# The Dakota Aquifer Program
# Annual Report, FY 93

by

P. Allen Macfarlane, D.O. Whittemore, John H. Doveton,
Tyan-ming Chu, Martin Smith, Howard Feldman

Kansas Geological Survey, The University of Kansas
Lawrence, Kansas

and

N.C. Myers and J.B. Gillespie
U.S. Geological Survey
Lawrence, Kansas

Kansas Geological Survey Open-file Report 94-1
September 1993

GEOHYDROLOGY

DAKOTA AQUIFER PROGRAM

# The Dakota Aquifer Program
# Annual Report, FY 93

by

P. Allen Macfarlane, D.O. Whittemore, John H. Doveton,
Tyan-ming Chu, Martin Smith, Howard Feldman

Kansas Geological Survey, The University of Kansas
Lawrence, Kansas

and

N.C. Myers and J.B. Gillespie
U.S. Geological Survey
Lawrence, Kansas

Kansas Geological Survey Open-file Report 94-1
September 1993

# THE DAKOTA AQUIFER PROGRAM: ANNUAL REPORT, FY93

## EXECUTIVE SUMMARY

Localized depletion of near-surface sources of water coupled with the need to develop new water supplies in western and central Kansas is focusing attention on the next available source of ground water, the Dakota aquifer. Insufficient information on the Dakota has limited the ability of State agencies to evaluate the aquifer as a major water source for the future. Those areas of the Dakota aquifer currently undergoing development are managed with little or no technical guidance for policy decisions.

On the basis of work conducted by the Kansas Geological Survey in FY89, several water quantity-quality problems associated with long-term development 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 withdrawals of water from the Ogallala and Dakota aquifer in southwestern Kansas on future water-supply availability, (4) the effect of shallow disposal of produced oil brines in shallow subjacent zones on the Dakota aquifer in central Kansas, (5) the definition of usable zones in the Dakota aquifer, and (6) the effect of saltwater discharge from the Dakota aquifer on water quality in central Kansas stream-aquifer systems.

In FY90-93 the overall objective of the Dakota aquifer program is to characterize subregionally the water-resources potential of areas where the Dakota aquifer is shallowest and is undergoing development in central and southwestern Kansas. This region was subdivided geographically into three separate subareas of investigation. In these subareas, the aquifer is used extensively for irrigation, public water supply, and industrial uses. Insufficient up-to-date information is available in the three main sub-areas of investigation to determine how past development has affected this source of water and to project the effects of future management policies.

In FY93, Kansas Geological Survey conducted a diverse research program in subsurface geology, geohydrology, and geochemistry that focuses on the three subarea investigation areas defined in the FY90 Annual Report. The major emphasis of the FY93 Dakota aquifer program is the integration and synthesis of results from the subarea investigations in southwestern and central Kansas to develop regional, two- and three-dimensional, steady-state models of ground-water flow in the Dakota and hydraulically-connected aquifer systems. The ground-water flow pattern is an important constraint on the quantity and quality of ground water available to wells. The regional models of the Dakota aquifer are being used to further investigate the flow system within the aquifer and its major influences and develop water budgets. Subregional model development to address water management issues in the 16 southwestern Kansas counties, including Southwestern Kansas Groundwater Management District #3, was initiated by the U.S. Geological Survey during this fiscal year. The results of the water sampling and analysis by the Nuclear Chemistry Division, Lawrence Livermore National Laboratory, reported in the FY92 and this year's annual reports are being used to help support the interpretation of regional hydrogeology from the steady-state northern vertical profile model, reported on in the FY92 Annual Report. Looking towards future work in northwest Kansas some preliminary work was carried out to assess the suitability of borehole geophysical logging techniques to determine water quality in the Dakota aquifer. In the area of research support, the FY92 Dakota aquifer program annual report was completed and published as KGS Open-file Report 93-1.

In FY94, the major program objectives are to: (1) complete the calibration and testing of all two- and three-dimensional steady-state regional models, (2) continue development of a management model of the High Plains/Dakota aquifer system in southwestern Kansas, (3) use geostatistical techniques to investigate the distribution of sandstone bodies within the Dakota aquifer, (4) develop maps of regional water quality in the northwest Kansas Dakota aquifer using borehole geophysical log analysis techniques, and (5) begin to lay the groundwork for developing models of the flow system in the Dakota of northwest Kansas and adjacent areas of Colorado and Nebraska. The regional models in Objective 1 will be used to (1) assess the influence of the hydrologic properties of the Dakota aquifer and the Upper Cretaceous aquitard and the effect of topography on the functioning of the flow system and (2) identify the major sources of recharge to and discharge from the Dakota.

## TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

## INTRODUCTION AND STATEMENT OF THE PROBLEM

Localized depletion of near-surface sources of water is occurring in the Ogallala and alluvial valley aquifers in western and central Kansas. These developments point clearly to the need to develop new water supplies in western and central Kansas before depletion becomes more widespread than at present. The next available source of water in this part of the state is the Dakota, an extremely complex and poorly understood aquifer system. On the basis of work conducted by the Kansas Geological Survey in FY89, several water quantity-quality problems associated with long-term development 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 withdrawals of water from the Ogallala and Dakota aquifers in southwestern Kansas on future water-supply availability, (4) the effect of shallow disposal of produced oil brines on the Dakota aquifer in central Kansas, (5) the definition of usable zones in the Dakota aquifer, and (6) the effect of saltwater discharge from the Dakota aquifer on water quality in central Kansas stream-aquifer systems. Those areas of the Dakota aquifer currently undergoing development are managed with little or no technical guidance for policy decisions.

## 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 eastern Colorado and Nebraska and is nearly as geographically extensive aquifer in Kansas as the High Plains (Ogallala and associated overlying alluvial) aquifers (Figure 1). The aquifer framework consists of interbedded lenses of sandstone and mudstones belonging to the Dakota and Kiowa Formations and the Cheyenne Sandstone (Figure 2). These geologic units were deposited in river valleys, in deltas, and in nearshore marine environments that with time, shifted laterally over much of the North American continental interior approximately 94–108 million years ago (early part of the Cretaceous Period) (Figure 3).

The Dakota is a near-surface aquifer in most of southeastern Colorado, and southwestern and central Kansas or underlies the High Plains and the Arkansas River valley aquifer. Elsewhere in Kansas and eastern Colorado, younger shales, chalks, and limestones of Cretaceous age overlie the Dakota aquifer. The main pattern of ground-water flow in the Dakota aquifer is from recharge areas in southeastern Colorado and southwest Kansas to discharge areas in central and north-central Kansas river valleys (Figure 4 ). The Dakota aquifer is recharged by precipitation in the outcrop areas of southeastern Colorado and central Kansas, by the overlying Ogallala and alluvial valley aquifers in southwest Kansas, and by the underlying Cedar Hills aquifer where both aquifers are hydraulically connected in the central part of the state. The

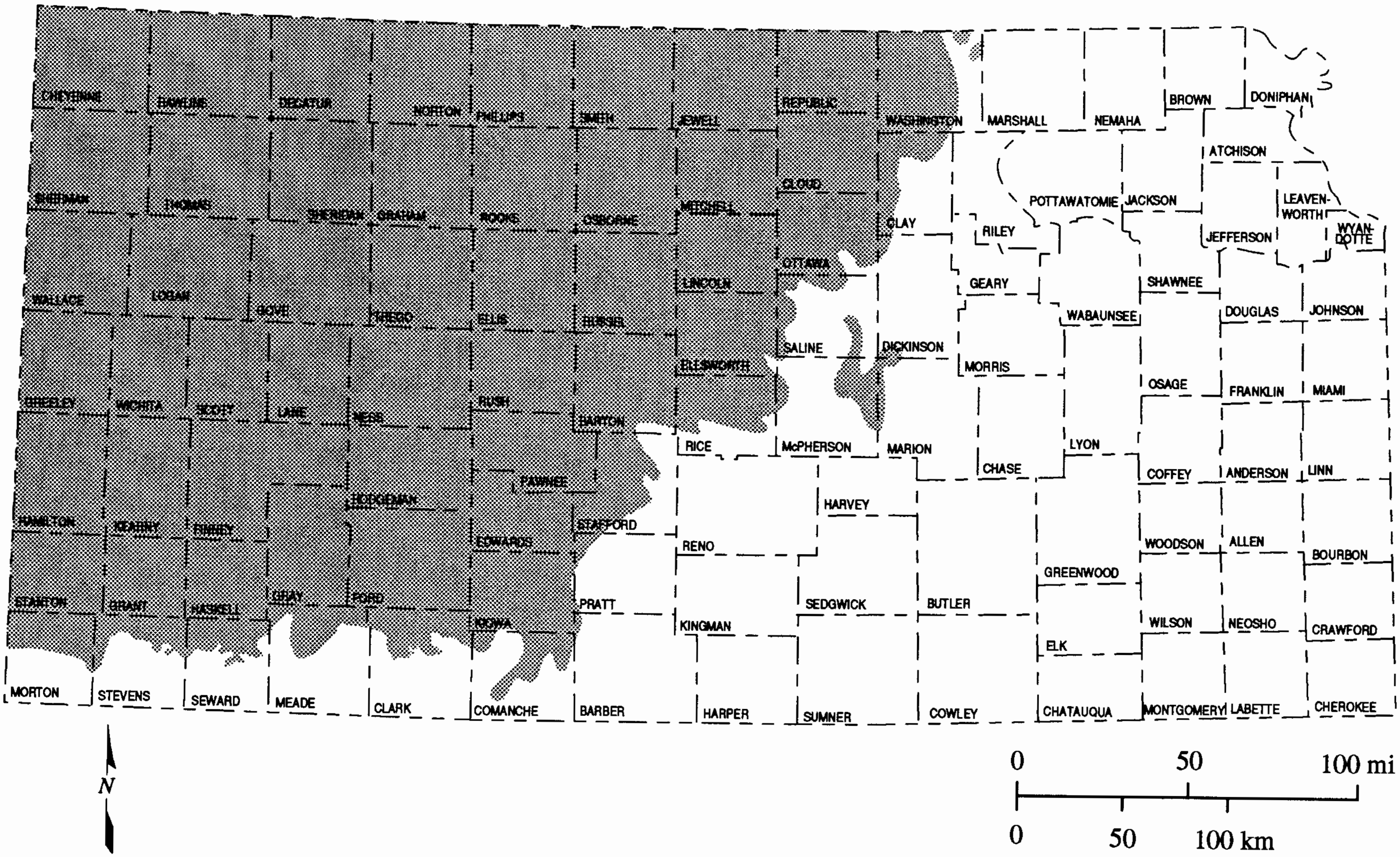

Figure 1. Extent of the Dakota aquifer in Kansas.

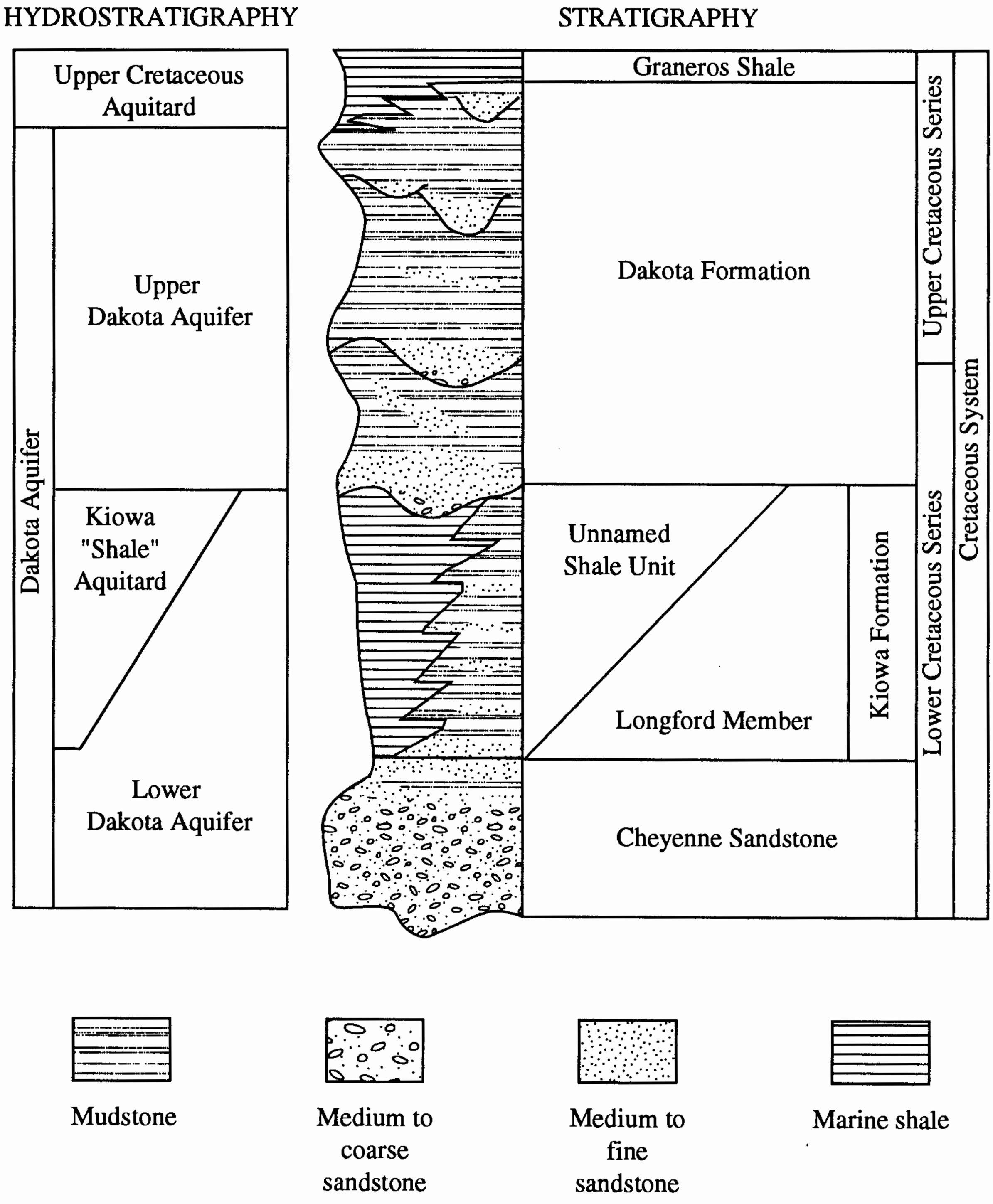

Figure 2. Stratigraphic and hydrostratigraphic classification of units that comprise the Dakota aquifer in Kansas.

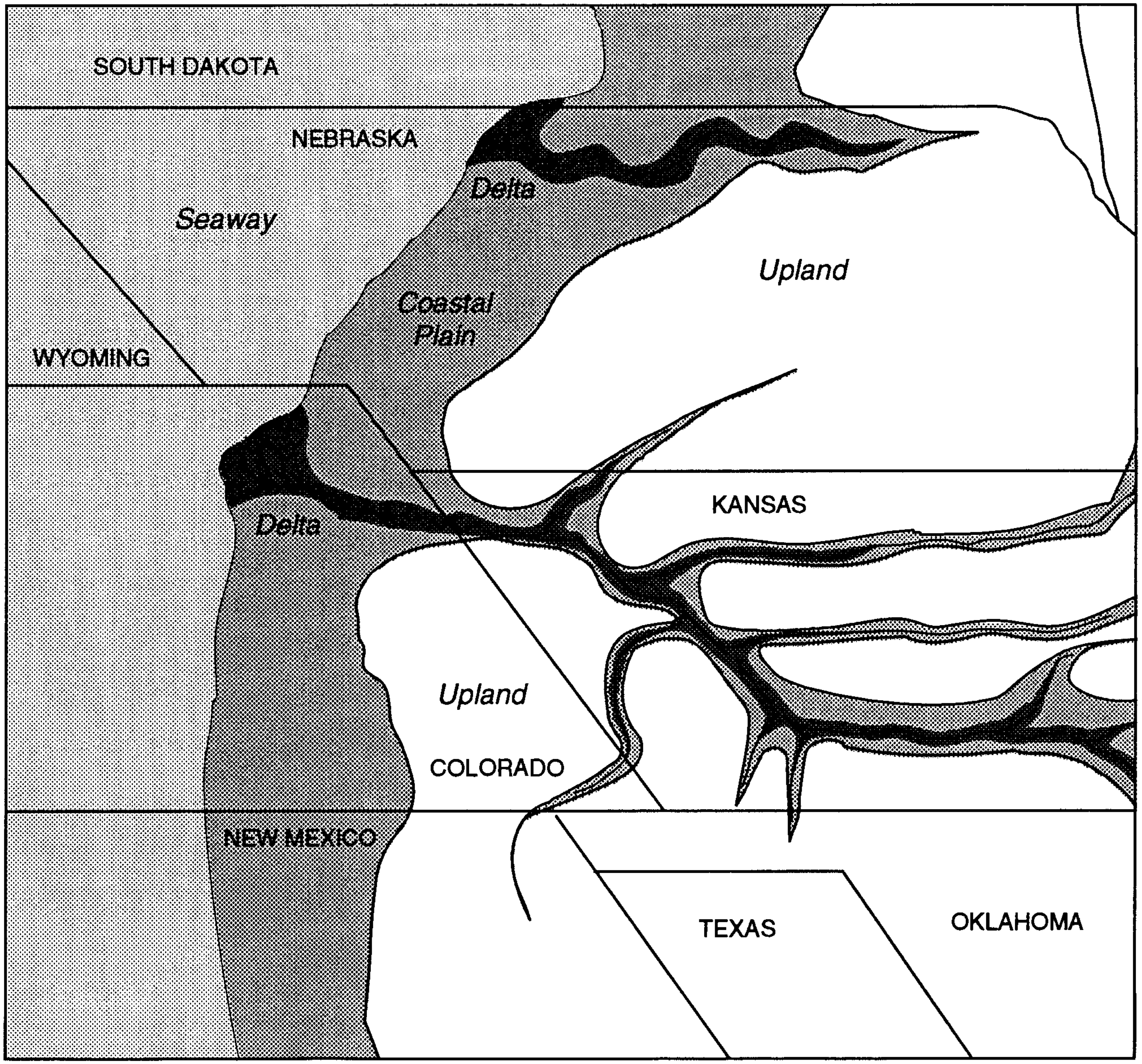

Figure 3. Midcontinent geography during deposition of the middle portion of the Dakota aquifer approximately 97 million years ago (early Dakota time).

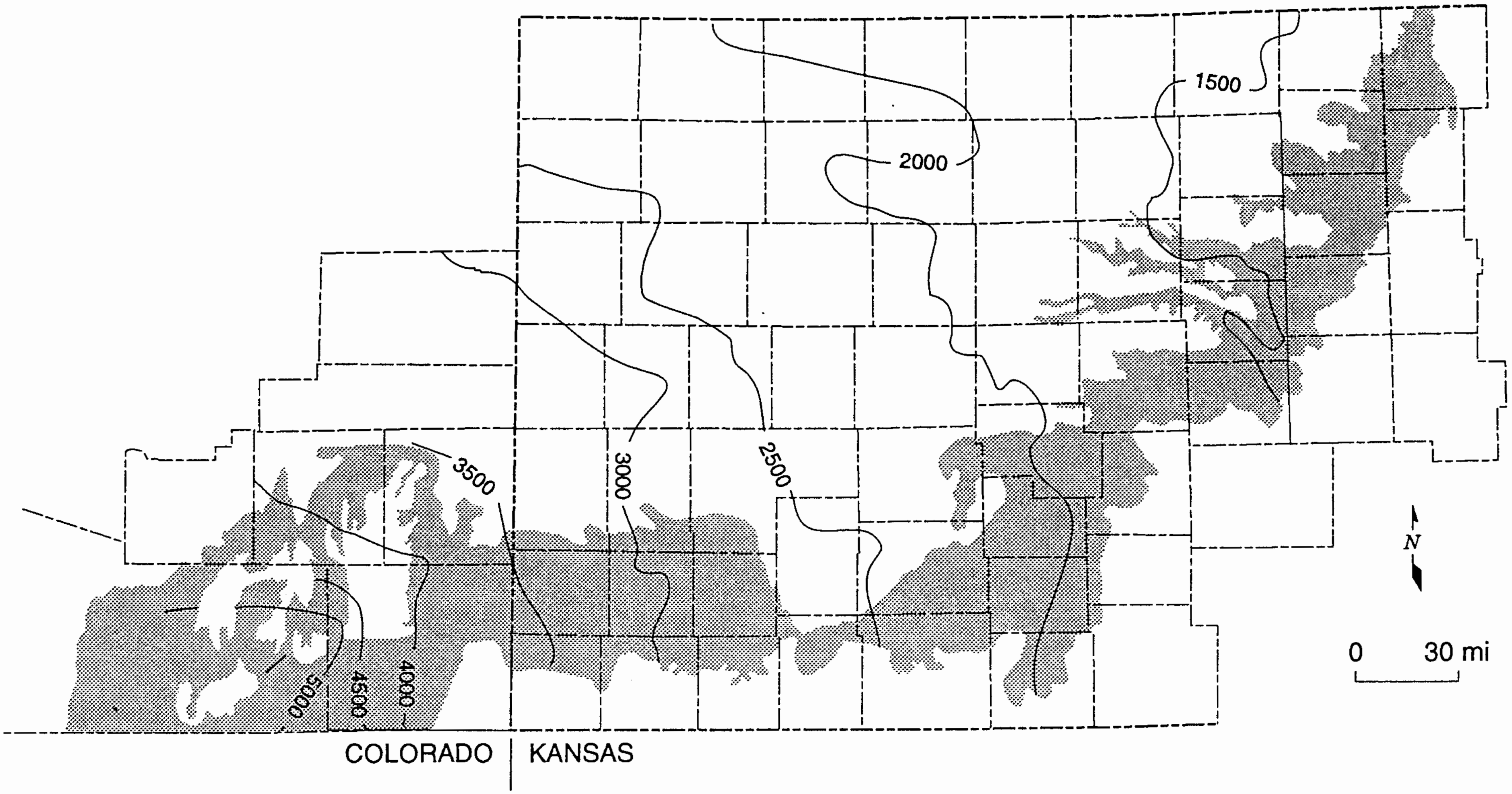

Figure 4. Configuration of the pre-development potentiometric and water-table surfaces of the upper part of the Dakota aquifer in Kansas and southeastern Colorado.

ability to transmit water laterally and vertically through the deeper aquifer systems depends on the hydraulic connection of sandstone aquifers, including fractures that penetrate the shale hydraulic properties of the sandstones.

Freshwaters occur along the eastern outcrop area, part of the eastern subcrop adjacent to the outcrop zone, and in the subcrop area of the Dakota aquifer in southwestern Kansas. The rates of change in dissolved-solids contents with areal distance are greatest along the easternmost subcrop from Republic County to Barton County. Saltwater in the Dakota aquifer in central Kansas is geochemically identified as derived primarily from solution of halite (rock salt) in Permian rocks, and has flowed upward into the Dakota. The upward movement from the Permian is affected by pinching out of confining layers and the presence of fractures and other geologic structures.

The Dakota aquifer has been used as a source of water in southeastern Colorado and Kansas for a century or more. Currently, there is scattered use of the Dakota for irrigation, public water supply, and industry in southeastern Colorado and southwestern and central Kansas. Reported well yields range up to 2,000 gallons per minute in central and southwestern Kansas and southeastern Colorado. In Kansas approximately 96% of the total volume of ground water withdrawn from the Dakota is from southwestern and south-central parts of the state.

Rates of withdrawal probably exceed recharge to the system in Kansas and eastern Colorado. Long-term historical water-level records to assess the effects of development are virtually nonexistent except for published reports from the early 1900's. What limited data exist suggest that water-level declines are on the order of 50 ft. or less in the southeastern Colorado-southwestern Kansas area. Flowing artesian water wells in the aquifer were once common in the Arkansas River valley (Figure 5). Now, these wells are rare where development has been the heaviest. Elsewhere, the data suggest that water-level declines are on the order of 10 ft. or less where development has been less extensive.

## PROGRAM OVERVIEW

The Dakota aquifer program began in state FY89. This program is an eight-year-long multi-agency effort to assess the water resources potential of the aquifer and is designed to meet the water-planning and regulatory needs of state and local agencies. The backbone of the program is an integrated, interdisciplinary research strategy that incorporates elements of hydrology, structural geology, sequence stratigraphy, borehole and surface geophysics, geochemistry, and mechanical engineering. Work completed at the end of the program's first year (FY89) included data-base development and research on stratigraphy, hydrogeology, water-quality, water-use, and energy-use by high capacity wells.

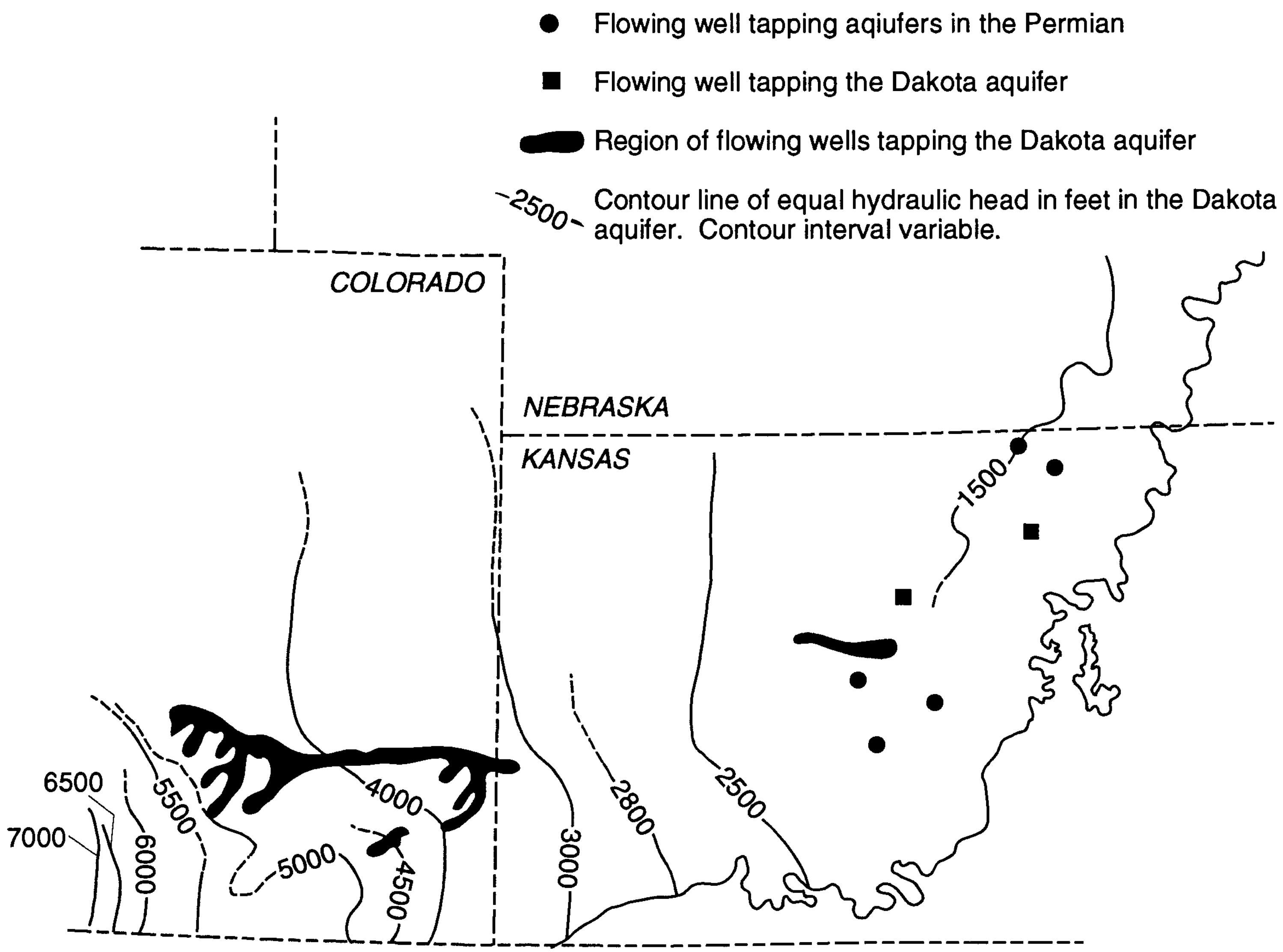

Figure 5. Areas of artesian flow in the Dakota aquifer mappedd by Darton in 1904.

The overall objectives of the Dakota aquifer program in FY90–94 are to (1) 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 (Figure 6) and (2) develop conceptual models of ground-water flow and assess water-planning and regulatory scenarios in FY92-94.

The following is an annual report of the Dakota aquifer program that summarizes the activities and results of the program during FY93. Details concerning specific areas of research in the program completed during FY93 will be reported as stand-alone chapters. Technical papers from the Dakota aquifer program will continue to be reported in the Kansas Geological Survey's Open-File Report series. Each annual report will be given a number, such as 93-1, and each chapter will be given the same number followed by a letter of the alphabet that corresponds to its position in the sequence of reports for that year, such as 93-1a.

## FY93 ACTIVITIES AND RESULTS

During FY93 diverse research and research support activities were initiated, continued, or completed to further the goals of the Dakota aquifer program in southwestern and central Kansas. Research activities were carried out to continue work to develop up-to-date characterizations of the Dakota aquifer framework, geohydrology, and geochemistry in those areas currently undergoing development. One of the primary goals of the FY93 Dakota aquifer program was to integrate the findings from the subregional investigations conducted during FY90–92 and use the data to investigate the major factors influencing flow systems within the Dakota using computer models.

The following FY93 tasks and milestones were accomplished in the Dakota Aquifer Program. In the area of the program emphasizing the geologic framework, work continued to obtain core samples of the Mesozoic part of the section at the Stanton County monitoring site. In the area of the program emphasizing geohydrology the following tasks were completed or initiated: (1) completion of the hydrologic testing of the Stanton county monitoring site; (2) assembly and initial calibration of a three-dimensional regional steady-state model of the Dakota aquifer for Kansas and adjacent parts of southeastern Colorado; (3) assembly of a subregional model of the coupled Dakota/High Plains aquifer system in southwestern Kansas; and (4) documentation and report writing on the development of the ARC-MOD interface.

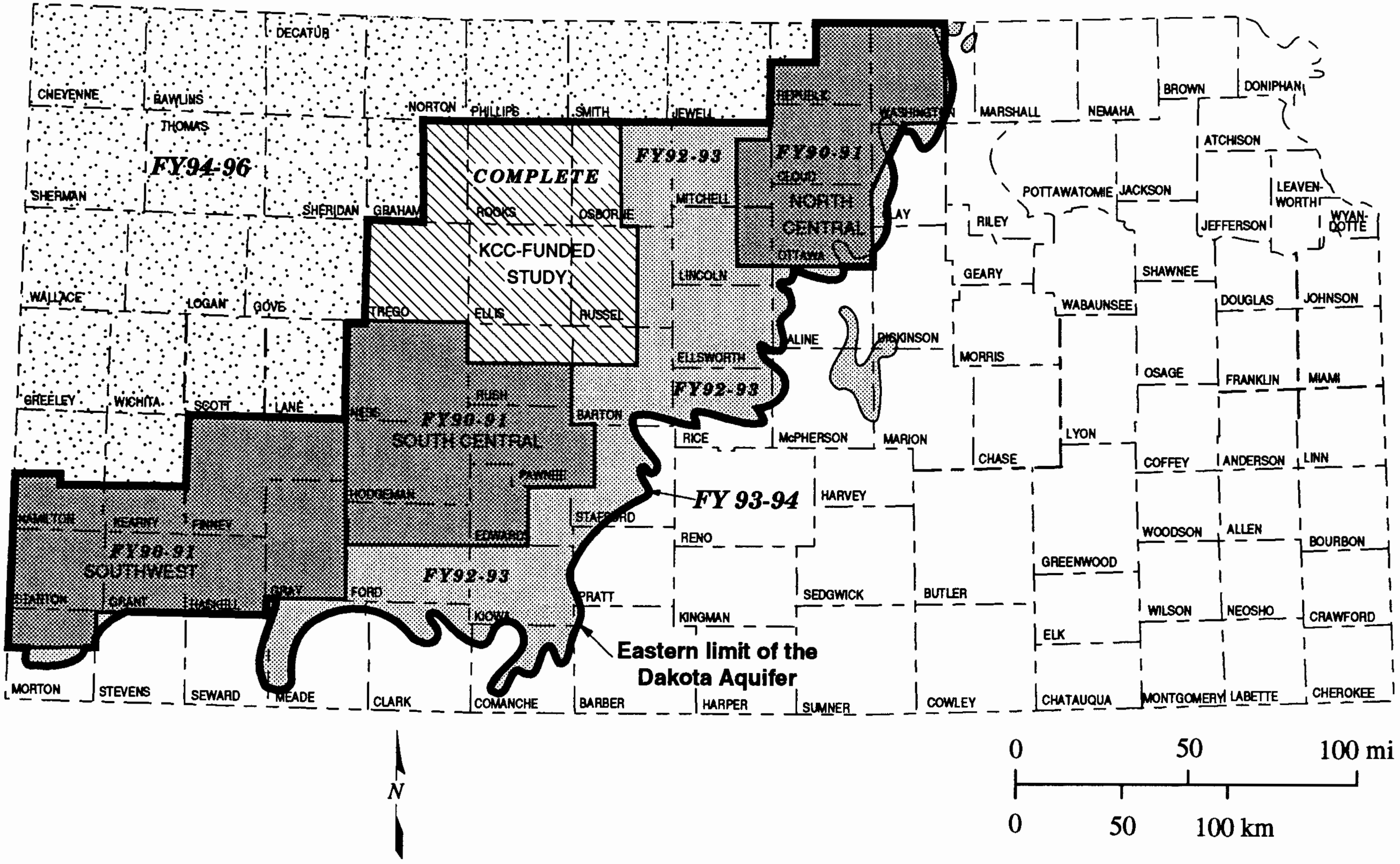

Figure 6. Extent of the Dakota aquifer in Kansas and subregional areas of investigation.

## GEOLOGIC FRAMEWORK

### Mesozoic Stratigraphy at the Stanton County Monitoring Site

After several attempts a nearly continuous core of the Mesozoic section at the Stanton County monitoring in SE, SW, SE Sec. 21, T. 29 S., R. 43 W. was collected by the Kansas Geological Survey. Figure 7 contains a diagrammatic description of the Cretaceous part of the section in the core. For comparison the gamma-ray log of borehole containing the piezometer screened in the underlying undifferentiated Jurassic-Triassic part of the section is included. The two boreholes are approximately 20 ft apart at the site. At the site, upper part of the Dakota Formation has been removed by pre-Ogallala erosion. The upper half of the Dakota has a very striking weathered appearance. The lower part of the formation (100–122 ft) just above the top of the Kiowa Formation is dominated by a basal, fining-upward fluvial sandstone. All of the Dakota above this fluvial sandstone is marine influenced, including the thick sandstone from 26–71 ft. in the core. Below the unconformity at the base of the Dakota Formation, a 20 ft. thick regressive sandstone occurs near the top of the Kiowa Formation in the core. Although the grain size shows very little variation in the core, the sorting seems to improve vertically and is reflected by a decrease in gamma-ray activity upward from the base of the sand body. The kick in the gamma-ray log at the base of the sandstone may represent a phosphatic shell lag near the base of the regressive sandstone. The remainder of the Kiowa consists of gray siltstone characteristic of the marine facies observed in outcrop in southern Kansas. Below the Kiowa is a thick, fluvial sandstone body (from 198–286 ft) which belongs to the Cheyenne Sandstone. Grain size within the sandstone body shows little variation vertically, except at the bottom just above the basal Cretaceous unconformity where the Cheyenne is conglomeratic. Below the Cheyenne the uppermost undifferentiated Jurassic-Triassic section consists of a 2 ft. thick layer of siltstone with very fine sandstone underneath.

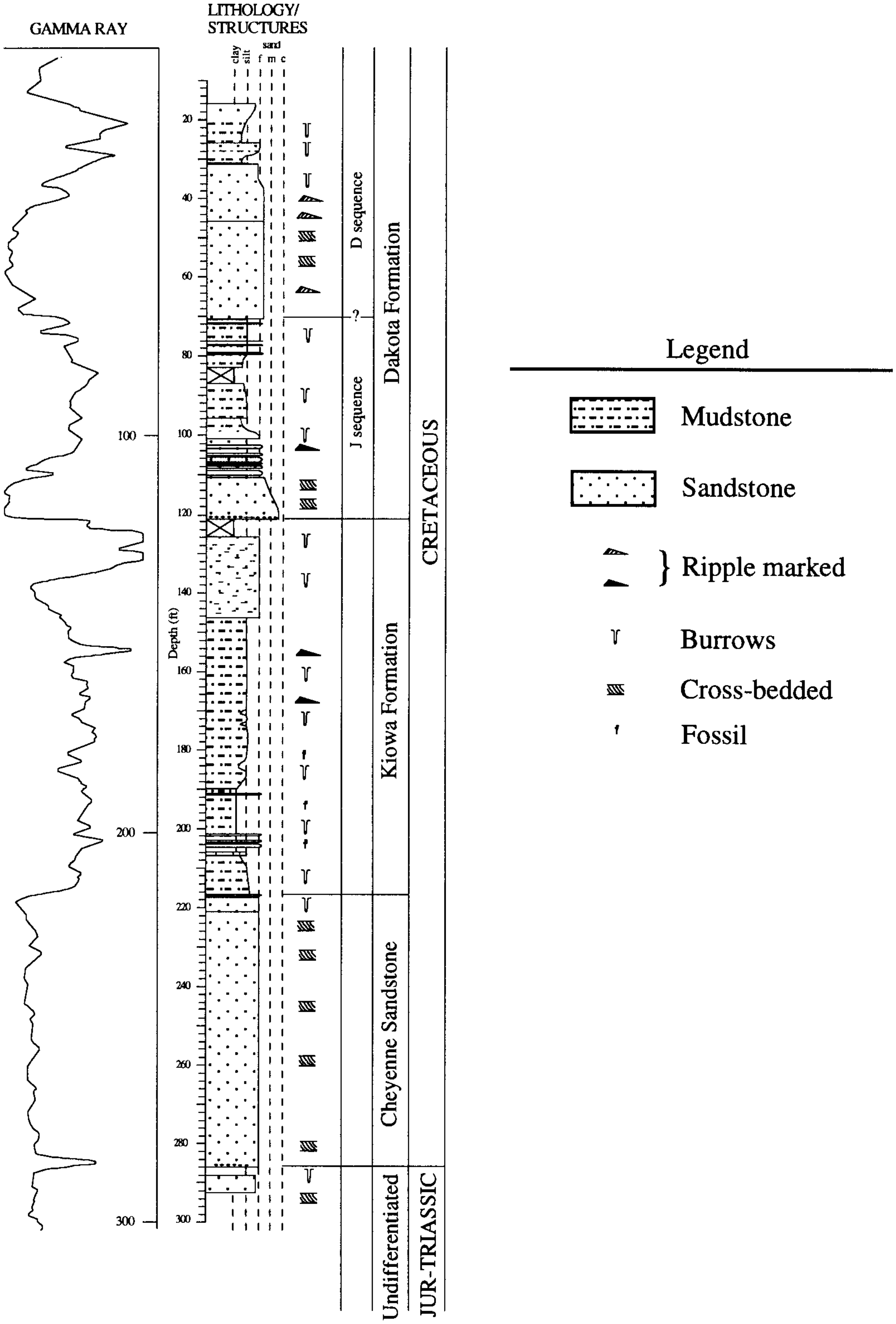

Figure 7. Cretaceous stratigraphy at the Stanton County monitoring site, SE, SW, SE Sec. 21, T. 29 S., R. 43 W. The gamma-ray log is from the borehole containing the piezometer in the Jurassic-Triassic deposits, approximately 20 ft. away from the core hole.

