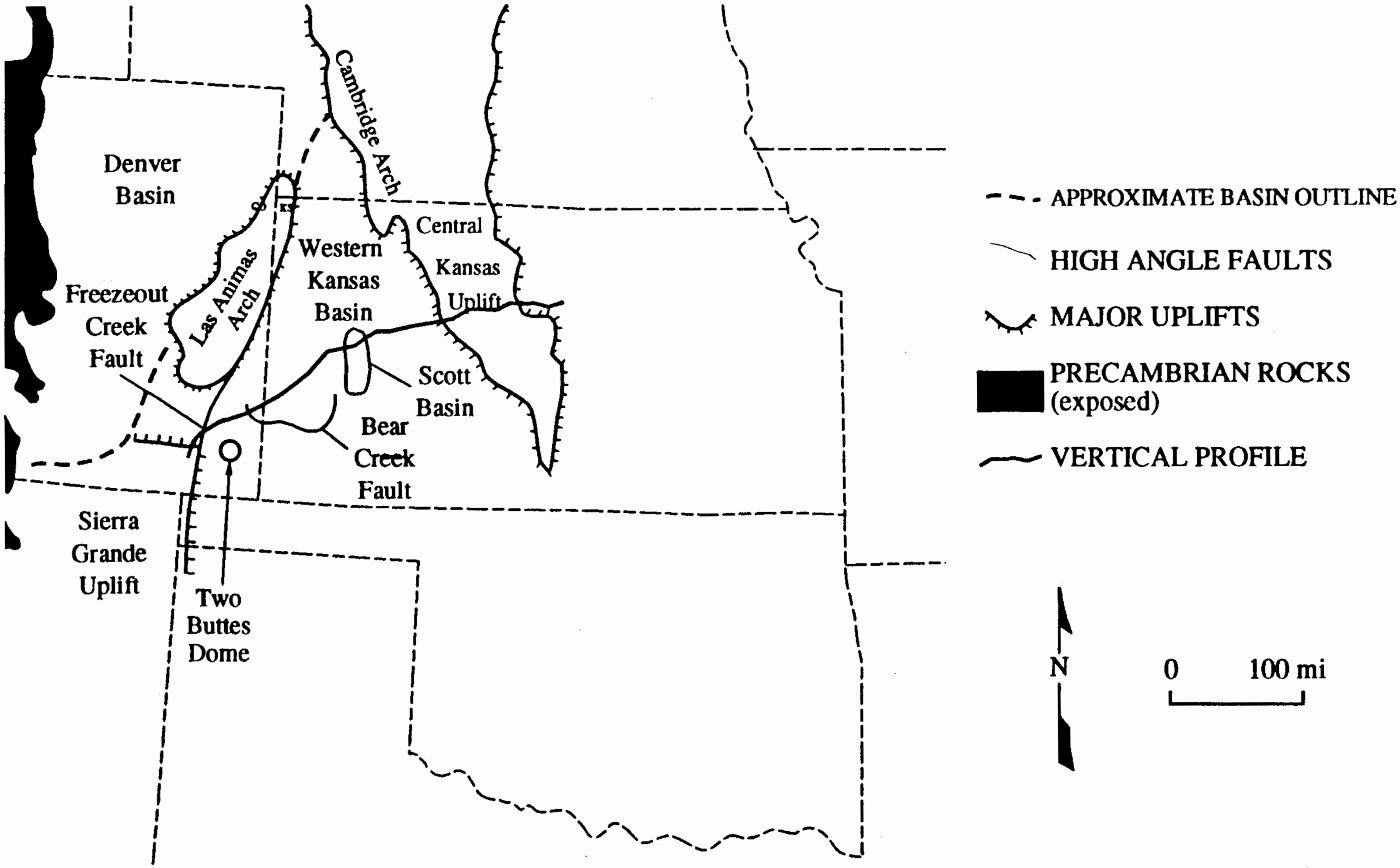


Figure 18. Major structural features of eastern Colorado and western and central Kansas and adjacent areas reflected in Precambrian and younger rocks.

Geologic Structure

An understanding of the geologic structure is useful for delineating zones where tectonic activity or local subsidence from salt dissolution may have created vertical pathways for fluid transmission between aquifer units (Zeller et al., 1976; Bredehoeft et al., 1983; Kolm and Peter, 1984). In Kansas and in much of the Great Plains region, movement along these structures in response to changing stress fields has been episodic since the Precambrian Era (Merriam, 1963; Berendsen and Blair, 1986). Figure 18 shows the location of geologic structures referred to in this report.

Regional Hydrostratigraphy

The regional stratigraphy and hydrostratigraphy are summarized in Table 3, and the regional hydrostratigraphy is portrayed in Figure 19. The methodology used to define regional hydrostratigraphic units is discussed in detail by Macfarlane et al. (1992). The hydrostratigraphy consists of six major aquifers and three aquitards. The most important of these units to this research are the upper Dakota aquifer and the overlying Upper Cretaceous aquitard for two reasons. First, previous investigations have established the preeminence of the Upper Cretaceous aquitard as a major factor that exerts control on the flow system in the central Great Plains (Helgeson et al., 1993; Belitz, 1985; Beltiz and Bredehoeft, 1988; Leonard et al., 1983; Helgeson et al., 1982). Hence much of the attention is focused on the influence of the aquitard on the underlying flow system. Second, the upper Dakota aquifer is hydraulically continuous across the vertical profile and is more transmissive than the other shallow aquifers below the Upper Cretaceous aquitard. This suggests that the upper Dakota aquifer acts as a drain beneath the aquitard and transmits most of the water moving through the upper part of the flow system from southeastern Colorado to central Kansas.

Table 3. Stratigraphy and hydrostratigraphy of the shallow subsurface in southeastern Colorado and western and central Kansas.

ERA	SYSTEM	SERIES	E. LAS ANIMAS & W. BACA CO., COLORADO	CENTRAL & EASTERN BACA CO. COLORADO	W.-CENTRAL & SOUTHWESTERN KANSAS	CENTRAL KANSAS	HYDRO-STRATIGRAPHY
CENOZOIC	QUATERNARY	PLEISTOCENE	Dune Sand and Loess	Dune Sand, Loess, and Alluvium	Dune Sand, Loess, and Alluvium	Dune Sand, Loess, and Alluvium	High Plains and Alluvial Valley Aquifers
CENOZOIC	TERTIARY	MIOCENE-PLIOCENE	Ogallala Fm.	Ogallala Fm.	Ogallala Fm.	Ogallala Fm.	High Plains and Alluvial Valley Aquifers
MESOZOIC	CRETACEOUS	UPPER	Colorado Group	Colorado Group	Colorado Group	Colorado Group	Upper Cretaceous Aquitard
MESOZOIC	CRETACEOUS	LOWER	Dakota Ss.	Dakota Ss.	Dakota Formation	Dakota Formation	Upper (Dakota Aquifer)
MESOZOIC	CRETACEOUS	LOWER	Purgatoire Fm.: Kiowa Sh. Mbr.	Purgatoire Fm.: Kiowa Sh. Mbr.	Kiowa Fm.: Longford Mbr.	Kiowa Fm.: Longford Mbr.	Kiowa Shale Aquitard (Dakota Aquifer)
MESOZOIC	CRETACEOUS	LOWER	Purgatoire Fm.: Cheyenne Ss. Mbr.	Purgatoire Fm.: Cheyenne Ss. Mbr.	Cheyenne Ss.	Cheyenne Ss.	Lower (Dakota Aquifer)
MESOZOIC	JURASSIC	UPPER	Morrison Fm.	Morrison Fm.	Morrison Fm.		Morrison-Dockum Aquifer
MESOZOIC	TRIASSIC	UPPER	Dockum Group	Dockum Group			Morrison-Dockum Aquifer
PALEOZOIC	PERMIAN	UPPER	Lykins Fm	Upper Permian Series	Upper Permian Series	Upper Permian Series	(Permian-Pennsylvanian Aquitard)
PALEOZOIC	PERMIAN	LOWER	Lykins Fm	Dog Creek Sh.; Blaine Fm. Flower-pot Sh. (Nippewalla Gp.)	Dog Creek Sh.; Blaine Fm. Flower-pot Sh.; Cedar Hills Ss. (Nippewalla Gp.)	Blaine Fm. Flower-pot Sh. (Nippewalla Gp.)	Upper Evaporite Aquitard (Permian-Pennsylvanian Aquitard)
PALEOZOIC	PERMIAN	LOWER	Lyons Ss.	Cedar Hills Ss. Salt Plain Fm. Harper Ss. (Nippewalla Gp.)	Salt Plain Fm. Harper Ss. (Nippewalla Gp.)	Cedar Hills Ss. Salt Plain Fm. Harper Ss. (Nippewalla Gp.)	Permian Ss. Aquifer (Permian-Pennsylvanian Aquitard)
PALEOZOIC	PERMIAN	LOWER	Fountain Fm.	Sumner Gp.	Stone Corral Fm Ninnescah Sh.; Wellington Fm.: Hutchinson Salt Mbr. (Sumner Gp.)	Stone Corral Fm Ninnescah Sh.; Wellington Fm.: Hutchinson Salt Mbr. (Sumner Gp.)	Lower Evaporite Aquitard (Permian-Pennsylvanian Aquitard)
PALEOZOIC	PERMIAN	LOWER	Fountain Fm.	Chase Gp. Council Grove Gp. Admire Gp.	Chase Gp. Council Grove Gp. Admire Gp.	Chase Gp. Council Grove Gp. Admire Gp.	(Permian-Pennsylvanian Aquitard)
PALEOZOIC	PENNSYL-VANIAN		Fountain Fm. (cont.)	Wabaunsee Gp. Shawnee Gp. Douglas Gp. Lansing Gp. Pleasanton Gp. Marmaton Gp. Cherokee Gp. Undiff. Atokan Strata Kearny Fm	Not Present in the Shallow Subsurface	Not Present in the Shallow Subsurface	(Permian-Pennsylvanian Aquitard)
PALEOZOIC	MISSISSIPPIAN & CAMBRO-ORDOVICIAN		Undifferentiated Mississippian, Viola, & Arbuckle Gp.	Not Present in the Shallow Subsurface	Not Present in the Shallow Subsurface	Not Present in the Shallow Subsurface	Deep Carbonate Aquifer
PRECAMBRIAN	PRECAMBRIAN		Las Animas Fm. & Granitic Rocks	Not Present in the Shallow Subsurface	Not Present in the Shallow Subsurface	Not Present in the Shallow Subsurface	Precambrian Basement

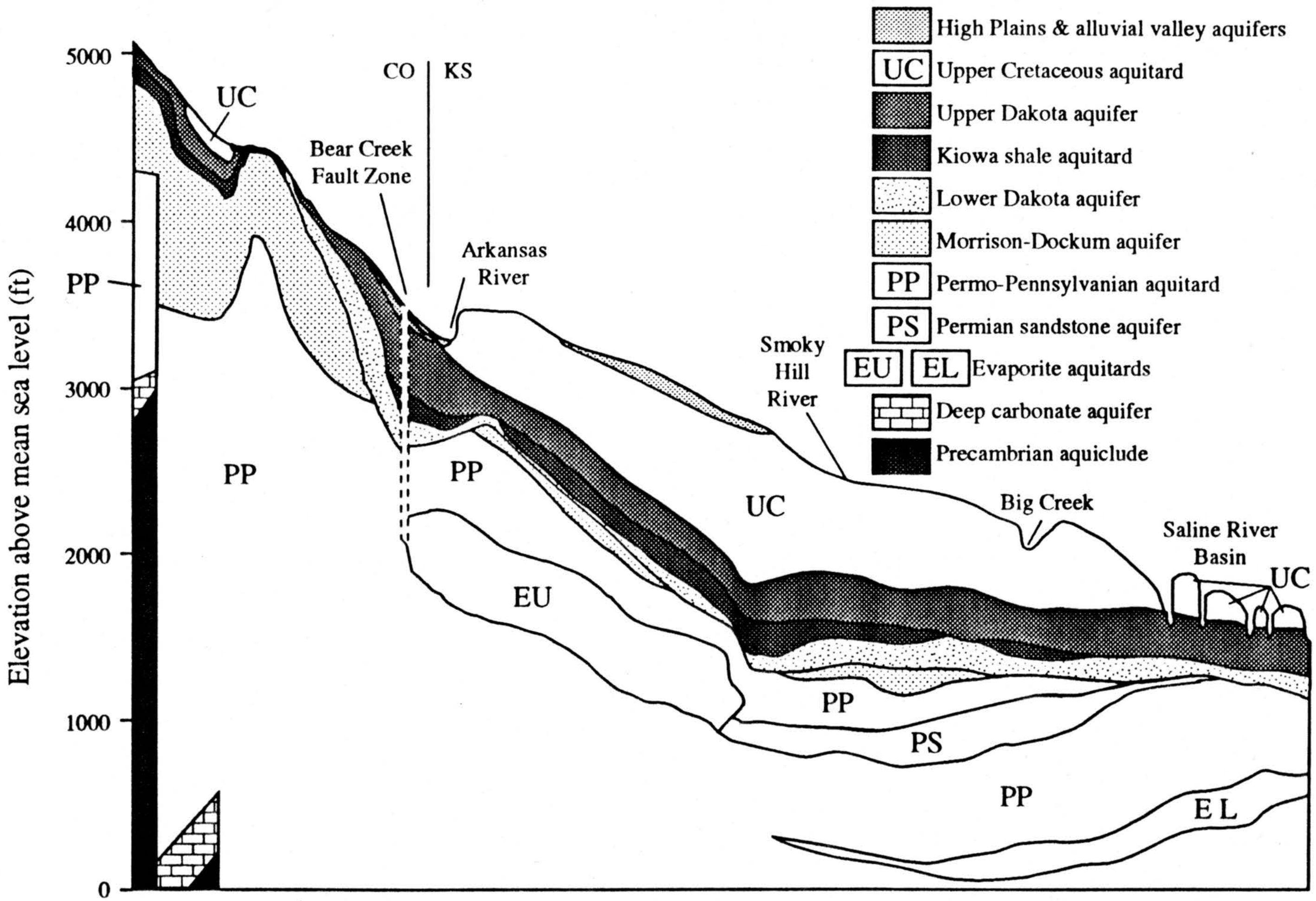


Figure 19. Hydrostratigraphy of the shallow subsurface above sea level in the vertical profile.

Upper Cretaceous Aquitard

The Upper Cretaceous aquitard consists of a thick sequence of rhythmically bedded chalky shale, massive limestone and chalky limestone, dark-gray noncalcareous to calcareous shale and siltstone, and thin seams of bentonite (Hattin, 1962, 1965, 1975, 1982; Hattin and Siemers, 1987). Included in this part of the section are strata from the Niobrara Chalk, the Carlile Shale, the Greenhorn Limestone, and the Graneros Shale (Table 3).

Upper Dakota Aquifer

The upper Dakota aquifer consists of mudstones and lenticular very fine to coarse-grained and conglomeratic sandstones belonging to the Dakota Formation in Kansas and its stratigraphic equivalent in southeastern Colorado, the Dakota Sandstone (McLaughlin, 1954; Franks, 1966, 1975; Macfarlane et al., 1990; Macfarlane et al., 1991; Table 3). Sandstone composes 30–40% of the aquifer framework regionally (Keene and Bayne, 1977), but locally the percentage of sandstone can range widely: from less than 10% to almost 100% (Macfarlane et al., 1992). The thickness of the upper Dakota aquifer ranges up to more than 350 ft (107 m) in parts of west-central Kansas and to more than 200 ft (61 m) in Baca County, Colorado.

Sediments belonging to the Dakota Formation and the Dakota Sandstone were deposited in fluvial, coastal plain, deltaic, and shallow marine environments in association with the developing Western Interior Sea (Weimer, 1984). Fluvial channel sandstones were deposited in incised valleys and in coastal plain settings in stacked fining-upward sequences up to 100 ft in thickness (Hamilton, 1989; Macfarlane et al., 1991). Finer-grained deltaic and shallow marine sandstones are present in the upper part of the Dakota Formation and are generally much less than 100 ft (30 m) in thickness in central Kansas. However, deltaic deposits make up most of the thickness of the Dakota Formation in western Kansas and southeastern Colorado.

Steady-State Regional Ground-Water Flow in the Major Aquifers

To gain insight into the functioning of the regional flow system, one must know the head distribution in the major aquifer systems because they are the main paths of transmission of ground water through the system (Freeze and Witherspoon, 1967). The major aquifer systems in the shallow subsurface of southeastern Colorado and western Kansas are the High Plains and alluvial valley aquifers, the Dakota aquifer, the Morrison-Dockum aquifer, and the Permian sandstone aquifer. The deep carbonate aquifer is not included in this discussion because it is present only in the shallow subsurface of southeastern Colorado. For this discussion only the flow system in the upper Dakota aquifer is discussed in detail because, outside southeastern Colorado and extreme southwestern Kansas, the hydraulic head data are inadequate to fully portray the flow system in the lower Dakota aquifer. However, the flow patterns in the lower Dakota are believed to be similar to those in the upper Dakota in most of Kansas.

Determination of Ground-Water Flow Directions

The hydraulic head at a point in an aquifer is a measure of the potential energy per unit weight of ground water at that point and is the algebraic sum of two components, the pressure head and the elevation head (Freeze and Cherry, 1979). In an ideal piezometer, which is in hydraulic connection with the surrounding aquifer only at its base, the hydraulic head is equivalent to the elevation of the water level with respect to a datum. The direction of ground-water flow is determined from the hydraulic head gradient and is downgradient in isotropic porous media.

Potentiometric-surface and water table maps indicate the lateral variation in head and thus are used to determine the lateral directions of ground-water flow. Predevelopment regional water table and potentiometric-surface maps of the major aquifers in southeastern Colorado and Kansas were derived using existing maps of these surfaces. The maps were joined together and carefully edited to make the water-table-surface and potentiometric-surface contours continuous across the Kansas-Colorado border.

Measurements of fluid pressure or the hydraulic head taken at vertically adjacent points below the water table indicate the direction of vertical flow. Where available, fluid pressure *vs.* depth profiles provide the best indication of the tendency for vertical flow in ground-water systems because they are derived from measurements made at vertically adjacent points. The fluid pressures can be calculated from the difference in elevation between the water level and the midpoint of the screened interval in the piezometer multiplied by 0.433 psi/ft, a factor that assumes a freshwater fluid density of 62.4 lb/ft^3. Under conditions of no vertical flow and in a homogeneous and isotropic unconfined aquifer, the fluid pressure versus depth profile approximates a straight line with a slope of 2.309 ft/psi in a freshwater aquifer (Toth, 1979). If the fluid pressure versus depth profile has a slope greater than 2.309 ft/psi, downward flow is indicated; conversely, if the slope is less than 2.309 ft/psi, upward flow is indicated (Figure 20). In a confined aquifer the fluid pressure versus depth profile may be segmented because of the confining layer.

Other indirect methods were also applied to determine the overall direction of vertical flow in the Dakota aquifer. A plot of the fluid pressure versus the depth to the midpoint of the screened interval can be constructed using a large number of well measurements (Fogg et al., 1983). The slope value of the best-fitting line through the data can be computed by linear regression. If the slope is greater than 2.309 psi/ft, the slope of the hydrostatic line, the head increases with depth and the tendency for flow is upward, which is characteristic of superhydrostatic conditions and discharge zones (Toth, 1972, 1979). Likewise, if the slope of the best-fitting line is less than the slope of the hydrostatic line, the head decreases with depth and the tendency for flow is downward, which is characteristic of subhydrostatic conditions and recharge zones (Toth, 1972, 1979). If the slope of the best-fitting line is not significantly different from the slope of the hydrostatic line, there is no overall tendency for vertical flow.

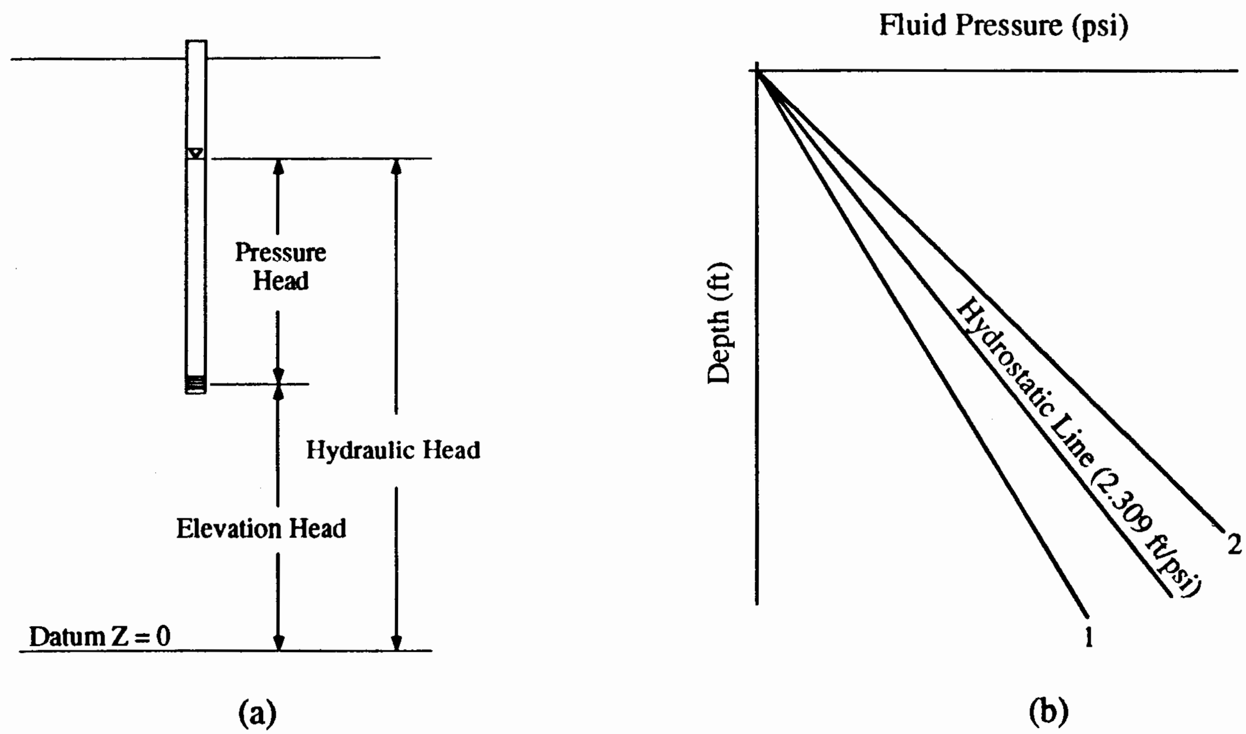


Figure 20. Components of hydraulic head and determination of ground-water flow directions. (a) Components of hydraulic head in a piezometer open only at the botttom for a short distance. (b) Determination of vertical flow from measurements of fluid pressure taken at vertically adjacent points in the flow system, assuming a homogeneous aquifer. Profile 1 indicates downward flow because its slope is greater than the slope of the hydrostatic line (2.309 ft/psi) and profile 2 indicates upward flow because its slope is less than the slope of the hydrostatic line.

Results and Interpretation

The High Plains aquifer is the shallow water table aquifer in southeastern Colorado and in most of western Kansas. This aquifer overlies the Dakota aquifer and the Upper Cretaceous aquitard in southeastern Colorado and the Upper Cretaceous aquitard in west-central Kansas (see Figure 19). Ground water in the High Plains aquifer moves from west to east across the study area, from the elevated parts of the region in southeastern Colorado and western Kansas to topographically lower areas, primarily in the river valleys near the aquifer's eastern extent (Figure 21). The aquifer is recharged primarily by infiltration of precipitation below the root zone in southeastern Colorado and western Kansas (Stullken et al., 1985). Other sources of recharge include the Dakota aquifer in southwestern Kansas and southeastern Colorado (Helgeson et al., 1993) and infiltration of streamflow (Stullken et al., 1985). Ground water is discharged from the aquifer to springs, seeps, and streams in western and central Kansas.

The Dakota aquifer is the most geographically extensive of all the bedrock aquifers in western Kansas and southeastern Colorado. In parts of southwestern Kansas and southeastern Colorado the Dakota is hydraulically connected to the High Plains, alluvial valley, and Morrison-Dockum aquifers (Robson and Banta, 1987; Kume and Spinazola, 1985). In central Kansas the Dakota aquifer is hydraulically connected to the Permian sandstone aquifer and alluvial valley aquifers (Macfarlane et al., 1988) (Figure 19). The Dakota aquifer is confined by the Upper Cretaceous aquitard in most of western Kansas and southeastern Colorado and is the near-surface aquifer in western Baca and eastern Las Animas counties in Colorado.

Two distinct ground-water flow corridors can be distinguished from the Dakota predevelopment potentiometric surface map (see Figure 15). The northern flow corridor begins in eastern Las Animas County and extends northeastward across the Arkansas River into west-central and northwestern Kansas and turns eastward into central Kansas. The southern flow corridor begins in eastern Las Animas County and extends eastward into southwestern Kansas and then turns northeastward toward central Kansas. The potentiometric-surface map suggests that the primary recharge area for the Dakota aquifer in Kansas is southeastern Las Animas and

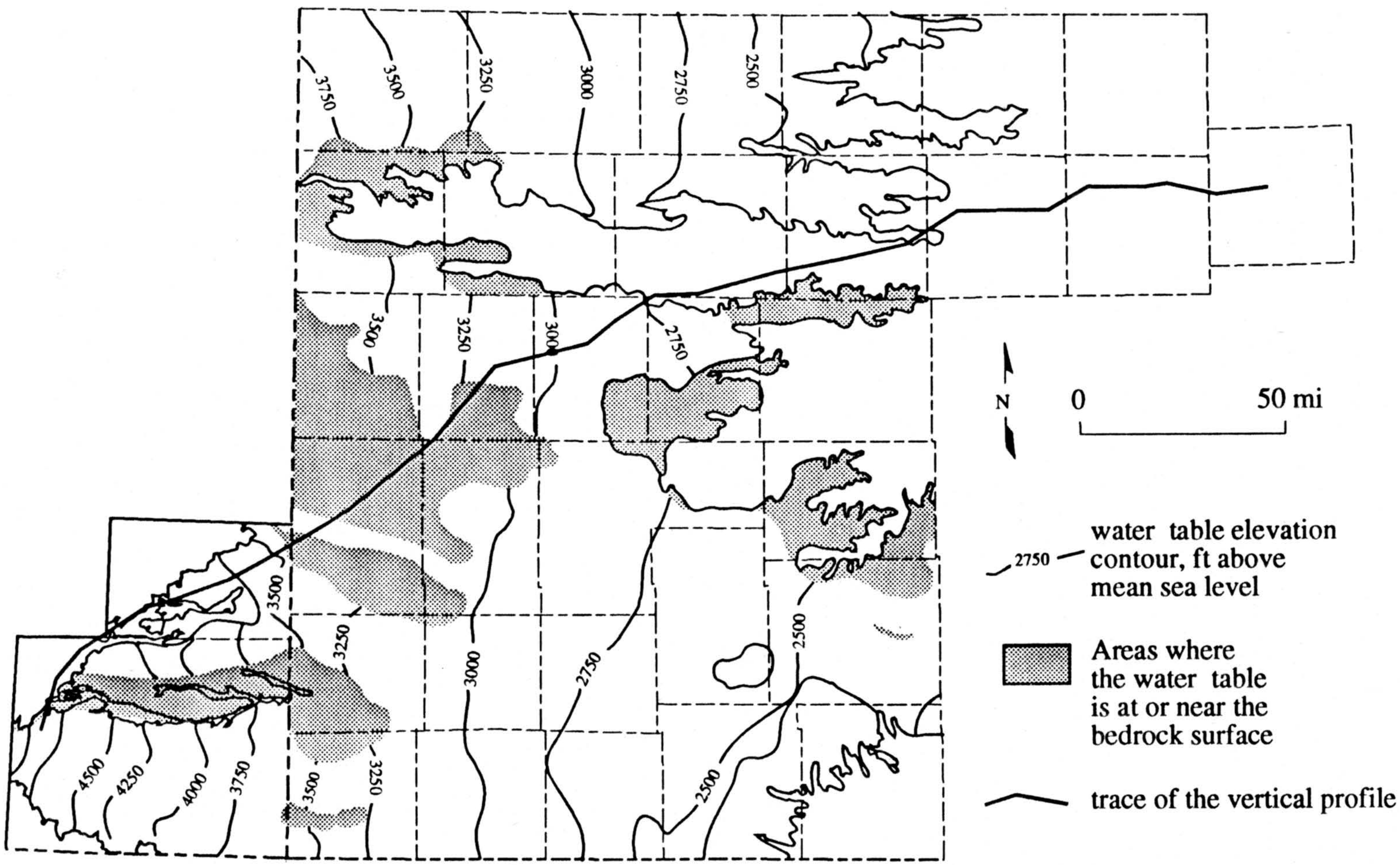


Figure 21. Elevation of the water table in the High Plains aquifer in southeastern Colorado and western Kansas.

western Baca counties in Colorado on the Sierra Grande uplift. In this area the Dakota aquifer is at the surface and is recharged directly by infiltrating precipitation. The primary ground-water discharge area appears to be central Kansas where the Smoky Hill, Saline, and Solomon rivers cross the outcrop of the Dakota aquifer. The 1,500-ft (460-m) head contour suggests that ground-water flow is focused in this part of the outcrop zone (see Figure 15). In this area salt springs, seeps, and marshes are a common occurrence (Macfarlane et al., 1990). The vertical profile is parallel to one of the flow paths in the northern flow corridor. The slope of the potentiometric surface in the vertical profile ranges from 24.8 ft/mi (4.70 m/km) in southeastern Colorado to 10 ft/mi (1.9 m/km) in southwestern Kansas to 6.8 ft/mi (1.3 m/km) in central Kansas and reflects the eastward decrease in regional topographic slope.

In Figure 22 the overall high degree of correlation ($r = 0.993$) between hydraulic head in the Dakota aquifer and land-surface elevation suggests that regional topography is a primary control on regional ground-water flow. However, near the 3,250-ft (991-m) land-surface elevation, some of the data points significantly depart from the best-fitting line; this area coincides with areas of western Kansas where the Upper Cretaceous aquitard is thickest. This suggests that the effect of topography on regional flow is diminished in favor of the effect of confining layers above the Dakota aquifer.

The lateral flow component in the Dakota aquifer and the tendency for downward flow from the surface to the Dakota are shown by nearly all the fluid pressure versus depth profiles and the well depth versus fluid pressure plots. Most of the fluid pressure versus depth profiles come from sites located just upgradient from the Dakota aquifer discharge area in central Kansas. In all but two profiles, the slope of the profile in the Upper Cretaceous aquitard–Dakota aquifer interval approximates the hydrostatic rate of increase of fluid pressure but is shifted downward below the hydrostatic line (Figure 23). This indicates a tendency for downward flow across the aquitard. The fluid pressure versus depth profile from NWNWNW sec. 6, T. 14 S., R. 13 W., indicates downward flow across both the Upper Cretaceous aquitard and the upper Dakota to lower zones (Figure 23a, profile 1). The other profile is from the Haberer salt marsh in

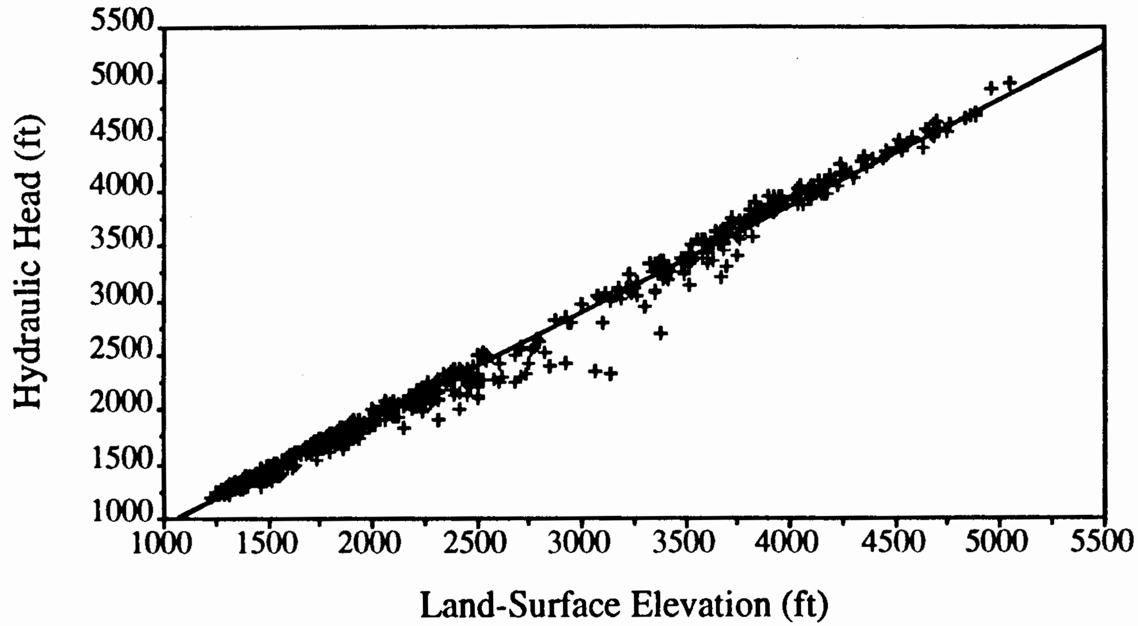


Figure 22. Land-surface elevation versus hydraulic head in the Dakota aquifer in southeastern Colorado and western and central Kansas.

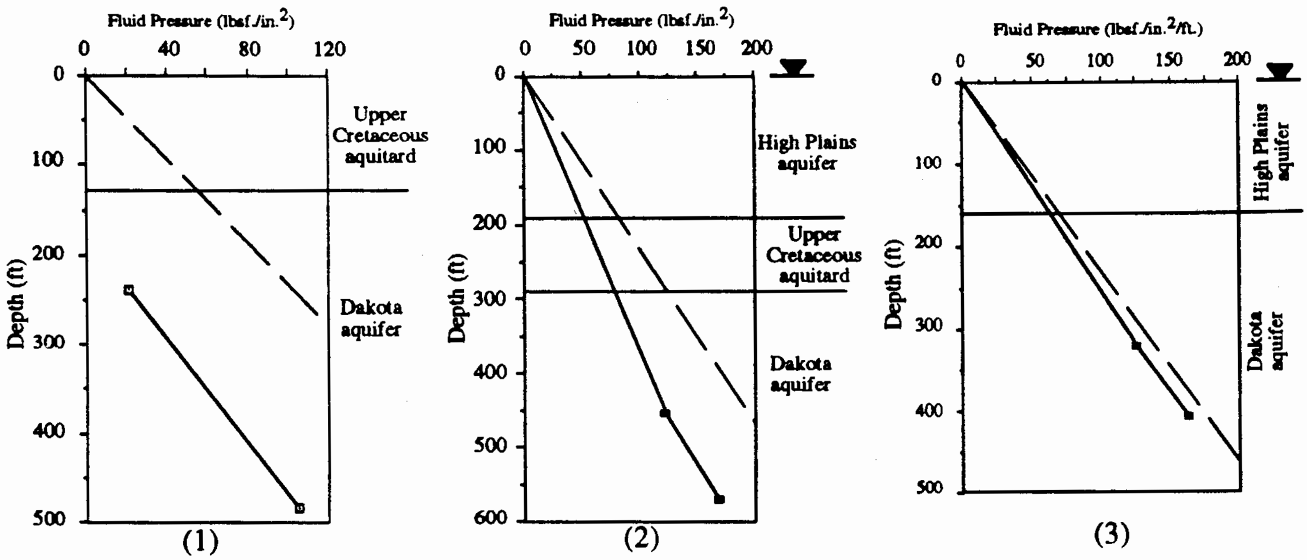


Figure 23a. Fluid pressure-depth profiles from field measurements collected at (1) NWNWNW sec. 6, T. 14 S., R. 13 W., (2) SENENW sec. 29, T. 28 S., R. 26 W., and (3) NESWSWNW sec. 30, T. 28 W., R. 22 W. The dashed line represents the hydrostatic line, 2.309 ft/psi.