## GEOHYDROLOGY

### Comparison Of The Northern Cross-Section Modeling Results To The Major Ion Water Chemistry, $^{14}C$ Apparent Age Dates, And The Distribution Of $^{36}Cl$

#### *The steady-state regional ground-water flow system*

In his reconnaissance reports Darton (1905, 1906) considered the Dakota aquifer a classic example of an artesian system. However, in most of western and central Kansas and eastern Colorado water-levels in the Dakota aquifer are as much as 2,500 ft lower than the elevation of the overlying water table (Macfarlane, 1993; Helgeson *et al.*, 1994). One possible explanation for these low water levels is that the hydrology of the upper part of the regional flow system, including the confined Dakota aquifer, is influenced primarily by a thick, shale and chalk sequence that constitutes the Upper Cretaceous aquitard (Table 1, Figure 8). The Upper Cretaceous aquitard is believed to severely retard the downward movement of significant recharge to the Dakota aquifer from the overlying water table in most of eastern Colorado and in Kansas except where it is thin. Parts of the flow system in the confined Dakota may also be influenced by the Arkansas River valley in southeastern Colorado and adjacent Hamilton County in Kansas and the Saline River drainage in central Kansas (Figure 8). The Arkansas River valley is located just downgradient of the main recharge area in southeastern Colorado and appears to be a major discharge area for Dakota aquifer. Because of this discharge, flow to the confined Dakota aquifer is reduced in western Kansas. Farther to the east in central Kansas, the Saline and Smoky Hill Rivers have eroded through the Upper Cretaceous aquitard to the west of the main outcrop area of the Dakota. This may have improved the hydraulic connection between the confined aquifer and its discharge area, resulting in a further reduction of head in the Dakota.

During FY92–93 the main thrust of the hydrology research has been directed toward testing the hypothesis outlined above. To facilitate the analysis, two-dimensional vertical profile (cross-sectional) and three-dimensional conceptual models of the shallow part of the regional flow system in southeastern Colorado and western and central Kansas have been developed. Detailed discussion of this analysis can be found in Macfarlane *et al.* (1992) and Whittemore *et al.* (1993). The results for the vertical profile modeling will be only briefly summarized here for the northern vertical profile model.

The northern vertical profile is at least sub-parallel to direction of flow in all of the major aquifer systems and extends from the regional recharge area in southeastern Colorado to the regional discharge area in central Kansas (Figure 8). Within the model there are six regional aquifers, the High Plains, alluvial valley, the upper and lower Dakota, the Morrison-Dockum, and the Permian sandstone aquifers, and three regional aquitards, the Upper Cretaceous, the Kiowa shale, and the Permian-Pennsylvanian (Figure 9). The ground-water flow model of the

| ERA | SYSTEM | ROCK STRATIGRAPHIC UNITS | HYDROSTRATIGRAPHIC UNITS |
|---|---|---|---|
| Cenozoic | Quaternary | Unconsolidated Sediments | High Plains & Alluvial Valley aquifers |
| | Tertiary | Ogallala Fm. | |
| Mesozoic | Cretaceous | Colorado Group | Upper Cretaceous aquitard |
| | | Dakota Ss./Dakota Fm. | Upper Dakota aquifer |
| | | Purgatoire Fm./ Kiowa Fm. | Kiowa Shale aquitard |
| | | | Lower Dakota aquifer |
| | Jurassic/Triassic | Morrison Fm.<br>Dockum Group | Morrison-Dockum aquifer |
| Paleozoic | Permian/ Pennsylvanian | Permian Undiff. | Permian-Pennsylvanian aquitard |
| | | Lyons Ss/Cedar Hills Ss. | Permian Sandstone aquifer |
| | | Permian/Pennsylvanian Undiff. | Permian-Pennsylvanian aquitard |

Table 1. Stratigraphy and hydrostratigraphy of the shallow subsurface in the vertical profile from southeastern Colorado to western and central Kansas.

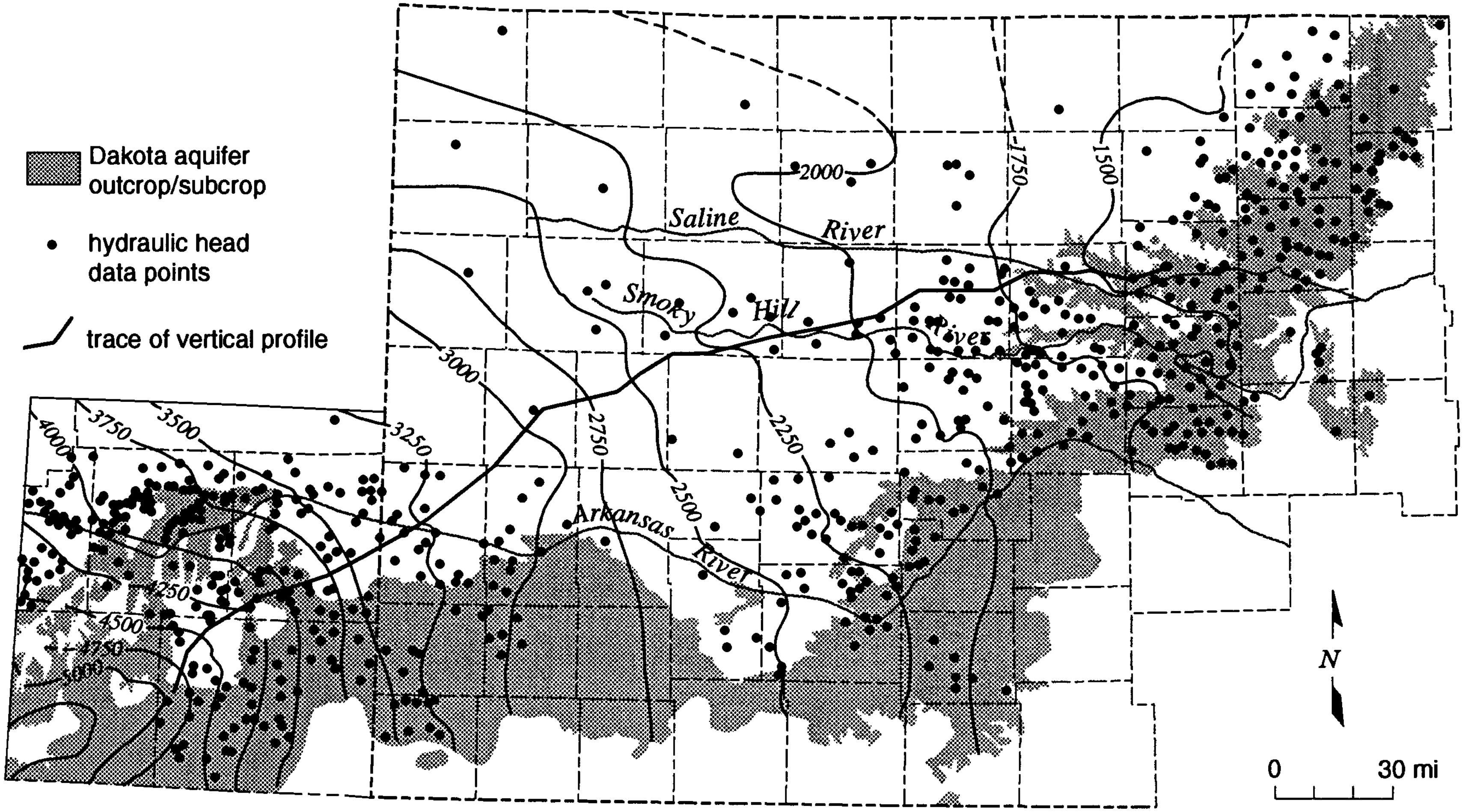

Figure 8. Elevation in feet above mean sea level of the predevelopment potentiometric surface of the Dakota aquifer in southeastern Colorado and western Kansas. The shaded area shows the area of outcrop, primarily in central Kansas, and subcrop beneath Pleistocene and Tertiary deposits in southwestern Kansas and southeastern Colorado. Hydraulic head data are from the U.S. Geological Survey's Central Midwest Regional System Analysis Program.

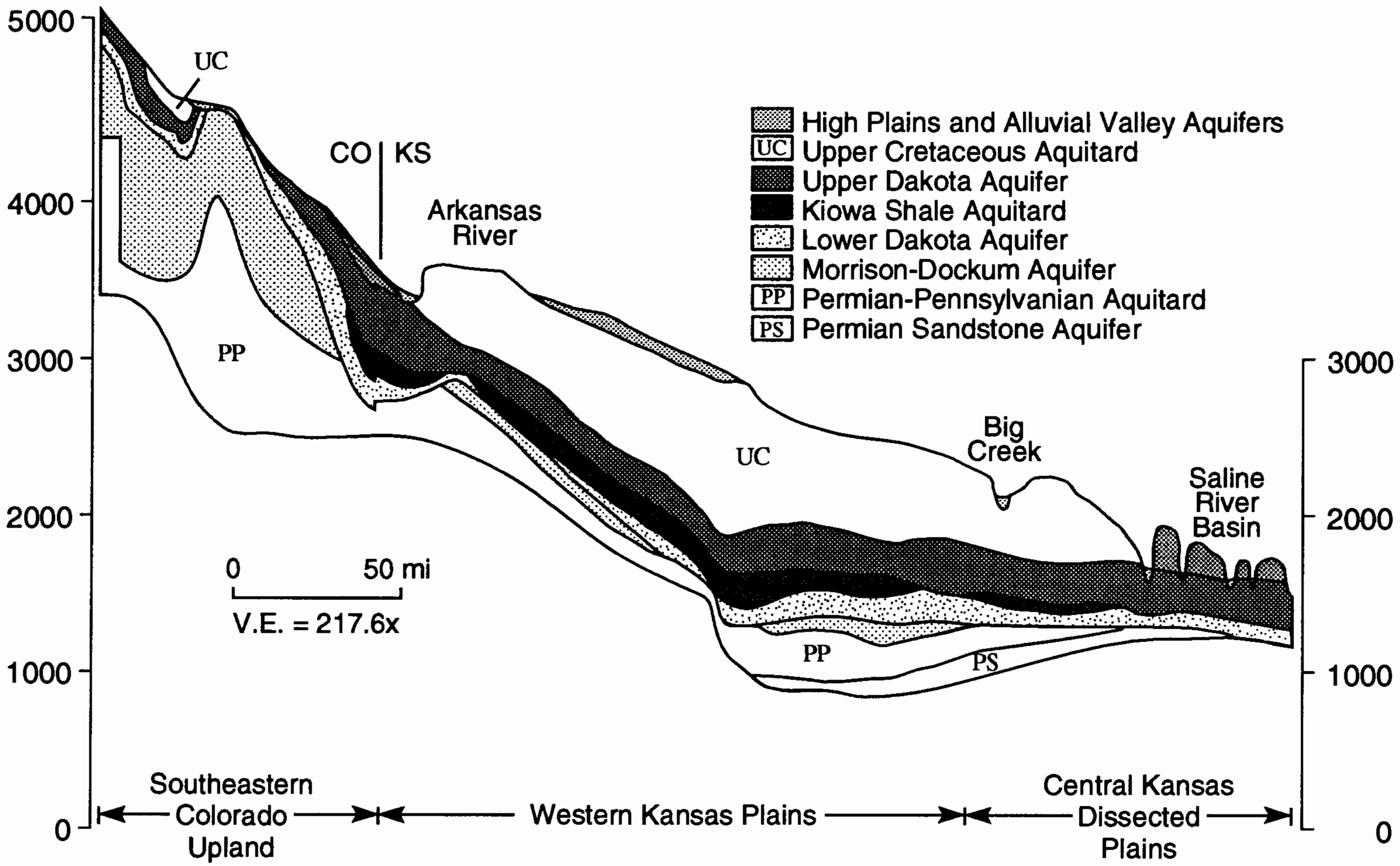

Figure 9. Regional hydrostratigraphy of the shallow subsurface along the trace of the northern vertical profile

hydrogeology in vertical profile is subdivided into the southeastern Colorado upland, the western Kansas plains, and the central Kansas dissected plains subsections on the basis of regional and local topographic relief (Figure 10). Ground-water flow is gravity-driven from the higher elevation areas in the southeastern Colorado upland toward the lower elevation areas in the central Kansas dissected plains. The steady-state model shows that the upper part of the flow system in the southeastern Colorado upland and the central Kansas dissected plains subregions is dominated by local flow systems due to the relatively high local topographic relief in these sections. The deeper part of the flow system in the southeastern Colorado upland subregion and all of the western Kansas plains subregion is dominated by the intermediate-scale flow system. In the southeastern Colorado upland and the central Kansas dissected plains sections most of the water that enters the model through the upper boundary is discharged locally and very little is contributed to regional flow (Figure 11). Approximately 10% of the water that enters the model in the southeastern Colorado upland section appears to move northeastward into the western Kansas plains section downgradient of the Arkansas River valley. In contrast, only 0.9% of the total model water budget recharges the flow system in the western Kansas plains section of the model. Recharge from above to the confined Dakota aquifer is less than 1% of the lateral flow (Macfarlane, 1993). Modeling experiments show that the flow system is most sensitive to the vertical hydraulic conductivity of the Upper Cretaceous aquitard (Figure 12). In simulations where the Arkansas and Saline river valleys were removed, the head difference between the water table and the underlying upper Dakota in western Kansas was significantly reduced (Figure 13).

### *The major ion chemistry*

Water chemistry analyses were compiled from county and regional reports on water quality in southeastern Colorado and western and central Kansas in order to characterize the ground-water geochemistry along the vertical profile. It is believed that water-resources development in most areas has not significantly altered water quality in the major aquifers. Thus, the reported results in the more recent U.S. Geological Survey Water Supply Papers and in the Kansas Geological Survey Bulletins approximately represent the geochemistry of ground water as it probably existed under pre-development conditions. Due to the lack of data, additional water samples were collected from the Dakota aquifer along the surface trace of the vertical profile through southeastern Colorado and western and central Kansas during May and July, 1992. The results from these surveys are reported later in this annual report. All of the water sample analyses reported in the literature and from the recent field sampling were collected from wells located within 6 mi of the vertical profile used in the conceptual modeling of the

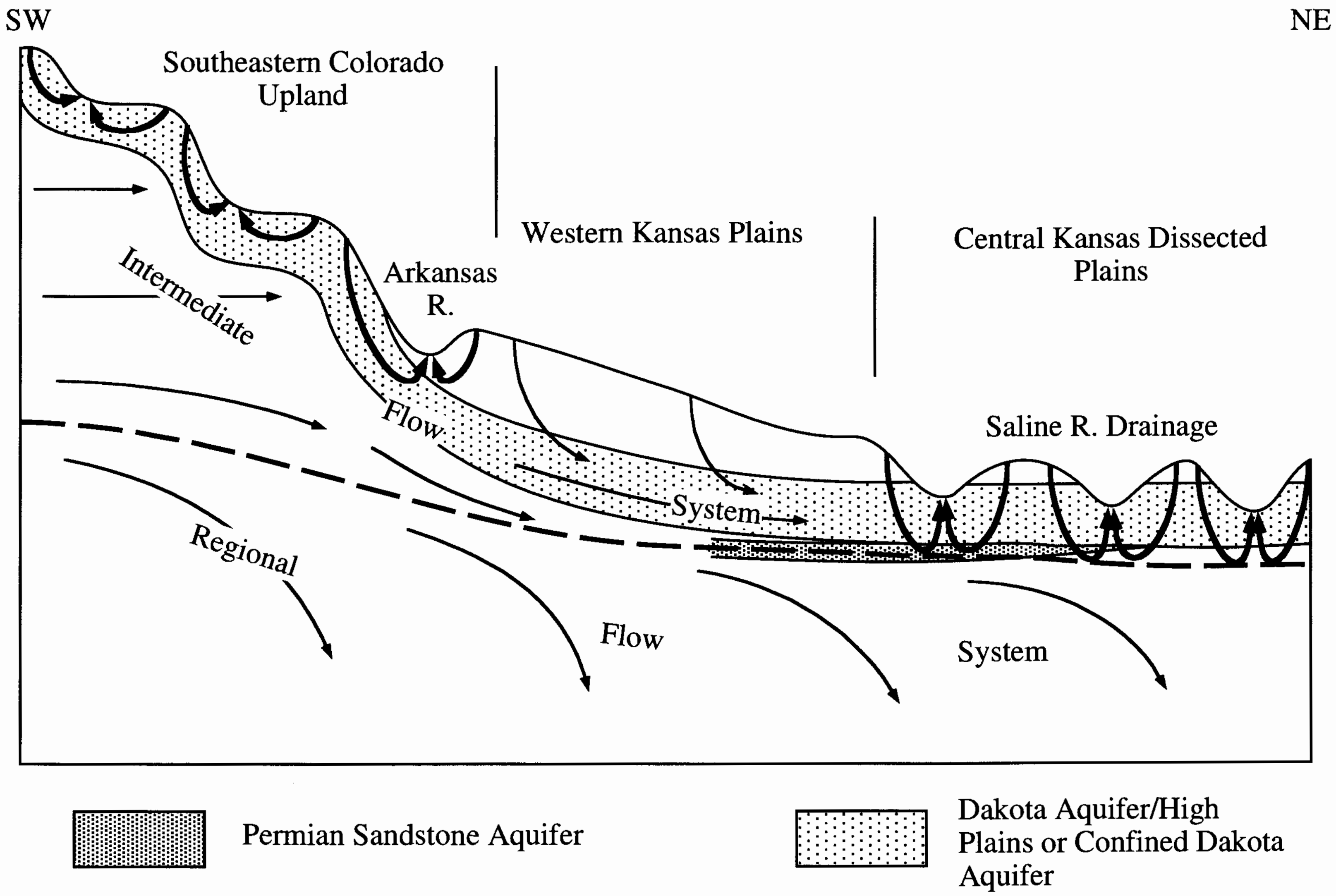

Figure 10. A conceptual model of ground-water flow in the vertical profile that extends from southeastern Colorado into western and central Kansas.

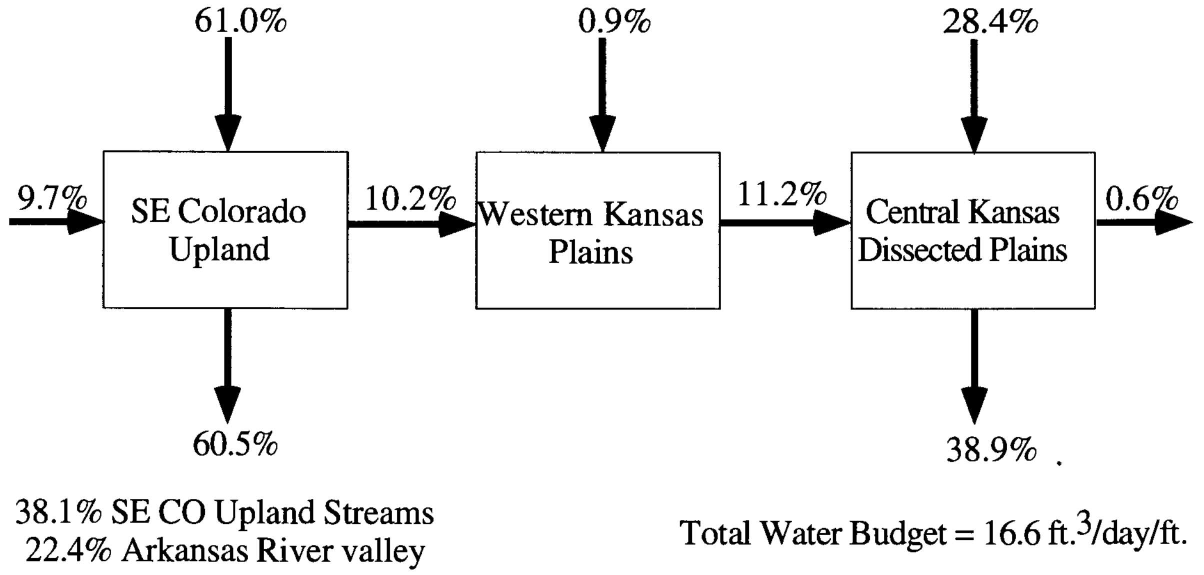

Figure 11. The flux of water through the major subdivisions of the steady-state flow system in the vertical profile.

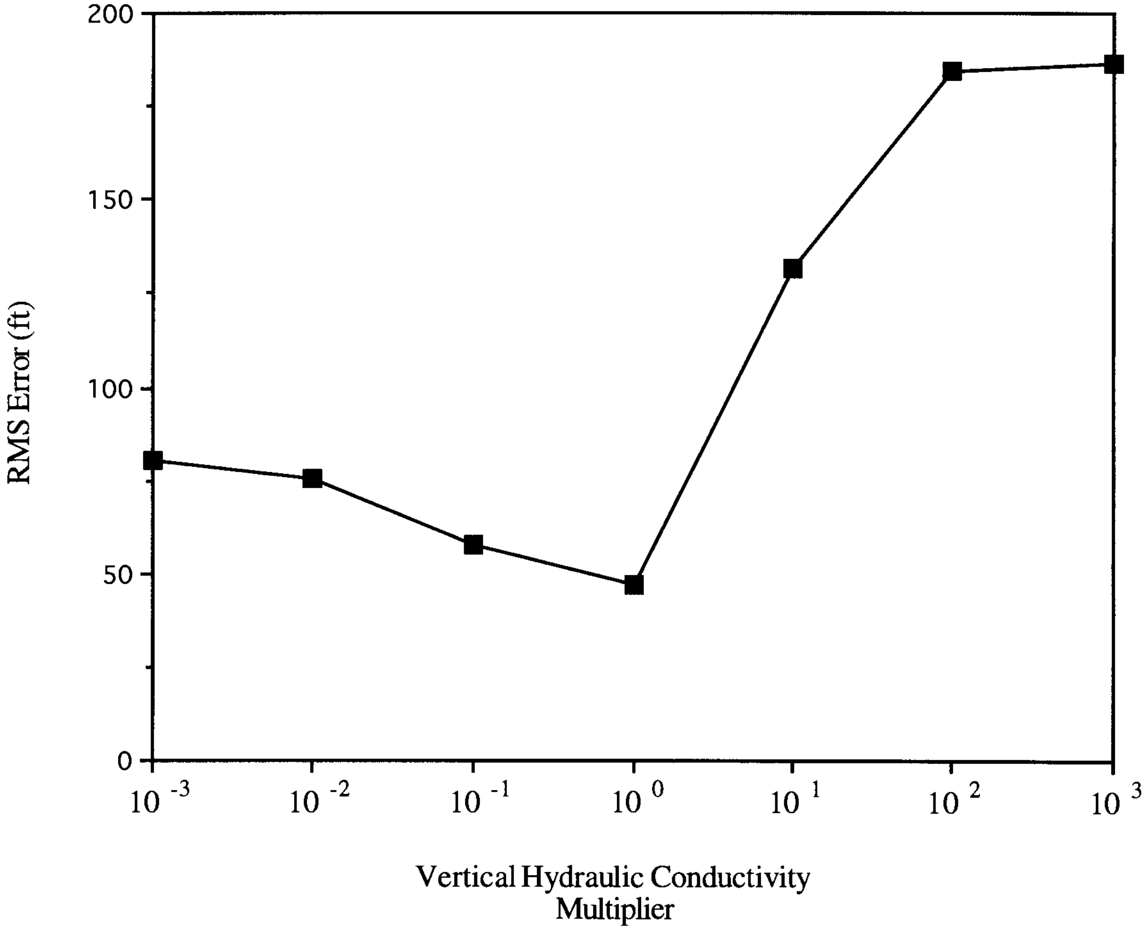

Figure 12. Model sensitivity to the nonuniform vertical hydraulic conductivity of the Upper Cretaceous aquitard in the partially calibrated model, expressed as RMS error.

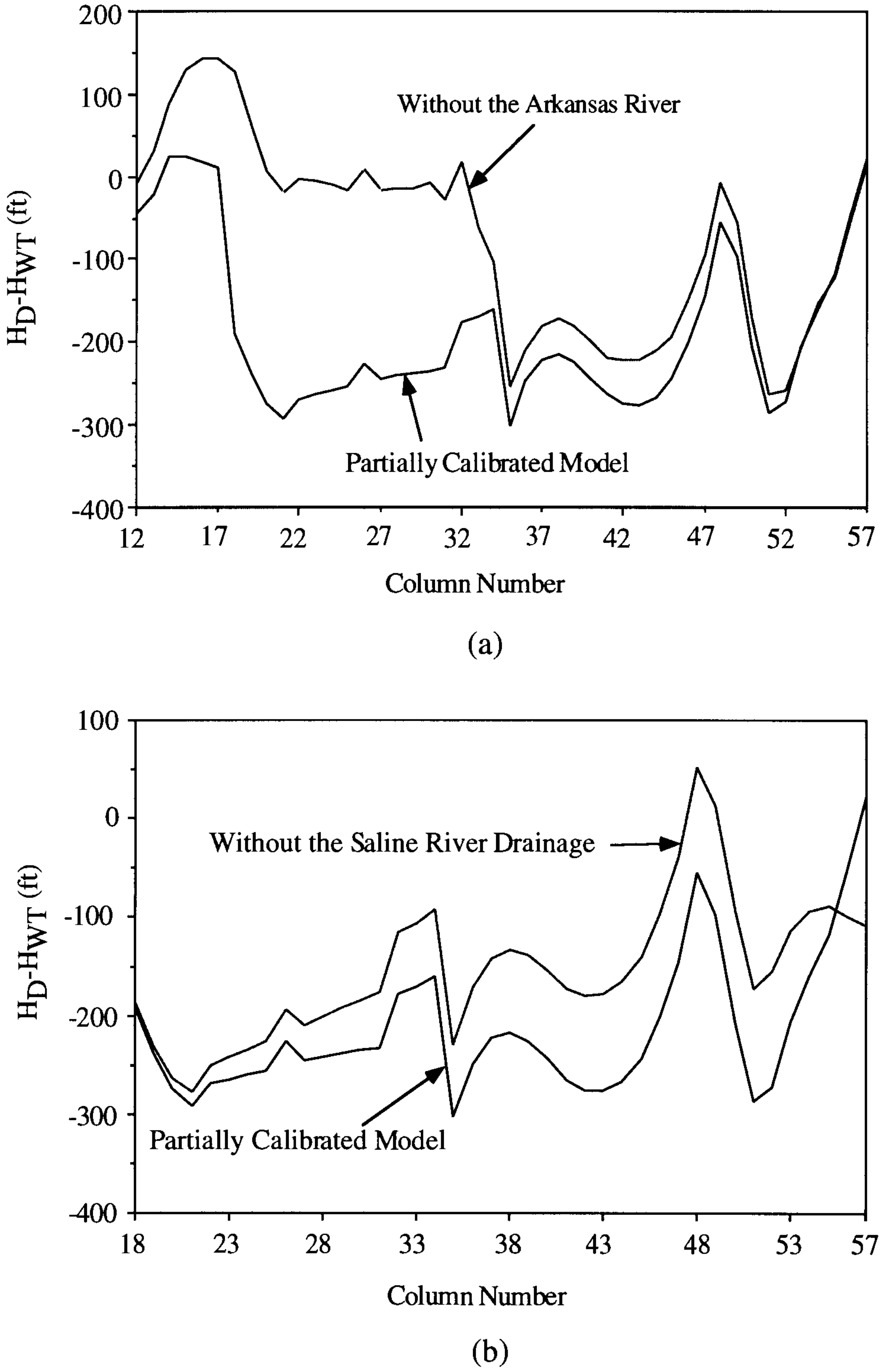

Figure 13. The head difference between the upper Dakota aquifer ($H_D$) and the overlying water table ($H_{WT}$) when the Arkansas River valley (a) and Saline River drainage (b) are removed from the simulation. The head difference in the partially calibrated model is shown for comparison.

regional flow system. However, one sample was collected in Lincoln County, Kansas, 15 mi to the east of the northeast end of the vertical profile where the upper Dakota aquifer is at the surface in the Saline River valley. The water samples were analyzed by the Analytical Services Section, Kansas Geological Survey, the Nuclear Chemistry Division, Lawrence Livermore National Laboratory, and the U.S. Geological Survey to determine the major ions in solution (calcium, magnesium, sodium, carbonate, bicarbonate, sulfate, chloride, and nitrate) and selected minor and trace constituents and stable and radiogenic isotopes.

No analyses are available for samples collected from the Morrison-Dockum aquifer near the vertical profile. However, McLaughlin (1954) reported analytical results for samples from Baca County to the south of the vertical profile near the Cimarron River valley and where the Morrison-Dockum is overlain by the High Plains and alluvial valley aquifers in eastern Baca County, Colorado. One analysis of ground water from the Dockum Group along the Colorado-New Mexico border is reported by Cooper and Davis (1967). One sample was collected during the May, 1992, sampling from a piezometer in Stanton County, Kansas, near the Kansas-Colorado border.

Few ground-water chemistry data are available for the Permian sandstone aquifer along the vertical profile. Chloride data obtained from water samples collected during the well development (swabbing) of injection wells were provided by the Kansas Corporation Commission. An analysis of a water sample from a monitoring site in northern Ellis County, Kansas, was reported in Macfarlane *et al.* (1988) and contains information on major and selected minor and trace constituents.

Each water sample was classified according to the following rules used in Macfarlane *et al.* (1990) for the classification of ground-water types in the Dakota aquifer. If the primary cation or anion comprised more than 50% of the total equivalents of the cations or anions, respectively, the secondary cation or anion had to constitute more than 33% of the total. If the primary cation or anion constituted less than 50% of the total equivalents of the cations or anions, respectively, then the secondary cation or anion had to constitute more than 30% of the total.

The ground-water chemistry data for samples collected along and adjacent to the vertical profile reveals a wide range of TDS concentrations, from less than 400 mg/l to nearly 30,000 mg/l. Along with this wide range of TDS concentrations, there is also a wide range of water types defined by the proportions of the various major constituents (Figure 14). Bicarbonate type waters with low TDS concentrations (less than 500 mg/l) are the most common in the Dakota aquifer in the southeastern Colorado upland. The TDS concentrations increase slightly along the flow path and beneath the Arkansas River valley and sulfate becomes a dominant anion in the water. The deeper part of the flow system is believed to contain a mixed cation–sulfate,

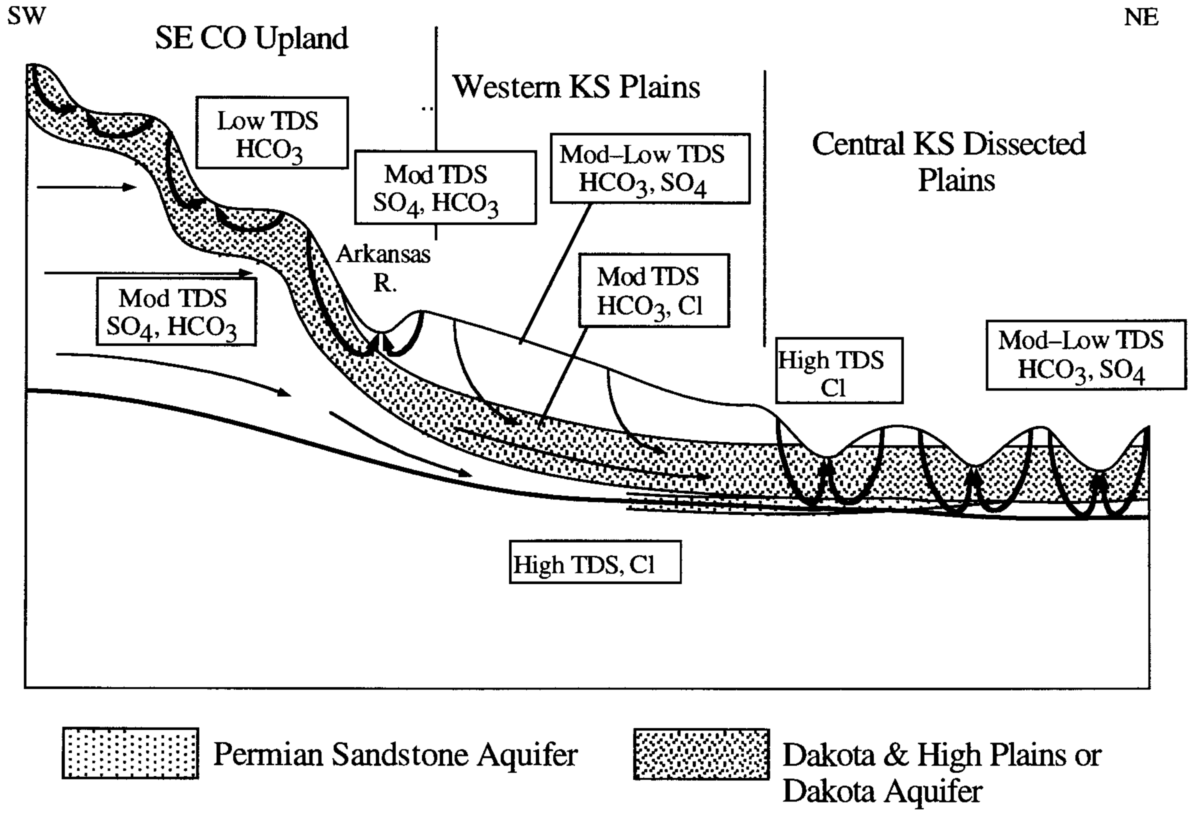

Figure 14. TDS concentrations and the dominant anions in ground water in the vertical profile from southeastern Colorado to central Kansas. Low TDS concentrations range up to 500 mg/l; mod TDS concentrations range from 500 to 1,000 mg/l; and high TDS concentrations are greater than 1,000 mg/l.

bicarbonate type water with moderate TDS concentrations (500 mg/l to 1,000 mg/l). The increasing sulfate concentration in the upper Dakota aquifer probably results from water moving downward across the Upper Cretaceous aquitard near the valley (Macfarlane *et al.*, 1992).

Except for where the Dakota aquifer is confined by the overlying Upper Cretaceous aquitard, most of its recharge comes from infiltrated precipitation or from hydraulic connection with the overlying High Plains aquifer in this part of the vertical profile. Where the Dakota aquifer is hydraulically connected to the High Plains aquifer, TDS concentrations are generally low (Robson and Banta, 1987). Robson and Banta reported moderate TDS concentrations upgradient of Baca County in eastern Las Animas County where the High Plains aquifer has been removed by erosion. They attributed the improved water quality in Baca County to recharge of better quality water from the High Plains aquifer.

In the western Kansas plains section of the vertical profile, the TDS concentrations of water samples from the Dakota aquifer continue to rise abruptly up to moderate (500 mg/l to 1,000 mg/l) to high (greater than 1,000 mg/l) levels and the water type changes to a sodium–bicarbonate type (Figure 14). In contrast, ground water in the High Plains aquifer is a calcium–bicarbonate type waters with low TDS concentrations. Eastward, the chloride concentration rises gradually in the upper Dakota aquifer from less than 50 mg/l up to approximately 1,000 mg/l and the water is a high TDS concentration, sodium–chloride type. Below, water samples from minor aquifers in the Permian-Pennsylvanian aquitard contain high concentrations of chloride and are believed to be a sodium–chloride type that has resulted from the dissolution of halite. Ground water from the Permian sandstone aquifer has very high chloride concentrations above 5,000 mg/l, and more typically 15,000 to 20,000 mg/l. Chloride is believed to diffuse upward from Permian sources into the upper Dakota aquifer where it is transported laterally by advective dispersion (Whittemore and Fabryka-Martin, 1992). Whittemore and Fabryka-Martin also reported that some chloride from residual formation water in the less permeable parts of the aquifer is probably still diffusing into the permeable part of the aquifer. The presence of sodium-bicarbonate and sodium-chloride type ground water in the upper Dakota and other aquifers beneath the Upper Cretaceous aquitard provides additional evidence of the very small amount of freshwater recharge that is available to flush this part of the flow system of remnant formation water (Macfarlane *et al.*, 1990; Whittemore and Fabryka-Martin, 1992).

In the central Kansas dissected plains section, ground-water TDS concentrations rise abruptly up to more than 10,000 mg/l in the upper Dakota beneath the Saline River (Figure 14). Ground water beneath the Saline River is a highly saline sodium–chloride type that eventually makes its way into the stream as baseflow. The discharge of saline ground water to the Saline River provides additional evidence of upward flow from the lower Dakota and Permian sandstone aquifers beneath the river in local flow systems. Downgradient of the Saline River, the chloride and TDS concentrations slowly decrease in the upper Dakota aquifer to moderate levels. Near the northeast end of the vertical profile and beyond, the TDS concentrations fall to low levels and bicarbonate type waters again become the most prevalent. The presence of sodium-bicarbonate and sodium-chloride type ground water in the upper Dakota where it is confined by the Upper Cretaceous aquitard provides good evidence that only a small amount of freshwater recharge moves through the aquitard to the upper Dakota in this part of the flow system (Macfarlane *et al.*, 1990).

### *Apparent $^{14}C$ age and $^{36}Cl$ abundance*

The $^{14}C$ and $^{36}Cl$ abundances in ground water are indicators of ground-water residence time. As such, they provide independent calibration of flow system models in addition to the more traditional measures (Mazor and Nativ, 1992; Bentley *et al.*, 1986). The half-lives of $^{14}C$ and $^{36}Cl$ are 5,730 yrs and $3.1 \times 10^5$ yrs, respectively. Hence, $^{14}C$ is a useful tracer of relatively young, shallow ground-water masses, whereas $^{36}Cl$ is a more useful tracer for older ground water (up to 2.5 million yrs) in deeper parts of the flow system.

During the May and July, 1992, water sampling, 13 water samples were collected from wells along the trace of the northern vertical profile. The abundances of $^{36}Cl$, $^{14}C$ activity, and $^{13}C$ content were determined at Lawrence Livermore National Laboratories, Livermore, California. Table 2 lists the apparent $^{14}C$ ages, $^{14}C$ activity, $^{13}C$ content, $^{36}Cl/Cl$ ratio, $^{36}Cl$ abundance/l, and the bicarbonate and chloride concentrations of the water samples collected during the May and July, 1992, sampling periods. The apparent $^{14}C$ age is not the "true" age because the effects of geochemical processes acting on the total inorganic carbon content of the water have not been taken into account (Fontes, 1980).

The apparent $^{14}C$ ages of water samples from the Dakota aquifer where it is an unconfined aquifer in southeastern Colorado and in central Kansas are all significantly less than 10,000 yrs. Samples from sites 77 and 78 in central Kansas contain appreciable tritium suggesting that recent recharge has moved down the borehole into the gravel pack of each of sampled wells. In contrast, those samples from the confined Dakota appear to be much older, in the range 20,000 yrs or more.

The $^{36}Cl/Cl$ ratios range over more than three orders of magnitude in the samples collected along the vertical profile. Ground-water samples from the collected south of the Arkansas River have $^{36}Cl/Cl$ ratios that range from 980 to $1{,}500 \times 10^{-15}$. In the confined portion of the aquifer the $^{36}Cl/Cl$ ratio drops to $1.4 \times 10^{-15}$ (below analytical precision) as the chloride concentration increases to 1,363 mg/l at sample site 75.

The apparent $^{14}C$ ages and the $^{36}Cl$ content generally reflect the degree of confinement of the Dakota and its resultant isolation from recharge due to infiltrated precipitation. In

Table 2. Bicarbonate, chloride, carbon and chlorine isotope data from water samples collected in southeastern Colorado and western and central Kansas.

| SAMPLE SITE NUMBER | LOCATION | AQUIFER | BICARBONATE (mg/l) | $^{14}C$ FRACTION (PMC) | DEL $^{13}C$ | $^{14}C$ APPARENT AGE (yrs) |
|---|---|---|---|---|---|---|
| 52 | KANSAS<br>29S-43W-21DCDD02 | Morr-Dockum | 236 | 0.1791 | -6.62 | 14,218 |
| 53 | COLORADO<br>31S-46W-04-BCCB01 | High Plains, Upper and Lower Dakota | 136 |  | -3.00 | 1,736 |
| 54 | COLORADO<br>30S-46W-31AAAA01 | Upper Dakota | 170 |  | -5.40 | 2,440 |
| 55 | COLORADO<br>31S-48W-13ACCD01 | Upper Dakota | 269 | 0.2779 | -4.85 | 10,586 |
| 56 | COLORADO<br>30S-49W-36ADDA01 | Upper Dakota | 167 |  | -5.70 | 7,458 |
| 57 | COLORADO<br>32S-49W-08BAAA01 | Upper Dakota | 198 | 0.7496 | -5.17 | 2,383 |
| 58 | COLORADO<br>30S-43W-32DBCD01 | Lower Dakota | 247 | 0.7235 | -7.40 | 2,676 |
| 59 | COLORADO<br>30S-43W-32CCDC01 | Lower Dakota | 240 | 0.6821 | -6.24 | 3,163 |
| 60 | COLORADO<br>25S-42W-11BBBB01 | Upper Dakota | 184 | 0.3751 | -7.74 | 8,106 |
| 61 | COLORADO<br>25S-44W-16ACAC01 | Upper Dakota | 224 | 0.4458 | -8.63 | 6,679 |
| 62 | COLORADO<br>31S-45W-02CABC01 | Morr-Dockum, Lower Dakota | 234 | 0.2156 | -6.33 | 12,684 |
| 63 | KANSAS<br>23S-43W-14CDCA02 | Upper Dakota | 197 | 0.3574 | -4.50 | 8,506 |
| 68 | KANSAS<br>21S-41W-02BBBB01 | Upper and Lower Dakota | 280 | 0.0226 | -9.01 | 31,330 |
| 69 | KANSAS<br>18S-37W-24BACC02 | High Plains | 216 | 0.7094 | -8.09 | 2,838 |
| 70 | KANSAS<br>18S-37W-24BACC02 | Upper Dakota | 345 | 0.003 | -8.44 | 43,477 |

Table 2. (continued)

| SAMPLE SITE NUMBER | LOCATION | AQUIFER | BICARBONATE (mg/l) | $^{14}C$ FRACTION (PMC) | DEL $^{13}C$ | $^{14}C$ APPARENT AGE (yrs) |
|---|---|---|---|---|---|---|
| 71 | KANSAS<br>18S-28W-22DACD01 | Upper Dakota | 340 |  | -5.10 | 15,750 |
| 72 | KANSAS<br>15S-28W-21BCCC01 | Upper Dakota | 384 | 0.0556 | -6.39 | 23,888 |
| 73 | KANSAS<br>15S-24W-15CCCB01 | Upper Dakota | 356 |  | -4.10 | 57,720 |
| 74 | KANSAS<br>14S-22W-33AACC01 | Upper Dakota | 442 | 0.0128 | -6.50 | 36,030 |
| 75 | KANSAS<br>12S-18W-34CDDA01 | Upper Dakota | 387 | 0.0167 | -7.30 | 33,831 |
| 76 | KANSAS<br>11S-11W-13DCBB01 | Upper Dakota | 547 | 0.1876 | -8.00 | 13,834 |
| 77 | KANSAS<br>11S-08W36AAAB01 | Upper Dakota | 379 | 0.7995 | -7.95 | 1,850 |

Table 2. (continued)

| SAMPLE SITE NUMBER | LOCATION | AQUIFER | CHLORIDE (mg/l) | $^{36}Cl/Cl \times 10^{14}$ | $^{36}Cl \times 10^{8}$ (atoms/l) |
|---|---|---|---|---|---|
| 52 | KANSAS<br>29S-43W-21DCDD02 | Morr-Dockum | 20.3 | 100.5 | 3.464 |
| 53 | COLORADO<br>31S-46W-04-BCCB01 | High Plains, Upper and Lower Dakota | 25.0 | 123.1 | 5.226 |
| 54 | COLORADO<br>30S-46W-31AAAA01 | Upper Dakota | 20.4 | 150.6 | 5.217 |
| 55 | COLORADO<br>31S-48W-13ACCD01 | Upper Dakota | 23.6 | 118.9 | 4.768 |
| 56 | COLORADO<br>30S-49W-36ADDA01 | Upper Dakota | 2.6 | 110.2 | 0.487 |
| 57 | COLORADO<br>32S-49W-08BAAA01 | Upper Dakota | 7.7 | 97.7 | 1.278 |
| 58 | COLORADO<br>30S-43W-32DBCD01 | Lower Dakota | 49.1 | 111.0 | 9.256 |
| 59 | COLORADO<br>30S-43W-32CCDC01 | Lower Dakota | 22.2 | 110.2 | 4.154 |
| 60 | COLORADO<br>25S-42W-11BBBB01 | Upper Dakota | 7.5 | 107.5 | 1.369 |
| 61 | COLORADO<br>25S-44W-16ACAC01 | Upper Dakota | 9.2 | 115.6 | 1.806 |
| 62 | COLORADO<br>31S-45W-02CABC01 | Morr-Dockum, Lower Dakota | 5.4 | 107.5 | 0.986 |
| 63 | KANSAS<br>23S-43W-14CDCA02 | Upper Dakota | 11.9 | 129.1 | 2.609 |
| 68 | KANSAS<br>21S-41W-02BBBB01 | Upper and Lower Dakota | 16.6 | 47.8 | 1.347 |
| 69 | KANSAS<br>18S-37W-24BACC02 | High Plains | 30.8 | 86.3 | 4.514 |
| 70 | KANSAS<br>18S-37W-24BACC02 | Upper Dakota | 63.6 | 37.9 | 4.093 |

Table 2. (continued)

| SAMPLE SITE NUMBER | LOCATION | AQUIFER | CHLORIDE (mg/l) | $^{36}Cl/Cl \times 10^{14}$ | $^{36}Cl \times 10^{8}$ (atoms/l) |
|---|---|---|---|---|---|
| 71 | KANSAS<br>18S-28W-22DACD01 | Upper Dakota | 300 | 19.5 | 9.939 |
| 72 | KANSAS<br>15S-28W-21BCCC01 | Upper Dakota | 168 | 11.6 | 3.309 |
| 73 | KANSAS<br>15S-24W-15CCCB01 | Upper Dakota | 278 | 5.9 | 2.785 |
| 74 | KANSAS<br>14S-22W-33AACC01 | Upper Dakota | 365 | 3.2 | 1.983 |
| 75 | KANSAS<br>12S-18W-34CDDA01 | Upper Dakota | 1,363 | 0.1 | 0.231 |
| 76 | KANSAS<br>11S-11W-13DCBB01 | Upper Dakota | 100 | 9.4 | 1.596 |
| 77 | KANSAS<br>11S-08W36AAAB01 | Upper Dakota | 58.5 | 53.3 | 5.295 |

southeastern Colorado the apparent $^{14}C$ age of the water sample from site 57 at the southwest end is approximately 2,400 yrs whereas the apparent age of a water sample from site 56 is approximately 6,700 yrs. The apparent age difference between the two samples may be related to local hydrogeologic setting of the wells that were sampled. Site 57 is located where the Dakota is directly overlain by the High Plains aquifer, whereas the well at site 56 is located where both aquifers are separated from each other by the Upper Cretaceous aquitard. The age difference suggests that the Dakota is receiving significant amounts of young recharge from the overlying High Plains aquifer at the upgradient site (Robson and Banta, 1987). This is also corroborated by the apparent $^{14}C$ age of a ground-water sample from High Plains aquifer at site 69, of approximately 3,000 yrs. Closer to the Arkansas River in southeastern Colorado, the High Plains and alluvial valleys aquifers are separated from the underlying upper Dakota aquifer by a thin Upper Cretaceous aquitard. The apparent $^{14}C$ ages of water samples from the Dakota aquifer in this segment of the vertical profile are in the range of 8,000 yr., which is close to the age of the sample from site 56. The slight increase in the apparent age of samples collected from the confined Dakota in comparison to those samples from the unconfined aquifer suggests that recharge from infiltrated precipitation moving across the aquitard is less than in unconfined areas.

Figure 15 is a plot of the number of $^{36}Cl$ atoms/l vs. Cl concentration data for the samples collected along the traverse of the northern vertical profile. The data from southeastern Colorado and the High Plains aquifer sample from Leoti, Kansas plot along a diagonal line that passes near a point that represents the calculated number of $^{36}Cl$ atoms/l and the presumed chloride concentration of precipitation for the region. This line appears to represent the simultaneous concentration of both chloride and $^{36}Cl$ by evapotranspiration processes in recharge moving down from the surface. Data from Bentley *et al.* (1983) suggest that subsurface generation does not appear to have significantly added $^{36}Cl$ to these or most of the other samples.

Between the Arkansas and the Saline Rivers, the Dakota is confined by up to more than 900 ft of the Upper Cretaceous aquitard and thus is relatively isolated from overlying sources of relatively young recharge. Figure 16 shows the distribution of apparent $^{14}C$ ages in comparison to the predicted water age from the model results. Near the Arkansas River the apparent ages of the water samples are very much older than the ages predicted by the model results. The sodium-bicarbonate type water in this part of the aquifer suggests that the older apparent ages result from the addition of "dead" carbon, devoid of $^{14}C$, to the ground water as a result of the exchange of sodium for calcium on clays within the Dakota aquifer framework (Figure 14). The exchange process promotes the dissolution "dead" carbon (that is, older water that contains no $^{14}C$) in the calcite of the aquifer framework. The model results indicate a minor input of presumably older

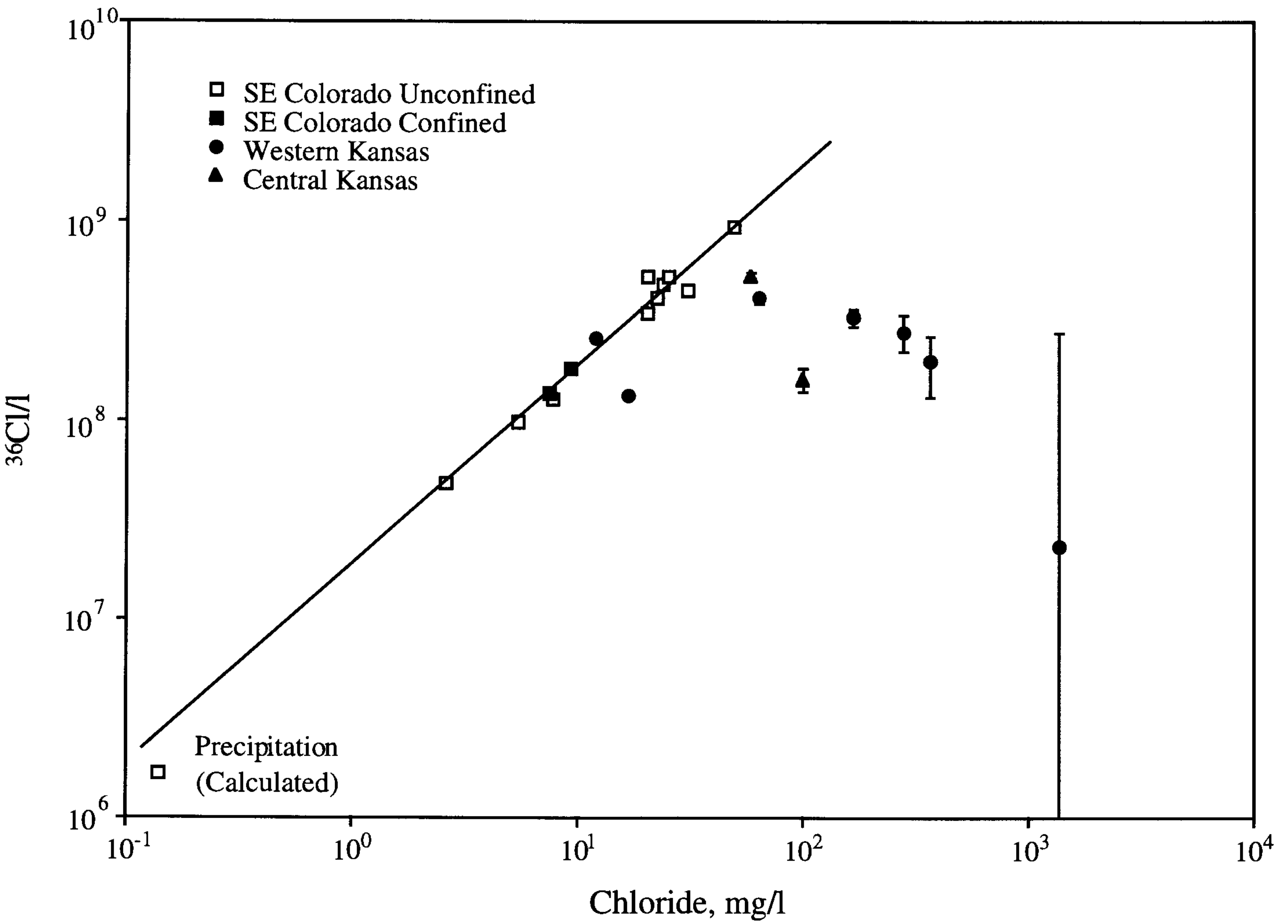

Figure 15. Chloride concentration vs. $^{36}Cl$ abundance in water samples collected from sites in southeastern Colorado and western and central Kansas.

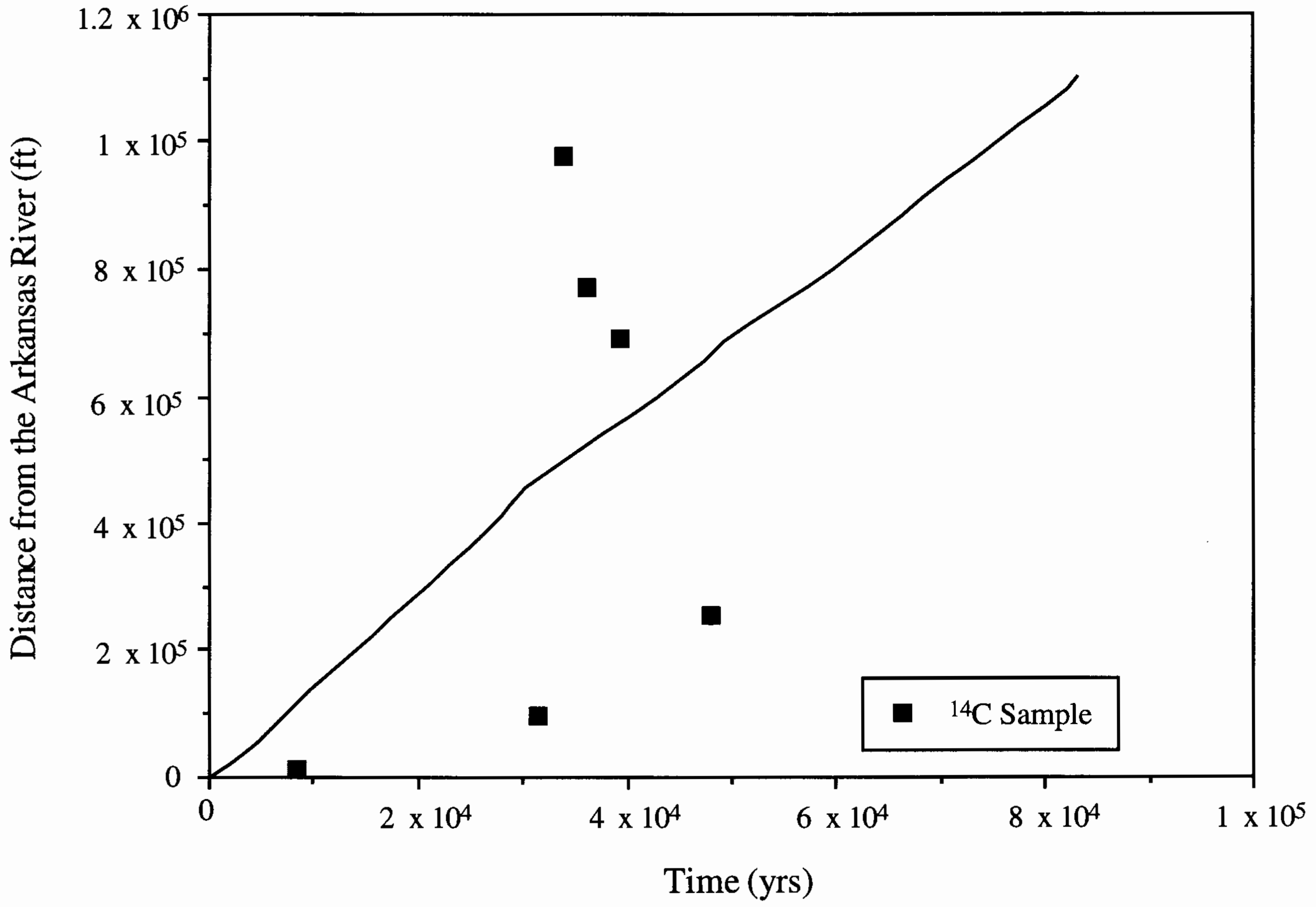

Figure 16. Time of travel vs. distance from the Arkansas to the Saline River in the northern vertical profile model in comparison to apparent $^{14}C$ age.

water from below moving across the Kiowa shale aquitard in this part of the vertical profile. Thus the water in the upper Dakota aquifer appears to be much older. Further downgradient, the apparent $^{14}C$ ages are less than the predicted water age from the steady-state model.

The $^{36}Cl$ in the first two samples northeast of the Arkansas River in Hamilton County (from sites 63 and 68) appear to be influenced more by the southeastern Colorado portion of the flow system than by confined aquifer conditions. Sample 63 from Coolidge was collected from a well screened in the confined upper Dakota aquifer and located approximately two miles away from the Arkansas River. The chloride concentration and the number of $^{36}Cl$ atoms/l in this sample plot along the line of concentration by evapotranspiration (Figure 15). The sample from site 68 is depleted in $^{36}Cl$ relative to the samples from both Coolidge and Leoti and the chloride concentration is higher than in the sample from Coolidge but lower than in the sample from Leoti (Figure 15). This is the only sample from a well screened in the lower Dakota aquifer along this part of the traverse. This suggests that the water sampled at site 68 did not enter the flow system at the same point as the ground water sampled at other downgradient sampling sites beginning with Leoti.

Farther along in the confined upper Dakota aquifer, the number of $^{36}Cl$ atoms/l is influenced primarily by the lateral flow within the aquifer and the recharge that enters the aquifer through the overlying confining layer and from below. Figure 17 is a plot of distance downgradient from the Arkansas to the Saline River vs. the number of $^{36}Cl$ atoms/l in the samples collected from wells along the trace of the vertical profile. Also plotted on Figure 17 are three models of $^{36}Cl$ abundance assuming a range of transmissivities in the upper Dakota. The three simple models assume negligible production of $^{36}Cl$ in the subsurface and advective transport of $^{36}Cl$ in the flow system. The effective porosity of the upper Dakota and the Upper Cretaceous aquitard are assumed to be 30% and 5%, respectively. The amount of recharge entering the upper Dakota ranges from 0.4–5.2% of the total flow in the aquifer for all three models. The assumed initial concentration is close to a cluster of $^{36}Cl$ values for samples collected from the upper and lower Dakota in southeastern Colorado, $4.00 \times 10^8$ atoms/l. The transmissivity of the upper Dakota ranges from the 100% to 50% of the calibrated set of values for the layer. Figure 18 shows that the steady-state flow model is not very sensitive to the transmissivity of the upper Dakota aquifer. The "true" calibrated set of transmissivities may be as low as 50% of the partially calibrated set of values or somewhat higher.

The results in Figure 17 seem to indicate that the best fit to the $^{36}Cl$ data occurs when the transmissivities of the upper Dakota are 50% of the partially calibrated set of values. Near the downgradient end at sample sites 74 and 75, two of the three models significantly overpredict the amount of $^{36}Cl$ in the aquifer. This may indicate significant recharge to the upper Dakota from

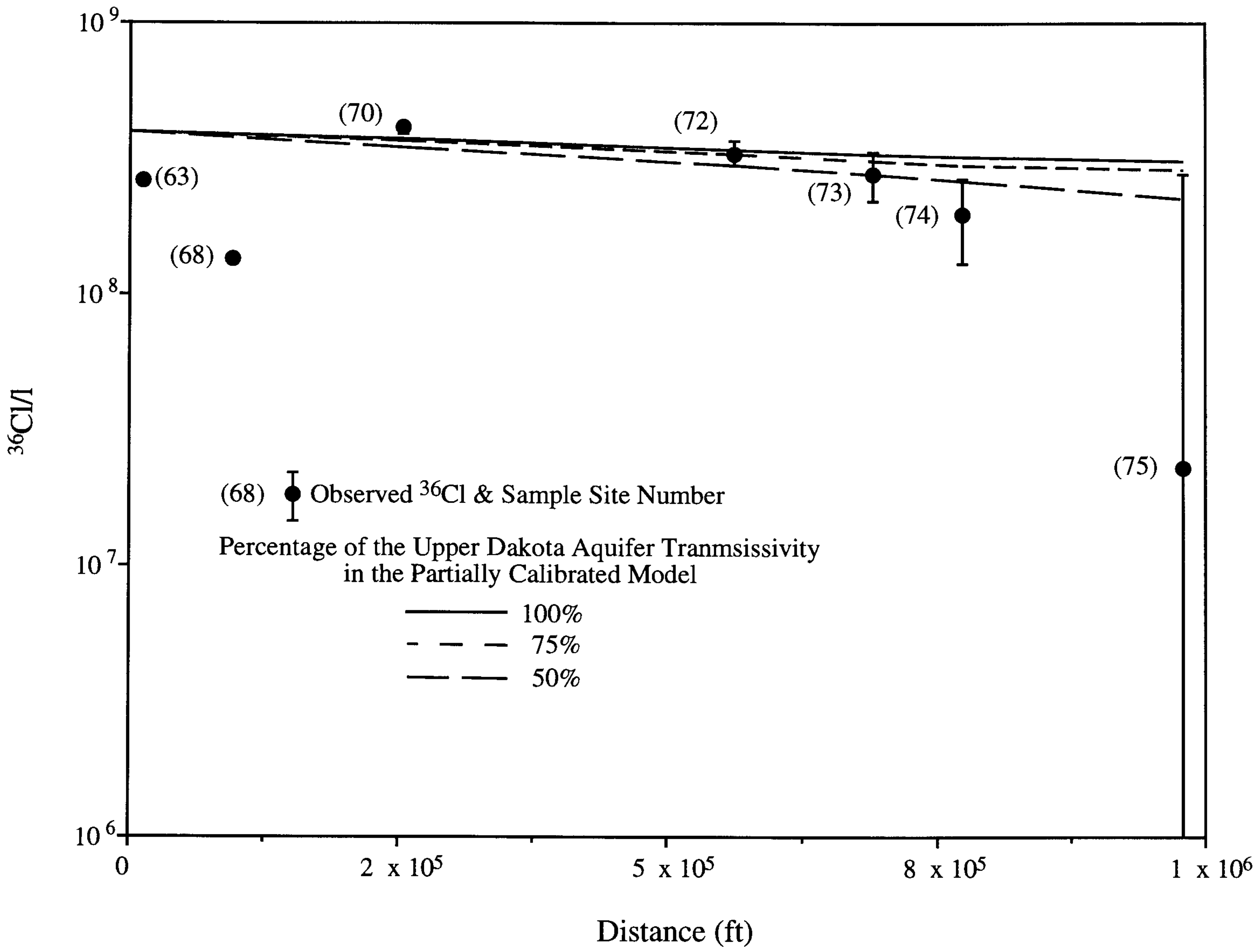

Figure 17. Predicted $^{36}Cl$ abundance in the upper Dakota aquifer as a function of transmissivity and distance from the Arkansas River in the northern vertical profile steady-state model. Upper Dakota aquifer and Upper Cretaceous aquitard porosities are assumed to be 30% and 5%, respectively. Subsurface generation of $^{36}Cl$ is assumed to be negligible, overall.

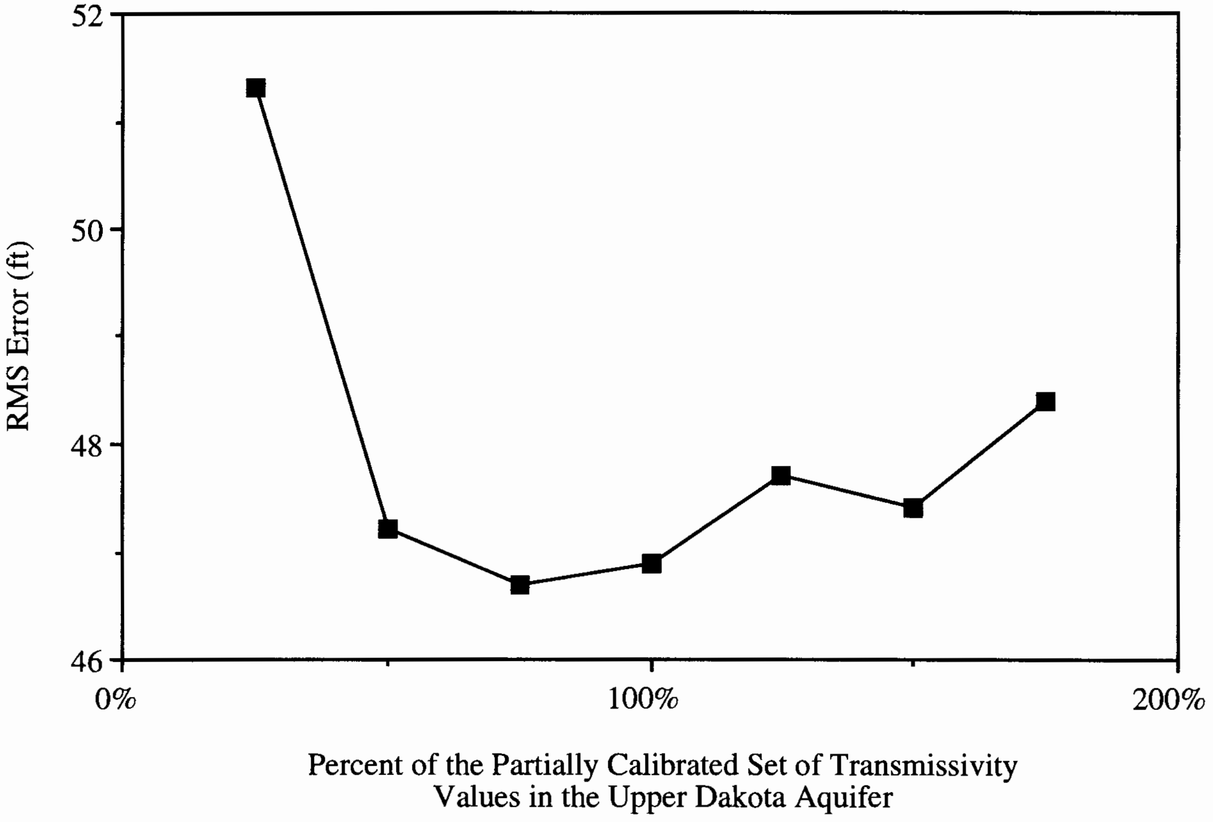

Figure 18. Model sensitivity to the transmissivity of the upper Dakota aquifer in the partially calibrated model, expressed as RMS error.

underlying aquifers near these sites. The underlying Cedar Hills Sandstone aquifer is a source of much older chloride from the dissolution of Permian halite. Figure 14 shows that the chloride concentration increases at a faster rate between samples 73 and 75 than between samples 70 and 73 which suggests dilution of $^{36}Cl$ by recharge from below. These samples come from sites just upgradient of the area of lower Dakota-Cedar Hills Sandstone aquifer hydraulic connection.

The results also suggest a much greater rate of recharge to the upper Dakota aquifer through the Upper Cretaceous aquitard just downgradient of the Coolidge well than is predicted in the steady state model. The model predicts only a small net upward discharge of flow to the valley at this location on the north side of the valley. In each of the three models, the assumed initial $^{36}Cl$ content is 4.00 x $10^8$ atoms/l, which is close to the amount of $^{36}Cl$ found in the High Plains aquifer at Leoti, sample site 69. Assuming that the number of $^{36}Cl$ atoms in the sample from the Coolidge well is representative of ground water in the upper Dakota moving downgradient from the Arkansas River less than two miles away, the recharge rate is approximately 73% of the lateral flow. Assuming a 5% effective porosity in the Upper Cretaceous aquitard and an initial $^{36}Cl$ content of 4.514 x $10^8$ atoms/l in the recharge moving across the aquitard, the vertical hydraulic conductivity of the aquitard is approximately 6.7 x $10^{-7}$ ft/day which is nearly twice value predicted by the steady-state model. This suggests that the model grid is too coarse to show both discharge to the valley from the local flow system and recharge to the intermediate-scale system in the upper Dakota across the upper Cretaceous aquitard.

### Development Of The Three-Dimensional Regional Flow Model Of The Kansas Dakota Aquifer

This section of the annual report describes research progress on the construction of a regional ground water flow model of the Dakota aquifer in Kansas and southeastern Colorado. The purpose of the numerical model is to aid in the regional characterization of the steady-state Dakota aquifer flow system and its relationship to other flow systems in Kansas. Additionally, the model will provide information on the gross features of the regional system, and its influences. The regional model will also provide boundary conditions for smaller-scale models, from which subregional and local concerns can be addressed. Local concerns can not addressed with this model since the scale of the model is too large to properly address them. Currently, a subregional model of southwestern Kansas is under development that will address management issues in the Southwest Groundwater Management District No. 3.

This summary consists of six main sections. The first section is an outline of the hydrostratigraphy of the shallow subsurface, including the Dakota aquifer and how aspects of the arrangement of aquifer and aquitard units affect the overall construction of the model. The second section contains information on the specifics of the model, including layer/grid design and boundary conditions. The third section describes the data used in the construction of the model. The fourth section contains a description of the use of the numerical modeling program, MODFLOW, with the geographic information system, ARC/INFO, as a pre- and post-processor for the model. The fifth section describes the procedure used to calibrate the model. The sixth and final section is a preliminary interpretation of model results to date.

### *Regional hydrostratigraphy*

The term hydrostratigraphy refers to the grouping of rock units having similar hydrologic properties. For the purpose of this study, rock units in the shallow subsurface in Table 1 (approximately down to the base of the Permian Cedar Hills Sandstone) have been grouped into hydrostratigraphic units ordered according to increasing depth following Macfarlane *et al.* (1992), Whittemore *et al.* (1993), and Macfarlane (1993):

1) Quaternary and Tertiary unconsolidated of silts, sands, and gravels constitute the High Plains aquifer of western and south-central Kansas and southeastern Colorado and alluvial valley aquifers in central Kansas and in the Arkansas River Valley of southeastern Colorado;
2) Upper Cretaceous shales and chalks constitute the upper Cretaceous aquitard;
3) Upper and Lower Cretaceous sandstones, mudstones, and shales of the Dakota and uppermost Kiowa Formations constitute the upper Dakota aquifer;
4) Lower Cretaceous marine shale of the Kiowa Formation constitutes the Kiowa shale aquitard;
5) Lower Cretaceous sandstones and mudstones of the Longford Member (Kiowa Formation) and the Cheyenne Sandstone constitute the lower Dakota aquifer;
6) Upper Permian red beds and evaporites constitute the upper Permian aquitard; and
7) Lower Permian sandstones of the Cedar Hills Sandstone and the Salt Plain Formation constitute the Cedar Hills sandstone aquifer.

The low permeability limestones, shales, chalk, and evaporites are grouped into regional aquitard units, whereas the sandstones, interbedded sandstones and shales, and the surficial unconsolidated sands and gravels are grouped into regional aquifer units.

Periods of erosion/deposition and tectonic activity through geologic time have complicated the "layer-cake" hydrostratigraghy of southeastern Colorado and western and central Kansas presented above. Figure 19 shows a generalized southwest to northeast cross-section of the hydrostratigraphy in the region. Differential uplift and erosion beveled Jurassic and Permian strata prior to the deposition of the lower Cretaceous units. As a result, the Permian sandstone aquifer subcrops beneath the Dakota aquifer in central Kansas (Figure 19). The distribution of

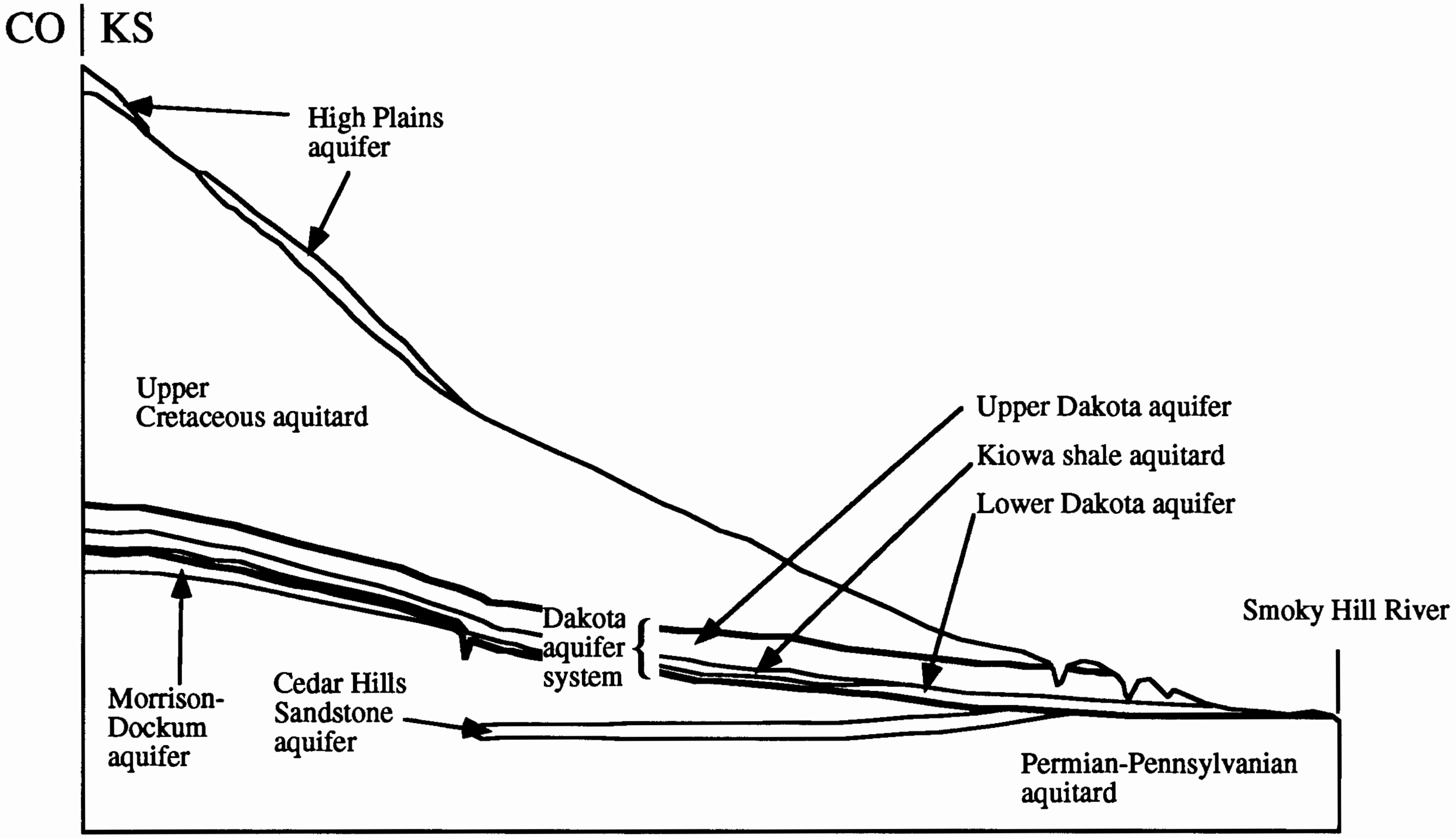

Figure 19. Generalized cross section along T. 16 S. from the Kansas-Colorado state border to central Kansas showing the major hydrostratigraphic units of the shallow subsurface. Not to scale.

the Ogallala Formation and Quaternary deposits reflects Miocene-Pliocene deposition of sediment on the eroded late Tertiary High Plains surface and subsequent renewed Pliocene uplift and Quaternary erosion and deposition. Consequently, the High Plains aquifer and the alluvial valley aquifers are hydraulically connected to the underlying Dakota aquifer in southeastern Colorado and southwestern and central Kansas (Figure 20). The Dakota aquifer crops out at the surface in north–central Kansas and more locally in southwestern Kansas and southeastern Colorado (Figure 8). Elsewhere, the Dakota is overlain by the Upper Cretaceous aquitard. The aquitard ranges up to more than 2,000 ft in thickness near the northwest corner of Kansas.