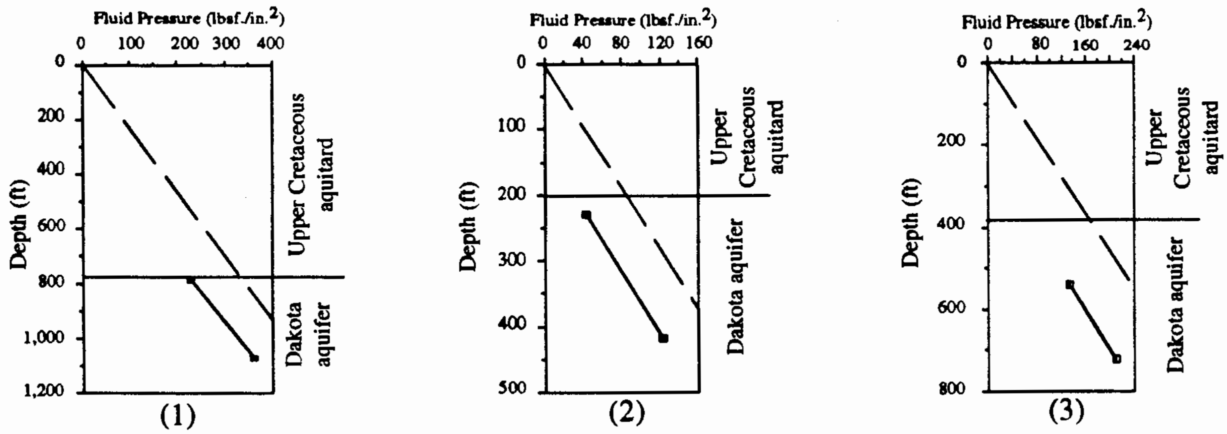


Figure 23b. Fluid pressure–depth profiles from measurements collected at (1) NWSESW sec. 2, T. 8 S., R. 23 W., (2) NWSWNW sec. 14, T. 12 S., R. 16 W., and (3) SWSWSW sec. 31, T. 12 S., R. 17 W. The dashed line represents the hydrostatic line, 2.309 ft/psi.

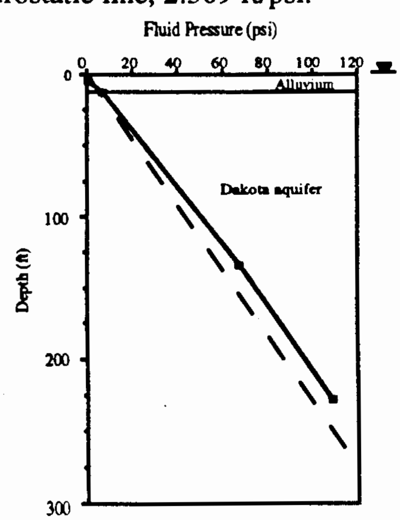


Figure 23c. Fluid pressure vs. depth profile in the Haberer salt marsh in NW sec. 14, T. 12 S., R. 15 W., Russell County, Kansas. The dashed line represents the hydrostatic line with a slope of 2.309 ft/psi.

northwestern Russell County, Kansas (Figure 23c), and is located where the Dakota aquifer discharges to the overlying alluvial aquifer in the Saline River valley. In the upper 130 ft of the Dakota aquifer and the lower part of the alluvial aquifer the slope of the fluid pressure versus depth profile is higher than the slope of the hydrostatic line. This indicates a significant tendency for upward flow from the Dakota to the overlying alluvial aquifer.

In Figure 24 the fluid pressure versus depth slope for wells where the Dakota aquifer is confined by the Upper Cretaceous aquitard is less than the slope of the hydrostatic line. This indicates that the direction of flow is generally downward across the aquitard and affirms that heads in this part of the aquifer are subhydrostatic. The t-test shows that the slope of the best-fitting line through the data (0.29 psi/ft) is significantly less than the slope of the hydrostatic line (0.433 psi/ft). The value of the correlation coefficient is approximately 0.90. The low slope value and the high correlation suggest that the Dakota aquifer receives some recharge through the aquitard and that flow in the Dakota is uniform and primarily lateral (Fogg and Prouty, 1986), which is supported by the fluid pressure versus depth profiles (Figures 23a, profile 1 and 23b).

Fluid pressures generally plot below the hydrostatic line where the Dakota is the near-surface aquifer (Figure 25). A t-test shows that the slope of the best-fitting line through the data (0.29 psi/ft) is significantly less than the slope of the hydrostatic line. This indicates that recharge moves readily downward into the Dakota aquifer from the surface in central Kansas and southeastern Colorado where the Dakota is the near-surface aquifer. The value of the correlation coefficient, 0.85, reflects the scatter in the data because of the (1) great variability in flow direction in recharge, discharge, and midline areas of local flow systems (Toth, 1963; Freeze and Witherspoon, 1967) and (2) errors attributed to the depth approximation.

Fluid pressures plot both above and below the hydrostatic line where the Dakota is overlain by the High Plains and alluvial valley aquifers (Figure 26). A t-test shows that the slope of the best-fitting line (0.38 psi/ft) is significantly less than the slope of the hydrostatic line by a small margin. The value of the correlation coefficient is 0.90. The fluid pressure versus depth data show that, where the Dakota aquifer is overlain by the High Plains and alluvial valley

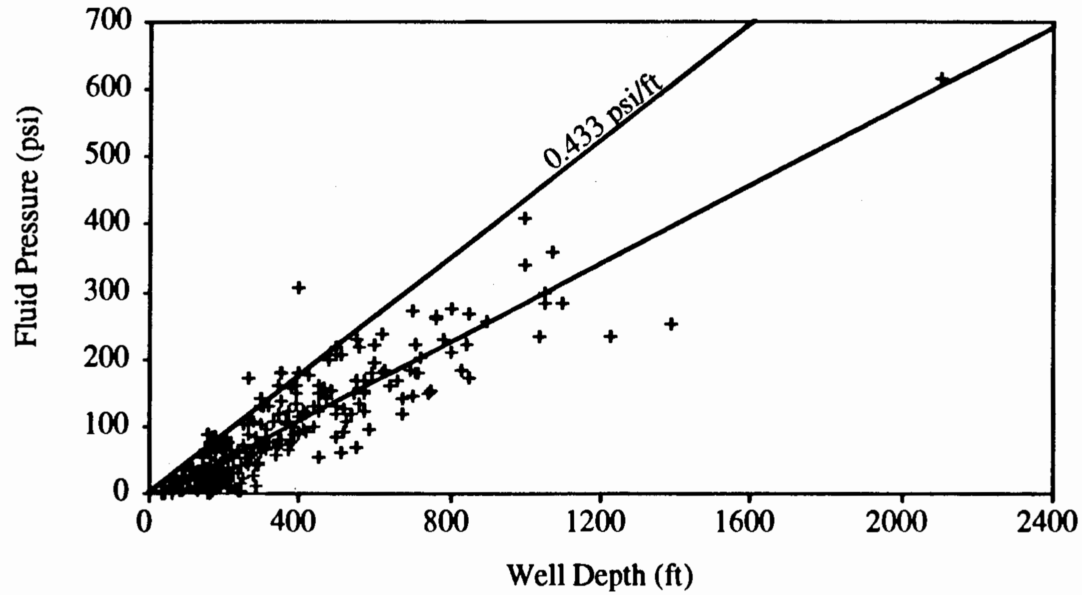


Figure 24. Well depth versus fluid pressure for data collected from areas where the Dakota is a confined aquifer. Fluid pressure is calculated from water-level and well-construction information. The slope of the best-fitting line is 0.293. The correlation coefficient r is 0.90 and is statistically significant ($p = 0.0001$). The best-fitting line slope is significantly less than the slope of the hydrostatic line ($p < 0.025$).

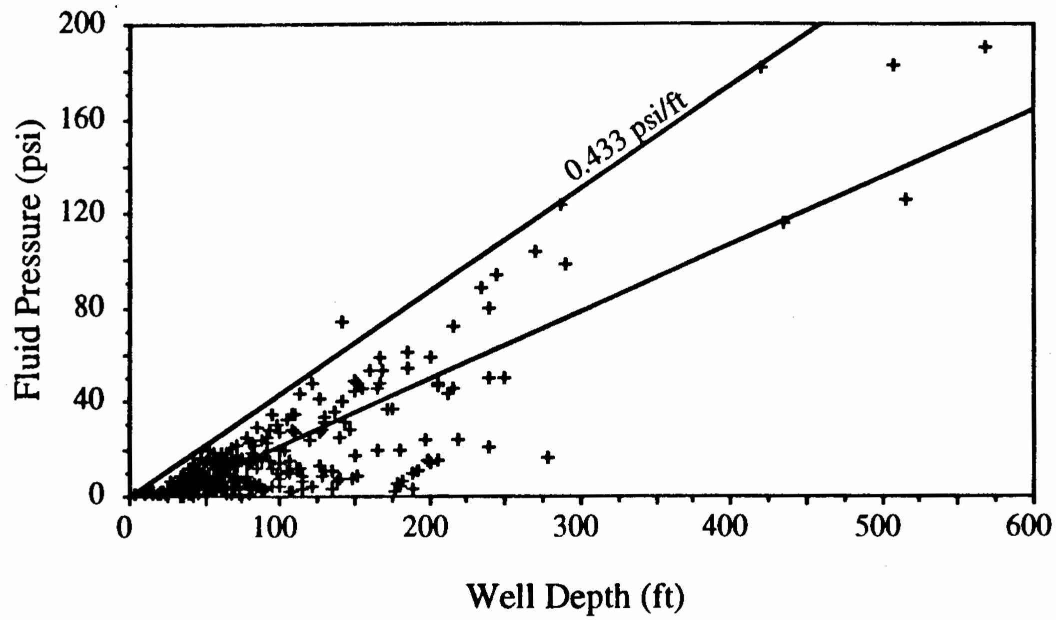


Figure 25. Well depth versus fluid pressure for data collected from areas where the Dakota is the near-surface aquifer. Fluid pressure is calculated from water-level and well-construction information. The correlation coefficient r is 0.85 and is statistically significant ($p = 0.0001$). The slope of the best-fitting line is 0.289 and is significantly less than the slope of the hydrostatic line ($p < 0.025$).

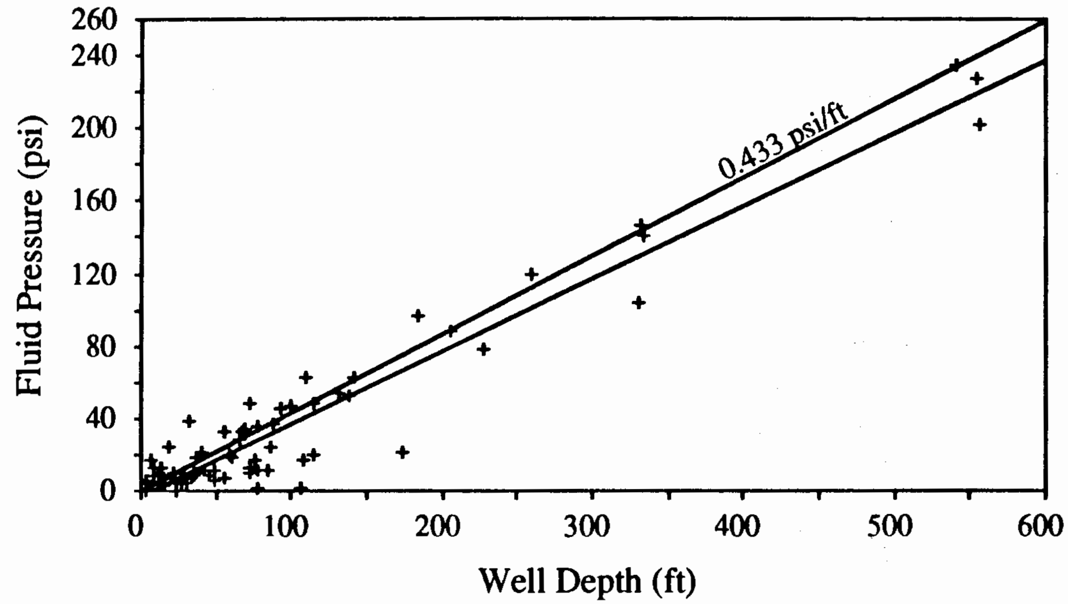


Figure 26. Well depth versus fluid pressure for data collected from areas where the Dakota aquifer is overlain by the High Plains and alluvial valley aquifers. Fluid pressure is calculated from water-level and well-construction information. The slope of the best-fitting line is 0.399 psi/ft. The correlation coefficient r is 0.90 and is statistically significant ($p = 0.0001$). The best-fitting line slope is significantly less than the slope of the hydrostatic line ($p < 0.025$).

aquifers, the vertical flow direction may vary in southeastern Colorado and southwestern Kansas, where most of the data were collected. However, the data demonstrate that the overall direction of vertical flow is downward from the High Plains to the Dakota aquifer. This is also supported by the slightly higher slope of the fluid pressure versus depth profile in the uppermost part of the Dakota and High Plains aquifers in Figure 23a (profile 3). The higher slope value and good correlation also suggest that the flow system in the Dakota where it is overlain predominantly by the High Plains aquifer in parts of southwestern Kansas and southeastern Colorado is part of the intermediate flow system.

The Morrison-Dockum aquifer is present in much of southeastern Colorado and the northwestern third of Kansas and is hydraulically connected to the overlying lower Dakota aquifer (Robson and Banta, 1987; Macfarlane et al., 1990). Where there are sufficient data to define a potentiometric surface, it appears that ground-water flow is from southeastern Colorado into Kansas along the same two flow corridors described for the overlying Dakota aquifer (Figure 27). It is assumed that elsewhere the potentiometric surfaces of the two aquifers behave similarly because of their hydraulic connection. In the vertical profile the Morrison-Dockum aquifer is probably recharged primarily by underflow of ground water from sources upgradient from the vertical profile. Higher hydraulic heads in the Dakota aquifer than in the Morrison-Dockum aquifer indicates downward flow from the Dakota (see Figures 15 and 27). The aquifer crops out in a small area around Two Buttes dome in southeastern Colorado and probably receives only a small amount of recharge from infiltrated precipitation and the overlying High Plains aquifer. Discharge from the Morrison-Dockum aquifer is believed to occur where the aquifer pinches out in the vertical profile.

The Permian sandstone aquifer is the second most geographically extensive bedrock aquifer in western and central Kansas. The entire aquifer is confined by the Permian-Pennsylvanian aquitard, except in central Kansas where it is hydraulically connected to the overlying lower Dakota aquifer (see Figure 19). The Permian sandstone aquifer has been used as a disposal zone for oil brines and some industrial wastes in Kansas and Oklahoma since the

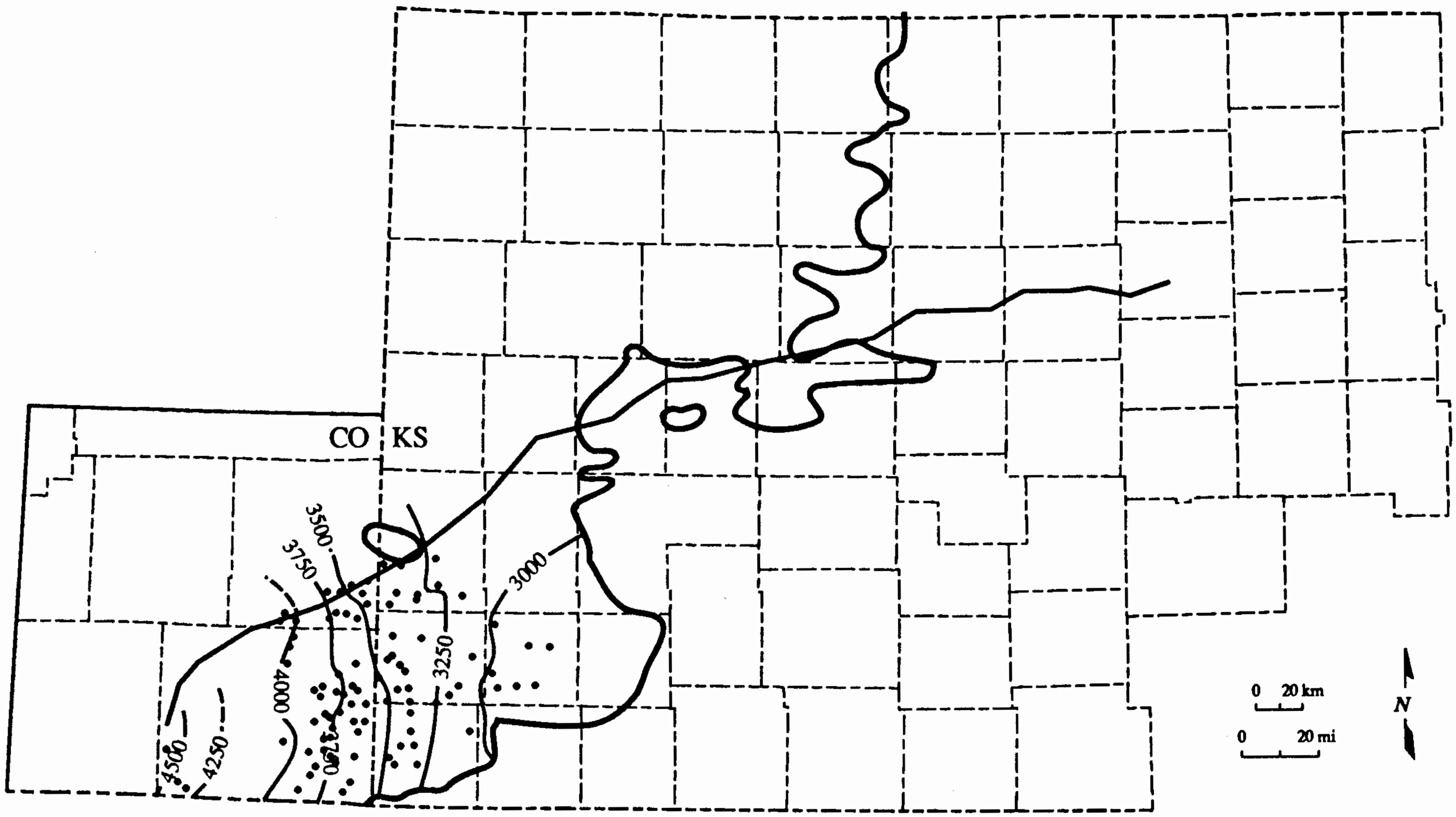


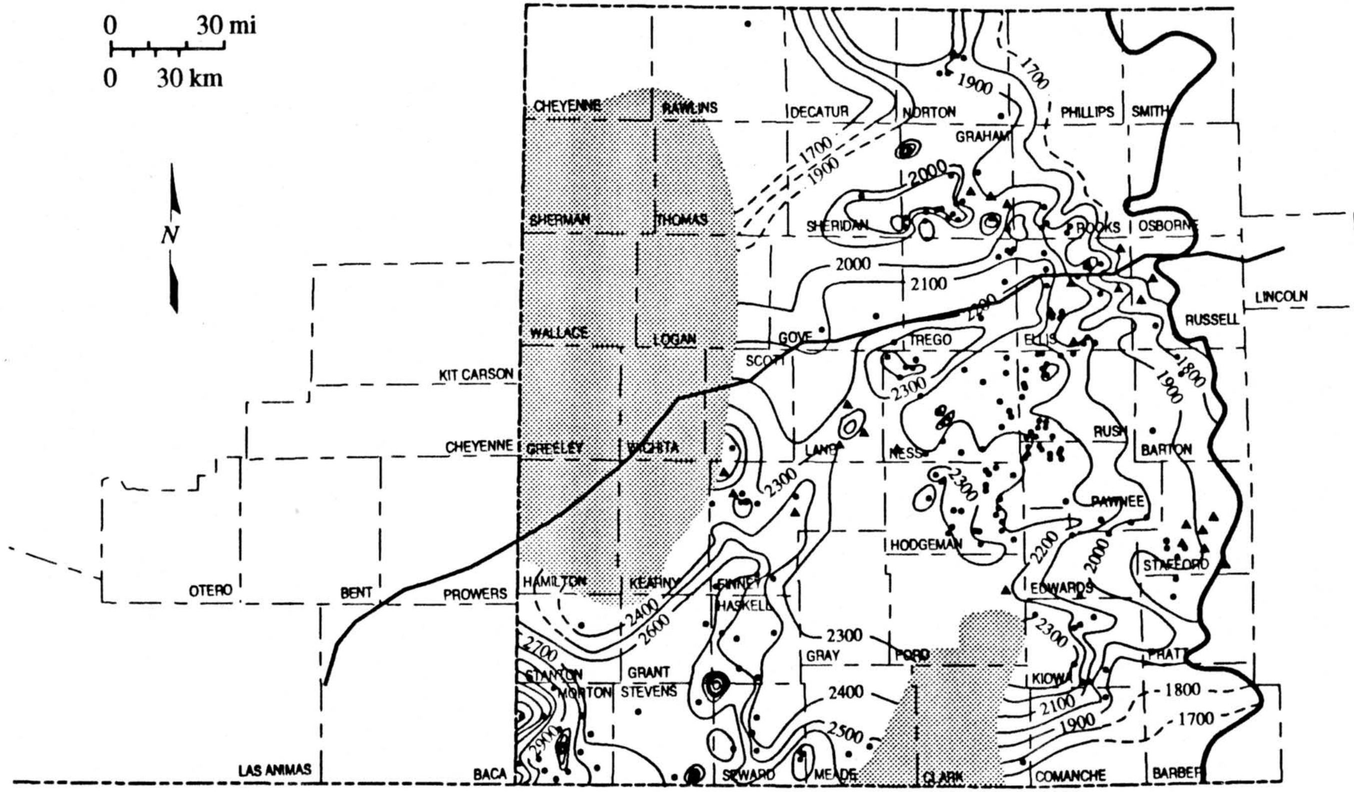
Figure 27. Elevation of the potentiometric surface of the Morrison-Dockum aquifer, southeastern Colorado and southwestern Kansas.

1940's (Walters, 1991; Irwin and Morton, 1969). As a result, the effects of underground injection practices appear on the potentiometric-surface map for the 1970's as isolated areas of higher head in between areas of lower head (Figure 28). These anomalous areas of higher hydraulic head are especially pronounced in central Kansas, where most of the disposal has taken place. Nevertheless, the potentiometric-surface map shows that the predominant direction of ground-water flow is from southwestern Kansas to central Kansas toward the pinchout beneath the Dakota and High Plains aquifers and toward areas in southern Kansas where the aquifer crops out at the surface.

With the exception of the central Kansas region, the Permian sandstone aquifer potentiometric surface is much lower than the potentiometric surfaces of the Dakota, the Morrison-Dockum, and the High Plains aquifers outside the areas that have been most affected by disposal of brines (Figures 19, 22, 27, and 28). This suggests that under predevelopment conditions the primary direction of vertical flow was downward from overlying aquifers to the Permian sandstone aquifer and across the Permian-Pennsylvanian aquitard. In central Kansas the magnitude and direction of predevelopment vertical flow is uncertain. Upward flow to the overlying Dakota and alluvial valley aquifers may have occurred beneath the river valleys where the aquifer is hydraulically connected to the overlying lower Dakota aquifer.

Ground-Water Flow Patterns in the Upper Part of the Regional Flow System

Figure 29 is a vertical profile of freshwater equivalent hydraulic heads in the upper part of the regional flow system. Ground-water flow directions are assumed to be from higher to lower head and perpendicular to the equipotentials. The dominant flow direction in the upper aquifers above the Permian-Pennsylvanian aquitard is parallel to the regional topography from elevated recharge areas in southeastern Colorado to discharge areas in central Kansas. In the deeper part of the system in southeastern Colorado, the flow direction is downward and away from the upthrown Precambrian block on the west side of the Freezeout Creek fault zone. Farther east in the Western Kansas basin and the Central Kansas uplift areas, the vertical flow



Approximate eastern boundary of the Cedar Hills Sandstone

Fluid level elevation in feet above mean sea level, dashed where inferred

Cedar Hills Sandstone cemented by evaporites

• Control point from oil industry report

▲ Control point from KGS and USGS measurement

Figure 28. Elevation of the potentiometric surface of the Permian sandstone aquifer (Cedar Hills Sandstone) in Kansas. Potentiometric highs are believed to be related to oil-brine disposal in central and parts of southwest Kansas.

direction is downward across all the aquitards toward the deeper part of the regional flow system. In these areas the nearly horizontal orientation of the equipotentials in the Permian-Pennsylvanian and evaporite aquitards indicates that the Dakota aquifer and other shallow aquifers are hydraulically isolated from the deeper aquifers below the evaporite aquitards.

The boundary separating the upper from the lower part of the flow system is a flow line and is shown in Figure 29. Ground-water flow above this flow line is dominated by the lateral movement of ground water in aquifers from recharge areas in southeastern Colorado to discharge areas in central Kansas and points eastward. Below the boundary ground-water flow is across the thick Permian-Pennsylvanian and the evaporite aquitards to the deeper aquifers in southeastern Colorado and western and central Kansas. This conceptualization of the flow system is consistent with Belitz (1985), Belitz and Bredehoeft (1988), and Jorgensen et al. (1993). The upper portion of the flow system is interpreted as part of a large intermediate-scale system, whereas the lower part is interpreted as a portion of the regional system.

Simulation of the Steady-State Intermediate-Scale Flow System

Computer simulation of the intermediate-scale flow system was a three-stage process, which included model design, derivation of hydraulic properties, and sensitivity analysis of the resultant partially calibrated model. Model design involved discretization of the vertical profile that encompasses the intermediate-scale flow system and setting the boundary and initial conditions and the initial hydraulic parameter estimates for each of the hydrostratigraphic units. In the second stage the steady-state model was treated as an inverse problem. The model was used to estimate the vertical hydraulic conductivity of the aquitards and the transmissivity of the aquifers using known hydraulic head and flow rate information. Finally, sensitivity analysis was applied to the partially calibrated model developed in the second stage to determine the major influences on the flow system.

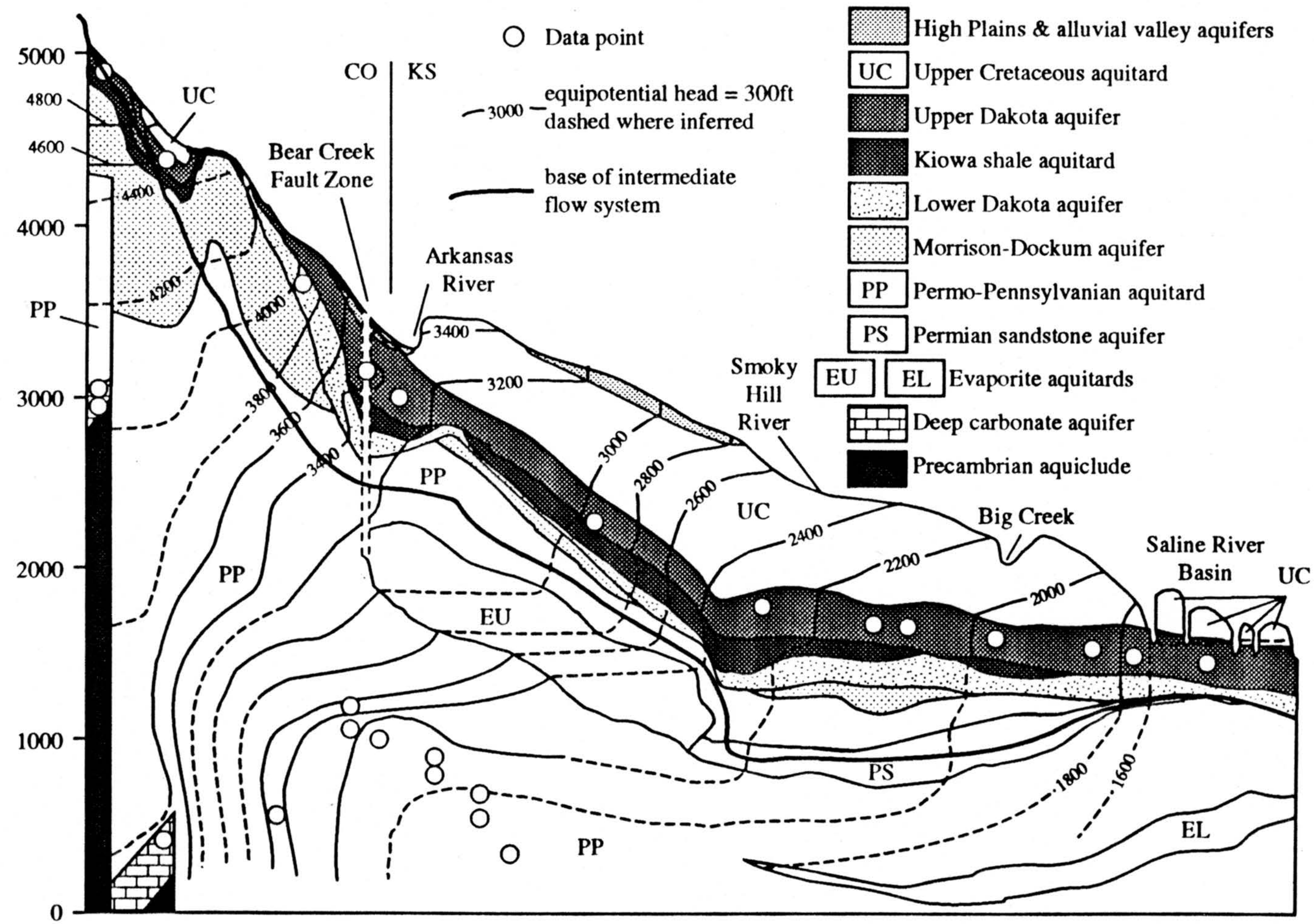


Figure 29. Predevelopment distribution of head (ft above mean sea level) in the vertical profile. The boundary between the intermediate-scale flow system and the regional flow system is shown by the bold line.

Governing Equation

The governing equation that describes the flow of ground water in a vertical profile parallel to the flow direction is (Anderson and Woessner, 1992)

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) + R = 0 \,, \qquad (1)$$

where R is a source/sink term and K_x and K_z are the x and z components of hydraulic conductivity. Equation (1) describes ground-water flow through a heterogeneous and anisotropic porous medium where the principal axes of hydraulic conductivity are aligned with the orthogonal x and z coordinate system axes. Sources of recharge to and discharge from the model are not indicated explicitly because they are handled separately as part of the boundary conditions, which are discussed later.

MODFLOW (McDonald and Harbaugh, 1988) was used to solve the two-dimensional flow equation along with its attendant boundary and initial conditions in the vertical profile. MODFLOW is a block-centered finite-difference code that can be used to simulate ground-water flow in two or three dimensions. The model has a modular structure and consists of a main program and a series of subroutines referred to as modules. These subroutines are grouped into packages that deal with specific features of the hydrologic system to be simulated or with a numerical technique to solve the finite-difference formulation of the flow equation. MODFLOW was selected for this application because it can be readily adapted to a vertical profile model (Anderson and Woessner, 1992).

Model Grid

In the vertical profile view of the regional ground-water flow system, the equipotentials near the Freezeout Creek fault zone in southeastern Colorado were drawn based on head values calculated from drill-stem tests (Figure 29). Subsequently, the equipotentials were used to locate the boundary between the intermediate-scale and regional flow systems. The flow pattern implied by the observed head distribution suggests that this boundary, a flow line, crosses the Dakota aquifer and intersects the water table near the underlying fault zone. This implies that all the flow in the Dakota and the other shallow aquifers upgradient from the fault zone moves downward to recharge the deeper part of the regional flow system. This interpretation, although plausible, seems unlikely because it suggests that all the recharge that enters the upper part of the flow system in eastern Las Animas County, Colorado, where the Dakota potentiometric surface is highest and upgradient of the fault zone, moves downward to recharge the regional flow system. A more likely explanation is that the deeper part of this segment of the regional flow system is recharged by underflow from upgradient sources and by some leakage from overlying aquifers. In this interpretation the flow direction in the shallow aquifers is laterally downgradient from the potentiometric high near the crest of the Sierra Grande uplift rather than primarily cross-formational upgradient from the fault zone. This indicates that the equipotentials are located incorrectly because the heads calculated from the drill-stem test results are too low. Hence the location and the nature of the boundary between the intermediate-scale and regional flow systems are uncertain because of a lack of reliable data. To help minimize this uncertainty, we constructed a simplified model of the regional flow system to determine the likely head distribution in the vicinity of the fault. The model construction, the parameters used in the simulation, and the model results are described by Macfarlane (1993). From the model results the lower and upgradient boundaries were modified in the vertical profile model grid, which was used in the computer simulation of the intermediate-scale flow system.

The model grid consists of 8 layers, 1 row, and 73 columns (Figure 30). The row has a unit length of 1 ft (0.3 m) and the length of each cell in the column direction varies from 5,709 ft (1,740 m) to 28,546 ft (8,700.8 m). The length in the column direction is variable to more accurately simulate the upper water table boundary in the vicinity of the river valleys. The total length of the vertical profile from southeastern Colorado to central Kansas is 315.7 mi (508.1 km).