Depositional patterns and subsequent erosion have also played a key role in defining the regional hydrostratigraphy of the Dakota aquifer. Shale was deposited in predominantly offshore marine environments of the Kiowa sea whereas the marine and nonmarine interbedded shale, sandstone, and mudstone was deposited closer to the ancient shoreline of the Kiowa sea. The resulting assemblage of deposits was subsequently uplifted and eroded prior to deposition of interbedded sandstone, mudstone, and shale sequence in the Dakota Formation. As a result, transitional deposits belonging to the Longford Member constitute the bulk of the Kiowa Formation in central Kansas, whereas the marine shales constitute the bulk of this unit in western southern Kansas (Figure 21). In central Kansas, the upper and lower Dakota aquifers are considered to be hydraulically connected because the marine black shales are either absent or account for only a small proportion of the Kiowa Formation. During Dakota time in central Kansas, an alluvial sequence of interbedded sand and mud was deposited in river valleys eroded into the underlying Kiowa Formation within the upper part of a coastal plain adjacent to the Western Interior sea. The interbedded sand and mud sequence is increasingly marine influenced westward of central Kansas and appears to have been deposited in the lower part of the coastal plain along a shoreline in shallow marine and shoreface environments.

### *The ground-water flow model*

The quasi three-dimensional, ground-water flow model includes most of the western two-thirds of Kansas and the adjacent parts of southeastern Colorado and Nebraska. Figure 22 shows the extent of the model region. The active region of the model, where ground-water flow is simulated, is indicated by the cross-hatched pattern in the model region. In the vertical direction the model extends from the water table downward to 100 ft below the top of the Permian System and incorporates all hydrostratigraphic units in between. Where an unconfined aquifer is not the present the water table is taken to be the top of the zone of saturation, which is considered to be equivalent to the land surface (Macfarlane, 1993).

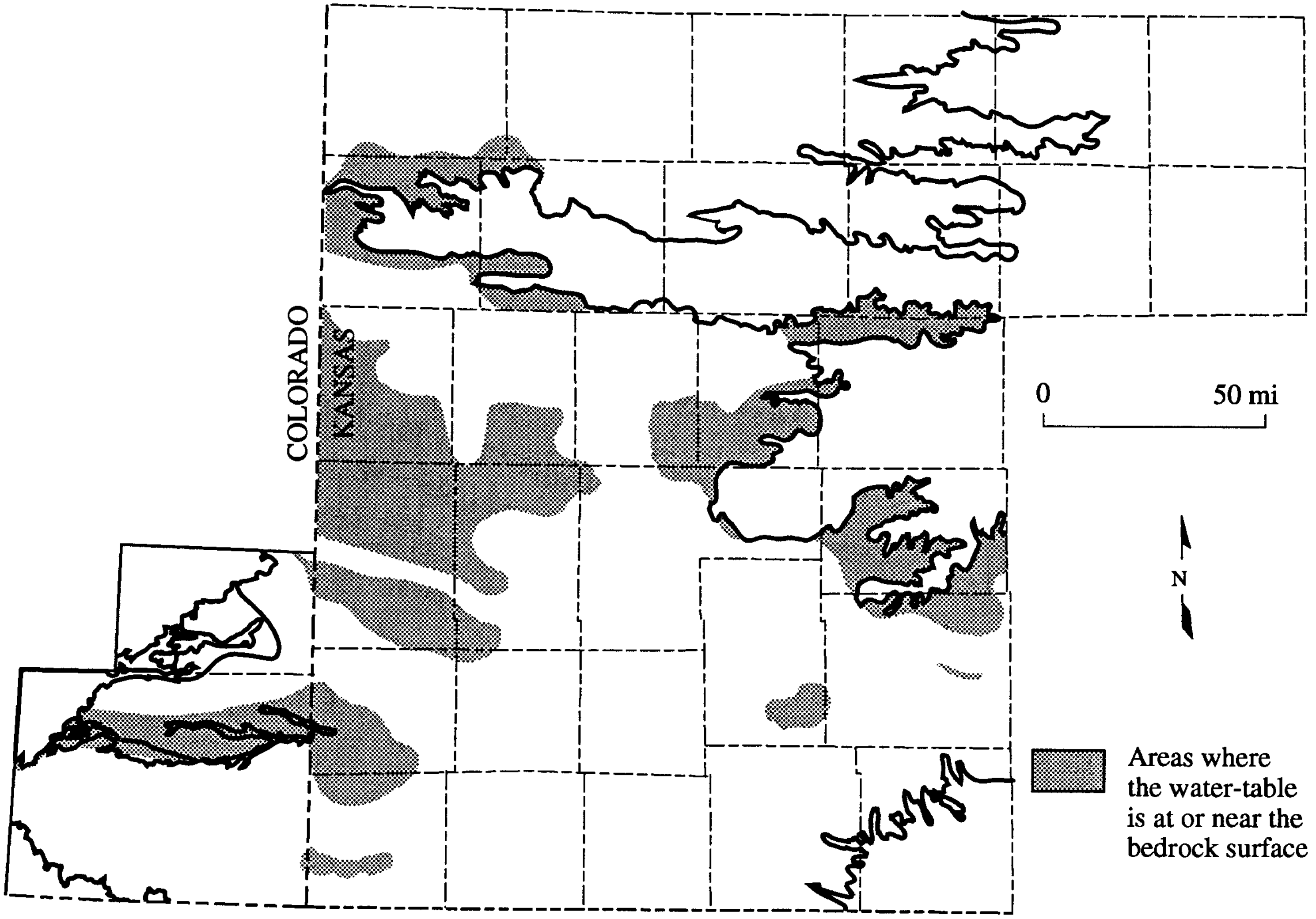

Figure 20. Extent of the High Plains aquifer in southeastern Colorado and western Kansas.

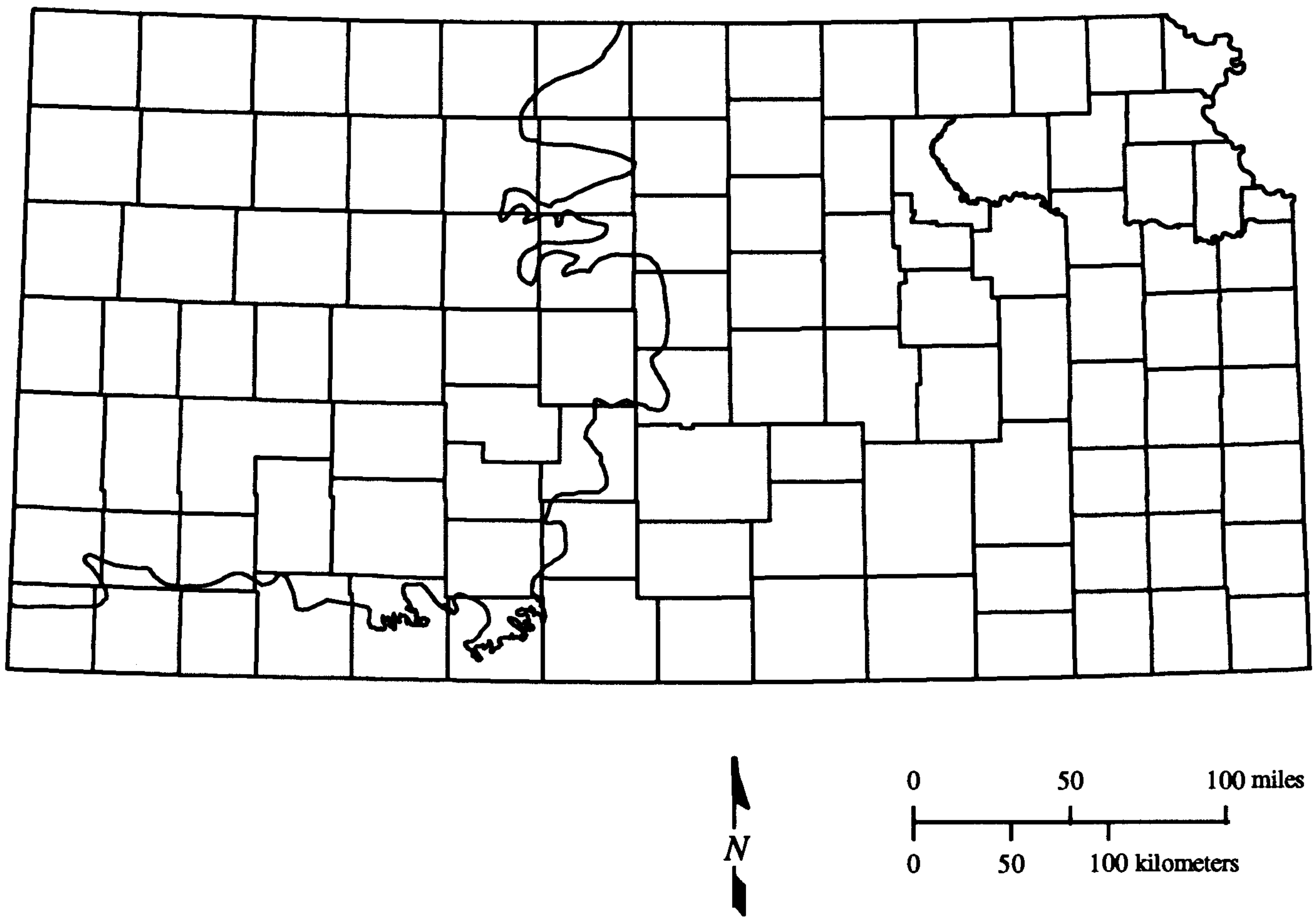

Figure 21: Extent of the Kiowa shale aquitard in western and central Kansas.

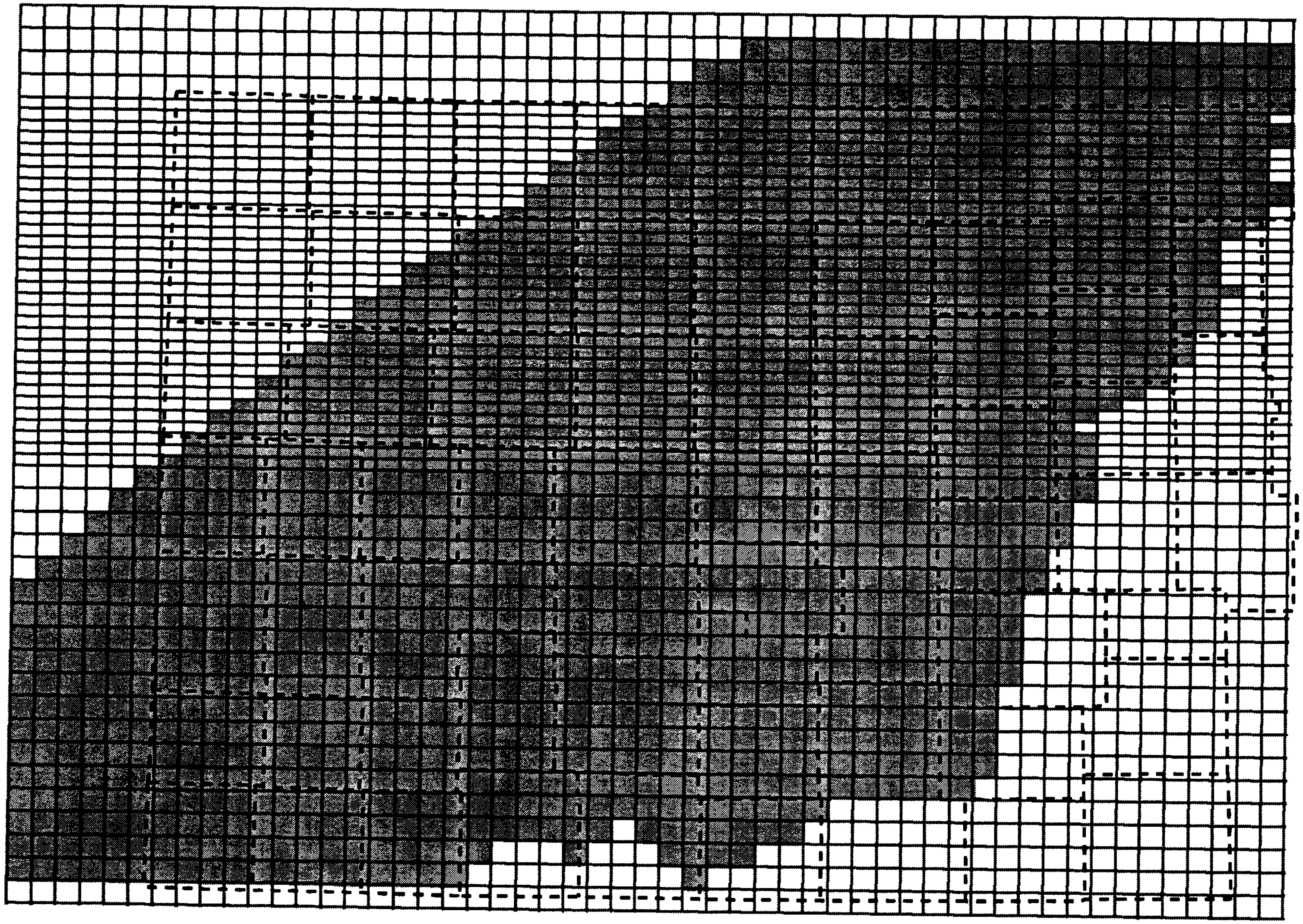

Figure 22: Shown are the model grid and the western counties of Kansas. The area being modeled is shaded in gray.

The governing equation that describes the steady-state flow of ground water in each of the hydrostratigraphic units in the quasi three-dimensional model is (Anderson and Woessner, 1992):

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) + R = 0 \qquad \text{(Eq.1)}$$

where R is a source/sink term and $K_x$, $K_y$, and $K_z$ are the x, y, and z components of hydraulic conductivity. Eq. 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, y, and z coordinate system axes. In this model the x and y axes are aligned with the north-south and east-west directions, respectively, and the z axis is in the vertical direction. It is assumed that all of the hydrostratigraphic units are isotropic with respect to the horizontal components of hydraulic conductivity. Thus $K_x$ and $K_y$ are equivalent.

MODFLOW (McDonald and Harbaugh, 1988) was used to solve the three-dimensional flow equation along with its attendant boundary and initial conditions in the model region. 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.

The model consists of five layers of model cells, each cell representing the average properties and attributes of a discrete volume of the subsurface at a particular location. Figure 23 shows the grouping of hydrostratigraphic units into model layers. The Kiowa shale aquitard is not treated as a distinct layer in the model but is a quasi layer and its effect on vertical flow is taken into account in the model. Quasi layers can be incorporated into a model in MODFLOW if the flow is primarily across and not horizontally within the layer representing an aquitard (McDonald and Harbaugh, 1988).

Figure 24 is a cross-section showing the model-layer configuration conceptually. Several of the layers are not continuous and pinchout in the model. The pinchout out of layers is taken into account where it occurs by continuing the layer across the model as a "phantom" with a transmissivity and 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 assuming the layers above and below the "phantom" layer are in

| ROCK STRATIGRAPHIC UNITS | HYDROSTRATIGRAPHIC UNITS | MODEL LAYERS |
|---|---|---|
| Unconsolodated Sediments | High Plains and Alluvial Valley Aquifers | Layer 1 |
| Ogallala Fm. | | |
| Colorado Group | Upper Cretaceous Aquitard | Layer 2 |
| Dakota Ss. / Dakota Fm. | Upper Dakota Aquifer | Layer 3 |
| Purgatoire Fm. / Kiowa Fm. | Kiowa Shale Aquitard | Quasi-Layer |
| Cheyenne Ss. | Lower Dakota Aquifer | Layer 4 |
| Morrison Fm. / Dockum Group | Morrison-Dockum Aquifer | Layer 5 |
| Permian Undiff. | Upper Permian Aquitard | |
| Cedar Hills Ss. | Permian Sandstone Aquifer | |

Figure 23. Rock stratigraphic and hydrostratigraphic units incorporated into the regional model and model layer groupings.

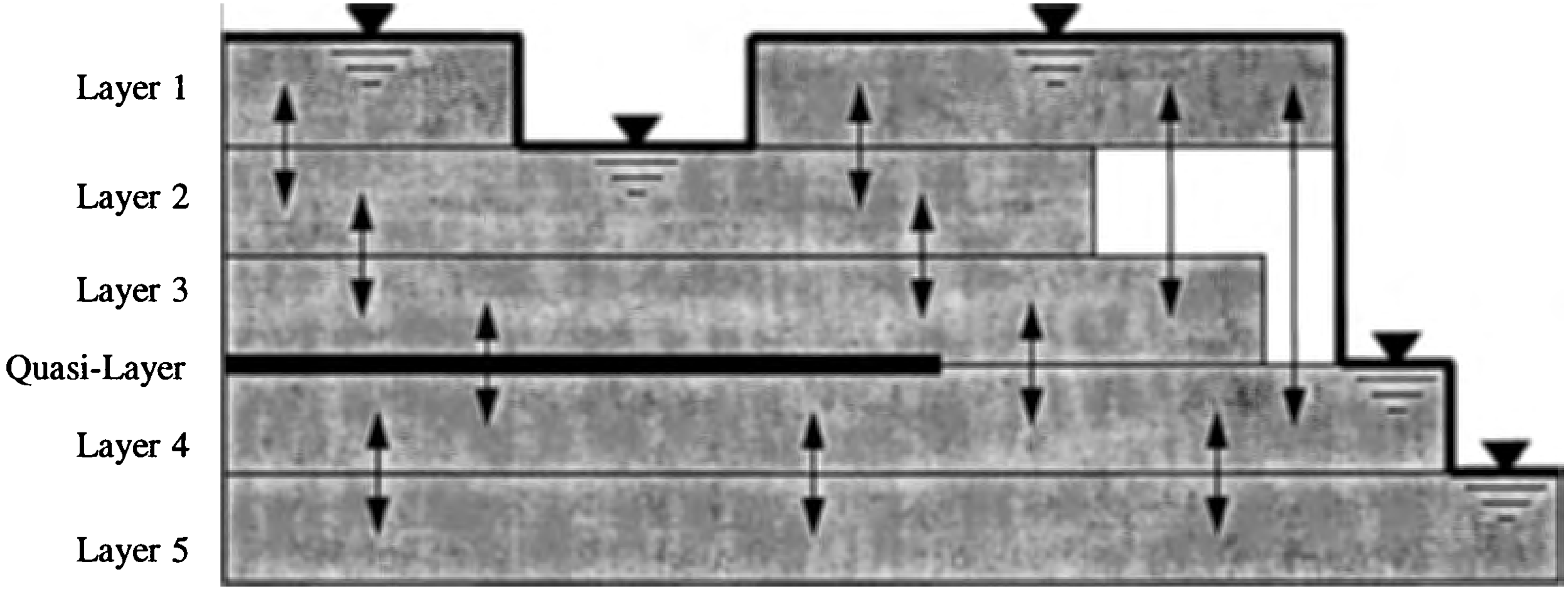

Figure 24: Conceptual model layer configuration showing the five simulated layers and the quasi-layer. Arrows show vertical connection, and triangles show which layer contains the water-table aquifer.

physical contact. The result is no horizontal flow where the geologic units are not present. Thus, only a vertical hydraulic connection between the layers is maintained through the "phantom" layer.

Each model layer consists of 55 rows and 53 columns of these model cells (Figure 22). The model cell dimensions in map view are 6 mi x 6 mi in the southern part of the model and 6 mi x 3 mi. in the northern part. The rectangular shape of the smaller model cells in the northern part of the model allows for a more accurate representation of the local topographic relief in central Kansas. In this part of the state there has been significant incisement by eastward-flowing rivers along the Dakota aquifer outcrop belt which corresponds to the longer dimension of the cells in this region of the model.

There are three options for cell types made available within MODFLOW. These are active cells, inactive cells, and constant head cells. In the development of the regional model all of these cell types were used in the model. Figures 25a–e show the location of the active, specified-head and inactive cells for each layer. The majority of the model consists of active cells, not associated with specific boundary conditions in the model. The other two cell types are used to define the boundary conditions around the edge of the model. From the available data, it appears reasonable to assume that ground-water flow in all of the other aquifer units in the shallow subsurface is at least sub-parallel to the flow in the upper Dakota aquifer (Macfarlane, 1993). Consequently, the boundary conditions are applicable to all of the layers in the model. Constant head cells are used for specified-head boundary conditions. Specified-head cells will always remain at a fixed value of hydraulic head during the simulation and can act as an inexhaustible source or sink for water in the model. The southwestern edge of the model in southeastern Colorado is a specified-head boundary. The cells along the southern and eastern edge of the model are also specified head cells set equal to their pre-development water level. Inactive cells are used to define regions outside of the model, and no-flow boundary conditions on the model boundary. No-flow boundary conditions exist along hydraulic divides. In isotropic media hydraulic divides coincide with flow lines and are perpendicular to equipotentials. The northwestern and northern boundaries of the model correspond to a flow line within the upper Dakota aquifer and hence are treated as no-flow boundaries in the steady-state model (Figure 26). Model cells to the north and northwest of these no-flow boundaries are inactive since they are outside of region of flow being simulated. It is assumed that pre-development water-table fluctuations are insignificant and the water table accurately represents the steady-state condition. With this simplification, the water table can be treated as a specified-head boundary. By making this assumption the uncertainty of estimating recharge from infiltrating precipitation are avoided.

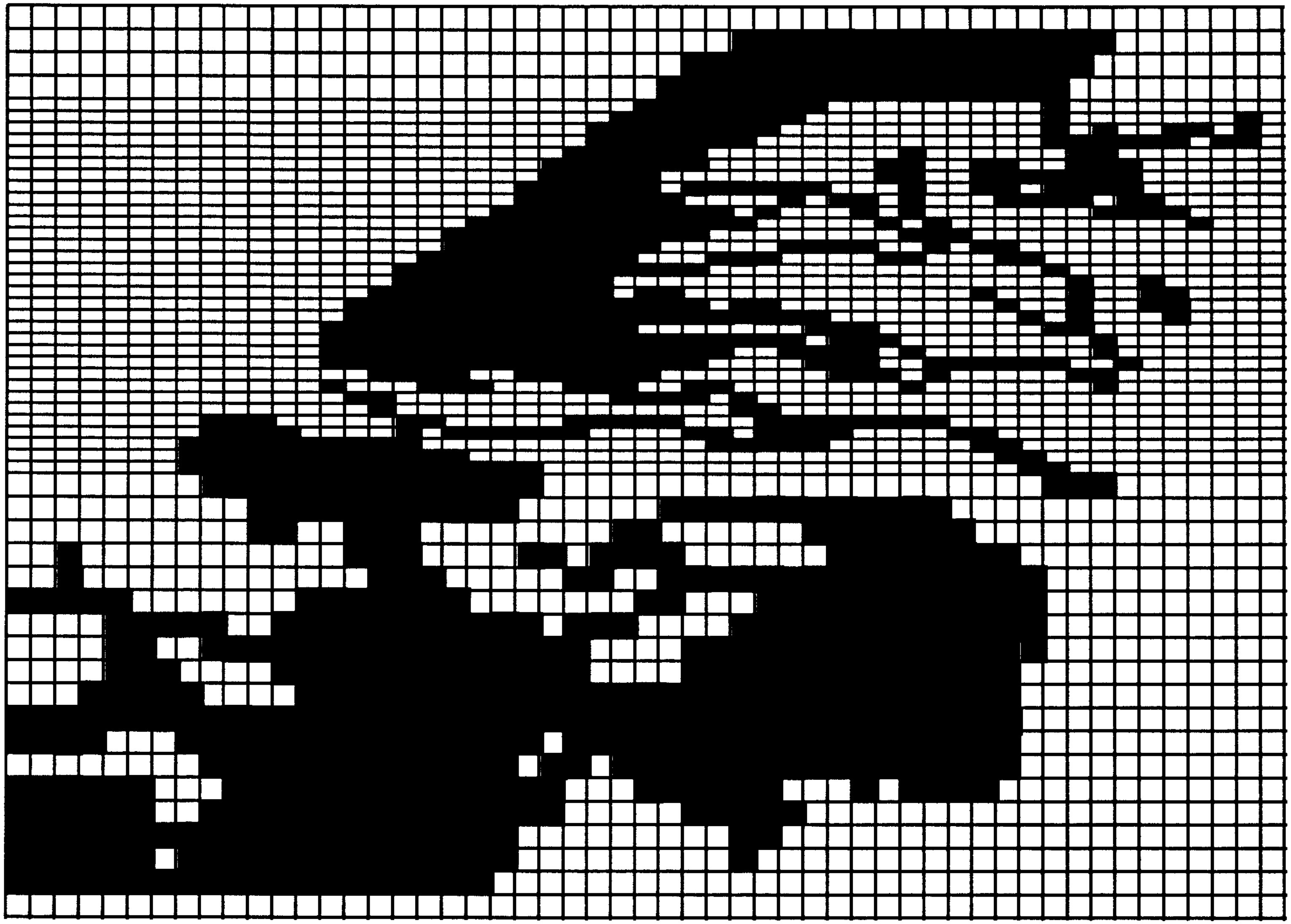

Figure 25a: Grid cells in layer 1 (High Plains and alluvial valley aquifers). Model cells in black are constant head cells. All other cells are inactive.

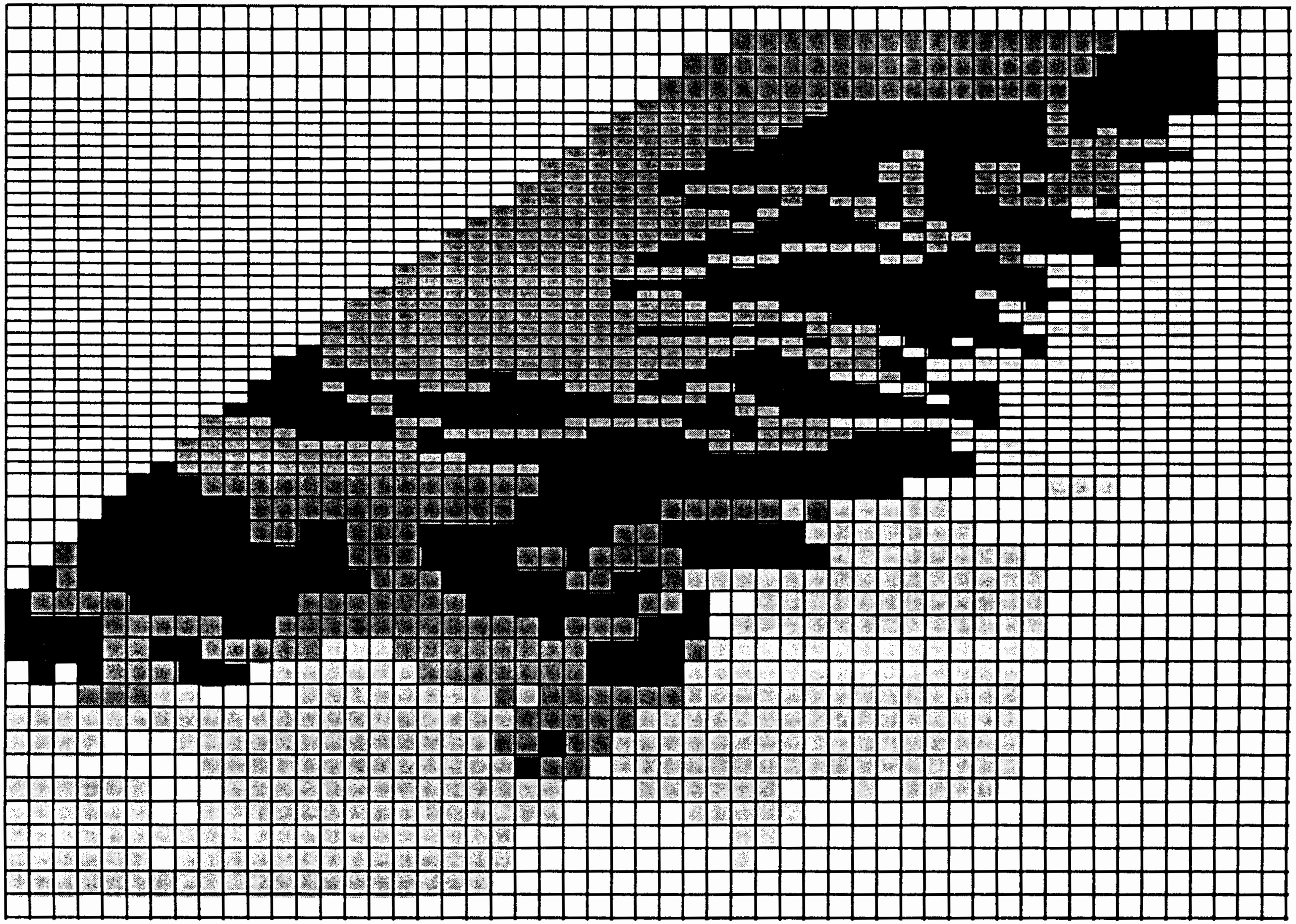

Figure 25b. Grid cells in layer 2 (Upper Cretaceous aquitard). Grid cells in black are constant head cells. Grid cells in dark gray are active grid cells with thickness greater than zero. The cells in light gray are active grid cells with zero thickness. All other cells are inactive.

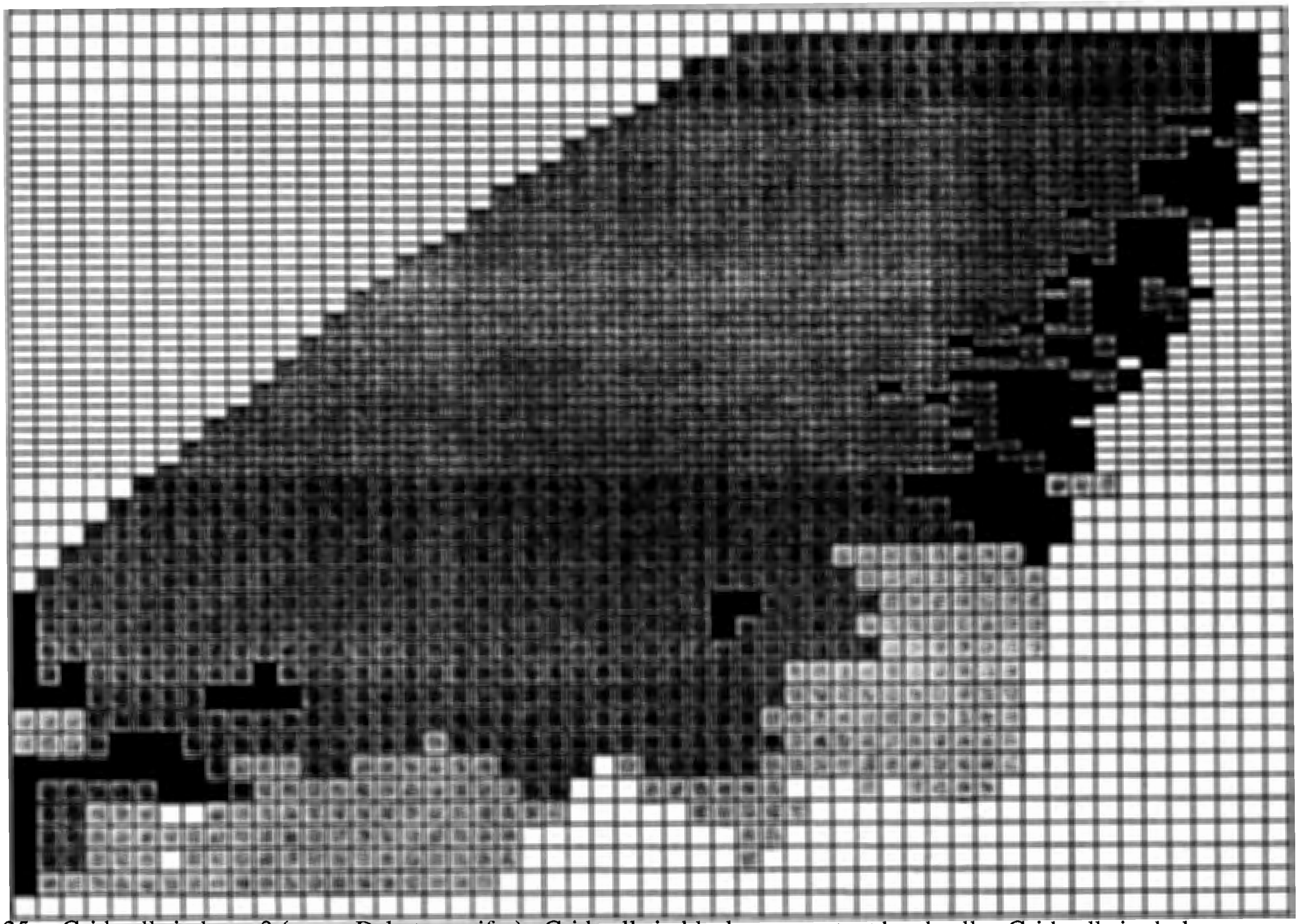

Figure 25c. Grid cells in layer 3 (upper Dakota aquifer). Grid cells in black are constant head cells. Grid cells in dark gray are active grid cells with a thickness greater than zero. Grid cells in light gray are active grid cells with zero thickness. All other cells are inactive.

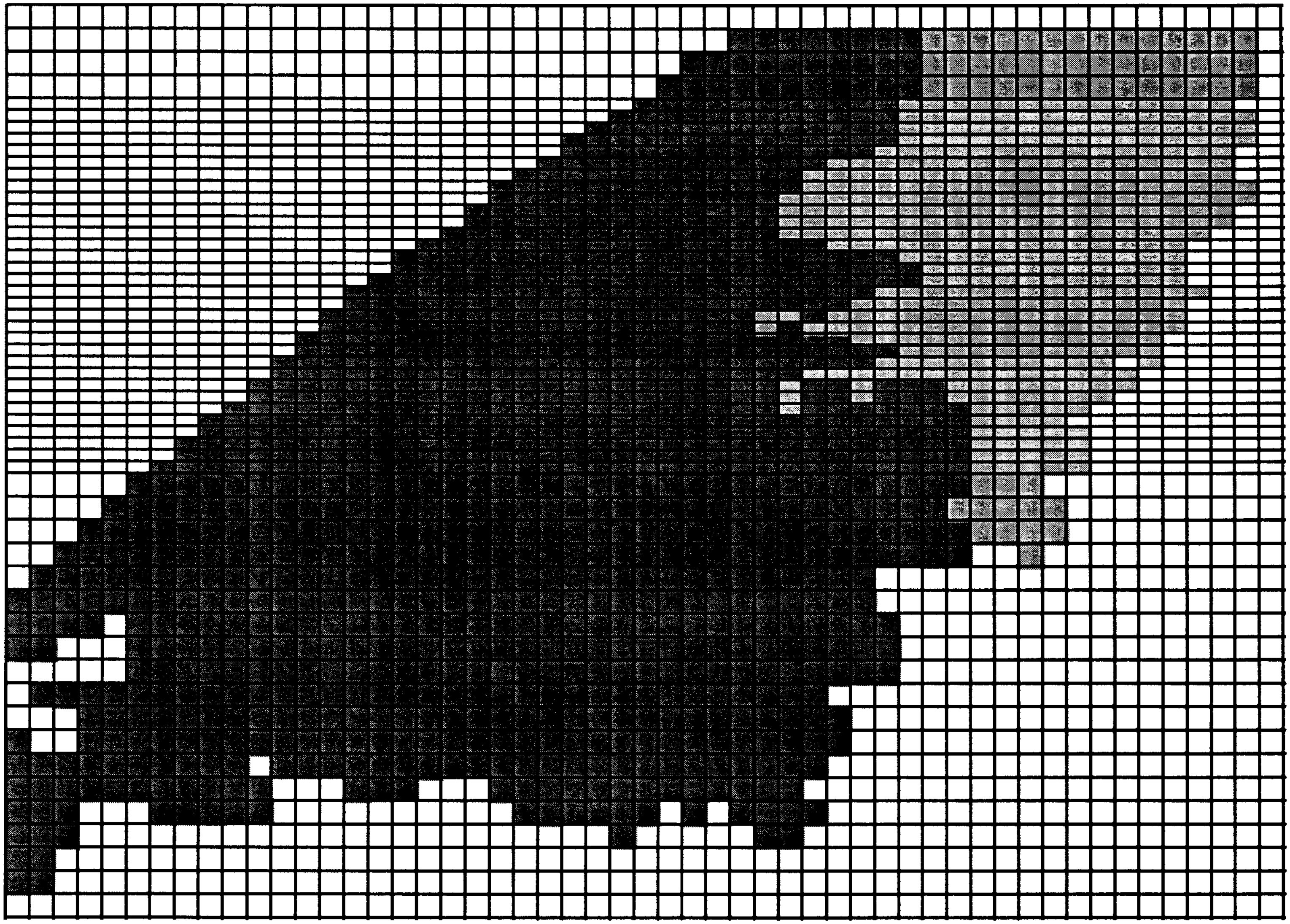

Figure 25d: Grid cells where the quasi-layer exists (Kiowa Shale aquitard). Dark gray color indicates the region where the Kiowa Shale exists. Light gray color indicates the region where the Kiowa shale is absent due to non-deposition, and therefore the area where the Upper and Lower Dakota aquifers have been combined into one unit.

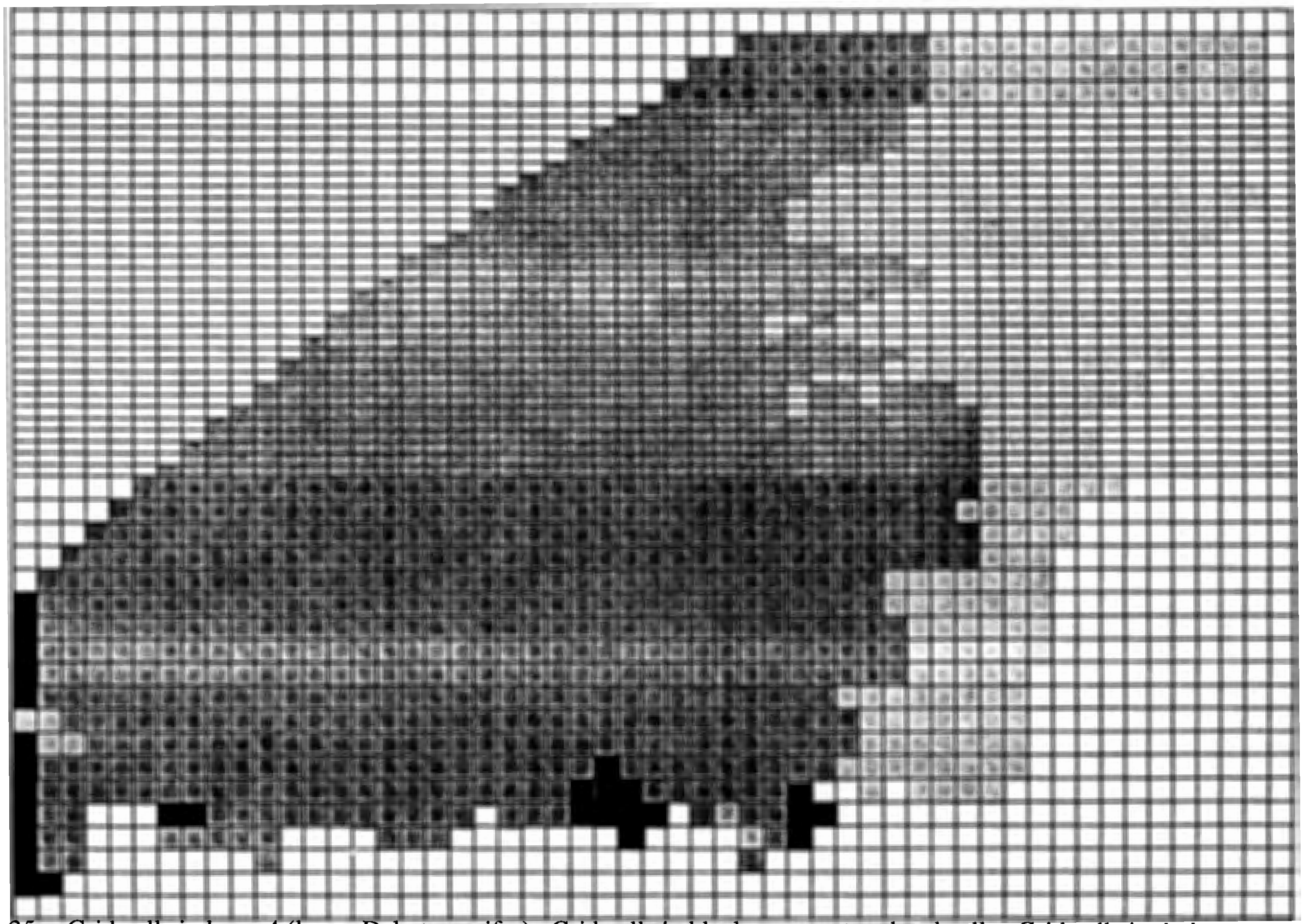

Figure 25e. Grid cells in layer 4 (lower Dakota aquifer). Grid cells in black are constant head cells. Grid cells in dark gray are active grid cells with thickness greater than zero. The cells in light gray are active grid cells with zero thickness. All other cells are inactive.

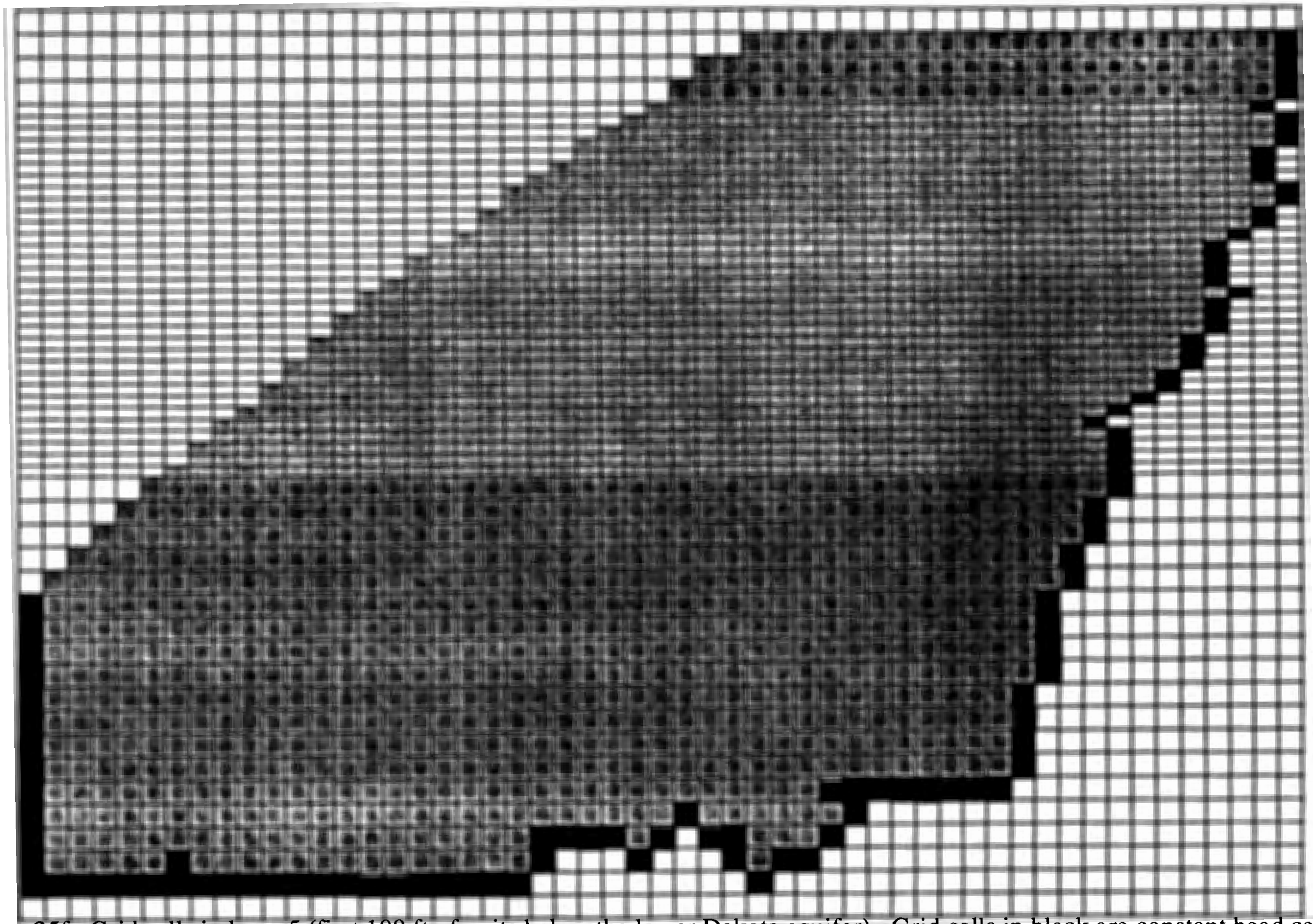

Figure 25f. Grid cells in layer 5 (first 100 ft of units below the lower Dakota aquifer). Grid cells in black are constant head cells. Grid cells in dark gray are active grid cells. All other cells are inactive.

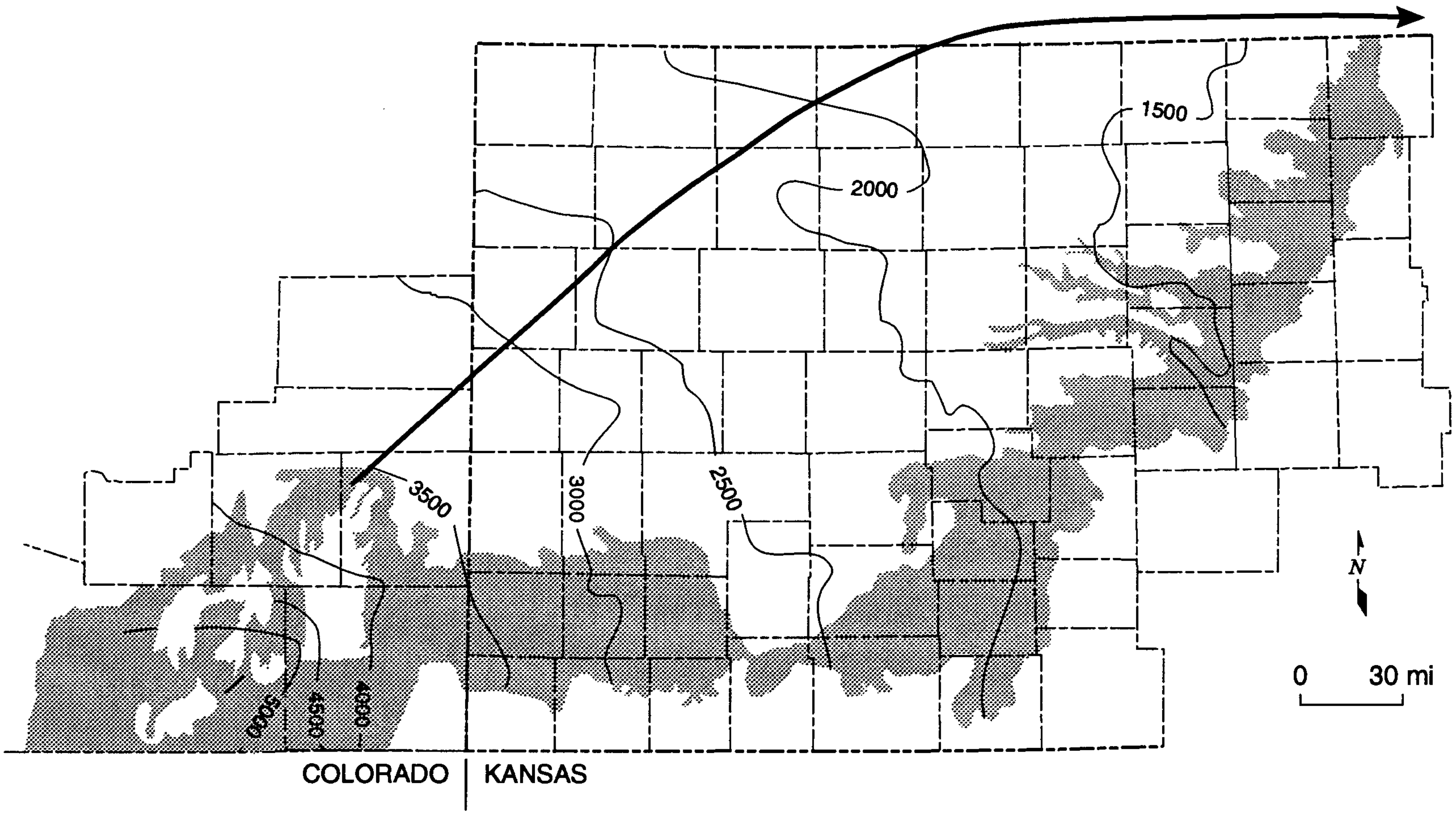

Figure 26. Regional flow line used in the 3-D regional Dakota aquifer modeling project.

### *Preliminary processing of the data sets used for input into ARC/INFO*

The data used to assemble the model came from published maps produced from earlier projects in the Dakota Aquifer Program. These maps portray information on the depth to the top, thickness, and extent of the various geologic units in the model region. Most of the raw data used to produce these maps are from gamma-ray logs of exploration and production boreholes drilled for oil and gas and from test holes drilled for the Dakota Aquifer Program. Supplemental data from the subcrop region come from published contour maps of the elevation and configuration of the bedrock surface beneath the High Plains aquifer in southwest and south–central Kansas. The data-density across the modeled region is highly variable. In some areas, hand contouring had to be done before proceeding further with model input where more than one map was needed to portray either a top configuration or a thickness. In some situations, additional information on the tops and thicknesses of units had to be collected and hand contoured where data was lacking. Land-surface elevations were derived from either digital elevation models (DEM) or from topographic maps.

The hydrologic data required for the model included hydraulic-heads and hydraulic conductivities for the various aquifer and aquitard units in the modeled region. The hydraulic-head data were also hand-contoured to create continuous water-table and potentiometric surfaces. Availability of information on the water-table and potentiometric surface elevations varied for the different layers. Information on the elevation and configuration of the pre-development water table in the unconfined High Plains aquifer and some of the alluvial valley aquifers and the potentiometric surface of the upper Dakota aquifer came from published and unpublished maps. Pre-development water levels are less much abundant in the upper Dakota aquifer than in the High Plains aquifer, particularly where the Dakota is deeply buried in the northwest quarter of Kansas. Figure 27 shows the distribution of hydraulic head data for the upper Dakota aquifer used to define the Dakota pre-development water-table and potentiometric surfaces. Pre-development water-level data for the Dakota aquifer in far northwest Kansas and for the deeper aquifer units below the upper Dakota are insufficient to accurately determine the configuration of their potentiometric surfaces. Pre-development hydraulic head data for the aquitards are non-existent. Because of this paucity of data it was assumed that the water levels in the lower Dakota aquifer (Layer 4) and the Morrison and upper Permian (Layer 5) were approximately equal to the pre-development water level of the upper Dakota aquifer for the purpose of model input.

Information on the vertical and horizontal components of hydraulic conductivity came from published and unpublished reports of pumping test results, core analyses, and values assigned in previous modeling investigations. Pumping test results from aquifer tests in the High Plains and alluvial valley aquifers were abundant. The data for the upper Dakota were much less plentiful and came from pumping tests conducted where the aquifer is shallow. Additional data

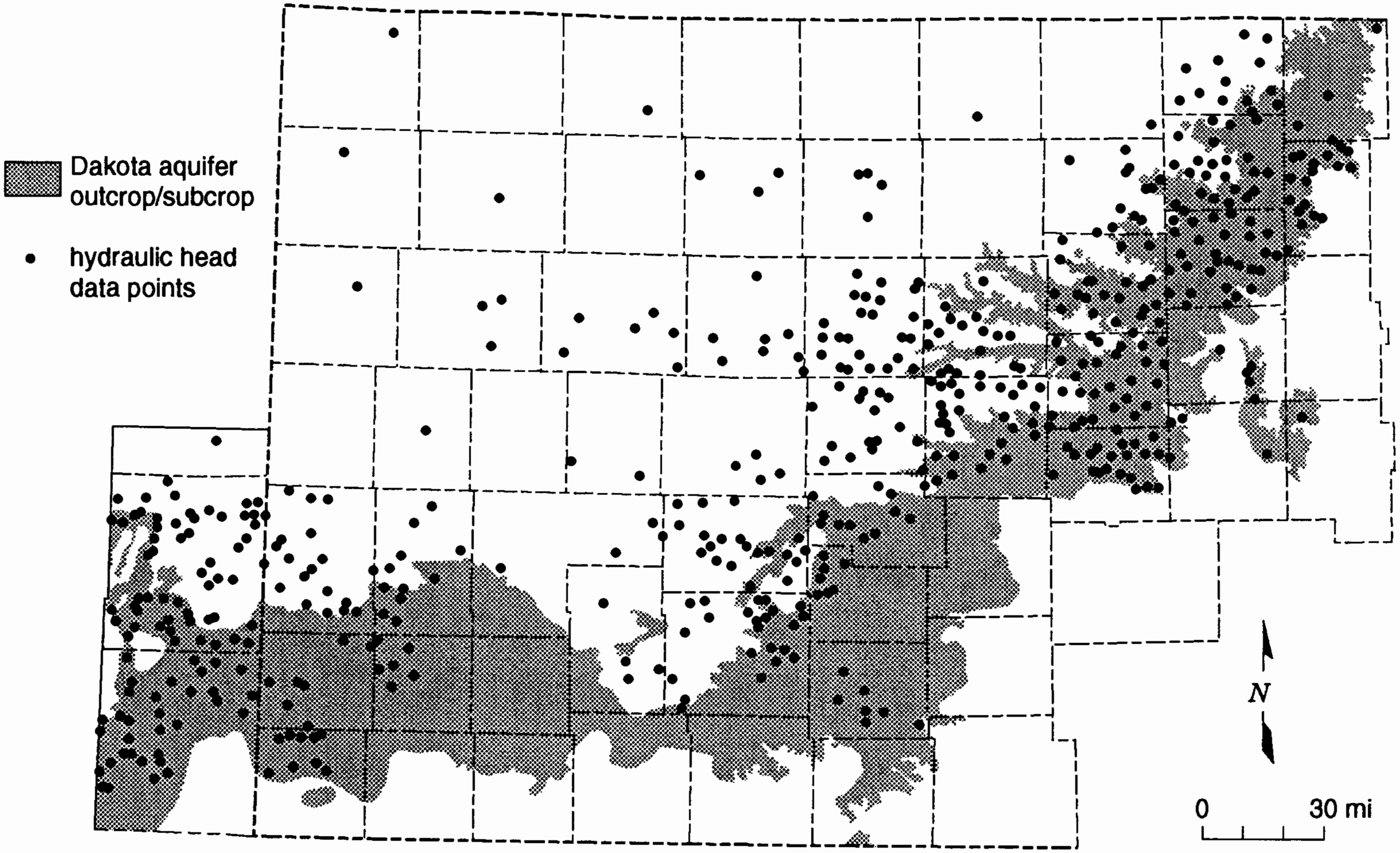

Figure 27. Distribution of data points used to define the potentiometric surface of the Upper Dakota aquifer (layer 3) in the regional model.

were also available from laboratory tests on core samples from test holes in central and northwest Kansas. Outside of the study region to west in the deeper part of the Denver basin, data on the permeability of Dakota Group sandstones were found to be plentiful. Hydraulic conductivity data for the other aquifer and aquitard units in the study area are virtually nonexistent and were derived from a literature review (Macfarlane *et al.*, 1992; Whittemore *et al.*, 1993; and Macfarlane, 1993).

### *ARC-MOD (ARC/INFO–MODFLOW) interface operation*

The ARC/INFO geographic information system is being used for the management, mapping, and analysis of various geologic and hydrologic data sets discussed in the previous sections. MODFLOW requires an enormous amount of input data for the regional model and the model output is difficult to process manually for display and interpretation. For this reason, ARC/INFO is used also as a pre- and post-processor for the model data. Figure 28 is a flow chart illustrating the role of ARC/INFO in the flow of information to and from the ground-water flow model.

The geologic and hydrologic input data was first put into the INFO part of the geographic information system. Coverages containing the elevations, thicknesses, and extents of hydrologic and geologic data were generated from the continuous surfaces developed initially from hand-contouring, digitizing, or a DEM. In areas where data was lacking, ARC/INFO was used for extrapolation. This was primarily done by extending the contours following the general trend of the data. Parameter values were extracted from the continuous surface for a particular model layer and assigned to the center of each cell in the model region. The following paragraph describes the procedure used to assign parameter values to nodal points.

Once a continuous surface covering the model region was produced, a three dimensional representation of that surface was constructed using the Triangular Irregular Network (TIN) function available in ARC/INFO. A TIN is essentially a planar surface produced by linear interpolation between the control points of a data coverage. The control points come from either the point locations of the original data or from points sampled by the program along contour lines. The tinspot procedure was the method used to assign values from a TIN to a coverage containing points representing the distribution of model nodes within a layer. Figure 29 illustrates the tinspot procedure. Parameter values from the TIN surface are projected onto and assigned to the coverage of model cell centers for the appropriate model layer.

While using ARC/INFO to create the surfaces representing the thickness of different model layers, it was discovered that the best results were achieved by working directly with thickness data rather than the model layer tops data. This method eliminates the possibility of negative thicknesses which can occur when the elevations of the top and bottom of a layer are

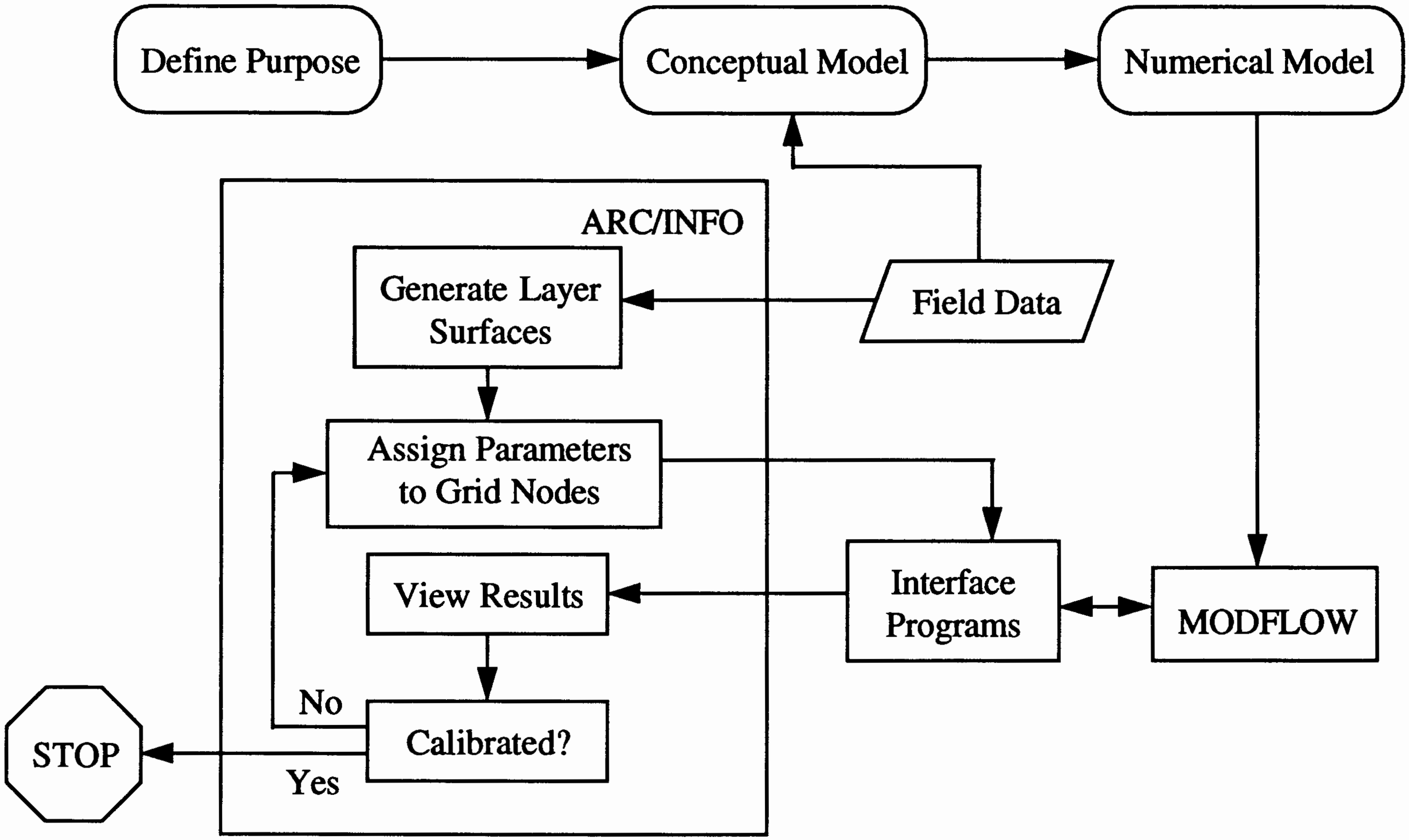

Figure 28: Shown is a summary flow chart of the automated ground-water modeling procedure.

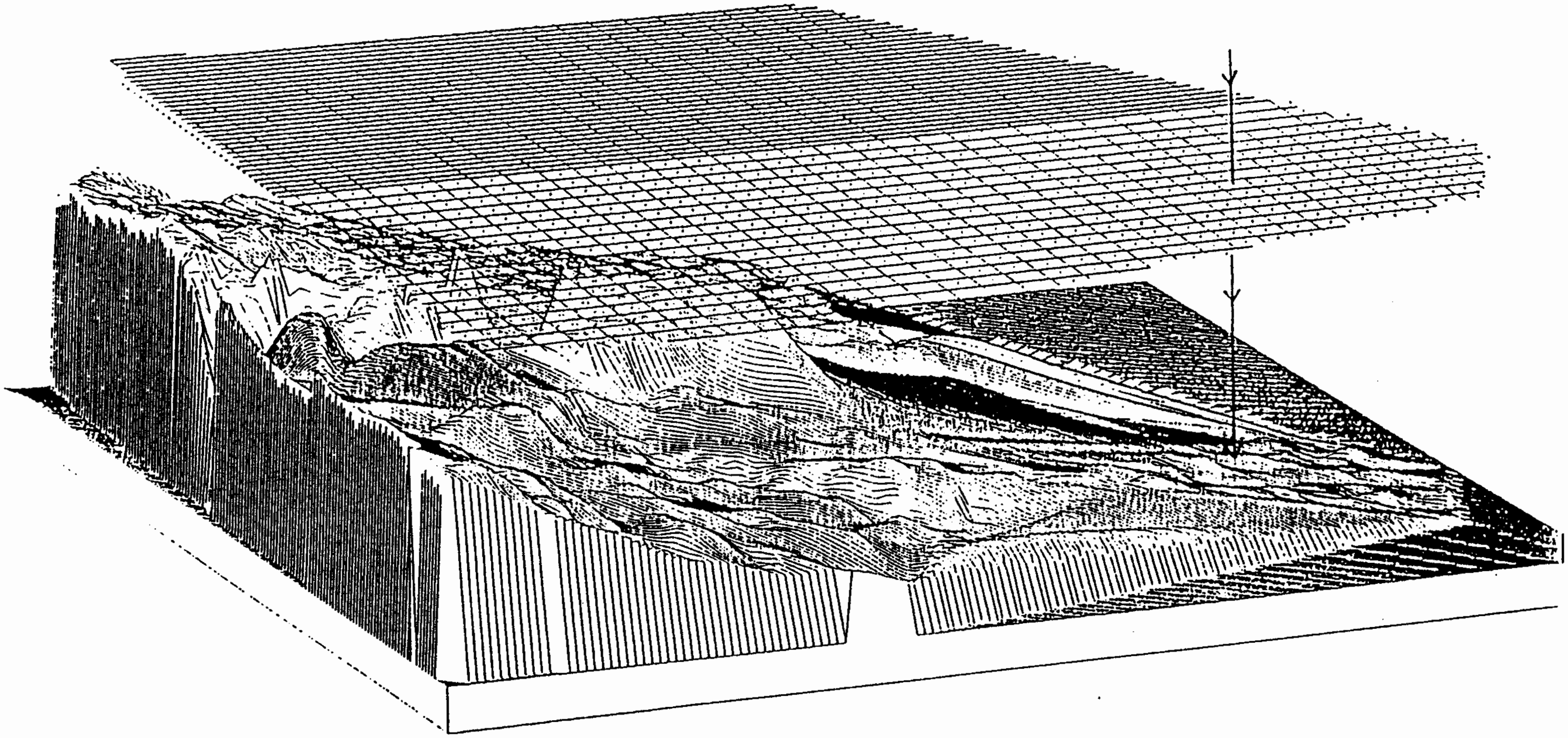

Figure 29. Conceptual illustration of the TINSPOT command. This figure shows a grid of points (shown in the center of the cells) as an overlay above a three-dimensional view of a TIN surface (vertically-exaggerated 400 times). The grid corresponds to the MODFLOW model grid. In the ARC/INFOsoftware, the elevation directly beneath the center of each block in the grid is determined and is assigned to the grid-point coverage's attribute table (.PAT).

subtracted from each other. Negative thicknesses are a result of the error involved in the interpolation procedure used by the TIN function for the creation of a parameter surface. This primarily occurs near pinchouts or where the bounding surfaces of the layer are irregular. Good results were also obtained using both the original data points and the hand-drawn contours on the map or the hand-drawn contours alone. This is because where the data distribution is sparse natural features are not brought out by a linear interpolation done by the computer. Manual contouring of irregular surfaces, such as geologic structure and topography, is necessary so that the surface representing the variation of a given parameter is represented in a way that is geologically plausible. Once the coverage of grid points was assembled, the accuracy of the data was verified to assure quality control. The automated contouring package of ARC/INFO was used to generate both elevations and thicknesses of model layers. The resulting contours were then compared with contours of the original data to check for discrepancies.

The input data are passed from ARC/INFO to MODFLOW using the interface program ARC-MOD. The interface program transforms the grid-point coverages into ASCII text files that can be read by MODFLOW. Once the ASCII text files are created, program execution in MODFLOW begins.

Output from MODFLOW is in the form of cell-by-cell flow rates, drawdowns, and hydraulic head values for all of the model layers. In order to display the model results, ARC-MOD takes the unformatted output files from MODFLOW and transforms them into coverages in ARC/INFO. The data in the coverages can then be evaluated in three ways through various options available within ARC/INFO: (1) contoured maps of the head and drawdown distributions, (2) three-dimensional representations of the results, or (3) model uncertainty or error.

### *Input hydraulic conductivities*

Hydraulic conductivities for the various model layers are not well known for all of the aquifer and aquitard units represented in the model. Most of the data come from pumping tests of wells in the High Plains, alluvial valley, and in the shallow upper and lower Dakota aquifers. A few drill-stem tests in the upper Dakota are available from northwest Kansas and hydraulic conductivities derived from laboratory tests on core samples are available for samples from two test holes, one in central and one in northwest Kansas. Aquitard hydraulic conductivities are unknown in Kansas. However, the plausible ranges of hydraulic conductivity values for these hydrostratigraphic units are known for the different layers from the literature. From these plausible ranges, starting values of hydraulic conductivity were selected for input into the model and are given in Table 3.

### *Model calibration*

Calibration of ground-water flow models usually consists of adjusting the input parameters until a satisfactory match is achieved between the observed and 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 cell-by-cell adjustment of layer hydraulic conductivity to match hydraulic head data in layer 3, the upper Dakota aquifer, and flow rates from the model. Because most of the head data were primarily from the High Plains, alluvial valley, and upper Dakota aquifers, very little adjustment was made in the hydraulic parameters of layers below the upper Dakota aquifer.

Table 3. Input hydraulic conductivity values (ft/day) for the quasi three dimensional regional flow model.

| MODEL LAYER | HYDROSTRATIGRAPHIC UNIT | $K_h$ | $K_v$ |
|---|---|---|---|
| 1 | High Plains/alluvial valley aquifer | 78.0 | 7.8 |
| 2 | Upper Cretaceous aquitard | $3.0 \times 10^{-6}$ | $3.0 \times 10^{-7}$ |
| 3 | Upper Dakota aquifer | 4.0 | $3.7 \times 10^{-3}$ |
| Quasi-Layer | Kiowa shale aquitard | – | $1.0 \times 10^{-6}$ |
| 4 | Lower Dakota aquifer | 1.0 | $3.7 \times 10^{-3}$ |
| 5 | Permian-Pennsylvanian aquitard | $2.7 \times 10^{-4}$ | $4.4 \times 10^{-4}$ |
| | Permian Sandstone aquifer | 0.16 | 0.016 |

The main parameters that were adjusted were the horizontal hydraulic conductivity ($K_h$) of layer 3 and the vertical hydraulic conductivity ($K_v$) of layer 2. Macfarlane (1993) reported that these two parameters seem to be the most important hydrostratigraphic influences on the steady-state flow system in the upper Dakota aquifer. The results of each round of calibration were evaluated by computing the root mean square (RMS) error:

$$\text{RMS error} = [(1/n)\Sigma(h_m - h_s)^2]^{0.5} \qquad \text{Eq. 2}$$

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). As a further check on the calibration, the errors were examined for trend by visual inspection of the drawdown distribution coverage for each run. Calibration of the regional is not yet complete, but will be continued in FY94 until the model achieves partial calibration. The steady-state model will be considered to be partially calibrated when the RMS error is less than 50 ft., which is approximately 2% of the total head decline across the model and is within the error of many of the calibration target heads. Only a partial calibration can be achieved because the hydraulic head distribution is not well known in the lower Dakota, and Cedar Hills Sandstone aquifers.

### *Model results to date*

Figure 30 shows the model results for layer 3 using the starting values of hydraulic conductivity for input in Table 3. The RMS error for this model run is 83 ft. The pre-development potentiometric surface of the upper Dakota aquifer is shown for comparison. The model results reproduce the regional characteristics of the pre-development potentiometric surface reasonably well. In succeeding model runs, the adjustments of layer 2 $K_v$ and layer 3 $K_h$ produce only minor changes in the layer 3 potentiometric surface. As of this writing RMS error has been reduced to 60 ft. During the calibration process to date we have observed the influence of these parameters on the potentiometric surface of layer 3. The model appears to be more sensitive to the layer 2 $K_v$ than layer 3 $K_h$ because the vertical hydraulic conductivity of layer 2 controls the recharge to layer 3 from the overlying water table. Layer 2 $K_v$ generally increases as the layer thickness decreases near its southern and eastern extents in the model. Where layer 2 is thickest, its vertical hydraulic conductivity is on the order of $10^{-7}$ ft/day. Near its eastern and southern extents, the vertical hydraulic conductivity increases to $10^{-6}$ or $10^{-5}$ ft/day. Layer 3 $K_h$ seems to increase in an easterly direction towards the outcrop area of the upper Dakota aquifer. Where layer 3 is a confined aquifer $K_h$ is only a few ft/day. However, $K_h$ is on the order of several 10's of feet/day in the outcrop area of central Kansas.

## **Development Of A Ground-Water Flow Model For The Dakota Aquifer In Southwestern Kansas**

### *Abstract*

A subregional ground-water flow model to simulate a part of the Dakota aquifer in southwestern Kansas is being developed in conjunction with the development of a regional ground-water flow model. The subregional-model grid covers all or parts of 19 southwestern Kansas counties and consists of 64 rows, 76 columns, and grid cells that represent 1.5 miles on each side. A five-layer model is planned. Three geographic-information-system (GIS) coverages represent the model grid and contain model input data. In addition, one GIS coverage represents

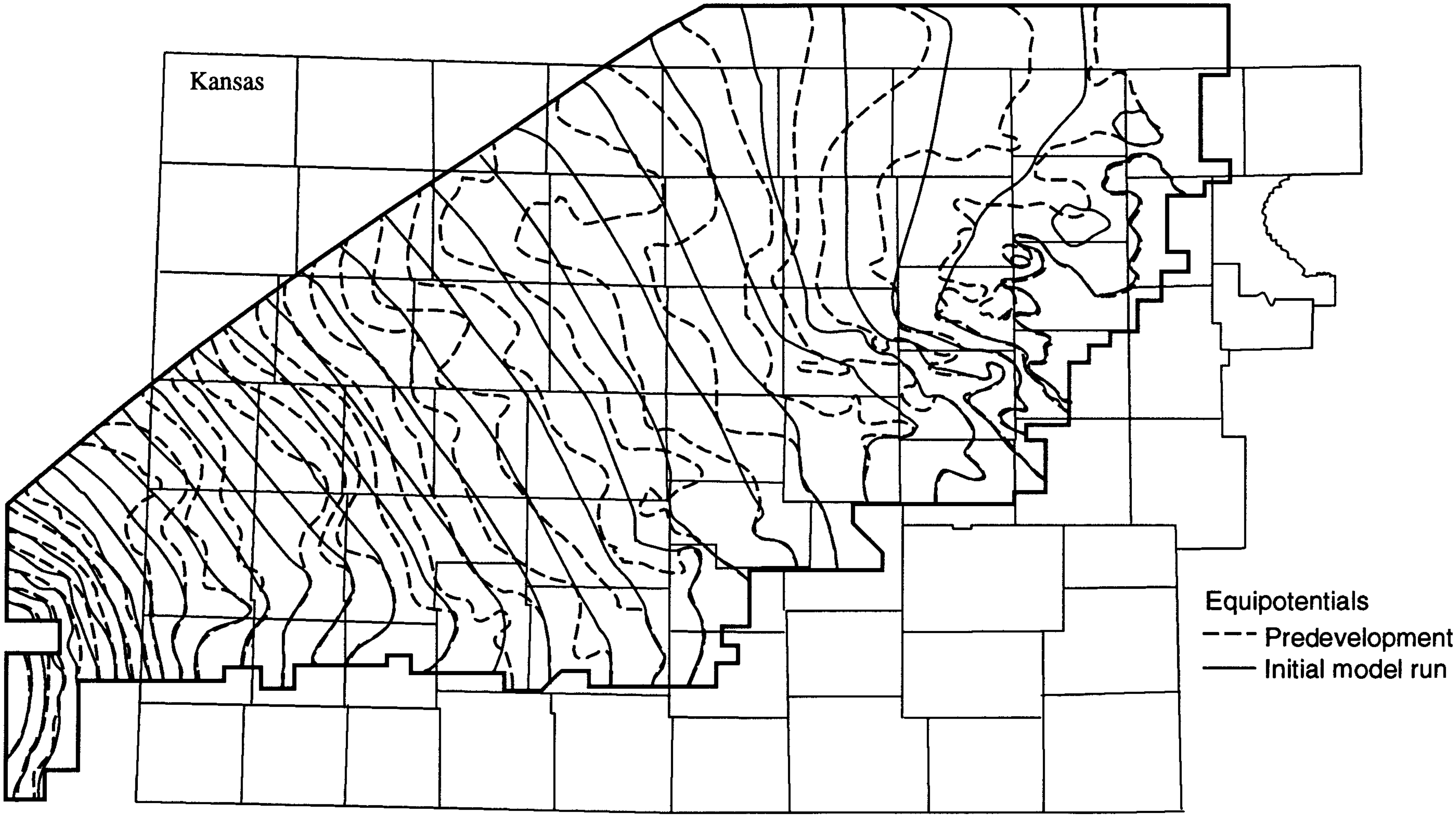

Figure 30. Potentiometric surface from the initial run of the regional model in comparison to the predevelopment potentiometric map of the upper Dakota aquifer (layer 3).

streams in the model area, and one GIS coverage represents the boundary and extent of the overlying High Plains aquifer within the model area.