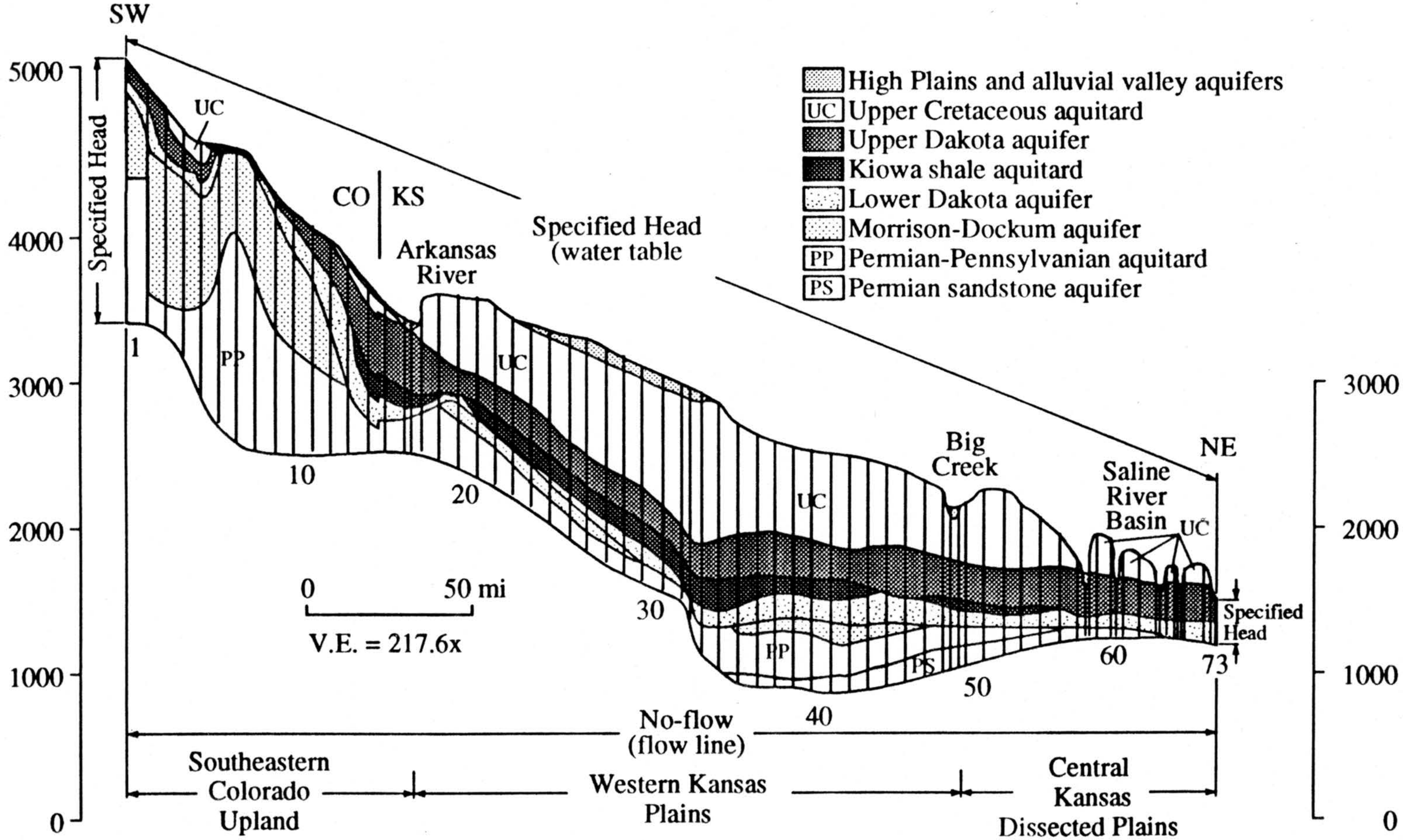


Figure 30. Vertical profile model grid, which consists of 8 layers, 1 row, and 73 columns. The length of each cell in the column direction is variable and ranges from 5,709 ft to 28,546 ft. The length of each cell in the row direction is 1 ft.

Each of the model layers represents a hydrostratigraphic unit. Layer 1 is the High Plains and alluvial valley aquifers and is treated as the upper, unconfined aquifer by MODFLOW. Layers 2 and 3 are the Upper Cretaceous aquitard and the upper Dakota aquifer, respectively. These layers are treated by MODFLOW as fully convertible layers between confined and unconfined conditions with negligible loss of transmissivity. Layer 4 is the Kiowa shale aquitard; layer 5 is the lower Dakota aquifer; layer 6 is the Morrison-Dockum aquifer; layer 7 is the Permian-Pennsylvanian aquitard; and layer 8 is the Permian sandstone aquifer. Layers 4 through 8 are all treated as confined layers by MODFLOW. The terms *confined* and *unconfined* do not necessarily denote aquifer units in the model and, with the exception of layer 1, indicate only whether a particular layer is uppermost at some point in the model.

All the major geologic and geomorphic features traversed by the vertical profile along its length were simulated, including the Sierra Grande and Las Animas uplifts, Two Buttes dome, the Arkansas River, the Saline River drainage, and Big Creek. The Bear Creek fault was not simulated in the vertical profile because its influence on the flow system is uncertain and is probably only local.

The model grid was subdivided into three major sections on the basis of relative local and regional topographic relief in vertical profile view (Figure 30). The southeastern Colorado upland extends from the southwestern end of the model to the Arkansas River in column 17. In this part of the model the regional topographic slope is steep and the local topographic relief is moderate. The western Kansas plains part of the model extends from column 18 to the north bank of Big Creek in column 50. In this section, the regional topographic slope is moderate and the local topographic relief is low. The central Kansas dissected plains section extends from column 51 to the northeast end of the model in column 73. In this part the regional topographic slope is low and the local topographic relief is high.

The model grid and the input parameters were designed to reflect changes in the hydrostratigraphy in the vertical profile caused by the pinching out of model layers. This happens to several of the layers in the model (Figure 30). The pinchout of layers is taken into account where it occurs by continuing the layer across the model as a phantom with a transmissivity and a layer thickness of zero. Vertical hydraulic continuity is maintained where the layer is not present by assigning the same vertical conductance to the cells in the phantom layer that is assigned to cells in the overlying layer. The vertical conductance of each cell in the overlying layer was calculated by assuming that the real layer above and the real layer below the phantom layer are in physical contact.

Boundary Conditions

The boundary conditions define the hydraulic conditions on the perimeter of the model and are necessary to produce a unique solution to the flow equation (Anderson and Woessner, 1992). In the vertical profile model specified-head and no-flow boundary conditions were imposed on the perimeter.

The upper model boundary represents the water table and is considered a specified-head boundary (see Figure 16). At this boundary temporal fluctuations in head are small relative to the total head difference on the water table across the model [3,560 ft (1,085 m)] and the maximum vertical extent of the model [up to 1,700 ft (518 m)]. The specified-head boundary condition was applied instead of a flux boundary to minimize the number of parameters that needed adjusting during calibration. The specified-head condition also allows a flux of water (recharge or discharge) to cross the water table during model execution to maintain the constant head. The distribution of recharge and discharge across the upper model boundary is an output from the model.

Specified-head boundary conditions were also applied at two sites where there are time-invariant vertical hydraulic head gradients that are not significant relative to the scale of the regional model. The southwestern boundary corresponds to the 5,000 ft (1,524 m) equipotential (Figure 30). Placement of this boundary was guided by the results of modeling experiments discussed by Macfarlane (1993). The northeastern boundary corresponds to an assumed, vertical head difference of 0.5 ft (0.15 m) between the upper and lower Dakota aquifers at the northeastern end of the model in Lincoln County, Kansas.

A no-flow boundary was used along the bottom of the model to simulate the flow line that approximates the boundary separating the upper, intermediate flow system from the lower regional flow system (Figure 30). This flow line was drawn on the basis of modeling results described by Macfarlane (1993).

Initial Parameter Estimates

The horizontal hydraulic conductivity of the High Plains aquifer was assumed to be 80 ft/day (24 m/day), which is the arithmetic mean calculated by Stullken *et al.* (1985) for the aquifer in southwestern and west-central Kansas (Table 4). Warren and Price (1961) suggest that the arithmetic mean hydraulic conductivity is more appropriate in instances where the hydrostratigraphic unit is horizontally continuous. Anisotropy and extreme heterogeneity are expected to be more significant in the bedrock units than in the shallow unconsolidated sediments in the High Plains aquifer. The horizontal hydraulic conductivity of the alluvial aquifers was assumed to be 250 ft/day (76 m/day). This assumed value is lower than most of the values cited by Macfarlane et al. (1992) because it is believed that values greater than 250 ft/day are probably not representative of these aquifers.

The horizontal hydraulic conductivity of the upper Dakota aquifer was assumed to vary from 4 ft/day (1.2 m/day) in southeastern Colorado to 10 ft/day (3 m/day) in central Kansas. In southeastern Colorado pumping-test values of horizontal hydraulic conductivity in the upper Dakota range from less than 1 to 10 ft/day (0.3–3 m/day) (McLaughlin, 1954; Wilson, 1965). Near Hays, in central Kansas, horizontal hydraulic conductivities calculated from pumping tests in the upper Dakota aquifer range from 8 to 10 ft/day (2.4–3 m/day) (Robert Vincent, personal communication, 1992).

Table 4. Input hydraulic conductivity data for the hydrostratigraphic units in the vertical profile.

Hydrostratigraphic Unit	Horizontal Hydraulic Conductivity (ft/day)	Vertical Hydraulic Conductivity (ft/day)
High Plains aquifer	80	8.0
Alluvial valley aquifers	250	25
Upper Cretaceous aquitard	9.0×10^{-7}	9.0×10^{-8}
Upper Dakota aquifer	4 – 10	3.1×10^{-3}
Kiowa shale aquitard	1.3×10^{-5}	1.3×10^{-6}
Lower Dakota aquifer	2.3 – 2.0	3.1×10^{-3}
Morrison-Dockum aquifer	0.15 – 0.5	0.015 – 0.05
Permian-Pennsylvanian aquitard	$2.7 \times 10^{-3} - 2.7 \times 10^{-5}$	$2.7 \times 10^{-4} - 2.7 \times 10^{-6}$
Permian sandstone aquifer	1.6	0.16

The horizontal hydraulic conductivity of the lower Dakota aquifer was assumed to decrease from 2.3 ft/day (0.70 m/day) in southeastern Colorado to 2.0 ft/day (0.61 m/day) in west-central and central Kansas. The arithmetic average value of the horizontal hydraulic conductivities computed from two pumping tests of the lower Dakota in southeastern Colorado is 2.3 ft/day (0.70 m/day) (McLaughlin, 1954). Merriam et al. (1959) reported horizontal hydraulic conductivities of the order of 2.0 ft/day (0.61 m/day) for core samples of sandstone from the lower Dakota aquifer in a test hole drilled in northwest Kansas.

The horizontal hydraulic conductivities of the Morrison-Dockum aquifer are based on values of transmissivity used in steady-state models of the regional flow system in the Denver basin reported by Belitz (1985) and Belitz and Bredehoeft (1988). In this part of Kansas Doveton and Chang (1991) reported that the Morrison formation consists of more than 50% sandstone, a much higher percentage than that used to calculate bulk hydraulic conductivity by Belitz (1985) and Belitz and Bredehoeft (1988). The horizontal hydraulic conductivity of the Morrison-Dockum aquifer in southeastern Colorado is assumed to range from 0.15 ft/day (0.045 m/day) in southeastern Colorado to 0.5 ft/day (0.15 m/day) in west-central Kansas.

The horizontal hydraulic conductivity of the Permian sandstone aquifer in the vertical profile is assumed to be higher than the geometric mean value of 0.6 ft/day (0.18 m/day), derived from the slug tests in south-central Kansas. In west-central and central Kansas the lithology of the aquifer is less silty and is assumed to be more permeable (Macfarlane *et al.*, 1990). Accordingly, the initial value of horizontal hydraulic conductivity used in the model was arbitrarily set at 1.6 ft/day (0.49 m/day).

Data from field and laboratory studies on the vertical hydraulic conductivity of the upper and lower Dakota aquifers are few. The geometric mean vertical hydraulic conductivity from the core permeameter tests of sandstone samples is 2.89 ft/day (0.88 m/day). Wade (1991) reported a vertical hydraulic conductivity of 2.2 ($\pm$ 0.6) $\times 10^{-3}$ ft/day (6.7×10^{-4} m/day) for the mudstone portion of the Dakota aquifer from a pumping test in Washington County, Kansas. Assuming that the average percentage of sandstone in the upper and lower Dakota aquifers is approximately 30% in western and central Kansas (Keene and Bayne, 1977), the equivalent vertical hydraulic conductivity of the upper and lower Dakota is approximately 3.1×10^{-3} ft/day (9.4×10^{-4} m/day). The vertical hydraulic conductivities of the other aquifer units are assumed to be one-tenth of their horizontal hydraulic conductivity to take into account the effects of stratification (Domenico and Schwartz, 1990).

The vertical hydraulic conductivity of the Permian-Pennsylvanian aquitard was taken directly from core data and was assumed to be 2.7×10^{-4} ft/day (8.2×10^{-5} m/day) in southeastern Colorado and southwestern Kansas and 2.7×10^{-6} ft/day (8.2×10^{-7} m/day) eastward of the Scott basin axis. The decrease in vertical hydraulic conductivity reflects the eastward decrease in sandstone content of the aquitard. Values of vertical hydraulic conductivity for layer 4 (the Kiowa shale aquitard) and layer 2 (the Upper Cretaceous aquitard) were derived from modeling studies. The value of vertical hydraulic conductivity for the Kiowa shale aquitard that was input into the model is 1.3×10^{-6} ft/day (4.0×10^{-7} m/day). This value was derived from other modeling studies reported by Bredehoeft et al. (1983) and was later used in a modeling study of the Dakota aquifer in southwestern Kansas (Watts, 1989). The initial value of vertical hydraulic conductivity for the Upper Cretaceous aquitard that was input into the model was 9.0×10^{-8} ft/day (2.7×10^{-9} m/day) and was derived from a modeling study of the Denver basin reported by Belitz (1985) and Belitz and Bredehoeft (1988). The horizontal hydraulic conductivity for all the aquitards was assumed to be 10 times the value of the vertical hydraulic conductivity, which is consistent with anisotropy ratios given by Domenico and Schwartz (1990).

Calibration

Calibration of ground-water flow models usually consists of adjusting the input parameters until a satisfactory match is achieved between the observed and the simulated hydraulic heads, fluxes, or other calibration targets (Wang and Anderson, 1982). In this research a fully calibrated model of the flow system was deemed inappropriate because of the lack of head data for many of the layers below the upper Dakota aquifer. Model calibration was carried out manually by trial-and-error adjustment of the hydraulic conductivity input data to match hydraulic head measurements and flow rates in the model. Because most of the head data were primarily from the High Plains, alluvial valley, and upper Dakota aquifers, little adjustment was made in the hydraulic parameters of layers below the upper Dakota aquifer. All the adjustments made in the values of these parameters were guided by the sensitivity analyses. Fourteen target head values were available in the upper and lower Dakota aquifers to check the progress of calibration. The location of the target heads is shown in Figure 29. Calibration of the vertical profile model was also guided by the results of pumping tests of nearby wells in central Kansas and in southeastern Colorado and measurements of baseflow in the Saline River in central Kansas from seepage runs.

The results of each round of calibration were evaluated by computing the root mean square (RMS) error:

$$\text{RMS error} = [(1/n)\sum (h_m - h_s)^2]^{0.5}, \quad (2)$$

where h_m and h_s are the measured and simulated heads, respectively. This criterion was chosen because the RMS error is thought to be the best measure of uncertainty if the errors are normally distributed (Anderson and Woessner, 1992). The RMS error was also used to evaluate model sensitivity to systematic changes in layer hydraulic conductivity and boundary conditions.

As a further check of the calibration, the errors were examined for trend by producing a plot of the errors and the calibration target heads and computing a best-fitting regression line by least squares through the data points. No trend is indicated in the errors if the slope of the best-fitting line is judged to be not significantly different from zero.

The steady-state model was considered to be partially calibrated when the RMS error was less than 50 ft (15 m), which is 1.4% of the total head decline [3,560 ft (1,085 m)] across the model. This value of the RMS error is also within the error of many of the calibration target heads. The RMS error of the partially calibrated model is 46 ft (14 m). The slope of the best-fitting line was –0.016 and was found to be not significantly different from zero.

Assumptions and Limitations of the Model

The assumptions made in developing the vertical profile model were (1) the ground-water flow system contains fluids of uniform density and viscosity (homogeneous fluids), (2) the heterogeneity of the geologic framework can be reasonably simulated using a three-dimensional orthogonal grid, and (3) there is no flow into or out of the plane of the vertical profile.

MODFLOW is not designed to simulate variable-density ground-water flow caused by thermal effects or total dissolved solids (TDS) concentration. Stavnes and Steeples (1982) and Repplier and Fargo (1981) in Kansas and Colorado, respectively, indicate no significant thermal anomalies in the area traversed by the vertical profile. The geothermal gradient ranges from slightly less than 1.97°F/100 ft to 2.24°F/100 ft in the study area. Overall, the TDS concentration of ground water in the vertical profile ranges up to 30,000 mg/l. Ground water containing elevated TDS concentrations is restricted to the lower part of the profile in the Permian sandstone aquifer and in the lower Dakota aquifer in west-central and central Kansas and to beneath the

Saline River valley. The narrow range in the geothermal gradient and ground-water TDS concentrations in the vertical profile indicates that ground-water density and viscosity should not vary appreciably.

MODFLOW is also limited in its ability to simulate complex geometries because of its finite-difference formulation. McDonald and Harbaugh (1988) note that the method of handling the vertical grid spacing may introduce small errors into the calculation of hydraulic heads. The model is also limited in its ability to simulate ground-water flow where the hydrostratigraphic units are tilted because of the model's reliance on an orthogonal grid. This limitation is not considered serious because the hydrostratigraphic units are relatively flat-lying across most of the vertical profile except in the vicinity of Two Buttes dome, where the maximum dip on the beds is less than 10° from the horizontal (Sanders, 1934). In areas where there is significant topographic relief, a finer grid spacing was used to minimize this problem.

The trace of the vertical profile is parallel to the flow directions indicated by the Dakota aquifer potentiometric surface. In west-central Kansas the general flow directions in the Permian sandstone aquifer are assumed to be toward its subcropping boundary in central Kansas. However, a significant flow component is recorded to the northwest and may include the west-central Kansas portion of the aquifer. These flows into and out of the plane of the vertical profile violate the assumptions of the analysis but are not significant, considering the other uncertainties in the model.

Ground-Water Flow in the Steady-State Model

The head distribution in the partially calibrated model of the steady-state flow system is indicated by the pattern of the equipotentials shown in Figure 31. A plot showing the distribution of recharge and discharge across the upper model boundary was prepared to gain further insight into the behavior of the flow system (Figure 32). The cell-by-cell volumetric flow rates within the aquifer units were computed using ZONEBUDGET (Harbaugh, 1990), a computer program that calculates subregional water budgets from MODFLOW.

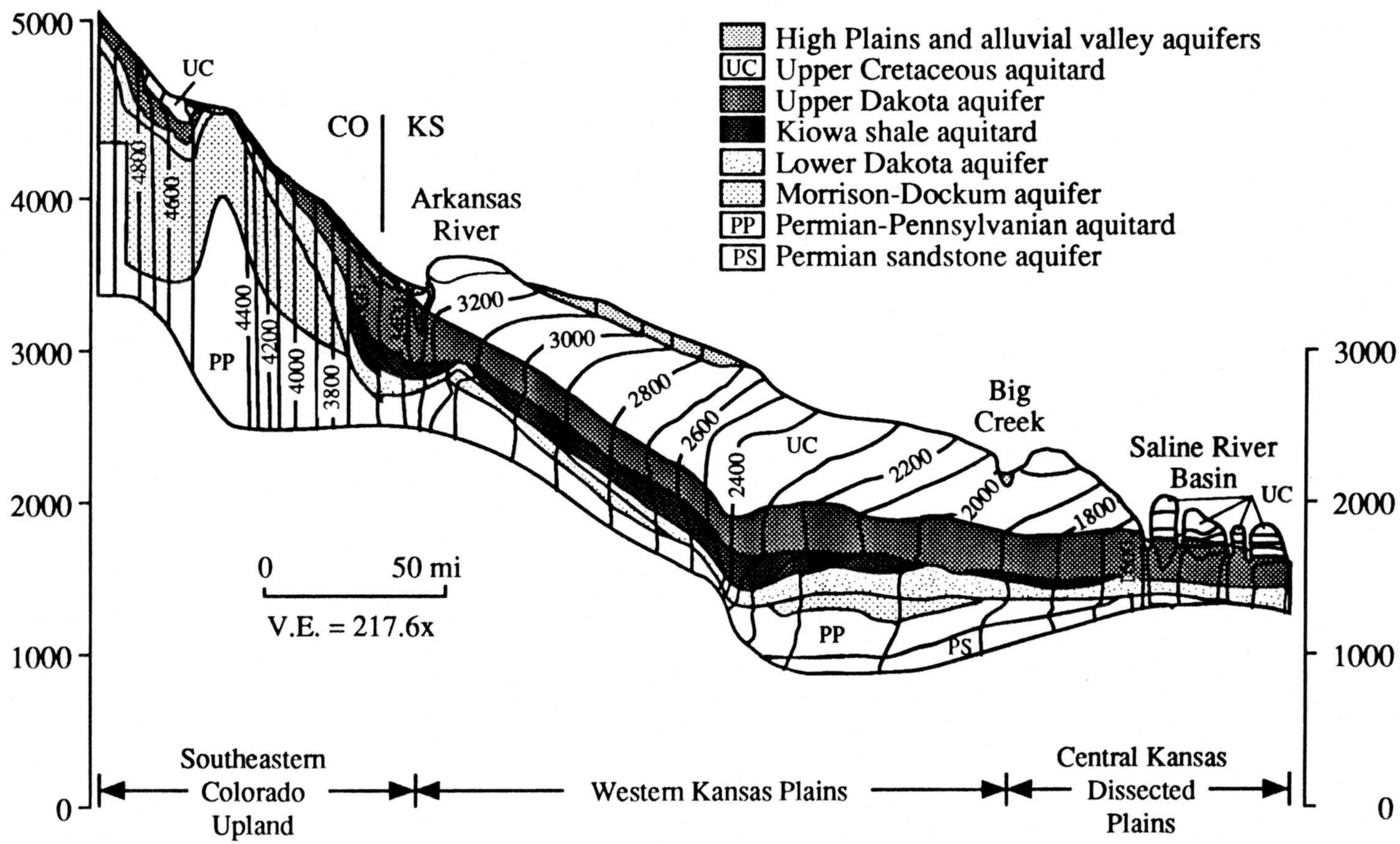


Figure 31. Steady-state head distribution in the partially calibrated vertical profile model. Ground-water flow is from regions of higher to regions of lower hydraulic head.

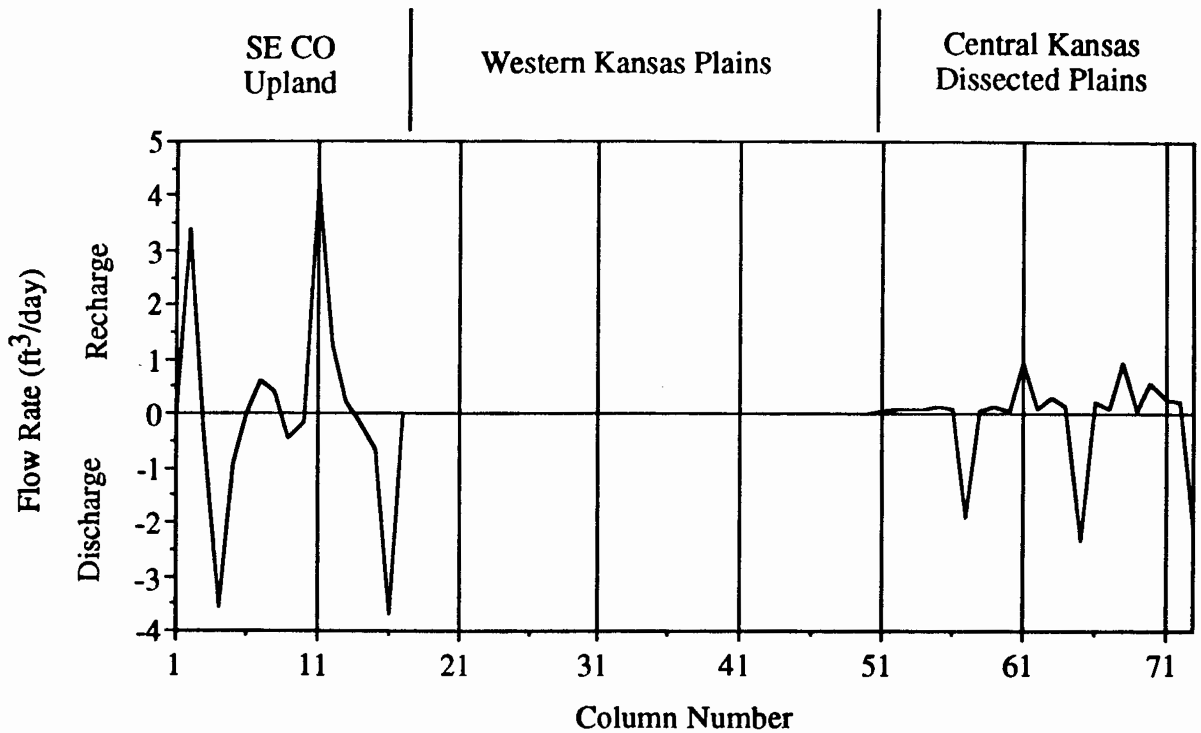


Figure 32. Distribution of recharge and discharge across the upper boundary of the partially calibrated vertical profile model. In the western Kansas plains part of the model only a small amount of recharge, of the order of 10^{-2} to 10^{-3} ft^3/day per model cell is added.

In the southeastern Colorado upland section of the model the equipotentials are spaced closely together and are vertical in orientation (see Figure 31). This indicates a steep head gradient from the southwest end of the model to the Arkansas River that is controlled by the high regional slope of the land surface. Figure 18 shows an alternation of recharge and discharge across the upper model boundary in this section. The alternation of recharge and discharge suggests laterally adjacent local flow systems, especially in the vicinity of Two Buttes dome. The U.S. Geological Survey 1:100,000 scale, 30′ × 60′ topographic maps of the Springfield and Two Buttes quadrangles show an abundance of springs in the vicinity of Two Buttes. The nearly vertical orientation of the equipotentials near the upper model boundary poorly defines these local flow systems because of the coarseness of the model grid. However, the moderate local relief suggests that the local flow systems are probably shallow in vertical extent (Toth, 1963). Darton (1906) considered most of the valley in the Two Buttes Creek drainage between Two Buttes dome and the Arkansas River as an area where flowing well conditions in the Dakota could be expected. This is consistent with the model results and the interpretation of laterally adjacent local flow systems. Figure 32 shows a small discharge of water from the flow system in columns 9 and 10, near where the Two Buttes Creek intersects the vertical profile. The model also shows the nearby uplands are recharge areas.

Upgradient from the Arkansas River in column 11, more than 4 ft^3/day (0.1 m^3/day) enters the model across the upper boundary (Figure 32). Toward the river the rate of recharge decreases rapidly until column 14, at which point water is discharged from the model at steadily increasing rates until the Arkansas River valley is reached in column 16. This pattern of recharge and discharge suggests that the vertical profile traverses a local flow system involving the south side of the Arkansas River valley and the adjacent upland. Recharge entering this part of the model must cross the Upper Cretaceous aquitard before it enters the upper Dakota aquifer (see Figure 31). The aquitard has a thickness of less than 100 ft (30 m) and has a vertical hydraulic conductivity of approximately 10^{-5} ft/day.

In the valley predicted steady-state heads are much higher than the elevation of the water table. Head differences in column 16 range from 18 ft (5.5 m) in the upper Dakota aquifer to 134 ft (40.8 m) in the lower Dakota aquifer. Haworth (1913) mentioned flowing wells in the vicinity of Coolidge, Kansas, in the river valley and reported that when the first wells were drilled, the static water level in these wells was approximately 20 ft (6 m) above land surface. Assuming that the water table was about 20 ft below land surface, the static water level elevation in these flowing wells was approximately 40 ft (12 m) above the water table.

Approximately 10 ft^3/day (0.3 m^3/day) enters the flow system in the southeastern Colorado upland southwest of the Arkansas River and 6.3 ft^3/day (0.2 m^3/day) is discharged to springs and streams locally (Figure 32). The remainder moves on toward the Arkansas River with the subsurface inflow that enters at the southwest end of the model [1.6 ft^3/day (0.05 m^3/day)]. The model results indicate that all of the flow in the upper Dakota aquifer in column 16 is discharged to the Arkansas River valley at a rate of 3.7 ft^3/day (0.1 m/day). Only a small amount is discharged from the upper Dakota aquifer directly beneath the river in comparison with the discharge on the south side of the valley. Most of the flow to the river comes from recharge that passes through a considerable thickness of the Upper Cretaceous aquitard from the north side of the valley before it enters the river or the upper Dakota aquifer.

In the western Kansas plains section of the model the intermediate-scale flow system is dominates and ground water is transmitted laterally beyond the Arkansas River to the central Kansas dissected plains section (see Figure 31). The High Plains aquifer is readily recharged by infiltrating precipitation. However, the nearly horizontal orientation of the equipotentials in the underlying Upper Cretaceous aquitard indicates that the flow system beneath the aquitard is hydraulically isolated from the High Plains aquifer. Recharge rates are negligible, of the order of 10^{-3} ft^3/day through each of the cells along the upper model boundary, and the total recharge to the flow system is relatively small, approximately 0.15 ft^3/day (0.004 m^3/day) (Figure 32). Figure 33 shows that flow through the aquitard to each of the model cells in the upper Dakota aquifer amounts to 0.5% or less of the total cell-by-cell volumetric flow rate (Figure 33). The

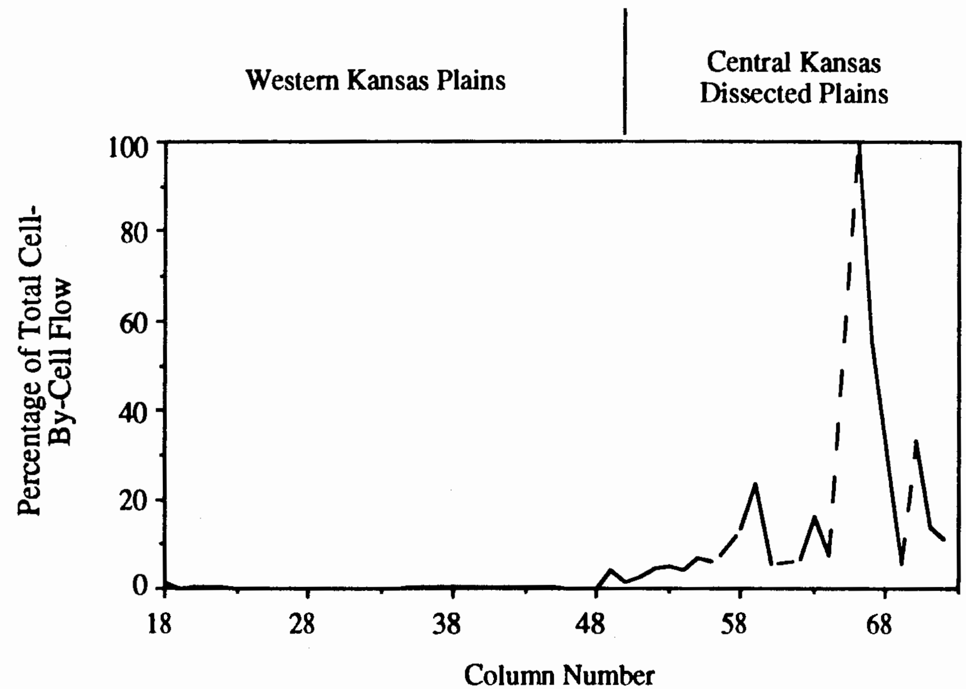


Figure 33. Percentage of the total cell-by-cell volumetric flow rate in the upper Dakota aquifer that comes from recharge through the Upper Cretaceous aquitard between the Arkansas River and the northeastern end of the partially calibrated steady-state model.

average cell-by-cell volumetric flow rate in the upper Dakota aquifer in this part of the model is approximately 1.6 ft^3/day (0.05 m^3/day) (Figure 34).

Farther east in the central Kansas dissected plains section of the model local topographic relief is pronounced where the model intersects the Saline River and its tributaries and where the regional slope of the land surface is relatively low. The high local topographic relief and the low regional slope favor local flow system development rather than a continuation of the intermediate-scale flow system into this section of the model from the western Kansas plains (Toth, 1963).

The flow patterns indicated by the equipotentials and the pattern of recharge and discharge across the upper model boundary indicate an alternation of gaining and losing streams and recharge to the flow system in the uplands (see Figures 31 and 32). The Saline River and two of its tributaries are gaining streams where they intersect the vertical profile, and two other tributaries are losing streams in their upper reaches. The total recharge to this section of the model is 4.7 ft^3/day/ft (0.3 m^3/day/m) and is much lower than the amount in the southeastern Colorado upland. Recharge through the aquitard constitutes up to 100% of the highly variable cell-by-cell volumetric flow rate in the upper Dakota aquifer, but on the average is less than 20% of the total (Figure 33). Discharge to all the streams does not occur in this part of the vertical profile because the aquitard does not allow sufficient recharge to the flow system downgradient of each of the gaining streams. Because of this deficiency, recharge must be supplied to the flow system where the upper reaches of the losing streams have cut down through the aquitard and into the upper Dakota aquifer.

The results of a seepage run indicate a discharge of approximately 1.3 ft^3/day (0.04 m^3/day) from the regional flow system to the Saline River (J.B. Gillespie, personal communication, 1993). This rate of discharge is reasonably close to the approximately 1.9 ft^3/day (0.05 m^3/day) predicted by the partially calibrated steady-state model when the Upper Cretaceous aquitard vertical hydraulic conductivity is approximately 10^{-6} ft/day in the vicinity of the river.

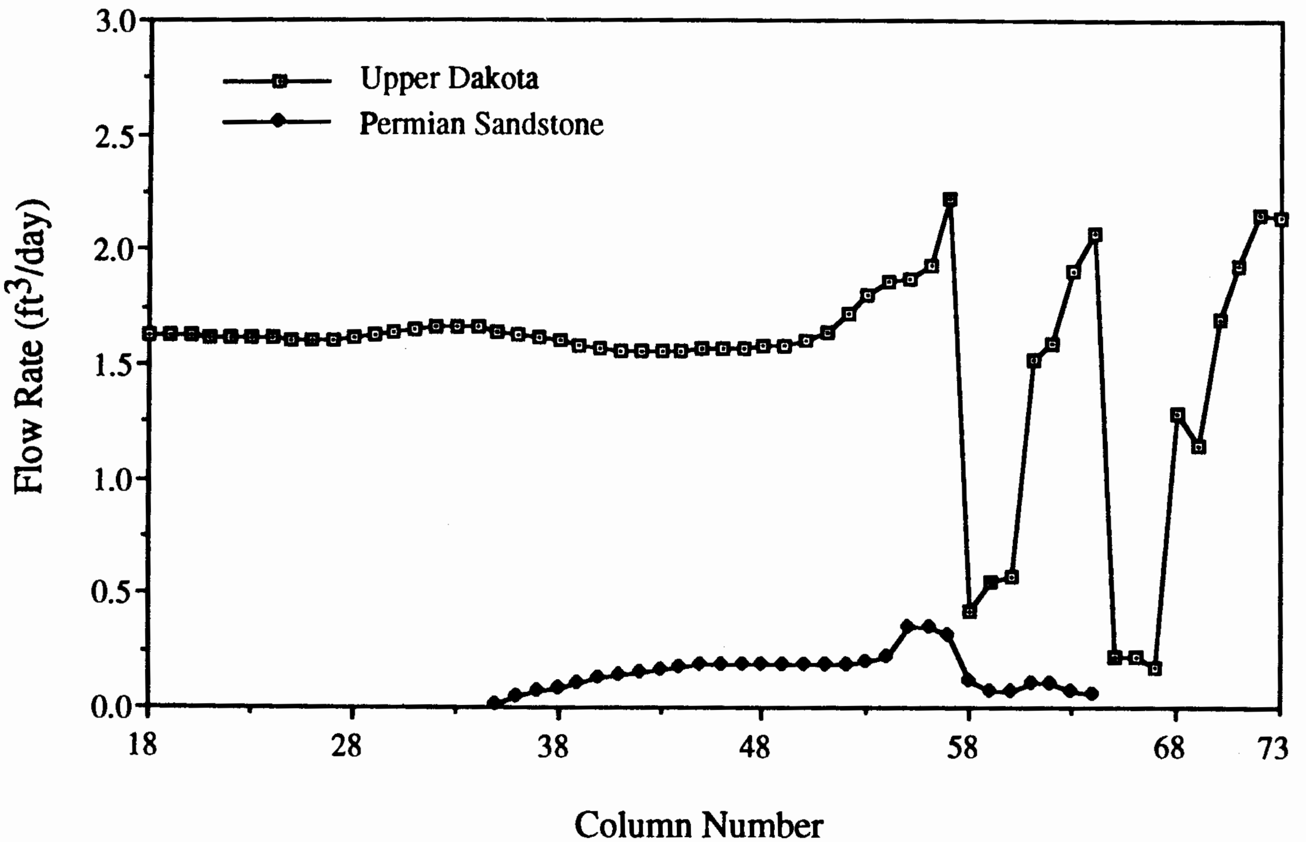


Figure 34. Cell-by-cell volumetric flow rate through the upper Dakota and Permian sandstone aquifers from the Arkansas River to the northeastern end of the model.