## *Introduction*

The Dakota aquifer is the focus of a study by the Kansas Geological Survey (KGS) to evaluate the aquifer's suitability as a future water supply for central and western Kansas. As part of their effort, KGS is developing a regional ground-water flow model of the entire Dakota aquifer within Kansas. The purpose of this report is to summarize the work completed by the U.S. Geological Survey (USGS) during FY93 on the development of a ground-water flow model for a part of the Dakota aquifer in southwestern Kansas. This subregional flow model coincides with part of the Kansas Geological Survey's regional model and is intended to be used to: (1) assess, in an area of intense water-use development in southwestern Kansas, the availability of ground water from the Dakota aquifer to supply or augment large water demands, such as municipal, industrial, and irrigation needs; (2) provide improved definition and understanding of the relation among the Dakota aquifer, the overlying, unconsolidated High Plains aquifer, and the underlying bedrock aquifers; (3) evaluate the effects of increased pumpage from the High Plains and Dakota aquifers on the water levels in the Dakota aquifer; and (4) evaluate the effect on the Dakota aquifer of various management practices that may be initiated by Groundwater Management District #3 (GMD3), such as minimum well-spacing and well-setback (from the aquifer outcrop or subcrop) requirements for pumping wells in the Dakota aquifer. Subregional-model development will be transferred to and completed by KGS following the 1993 fiscal year.

The MODFLOWARC ground-water model flow program (Orzol and McGrath, 1992) will be used for the subregional model. MODFLOWARC is a version of MODFLOW (McDonald and Harbaugh, 1988) that has been modified to read from and write to geographic-information-system (GIS) files. This modification allows the user access to the full capabilities of a GIS to interactively enter, analyze, and display the input and output model-data sets. The input data required for MODFLOWARC is the same as for MODFLOW.

## *Model grid*

The subregional-model grid covers all or parts of 19 southwestern Kansas counties, extends into Colorado and Oklahoma (Figure 31), and like the regional model, will be divided vertically into five layers. Areally, the grid was created using an Albers equal-area map projection and has 64 rows and 76 columns. The lower left corner of the subregional grid coincides with the lower left corner of the regional-model grid cell located at row 55, column 6 (Figure 32). Each subregional grid cell represents 1.5 miles on each side. The 1.5-mile grid-cell size was selected to be a divisor of the grid-cell spacing of 6 miles on a side used in the regional model and the 3-mile grid-cell spacing used by Stullken and others (1985). A 1-mile grid-cell spacing was considered but would have resulted in a total of 54,720 grid cells for the five-layer model, which is beyond the capabilities of the ground-water flow model program MODFLOWARC (Orzol and McGrath, 1992). The 1.5-mile subregional-model grid spacing results in a total of 24,320 grid cells for the five-layer model.

### *Coverages*

The subregional-model grid is represented by three GIS spatial data sets (coverages) named grid_arc, grid_pts, and grid_pol. The grid_arc coverage contains lines that represent the grid-cell boundaries. The grid_pts coverage contains points that are located at the centroid of each grid cell. The grid_pol coverage contains polygons representing the grid-cell boundaries and label points at the centroid of each grid cell. Data items contained in the feature attribute tables (FAT) of these coverages are described in Table 4. All of the items in Table 4, with the exception of ROW, COL, and SEQNUM, are assigned values by the GIS when the coverage is made or updated and, except as noted below, are not used in the model. The ROW, COL, and SEQNUM items contain the row, column, and a unique sequential number for each grid cell in the model. The GRID_ARC-ID, GRID_PTS-ID, and GRID_POL-ID items initially are assigned values by the GIS but may be changed by the user. In the grid_pol.pat FAT, the AREA item contains the area of each grid cell. This area may be useful in calculating, for example, the annual volume of precipitation for a grid cell: [precipitation (ft/year) x grid-cell area ($ft^2$) = precipitation volume ($ft^3$/year)]. Streams to be simulated in the model are shown in Figure 34 and are in a coverage named RIVDATA. These streams were extracted from a coverage named RRFILE (river-reach file) developed by the U.S. Environmental Protection Agency. Only those reaches of the streams that were indicated by Stullken and others (1985, Figure 12) to be perennial are included in the RIVDATA coverage. The FAT rivdata.aat in the RIVDATA coverage contains input data for the stream-routing package (Prudic, 1989). The stream-routing package has been incorporated into MODFLOWARC and will be used to simulate streamflow in the model. The item names in the rivdata.aat FAT correspond to the input-data names used by Prudic (1989) and are listed in Table 5 beginning with the item LAYER. All other items in Table 5 are assigned values by the GIS and, except LENGTH, are not used in the model. LENGTH contains the length of each stream reach and may be used in the calculation of the value for the COND item.

The streams are segmented into reaches by intersecting the RIVDATA coverage with the grid_pol coverage. Each stream reach corresponds to a model cell. The LENGTH item in Table 5 was calculated by the GIS during the intersection process and is the length of each stream reach.

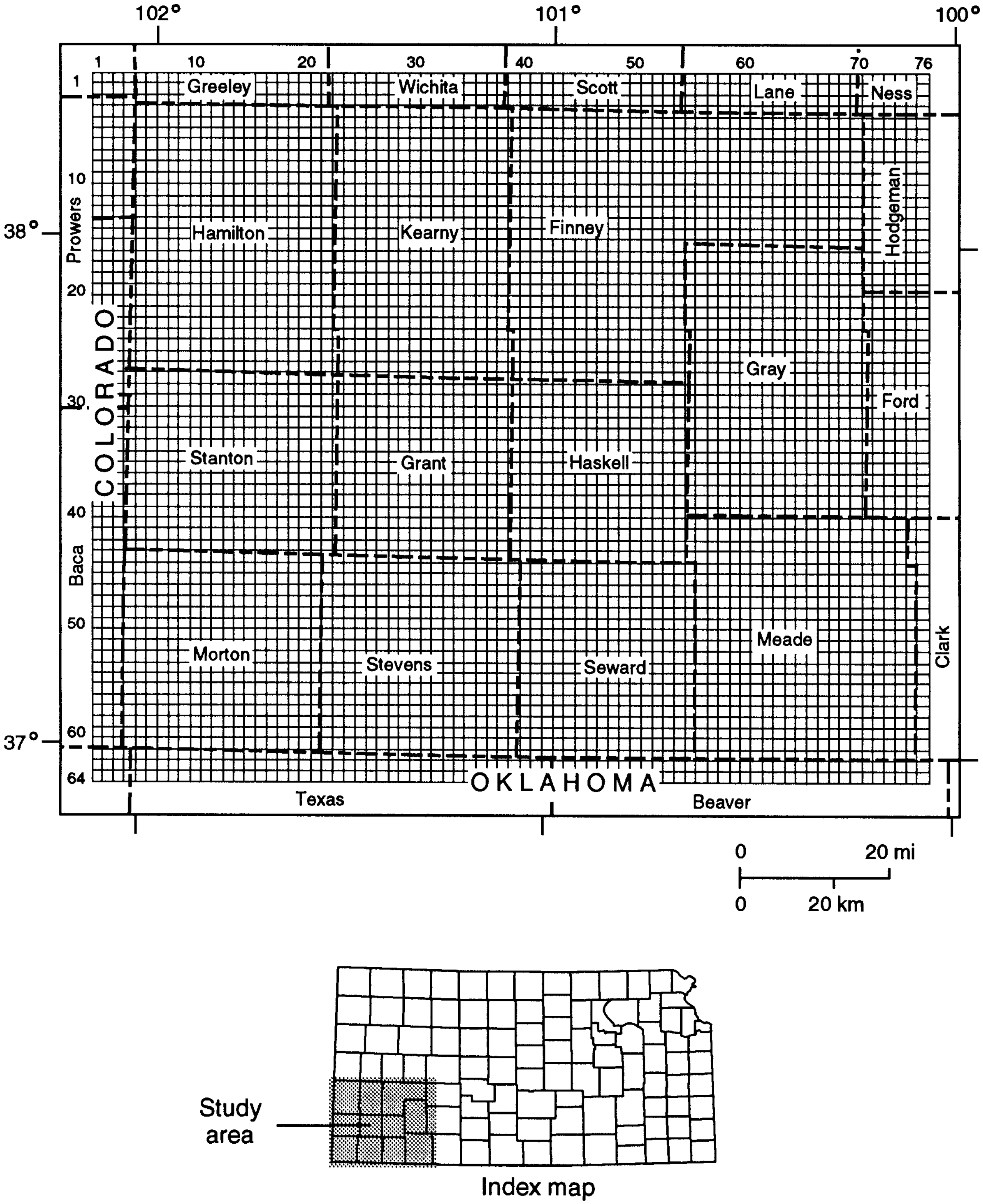

Figure 31. Location of subregional-model grid in southwestern Kansas and parts of Colorado and Oklahoma.

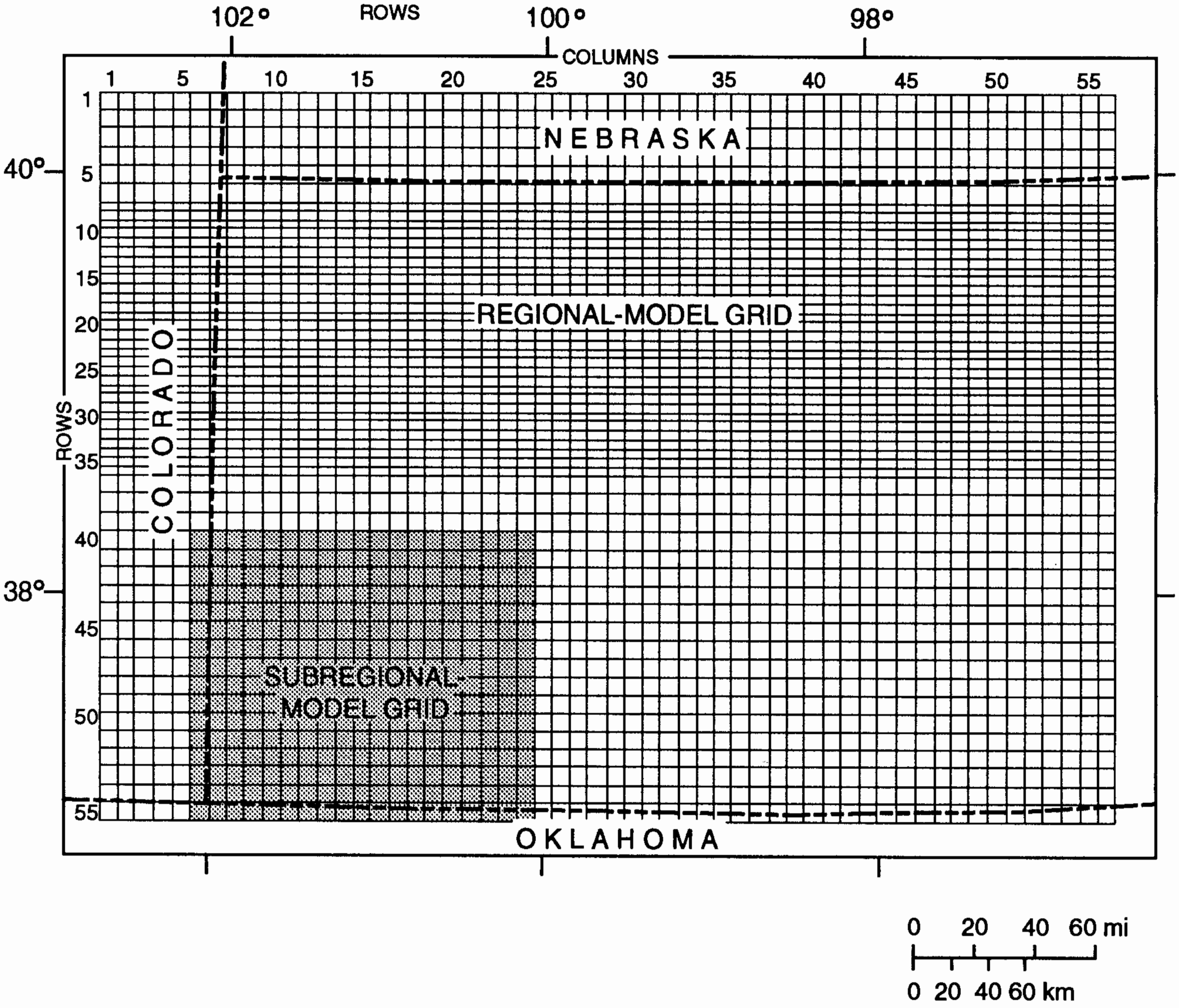

Figure 32. Regional and subregional model grids.

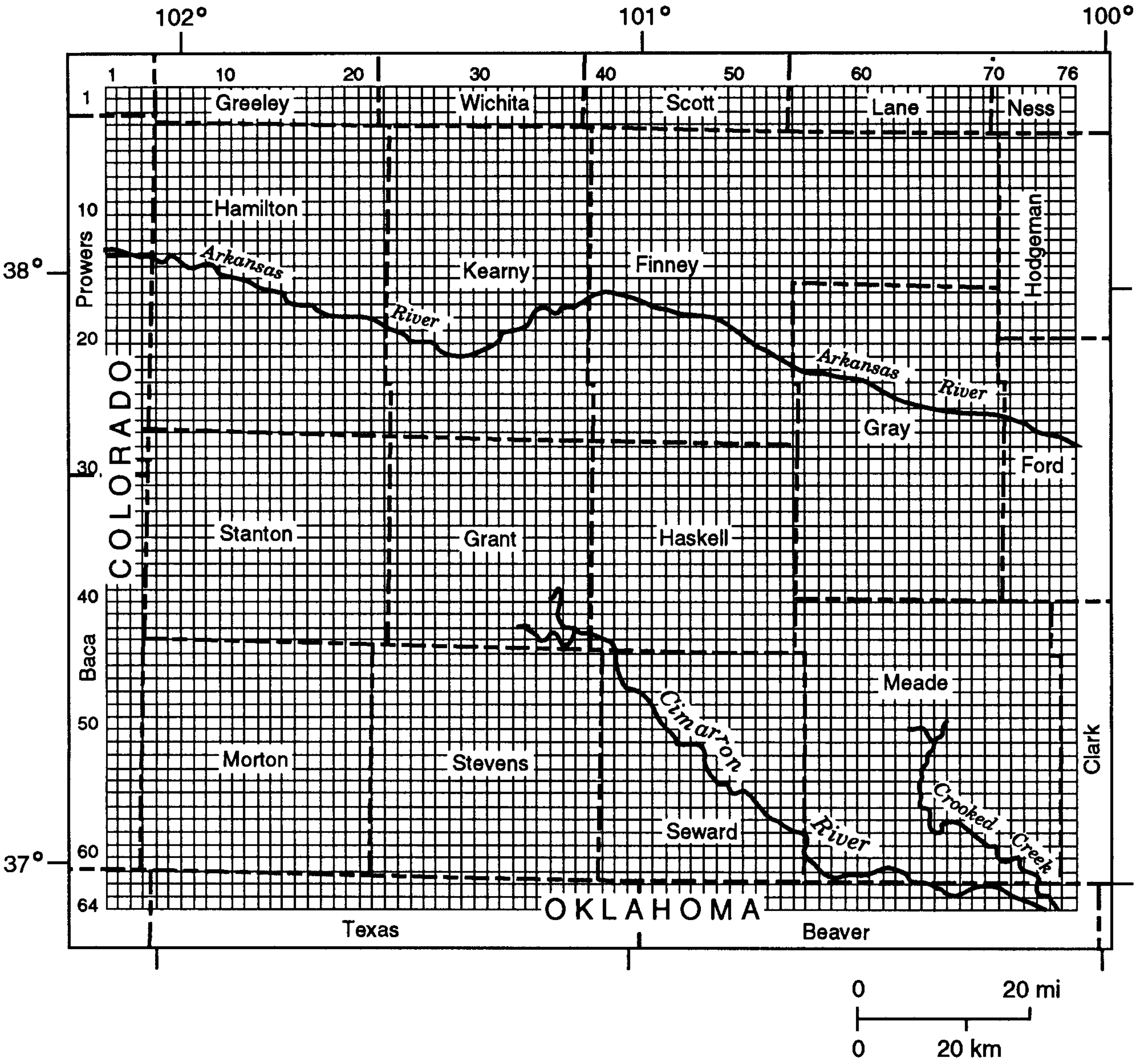

Figure 33. Streams simulated in subregional model.

Table 4. Items contained in feature-attribute tables grid_arc.aat, grid_pts.pat, grid_pol.pat, and grid_pol.aat.

| Item | Item Description |
|---|---|
| | ARC-ATTRIBUTE TABLE GRID_ARC.AAT<br>(grid-cell boundaries) |
| FNODE# | Internal sequence number of the "from" node, assigned by GIS |
| TNODE# | Internal sequence number of the "to" node, assigned by GIS |
| LPOLY# | Internal sequence number of the left polygon, assigned by GIS |
| RPOLY# | Internal sequence number of the right polygon, assigned by GIS |
| LENGTH | Length of arc in coverage units (feet), assigned by GIS |
| GRID_ARC# | Internal sequence number, assigned by GIS |
| GRID_ARC-ID | Internal sequence number, assigned by GIS. May be changed by user. |
| | POINT-ATTRIBUTE TABLE GRID_PTS.PAT<br>(centroids of grid cells) |
| AREA | Area of a polygon. Value is zero for points. |
| PERIMETER | Perimeter length of a polygon. Value is zero for points. |
| GRID_PTS# | Internal sequence number, assigned by GIS. |
| GRID_PTS-ID | Internal sequence number, assigned by GIS. May be changed by user. |
| ROW | Number of the model grid row. |
| COL | Number of the model grid column. |
| SEQNUM | Sequence number assigned to a model grid cell beginning with the upper left corner of the grid and progressing row by row. |
| | POLYGON-ATTRIBUTE TABLE GRID_POL.PAT<br>(label points at cell centroids) |
| AREA | Area of a polygon. Value is zero for points. |
| GRID_POL# | Internal sequence number, assigned by GIS |
| GRID_POL-ID | Internal sequence number, assigned by GIS. May be changed by user. |
| ROW | Number of the model grid row. |
| COL | Number of the model grid column. |
| SEQNUM | Sequence number assigned to a model grid cell beginning with the upper left corner of the grid and progressing row by row. |

Table 4. Items contained in feature-attribute tables grid_arc.aat, grid_pts.pat, grid_pol.pat, and grid_pol.aat. (Continued)

| Item | Item Description |
|---|---|
| | ARC-ATTRIBUTE TABLE GRID_POL.AAT<br>(grid-cell polygons) |
| FNODE# | Internal sequence number of the "from" node, assigned by GIS. |
| TNODE# | Internal sequence number of the "to" node, assigned by GIS. |
| LPOLY# | Internal sequence number of the left polygon, assigned by GIS. |
| RPOLY# | Internal sequence number of the right polygon, assigned by GIS. |
| LENGTH | Length of arc in coverage units (feet), assigned by GIS. |
| GRID_POL# | Internal sequence number, assigned by GIS. |
| GRID_POL-ID | Internal sequence number, assigned by GIS. May be changed by user. |

Short stream reaches that are located in the corners of the grid cells are joined with stream reaches in adjoining cells. The altitude of the top of the streambed (item STOP in Table 5) was determined by overlaying a plot of the model grid and streams on 7.5-minute U.S. Geological Survey topographic maps and interpolating between contour lines. Altitudes were picked at the midpoint of each stream reach. The altitude of the bottom of the streambed (item SBOT in Table 5) was assumed as 1 foot less than the top-of-streambed altitude. Water altitude in the stream (item STAGE in Table 5) was assumed as 1 foot greater than the top-of-streambed altitude. The boundary and extent of the unconsolidated (High Plains) aquifer, digitized from Gutentag and others (1981, Plate 2), are in a coverage named HPAQBD1 and are shown in Figure 34. The straight-line vertical and horizontal parts of the boundary shown in Figure 35 are the limits of the map from which the aquifer boundary was digitized and do not represent actual aquifer boundaries. The unconsolidated aquifer boundary for these areas will be extended based on other more general published maps and any available well-log data. The modified unconsolidated aquifer boundary will be used to define the active model cells for layer 1 (top layer). Items contained in the FAT hpaqbd1.aat of coverage HPAQ BD1 are listed in Table 6. None of these items will used in the model. Although not yet delineated, the active model cells for layers 2 through 5 will be based on mapped bedrock-unit boundaries.

Table 5. Items contained in feature-attribute table rivdata.aat.

| Item | Item Description |
|---|---|
| FNODE# | Internal sequence number of the "from" node, assigned by GIS. |
| TNODE# | Internal sequence number of the "to" node, assigned by GIS. |
| LPOLY# | Internal sequence number of the left polygon, assigned by GIS. |
| RPOLY# | Internal sequence number of the right polygon, assigned by GIS. |
| LENGTH | Length of arc in coverage units (feet), assigned by GIS. |
| RIVDATA# | Internal sequence number assigned by GIS. |
| RIVDATA-ID | Internal sequence number assigned by GIS. May be changed by user. |
| SEQNUM | Sequence number assigned to a model grid cell beginning with the upper left corner of the grid and progressing row by row. |
| LAYER | Number of the model layer occupied by stream. |
| ROW | Number of the model grid row occupied by stream. |
| COLUMN | Number of the model grid column occupied by stream. |
| SEG | Number of the stream segment. A segment is made up of one or more stream reaches. |
| REACH | Number of the stream reach. There is one reach for each model cell. |
| FLOW | Stream discharge in ft/time units. (Values not yet assigned.) |
| STAGE | Altitude of water in stream in feet. Values may be assigned by user or calculated by MODFLOW based on channel slope and roughness. |
| COND | Streambed conductance in ft/time units. (Values not yet assigned.) |
| SBOT | Altitude of bottom of streambed in feet. |
| STOP | Altitude of top of streambed in feet. |
| WIDTH | Width of stream channel in length units. (Values not yet assigned.) |
| SLOPE | Slope of the stream channel dimensionless. (Values not yet assigned.) |
| ROUGH | Manning's coefficient for streambed roughness. (Values not yet assigned.) |

Table 6. Items contained in feature-attribute table hpaqbd1.aat.

| Item | Item description |
|---|---|
| FNODE# | Internal sequence number of the "from" node, assigned by GIS. |
| TNODE# | Internal sequence number of the "to" node, assigned by GIS. |
| LPOLY# | Internal sequence number of the left polygon, assigned by GIS. |
| RPOLY# | Internal sequence number of the right polygon, assigned by GIS. |
| LENGTH | Length of arc in coverage units (feet), assigned by GIS. |
| HPAQBD1# | Internal sequence number, assigned by GIS. |
| HPAQBD1-ID | Internal sequence number, assigned by GIS. May be changed by user. |

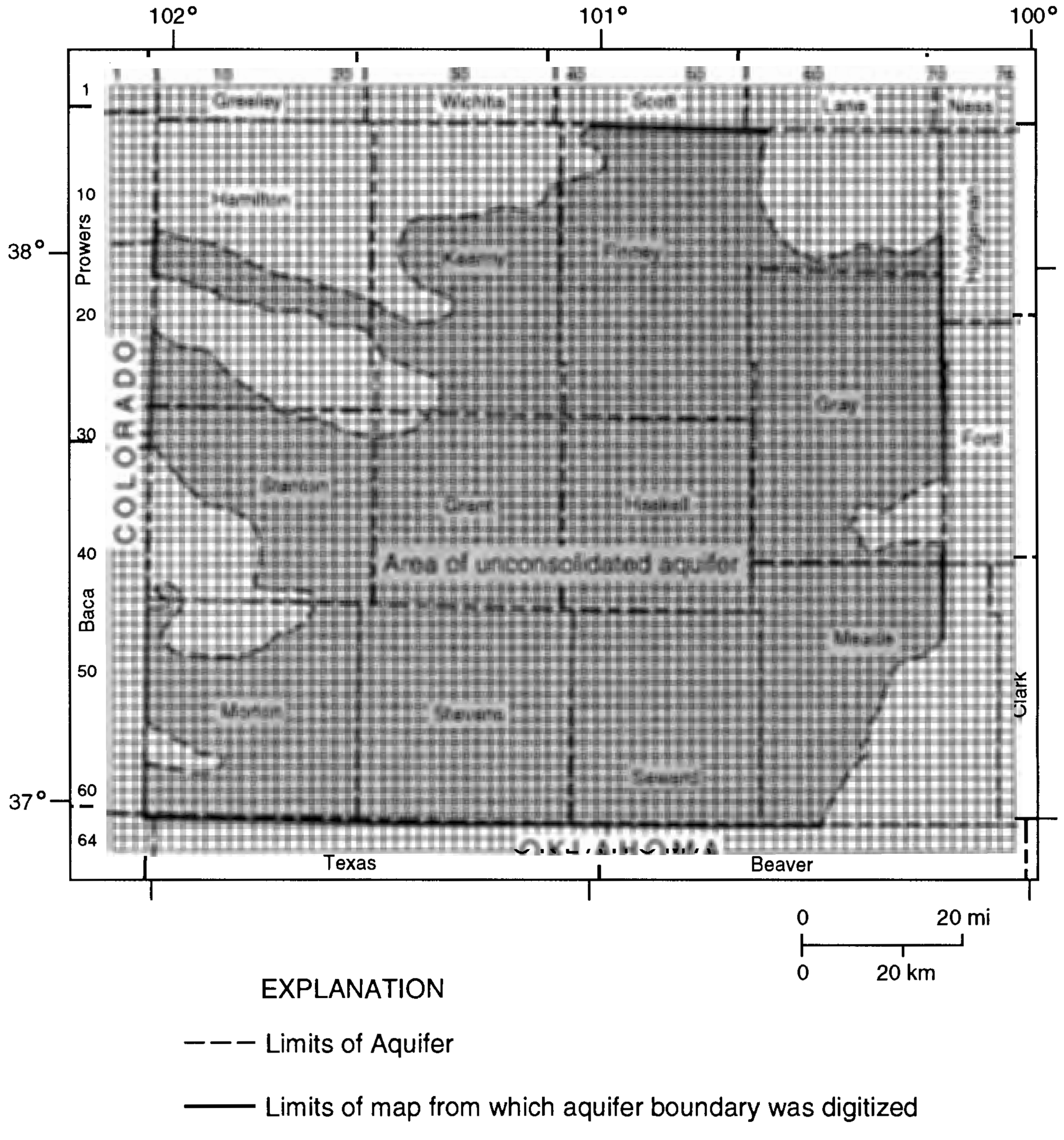

Figure 34. Boundary and extent of the consolidated (High Plains) aquifer in southwestern Kansas.

## GEOCHEMISTRY

### Water Quality Estimation from Wireline Logs in the Dakota Aquifer of Northwestern Kansas

Very little chemical data exist for the Dakota aquifer in northwestern Kansas. Knowledge of the water quality of the Dakota aquifer in northwestern Kansas is valuable not only for assessing the water-resource potential of the area, but also for determining the extent of protection needed relative to construction of oil and gas wells. What data do exist are distributed in scattered locations in the areas between northwestern Kansas and the north-central and west-central parts of the state. In general, the water-quality is believed to be saline based on drilling for oil and gas in the region. The depth to the Dakota aquifer in the area is great because there is a substantial thickness of overlying confining bedrock and also Ogallala Formation. Thus, observation or monitoring wells would be very expensive to install.

In FY93 the KGS was able to begin an investigation into the dissolved solids content of the Dakota aquifer in northwestern Kansas using interpretation of a large number of geophysical logs. The USGS interpreted the total dissolved solids and chloride content of the Dakota aquifer in northwest Kansas from a few geophysical logs during the regional aquifer study in Kansas, Colorado, and Nebraska. However, the number of points is too few to accurately portray the distribution of dissolved solids. In addition, the patterns for the dissolved solids and chloride concentrations on the USGS maps are not consistent with one another.

Although gamma-ray logs are generally a satisfactory medium for stratigraphic correlation and sandstone/shale discrimination, other logs can be used to assess important hydrologic questions concerning water quality, storage capacity, and the transmissive properties of the geologic framework. Because most logging tools have been run by the oil industry, log analysis of aquifers is a stepchild of a methodology geared to the location of oil and gas. Fortunately, many of the rock properties that are used to characterize hydrocarbon reservoirs are also key parameters of aquifers. However, there are some significant differences, so that adaptations of traditional methods of data analysis must be made with caution. Logs from the KGS observation well, Jones #1 (NE, NE, NE Sec. 2, T. 10 S., R. 8 W.; Lincoln County), are used to illustrate the techniques, but the methods have generalized application to many other logged boreholes that penetrate the Dakota aquifer.

The calculation of pore volume is readily made from either of three "porosity logs" (density, neutron, or sonic), using the same analysis procedures applied in the oil industry. It is common practice in recent years to run a pair of porosity logs (typically neutron and density) in order to provide some degree of automatic compensation for variations in lithology which affect porosity evaluation. An overlay of neutron and density logs is shown on Figure 35 for the

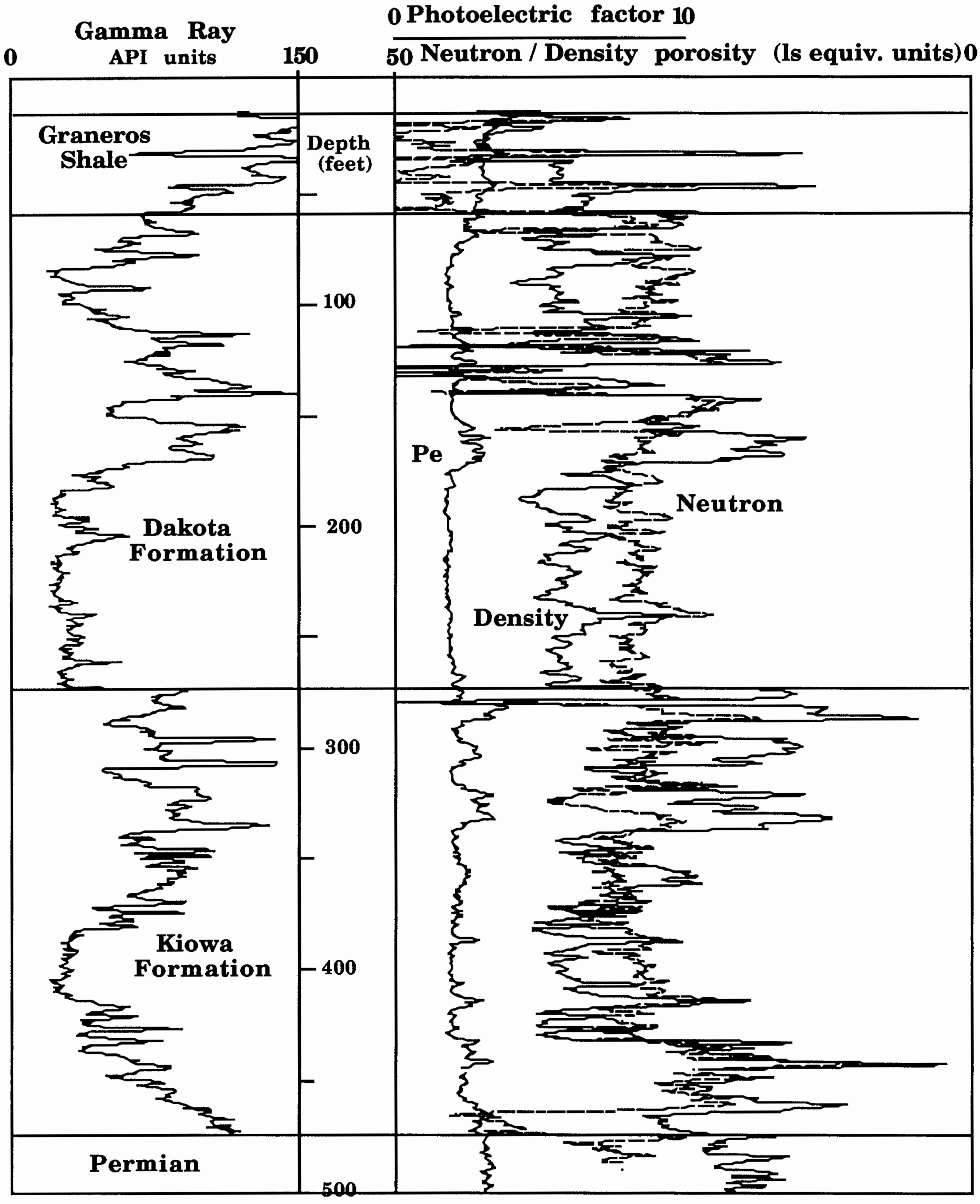

Figure 35: Gamma-ray and lithodensity-neutron logs from KGS Jones #1, NE-NE-NE 2-10S-8W Lincoln Co., Kansas

example Dakota aquifer section, referenced to an arbitrary standard scale of limestone-equivalent units. The separation of the porosity log curves reflects their varying responses to the compositions of the sandstone and shale units, while a true porosity estimate is approximately midway between their two readings.

Using simple computer methods, the neutron and density logs may be transformed into a volumetric profile of shale, quartz, and water (Figure 36). When compared with the shale content implied by the companion gamma-ray log, there are strong overall similarities with the neutron-density shale profile, even though they are based on radically-different properties. The volumetric profile of water (Figure 36) shows the vertical variation in effective porosity, which is generally on the order of 30% within the major sandstones. The shalier sandstones are commonly thinner and have markedly lower porosities.

The electric logs of spontaneous potential (SP) and resistivity (Figure 37) give important information concerning pore geometry, water quality, and the transmissive properties of the geologic framework. However, all of these attributes are inferred from empirical functions that relate electrical measurements to the framework and its porous media properties.

Semi-quantitative estimates of water quality can be made from the SP log, provided that the analysis is tied closely to local water-chemistry measurements. The SP tool measures natural electrical potentials that occur in boreholes and generally distinguishes porous, permeable formations from intervening, relatively impermeable shales. The "natural battery" effect is caused by the drilling of the borehole when the use of different drilling mud with a different salinity from the formation water juxtaposes two solutions with different ion concentrations. Ions diffuse from the more concentrated solution (typically formation water) to the more dilute. The ion flow is electrical current, with an associated potential measured in millivolts.

The conductivity of the drilling mud filtrate is measured at the well site so that the magnitude of the "battery effect" can be used to estimate formation-water resistivity. For a single salt solution, the fundamental equation is

$$SSP = -K\log(R_{mf}/R_{w}) \qquad \text{(Eq. 3)}$$

where SSP is the static self-potential, K is a function of temperature for an ideal ionic permeable membrane, and $R_{mf}$ and $R_{w}$ are the resistivities of the mud filtrate and the formation water, respectively. The calculation is made very commonly by petroleum log analysts as an important variable in the search for potential oil and gas zones.

The same method has been used to evaluate overall water quality of aquifers although care must be taken to ensure realistic conclusions. Although formation water compositions at greater depths tend to be dominated by high concentrations of sodium and chloride ions, other

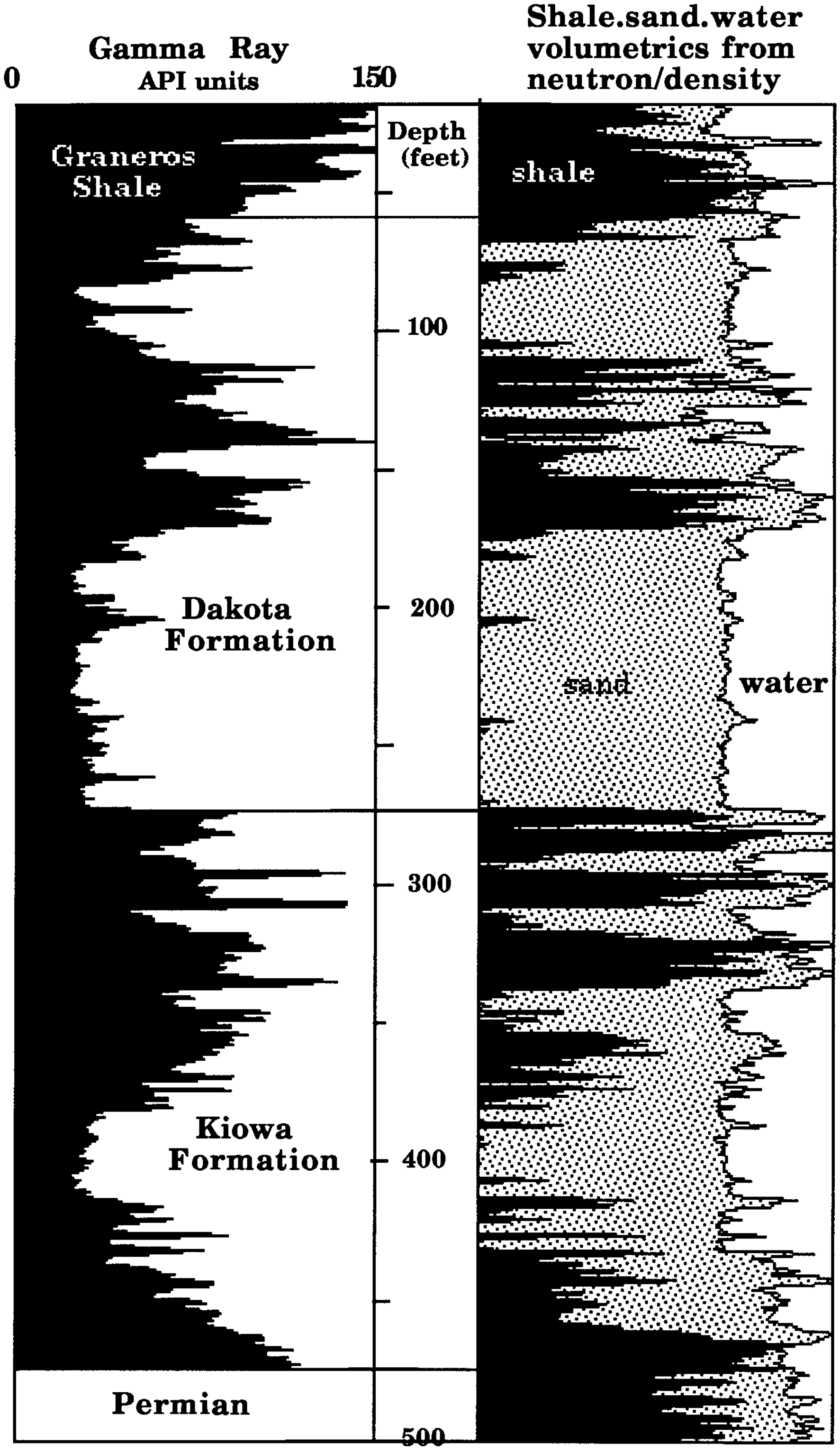

Figure 36: Volumetric summary of shale, quartz, and porosity characteristics indicated by gamma-ray and lithodensity-neutron logs from KGS Jones #1, NE-NE-NE 2-10S-8W Lincoln Co., Kansas.