Beneath the Saline River, the model predicts flowing well conditions in the upper and lower Dakota and Permian sandstone aquifers. The model results show that heads in the upper Dakota should be approximately 14 ft (4.3 m) higher than the elevation of the water table. Field measurements indicate that the head difference is approximately 8 ft (2.4 m) near the intersection of the vertical profile and the Saline River.

Over most of the lower part of the vertical profile the Permian sandstone aquifer is separated from the overlying Dakota aquifer by the Permian-Pennsylvanian aquitard. Significant head differences across the aquitard indicate that flow is reduced by its presence (see Figure 31). In Figure 34 the cell-by-cell volumetric flow rate increases steadily to approximately 0.2 ft^3/day (0.006 m^3/day) beneath the Permian-Pennsylvanian aquitard. Where the aquitard is not present, the fluctuations in volumetric flow rate suggest that water moves vertically between the Permian sandstone aquifer and the lower Dakota aquifer. The local flow system beneath the Saline River extends downward from the surface and into the Permian sandstone aquifer (see Figure 31). As a result, flow in the Permian sandstone aquifer moves upward into the overlying lower Dakota aquifer toward the river. Downgradient, the volumetric flow rate in the Permian sandstone aquifer is diminished and ground water from the overlying lower Dakota moves downward to recharge the aquifer (see Figure 34).

Steady-State Water Budget

The water budget is summarized in Figure 35 and shows the distribution of recharge to and discharge from the steady-state flow system for each of the three model sections. The total flow through the vertical profile is approximately 16.6 ft^3/day. (0.47 m^3/day) This volumetric flow rate agrees reasonably well with estimates of flow through the Dakota aquifer made by Helgeson et al. (1993). Helgeson and co-workers calculated a steady-state water budget of 342 ft^3/s (9.68 m^3/s) or approximately 13.4 ft^3/day (0.38 m^3/day) from their model of the Dakota aquifer system, which covers most of the central Great Plains, including southeastern Colorado and western and central Kansas.

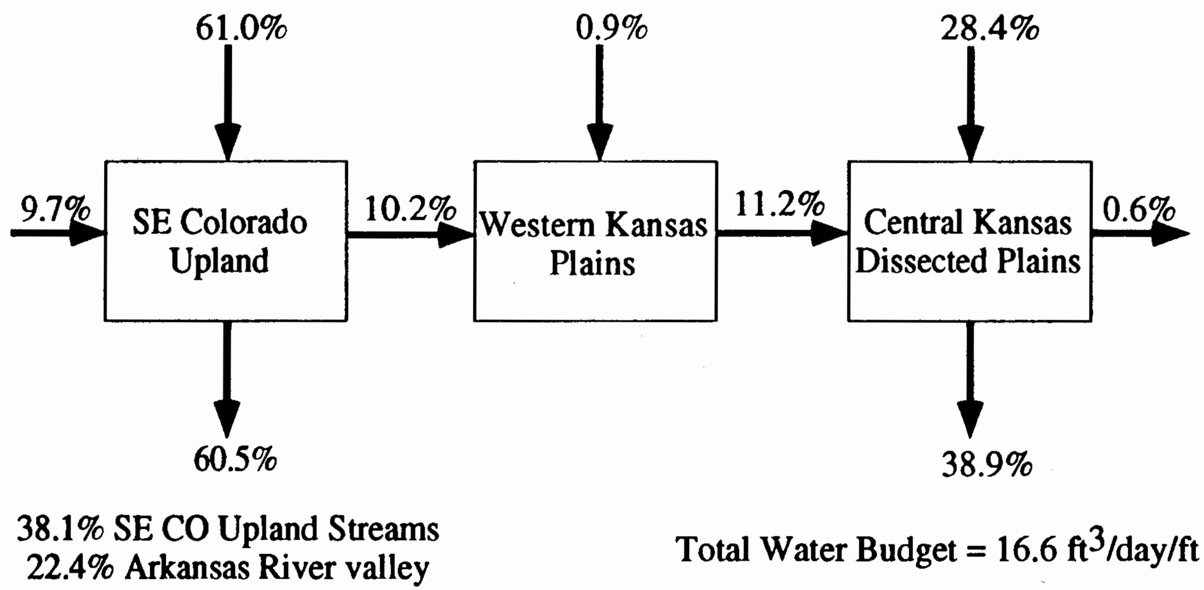


Figure 35. Total water budget for the steady-state flow system in the vertical profile by model section.

In the southeastern Colorado upland and in the central Kansas dissected plains most of the water that enters the model through the upper boundary is discharged locally and little is contributed to regional flow (Figure 35). Recharge entering the flow system across the water table accounts for 61% of the total water budget, but 60.5% is discharged locally to springs and streams. In the central Kansas dissected plains 28.4% of the total water budget enters the flow system through the Upper Cretaceous aquitard as local recharge, but 38.9% of the total is discharged locally. In contrast, only 0.9% of the total water budget recharges the flow system in the western Kansas plains section of the model. There is no local discharge to surface waters in this part of the flow system.

Recharge to the flow system entering through the Upper Cretaceous aquitard in all three model sections accounts for approximately 30% of the total volumetric flow rate in the model. Belitz (1985) reported that the probable amount of recharge through this confining layer in the Denver basin and adjacent areas to the east is in the range of 15–32% of the total volumetric flow rate through the system. In the vertical profile model more than 97% of the total recharge through the aquitard enters the system in the central Kansas dissected plains and in the southeastern Colorado upland section of the model where the aquitard is thinnest.

The steady-state water budget shows that local flow systems and the vertical hydraulic conductivity of the Upper Cretaceous aquitard heavily influence the water budget in all the model sections. Local flow systems are present in the southeastern Colorado upland and in the central Kansas dissected plains because the local relief and surface drainage systems are sufficiently developed. However, almost twice as much water cycles through the southeastern Colorado upland as through the central Kansas dissected plains. This is because the Upper Cretaceous aquitard's greater extent and lower vertical hydraulic conductivity in the central Kansas dissected plains restrict the flow of water through local flow systems. By comparison, the flow through the western Kansas plains section of the model is sluggish. The low local relief and moderate regional slope of the land surface do not favor local flow system development, and the aquitard has much greater thickness and lower hydraulic conductivity in this part of the model than elsewhere. Thus cross-formational flow characterizes the upper part of the flow system in the southeastern Colorado upland and in the central Kansas dissected plains, whereas lateral flow characterizes the system in the western Kansas plains and in the deeper subsurface in the southeastern Colorado upland.

Influence of the Upper Cretaceous Aquitard on the Flow System

In the first phase of the analysis, the goal was twofold: to evaluate model sensitivity to the Upper Cretaceous aquitard and to determine whether a uniform or a nonuniform vertical hydraulic conductivity could best explain the observed heads in the upper Dakota aquifer. This was done by first calibrating the model assuming a uniform value of vertical hydraulic conductivity in the layer. Adjustments were made in the hydraulic properties of all the layers to produce a minimum RMS error calculated using Eq. (2). In the next series of model runs the vertical hydraulic conductivity in the aquitard was allowed to vary. The model was then recalibrated using the results of the first model and adjusting only vertical hydraulic conductivity to produce a new minimum RMS error. Model sensitivity to the vertical hydraulic conductivity was evaluated by running series of simulations in which the vertical hydraulic conductivity was varied systematically through a range of values spanning two to three orders of magnitude. The effect on the model of changing the value of the parameter was determined by calculating the RMS error after each model run.

In the first series of simulations only a maximum value of the vertical hydraulic conductivity of the Upper Cretaceous aquitard could be determined from the RMS error. The asymmetry of the error curve suggests a maximum vertical hydraulic conductivity of 3×10^{-7} ft/day (9×10^{-8} m/day). The RMS error increases from 79 ft (24 m) to 164 ft (80 m) as the vertical hydraulic conductivity increases to 3×10^{-5} ft/day (9×10^{-6} m/day) Decreases in the vertical hydraulic conductivity below 3×10^{-7} ft/day (9×10^{-8} m/day) have little effect on the RMS error.

In the second series the vertical hydraulic conductivity of the aquitard was assumed to vary from cell to cell in the model. The resulting RMS error decreased by 42% to 46 ft (14 m). This indicates that a nonuniform vertical hydraulic conductivity is more appropriate than a uniform value for this model layer. The vertical hydraulic conductivity ranges from 3.0×10^{-4} ft/day to 1.8×10^{-7} ft/day (9×10^{-5} to 5.5×10^{-8} m/day) across the model (Figure 36). In the individual sections of the model the vertical hydraulic conductivity ranges from 3.0×10^{-4} to 2.0×10^{-5} ft/day (9×10^{-5} to 6×10^{-6} m/day) in the southeastern Colorado upland, 3.8×10^{-7} to 1.7×10^{-7} ft/day (1.2×10^{-7} to 5.2×10^{-5} m/day) in the western Kansas plains, and 6.3×10^{-6} ft/day to 7.1×10^{-7} ft/day (1.9×10^{-6} to 2.2×10^{-7} m/day) in the central Kansas dissected plains.

The results from both simulations are consistent with the results of Belitz (1985) and Belitz and Bredehoeft (1988). They found that only a maximum vertical hydraulic conductivity could be determined from model sensitivity if the vertical hydraulic conductivity was treated as a uniform property of the layer. Their maximum value is one order of magnitude less than the maximum value reported from the first simulation series. They also reported improvement in the error of their multilayer model of the Denver basin when the vertical hydraulic conductivity was treated as a depth-dependent variable ranging over three orders of magnitude from 100 ft to 10,000 ft (30–3,000 m) of depth. Figure 37 is a plot of the partially calibrated cell-by-cell vertical hydraulic conductivity versus the cell-by-cell node depth for the Upper Cretaceous aquitard. The log-log plot and the best-fitting line through the data show that vertical hydraulic conductivity generally decreases with depth. Vertical hydraulic conductivity decreases over three orders of magnitude for a depth range from 17.5 ft to 522.5 ft (5.3–159 m). The r^2 value indicates that approximately 61% of the variation in the data is explained by the log-log relationship between the two variables and demonstrates that vertical hydraulic conductivity is a depth-dependent variable in this aquitard.

In Figure 38 the RMS error is sensitive to the increase in hydraulic conductivity above the calibrated cell-by-cell set of values. The sensitivity of heads in the upper Dakota aquifer to the increase in vertical hydraulic conductivity of the aquitard results because more and more

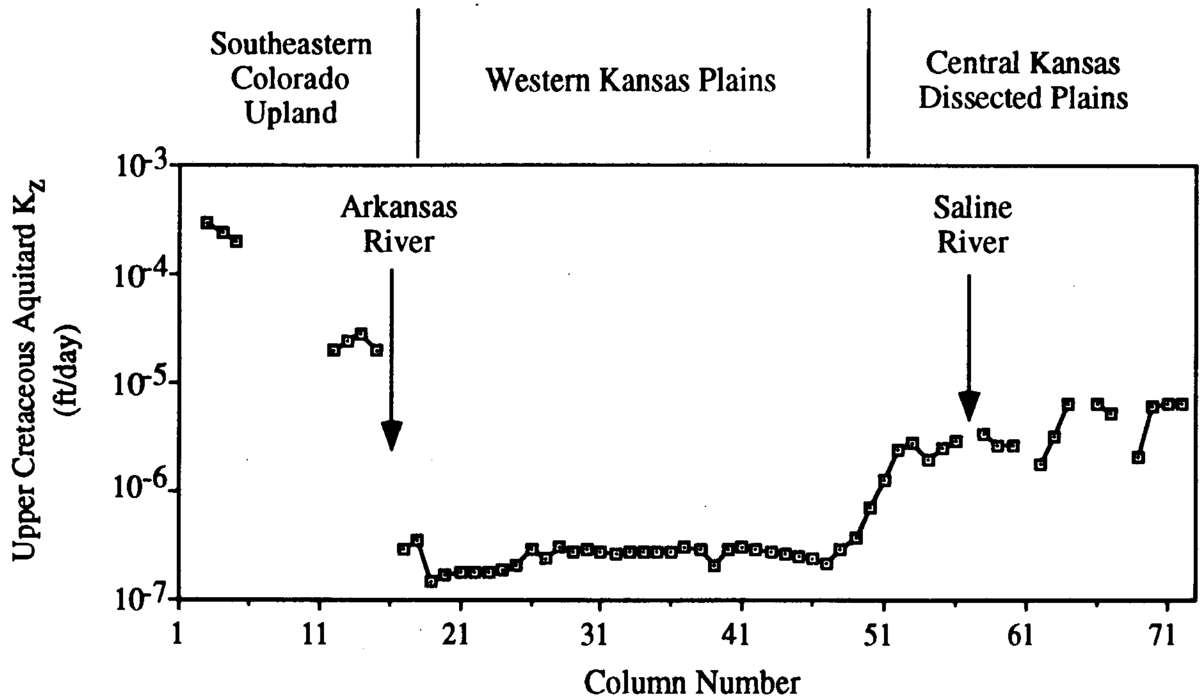


Figure 36. Variation in vertical hydraulic conductivity of the Upper Cretaceous aquitard from the partially calibrated steady-state model. Vertical hydraulic conductivity is lowest in the western Kansas plains section of the model and highest in the southeastern Colorado upland section.

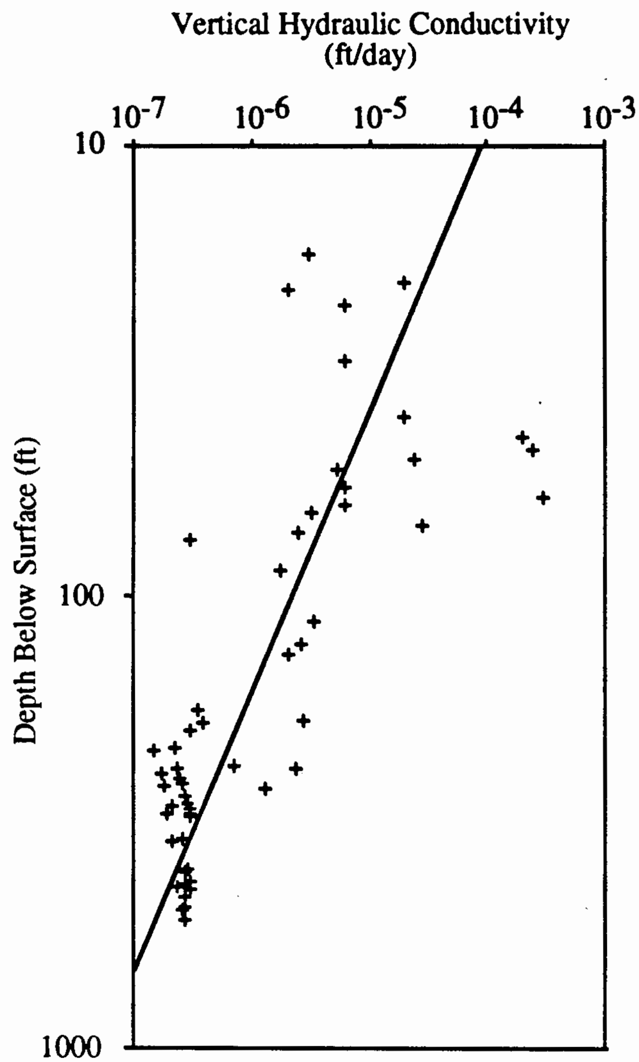


Figure 37. Vertical hydraulic conductivity of the Upper Cretaceous aquitard versus depth below land surface showing the best-fitting line by least-squares regression. The value of the correlation coefficient *r* is 0.78.

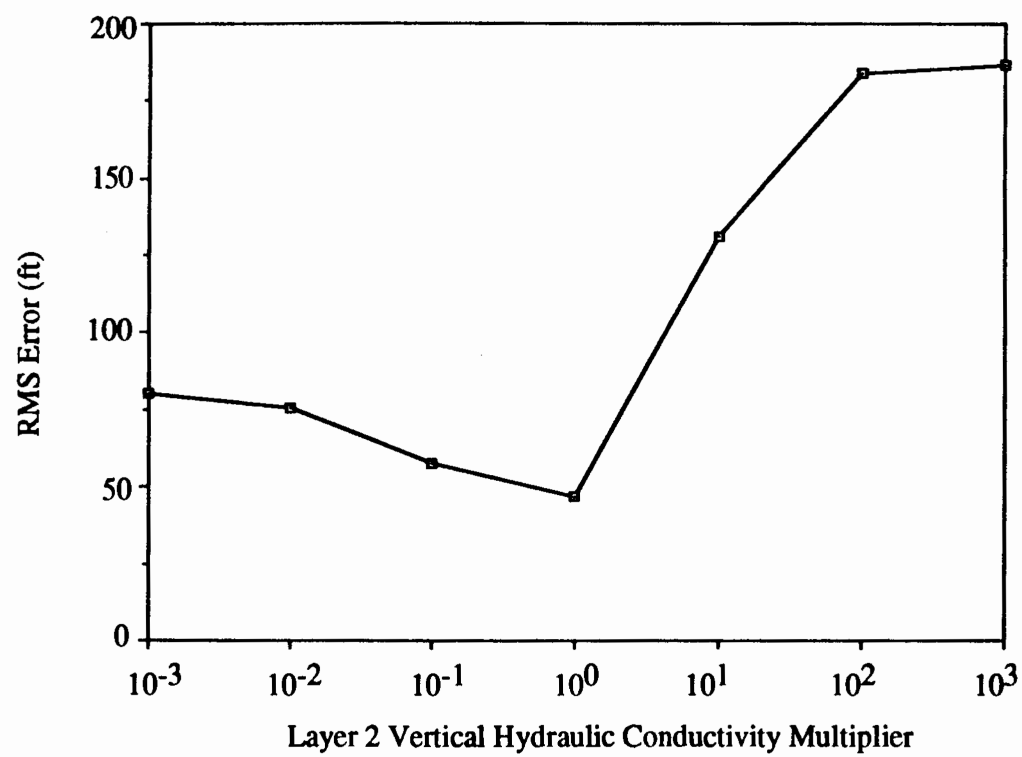


Figure 38. Model sensitivity to the nonuniform vertical hydraulic conductivity of the Upper Cretaceous aquitard in the partially calibrated model, expressed as RMS error.

recharge can enter the model. This causes heads in the upper Dakota aquifer to increase as the hydraulic connection between the aquifer and the overlying water table improves. The flux increase is most pronounced in the western Kansas plains, where the volumetric flow rate increases by more than two orders of magnitude. However, the recharge rate is still negligible with comparison to the other sections of the model. In the central Kansas dissected plains the volumetric flow rate increases by one order of magnitude, and all the streams receive discharge from the model. In the southeastern Colorado upland there is a small increase in the rate of recharge and discharge. With the increase in vertical hydraulic conductivity the total volumetric flow rate through the model increases to 193.5 ft^3/day (5.5 m^3/day), an increase of more than 1,000% over the total flow rate in the partially calibrated model. The heads in the upper Dakota are more than 200 ft (61 m) higher than those in the partially calibrated model between the two rivers in the western Kansas plains. The RMS error is not as sensitive to decreases in vertical hydraulic conductivity below the partially calibrated cell-by-cell set of values. As the aquitard becomes less permeable, recharge is progressively shut off to the model through its upper boundary. As a result, recharge to the upper Dakota is reduced and the heads in the aquifer decrease relative to the overlying water table. The decrease in vertical hydraulic conductivity causes a two to three order of magnitude decrease in recharge across the upper model boundary in the western Kansas plains. Recharge and discharge rates are also lower in the southeastern Colorado upland and the central Kansas dissected plains. The Saline River and some of its tributaries continue to receive discharge from the regional flow system but at lower rates. The other tributaries continue to supply recharge to the flow system but at higher rates. Discharge to the Arkansas River is unaffected by the vertical hydraulic conductivity decrease. The total volumetric flow rate decreases by 37% of the partially calibrated total volumetric flow rate to 10.4 ft^3/day (0.3 m^3/day) in this simulation. The decrease in vertical hydraulic conductivity causes the head difference between the water table and the upper Dakota aquifer to increase by approximately 50 ft (15 m) because of the reduction in recharge. This small increase in the head differential suggests that recharge to the upper Dakota aquifer from the Upper Cretaceous aquitard in the western Kansas plains is already small in the partially calibrated model relative to the underflow in the aquifer from upgradient parts of the model.

Role of River Valleys

Layer 1 was removed and replaced by layer 2 as the uppermost model layer. The upper model boundary was modified in the vicinity of the river by removing the valley and restoring hypothetically a semblance of the pre-erosional topographic profile. The specified heads along the upper boundary were increased in the vicinity of the river accordingly (columns 12–18). Other changes were made to the model input to reflect changes in the layering, layer thicknesses, and the location of the water table with respect to layer boundaries. In the second simulation the influence of the Saline River and its tributary streams on the flow system was examined using the same procedure that was outlined for the Arkansas River. Once the model grid was redesigned, the heads along the boundary were changed in columns 53–73 to reflect the modified upper model boundary. The head difference between the upper Dakota potentiometric surface and the water table was calculated for the partially calibrated model and the restored topography simulations and plotted to demonstrate the effect of the river valleys on the flow system.

Arkansas River Valley

The modifications made to the model grid produce major changes in the head distribution and in the cell-by-cell volumetric flow rate across the upper model boundary in the vicinity and downgradient of column 17 (Figure 39). Heads increase in the upper Dakota aquifer by as much as 200–300 ft (60–90 m) in the vicinity and downgradient of this location and only a small amount of water [0.04 ft^3/day (0.001 m^3/day)] is discharged across the upper model boundary. Downgradient from this region to column 32 of the model, heads in the upper Dakota aquifer are approximately equal to the elevation of the water table. However, beyond this point the head difference increases quickly with distance and significant subhydrostatic conditions are present in the upper Dakota aquifer eastward to the Saline River. The rapid increase in the head

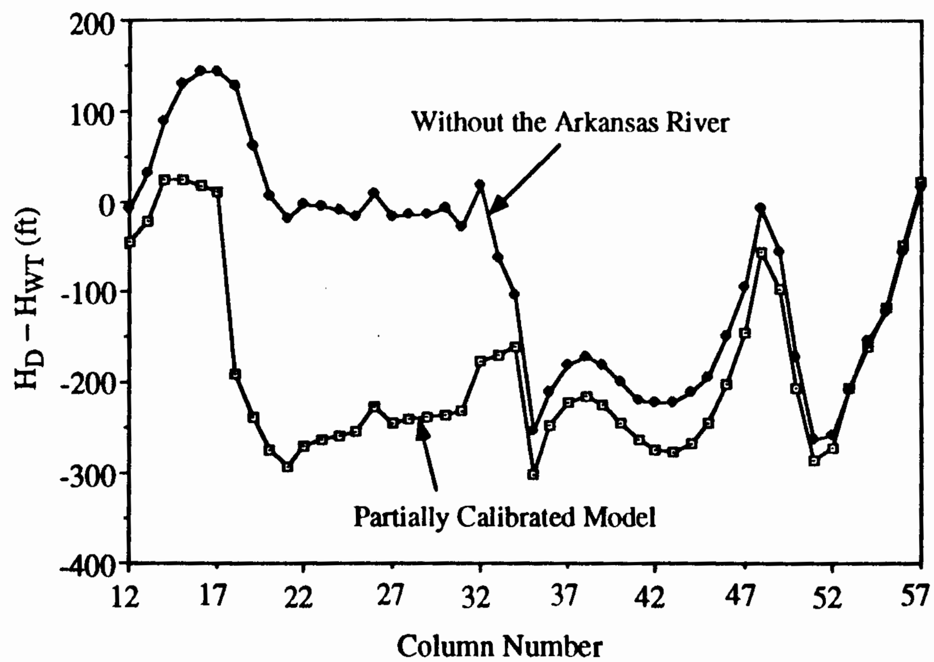


Figure 39. Head difference between the upper Dakota aquifer (H_D) and the overlying water table (H_{WT}) when the Arkansas River is removed from the simulation. The head difference in the partially calibrated model is shown for comparison.

difference may result because of the increase in the depth to the lower no-flow boundary near the axis of the Scott basin and beginning in column 32. This increases the cross-sectional area of the model and effectively lowers the rate of underflow per unit area through the model and causes a reduction in the head in the Dakota aquifer. Downgradient fromthe discharge near column 17, recharge to the model is essentially unchanged. Without the river there is a net decrease in the total volumetric flow rate through the model of 24%, which appears to reflect the loss of the Arkansas River valley as a major discharge zone.

Removal of the Arkansas River in this simulation appears to reconnect the upper Dakota in the western Kansas plains with its elevated recharge area south of the river. Thus it appears that the valley helps to maintain subhydrostatic conditions by short-circuiting some of the underflow back to the surface that otherwise would continue in the flow system. Without the river, heads in the upper Dakota aquifer are at or above land surface near column 17 and for a considerable distance downgradient. This demonstrates that the valley is an important hydrologic feature whose influence is more than local.

Saline River Drainage

Removal of the Saline River and its tributary streams from the model produces smaller but more widespread and significant changes in head in the model (Figure 40). The increase in head in the upper Dakota ranges from 1 ft (0.3 m) beneath the Arkansas River to slightly more than 100 ft (30 m) in west-central and central Kansas. The discharge across the upper model boundary in the central Kansas dissected plains disappears and becomes recharge to the model. Elsewhere, both the pattern and the amount of recharge and discharge are essentially unchanged, except for Big Creek which discharges a negligible amount of water [0.002 ft^3/day 6×10^{-5} m^3/day). The total water budget for the model decreases by 18%.

The head increase associated with removing the Saline River and its tributaries can be explained by using a simple model proposed by Belitz (1985). Belitz related the head in a confined aquifer to the hydraulic properties of the system, the head on the overlying water table

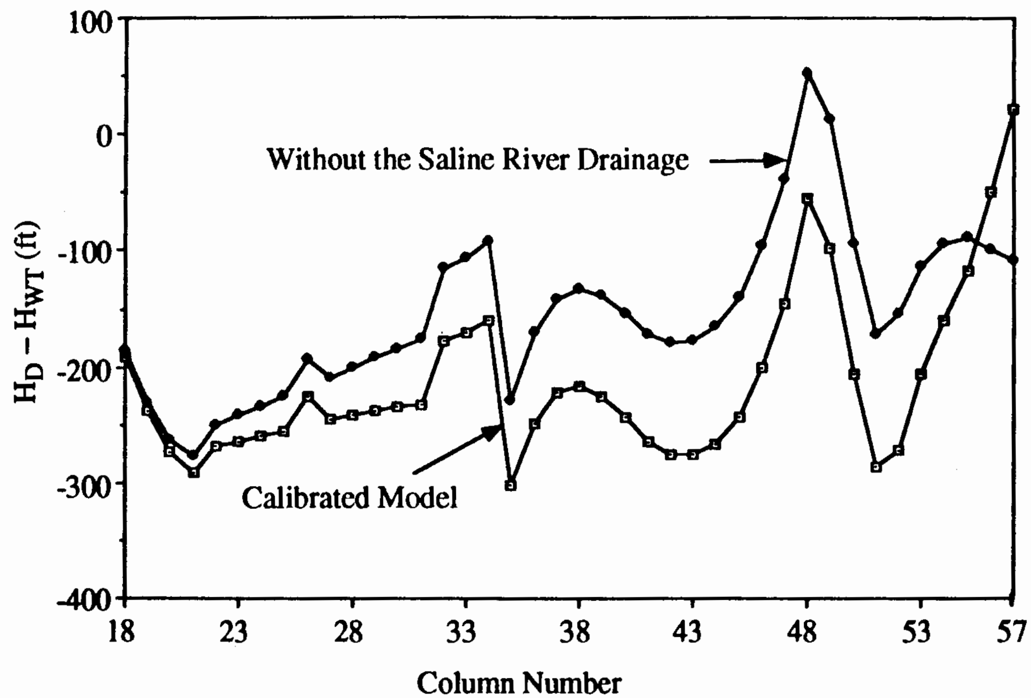


Figure 40. Difference in head between the upper Dakota aquifer (H_D) and the overlying water table (H_{WT}) when the Saline River drainage is removed from the model. The head difference in the partially calibrated model is shown for comparison.

and in the discharge area, and the geometry of the flow path from the water table to the discharge area (Figure 41):

$$(K_C/K_A)\,(L/D) = (H_B - H_D)/(H_R - H_B), \tag{3}$$

where K_A and K_C are the horizontal and vertical hydraulic conductivities of the aquifer and aquitard, respectively, L is the distance from a point in the confined aquifer to the discharge area, D is the aquitard thickness, and H_B, H_D, and H_R are the head in the confined aquifer at any point, the head in the discharge area, and the head on the overlying water table, respectively.

Removal of the Saline River drainage from the steady-state model moves the discharge point beyond the northeast end of the model and increases the distance L. Because the heads in the overlying water table and in the discharge area remain fixed, the increase in the distance to the discharge area must cause an increase in the head in the upper Dakota. In essence, the hydraulic connection between the aquifer and the overlying water table improves when the discharge area is moved farther away. In central Kansas the Saline and Smoky Hill rivers have cut valleys through this aquitard to the west of the main discharge area of the Dakota aquifer. These valleys have effectively reduced the lateral distance between the discharge area and the confined Dakota aquifer in western Kansas and thus have helped generate subhydrostatic conditions in the upper Dakota aquifer. This effect is suggested by the slight bending of the 1,500-ft and 1,750-ft potentiometric contours near where the Saline and Smoky Hill rivers have cut through the Upper Cretaceous aquitard in Ellis and Russell counties, Kansas (see Figure 19).

Conclusions

The hypothesis that is advanced here is that the upper part of the regional flow system, including the Dakota aquifer, is influenced primarily by the Upper Cretaceous aquitard, the Arkansas River in southeastern Colorado, and the Saline River drainage in central Kansas. The Upper Cretaceous aquitard is believed to allow significant recharge to the Dakota aquifer from the overlying water table in southeastern Colorado and in central Kansas where it is much thinner or absent. The Arkansas River is located just downgradient from the main recharge area in

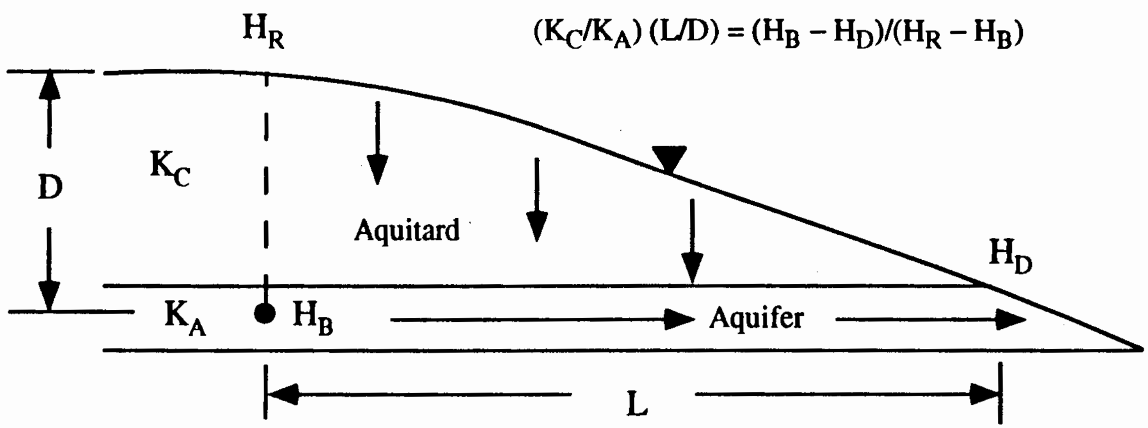


Figure 41. Combined effect of hydraulic conductivity, flow path geometry, and head on the water table and in the discharge area on the head in the confined aquifer at steady state. Modified from Belitz (1985).

southeastern Colorado and is believed to be a major discharge point from the western part of the flow system. The river influences the downgradient flow system by removing underflow that otherwise would continue into western Kansas. Consequently, the flow system beneath the Upper Cretaceous aquitard in western Kansas is isolated from its recharge area south of the river and from the overlying water table. The Saline River has eroded through the Upper Cretaceous aquitard to the west of the main outcrop area of the Dakota Formation in central Kansas and has effectively reduced the distance between the deeper, more confined parts of the Dakota aquifer and the discharge area. This has resulted in a further reduction of head in the Dakota aquifer upgradient from the discharge area. The Smoky Hill River in central Kansas may also influence the upgradient flow system in a similar way.

A steady-state numerical simulation of a portion of the intermediate-scale flow system in vertical profile view was developed to investigate the influence of these factors. The model results reveal significant development of local flow systems in the southeastern Colorado upland and the central Kansas dissected plains model sections (Figure 42). Local flow systems dominate in the central Kansas dissected plains section to the exclusion of the intermediate-scale flow system because of the high local relief associated with deeply incised river valleys. With the exception of the Arkansas River valley, local flow systems in the southeastern Colorado upland are not as well developed because of the high regional topographic slope but moderate local relief. The steady-state volumetric flux through the vertical profile is approximately 16.6 ft^3/day (0.5 m^3/day). Most of the recharge to the flow system is discharged to surface water locally in the southeastern Colorado upland and the central Kansas dissected plains sections. Ten percent of the total water budget moves beyond the Arkansas River and into the western Kansas plains. In this part of the model the amount of water moving into the intermediate-scale flow system through the Upper Cretaceous aquitard is 0.9% of the total volumetric flow rate.