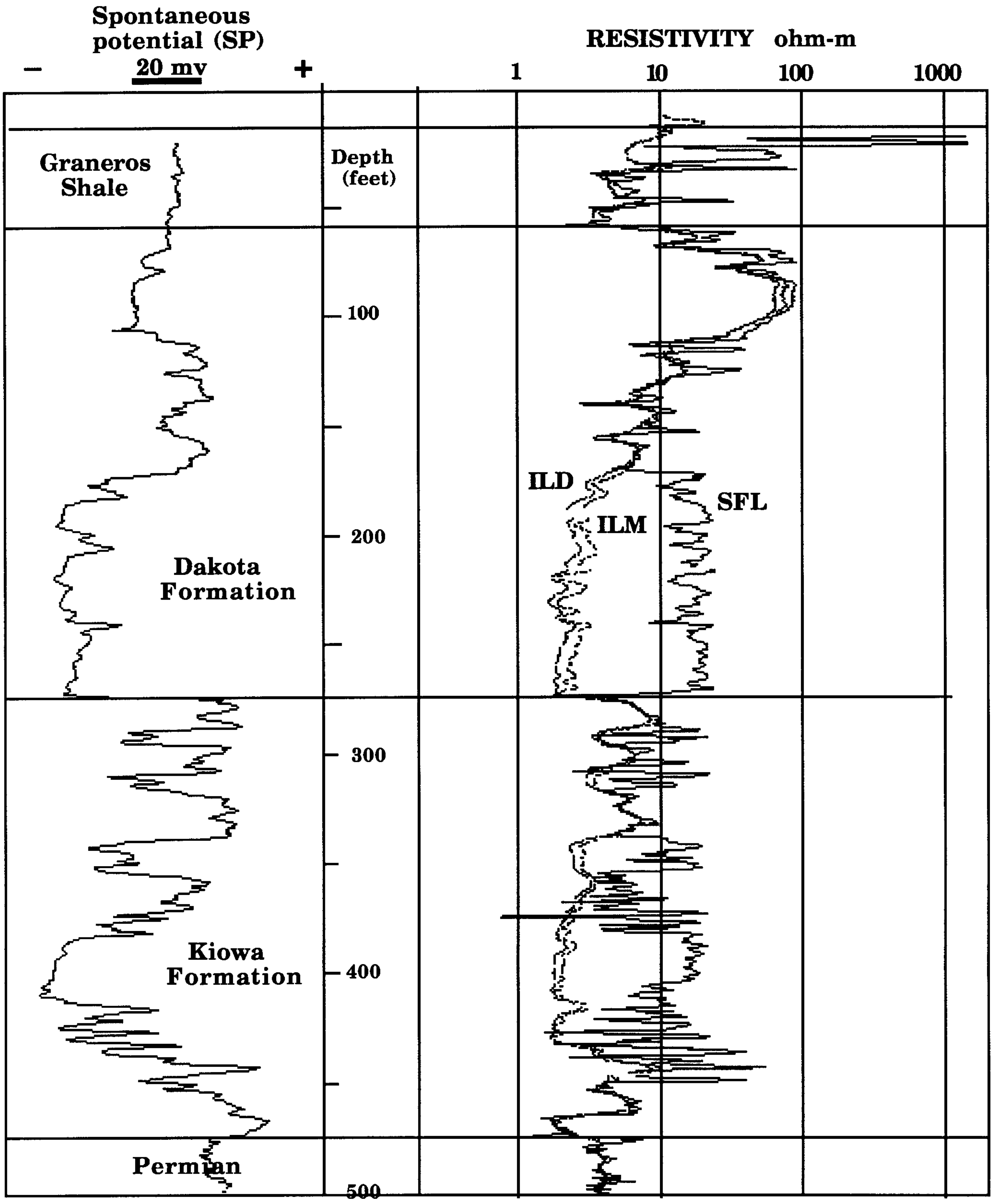

Figure 37: Spontaneous potential (SP), spherically-focussed (SFL), medium- (ILM) and deep- (ILD) induction resistivity logs from KGS Jones #1, NE-NE-NE 2-10S-8W Lincoln Co., Kansas

ionic constituents (primarily calcium, magnesium, bicarbonate, and sulfate ions) become more important in shallow aquifer waters which are variable multisalt solutions. As a result, the equations used by petroleum log analysts are only approximate and must be calibrated to the local ground-water chemical composition. This is particularly true in the case of divalent ions which make ions appear to be markedly more saline than they are using standard equations based on monovalent ions (Alger, 1966). In addition, the constant K is also controlled by the cation-exchange capacity of clay minerals, so that the constant will often be reduced from its ideal value (Silva and Bassiouni, 1981). The result of this factor is a counter tendency to generate water resistivities that are anomalously high.

The SP log of the Jones well (Figure 38) provides a good example of the conclusions that can be drawn concerning water quality. Notice that the shale baseline shows a distinctive drift with depth. The phenomenon is commonly observed in shallow sections and has been attributed to increases in relative oxidation as the surface is approached, with changes in redox potential that influence the SP measurement (Hallenburg, 1984).

The highest sandstone in the well has a muted deflection on the SP log as compared to the lower sandstones. This contrast is an immediate indication that water in the upper sandstone may be significantly fresher than waters in the lower sandstone. Water resistivity computed from the SP log in the upper sandstone is markedly lower than the resistivity of a produced water sample. In fact, the formation water is fresher than the invading mud filtrate from the borehole, so that the expectation would be a deflection of the curve in the opposite direction. The apparent anomaly is caused by the high activities of the divalent ions in the formation water that make it appear more saline than in equivalent water with monovalent ions.

By contrast, water resistivities estimated in the lower sandstones appear to be systematically higher than water resistivities measured from water samples in equivalent sections in the region. This same character was observed in Texas aquifers by Collier (1993) who attributed the problem partly to the operation of the shales as non-ideal membranes because of significant cation-exchange capacity mechanisms. Clearly, the use of SP logs in a systematic strategy to evaluate water quality must be calibrated to local water samples. A statistical model is probably the most realistic approach to absorb complex factors of shale properties, and variable ionic compositions in waters as they relate to observed SP log deflections.

In an alternative approach, formation water resistivities may be deduced from resistivity logs. In a sandstone/shale sequence, resistivity variation is controlled by a variety of phenomena, including cation-exchange mechanisms by clay minerals within shalier zones, conduction by metallic minerals, and dissolved ions within the pore water of the sandstones. Formation water resistivity may be estimated in shale-free sandstone zones that are logged by resistivity and porosity tools. To a first approximation, the bulk geologic framework can be subdivided into

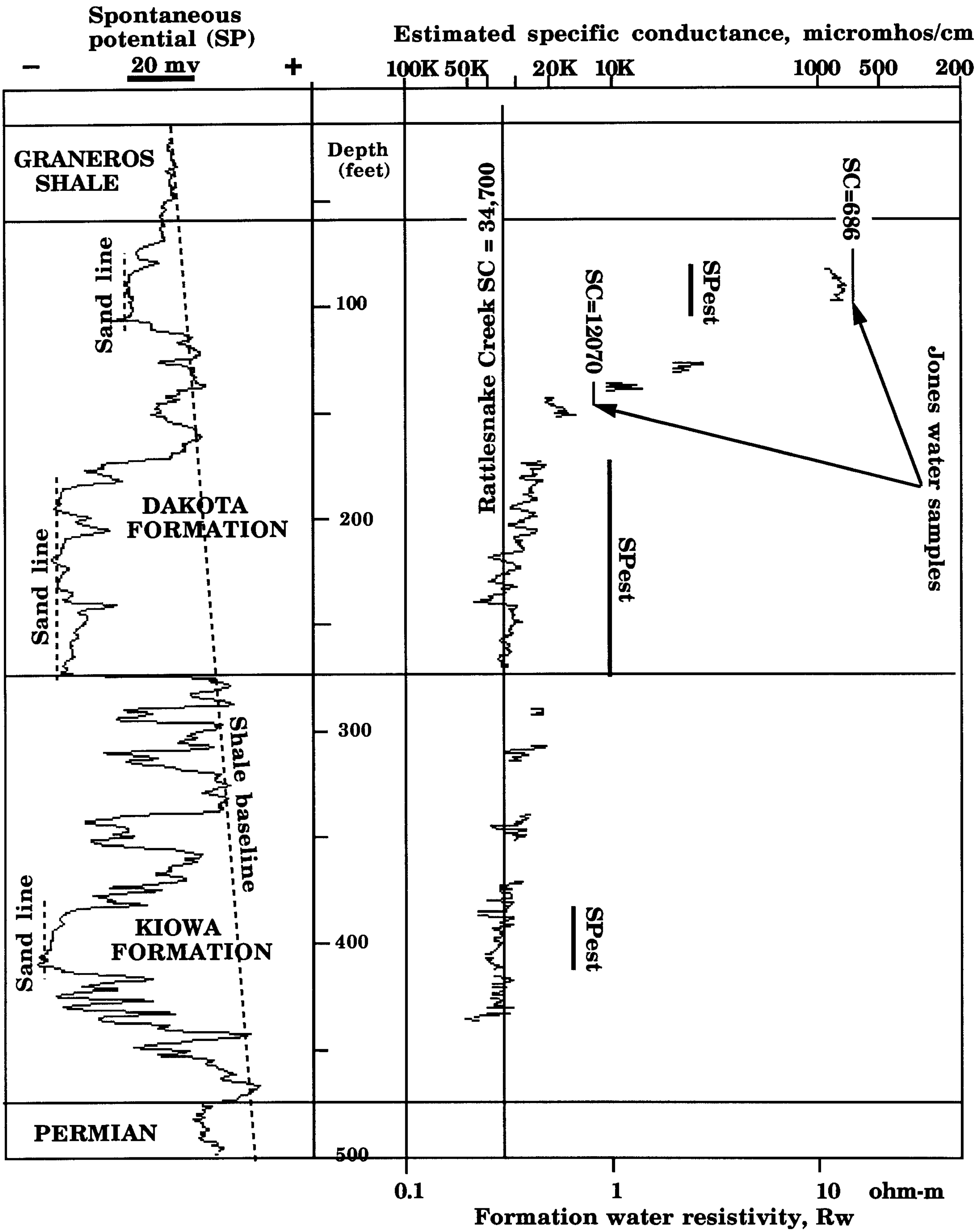

**Figure 38:** Indexed spontaneous potential (SP) and estimated specific conductance logs in KGS Jones #1, NE-NE-NE 2-10S-8W Lincoln Co., Kansas

effective porosity filled with conductive water and the rock framework that is considered to be non-conductive. The water resistivity ($R_W$) is calculated from the resistivity and porosity logs readings by the Archie equation (Archie, 1942). This relationship incorporates a "cementation factor" (m) expressing the tortuousity of the pore network as a modifier to the fractional volume of the pore space ($\Phi$)

$$R_W = R_0 \Phi^m \qquad \text{(Eq.4)}$$

where $R_0$ is the resistivity reading of the zone when it is completely saturated with water whose resistivity is $R_W$. The method is widely used by log analysts in the oil industry and generally gives good estimates of water resistivity in deeper (more saline) formation waters. Results are less reliable in shallower freshwater aquifers because of clay mineral effects and surface conduction on quartz grain surfaces.

Conductivity effects of clay minerals from their cation-exchange capacities are a component of all shaley sandstone resistivities. However, their contribution becomes particularly pronounced when the resistivity of the pore water is high. Archie equation computations of water resistivity will therefore be anomalously low in sandstones with significant clay content. Potential problems can be monitored by using the gamma-ray log to differentiate relatively shale-free sandstone zones for the best estimates of formation-water resistivity.

The Archie equation also does not account for surface conductivity effects at the interface between the quartz grains and the aqueous medium. This surface conductivity component is proportionately a much greater component of the total conductivity in fresher, more resistive pore waters than in deep aquifers with more concentrated saline waters. Its neglect by the Archie equation results in estimates of water resistivity that are too low in shallow, freshwater aquifers. Collier (1993) considers that the difference between real and anomalous resistivities becomes apparent in waters with resistivities greater than 2–3 ohm-meters (specific conductances less than 3,300–5,000 µS/cm). Unfortunately, it is impractical to correct for the surface conductivity effect in a systematic way because it is largely controlled by the internal surface area of the sandstone which will vary with the grain-size distribution.

A water resistivity/specific conductance profile was computed for the Dakota aquifer in the Jones well using the Archie equation with a cementation exponent (m) of 1.6 (appropriate for slightly cemented sandstone). The curve is shown only for zones of sandstone that are relatively low in clay content as indicated by the gamma-ray log. The estimated specific conductance trace is a highly acceptable match with sample measurements and appears to show a transition zone between the fresher water of the upper sandstone and the more saline water of the lower sandstone bodies. The computed value in the uppermost sandstone slightly underestimates the water-sample measurement and is probably fortuitous. However, the estimates of waters in the lower sandstones are reasonable expectations because their higher salinities will mean that the surface conductivity effects are proportionately minimized.

For the northwest Kansas area wells with both SP logs and water sample analyses were used to develop the relationships between the log and water-quality data. Most of these wells comprised observation or monitoring wells installed during the current and prior years of the Dakota Aquifer Program. Other data included observation wells drilled for examination of potential water supplies primarily in Ellis County Some locations of oil and gas boreholes with geophysical logs near to observation wells for which water-quality data exist were also used.

A plot of measured resistivities of Dakota aquifer waters versus calculated equivalent resistivities obtained from the SP curve on the geophysical logs was prepared. The empirical relationship between the measured resistivities and the equivalent water resistivities was then determined. This relationship is being applied to estimate equivalent water resistivities for SP curves available for oil and gas wells in northwestern Kansas.

### Water-Chemistry at the Stanton County Pumping-Test Site

Field analyses and sampling were conducted at the Stanton pumping-test site to determine the water quality of the Dakota aquifer at the well location and variation in the quality that occurs during pumping stress on the aquifer system. The well construction at the site is described in the fiscal year 1992 Annual Report (Whittemore, et al., 1993). Well location and a summary of construction information are listed in Table 7 (site sample numbers 52 and 78).

Field measurements of specific conductance, temperature, and pH were made and water samples taken during the pumping test of the 5-inch, 280 ft deep well conducted September 5-6, 1992, at the Stanton County site. The pumping well is completed in the Cheyenne Sandstone and has a screened interval of 240-280 ft below land surface. The test required pumping during two intervals due to problems with the generators. The initial water pumped was clear during removal of casing water; during the rest of the test the water withdrawn contained sediment. The specific conductance was monitored throughout the test and except for a value of 805 µS/cm 18 minutes after the start of the first pumping, remained within the range 835-850 µS/cm during both pumping intervals, a range within the instrument measurement error of ± 2%. Thus, no changes were observable in the ground-water salinity during pumping.

The water quality in the Cheyenne Sandstone at the site is fresh, with a total-dissolved-solids (TDS) content of 515 mg/L (Table 9). The water is of mixed cation-sulfate, bicarbonate type; sodium is the dominant cation. The sulfate concentration (207 mg/L) was appreciably higher than the chloride concentration (16 mg/L). The high sodium/chloride ratio and an

Table 7. Description and Location of Well Sites and Sample Dates for Cooperative Studies with LLNL and TBEG.

| Site sample number | Site description | Geologic unit | Type or use of well | Legal location | Sample date |
|---|---|---|---|---|---|
| | Southeastern Colorado sites | | | | |
| 57 | Commanche National Grasslands windmill | Dakota | Stock | 32S-49W-08BAAA | 5/20/92 |
| 56 | Town of Pritchett | Dak, Chey | Municipal | 30S-49W-36ADDA | 5/20/92 |
| 55 | Colorado State University Experiment Station | Dakota | Stock | 31S-48W-13ACCD | 5/20/92 |
| 54 | Town of Springfield, well 9 | Dakota | Municipal | 30S-46W-31AAAA | 5/20/92 |
| 53 | Town of Springfield, well 11 | Og, Dk, Cy | Municipal | 31S-46W-04BCCB | 5/19/92 |
| 62 | Town of Vilas | Ki, Cy, Mrsn | Municipal | 31S-45W-02CABC | 5/22/92 |
| 58 | Town of Walsh, well 3 | Cheyenne | Municipal | 30S-43W-32DBCD | 5/21/92 |
| 59 | Town of Walsh, well 2 | Cheyenne | Municipal | 30S-43W-32CCDC | 5/21/92 |
| 61 | Irrigation well, Double J hog farm | Dakota | Irrigation | 25S-44W-16ACAC | 5/21/92 |
| 60 | Rangeland windmill in Prowers County | Dakota | Stock | 25S-42W-11BBBB | 5/21/92 |
| | Kansas sites in general location of northern flow path | | | | |
| 52 | Morrison observation well in Stanton County | Morrison | Monitoring | 29S-43W-21DCDD | 5/19/92 |
| 78 | Cheyenne pumping test well in Stanton County | Cheyenne | Monitoring | 29S-43W-21DCDD | 9/6/92 |
| 46 | Town of Coolidge, south well | Dakota | Municipal | 23S-43W-14CDCA | 11/5/91 |
| 63 | Town of Coolidge, north well | Dakota | Municipal | 23S-43W-14CDCA | 5/22/92 |
| 68 | Terry Boy residence | Dak, Chey | Domestic | 21S-41W-02BBBB | 7/14/92 |
| 47 | Town of Leoti, Dakota well | Dakota | Municipal | 18S-37W-24BACC | 11/6/91 |
| 70 | Town of Leoti, Dakota well | Dakota | Municipal | 18S-37W-24BACC | 7/14/92 |
| 49 | Poky Feeders feedlot | Dakota | Stock | 20S-32W-18DBDC | 11/7/91 |
| 72 | Carlos Roberts stock well | Dakota | Stock | 15S-28W-21BCCC | 7/15/92 |
| 50 | Ranger Feeders feedlot, well 4 | Dakota | Stock | 18S-28W-22DBDC | 11/8/91 |
| 71 | Ranger Feeders feedlot, well 5 | Dakota | Stock | 18S-28W-22DACD | 7/15/92 |
| 73 | William Montgomery residence | Dakota | Domestic | 15S-24W-15CCCB | 7/15/92 |
| 74 | Cedar Bluffs Christian Camp | Dakota | Camp supply | 14S-22W-33AACC | 7/16/92 |
| 75 | Randy Marintzer residence | Dakota | Domestic | 12S-18W-34CDDA | 7/16/92 |
| 76 | Jacob Klein residence | Dakota | Domestic | 11S-11W-13DCBB | 7/16/92 |
| 77 | Melvin Obermuller residence | Dakota | Domestic | 11S-08W-36AAAB | 7/17/92 |
| | Kansas site between north and south flow path | | | | |
| 51 | KPL Sunflower power plant, Dakota well | Dakota | Industrial | 24S-33W-20CCCA | 11/9/91 |
| | Kansas sites, Ogallala wells | | | | |
| 48 | Town of Leoti, Ogallala well | Ogallala | Municipal | 18S-37W-24BACC | 11/6/91 |
| 69 | Town of Leoti, Ogallala well | Ogallala | Municipal | 18S-37W-24BACC | 7/14/92 |
| KS05 | Town of Scott City, well 4 | Ogallala | Municipal | 18S-33W-24ACDD | 11/8/91 |
| KS08 | KPL Sunflower power plant, Ogallala well | Ogallala | Industrial | 24S-33W-31CAC | 11/9/91 |

Letters after section number in legal locations refer to quarters in order of large to small.

Table 8. Well Information for Sample Sites in Cooperative Studies with LLNL and TBEG.

| Site sample number | Site name | Longitude | Land surface elevation, ft | Total well depth, ft bls | Bottom of well elevation, ft | Screened interval, ft | Middle of screened interval, depth, ft bls | Middle of screened interval, elevation, ft |
|---|---|---|---|---|---|---|---|---|
| | | | | Southeastern Colorado sites | | | | |
| 57 | Grasslands | 102.95 | 4951 | 261 | 4690 | | e230 | e4721 |
| 56 | Pritchett | 102.85 | 4775 | e370 | e1343 | | e340 | e4435 |
| 55 | CSU Exp. Station | 102.77 | 4666 | 270 | 4396 | 200-270 | 235 | 4431 |
| 54 | Springfield 9 | 102.62 | 4348 | 134 | 4214 | | e120 | e4228 |
| 53 | Springfield 11 | 102.61 | 4410 | 360 | 4050 | 90-130, 290-360 | 247 | 4163 |
| 62 | Vilas | 102.46 | 4160 | 305 | 3855 | 243.5-305 | 274 | 3886 |
| 58 | Walsh 3 | 102.29 | 3964 | 220 | 3744 | | e200 | e3764 |
| 59 | Walsh 2 | 102.28 | 3956 | 155 | 3801 | | e140 | e3816 |
| 61 | Hog farm | 102.37 | 3885 | 580 | 3305 | | e500 | e3385 |
| 60 | Prowers windmill | 102.16 | 3621 | 537 | 3084 | 236-537 | 387 | 3234 |
| | | | | Kansas sites in general location of northern flow path | | | | |
| 52 | Stanton Morrison | 102.02 | 3568 | 422 | 3146 | 395-415 | 405 | 3163 |
| 78 | Stanton Cheyenne | 102.02 | 3568 | 280 | 3288 | 240-280 | 260 | 3308 |
| 46 | Coolidge south | 102.01 | 3375 | 360 | 3015 | e270-340 | e305 | e3070 |
| 63 | Coolidge north | 102.01 | 3383 | 360 | 3023 | 270-340 | 305 | 3078 |
| 68 | Terry Boy | 101.95 | 3624 | 1025 | 2599 | 900-1000 | 950 | 2674 |
| 47 | Leoti Dakota | 101.36 | 3303 | 1050 | 2253 | 820-860, 930-970, 1010-1050 | 940 | 2363 |
| 70 | Leoti Dakota | 101.36 | 3303 | 1050 | 2253 | 820-860, 930-970, 1010-1050 | 940 | 2363 |
| 49 | Poky Feeders | 100.89 | 2920 | 1000 | 1920 | | e950 | e1970 |
| 72 | Roberts | 100.44 | 2502 | 700 | 1802 | 600-620, 640-700 | 655 | 1847 |
| 50 | Ranger Feeders 4 | 100.40 | 2678 | 942 | 1736 | | e860 | e1818 |
| 71 | Ranger Feeders 5 | 100.40 | 2678 | 925 | 1753 | 775-925 | 850 | 1828 |
| 73 | Montgomery | 99.96 | 2375 | 617 | 1758 | 365-375, 395-415, 520-560, 580-617 | 521 | 1854 |
| 74 | Christian Camp | 99.76 | 2185 | 470 | 1715 | 450-470 | 460 | 1725 |
| 75 | Marintzer | 99.31 | 2110 | 505 | 1605 | 485-505 | 495 | 1615 |
| 76 | Klein | 98.49 | 1660 | 232 | 1428 | 192-232 | 112 | 1548 |
| 77 | Obermuller | 98.15 | 1440 | 80 | 1360 | 60-80 | 70 | 1370 |
| | | | | Kansas site between north and south flow path | | | | |
| 51 | KPL Dakota | 100.97 | 2950 | 699 | 2251 | 479-699 | 589 | 2361 |
| | | | | Kansas sites, Ogallala wells | | | | |
| 48 | Leoti Ogallala | 101.36 | 3303 | 170 | 3133 | 132-142, 153-158 | 143 | 3160 |
| 69 | Leoti Ogallala | 101.36 | 3303 | 170 | 3133 | 132-142, 153-158 | 143 | 3160 |
| KS05 | Scott City 4 | 100.91 | 2964 | 214 | 2750 | | e204 | e2760 |
| KS08 | KPL Ogallala | 100.99 | 2916 | 437 | 2479 | 257-457 | 357 | 2559 |

Depths or elevations preceded by "e" are estimates.

Table 9. Chemical Properties, Major Constituent Concentrations, and Water Types for Cooperative Study Samples.

| Site sample | Site name | Sp.C., field, µS/cm | pH | T.D.S. mg/L | $SiO_2$ mg/L | Ca mg/L | Mg mg/L | Na mg/L | K mg/L | $HCO_3$ mg/L | $SO_4$ mg/L | Cl mg/L | Water type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Southeastern Colorado sites | | | | | | | | | | | | | |
| 57 | Grasslands | 388 | 7.45 | 235 | 21.8 | 57.2 | 10.3 | 6.9 | 2.6 | 198 | 17.0 | 7.7 | Ca-$HCO_3$ |
| 56 | Pritchett | 330 | 7.05 | 193 | 11.6 | 35.0 | 12.6 | 14.7 | 3.0 | 167 | 29.0 | 2.6 | Ca-$HCO_3$ |
| 55 | CSU Exp. Station | 916 | 7.45 | 577 | 8.5 | 48.4 | 30.5 | 104.0 | 10.3 | 269 | 217.0 | 23.6 | Na,Mg,Ca-$SO_4$,$HCO_3$ |
| 54 | Springfield 9 | 759 | 7.30 | 502 | 16.0 | 84.4 | 17.9 | 45.8 | 3.7 | 170 | 214.0 | 20.4 | Ca-$SO_4$ |
| 53 | Springfield 11 | 594 | 7.65 | 377 | 19.3 | 80.5 | 16.1 | 13.9 | 3.3 | 136 | 136.0 | 25.0 | Ca-$SO_4$,$HCO_3$ |
| 62 | Vilas | 484 | 7.60 | 290 | 10.9 | 37.3 | 18.4 | 41.1 | 4.3 | 234 | 55.3 | 5.4 | Ca,Na,Mg-$HCO_3$ |
| 58 | Walsh 3 | 1230 | 7.60 | 824 | 16.2 | 88.3 | 56.3 | 105.0 | 3.3 | 247 | 358.0 | 49.1 | Mg,Na,Ca-$SO_4$ |
| 59 | Walsh 2 | 824 | 7.60 | 536 | 17.8 | 62.7 | 36.3 | 66.7 | 3.7 | 240 | 198.0 | 22.2 | Ca,Mg,Na-$SO_4$,$HCO_3$ |
| 61 | Hog farm | 620 | 7.10 | 377 | 13.6 | 62.5 | 21.7 | 33.6 | 3.8 | 224 | 121.0 | 9.2 | Ca-$HCO_3$ |
| 60 | Prowers windmill | 522 | 7.40 | 329 | 15.3 | 58.8 | 16.7 | 23.8 | 4.0 | 184 | 100.0 | 7.5 | Ca-$HCO_3$ |
| Kansas sites in general location of northern flow path | | | | | | | | | | | | | |
| 52 | Stanton Morrison | 786 | 8.15 | 501 | 15.0 | 43.8 | 26.8 | 83.1 | 8.7 | 236 | 184.0 | 20.3 | Na,Mg,Ca-$HCO_3$,$SO_4$ |
| 78 | Stanton Cheyenne | 840 | 7.55 | 515 | 11.1 | 47.7 | 32.5 | 76.3 | 6.6 | 234 | 207 | 15.9 | Na,Mg,Ca-$SO_4$,$HCO_3$ |
| 46 | Coolidge south | 673 | 7.01 | 422 | 10.0 | 62.8 | 21.3 | 44.7 | 5.7 | 196 | 167.0 | 11.7 | Ca,Na,Mg-$SO_4$,$HCO_3$ |
| 63 | Coolidge north | 670 | 7.25 | 422 | 10.4 | 64.3 | 21.6 | 45.7 | 6.3 | 197 | 163.0 | 11.9 | Ca,Na,Mg-$SO_4$,$HCO_3$ |
| 68 | Terry Boy | 753 | 8.40 | 466 | 11.4 | 2.9 | 1.5 | 172.0 | 3.5 | 280 | 118.0 | 16.6 | Na-$HCO_3$ |
| 47 | Leoti Dakota | 1650 | 8.45 | 1033 | 10.2 | 5.5 | 2.0 | 369.0 | 4.6 | 345 | 407.0 | 61.6 | Na-$SO_4$ |
| 70 | Leoti Dakota | 1675 | 8.50 | 1049 | 11.6 | 5.4 | 2.5 | 367.0 | 4.8 | 345 | 421.0 | 63.6 | Na-$SO_4$ |
| 49 | Poky Feeders | 1503 | 7.32 | 985 | 61.9 | 84.8 | 60.6 | 149.0 | 8.5 | 371 | 289.0 | 124.0 | Na,Mg,Ca-$HCO_3$,$SO_4$ |
| 72 | Roberts | 1590 | 8.20 | 937 | 11.0 | 3.9 | 2.0 | 344.0 | 4.3 | 384 | 211.0 | 168.0 | Na-$HCO_3$,Cl,$SO_4$ |
| 50 | Ranger Feeders 4 | 1870 | 7.86 | 1025 | 11.7 | 6.3 | 2.7 | 376.0 | 6.7 | 268 | 113.0 | 374.0 | Na-Cl |
| 71 | Ranger Feeders 5 | 1800 | 7.65 | 996 | 14.2 | 18.2 | 8.2 | 351.0 | 7.0 | 340 | 126.0 | 300.0 | Na-Cl |
| 73 | Montgomery | 1950 | 7.85 | 1053 | 10.8 | 7.2 | 3.4 | 382.0 | 4.0 | 356 | 188.0 | 278.0 | Na-Cl,$HCO_3$ |
| 74 | Christian Camp | 2280 | 8.25 | 1288 | 10.3 | 5.3 | 3.0 | 480.0 | 5.8 | 442 | 196.0 | 365.0 | Na-Cl,$HCO_3$ |
| 75 | Marintzer | 5640 | 7.90 | 3233 | 11.5 | 15.5 | 20.5 | 1160.0 | 11.1 | 387 | 457.0 | 1363.0 | Na-Cl |
| 76 | Klein | 1450 | 8.05 | 892 | 8.8 | 21.0 | 4.3 | 324.0 | 3.4 | 547 | 159.0 | 100.0 | Na-$HCO_3$ |
| 77 | Obermuller | 1150 | 7.05 | 753 | 22.6 | 173.0 | 12.3 | 62.3 | 5.9 | 379 | 128.0 | 58.5 | Ca-$HCO_3$ |
| Kansas site between north and south flow path | | | | | | | | | | | | | |
| 51 | KPL Dakota | 458 | 7.45 | 279 | 13.8 | 40.6 | 12.0 | 37.4 | 3.5 | 183 | 74.0 | 5.6 | Na,Ca-$HCO_3$ |
| Kansas sites, Ogallala wells | | | | | | | | | | | | | |
| 48 | Leoti Ogallala | 550 | 7.52 | 353 | 53.0 | 53.5 | 22.7 | 19.8 | 4.5 | 195 | 46.0 | 38.7 | Ca-$HCO_3$ |
| 69 | Leoti Ogallala | 550 | 7.65 | 348 | 54.6 | 53.1 | 22.6 | 19.2 | 4.6 | 216 | 40.1 | 30.8 | Ca-$HCO_3$ |
| KS05 | Scott City 4 | | 7.85 | 371 | 58.2 | 51.0 | 22.6 | 30.0 | 6.3 | 209 | 54.1 | 27.9 | Ca,Mg-$HCO_3$ |
| KS08 | KPL Ogallala | | 7.78 | 254 | 20.0 | 50.0 | 9.8 | 21.2 | 3.0 | 175 | 48.9 | 6.5 | Ca-$HCO_3$ |

Data for the last two samples are from Dutton (1994).

equivalent concentration of magnesium exceeding that of calcium indicate that softening by cation exchange has affected the water chemistry.

The observation well completed in the Jurassic Morrison Formation underlying the Cheyenne Sandstone was sampled on June 5, 1992, prior to the pumping test. The screened interval of the well is 395-415 ft deep. The water collected from the well is slightly fresher (specific conductance 790 mg/L and TDS 501) than the ground water pumped from the overlying Cheyenne Sandstone (Table 9). The Morrison water is of sodium-bicarbonate, sulfate type; the equivalent concentrations of calcium and magnesium are approximately equal and the same is true for bicarbonate and sulfate contents. The water has been affected somewhat more by cation exchange softening than the water in the Cheyenne Sandstone as indicated by higher sodium and lower calcium and magnesium concentrations in the Morrison. The chloride concentration in the Morrison water is slightly higher (20 mg/L) and the sulfate content lower (184 mg/L) than that from the Cheyenne Sandstone. Therefore, the source of sulfate in the overlying Cheyenne water does not appear to be primarily from flow or diffusion of Morrison from below but could represent oxidation of pyrite within the Cheyenne sediments.

Nitrogen species were detectable in the Morrison water (nitrate-nitrogen concentration 0.2 mg/L, ammonium-nitrogen 0.08) and not detectable in the Cheyenne water (<0.02 and <0.08 mg/L, respectively, Table 10). Boron concentration is also higher in the Morrison than in the Cheyenne but fluoride is lower in the Morrison even though calcium is also somewhat lower than in the Cheyenne. Calcium and fluoride concentration are usually inversely related due to control of dissolved fluoride from dissolution of apatites (hydroxy calcium phosphates in which fluoride ion can substitute for the hydroxyl ion). The bromide/chloride and iodide/chloride mass ratios for the Cheyenne and Morrison waters are consistent with values for the mixing of low chloride recharge and additional chloride from halite (rock salt) dissolution from the underlying Permian strata. None of the heavy metal concentrations in either the Morrison or Cheyenne formations were unusually high (Table 11). Overall, the chemistries of waters from the two different formations are relatively similar and consistent with hydraulic connection between the units. However, the chemical differences suggest that the formations maintain some degree of hydrologic separation.

### Geochemical Characterization of Recharge and Aquifer Interactions Along the Flow Path from Southeastern Colorado to Central Kansas

Ground-water chemistry of the Dakota aquifer was examined relative to ground waters in underlying and overlying aquifers and the hydrogeology of the aquifer system in order to characterize recharge to the Dakota aquifer and interactions among the different aquifers. Two cooperative studies were conducted, one with the Texas Bureau of Economic Geology (TBEG),

Table 10. Minor Constituent Concentrations in Cooperative Study Samples.

| Site sample | Site name | F mg/L | NO$_3$-N mg/L | NH$_4$-N mg/L | PO$_4$-P mg/L | KGS Sr mg/L | LLNL Sr mg/L | LLNL Rb mg/L | KGS Ba mg/L | LLNL Ba mg/L | B mg/L | Br mg/L | I mg/L |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Southeastern Colorado sites | | | | | | | | | | | | | |
| 57 | Grasslands | 0.75 | 2.96 | <0.08 | 0.003 | 0.62 | 0.58 | 0.0012 | 0.180 | 0.231 | 0.048 | 0.079 | 0.0146 |
| 56 | Pritchett | 1.28 | <0.02 | <0.08 | 0.007 | 0.69 | 0.64 | 0.0047 | 0.019 | 0.024 | 0.119 | 0.043 | 0.0223 |
| 55 | CSU Exp. Station | 1.56 | <0.02 | 0.23 | 0.007 | 1.12 | 1.04 | 0.0188 | 0.014 | 0.018 | 0.317 | 0.400 | 0.0508 |
| 54 | Springfield 9 | 0.69 | 3.25 | <0.08 | 0.007 | 0.91 | 0.86 | 0.0039 | 0.037 | 0.049 | 0.162 | 0.199 | 0.0201 |
| 53 | Springfield 11 | 0.42 | 3.25 | <0.08 | 0.003 | 1.06 | 1.01 | 0.0018 | 0.042 | 0.056 | 0.064 | 0.320 | 0.0173 |
| 62 | Vilas | 1.64 | <0.02 | <0.08 | <0.003 | 0.79 | 0.71 | 0.0059 | | 0.042 | 0.200 | 0.070 | 0.0122 |
| 58 | Walsh 3 | 1.53 | 4.99 | <0.08 | 0.003 | 2.38 | 2.18 | 0.0047 | 0.053 | 0.070 | 0.446 | 0.390 | 0.0884 |
| 59 | Walsh 2 | 1.72 | 1.58 | <0.08 | 0.007 | 1.77 | 1.58 | 0.0040 | 0.038 | 0.052 | 0.335 | 0.137 | 0.0490 |
| 61 | Hog farm | 0.77 | <0.02 | <0.08 | <0.003 | 0.96 | 0.90 | 0.0033 | 0.024 | 0.031 | 0.108 | 0.154 | 0.0172 |
| 60 | Prowers windmill | 0.61 | 2.48 | <0.08 | 0.003 | 1.02 | 0.96 | 0.0029 | 0.019 | 0.026 | 0.103 | 0.085 | 0.0143 |
| Kansas sites in general location of northern flow path | | | | | | | | | | | | | |
| 52 | Stanton Morrison | 1.36 | 0.20 | 0.08 | 0.010 | 1.08 | 1.03 | 0.0092 | 0.031 | 0.038 | 1.420 | 0.191 | 0.0310 |
| 78 | Stanton Cheyenne | 1.89 | <0.02 | <0.08 | <0.010 | 1.29 | | | 0.018 | | 0.301 | 0.200 | 0.0336 |
| 46 | Coolidge south | 0.81 | <0.02 | <0.08 | <0.010 | 1.35 | | | 0.018 | | 0.094 | 0.165 | 0.0237 |
| 63 | Coolidge north | 0.84 | <0.02 | <0.08 | <0.003 | 1.39 | 1.32 | 0.0061 | | 0.025 | 0.167 | 0.158 | 0.0224 |
| 68 | Terry Boy | 2.11 | <0.02 | 0.47 | 0.013 | 0.06 | 0.06 | 0.0037 | 0.012 | 0.017 | 0.296 | 0.131 | 0.0297 |
| 47 | Leoti Dakota | 3.37 | <0.02 | 1.01 | 0.060 | 0.14 | | | 0.014 | | 0.900 | 0.496 | 0.0864 |
| 70 | Leoti Dakota | 3.10 | <0.02 | 1.09 | 0.029 | 0.14 | 0.13 | 0.0051 | 0.015 | 0.020 | 0.751 | 0.460 | 0.0870 |
| 49 | Poky Feeders | 2.64 | 4.29 | <0.08 | 0.010 | 3.27 | | | 0.022 | | 0.500 | 0.587 | 0.1070 |
| 72 | Roberts | 3.99 | <0.02 | 0.70 | 0.029 | 0.08 | 0.07 | 0.0032 | 0.018 | 0.025 | 0.630 | 0.360 | 0.0660 |
| 50 | Ranger Feeders 4 | 2.85 | <0.02 | 0.47 | 0.040 | 0.09 | | | 0.007 | | 0.410 | 0.213 | 0.0396 |
| 71 | Ranger Feeders 5 | 3.47 | <0.02 | 0.54 | 0.020 | 0.29 | 0.27 | 0.0066 | 0.022 | 0.029 | 0.469 | 0.300 | 0.0828 |
| 73 | Montgomery | 4.08 | <0.02 | 1.01 | 0.023 | 0.17 | 0.23 | 0.0049 | 0.015 | 0.024 | 0.654 | 0.300 | 0.0552 |
| 74 | Christian Camp | 5.16 | <0.02 | 1.17 | 0.026 | 0.10 | 0.10 | 0.0046 | 0.019 | 0.027 | 0.938 | 0.330 | 0.0606 |
| 75 | Marintzer | 3.35 | <0.02 | 1.79 | 0.033 | 0.46 | 0.46 | 0.0083 | 0.021 | 0.030 | 0.830 | 0.550 | 0.0650 |
| 76 | Klein | 2.16 | <0.02 | 0.31 | 0.039 | 0.33 | 0.30 | 0.0024 | 0.007 | 0.009 | 0.740 | 0.100 | 0.0090 |
| 77 | Obermuller | 0.29 | 23.27 | <0.08 | 0.062 | 0.63 | 0.58 | 0.0021 | 0.337 | 0.407 | 0.082 | 0.137 | 0.0036 |
| Kansas site between north and south flow path | | | | | | | | | | | | | |
| 51 | KPL Dakota | 1.09 | 0.11 | <0.08 | <0.010 | 0.63 | | | 0.035 | | 0.106 | 0.061 | 0.0198 |
| Kansas sites, Ogallala wells | | | | | | | | | | | | | |
| 48 | Leoti Ogallala | 1.47 | 3.70 | <0.08 | 0.010 | 1.21 | | | 0.110 | | 0.100 | 0.263 | 0.0492 |
| 69 | Leoti Ogallala | 1.47 | 3.12 | <0.08 | 0.010 | 1.21 | 1.14 | 0.0020 | 0.115 | 0.145 | 0.086 | 0.183 | 0.0366 |
| KS05 | Scott City 4 | 2.10 | 3.34 | | | 1.03 | | | 0.080 | | 0.150 | | |
| KS08 | KPL Ogallala | 0.56 | 1.72 | | | 0.62 | | | 0.050 | | -0.040 | | |

KGS and LLNL refer to the laboratory in which the samples were analyzed. Data for the last two samples are from Dutton (1994).