The sensitivity analysis demonstrates that the Arkansas River and the Saline River and its tributary streams in concert with the Upper Cretaceous aquitard heavily influence the flow system beneath the western Kansas plains. Of all the hydrostratigraphic units, the model was

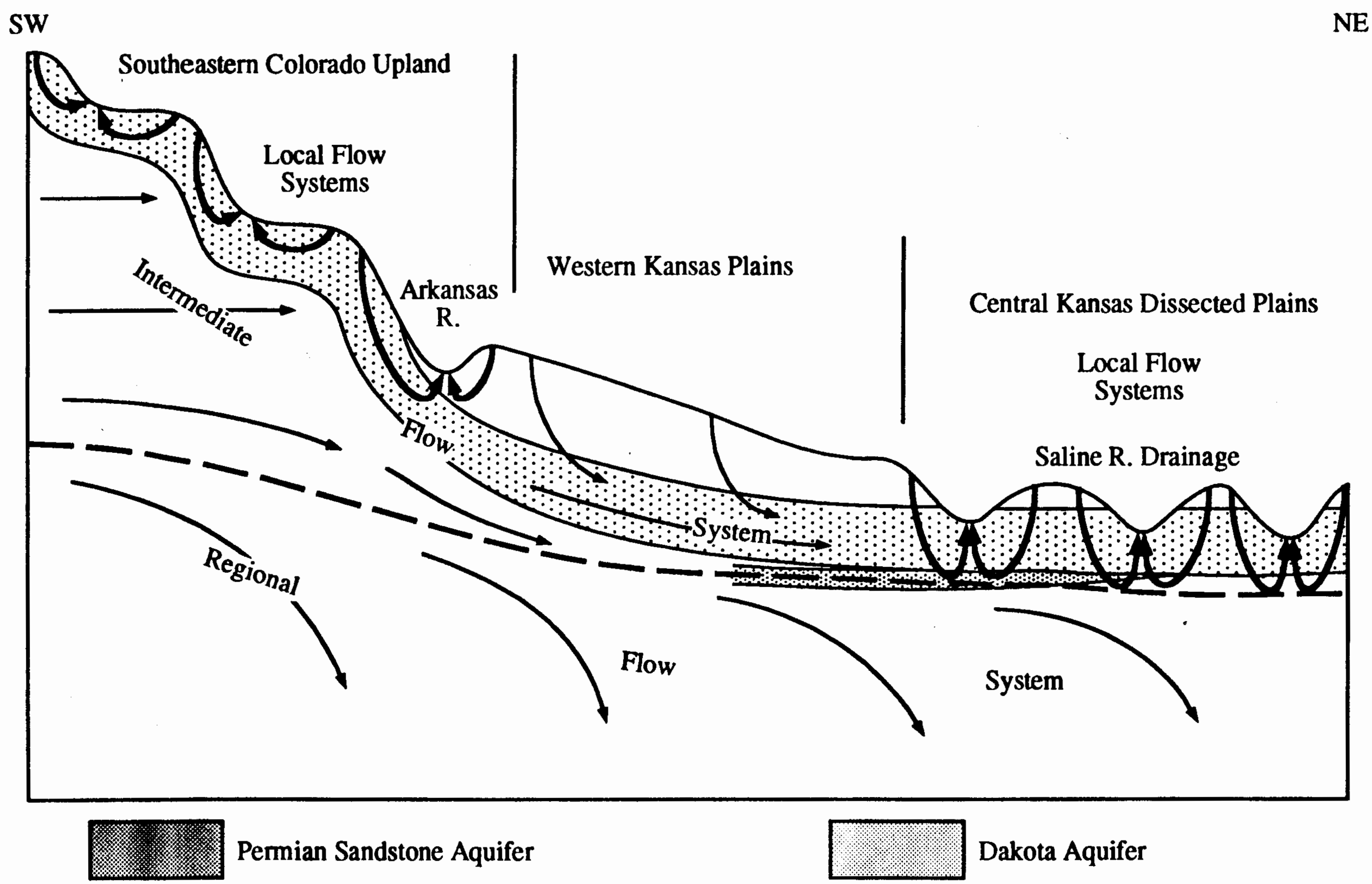


Figure 42. Conceptual model of ground-water flow in the vertical profile that extends from southeastern Colorado into western and central Kansas. In the southeastern Colorado upland the flow system is dominated by local flow systems and the intermediate-scale flow system. Beneath the western Kansas plains the intermediate-scale flow system dominates the flow of ground water northeastward from the Southeastern Colorado upland. In the central Kansas dissected plains subregion local flow systems completely dominate ground-water flow and the intermediate-scale system is not present.

most sensitive to increases in the vertical hydraulic conductivity of the Upper Cretaceous aquitard. The lowest RMS error resulted when the vertical hydraulic conductivity of the aquitard was treated as a nonuniform parameter. Large changes in the total volumetric flow rate, the distribution of recharge and discharge, and the head differences between the upper Dakota aquifer and the overlying water table caused by changes in layer vertical hydraulic conductivity indicate that the Upper Cretaceous aquitard restricts recharge to lower aquifer units and is a major factor that contributes to subhydrostatic conditions in the Dakota and underlying aquifers. Simulated removal of the Arkansas River increased heads in the upper Dakota aquifer by as much as 300 ft (90 m). In central Kansas simulated removal of the Saline River drainage increased heads in the upper Dakota aquifer by more than 100 ft (30 m) in parts of the western Kansas plains and the central Kansas dissected plains sections.

These results stress the importance of local flow systems in southeastern Colorado and central Kansas, a point not recognized in the simple artesian aquifer hypothesis applied by Darton (1905) to the Dakota aquifer. Darton was partially correct in recognizing that the steady-state flow system in the Dakota is topographically driven. From this he concluded that the high heads in the flowing wells in the Arkansas River valley resulted from elevated recharge areas south of the river. However, he did not recognize that the Arkansas River valley influences the downgradient flow system by removing underflow. Darton also believed that the Upper Cretaceous aquitard helped to maintain the head difference between the recharge area in southeastern Colorado and the discharge area in central Kansas, although he recognized that leakage through the aquitard could occur. The sensitivity analysis shows that, on the contrary, the Upper Cretaceous aquitard, in concert with the Arkansas and Saline rivers, fosters subhydrostatic conditions in the aquifers below the aquitard in western Kansas by hydraulically isolating them from sources of freshwater recharge. Darton viewed the Dakota aquifer as a uniformly dynamic system. He envisaged recharge entering the flow system in southeastern Colorado and moving northeastward toward central Kansas and returning to the surface in springs and rivers. The steady-state model shows that the flow system is dynamic only in southeastern Colorado and central Kansas with relatively high volumetric flow rates because of the local flow systems that have developed. Most of the water that enters the flow system in these areas is discharged locally, and little moves from southeastern Colorado to central Kansas.

The modeling results have implications for the assessment of the suitability of disposing wastes, primarily oil brines, into the Cedar Hills Sandstone and the future development of water resources in the upper Dakota aquifer in west-central and central Kansas. The Cedar Hills Sandstone is more suitable as a disposal zone where the Permian-Pennsylvanian aquitard is present. Flow rates in this zone suggest that it is relatively isolated from the rest of the flow system and that the brines will not migrate far from their point of injection. In central Kansas the flow system is much more dynamic, and the flow in the Cedar Hills Sandstone is highly variable and not isolated from the rest of the flow system. Thus the potential for contamination of shallow ground water is much higher in central Kansas than in areas to the west. In the area of water supply the primary factors determining the success of long-term use of the upper Dakota aquifer in western and central Kansas are the sources and rates of recharge to the aquifer. In west-central Kansas, the major source of recharge is the underflow from upgradient sources, which averages 1.6 ft^3/day (0.05 m^3/day) for each model cell. This, coupled with the low aquifer transmissivities, indicates that well fields should be designed using many low-capacity wells and large well spacing to capture the underflow and to minimize overdrafting. In central Kansas the major sources of recharge are more local but involve both freshwater and saltwater sources. Thus an additional concern is upconing of high-TDS-concentration saline ground water from the deeper aquifers during pumping.

Geochemistry

Water Chemistry at the Finney and Hodgeman County Pumping-Test Sites

Field analyses and sampling were conducted at the pumping-test sites to determine the water quality of the Dakota aquifer at the well location and variations in the quality that occur during pumping stress on the aquifer system. The construction of the Finney and Hodgeman county sites is described in the FY91 annual report (Macfarlane et al., 1992), and a summary of the hydrologic testing is given in a previous section in this report.

Field measurements of specific conductance, temperature, and pH were made and water samples were taken during the pumping test of the 5-in., 494-ft-deep (151-m-deep) well conducted on June 1–2, 1992, at the Finney County site. The specific conductance was monitored throughout the test and was found not to vary based on values that remained within the instrument measurement error of ±2%. The concentrations of major and minor dissolved constituents determined for water samples taken at 4.2 hr and 21.7 hr after the start of pumping were within analytical error, also indicating no detectable change in chemistry with time. The waters appear to have been pumped from within the more permeable strata horizontally with no detectable amounts of more saline water drawn from either the greater or the shallower depths during the test. This suggests that less permeable layers in the Dakota aquifer can restrict movement of overlying or underlying ground water at the site. The water quality in the Dakota Formation at the Finney County site is very fresh, with a specific conductance of 476 μS/cm and a total dissolved solids (TDS) content of 288 mg/l. The sulfate concentration (74 mg/l) was appreciably higher than the chloride concentration (6.1 mg/l), and the nitrate and ammonium ion contents were less than detection (0.1 mg/l as nitrogen). The site lies in the Arkansas River floodplain at the edge of an irrigated field where corn was being grown. The high sulfate/chloride ratio with undetectable nitrogen suggests that waters from the overlying alluvium of the Arkansas River that received sulfate-rich floodwaters in the past may have affected the chemistry over recent geologic time and that infiltration of water passing through the soils during agricultural use has not yet affected the water quality.

Water samples were collected soon after development from the three wells drilled by a private contractor for the KGS at the Hodgeman County site. The wells include an observation well and the pumping-test well screened in the Dakota Formation and a deeper observation well screened in the Cheyenne Sandstone underlying shale of the Kiowa Formation. The specific conductances of the waters from the Dakota wells (1,240–1,300 μS/cm) indicate that the waters were fresh with TDS contents less than 900 mg/l. The water collected from the Cheyenne well after development was saline. Field measurements were made and water samples were collected from the pumping well during the pumping test of June 3–4, 1992. The specific conductance rose from 1,200 to 7,300 µS/cm during the pumping. Extensive field studies were conducted to determine the cause of the salinity increase, and then the Cheyenne well was plugged. Field tests are continuing to examine the status of the site.

Characterization of Aquifer Interactions and Recharge Using Geochemistry

The chemistry of ground waters collected from the Dakota aquifer is being examined relative to the chemistry of precipitation, surface water, and ground waters in underlying and overlying aquifers and to the hydrogeology of the aquifer system in order to characterize recharge to the Dakota aquifer and interactions among the different aquifers. The initial results for the Ogallala aquifer-Dakota aquifer interaction at the Gray County monitoring site have been described earlier in this report (geohydrology section). The Gray County site is part of a cooperative effort with Southwest Groundwater Management District No. 3 (GMD3). Two other cooperative studies are being conducted, one with the Texas Bureau of Economic Geology and one with the Lawrence Livermore National Laboratory. The work of these institutions on the Dakota aquifer is providing additional information for the Dakota aquifer that could not be afforded under the present level of state funding. The work conducted and in progress in the Dakota aquifer program has established a knowledge base on which cooperative projects can build by sharing research and information resources.

Alan Dutton of the Texas Bureau of Economic Geology has focused his research on the paleohydrology of aquifers in the Great Plains. His research is designed (1) to determine whether certain ground waters beneath the Great Plains are "fossil" (ancient) water as a result of landscape evolution, (2) to determine whether a paleorecharge model for the southern Great Plains applies to other parts of the Great Plains, including western Kansas, and (3) to evaluate the implications of the results to paleoclimatology. A joint sampling of selected Dakota aquifer and

High Plains wells was conducted in early November 1991. The KGS collected water samples for determination of dissolved major, minor, and trace inorganic and radiochemical constituents; Dutton collected samples for measurement of isotopic and selected dissolved inorganic constituents. The isotopes of interest include carbon-13, carbon-14, chlorine-36, and the stable isotopes oxygen and deuterium for estimating the climatic characteristics and the age of the recharge.

A few staff members of the Lawrence Livermore National Laboratory (LLNL) of Livermore, California, are interested in applying measurement of several isotopic and dissolved trace gas and inorganic constituents to improve methods for characterizing the paleohydrology, especially recharge, and the hydrogeochemistry of aquifer systems. The LLNL has facilities that have been used mainly in examining nuclear testing sites and present and proposed locations of nuclear waste disposal. The laboratory wishes to expand the application of these facilities to aid in resource and environmental studies of the United States. The research being conducted on the Dakota aquifer by the KGS provides a valuable field test for these methods. In turn, the state of Kansas will obtain additional data that will assist in assessing the recharge and hydrology of the Dakota aquifer system.

Staff members of the KGS and LLNL planned for sampling well waters in the Dakota aquifer system along a flow path from a recharge area in southeastern Colorado through the confined aquifer in southwestern and central Kansas to a discharge area along the eastern outcrop band. The flow path is shown in Figure 4. A geologic cross section along the flow path is illustrated and discussed in the FY91 Annual Report (Macfarlane Et al., 1992, Figure 39, p. 66). The first joint sampling was conducted in May 1992 in southeastern Colorado and southwestern Kansas. The second sampling took place in July 1993 from southwestern to central Kansas. Most of the sample locations of the joint study with Alan Dutton are in the vicinity of the same flow path being studied in cooperation with the LLNL, whereas two of the wells sampled are along the southern flow path or cross section illustrated in Figure 38 of the FY91 annual report

(Macfarlane et al., 1992, p. 65). Results from both the Texas and LLNL cooperative studies will be discussed n the FY93 annual report.

Coupled Geochemical and Mass Transport Model for North-Central Kansas

Work on the simulation of salinity and chemical changes in the Dakota aquifer in north-central Kansas based on a coupled geochemical and flow model focused on establishing the geochemistry of the cross sections to be modeled. One section is the saline-freshwater transition zone in the Dakota aquifer along the drainage divide between the Solomon and Republican rivers from the southeastern corner of Jewell County through the northeastern corner of Mitchell County to west-central Cloud County. The other cross section involves stream-aquifer interactions across the Republican River valley at Concordia in north-central Cloud County. A copy of the program selected for the coupled mass transport and geochemical simulations, HYDROGEOCHEM, has been obtained. The program was adapted to run on a microcomputer and initial testing was conducted.

In north-central and central Kansas the ground-water chemistry data indicates that ground water in the Dakota aquifer is a mixture of waters from the Permian Cedar Hills Sandstone, regional flow within the aquifer from the west, and local surface recharge. The Cedar Hills Sandstone is part of the Permian red bed evaporite sequence. In western Kansas the Cedar Hills Sandstone is cemented by halite and other minerals, such as anhydrite, magnesite, and dolomite. Along the east margin of the Permian salt basin, halite cement is not present in the Cedar Hills Sandstone because it was removed by dissolution during subaerial exposure in pre-Cretaceous time and by ground-water recharge and discharge after it had been deposited. Na-Cl water from halite dissolution is the dominant water type in the Cedar Hills aquifer.

Computations based on the geochemical model SOLMINEQ88 were made to determine the state of saturation of Dakota ground water relative to major minerals. The geochemical model results show that ground water in the Cedar Hills Sandstone is only slightly undersaturated with respect to anhydrite ($CaSO_4$), which means that some dissolution of anhydrite could occur in the formation. The model also indicates that the Cedar Hills water is saturated with magnesite ($MgCO_3$) when the water is forced to be saturated with calcite by allowing the pH to be adjusted by the program. The resultant computed pH values were between 7 and 6.3. Magnesite has been observed in cores of the Cedar Hill Sandstone in western Kansas. Recharge of water from overlying units in parts of the Cedar Hills Sandstone causes dissolution of magnesite and elevation of magnesium and bicarbonate concentrations. High magnesium and bicarbonate water also occurs near the contact of the Dakota and Cedar Hills aquifers where the Cedar Hills discharges to the base of the Dakota aquifer.

The Dakota water immediately west of the Cedar Hills subcrop is characterized by Na-HCO_3 type water, which is a result of cation exchange of calcium and magnesium for sodium. The typical range of ground-water TDS concentration in this area is 900–1800 mg/l. Based on water samples obtained from Trego County and the western part of Ellis County, typical concentrations of calcium and magnesium are in the ranges 8–12 mg/l and 3–5 mg/l, respectively, and the Ca/Mg equivalent ratios are in the range of 1–1.7. The depletion of calcium causes dissolution of calcite, which increases the ground-water pH to as high as 8.5.

The geochemical model shows that dissolution/precipitation of calcite is a major factor controlling ground-water chemistry throughout the entire system. Precipitation of calcite keeps the bicarbonate concentration low in the Cedar Hills water. In the confined Dakota aquifer cation exchange keeps the calcium concentration low while equilibrium with calcite maintains the bicarbonate concentration at a relatively high level (Figure 43).

Analysis using theoretical mixing curves of (calcium and magnesium versus sodium) indicates that factors other than simple mixing of Cedar Hills and confined Dakota waters occur in the system. The data indicate that after intrusion of Cedar Hills water into the Dakota aquifer, the magnesium concentrations in the mixed water are lower than the conservative mixing curve. If the concentrations of sodium and chloride in the high-TDS water are assumed to have come from dissolution of halite only, then the mole concentrations of sodium and chloride should be about equal. However, the difference of absolute mole values between the sodium and the

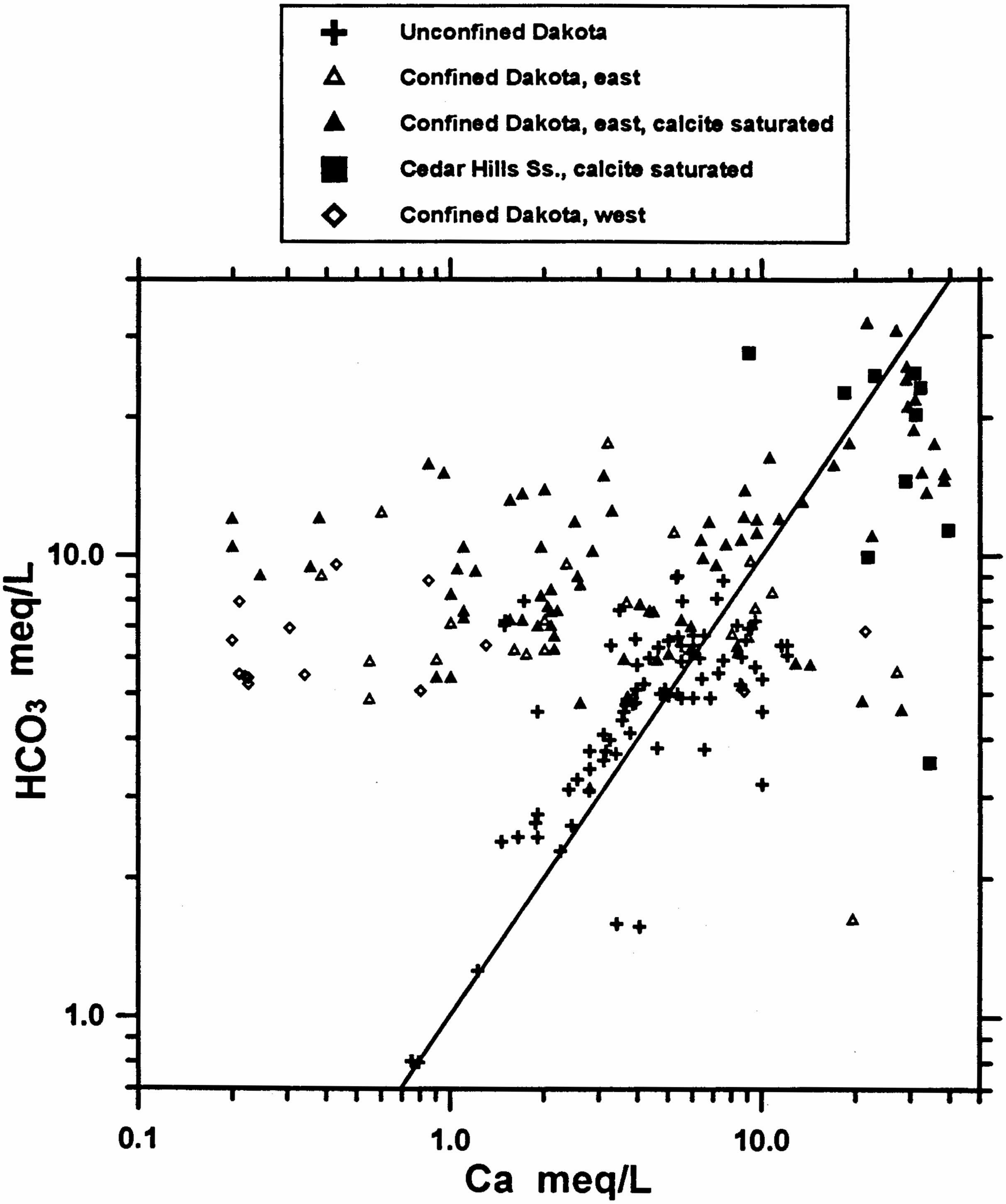


Figure 43. Bicarbonate versus calcium equivalent concentration for ground waters in the confined and unconfined Dakota aquifer and the Cedar Hills Sandstone in central and north-central Kansas. The line indicates the 1:1 relationship of the two constituents.

chloride shows that the sodium exceeds the chloride by about 47 meq/l for the water near the contact of the Cedar Hills and Dakota aquifers. Normally, water samples from the confined Dakota aquifer have sodium exceeding the chloride concentration only by about 5 meq/l. The difference is believed to be a result of cation exchange. The most extensive cation exchange occurs in the zone of mixing of Cedar Hills and Dakota waters because of the extremely high magnesium concentration from the Cedar Hills water. The intensity of cation exchange decreases along the ground-water flow downstream to the east. This feature can be illustrated by the difference between the sodium and chloride concentrations in the ground-water samples. Figure 44 shows that the cation exchange process not only decreases the calcium and magnesium concentrations in the Dakota aquifer but also increases the calcium/magnesium ratio from less then 0.2 to about 1.5 because of greater exchange of magnesium for sodium in the early stage of ion exchange. The quantity of cation exchange capacity and the selectivity coefficients to be used in the coupled flow and chemical reaction model will be estimated using sensitivity analysis in the coupled hydrochemical model.

Some lenses of calcite or high-magnesian calcite cemented sandstone found near the western portion of the eastern band of outcropping Dakota strata may indicate that the mixing of confined Dakota water with surface recharge in the outcrop area causes precipitation of calcite in the chemical transition zone. This point will be examined further during simulations of the coupled hydrochemical model.

Salinity Source Investigations in Central Kansas

Saltwater Sources in the Smoky Hill, Saline, and Solomon Rivers

Ground water discharges from the Dakota aquifer to alluvial aquifers along the eastern outcrop-subcrop belt. The discharge mixes with direct recharge from precipitation on the alluvium, with recharge from rock units younger and older than the Dakota Formation and with recharge from Dakota rocks cropping out at higher elevations where river valleys have cut deeply into the aquifer strata. The mixture of recharge in the alluvium then discharges to the river and is

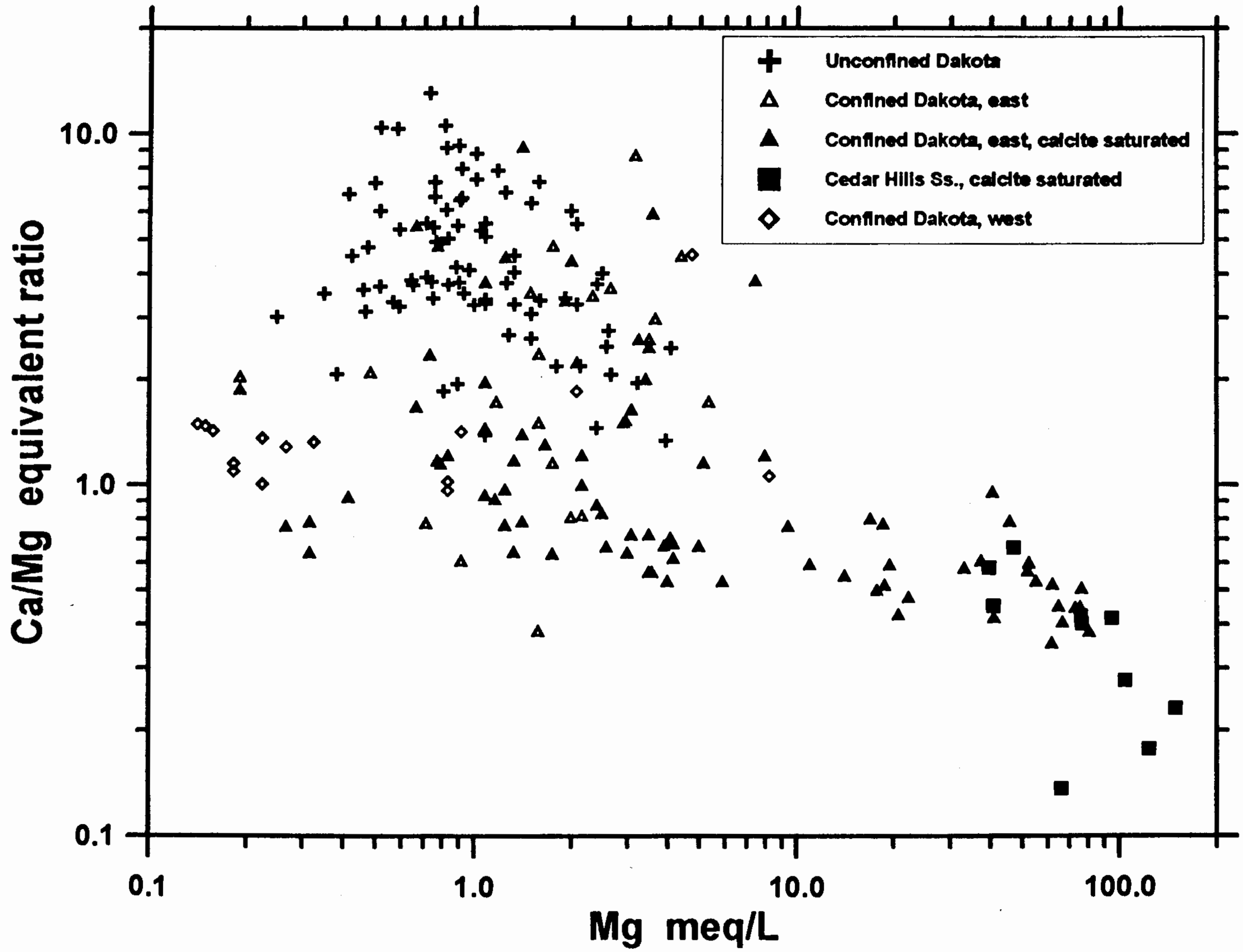


Figure 44. Calcium/magnesium equivalent ratio versus magnesium equivalent concentration for ground waters in the confined and unconfined Dakota aquifer and the Cedar Hills Sandstone in central and north-central Kansas.

the main control on the major dissolved constituents in the river water during moderate to low flows. Ground water in the Dakota to the west of the outcrop-subcrop boundary of the aquifer in central Kansas is saline. Where the saline water has not been diluted by local freshwater recharge to outcropping Dakota strata, the saline discharge contributes to the salinity of stream and river waters.

Four river valleys cross the eastern edge of the confined Dakota aquifer where saline ground water is present: the Republican, Solomon, Saline, and Smoky Hill rivers. Saline Dakota discharge enters the alluvium of the Republican River valley in southwestern Republic and northern Cloud counties, the Solomon River valley in Mitchell and southwest Cloud counties, the Saline River valley in Russell and Lincoln counties, and the Smoky Hill River valley in southeast Ellis, southern Russell, and northwest Ellsworth counties. The most saline water generally discharges several miles or more downstream of where the outcrop-subcrop boundary first crosses the river valley. The impact on the river-water quality depends not only on the amount of the saline ground-water discharge but also on the river flow that dilutes the discharge.

Appreciable portions of the areas of natural saline discharge to the Smoky Hill and Saline River valleys are also within oil and gas fields. Although oil fields are not present in the area of saline Dakota discharge to the Solomon River valley, they do occur upstream in the South and North forks of the river. A water-quality concern is the possible contribution of oil-field brine pollution to the total salinity of the alluvial aquifer and hence the river. The Kansas Water Office (KWO) and the KGS conducted a study of selected portions of the Solomon, Saline, and Smoky Hill rivers to assess whether oil brine is currently contributing to the total salinity of the river water. The KWO collected river-water samples during low flows in October 1991 and January 1992 (Table 5) and gave them to the KGS for geochemical identification of salinity sources. The KGS had previously collected samples in 1988 from the Saline River above and below the Haberer salt marsh in northwestern Russell County; these samples are included in the discussion. During the sampling in January 1992, the KWO also collected municipal waste water discharged from the cities of Stockton and Hayes and saltwater from a well in the Cedar Hills Sandstone in north-central Ellis County to provide waters that could be used to assist in the differentiation of natural and anthropogenic salinity.

The chloride sources were identified using mixing curves and background data for halite solutions in Permian strata, ground waters in the Dakota aquifer system, and oil brines in central Kansas. The method is based on the occurrence of different bromide/chloride ratios in saltwaters of different origin and the conservative behavior of chloride and bromide in surface and ground waters. Sulfate/chloride ratios are also useful for complementing interpretations based on the bromide/chloride data. Halite solutions have low bromide/chloride ratios, whereas oil brines in Kansas typically have ratios more than 20 times greater. Saline ground waters in the Dakota aquifer have low bromide/chloride ratios, indicating intrusion of underlying Permian saltwater, although the ratios are slightly elevated over most halite dissolution waters given the same chloride concentration. These relationships are illustrated in Figure 45, which contains a zone of mixing between freshwaters and saltwaters in the Dakota aquifer and points for oil-field brines in central Kansas. Each curve on the diagram represents the conservative mixing between two end-point waters. Points for Dakota waters are not plotted in Figure 45 but would plot between the two solid curves that form the boundaries of the Dakota mixing zone. The zone of mixing of freshwaters with chloride contents less than 100 mg/l with oil brines is bounded by the two dashed curves. The estimation of chloride concentrations from a mixture of two salinity sources can be estimated using intersecting mixing curves on a bromide/chloride versus chloride graph. The method has been successfully used at the KGS for saltwater source identification in many different locations.

Waters from the South Fork Solomon River in Rooks and Osborne counties contain a greater concentration of sulfate (in mg/l) than chloride (Table 6). The main influence on the major dissolved constituents is probably mineralized ground-water discharge from Upper Cretaceous rocks. In general, the waters become fresher in the downstream direction as the river flow increases. The chloride concentration remains below the recommended limit for drinking

Table 5. Location Description and Flow for River Water Samples.

Location description	Location[a]	Sample date	Flow (cfs)
South Fork Solomon River			
1 mi east of Graham County at gage above Webster Reservoir, stage 1.09	8S 20W 07AD	1-08-92	<1
3 mi west of Stockton, river pool	7S 18W 33BC	1-08-92	<1
Just south of Stockton	7S 18W 25AC	1-08-92	1
South of Woodston at gage, stage 4.03	7S 16W 16DD	1-08-92	1.5
South of Alton, beaver dam upstream	7S 15W 12CA	1-08-92	9
South of Bloomington	7S 13W 18DD	1-08-92	12
Osborne at gage, beaver dam nearby	7S 12W 19DA	1-08-92	12
North of Corinth	7S 11W 22BB	1-08-92	13
Saline River			
1 mi upstream of Haberer salt marsh	12S 15W 15ABBB	7-07-88	N[b]
100 ft below stream from Haberer salt marsh, north side of river	12S 15W 14CAA	7-07-88	N
Bridge 1 mi downstream of Haberer salt marsh	12S 15W 13CBA	7-07-88	N
At gaging station near bridge of US–281, 4 mi north of Russell	12S 14W 34ADDD	10-29-91	<1
Bridge north from Bunker Hill	12S 13W 25BCCC	10-29-91	<1
Smoky Hill River and Big Creek			
1 mi east of Pfeifer, ponded, no flow	15S 17W 25DD	1-07-92	0
3 mi west of Russell County line, north side of river	15S 16W 27BD	1-09-92	0.5
1 mi east of Ellis County line, ponded, beaver dams, south side of river	15S 15W 20BB	1-07-92	N

Table 5 (cont.).

Location description	Location[a]	Sample date	Flow (cfs)
Smoky Hill River and Big Creek (cont.)			
4 mi east of Ellis County line, south side of river	15S 15W 10DDA	1-07-92	N
Above junction with Big Creek, north side of river, flow measured 1-09-92	15S 14W 06BC	1-07-92	1.6
Big Creek near junction with Smoky Hill River, flow measured	14S 15W 31BCC	1-07-92	5.0
2 miles west of US–283, north side of river	14S 14W 33BBB	1-07-92	11
Bridge of US 281, 6.5 miles south of Russell, north side of river	15S 14W 02BCCC	10-30-91	<2
As above		1-07-92	N
Bridge 4.5 miles south, 1 mile east of Homer, north side of river	14S 13W 32ADAD	10-30-91	2.5
As above, stage 2.21	"	1-07-92	12
Bridge 5 miles south of Bunker Hill, north side of river	14S 13W 36ADDA	10-30-91	3
As above	"	1-07-92	N
Bridge 3 miles south of Dorrance, north side of river	14S 11W 31BADC	10-30-91	3
As above, flow measured	"	1-07-92	15.5

The samples are listed in downstream order for each river. The first three samples from the Saline River were collected by the Kansas Geological Survey; the other samples were collected by the Kansas Water Office. Flows are estimated except where indicated as measured.
a.Township, range, section, quarter sections from largest to smallest quarter, A = NE, B = NW, C = SW, D = SE.
b.Flow not estimated.

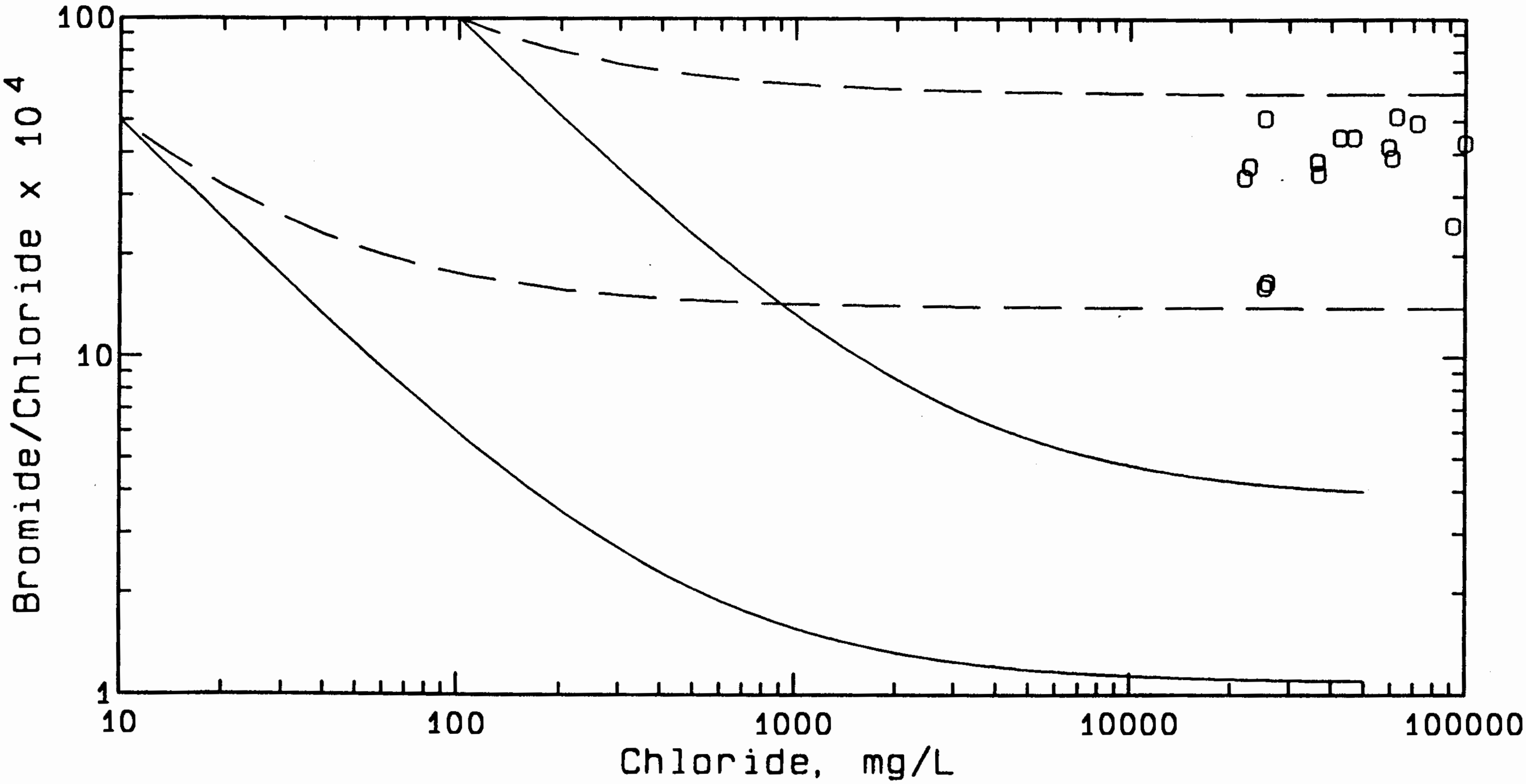


Figure 45. Zone of mixing of freshwaters with natural saltwaters in the Dakota aquifer and zone of mixing of Dakota freshwaters with oil brines in central Kansas based on bromide/chloride mass ratio versus chloride concentration. The open circles are oil brines.

Table 6. Specific Conductance and Dissolved Constituent Concentrations for the River Waters.

Sample description	Sample date	Sp.C. (μS/cm)[a]	Cl (mg/l)	SO_4 (mg/l)	F (mg/l)	Br (mg/l)
South Fork Solomon River						
1 mi east of Graham County line	1-08-92	1,645	157	281	0.40	0.28
3 mi west of Stockton	1-08-92	1,380	138	318	0.39	0.21
Just south of Stockton	1-08-92	1,650	234	260	0.30	0.16
South of Woodston at gage	1-08-92	1,450	148	298	0.30	0.28
South of Alton	1-08-92	1,165	101	255	0.29	0.20
South of Bloomington	1-08-92	1,135	89.4	229	0.28	0.18
Osborne at gage	1-08-92	1,125	87.5	229	0.27	0.18
North of Corinth	1-08-92	1,145	88.4	232	0.26	0.18
Saline River						
Upstream of salt marsh	7-07-88	2,430	405	531	0.5	0.52
At salt marsh	7-07-88	3,600	735	595	0.6	0.69
Downstream of salt marsh	7-07-88	3,650	747	601	0.6	0.70
North of Russell	10-29-91	16,150	4,650	1,431	0.75	1.70
North of Bunker Hill	10-29-91	25,300	7,720	2,100	0.72	1.97
Smoky Hill River and Big Creek						
1 mi east of Pfeifer	1-07-92	1,790	134	633	0.28	Int.[b]
3 mi west of Russell County line	1-09-92	2,440	408	422	0.90	0.24
1 mi east of Ellis Co. line	1-07-92	3,310	724	399	0.80	0.32
4 mi east of Ellis Co. line	1-07-92	3,500	760	401	0.89	0.31
Above jct. with Big Creek	1-07-92	6,810	1,781	556	0.75	0.50
Big Creek near junction	1-07-92	1,800	330	203	0.59	0.58
2 mi west of US–281	1-07-92	3,800	910	340	0.64	0.69
US–281 south of Russell	10-30-91	7,020	1,879	530	0.56	2.69
"	1-07-92	3,600	843	328	0.63	0.74
South of Homer	10-30-91	6,450	1,702	538	0.55	2.29
"	1-07-92	3,310	790	293	0.58	0.98
South of Bunker Hill	10-30-91	4,590	1,184	293	0.56	2.14
"	1-07-92	3,200	746	268	0.53	1.04
South of Dorrance	10-30-91	4,230	1,061	313	0.55	1.92
"	1-07-92	3,700	902	292	0.51	1.16
Wastewater discharges						
Stockton	1-23-92	3,300	638	371	0.38	0.18
Hays	1-23-92	1,690	220	299	1.02	0.16
Cedar Hills Sandstone						
11S 18W 26CAA	1-07-92	52,600	18,420	4,937	0.94	7.9

Samples are listed in the same downstream order as in Table 5. Additional samples include waste water discharge that enters the South Fork Solomon River below Stockton and Big Creek below Hays and ground water from a well yielding saltwater from the Cedar Hills Sandstone in north-central Ellis County.

a.Specific conductance in micro-Siemens or μmho/cm at 25°C.

b.Interference; sample was collected from a ponded location without flow.

water of 250 mg/l. No oil brine could be conclusively identified as contributing substantially to the chloride content of waters from the South Fork Solomon River.

One sample site, that just south of Stockton, appears to have an anomalously high chloride concentration compared with the other sites. The substantial increase in chloride in the river water at Stockton accompanied by decreases in the bromide/chloride and sulfate/chloride ratios fits the chemistry of the municipal waste-water discharge, which has a low bromide/chloride ratio for the chloride content present. Some waste waters from homes and municipalities have been found to be saline from the discharge of brine from water softeners. The bromide/chloride ratio for the waste-water discharge is low because the salinity source is halite, which is used to regenerate the capacity of a water softener to reduce hardness by exchanging calcium and magnesium for sodium. An estimated 90 mg/l of the chloride in the river at Stockton is probably derived from the mixture of the waste-water discharge and the river water (Table 7). Downstream, the river water chemistry returns to a trend more consistent with predominantly natural sources of major dissolved constituents. The next site downstream of Stockton (south of Woodston site) probably does not contain more than 20 mg/l chloride, which could be attributed to the sewage effluent.

Both chloride and sulfate concentrations increased greatly in the Saline River from northwest Russell to central Russell County, where the highest values are observed for any rivers in central and north-central Kansas (see Table 6). The waters from the Saline River have decreasing bromide/chloride ratios that reflect conservative mixing with a halite-dissolution brine (Figure 46) the bromide/chloride ratios are somewhat elevated relative to samples obtained from the Cedar Hills Sandstone and other Permian strata in the Nippewalla Group in Stafford and Pratt counties. The mixing curve for the Saline River waters (the dashed curve in Figure 46) falls within the band of points for naturally saline Dakota ground waters in central Kansas (the area between the two solid lines). The amount of any oil-field brine in the river waters, if present, would contribute less than a few percent to the chloride concentration. Although the sulfate concentrations increase appreciably, the sulfate/chloride ratios of the Saline River waters

Table 7. Estimate of the Natural, Oil-Brine, and Waste Effluent Contributions to the Chloride Concentration of the Water Samples from the Solomon River and Smoky Hill Rivers.

	Chloride (mg/l)				Oil
Sample description	Total	Natural	Waste effluent	Oil-brine	Oil brine, %[a]
South Fork Solomon River					
1 mi east of Graham County line	157	157	c	<10	<10
3 mi west of Stockton	138	138	c	<10	<10
Just south of Stockton	234	140	90	<10	<5
South of Woodston at gage	148	>130	<20	<10	<10
South of Alton	101	>90	<10	<10	<10
South of Bloomington	89.4	>80	<10	<10	<10
Osborne at gage	87.5	>80	<10	<10	<10
North of Corinth	88.4	>80	<10	<10	<10
Smoky Hill River samples collected October, 1991					
US–281 south of Russell	1,879	1,340	b	540	29
South of Homer	1,702	1,250	b	450	26
South of Bunker Hill	1,184	730	b	450	38
South of Dorrance	1,061	670	b	390	37
Smoky Hill River and Big Creek Samples collected January, 1992					
1 mi east of Pfeifer	134	134	c	d	d
3 mi west of Russell County line	408	408	c	<20	<5
1 mi east of Ellis County line	724	724	c	<30	<5
4 mi east of Ellis County line	760	760	c	<40	<5
Above jct with Big Creek	1,781	1,781	c	<90	<5
Big Creek near junction	330	230	b	100	30
2 mi west of US–281	910	810	b	100	11
US–281 south of Russell	843	740	b	100	12
South of Homer	790	640	b	150	19
South of Bunker Hill	746	560	b	190	25
South of Dorrance	902	700	b	200	22

The estimated error in the chloride concentration estimates for the oil brine contribution is ±20% which is equivalent to an error of 5–6% in the oil-brine percentage for the October 1991 Big Creek samples and 2–5% for the January 1992 samples from the Smoky Hill River.

a. Percentage of total chloride that is attributed to an oil-brine source.

b. Amount contributed probably less than a few percent.

c. Amount contributed unknown but probably small.

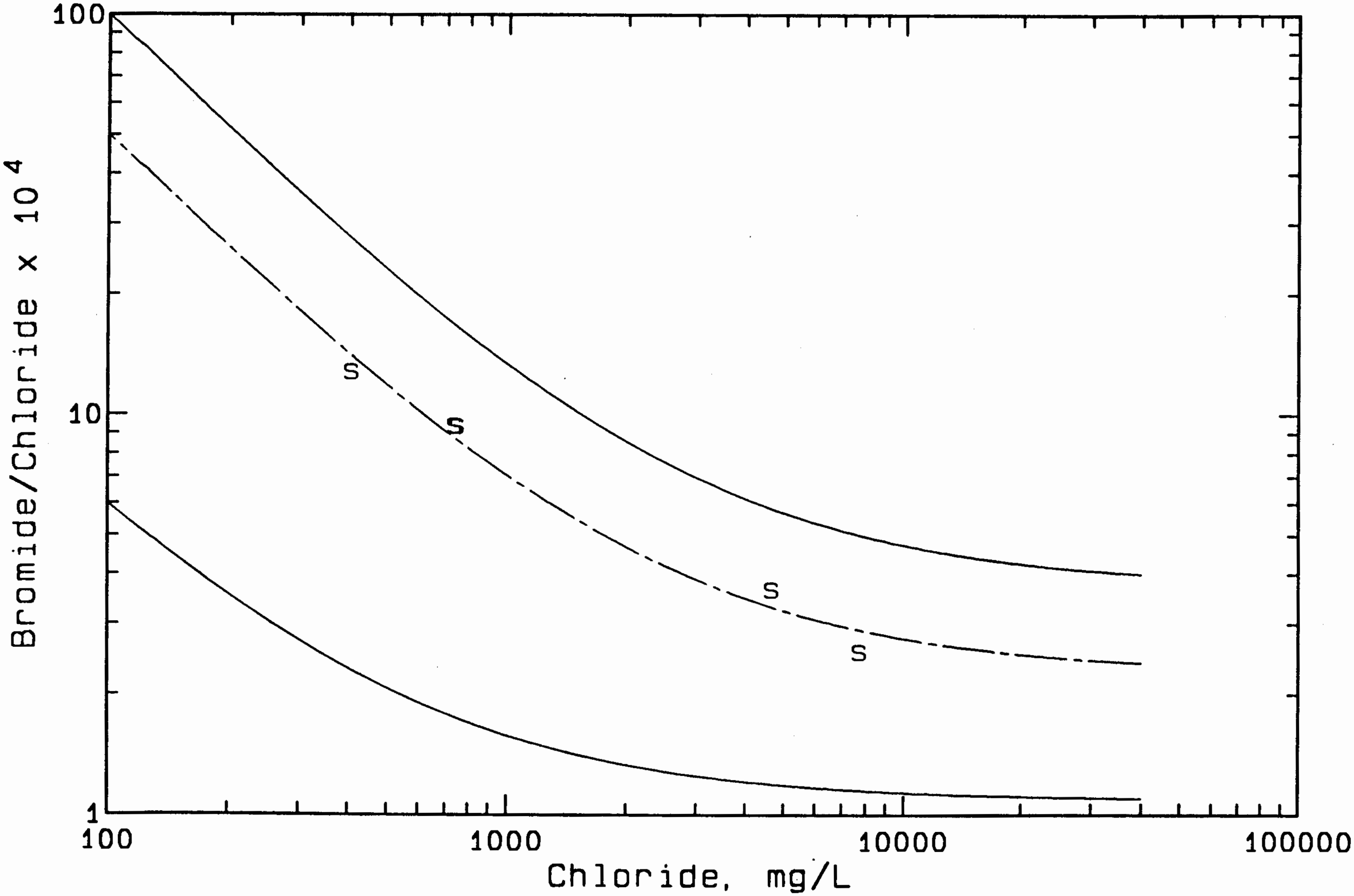


Figure 46. Mixing of freshwater and saline water in the Saline River in central Kansas based on bromide/chloride mass ratio versus chloride concentration. The solid curves are the boundaries of the mixing zone for freshwaters and natural saltwaters in the Dakota aquifer shown in Figure 45. "S" indicates Saline River water.

decrease from upstream of the Haberer salt marsh to the downstream site north of Bunker Hill. The sulfate/chloride ratio at the site north of Bunker Hill is still much greater than the low ratios for most oil brines in central Kansas. The sulfate/chloride ratio reflects the input of the sodium-chloride water with high sulfate contents in the saltwater-containing portions of the Dakota aquifer. The high sulfate is principally derived from anhydrite dissolution in underlying Permian strata.

The salinity source in the Smoky Hill River waters upstream from Big Creek is essentially all natural ground-water discharge based on the chemistry. Figure 47 includes the same solid curves as Figure 46, which bound the regional zone of freshwater-saltwater mixing in the Dakota aquifer. The points for Smoky Hill River waters above Big Creek can be fitted well with a mixing line (long and short dashed curve) with a saltwater end-point having a bromide/chloride ratio lower than that for the saltwater end-member for the Saline River curve. The lower end-point ratio fits the trend to even lower ratios for saltwater in Permian strata farther to the south in Stafford and Pratt counties. Oil brine, if present, does not contribute more than a few percent to the chloride concentration. In Ellis County the Smoky Hill River waters are characterized by a higher sulfate content (in mg/l) than the chloride content (see Table 2), probably reflecting the influence of Upper Cretaceous rocks. The amount of chloride from waste-water discharges from towns is unknown but is probably small. As the waters approach the Ellis-Russell county line, the sulfate concentration decreases and the chloride concentration increases. Downstream from the Ellis-Russell county line the chloride content of the river increases and the sulfate content decreases slightly to a relatively constant value, then the chloride content increases substantially because a large influx of saline water enters just above the junction with Big Creek. A comparison of the higher flow and lower salinity for river waters collected farther downstream in January 1992 with the values for the same sites in October 1991 suggests that the salinity of the river before the Big Creek junction was greater during the previous October. The increase in chloride content with a relatively moderate decrease in

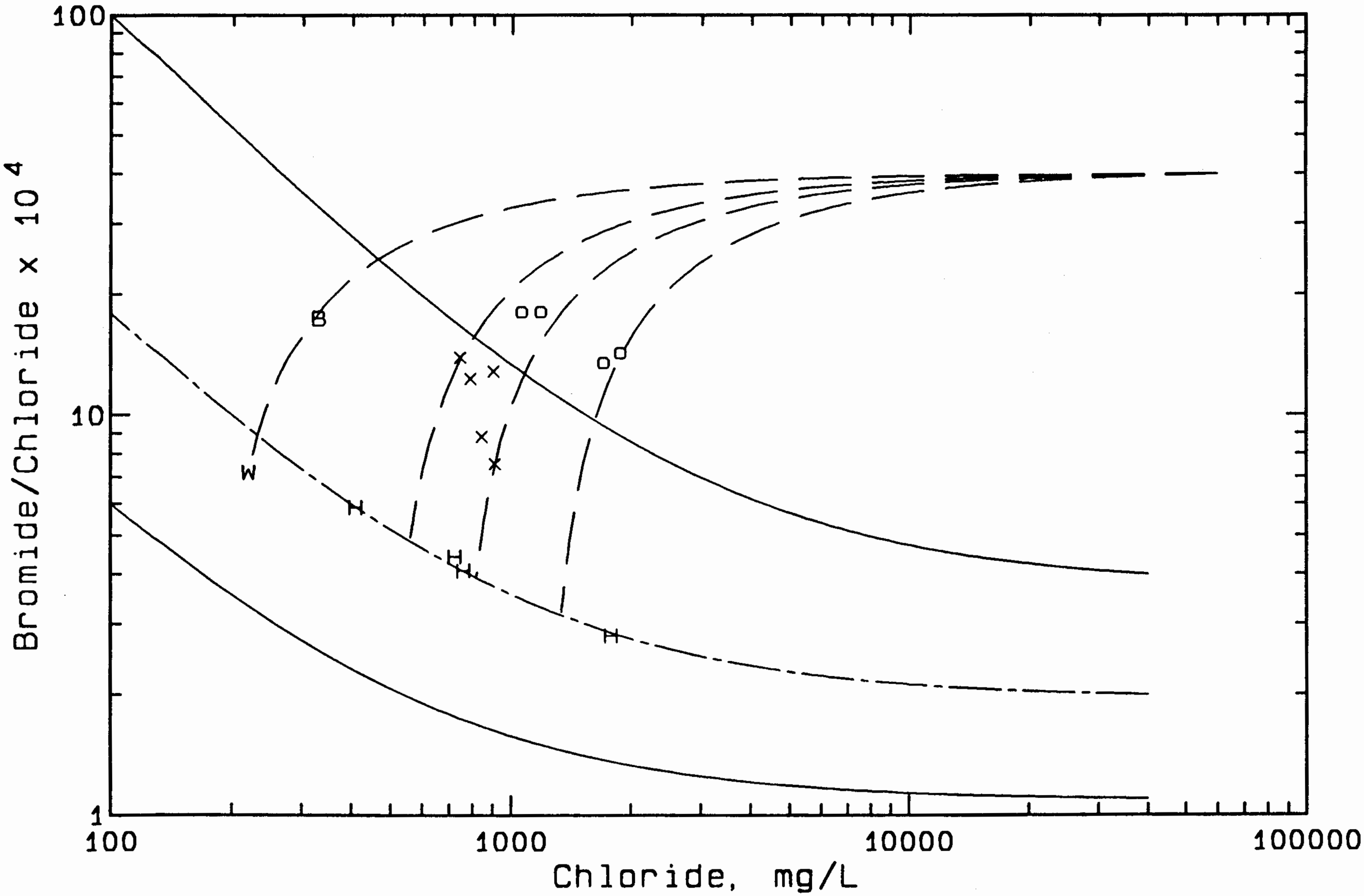


Figure 47. Mixing of freshwater, natural saline water, and oil brine in the Smoky Hill River in central Kansas based on change in bromide/chloride mass ratio with chloride concentration. The solid curves are the boundaries of the mixing zone for freshwaters and natural saltwaters in the Dakota aquifer shown in Figure 45. H, uncontaminated Smoky Hill River; o, contaminated Smoky Hill River, October 1991; X, contaminated Smoky Hill River, January 1992; B, Big Creek; W, Hays municipal waste water.

sulfate/chloride ratio in the river water above Big Creek also fits the chemistry of saltwater in the Dakota as derived from underlying Permian strata.

The water from Big Creek just above the confluence with the Smoky Hill River is slightly saline but contains a much lower chloride concentration than in the Smoky Hill River 1 mi (0.6 km) directly south (see Table 6). The bedrock channel of the Smoky Hill River at this location probably cuts deeper into the Dakota aquifer, where the water is more saline, than the bedrock valley of Big Creek. The Big Creek sample is more saline than the waste water from Hays. The waste-water discharge is expected to contribute a significant amount of flow to Big Creek during low flow periods. The bromide/chloride ratio is appreciably greater (see Figure 47) and the sulfate/chloride ratio is lower in the Big Creek sample than in the waste water and, given an equivalent chloride content, in the Smoky Hill River water in southwest Ellis County.

The curves with equal-length dashes in Figure 47 represent the mixing of average oil brine with Dakota ground waters of different salinities. Each curve was calculated such that it extends from the oil-brine end-point through a river water with an elevated bromide/chloride ratio to the mixing curve for a natural saltwater source for the Smoky Hill River. The chloride concentration at the intersection of the oil-brine mixing curve with the curve for natural saltwater represents the natural source in the polluted water. The intersection value for Big Creek water is listed in Table 7 along with the contribution from oil brine calculated as the difference between the natural source and total concentration of chloride. Thus Big Creek water appears to be contaminated by oil brine; the oil-brine contribution to the chloride concentration is estimated as 100 mg/l, which is 30% of the total chloride in the sample. The extension of the dashed curve for the Big Creek sample meets almost exactly the point for the waste water from Hays, suggesting that the waste water might be the main contributor to the flow at the sampling time. Thus the chemistry of the Big Creek sample appears to fit the mixing of waste-water discharge and oil brine diluted by freshwater. The larger the contribution of waste water to the chloride, the smaller the natural contribution and the larger the oil brine contribution to the chloride content based on mixing curve computations.

The true oil-brine contribution to the Big Creek water and to the other samples with elevated bromide/chloride ratios depends on the bromide/chloride ratio of the oil brines that actually cause the contamination. A higher oil-brine ratio would give a mixing line with a greater curvature, resulting in an interpretation of a higher contribution of natural chloride and a lower percentage of oil-brine contamination; the lower the oil-brine ratio, the higher the oil-brine percentage.

The water in the Smoky Hill River below the junction with Big Creek becomes less saline as a result of the dilution with Big Creek water and, possibly, with additional fresh discharge from the alluvium of the river valley. The river water continues to drop in salinity, although the salinity increased at the site south of Dorrance for the January 1992 sampling in comparison with the continued decrease at the Dorrance site for the October 1991 sampling. The salinity was lower for the higher flows in January 1992 compares with the approximately five–times lower flow in October 1991.

The bromide/chloride ratios for the Smoky Hill River waters below the junction with Big Creek are appreciably higher than the ratios for the mixing of freshwater and natural saltwater discharge from the Dakota aquifer (see Figure 47). The chemistry indicates that the source of salinity in Smoky Hill River waters downstream from Big Creek is a mixture of freshwater, Dakota aquifer saltwaters, and oil brine. Curves illustrating the mixing of average oil brine with naturally saline river water are shown in Figure 47 for three of the river samples.

The contribution of oil brine to the chloride content in the section of the Smoky Hill River from below Big Creek to south of Dorrance ranged from 390 to 540 mg/l in October 1991 and from 100 to 200 mg/l in January 1992. The percentage of oil brine in the total chloride content was also greater during October than in January. The oil-brine pollution appears to contribute not only higher concentrations of chloride during lower flows but also a greater proportion of the total salinity. The changes in oil-brine contamination downstream from the junction with Big Creek exhibited both similarities and differences between the October and January samplings. At both sampling times the percentage of oil-brine pollution first increased to south of Bunker Hill and then leveled out. This suggests that the main entrance of oil brine is within the Big Creek to Bunker Hill section. Both the total chloride concentration and the oil-brine chloride content decreased downstream from Big Creek in October; the total chloride decreased to south of Bunker Hill and then increased to Dorrance and the oil-brine chloride concentration increased to Bunker Hill and was about the same at Dorrance in January. The river flows in this section generally increased downstream, giving a mass flow of oil-brine chloride that was relatively constant from Big Creek to south of Dorrance in October in contrast to an increasing mass of oil-brine chloride downstream in January. Therefore different stream-aquifer interactions in changing climatic conditions are important in controlling both the quantities and the percentage of contamination at each location along the river.

Sulfate concentrations generally decrease and sulfate/chloride ratios remain relatively constant downstream in the Smoky Hill River below the junction with Big Creek. If the oil-brine contribution to the chloride content were subtracted from the Smoky Hill River samples, the sulfate/chloride ratios would be higher and closer to the range for the Saline River waters. The sulfate concentration in the oil brines is typically so low compared with the chloride concentration that it contributes little, if at all, to the sulfate concentration in polluted water.

Most of the Smoky Hill River from Big Creek to south of Dorrance passes through oil and gas fields, specifically, the southern parts of the large Gorham and Hall-Gurney fields. The source of the oil-field pollution in the river water could be from saline ground water discharging from the alluvial aquifer contaminated by surface disposal ponds and/or discharge of brine from the Dakota aquifer into the alluvium along the bedrock channel underlying the river valley. Frye and Brazil (1943) indicate that in the early 1940's some oil brines from these fields were being disposed in wells in Cretaceous sandstones of the area and in deep disposal wells. Surface disposal ponds were probably more prevalent before subsurface disposal become the general practice in the area. A map in Frye and Brazil's (1943) bulletin shows that a few of the shallow disposal wells were located near the Smoky Hill River valley from Big Creek to south of Homer.

The fluoride concentrations are lower in the waters from the South Fork Solomon, Saline, and Smoky Hill rivers than in ground water in the Dakota aquifer near the sampling sites. This reflects dilution of the Dakota aquifer water that enters the base of the alluvium with freshwaters in the alluvium derived from direct recharge or recharge through outcropping strata overlying the Dakota Formation. Although fluoride concentrations in the river waters generally increase with increasing salinity, the total range is relatively small and is not as useful as the bromide, chloride, and sulfate concentrations for saltwater source identification.

The well-water sample from the Cedar Hills Sandstone collected in January 1992 has a salinity close to that of seawater. A point for the water would plot slightly above the mixing zone for freshwater and natural saltwater in the Dakota aquifer shown in Figures 45–47. A few percent of the chloride content could be from oil brine, especially because the well is in an oil field. An oil-brine source is also suggested because the bromide/chloride ratio is higher than tge ratui cakcykated for the monitoring well in the Cedar Hills Sandstone drilled in northern Ellis County (NENE sec. 30, T. 12 S., R. 18 W.) for previous Dakota studies. However, there is not enough data available to rule out the possibility that the composition is natural and may reflect a few percent of seawater trapped in low-permeability shales that is still diffusing into the more permeable sandstone, increasing the bromide/chloride ratio. A comparison of the bromide/chloride ratios with geographic location for the Dakota aquifer and for the KGS monitoring well in the Cedar Hills Sandstone in northern Ellis County are considered further in the next section.

Saltwater Sources in Test Wells of the City of Hays

As a result of growing demands for water supplies, limits on increasing the amount of ground water from Smoky Hill River alluvium, and problems in obtaining good-quality surface waters, the city of Hays investigated the potential use of the Dakota aquifer as a supplemental water source. Several test wells were drilled recently in an attempt to determine where and at what depth sufficient quantities of usable water could be found in Dakota sandstones in Ellis

County, preferably relatively close to Hays. Slightly saline water was considered usable because it could be mixed in small quantities with fresher water from the current supply. In addition, the city was considering methods of treatment to lower salinity, such as electrochemical dialysis and reverse chemical osmosis.

Several test wells were drilled in the spring of 1992 in the Dakota aquifer a few miles southwest of Hays. Production wells were also later installed in parts of the area. Oil fields are present in the test and production well area; therefore a concern of the Kansas Corporation Commission and of the city was whether oil-brine contamination is present in the Dakota aquifer either from brine migration upward along the annular space in oil production or saltwater disposal wells or from past injection into the Cedar Hills Sandstone underlying the Dakota aquifer. If oil-field brine were not present, another concern was whether the oil and disposal wells have allowed additional Permian saltwater to enter the Dakota aquifer. Samples of the test wells were sent to the KGS for geochemical identification of salinity source, using the same method as that described in the previous section for river waters. The chemical character of the test-well water was also examined for anomalous concentration relationships relative to other data for central Kansas.

Thirty-six samples from 13 boreholes drilled into the Dakota aquifer were sent to the KGS for analysis. The multiple samples for some holes were collected at different depths in the Dakota aquifer. One other sample was collected from a borehole drilled as a test well into a plugged oil well to within the depth of Dakota strata and then perforated. The chloride concentration for the test-well samples ranged from 445 to 2,344 mg/l as shown in Figure 48, and the chloride in the water from the perforated oil well was 3,230 mg/l (shown as a circle in Figure 48).

The points for the test-well waters follow a curve (one long and two short dashes) for the mixing of freshwater and natural saltwater in the Dakota aquifer that was derived from the underlying Permian strata through geologic time. The mixing curve falls between the mixing lines (alternating long and short dashes) for natural salinity that discharges from the Dakota

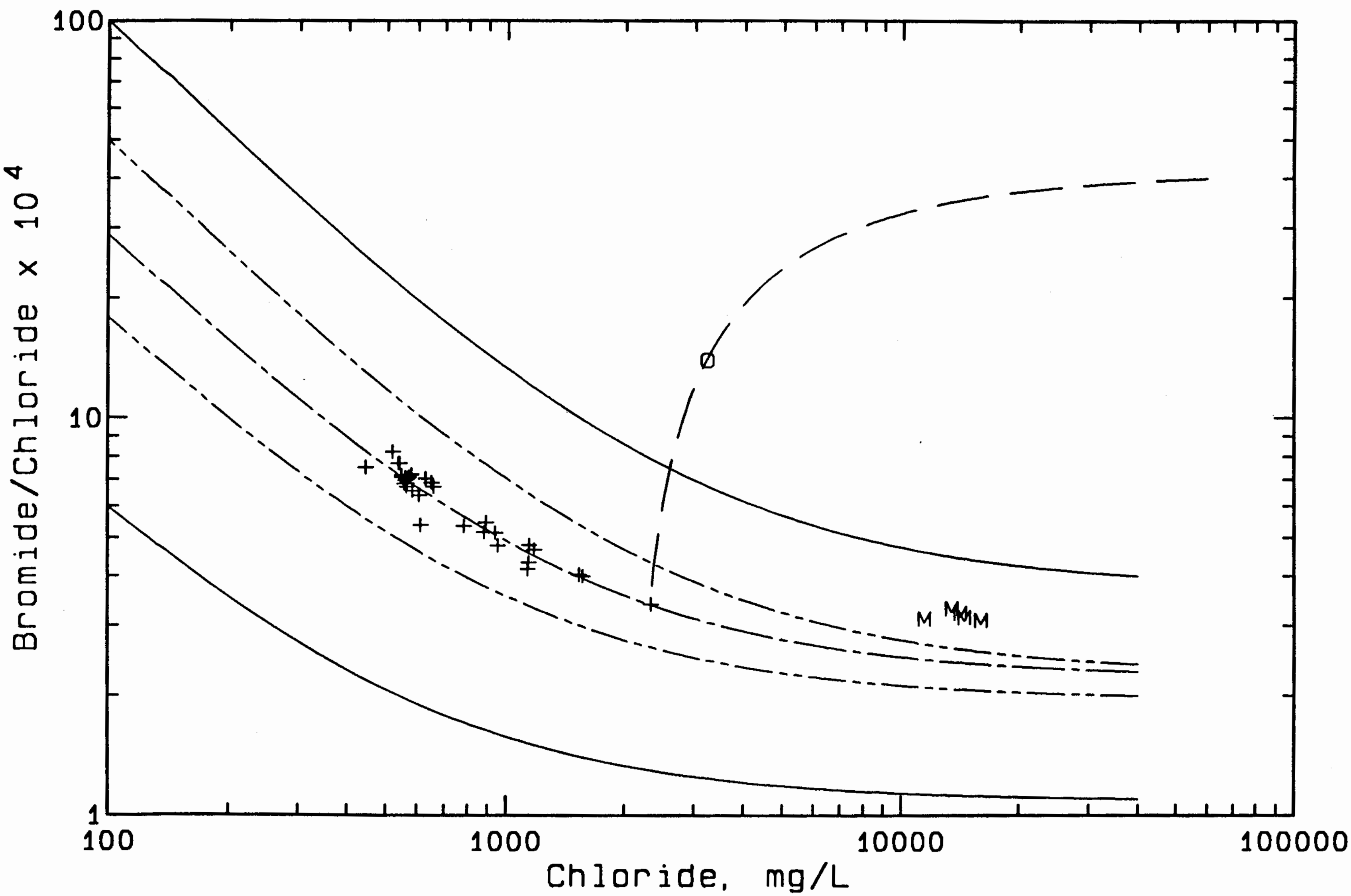


Figure 48. Mixing curves for ground waters from test and monitoring wells in the Dakota aquifer in Ellis County based on change in bromide/chloride mass ratio with chloride concentration. The solid curves are the boundaries of the mixing zone for freshwaters and natural saltwaters in the Dakota aquifer shown in Figure 45. The dashed curve above the Hays test-well curve is for the Saline River as shown in Figure 46; the dashed curve below the Hays test-well curve is for the Smoky Hill River, as shown in Figure 47. +, Hays test well; o, drilled and perforated oil-well plug; M, KGS monitoring well in northern Ellis County.

aquifer to the Saline and Smoky Hill rivers. The two solid curves are the boundaries for regional data that show mixing of freshwaters and natural saltwaters in the Dakota aquifer. These curves and those for the Saline and Smoky Hill rivers are also shown in Figures 46 and 47. The results indicate that no detectable contamination from oil brine is present in the test-well waters.

The location of the mixing curve for the test-well waters between those for the Saline and Smoky Hill rivers fits the geographic location of the test wells between the two rivers. Points for the monitoring wells in a borehole drilled by the KGS in northern Ellis County (NENE sec. 30, T. 12 S., R. 18 W.) for previous Dakota studies are also included in Figure 48. The monitoring wells are screened in the Cedar Hills Sandstone, the Cheyenne Sandstone, and the upper and lower Dakota Formation. The consistency of the bromide/chloride ratios for the monitoring-well waters indicates a Permian source of saltwater to the Dakota and an absence of oil brine. The trend of increasing bromide/chloride ratios for the saltwaters in the direction from the Smoky Hill River curve to the monitoring well suggests that greater amounts of remnant seawater trapped in low-permeability shales and diffusing to coarser parts of the Dakota could be present in northern Ellis and Russell counties compared with southern Ellis and Russell counties. The bromide/chloride ratio of seawater is 0.0035, a value within the range of oil brines in central Kansas, although the average oil brine value is greater.

In the test well area lower chloride concentrations were generally encountered in sandstones of greater permeability. The chloride content tended to increase with depth in the strata with overall finer-grained sediments, whereas decreases in chloride content were observed with depth at selected intervals in some wells. The salinity distribution suggests that the most permeable sandstone units have allowed faster flushing of old saltwater by fresher regional flow from the west. The decreases in salinity with depth could represent penetration into coarser sediments in the sandstone river channels in the aquifer.

The sample from the perforated borehole in the plugged oil well appears to be a mixture of oil brine and natural Dakota aquifer water. The curve with long dashes (see Figure 48) extends from an end-point representing average oil brine in central Kansas through the sample to intersect with the mixing curve for the Hays test-well waters. The intercept of the two curves is the expected chloride concentration in uncontaminated Dakota aquifer water (2,330 mg/l) outside the plugged well. Although the amount of oil brine interpreted in the sample (900 mg/l chloride) is 28% of the total chloride concentration in the sample, the amount is only about 1.5% of the concentration in the average oil brine. The attempt to perforate the well was apparently not successful, as indicated by a small yield of water, probably a result of the thickness of the cement in the annulus. Because less than 2% by volume of oil brine would be needed to mix with Dakota water to produce the observed chemistry, the water sample could be as easily explained by small amounts of remnant oil brine trapped somewhere in the casing and annular zone or by contamination of the Dakota aquifer outside the plugged well.

Hydrogeochemistry of Fluoride in the Dakota Aquifer

Fluoride concentrations range from less than 1 to greater than 7 mg/l in waters in the Dakota aquifer. High-fluoride water is of concern for drinking-water supplies because the maximum contaminant level for public water systems is 4 mg/L and the secondary (recommended) level is 2 mg/l. Dissolved fluoride is usually less than 1 mg/l in the eastern band of the aquifer where the Dakota crops out or underlies unconsolidated Quaternary sediments. Fluoride concentrations are 1–3 mg/l in both the Dakota and the Ogallala aquifers in most of the region where the Dakota directly underlies the Ogallala aquifer in southwest Kansas. Fluoride content generally increases from about 1 mg/l near the boundary of the Dakota aquifer confined by Upper Cretaceous rocks to greater than 4 mg/l in the Dakota aquifer where overlain by an appreciable thickness of confining rocks.

Fluoride concentration in Dakota aquifer water is correlated with the concentrations of certain major dissolved constituents. Fluoride is generally inversely related to dissolved calcium and magnesium. Although low fluoride content (<1 mg/l) exists in a wide range of calcium concentrations, the calcium is always greater than 30 mg/l (Figure 49a). Moderately high fluoride levels (>2 mg/l) nearly always occur in waters with calcium contents of less than 100

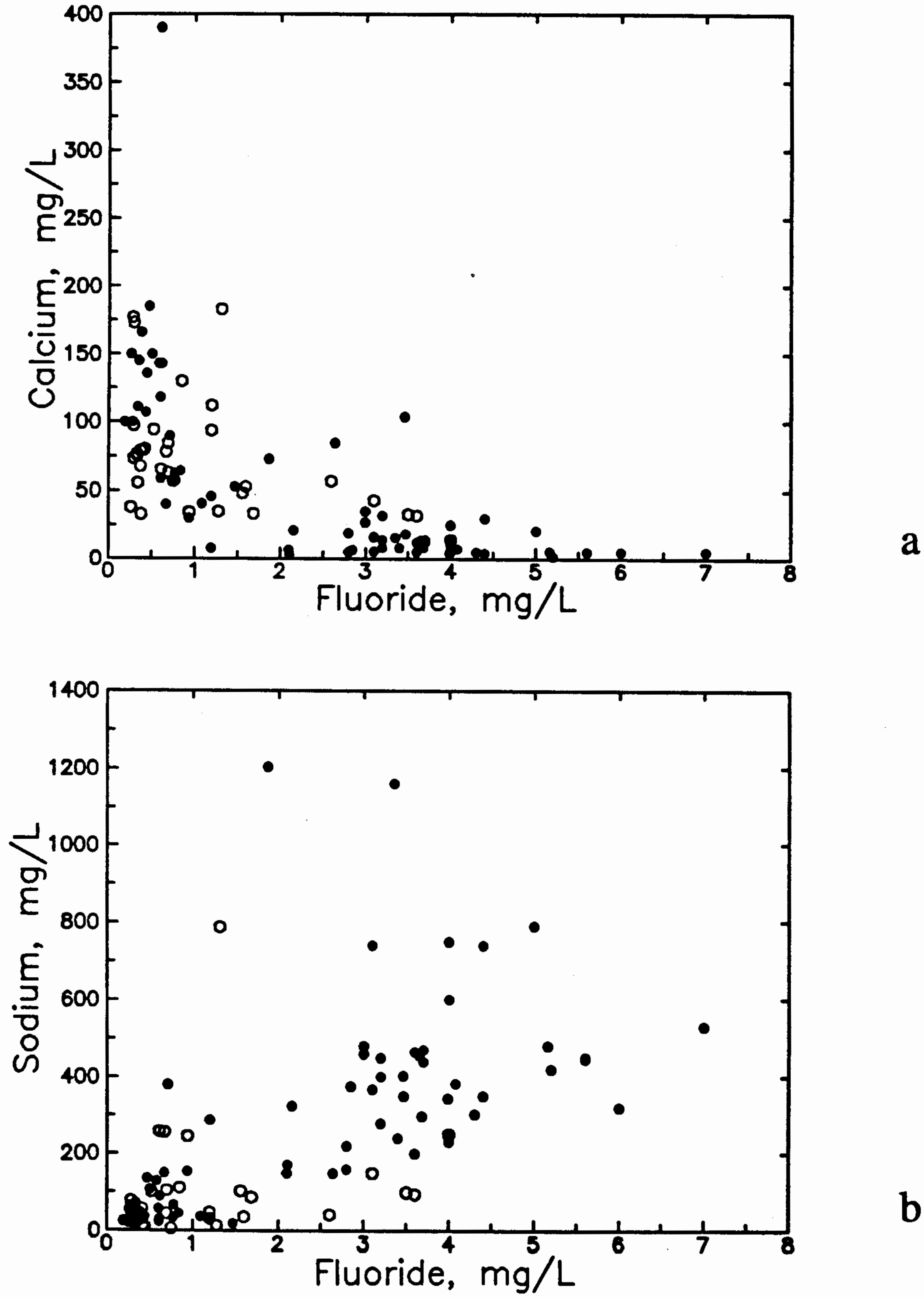


Figure 49. Association of (a) calcium and fluoride concentrations and (b) sodium and fluoride concentrations in ground waters from the Dakota aquifer. Open circles are for the Dakota outcrop or subcrop; filled circles are for the Dakota aquifer where confined by Upper Cretaceous strata.

mg/l and very high fluoride (>4 mg/l) are found only when dissolved calcium is less than 30 mg/l. The association with magnesium is similar, although not as distinct. Fluoride is generally directly related to dissolved sodium and bicarbonate concentrations and pH (Figures 49b and 50). Although the correlation with sodium and bicarbonate is poor as a whole, the lower and upper parts of the point distributions in Figures 49b and 50a form better linear relationships such that the sodium-fluoride distribution forms a fan starting from low sodium and fluoride and the bicarbonate-fluoride distribution forms a band extending to higher values.

The calcium-fluoride, sodium-fluoride, and bicarbonate-fluoride relationships can be expressed as the common association of low fluoride concentration with Ca-HCO_3 waters that are found in the outcrop and subcrop areas of the Dakota aquifer. Higher fluoride concentrations occur in Na-HCO_3 waters or in mixed cation-anion type waters with lower calcium and magnesium and appreciable percentages of sodium and bicarbonate. These waters tend to occur in the part of the aquifer confined by Upper Cretaceous rocks. The relationship of the fluoride concentration with the aquifer type is illustrated in Figures 49 and 50. Low to moderately high fluoride concentrations occur in ground waters in both the outcrop and subcrop and confined regions of the aquifer, whereas high fluoride concentrations exist only in the confined aquifer.

Data for wells and boreholes in central Kansas indicate that in the confined region the dissolved fluoride concentration is low in the Upper Cretaceous aquitard and increases with depth from the top of the Dakota and then decreases with depth at the bottom of the Dakota aquifer into Permian strata. The calcium and magnesium concentrations of ground waters in the same sequence of strata in central Kansas follow an inverse pattern, first decreasing and then increasing from the top to the bottom of the Dakota aquifer system. Dissolved sodium and chloride contents generally increase throughout the aquifer, although the changes occur at different rates and depend on the permeability of the strata. Sulfate either increases or first decreases and then increases from the top to the bottom of the Dakota aquifer.

An example of the changes with depth and pH in these dissolved constituents in the Dakota Formation is illustrated in Figures 51 and 52 for a test well in Ellis County. The decrease

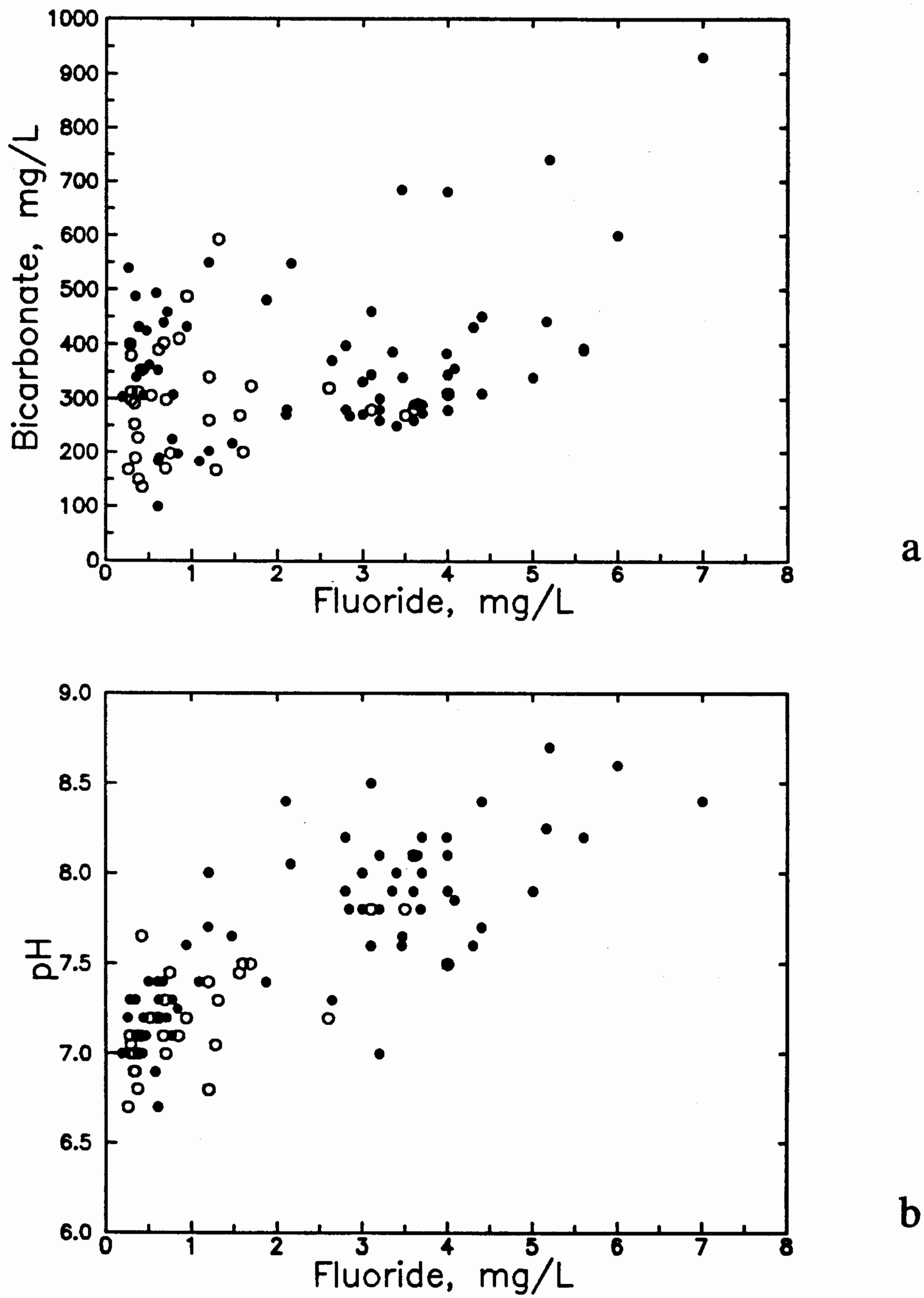


Figure 50. Association of (a) bicarbonate and fluoride concentrations and (b) pH and fluoride concentration in ground waters from the Dakota aquifer. Open circles are for the Dakota outcrop or subcrop; filled circles are for the Dakota aquifer where confined by Upper Cretaceous strata.

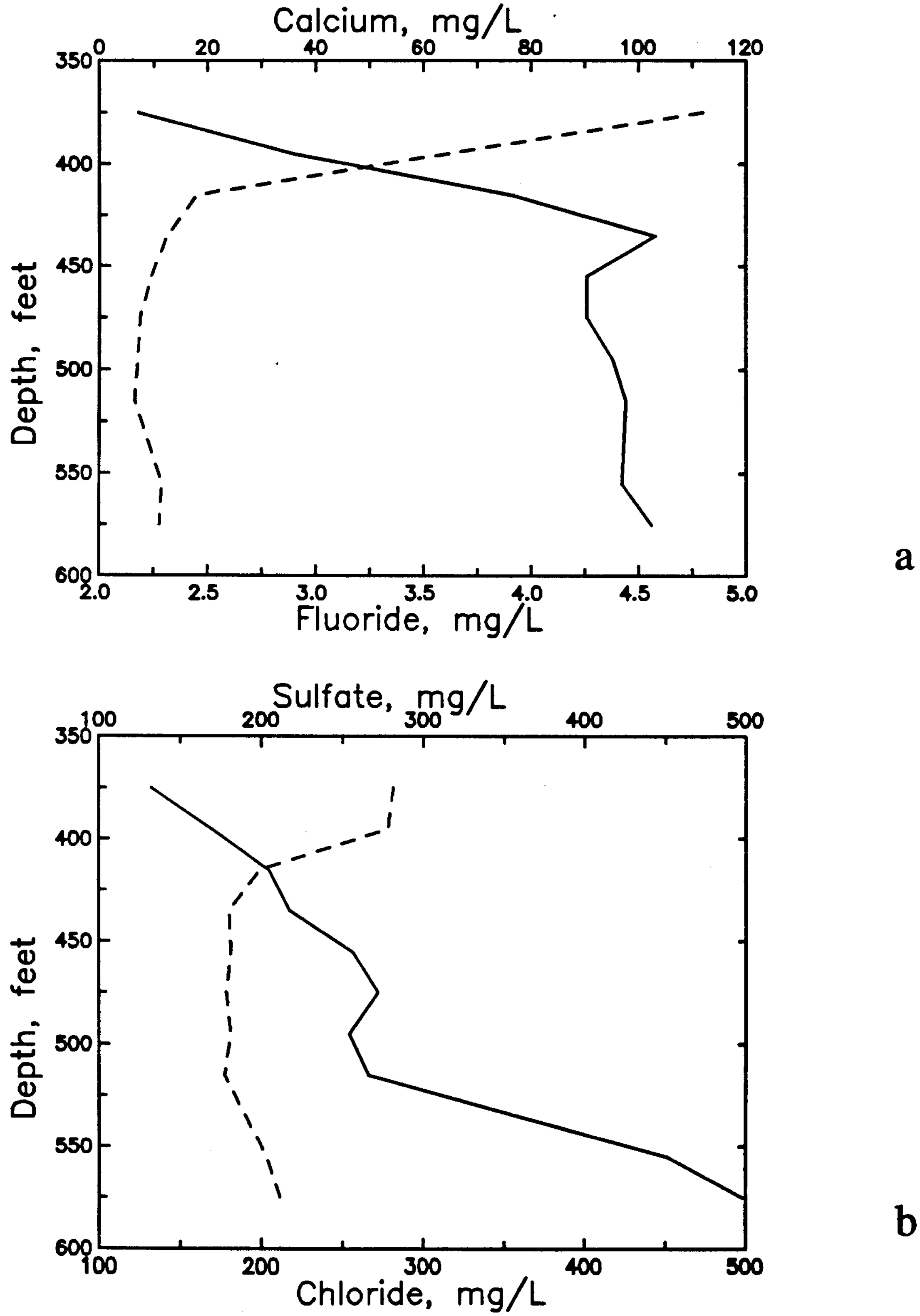


Figure 51. Changes in (a) calcium and fluoride concentrations and (b) sulfate and chloride concentrations with depth in ground waters from the Dakota Formation in a test well in Ellis County.

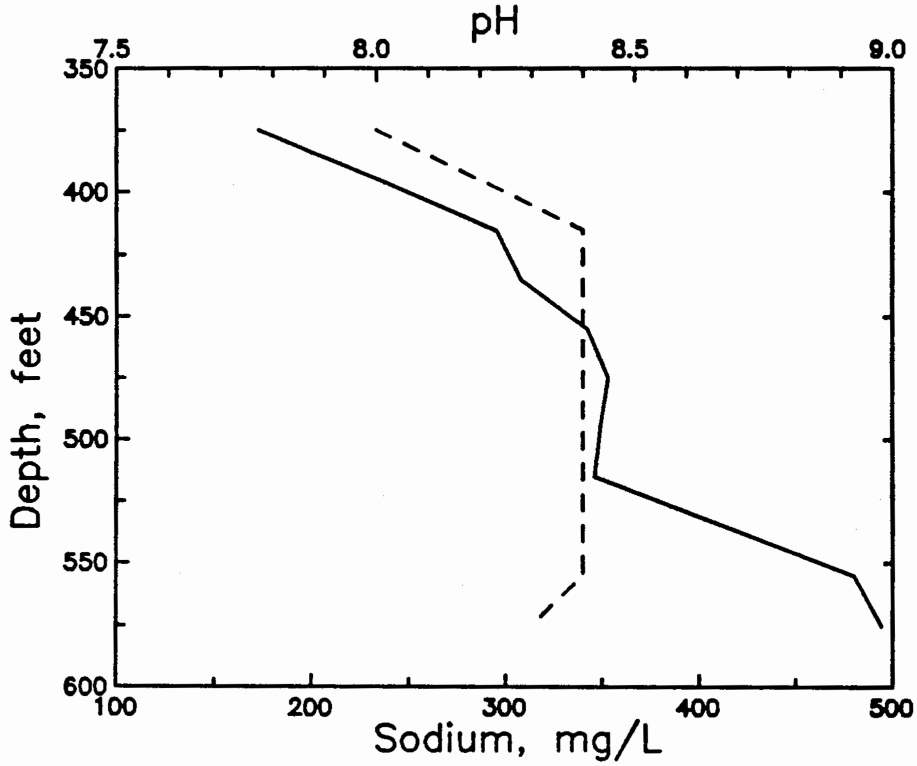


Figure 52. Changes in pH and sodium concentration with depth in ground waters from the Dakota Formation in a test well in Ellis County.

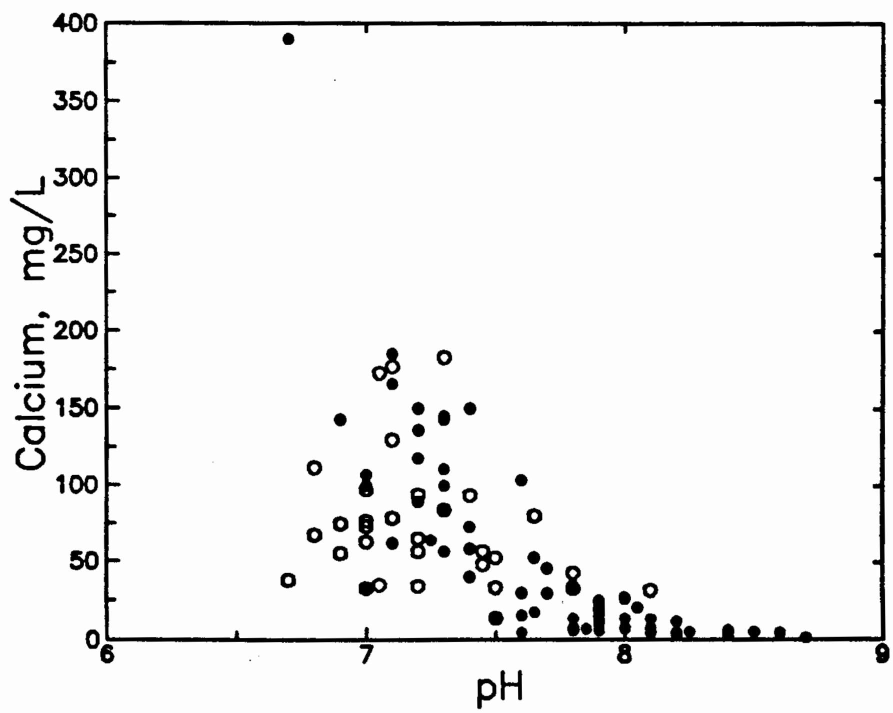


Figure 53. Association of calcium concentration and pH in ground waters from the Dakota aquifer. Open circles are for the Dakota outcrop or subcrop; filled circles are for the Dakota aquifer where confined by Upper Cretaceous strata.

in calcium (and magnesium) and the increase in sodium content is marked in the upper part of the aquifer. The increase in dissolved sodium is greater than that of chloride in the upper part of the formation, whereas the increase in chloride is greater toward the bottom. Cation exchange of calcium and magnesium for sodium on clays in the strata explains the changes. The exchange positions on the clays in the Dakota sediments were probably first saturated with more sodium than calcium and magnesium as a result of the presence of marine water in the sediment pores followed by later diffusion and dispersion of Na-Cl waters from the underlying Permian rocks. After uplift and erosion of much overlying strata, recharge with $Ca\text{-}HCO_3$ waters from southeastern Colorado and southwestern Kansas flowed through the Dakota aquifer to dilute and flush saltwater. The throughflow increased as discharge became greater near the boundary of the confined and outcrop and subcrop parts of the system as a result of erosion of Dakota strata. The calcium plus magnesium to sodium ratios in the throughflow water and in the recharge containing moderate to high calcium and magnesium flowing from the Upper Cretaceous rocks to the top of the Dakota Formation were appreciably higher than the ratio in the water in equilibrium with the clays. The resultant replacement of much sodium by the doubly charged cations caused decreases in calcium and magnesium to below several milligrams per liter and increases in sodium to produce molar sodium/chloride ratios of greater than 1 in some Dakota waters.

The upper limits of the point distribution for observed fluoride and calcium concentrations in Figure 49a form a hyperbolic curve that suggests that solubility of calcium- and fluoride-containing minerals controls the concentration. Activity products were calculated for chemical species in solution in Dakota waters and were compared with the solubility products of different minerals using the geochemical model SOLMINEQ.88. The computations for Dakota ground waters containing higher fluoride concentrations indicate that the waters are usually somewhat undersaturated (a potential to dissolve more of a mineral in water) with respect to fluorite. The waters are undersaturated to supersaturated (a potential to precipitate a mineral from water) with respect to hydroxyapatite and supersaturated with respect to fluorapatite. The results and the expected mineralogy of the aquifer sediments suggest that hydroxyapatite, in which some of the hydroxyl positions are occupied by fluorine, could be a major mineralogical source of the dissolved fluoride. Precipitation of fluorite might limit fluoride concentration in zones where Permian waters with high calcium concentrations mix with high-fluoride waters in the lower part of the Dakota aquifer. The diffusion and dispersion of high-calcium waters from the Permian certainly would limit the dissolution of apatites in the lower Dakota aquifer.

A source of additional fluoride at higher pH (Figure 50b) could be the exchange of hydroxyl ions for fluoride ions in labile positions on fluorine-containing hydroxyapatite and in phyllosilicates, mainly clays and weathered micas, such as biotite, that are present in the fine-grained sediments of the Dakota aquifer. pH values of greater than 8.5 are probably necessary for this process to be a substantial fluoride source relative to dissolution of apatites because the hydroxyl ion concentration would be too low at lower pH values. Alkaline pH can be generated by the dissolution of carbonate minerals, which could occur after cation exchange decreased calcium and magnesium concentrations to give solutions undersaturated with respect to calcite and dolomite. The general increase in pH with the decrease in dissolved calcium is illustrated in Figure 53. The highest pH's occur in the confined portion of the aquifer, as expected from the greater cation exchange and the concomitant carbonate dissolution in that aquifer environment. No pH's higher than 9 appear to occur in the Dakota aquifer based on available analyses.

Dissolution of carbonates is a major contributor to higher bicarbonate concentration in the Dakota aquifer. The association of higher bicarbonate and lower calcium with dissolution of apatite minerals explains the correlation of fluoride and bicarbonate (see Figure 50a). Again, the highest bicarbonate and fluoride contents occur in the confined aquifer. Another contributor to bicarbonate in the confined portions of the aquifer is oxidation of organic matter to produce dissolved carbon dioxide. Formation of bicarbonate from the carbon dioxide produces acidity, which further drives the dissolution of carbonate minerals or buffers the pH increase from carbonate dissolution caused by the decrease in calcium and magnesium from cation exchange.

The wide band of increasing bicarbonate with increasing fluoride in Figure 50a is probably related to both processes.

Although geochemical equilibria computations indicate that some Dakota waters are in equilibrium with respect to calcite and dolomite (i.e., they would not dissolve or precipitate these minerals), other portions of the aquifer contain waters moderately undersaturated with respect to these minerals. The undersaturation could occur in those strata where essentially all available calcite and dolomite have been dissolved. The strata either could have had low initial contents of the carbonate minerals or are more permeable sediments that have allowed a greater throughflow of waters that have been able to dissolve and remove existing carbonate minerals. Greater oxidation of organic matter in portions of the aquifer sediments could also have increased the rate of carbonate dissolution in the past, especially where throughflow could more readily transport dissolved oxygen in the recharge areas.

Another contributor to the range in the constituent concentrations correlated with fluoride at a given fluoride value is the effect of ionic strength on mineral solubilities. As the total concentration of charged species dissolved in water increases in the range from freshwater to saltwater, the solubility of a mineral increases because of the interaction of the charged ions. Although much of the correlation between sodium and fluoride in Figure 49b is related to the increase in sodium with cation exchange and the associated decrease in calcium and dissolution of apatites, some of the correlation could be caused by the ionic strength effect. The sodium, along with the chloride, from the underlying Permian is the main contributor to increasing ionic strength in Dakota aquifer waters. However, the Na-Cl water from the Permian strata also contains relatively high calcium and magnesium contents which limit the cation exchange and dissolution of fluoride-containing apatites in the lower Dakota aquifer. The combined result of all the processes is the fanlike appearance of the point distribution in the sodium and fluoride graph.

Finally, another contribution to the range in calcium and bicarbonate concentrations at a given dissolved fluoride value is the effect of sulfate on calcite and dolomite solubility. Sulfate forms the ion pairs $CaSO_4^0$ and $MgSO_4^0$ dissolved in water, thereby decreasing the free concentrations of dissolved Ca^{2+} and Mg^{2+} that enter into the solubility equations for calcite and dolomite. A larger sulfate concentration has the indirect result of increasing the solubility of calcite and dolomite. The concentration of sulfate varies in the upper Dakota aquifer because of differences in the composition of recharge and oxidation of sulfide in pyrite within the Dakota and increases in the lower Dakota from the upward diffusion and dispersion of Permian saltwater. The source of the sulfate in the recharge is largely dissolution of gypsum formed during pyrite weathering in the presence of high calcium water. The sulfate source in the Permian saltwater is dissolution of anhydrite in Permian strata. Some areas of lower sulfate content in the Dakota aquifer could be related to reduction of some sulfate to sulfide during the oxidation of organic matter. Such waters would be expected to have a hydrogen sulfide odor, as observed in a few well waters.

The present distribution of fluoride in the Dakota aquifer is controlled by chemical processes and by the relative rates of recharge and discharge in different parts of the system. The chemical processes have had an appreciable time to operate during the recharge of water into the Dakota in southeastern Colorado and southwestern Kansas and operate in the discharge area along the eastern outcrop and subcrop area. Local recharge and discharge in southeastern Colorado and southwestern Kansas and in the outcrop zone in central Kansas are more rapid than the regional flow and have flushed out past high-fluoride Na-HCO_3 type water, which probably existed in that area when the aquifer was covered by confining sediments. The faster flow rates have also removed the high sodium content of the sediments by faster attainment of equilibrium with the higher calcium and magnesium to sodium ratio of the recharge. The highest fluoride concentrations in the aquifer occur in the confined aquifer in west-central Kansas, where regional flow is slowly flushing saline water from the aquifer, but the processes have not yet had time to substantially reduce the high sodium content of the clays. Continued cation exchange and concomitant dissolution of fluoride-containing minerals and an increase in pH from carbonate dissolution and concomitant exchange of hydroxyl ions for labile/exchangeable fluoride ions on clays and micas can occur in this area because the capacity of the sediments and the time for the processes to occur is sufficient, and because the amount of regional flow and recharge from overlying rocks is sufficient to supply waters with a relatively high calcium plus magnesium to sodium ratio without being so high that flushing removes and dilutes the Na-HCO_3 water at a substantial rate.

Water-Quality Distribution Maps

Draft copies of a series of maps have been prepared to display the concentration distribution of total dissolved solids (TDS), hardness, sodium-adsorption ratio, and the constituents chloride, sulfate, nitrate, and fluoride. The TDS and chloride distribution maps show where waters are fresh or saline and thus allow a general determination of the usability of waters for municipal, agricultural, and industrial supplies. Draft copies of the TDS and chloride maps have been given for review to and use by selected state and local agencies. Other draft maps were displayed during the Dakota Technical Committee meeting. During FY92 several items related to map revision were considered and examined, including additional data (both existing and recent analyses), inconsistencies and sparse data in northwestern Kansas, the effect of surface contamination on constituent concentrations, and recontouring of the fluoride map based on the new drinking-water standards. A decision was made to produce the water-quality atlas after the revisions were completed so that fewer maps would be out of date. Important aspects of the revisions made and in progress are discussed in what follows.

Little or no water-quality data is available for northwestern Kansas. Contours drawn in northwestern Kansas in the current draft maps are based on a few points of actual water samples or estimates of water chemistry from the interpretation of geophysical logs of oil and gas wells. The log-interpreted values were made by the U.S. Geological Survey during a regional study of the Great Plains (Dakota) aquifer in the west-central United States. However, the regional TDS and chloride contour maps of the U.S. Geological Survey do not appear consistent in northwestern Kansas,; that is, there are different patterns of TDS and chloride concentrations where similar patterns were expected. The KGS is planning to estimate TDS from a more intensive study of available geophysical logs in northwestern Kansas and to estimate chloride from the TDS values. The research will enable revision for better accuracy and consistency of the TDS and chloride maps.

The water-quality distributions for most of the dissolved constituent and chemical property maps are illustrated as contoured intervals with different colors that become more intense with increasing concentration. The maps are prepared by computer extraction and plotting of chemical data for well locations using the database management system ARC/INFO, contouring by hand based on a knowledge of the hydrogeology, digitizing the contours, and generating and plotting maps with ARC/INFO. The maps show distributions for the naturally occurring concentrations or values for water-quality parameters.

Nitrate, one of the inorganic constituents of special interest for drinking water assessment, occurs naturally at low concentrations, below a few milligrams per liter as nitrate-nitrogen, in most aquifers. High nitrate concentrations are derived from anthropogenic activities and are generally local. Thus contouring of nitrate values in a manner similar to the contouring of dissolved constituents with a mainly natural source would produce a regional map that would incorrectly predict nitrate concentrations in the aquifer, because the distances between wells typical for the density of water-quality data available for the Dakota aquifer are much greater than those for wells used to assess the influence of local contamination. The procedure selected for displaying nitrate concentrations involves computer selection of circles filled with different colors for ranges of nitrate values, with the size of the circle proportional to the actual nitrate concentration.

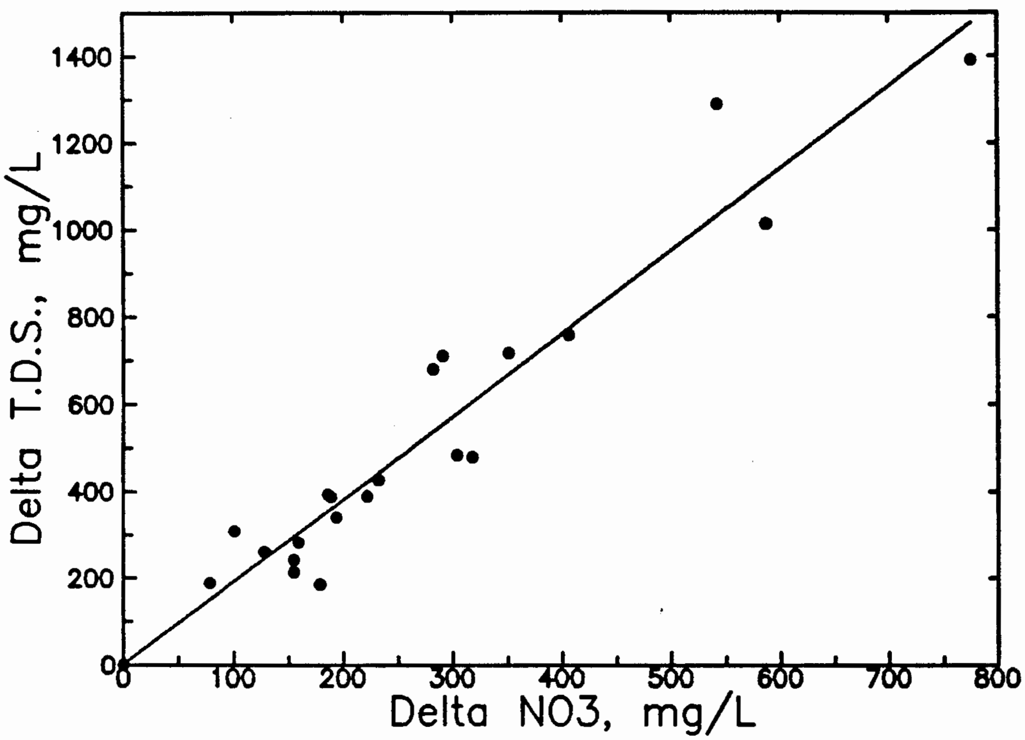
The number of wells in the Dakota aquifer yielding high nitrate concentrations is appreciably larger in the eastern outcrop and subcrop band than in the confined aquifer and the subcrop area overlain by the High Plains aquifer. The eastern outcrop and subcrop area also contains a greater density of all wells than the confined and High Plains subcrop areas. However, the percentage of wells with high nitrate concentrations is also greater in the eastern outcrop and subcrop area compared with the other two types of areas. In the outcrop and subcrop area Lincoln County contains a greater number of wells with high nitrate concentrations than the other counties.

Most of the wells in the outcrop and subcrop area are used for domestic and stock purposes. Although some higher nitrate contents have been found in some of the ground waters collected and analyzed by the KGS, most of the high nitrate concentrations tend to be in samples with older collection dates. Irrigation wells and newer domestic and stock wells tend to yield water with substantially lower nitrate content. The waters at or near the surface in rural areas or small towns often are high in nitrate because of the oxidation of nitrogen-containing animal wastes in barnyard areas and human wastes in septic tanks and drainage lines. Older well construction methods, in which a gravel pack was often placed in the drilled borehole to nearly the surface or in some cases where the annular space was left open, have probably allowed surface or near-surface drainage containing wastes to enter the well. Several older wells in the confined Dakota area near the eastern subcrop and outcrop band also yielded waters with high dissolved nitrate contents, definitely indicating well construction as the problem, because recharge could not penetrate to the confined Dakota aquifer in the time since European settlement of the area. Improved regulations on domestic and stock well construction, promulgated and enforced by the Kansas Department of Health and Environment and carried out by well construction companies, appear to have resulted in better protection of the Dakota aquifer from high nitrate concentrations associated with older well construction practices.

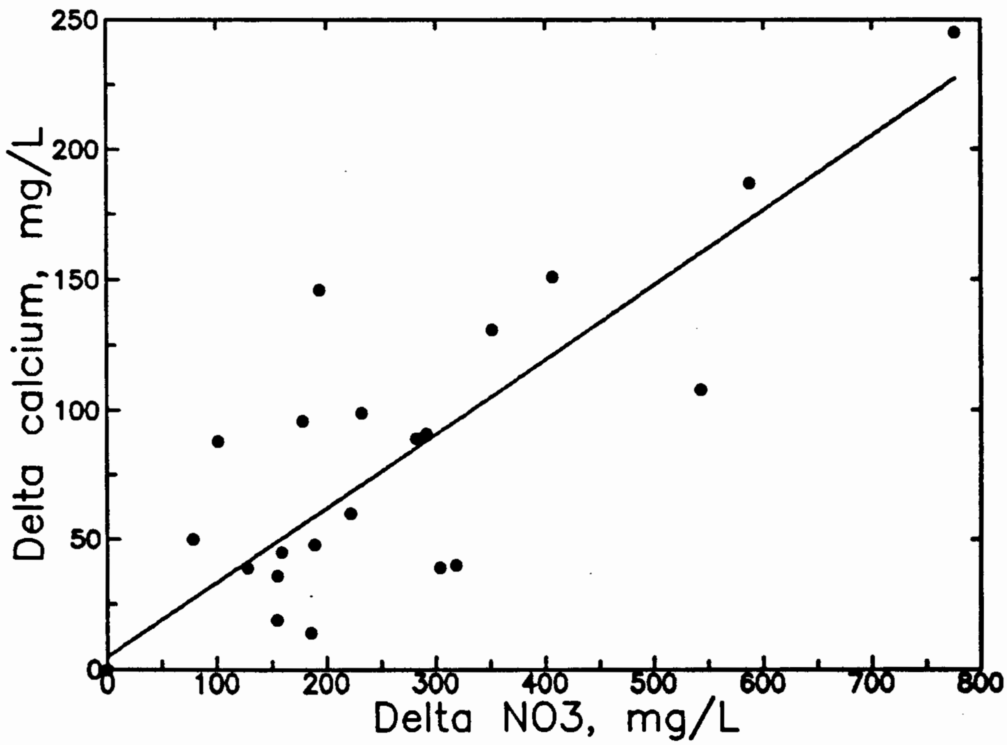
High nitrate concentrations add to the TDS content of a water and are also accompanied by other dissolved constituents that affect their total content in the ground water. The local contamination of ground waters in the Dakota aquifer affects the concentrations of constituents that are naturally present and for which contoured distribution maps have been prepared. Therefore the natural distributions of the constituents most associated with the high nitrate are distorted. The chemistry of the high-nitrate waters was examined to determine the correlation with other dissolved constituents and to remove this distortion in the maps.

Preliminary examination of the high-nitrate ground waters in the Dakota aquifer indicates that the contents of calcium, sodium, chloride, and magnesium are greater than expected for nearby ground waters. Data for other aquifers also suggest that these are the constituents usually associated with high nitrate. Data for high-nitrate well waters in the Dakota aquifer were then compared with low-nitrate ground waters in the same area containing similar ranges of sulfate and bicarbonate contents to determine calcium, magnesium, sodium, chloride, and TDS concentrations added by the local contamination. The difference (delta) in the concentrations of each constituent and TDS for each pair of high- and low-nitrate analyses was plotted against the nitrate difference, and an equation was fitted to the data based on linear regression. The best correlation was obtained for delta TDS versus delta nitrate (see Figure 54a), but significant correlations were also obtained for delta calcium, magnesium, sodium, and chloride (Figures 54b–56a). The delta calcium plus magnesium represented as hardness associated with the nitrate increase is shown in Figure 56b. The linear regression equations for each association are listed in Table 8. The scatter in the plots is probably related to the various sources of high nitrate, including animal wastes, septic effluents, nitrogen fertilizers, and the oxidation of nitrogen-containing organic matter in soil. Each of these sources could have different relative amounts of cations and anions associated with the nitrate.

The increases in TDS and hardness from nitrate contamination are several hundred milligrams per liter for many waters (see Figures 54a and 56b) and can be as high as a few hundred milligrams per liter for calcium and chloride (see Figures 54b and 56a) and tens of milligrams per liter for magnesium and sodium (see Figure 55). These increases substantially affect the values used for generating contours for the maps of each of these chemical parameters. Correction equations based on the linear regressions were incorporated into a computer program that links with the database in ARC/INFO. The program examines each record in the database for nitrate and generates a corrected value for each chemical parameter associated with nitrate if the nitrate-nitrogen content in the water-quality record is over 3 mg/l. The corrected values were



a



b

Figure 54. Increase in (a) total dissolved solids (TDS) concentration and (b) calcium concentration with increase in nitrate contamination of ground waters in the Dakota aquifer.

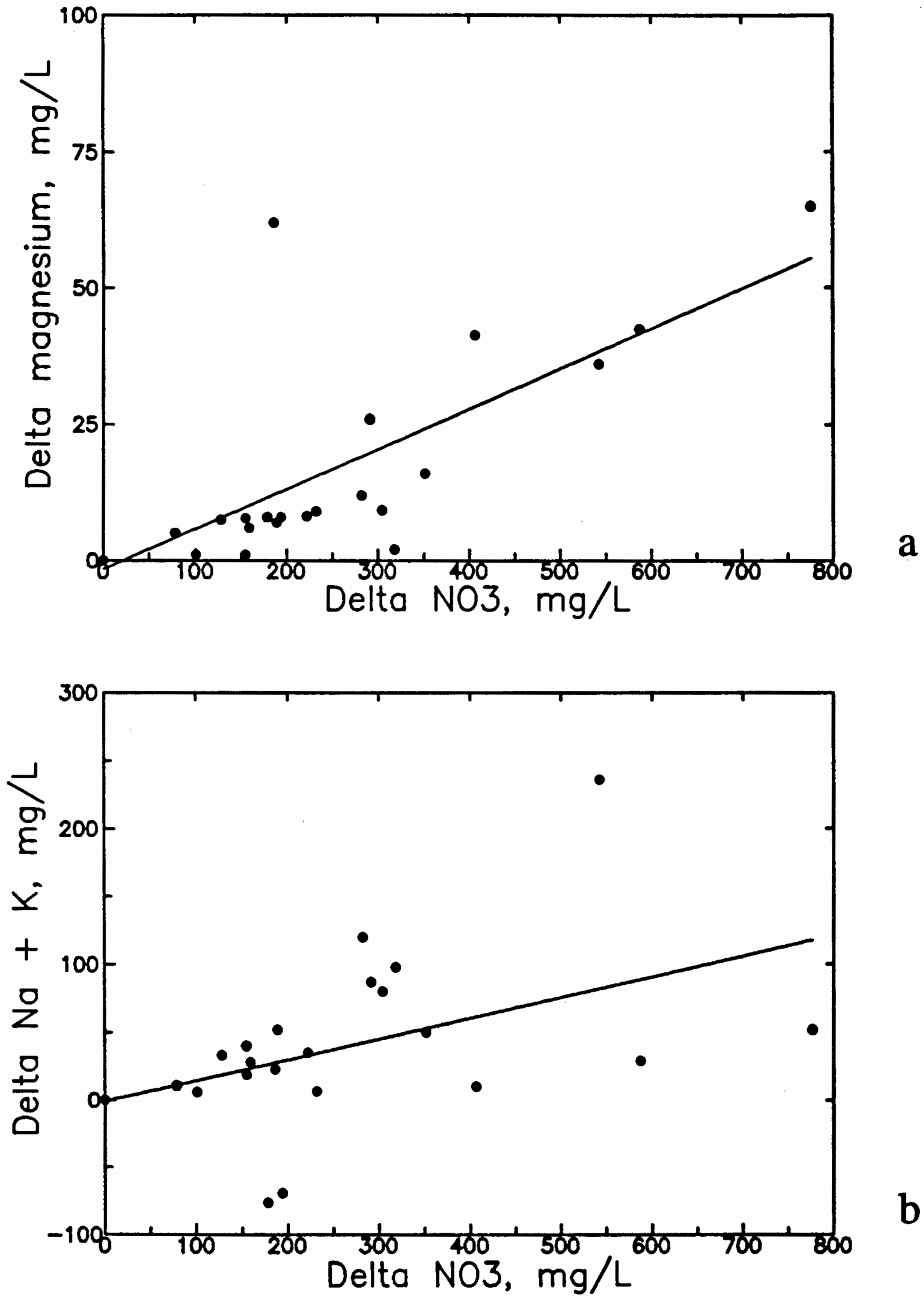
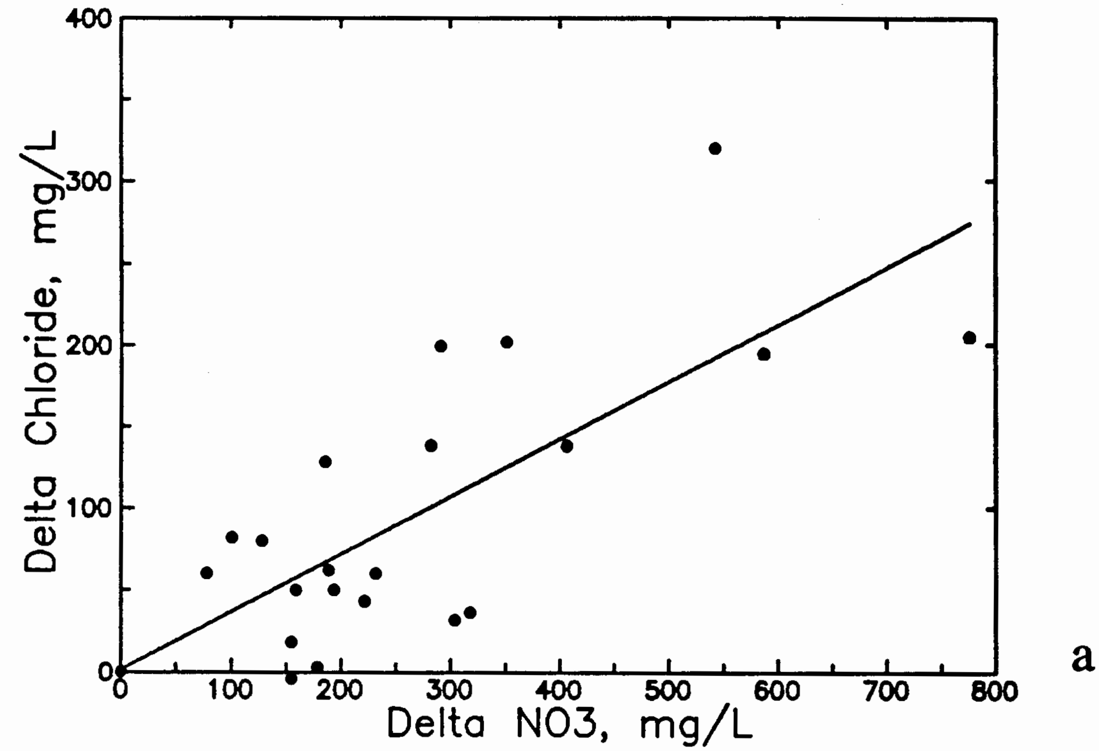


Figure 55. Increase in (a) magnesium concentration and (b) sodium and potassium concentrations with increase in nitrate contamination of ground waters in the Dakota aquifer.



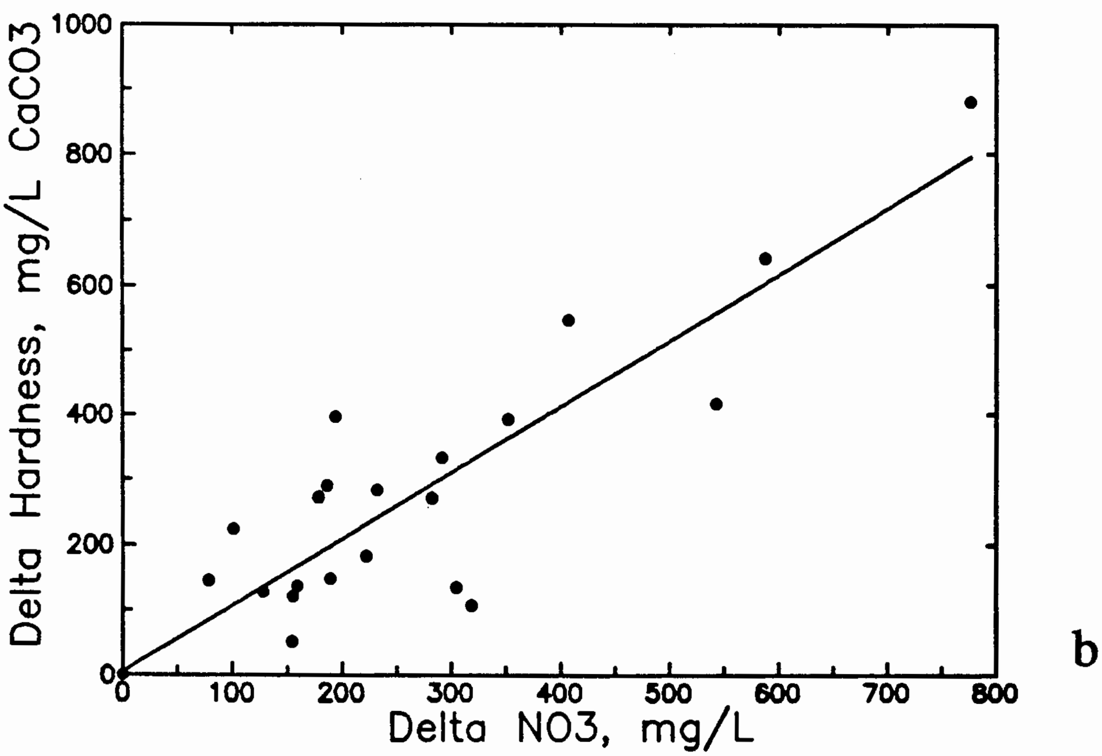


Figure 56. Increase in (a) chloride concentration and (b) hardness concentration with increase in nitrate contamination of ground waters in the Dakota aquifer.

plotted next to a point for each well along with points and values for the low-nitrate waters on a map to allow revision of the isoconcentration contours.

The draft fluoride map was originally contoured for the intervals <1, 1–2.5, 2.5–5, and >5 mg/l. The standard for fluoride in public water supplies in Kansas was recently increased from 1.8 mg/l to 4 mg/l to fit the maximum contaminant levels established by the federal government. A level of 2 mg/l is the recommended level. The contours will be revised to reflect these levels by changing to intervals of <1, 1–2, 2–4, 4–6, and >6 mg/l dissolved fluoride.

Water-Quality Use Assessment for Water Supplies

Assessment of the water-quality data for use as drinking and agricultural supplies was continued as additional data were found and new data became available. The new data are results for samples collected and analyzed at the KGS as part of the Dakota Aquifer Program. The overall assessment based on all data available for the Dakota aquifer for this report is summarized in Table 9. The criteria listed are those currently used or suggested by the Kansas

Table 8. Equations for the Association of Dissolved Constituents with Nitrate Contamination of Ground Waters in the Dakota Aquifer.

<u>Equations for nitrate expressed as nitrate-nitrogen</u>

Delta TDS = 8.406 (NO_3–N – 3) + 2.1
Delta Hardness as $CaCO_3$ = 4.506 (NO_3–N – 3) + 5.6
Delta Ca = 1.269 (NO_3–N – 3) + 4.8
Delta Mg = 0.325 (NO_3–N – 3)
Delta Cl = 1.556 (NO_3–N – 3) + 1.5
Delta Na = 0.675 (NO_3–N – 3)

<u>Equations for nitrate expressed as nitrate</u>

Delta TDS = 1.899 delta (NO_3 – 13.3) + 2.1
Delta Hardness as $CaCO_3$ = 1.018 (NO_3 – 13.3) + 5.6
Delta Ca = 0.287 (NO_3 – 13.3) + 4.8
Delta Mg = 0.073 (NO_3 – 3)
Delta Cl = 0.352 (NO_3 – 13.3) + 1.5
Delta Na = 0.152 (NO_3 – 13.3)

The delta concentration refers to the increase in a dissolved constituent concentration (in mg/l) associated with a nitrate-nitrogen content greater than 3 mg/l. The maximum natural nitrate was selected as 3 mg/L nitrate-nitrogen (13.3 mg/l as nitrate).

Table 9. Assesment of Water-Quality Data for the Dakota Aquifer Based on Drinking-Water and Water-Classification Limits[a]

Constituent	Number analyzed: Sites	Number analyzed: Samples	Concentration (mg/l): Minimum	Concentration (mg/l): Average	Concentration (mg/l): Median	Concentration (mg/l): Maximum	Criterion	Number above criterion: Sites	Number above criterion: Samples	Percentage above criterion: Sites	Percentage above criterion: Samples	Limit of detection (mg/l)	Number of < values[b]
Alkalinity	864	1224	<1	294	260	1600	300	310	384	35.9	31.4	1	0
Ammonia-N	68	114	<0.01	0.392	0.078	5.823	0.1	36	52	52.9	45.6	0.01	19
Arsenic	136	159	<0.001	0.005	<0.001	0.096	0.05	2	2	1.5	1.3	0.001	88
Barium	104	109	<0.001	0.075	0.034	0.366	1	0	0	0.0	0.0	0.001	1
Cadmium	66	71	<0.001	0.001	<0.001	0.020	0.005	3	3	4.6	4.0	0.001	54
Calcium	919	1285	1.6	111	71	2130	200	108	114	11.8	8.9	0.1	0
Chloride	997	1352	2.7	1229	65	36500	250	263	327	26.4	24.2	0.1	0
Chloride	997	1352	2.7	1229	65	36500	500	188	215	18.9	15.9	0.1	0
Chloride	997	1352	2.7	1229	65	36500	5000	74	75	7.4	5.6	0.1	1
Chromium	103	106	<0.001	0.003	0.004	0.013	0.1	0	0	0.0	0.0	0.001	29
Copper	64	74	<0.001	0.013	0.003	0.330	1.3	0	0	0.0	0.0	0.001	17
TDS	861	1218	58	2908	600	63800	500	524	685	60.9	56.2	1	0
TDS	861	1218	58	2908	600	63800	1000	287	368	33.3	30.2	1	0
TDS	861	1218	58	2908	600	63800	10000	71	72	8.3	5.9	1	0
Fluoride	768	1129	0.1	1.36	0.60	9.00	4	61	67	7.9	5.9	0.01	0
Hardness	920	1291	6.1	475	239	9000	400	256	325	27.8	25.2	0.1	0
Iron	691	937	<0.005	2.91	0.40	25.60	0.3	410	508	59.3	54.2	0.005	3
Lead	63	69	<0.001	0.006	0.003	0.040	0.015	6	7	9.5	10.1	0.001	21
Magnesium	916	1284	0.5	46.1	14.0	1090.0	150	69	70	7.5	5.5	0.1	0
Manganese	295	426	<0.005	0.186	0.056	4.300	0.05	132	214	44.8	50.2	0.005	67
Mercury	88	110	<0.0002	0.0004	<0.0002	0.0056	0.002	6	6	6.8	5.5	0.0002	74
Nitrate-N	602	804	0.02	6.80	1.13	175.98	10	88	107	14.6	13.3	0.01	0
Phosphorus	108	191	<0.01	0.565	0.06	3.261	5	0	0	0.0	0.0	0.01	20
Potassium	472	732	0.4	7.15	4.50	156.00	100	4	4	0.9	0.6	0.1	0
Selenium	138	165	<0.001	0.003	0.001	0.042	0.05	0	0	0.0	0.0	0.001	80
Silica	538	890	2	18.9	16.0	61.9	50	3	3	0.6	0.3	0.1	0
Silver	104	106	<0.001	0.002	0.002	0.010	0.05	0	0	0.0	0.0	0.001	46
Sodium	905	1273	3.2	808	74	22000	100	426	564	47.1	44.3	0.1	0
Sulfate	893	1256	<1	329	99	6200	250	268	268	30.0	21.3	1	1
Zinc	127	145	<0.005	0.143	0.021	2.000	5	0	0	0.0	0.0	0.005	29

a. Criteria are current primary or secondary drinking-water standards or, in the absence of a promulgated standard, suggested upper limits of the Kansas Department of Health and Environment for drinking water. The two higher limits for chloride and TDS are classification values for fresh and usable water.

b .Number of values less than the limit of detection.

Department of Health and Environment. The three sets of criteria for chloride and TDS concentrations are based on drinking-water limits (the lowest values) and the divisions between fresh (<500 mg/l chloride and <1,000 mg/l TDS), usable (500-5,000 mg/l chloride and 1,000–10,000 mg/l TDS), and mineralized waters (>5,000 mg/l chloride and >10,000 mg/l TDS) as defined in Kansas.

Table 9 reflects the recent changes in the maximum contaminant levels for several heavy metals. The standard for selenium was increased from 0.01 mg/l to 0.05 mg/l, resulting in former exceedances of several percent being reduced to zero. The standard for chromium was increased from 0.05 mg/l to 0.1 mg/l; no exceedances existed before and thus no exceedances occur under the revised standard. The maximum contaminant level for cadmium decreased from 0.01 mg/l to 0.005 mg/l; the result changed the assessment from zero exceedance to a few percent exceedances for the samples collected. The standard for lead changed from the maximum contaminant level to a performance standard in the water system; that is, the lead should not exceed the criterion listed after water treatment. Although this lead level relates to the water in a distribution system as delivered to consumers, the level is used in Table 9 as the criterion because, if exceeded, it either represents a level that must be treated in a public water supply or is a concentration above which rural water users may wish to consider some form of treatment. The exceedances for lead went from zero for the former standard to about 10% for the new level. Most of the waters exceeding the lead performance level are from rural wells that could possibly be obtaining lead from the metals in the well and piping system before the sampling point. The new fluoride standard was already incorporated into table 9 in the FY91 annual report (Macfarlane et al., 1992).

Geographic Information System and Database Management Activities for FY92

The first database management activity during FY92 was the correction and archiving of the geophysical log data ase. This database consists of over 1,300 geophysical logs that cover most of western Kansas [see Macfarlane (1992, Figure 7)]. The logs are used to support ongoing projects that involve the determination of sequence stratigraphy in the Dakota aquifer and the hydrostratigraphic definition of sandstone aquifers. The original logs were sent to a private contractor for digitization into an electronic format and then were returned to the KGS in late FY91. The digitized well logs were converted from the contractor's personal computer format and transferred to the Data General computer at the KGS. All the files were grouped according to township (T. 1 S. to T. 33 S.). During the conversion process, we discovered that, starting with the T. 17 S. logs, the header section containing information such as the log location, site and type of well had been offset by one log. Essentially, any given digitized log south of T. 16 S. had the header information from the digitized log preceding it. Once this error was detected, KGS staff members wrote several computer programs to associate the correct header information with the digitized well logs. The logs were then archived to computer tape.

The primary objective of the FY92 database work was the development of an interface between ARC/INFO, the geographic information system (GIS) used at the KGS, and the ground-water flow model MODFLOW. Instead of recreating work that had already been completed by someone else, we chose to modify an existing interface that was primarily designed and written by Peter Van Metre of the Austin, Texas, Field Unit of the U.S. Geological Survey.

The incorporation of ARC/INFO with the MODFLOW groundwater model in the interface is intended to facilitate movement of the Dakota aquifer databases from the GIS to the flow model and subsequently to return the output to a form that allows for easy postprocessing. Therefore the GIS acts as both a preprocessor and a postprocessor. Output can be in tabular data sets or maps, either of which can be created relatively quickly. The characteristic of the interface that is probably most valuable is the automation of many aspects of the modeling process. The GIS allows for interpolation of values for grid nodes that can be completed much faster than could be done by hand. This aspect becomes especially important when modeling a system as large and complex as the Dakota aquifer. It also allows for interactive editing of parameters at the nodes in the model cells, either visually by plotting the grid on the screen or in the relational database of ARC/INFO. As mentioned previously, the GIS also makes it convenient for creating map products of both input data and output results. The interface itself does not transform or manipulate the data and is used only for the storage and movement of the data into and out of the GIS.

The interface developed by Van Metre was designed for a Prime computer system and was primarily based on the Control Program Language, INFO programs, and Fortran programs operating on the Prime. Most of the interface needed conversion before use on the KGS computer system. Four major guidelines made this interface attractive:

1. There was no need for changes to the groundwater model code.
2. The data structure was designed within the GIS to match MODFLOW.
3. The interface would be flexible enough to allow for all of the options available in MODFLOW.
4. The interface would be efficient in terms of computer time and space.

The first guideline proved to be the first major stumbling block in the conversion of the interface to the KGS computer system. Changes do need to be made to the model code in our version of the interface. However, the changes needed are not specifically in the model itself but in the opening of data files. As written by Van Metre, files for input and output would be opened externally of the MODFLOW program. However, the KGS computer system does not allow for this type of operation and requires that all file opening take place in the code of the program itself. This is not a major problem and does not cause any change in the model output. It does cause an inconvenience whenever the interface and MODFLOW program are moved to another location. Steps are now underway to make the interface query the user for file locations and then to make the necessary modifications based on the response given by the user. The remaining three guidelines hold true for our version of the interface.

There are essentially five steps to the flow of the interface program. The program (1) enters INFO, determines which packages are in use, and determines the parameters required for the model run, (2) runs the INFO package output program using the control files containing the parameters and outputs system files for the model run, (3) executes MODFLOW, which opens and uses the system files that were output in the previous step, and (4) executes a FORTRAN program that opens selected output files and reformats the records for input back into INFO. At this point the user can view the output files to determine whether the results are reasonable. If the results are unacceptable, the user can then take advantage of the interactive capabilities of the GIS to correct controls or values being fed into the system and then reexecute the interface and model. If, however, the results appear to be satisfactory, the user can execute one or both of the final programs to produce GIS coverages, which can then be used to produce map output. The last step of the interface program is (5) execution of one of two programs that allow the user to produce GIS coverages of either hydraulic heads and drawdowns or flow terms.

Figure 57 shows a simplified flow chart of the processes and options of the interface. The interface allows input of data in several forms, including the GIS databases and the original file format that MODFLOW was originally designed to handle. Output can either consist of ARC/INFO databases in the form of coverages or the original MODFLOW output file in an ASCII format.

To test the interface from start to finish, we set up a simple hypothetical example including a small grid and sample data set. The results showed that the interface performed properly for data handling. The next step is to test the program using a large data set with actual values for the Dakota aquifer. The grid is for the regional flow model and covers a large portion of central and western Kansas and a small part of southeast Colorado.

Liaison Activities with Federal, Other State, and Local Agencies and the Public

The KGS worked with and provided information on the Dakota aquifer to several federal, state, and local agencies and the public in FY92. Research was conducted with the U.S. Geological Survey through a cooperative arrangement between the two agencies, primarily for work in southwestern Kansas. The U.S. Geological Survey installed wells at the monitoring site in Stanton County, made data retrievals for the program, and provided analytical support for

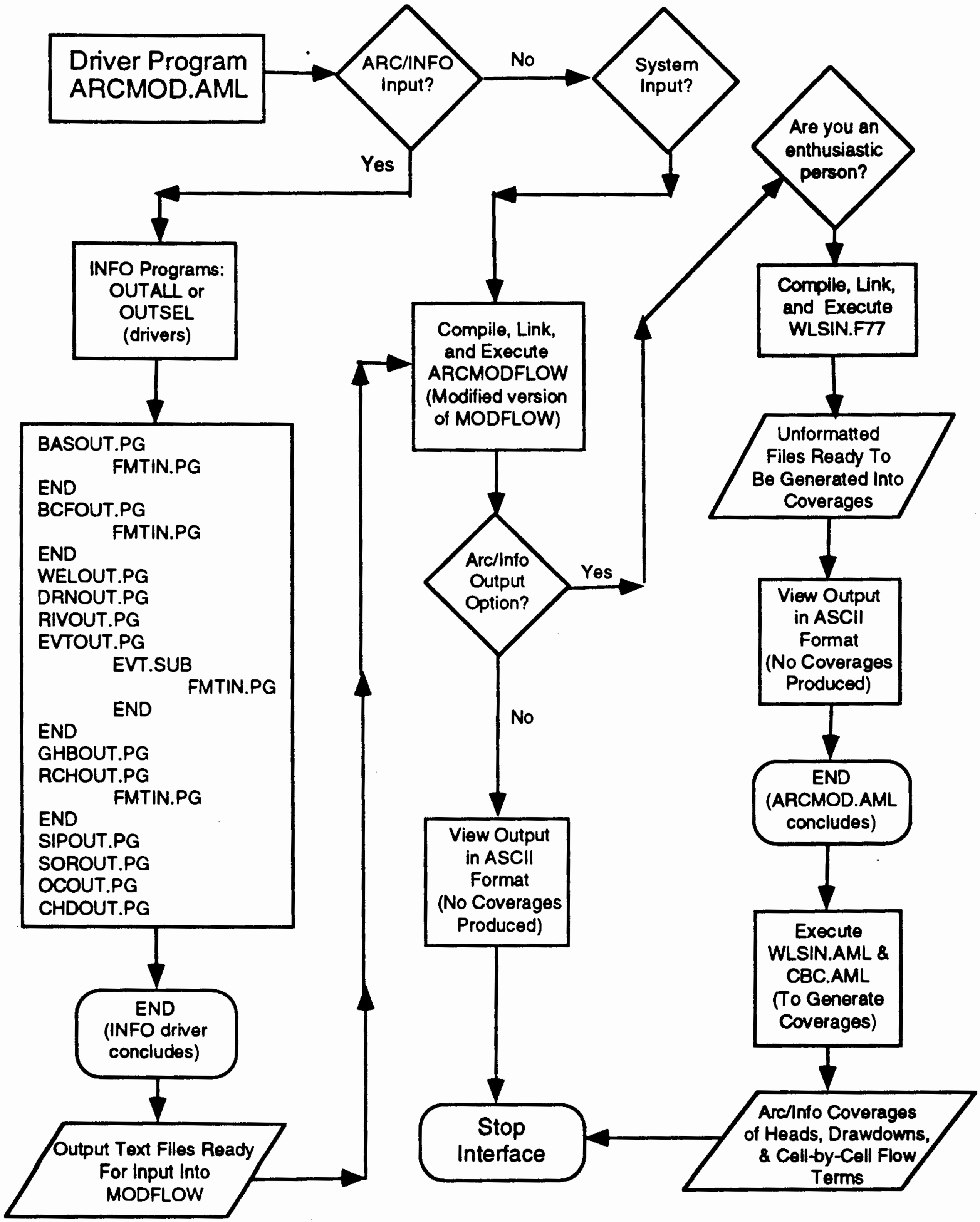


Figure 57. Simplified flow chart of the MODFLOW-ARC/INFO interface. This chart is intended to show an overview of the processes and options available.

determination of radioactive and stable isotope concentrations. Both the KGS and the U.S. Geological Survey worked with the GMD3 in southwestern Kansas on research plans and needs of the district. The district also was involved in a cooperative project with the KGS for obtaining information on the interaction between the Ogallala and Dakota aquifers. The district contracted for the drilling of the wells at the Gray County monitoring site as part of the project. Lawrence Livermore National Laboratory is cooperating with the KGS on research directed to geochemical characterization of recharge and flow in the Dakota aquifer system. The Texas Bureau of Economic Geology conducted joint sampling during FY92 as part of a project to determine interactions among the Dakota and other aquifers in the Great Plains.

The KGS provided information on the hydrogeology and water quality of the Dakota aquifer to Hays as a part of the city's search for additional supplies of ground water for municipal use. An additional part of this information included cooperating with the Kansas Corporation Commission and the city of Hays during the drilling of the test wells in the Dakota aquifer to determine the source of saline water found in the ground water. In another cooperative project with a state agency, the Kansas Water Office sampled the Smoky Hill, Saline, and South Fork Solomon rivers, and the KGS determined saltwater sources of saline river waters that receive discharge from Cretaceous strata.

The KGS organized a symposium at the University of Kansas to present research accomplishments and plans of the Dakota aquifer program to many state and local agencies, university and industry staff, and the public. The symposium provided a useful forum for communication of results and receipt of needs and suggestions for proposed work. Other information transfer concerning the program included answering questions and providing data in response to many requests for information on the Dakota aquifer from a wide variety of individuals.

Relationship of the FY92 Dakota Aquifer Program to Future Research Directions

The overall objectives of the Dakota aquifer program in FY90–95 are (1) to characterize subregionally the water-resources potential of the areas where the Dakota aquifer is shallowest and is undergoing development in central and southwestern Kansas in FY90–91, (2) to develop conceptual and digital models of ground-water flow and water quality in FY92 to early FY94 for central and southwestern Kansas that can be used as the basis for assessing water management, regulatory, and planning actions in late FY94 to FY95, and (3) to characterize the water-resources potential of the west-central portion of the aquifer and extrapolate to northwest Kansas in late FY94 to FY95. The geographic subdivisions of the areas of investigation in Kansas were illustrated previously in this report in Figure 2. Much progress has been made in characterizing the properties of the Dakota aquifer, but the projects that will continue and the additional phases that will be initiated are necessary for determinating the effects of past, current, and projected future development of the aquifer for use in water resources regulatory and planning policies.

The primary emphases during the latter part of the FY92–95 period are (1) to integrate the geologic, geohydrologic, and geochemical results from previous research to form conceptual models of the aquifer system and useful products for water-resource evaluation and (2) to develop three-dimensional digital models of the Dakota and adjacent aquifers in southeastern Colorado and southwestern and central Kansas that can be used to simulate the flow of water, transport of solutes, and chemical reactions along the flow path. These simulations will be useful for testing hypotheses about the nature of the flow system in the Dakota aquifer, for determining rates of interchange between aquifers, and for assessing the effects of pumping on water availability and quality. Development and the use of the quasi-three-dimensional models to simulate the hydrology are being carried out in phases. Phase 1 work is reported in this FY92 report and includes determination of the factors controlling the ground-water flow system (such as the arrangement of aquifer and aquitard units), the effect of topography, and a conceptual water budget that estimates the amount of recharge to and discharge from the aquifer along a cross section from southeastern Colorado to central Kansas. Work on the regional and subregional steady-state simulations of the Dakota aquifer will continue through FY93. In the latter part of FY94 work will begin on developing a transient-flow model that will be completed in FY95 for southwestern Kansas to allow simulation of the effect of pumping. The transient-flow, regional steady-state flow, and coupled flow and chemical models will be used to assess the effect of various water-management options in FY95.

Late in FY94 research will also shift to the deeper subsurface of west-central, northwest, and north-central Kansas. In these areas readily available data are sparse, the depth to the top of the Dakota aquifer is considerable, and salinities are commonly high. The main focus will be on the areas adjacent to the region under present development and areas that are predicted to have usable water quality. The area comprises Greeley, Wichita, Scott, Lane, Wallace, Logan, Gove, and parts of Hamilton, Kearny, Sheridan, and Graham counties in west-central Kansas as indicated in Figure 3 of this report. A map of TDS concentration produced during the Dakota program predicts that the ground waters are fresh (less than 1,000 mg/l TDS) in approximately 46% and between 1,000 and 2,000 mg/l TDS in 37% of this area. A monitoring site is being planned for the Dakota aquifer in northeast Gove County to assess the potential for new supplies of water in the subregion. Some preliminary sampling in a few wells will be conducted in FY93 in the southern portion of this area as part of the cooperative project with the Lawrence Livermore National Laboratory. Additional work will be conducted in FY94–95 for northwestern Kansas, and in Jewell, Smith, and Phillips counties in northern Kansas where the water quality is generally poor because of high TDS concentrations.

Acknowledgments

The following individuals are acknowledged for their contributions to the research of the Dakota Aquifer Program or their assistance in the preparation of the FY92 Annual Report: Ramshankar Narasimhan (computer modeling of regional ground-water flow), Deb Kirshen (ARC/INFO processing for preparation of geologic maps), Xiaodong Jian (database management of water-quality information and ARC/INFO processing of chemical constituent maps), Lawrence Hathaway, Karmie Galle, and Truman Waugh (determination of chemical constituents in water samples), Wenzhi Liu and Yahya Yilmaz (slug and pumping tests of the monitoring wells), Don

Butcher, Kansas Corporation Commission (collection of Hays ground-water samples), Gerald Hargadine, Kansas Water Office (collection of river-water samples), Frank Cherry (budget and other business management), Mark Schoeneweis (production of final graphics for selected figures), Anna Kraxner and Adeline Ow (formatting and printing the report and producing the report copies), and Mimi Braverman (editing of the final report).

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Appendix A
List of Publications

The following is a list of reports, papers, and abstracts produced as a part of the Dakota Aquifer Program from FY89 to FY92. Copies may be purchased through the Kansas Geological Survey publications office, 1930 Constant Ave., Lawrence, Kansas 66047.

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