Table 11. Trace Metal and Semimetal Concentrations in Cooperative Study Samples.

| Sample site | Site name | KGS Fe µg/L | KGS Mn µg/L | LLNL Mn µg/L | KGS Al µg/L | KGS Cr µg/L | LLNL Cr µg/L | KGS Ni µg/L | LLNL Ni µg/L | KGS Cu µg/L | LLNL Cu µg/L | KGS Zn µg/L | LLNL Zn µg/L | KGS Cd µg/L | LLNL Cd µg/L |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Southeastern Colorado sites | | | | | | | | | | | | | | |
| 57 | Grasslands | 57 | 2 | 2.1 | 19 | 0.9 | 0.04 | <0.1 | 0.2 | 7.5 | 4.3 | 130 | 197 | 1.8 | 0.36 |
| 56 | Pritchett | 824 | 17 | 18 | 18 | 1.0 | | 0.1 | | <0.1 | | 28 | 9 | <0.1 | |
| 55 | CSU Exp. Station | 768 | 43 | 44 | 26 | 1.8 | 0.02 | 0.9 | 0.4 | <0.1 | 2.8 | 793 | | 0.2 | 0.05 |
| 54 | Springfield 9 | 29 | <2 | 1.0 | 33 | 1.6 | | 0.3 | | 0.1 | | 4 | | <0.1 | |
| 53 | Springfield 11 | <10 | <2 | 0.1 | 43 | 1.6 | | 1.0 | | 0.4 | | 36 | 58 | <0.1 | |
| 62 | Vilas | | | 34 | | | 0.04 | | 0.9 | | 1.4 | | 19 | | 0.03 |
| 58 | Walsh 3 | <10 | <2 | <0.2 | 32 | 2.5 | 0.11 | 0.2 | 0.3 | <0.1 | 5.2 | <2 | 20 | <0.1 | 0.01 |
| 59 | Walsh 2 | <10 | <2 | 0.2 | 16 | 1.5 | 0.29 | 0.3 | 0.9 | 0.4 | 1.1 | <2 | 12 | 2.2 | 0.03 |
| 61 | Hog farm | 1660 | 81 | 85 | 10 | 1.0 | 0.05 | 0.7 | 0.3 | 0.4 | 2.5 | 100 | 291 | 1 | 0.03 |
| 60 | Prowers windmill | 15 | 6 | 6.2 | 6 | 1.2 | 0.05 | 0.2 | 0.2 | <0.1 | 0.5 | <2 | 8 | <0.1 | 0.02 |
| | Kansas sites in general location of northern flow path | | | | | | | | | | | | | | |
| 52 | Stanton Morrison | <10 | 19 | 17 | 45 | 2.0 | 0.04 | 9.1 | 2.4 | 1.1 | 2.5 | 25 | 70 | 0.5 | 0.04 |
| 78 | Stanton Cheyenne | 44 | 54 | | 35 | 1.0 | | 2.4 | | 0.5 | | 64 | | 0.4 | |
| 46 | Coolidge south | 797 | 70 | | 3 | 0.3 | | | | 0.5 | | 31 | | <0.1 | |
| 63 | Coolidge north | | | 71 | | | 0.04 | | 0.7 | | 1.2 | | 40 | | 0.04 |
| 68 | Terry Boy | 108 | 7 | 7.4 | 45 | <0.1 | 0.07 | 2.0 | 0.3 | 0.2 | 0.3 | 2 | 19 | <0.1 | <0.1 |
| 47 | Leoti Dakota | <20 | 15 | | 3 | 0.2 | | | | 0.5 | | <4 | | 0.1 | |
| 70 | Leoti Dakota | 105 | 12 | 13 | 2 | 0.2 | 0.01 | 1.1 | 0.3 | 0.5 | 5.2 | <2 | 20 | 0.2 | 0.01 |
| 49 | Poky Feeders | <20 | 44 | | 6 | 0.1 | | | | 0.9 | | 115 | | 0.1 | |
| 72 | Roberts | 37 | 4 | 5.4 | 1 | 0.1 | <0.01 | 0.2 | 0.3 | 0.6 | 2.5 | 2 | 14 | <0.1 | 0.07 |
| 50 | Ranger Feeders 4 | 330 | 4 | | 7 | 0.1 | | | | 0.3 | | <4 | | <0.1 | |
| 71 | Ranger Feeders 5 | 675 | 36 | 37 | 4 | 0.2 | <0.01 | 1.8 | 0.9 | 0.8 | 2.9 | 7 | 29 | <0.1 | <.01 |
| 73 | Montgomery | 48 | 3 | 4.2 | 3 | 0.3 | <0.01 | 0.2 | 0.2 | 0.2 | 1.0 | 112 | | <0.1 | 0.08 |
| 74 | Christian Camp | 28 | 4 | 4.6 | 2 | 2 | <0.01 | 0.2 | 0.4 | 0.1 | 1.1 | <2 | 12 | <0.1 | 0.06 |
| 75 | Marintzer | 166 | 12 | 14 | 3 | 0.2 | 0.01 | 1.1 | 0.3 | 3.9 | 2.5 | 12 | 24 | <0.1 | 0.06 |
| 76 | Klein | <10 | 10 | 11 | 1 | 0.2 | 0.04 | 1.6 | 1.6 | 2.2 | 4.0 | 22 | 39 | <0.1 | 0.05 |
| 77 | Obermuller | 12 | <2 | 0.3 | 10 | 0.6 | 0.09 | 0.1 | 0.9 | 6.7 | 3.8 | 46 | 60 | <0.1 | 0.03 |
| | Kansas site between north and south flow path | | | | | | | | | | | | | | |
| 51 | KPL Dakota | 123 | 43 | | 8 | 0.2 | | | | 0.3 | | 7 | | 0.1 | |
| | Kansas sites, Ogallala wells | | | | | | | | | | | | | | |
| 48 | Leoti Ogallala | <20 | <4 | | 6 | 0.5 | | | | 0.8 | | 11 | | <0.1 | |
| 69 | Leoti Ogallala | <10 | <2 | <0.2 | 5 | 0.4 | 0.05 | 0.7 | 0.4 | 0.7 | 0.8 | 6 | 37 | 2 | 0.04 |

KGS and LLNL refer to the laboratory in which the samples were analyzed.

Table 11. Trace Metal and Semimetal Concentrations in Cooperative Study Samples (continued).

| Sample site | Site name | KGS Be µg/L | KGS As µg/L | LLNL As µg/L | KGS Se µg/L | LLNL Se µg/L | KGS Sb µg/L | KGS Ag µg/L | KGS Hg µg/L | LLNL Hg µg/L | KGS Tl µg/L | KGS Pb µg/L | LLNL Pb µg/L |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Southeastern Colorado sites | | | | | | | | | | | | |
| 57 | Grasslands | 0.22 | 0.3 | 0.2 | 5.8 | <.1 | 1.2 | <0.1 | <0.1 | <0.01 | <1 | 18 | 0.13 |
| 56 | Pritchett | 0.25 | <0.1 | <0.1 | 4.3 | <.1 | 1.9 | <0.1 | <0.1 | | <1 | 50 | |
| 55 | CSU Exp. Station | 0.20 | <0.1 | 0.4 | 5.3 | <.1 | 0.6 | <0.1 | 0.1 | 0.16 | <1 | 3.2 | 1.2 |
| 54 | Springfield 9 | 0.08 | <0.1 | 0.3 | 4.9 | 0.1 | 1.7 | <0.1 | <0.1 | | <1 | 4 | |
| 53 | Springfield 11 | 0.08 | 0.1 | 0.9 | 2.2 | 0.5 | 3.7 | <0.1 | <0.1 | | <1 | 0.5 | |
| 62 | Vilas | | | 0.7 | | <.1 | | | | 0.07 | | | 0.12 |
| 58 | Walsh 3 | 0.19 | <0.1 | 0.8 | 7.4 | 0.9 | 2.8 | <0.1 | <0.1 | <0.01 | 3 | <0.1 | 0.02 |
| 59 | Walsh 2 | 0.18 | 1.2 | 0.9 | 9.3 | 0.3 | 1.5 | 0.2 | <0.1 | <0.01 | 1 | 6.7 | 0.37 |
| 61 | Hog farm | 0.16 | 1.2 | 0.2 | 9.4 | <.1 | 3.3 | 0.2 | <0.1 | <0.01 | <1 | <0.1 | 0.16 |
| 60 | Prowers windmill | 0.19 | 1.1 | 0.1 | 9.2 | <.1 | 2.3 | <0.1 | <0.1 | 0.11 | 1 | 17.6 | 0.29 |
| | Kansas sites in general location of northern flow path | | | | | | | | | | | | |
| 52 | Stanton Morrison | 0.31 | 3.0 | 3.6 | 5.6 | 0.5 | 5.4 | <0.1 | <0.1 | <0.01 | 5 | 4.7 | 0.25 |
| 78 | Stanton Cheyenne | | 4.8 | | 0.4 | | | 0.5 | <0.1 | | | 8.0 | |
| 46 | Coolidge south | | 0.8 | | 1.7 | | | <0.1 | <0.1 | | | <0.1 | |
| 63 | Coolidge north | | | 0.2 | | <.1 | | | | <0.01 | | | <0.01 |
| 68 | Terry Boy | 0.01 | 0.5 | 1.2 | <0.1 | 0.3 | 1.3 | 0.4 | <0.1 | 0.02 | <1 | 11.2 | 0.51 |
| 47 | Leoti Dakota | | 1.2 | | 0.8 | | | <0.1 | 0.7 | | | <0.1 | |
| 70 | Leoti Dakota | 0.14 | 1.1 | 0.8 | 1.1 | 0.1 | 7.5 | 0.2 | 0.6 | <0.01 | <1 | 8.6 | 0.04 |
| 49 | Poky Feeders | | 5.4 | | 12 | | | <0.1 | 0.8 | | | 2.4 | |
| 72 | Roberts | 0.10 | 0.9 | 1.1 | <0.1 | 0.4 | 6.4 | <0.1 | 0.9 | 0.05 | <1 | 10.6 | 0.66 |
| 50 | Ranger Feeders 4 | | 1.2 | | 0.3 | | | 0.2 | 0.6 | | | <0.1 | |
| 71 | Ranger Feeders 5 | 0.23 | 1.1 | 3.2 | <0.1 | 1.3 | 4.3 | <0.1 | 0.9 | <0.01 | 1 | 9 | 2.0 |
| 73 | Montgomery | 0.10 | 1.1 | 3.4 | 0.1 | 1.6 | 3.2 | <0.1 | 0.9 | 0.04 | <1 | 15.2 | 0.68 |
| 74 | Christian Camp | 0.11 | 1.3 | 2.5 | <0.1 | 1.2 | 3.5 | <0.1 | 0.9 | 0.19 | 2 | 4.6 | 1.0 |
| 75 | Marintzer | <0.01 | <0.1 | 13.2 | 0.3 | 7.5 | 5.5 | <0.1 | 0.7 | 0.16 | 2 | 9.8 | 1.9 |
| 76 | Klein | 0.10 | 0.1 | 1.3 | <0.1 | 0.3 | 3.9 | <0.1 | 0.7 | <0.01 | <1 | 11.4 | 1.1 |
| 77 | Obermuller | <0.01 | 0.5 | 0.8 | 1.3 | 0.2 | 4.3 | <0.1 | 0.8 | 0.06 | <1 | 7.6 | 0.34 |
| | Kansas site between north and south flow path | | | | | | | | | | | | |
| 51 | KPL Dakota | | <0.1 | | 1.3 | | | <0.1 | 0.8 | | | 0.2 | |
| | Kansas sites, Ogallala wells | | | | | | | | | | | | |
| 48 | Leoti Ogallala | | 3.6 | | 3.7 | | | <0.1 | 0.8 | | | 0.8 | |
| 69 | Leoti Ogallala | 0.08 | 8.6 | 4.6 | 1.1 | 0.5 | 3.3 | 0.2 | 0.6 | <0.01 | <1 | 6.6 | 0.19 |

KGS and LLNL refer to the laboratory in which the samples were analyzed.

and one with the Lawrence Livermore National Laboratory (LLNL) as indicated in the fiscal year 1992 Dakota Aquifer Program report (Whittemore, et al., 1993).

The research of Alan Dutton of the Texas Bureau of Economic Geology focused on the sources and ages of ground water in unconfined and confined aquifers beneath the Great Plains. Dutton and the KGS collected ground waters from the Dakota and Ogallala aquifers in southwest Kansas for determination of dissolved major, minor, and trace inorganic and radiochemical constituents, and stable and radioactive isotopes. The isotopes included carbon-13 and -14, chlorine 36, and the stable isotopes oxygen and deuterium for estimating the climatic characteristics and the age of the recharge. Analyses for this study were completed in fiscal year 1993.

The KGS and Lawrence Livermore National Laboratories conducted a cooperative study of waters in the Dakota aquifer along a traverse from the recharge area in southeastern Colorado to the discharge area in central Kansas. The purpose of this work was to use several isotopic and dissolved trace gas and inorganic constituent distributions in the Dakota aquifer to improve methods for characterizing ground-water masses and flow paths through aquifer systems. The KGS and LLNL sampled 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 in the eastern outcrop band. The location, geology, and hydrology of the flow path are discussed and illustrated in the regional flow section, p. 40–108 of the fiscal year 1992 Dakota Program Annual Report (Whittemore, et al., 1993). The section is referred to as the northern flow path in the fiscal year 1992 report and in this report.

The first KGS-LLNL joint sampling was conducted at the end of fiscal year 1992 in southeastern Colorado and southwestern Kansas. The second sample set was collected at the beginning of fiscal year 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 one of the Dakota and one of the Ogallala wells sampled are to the south in Finney County near the southern flow path or cross section illustrated in Figure 38 (p. 65) in the fiscal year 1991 Dakota Aquifer Program Annual Report (Macfarlane et al., 1992). These two wells are located near the boundary where the Dakota aquifer subcropping under the Ogallala aquifer becomes confined by the Upper Cretaceous aquitard. Results from both the Texas and LLNL cooperative studies are discussed together in this fiscal year 1993 Annual Report.

### *Procedure*

Field chemical measurements of pH, temperature, and specific conductance were made during and at the time of water sample collection from municipal, stock, industrial, and monitor wells. Samples for dissolved constituent determinations were filtered through 0.45 μm membrane cartridge filters. Waters collected in different glass and polyethylene containers were acidified with hydrochloric or nitric acid as appropriate for preserving the particular constituents. Samples were analyzed for major, minor, and trace inorganic constituents at the laboratories of KGS, TBEG, and LLNL. The KGS sent selected samples to U.S. Geological Survey (USGS) laboratories for determination of deuterium, tritium, oxygen-18, gross alpha and gross beta radioactivity, and radium-226, radium-228, radon, and uranium concentrations. The TBEG analyzed samples for inorganic constituents and carbon isotopes and sent samples for analysis of deuterium, tritium, oxygen-18, and chlorine-36 isotopes (Dutton, 1994). The LLNL measured inorganic constituent concentrations (including heavy metals), deuterium, tritium, oxygen-18, chlorine-36, and strontium isotopic contents and/or ratios, and noble gas concentrations in water samples at their facilities.

### *Distribution of major constituents along the flow path cross section*

Location, geologic unit, and well-construction information for the sites in the cross-section sampling are given in Tables 7 and 8. Chemical results for the samples collected and analyzed by the KGS for major constituents are listed in Table 9. Additional minor constituent concentrations for samples collected and analyzed by KGS and LLNL are in Table 10. Trace metal data for samples collected and analyzed by the KGS and the LLNL are in Table 11. Radiochemical data for the samples collected by the KGS and submitted to the USGS regional laboratory for analysis are in Table 12. Stable isotope results for samples collected and analyzed by the TBEG and the LLNL and collected by the KGS and submitted to the USGS regional laboratory for analysis are in Table 13. Additional radiochemical and isotopic data of the TBEG and LLNL are in reports of these agencies. The tables include data for the waters sampled from the Ogallala Formation during the cooperative studies as well as for the samples collected during the Stanton County pumping-test.

Figure 39 is a cross section depicting the elevations of the land surface and the middle of the screened interval of the wells sampled. The general change in land surface slope is apparent near the boundary between Colorado and Kansas. The flow in the Colorado subregion of the cross section has been characterized as a local flow system in the fiscal year 1992 Annual Report (Whittemore, et al., 1993). The section in Kansas is confined until the farthest eastern well, although the confining strata is thin enough at the next to most eastern well that vertical recharge through the confining unit is sufficient to significantly change the water chemistry. The most eastern well is in the local recharge and discharge flow system of the outcropping Dakota aquifer. The cross section graphically illustrates that the wells in the Dakota aquifer are generally shallower in the western and eastern local flow areas and deeper in the confined

Table 12. Uranium and Radiochemical Constituent Concentrations in Cooperative Study Samples.

| Site sample | Site name | LLNL Tritium TU | USGS Tritium TU | Dutton Tritium TU | U μg/L | Gross alpha, μg/L as U-natural | Gross alpha minus U pCi/L | Gross beta, pCi/L as Sr/Yt-90 | Ra-226 pCi/L | Ra-228 pCi/L |
|---|---|---|---|---|---|---|---|---|---|---|
| | Southeastern Colorado sites | | | | | | | | | |
| 57 | Grasslands | 0.9 | | | 6.53 | 11.0 | 3.1 | 5.9 | 0.08 | <1.0 |
| 56 | Pritchett | 0.1 | | | | 13.0 | <9.1 | 6.1 | 2.20 | 4.1 |
| 55 | CSU Exp. Station | 0.7 | | | 0.06 | 12.0 | 8.4 | 15.0 | 1.80 | 2.5 |
| 54 | Springfield 9 | 5.8 | | | | 14.0 | <9.8 | 9.8 | 0.12 | <1.0 |
| 53 | Springfield 11 | 5.0 | | | | 14.0 | <9.8 | 13.0 | 0.34 | 1.2 |
| 62 | Vilas | 12.8 | | | 1.95 | | | | | |
| 58 | Walsh 3 | 1.1 | | | 23.20 | 43.0 | 13.9 | 21.0 | 1.80 | 3.2 |
| 59 | Walsh 2 | 4.0 | | | 15.50 | 23.0 | 5.3 | 14.0 | 0.56 | 2.0 |
| 61 | Hog farm | 0.1 | | | 0.59 | 84.0 | 58.4 | 24.0 | 31.00 | 2.4 |
| 60 | Prowers windmill | 0.4 | | | 4.14 | 10.0 | 4.1 | 7.7 | 1.40 | <1.0 |
| | Kansas sites in general location of northern flow path | | | | | | | | | |
| 52 | Stanton Morrison | 2.0 | | | 6.58 | 6.9 | 0.2 | 6.9 | 0.03 | <1.0 |
| 78 | Stanton Cheyenne | | 0 | | 0.53 | 5.1 | 3.2 | 8.2 | 0.45 | <1.0 |
| 46 | Coolidge south | | | 0.0 | | | | | | |
| 63 | Coolidge north | 0.0 | | | 1.33 | | | | | |
| 68 | Terry Boy | 1.4 | | | 0.00 | 3.0 | 2.1 | 4.3 | 0.37 | <1.0 |
| 47 | Leoti Dakota | | | 0.0 | | | | | | |
| 70 | Leoti Dakota | 0.6 | | | 0.03 | <0.6 | <0.4 | 4.6 | 0.37 | <1.0 |
| 49 | Poky Feeders | | 4.6 | 5.6 | 36.10 | 47.2 | 7.8 | 29.9 | 1.19 | |
| 72 | Roberts | 0.9 | | | 0.02 | 4.4 | 3.1 | 11.0 | 0.45 | <1.0 |
| 50 | Ranger Feeders 4 | | 0.2 | 0.0 | 0.01 | 2.0 | 1.4 | 7.5 | 0.28 | |
| 71 | Ranger Feeders 5 | 1.1 | | | 0.25 | 1.6 | 0.9 | 8.2 | 0.56 | <1.0 |
| 73 | Montgomery | 0.0 | | | 0.04 | 2.0 | 1.4 | 6.8 | 0.63 | <1.0 |
| 74 | Christian Camp | 0.9 | | | 0.03 | 9.9 | 6.9 | 7.2 | 0.51 | <1.0 |
| 75 | Marintzer | 0.3 | | | 0.03 | 3.9 | 2.7 | 9.6 | 1.60 | 1.8 |
| 76 | Klein | 5.7 | | | 0.68 | 3.9 | 2.3 | 4.6 | 0.28 | <1.0 |
| 77 | Obermuller | 3.7 | | | 10.90 | 39.0 | 19.7 | 23.0 | 4.60 | 6.2 |
| | Kansas site between north and south flow path | | | | | | | | | |
| 51 | KPL Dakota | | 0.1 | 0.0 | | | | | | |
| | Kansas sites, Ogallala wells | | | | | | | | | |
| 48 | Leoti Ogallala | | | 6.4 | | | | | | |
| 69 | Leoti Ogallala | 4.1 | | | 12.40 | 14.0 | 1.1 | 9.1 | 0.20 | <1.0 |
| KS05 | Scott City 4 | | | 0.9 | | | | | | |
| KS08 | KPL Ogallala | | | 0.0 | | | | | | |

LLNL, USGS, and BEG (Dutton, 1994) refer to the laboratory in which the samples were analyzed. Uranium values are from LLNL except for samples 49, 50, and 78 which are from USGS. All other values were determined by the USGS.

Table 13. Stable Isotope Concentrations in Cooperative Study Samples.

| Site sample | Site name | δ O-18 ‰ LLNL | δ O-18 ‰ USGS | δ O-18 ‰ Dutton | δ D ‰ LLNL | δ D ‰ USGS | δ D ‰ Dutton |
|---|---|---|---|---|---|---|---|
| | Southeastern Colorado sites | | | | | | |
| 57 | Grasslands | -9.84 | -9.85 | | -66.5 | -66.0 | |
| 56 | Pritchett | -11.49 | -11.55 | | -80.0 | -81.5 | |
| 55 | CSU Exp. Station | -14.12 | -14.20 | | -103.5 | -106.0 | |
| 54 | Springfield 9 | -10.67 | -10.70 | | -75.0 | -74.5 | |
| 53 | Springfield 11 | -11.43 | -11.05 | | -85.0 | -79.5 | |
| 62 | Vilas | -12.20 | | | -88.0 | | |
| 58 | Walsh 3 | -9.43 | -9.35 | | -68.0 | -65.0 | |
| 59 | Walsh 2 | -9.70 | -9.60 | | -66.0 | -66.5 | |
| 61 | Hog farm | -10.04 | -10.05 | | -69.0 | -69.0 | |
| 60 | Prowers windmill | -9.17 | -9.20 | | -60.0 | -63.0 | |
| | Kansas sites in general location of northern flow path | | | | | | |
| 52 | Stanton Morrison | -10.94 | -12.00 | | -79.0 | -85.5 | |
| 78 | Stanton Cheyenne | | -11.27 | | | -81.0 | |
| 46 | Coolidge south | | | -12.80 | | | -88.0 |
| 63 | Coolidge north | -13.02 | | | -93.0 | | |
| 68 | Terry Boy | -13.24 | -13.30 | | -99.0 | -97.5 | |
| 47 | Leoti Dakota | | | -12.05 | | | -88.5 |
| 70 | Leoti Dakota | -12.07 | -12.10 | | -90.0 | -88.5 | |
| 49 | Poky Feeders | | -8.50 | -7.93 | | -59.0 | -52.0 |
| 72 | Roberts | -11.75 | -11.80 | | -97.0 | -85.5 | |
| 50 | Ranger Feeders 4 | | | -12.95 | | | -93.0 |
| 71 | Ranger Feeders 5 | -12.52 | -12.60 | | -95.0 | -92.5 | |
| 73 | Montgomery | -11.95 | -11.90 | | -88.0 | -87.5 | |
| 74 | Christian Camp | -11.85 | -12.00 | | -87.0 | -86.5 | |
| 75 | Marintzer | -11.71 | -11.85 | | -88.0 | -86.5 | |
| 76 | Klein | -9.27 | -9.35 | | -64.0 | -61.5 | |
| 77 | Obermuller | -8.52 | -8.55 | | -61.0 | -57.5 | |
| | Kansas site between north and south flow path | | | | | | |
| 51 | KPL Dakota | | | -11.55 | | | -84.0 |
| | Kansas sites, Ogallala wells | | | | | | |
| 48 | Leoti Ogallala | | | -9.24 | | | -62.0 |
| 69 | Leoti Ogallala | -8.93 | -9.00 | | -61.0 | -61.5 | |
| KS05 | Scott City 4 | | | -9.40 | | | -60.5 |
| KS08 | KPL Ogallala | | | -10.11 | | | -74.5 |

Data for the last two samples are from Dutton (1994).

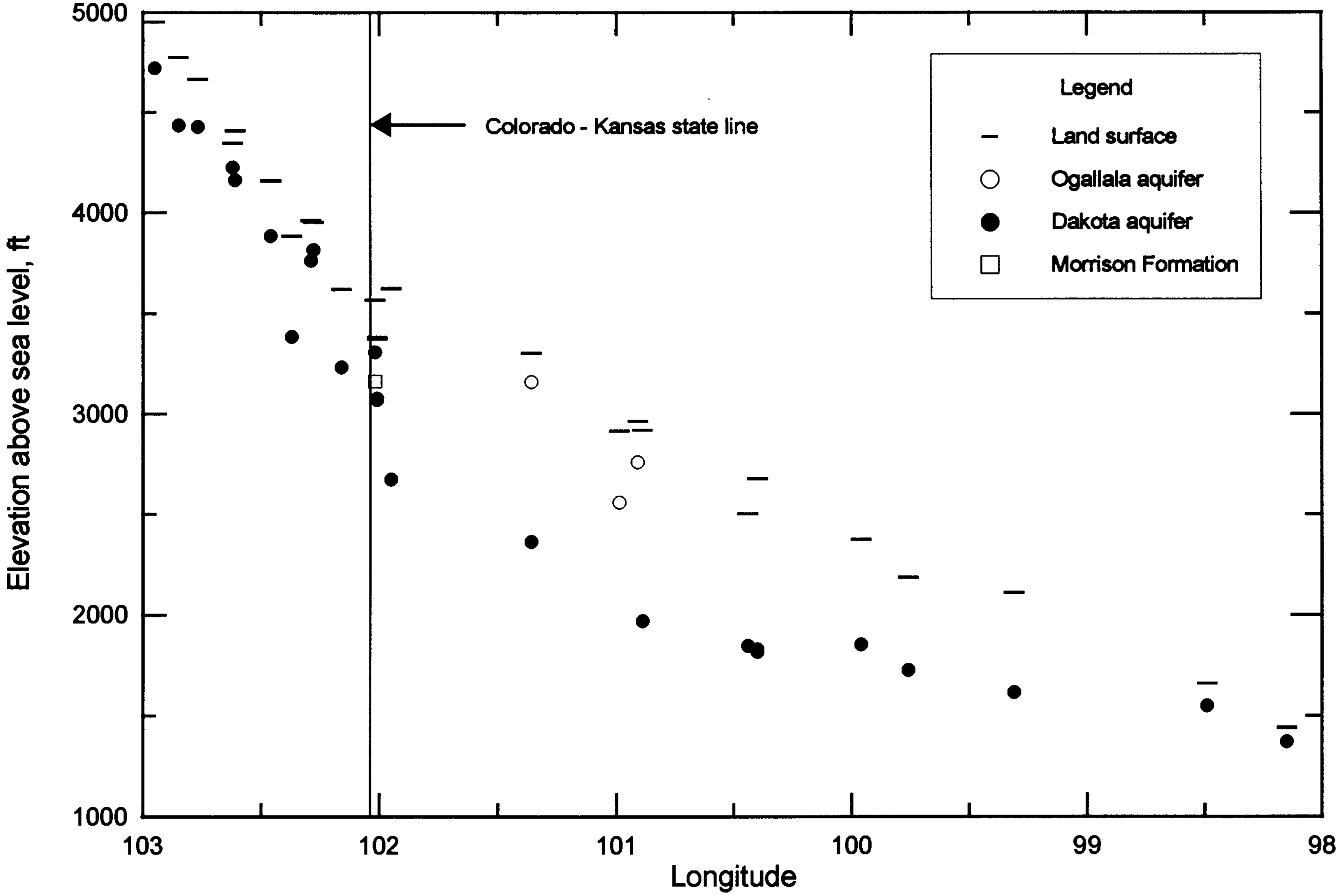

Figure 39. Location and Depth of the Middle of the Screened Interval for Wells Sampled along the Cross Section.

portion of the aquifer in western Kansas. Points for the three Ogallala water-supply wells and the Morrison observation well are included in Figure 39.

Figures 40–44 illustrate chemical changes along the flow path from southeastern Colorado to central Kansas. One of the Dakota well samples (the Poky Feeders well in southern Scott County) is represented as an open triangle because the chemical and isotopic composition indicate that enough water from the overlying bedrock and the Ogallala Formation is mixing with the Dakota water to cause appreciable changes in some of the chemical characteristics. This may be due to a gravel pack that extends up into the Ogallala sediments or a leaky seal in the well above the Dakota aquifer. The Dakota ground water collected from Finney County (KPL power plant) near the southern flow path is plotted as an open diamond in the figures to show the chemical contrast with ground waters in the northern flow path. The Finney County well lies near the boundary where Dakota strata becomes confined by overlying Upper Cretaceous shales. South of the boundary, the Dakota aquifer is directly overlain by the High Plains aquifer. Points for the waters sampled from the overlying Ogallala (open circles) and underlying Morrison (open square) formations in southwestern Kansas near the Colorado border are also plotted for comparison to the Dakota ground waters in the flow cross section.

The total-dissolved solids (TDS) concentrations in the Dakota aquifer generally increase from the recharge and local flow area of southeastern Colorado to the zone of Permian saltwater intrusion in the confined aquifer in central Kansas (Figure 40a). The TDS then decreases farther to the east in the discharge and local flow system of the outcrop/subcrop belt of the Dakota aquifer in central Kansas. The TDS concentrations in ground waters in the overlying Ogallala Formation, the underlying Morrison Formation near the Colorado border, and Dakota aquifer in the southern flow path are all in the same range as for the Dakota ground waters in southeastern Colorado.

Although chloride is the predominant anion contributing to the large increase in TDS concentration in the Dakota aquifer in central Kansas (Figure 40b), other anions are more important for the steady TDS increase in western Kansas, as indicated by the relatively low chloride content (<100 mg/L) up to about 101 ° Long.. Dissolved sulfate generally contributes a much greater proportion of the anionic composition in ground waters in southeastern Colorado and in Kansas west of 101 ° Long. than chloride (Figure 41a). The sulfate concentration is usually even larger than the bicarbonate concentration in these areas (Figure 41b), resulting in primarily sulfate type waters. Farther to the east in the Dakota flow section, the sulfate content varies substantially, whereas the bicarbonate concentration shows an increasing trend. Sulfate and bicarbonate contents of ground waters in the Ogallala Formation along the northern cross section and in the Dakota aquifer to the south near and within the unconfined areas tend to be substantially lower than in Dakota aquifer waters in the northern flow path at the same

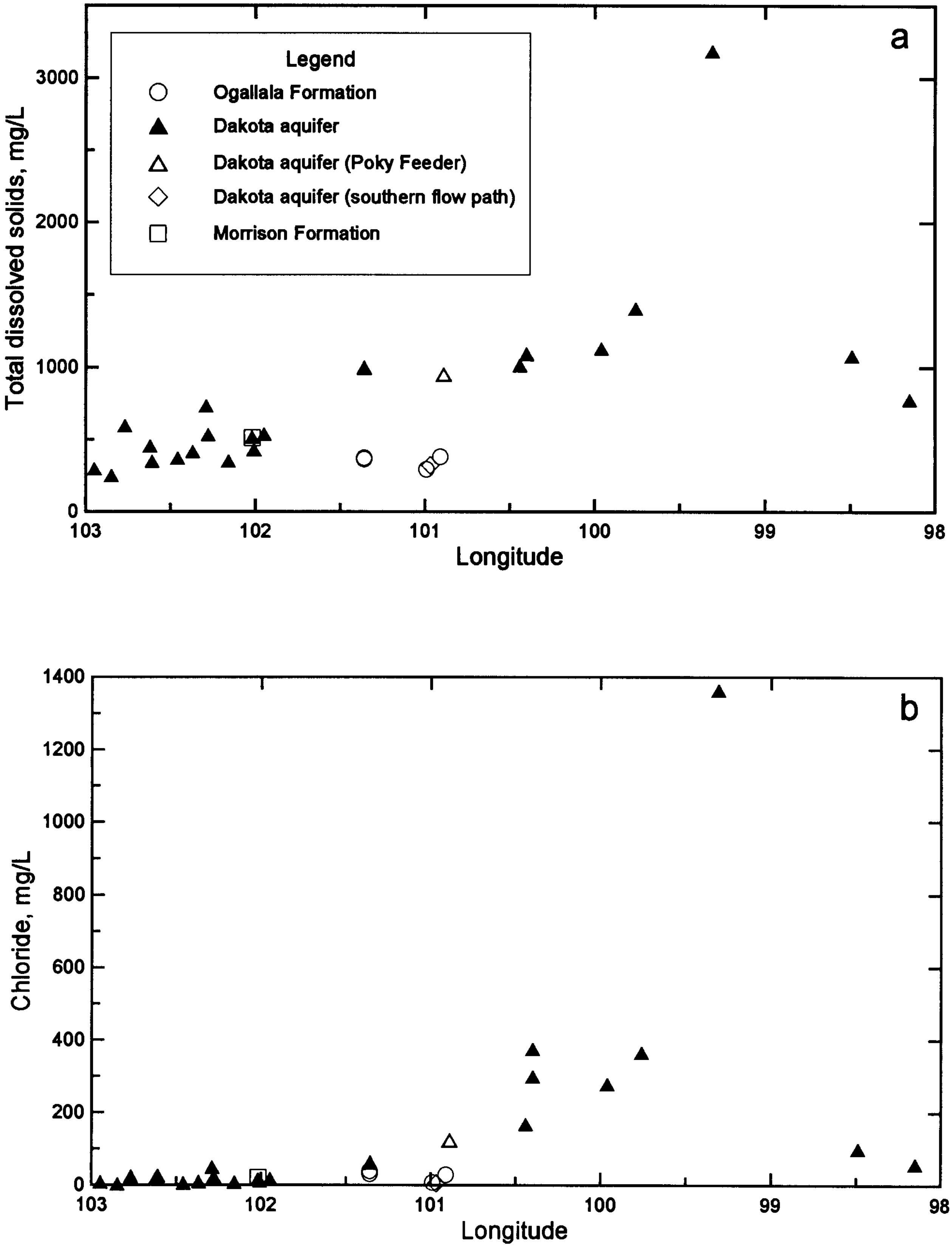

Figure 40. Distribution of Total Dissolved Solids (a) and Chloride (b) Concentrations along the Cross Section. The legend is the same for both figures.

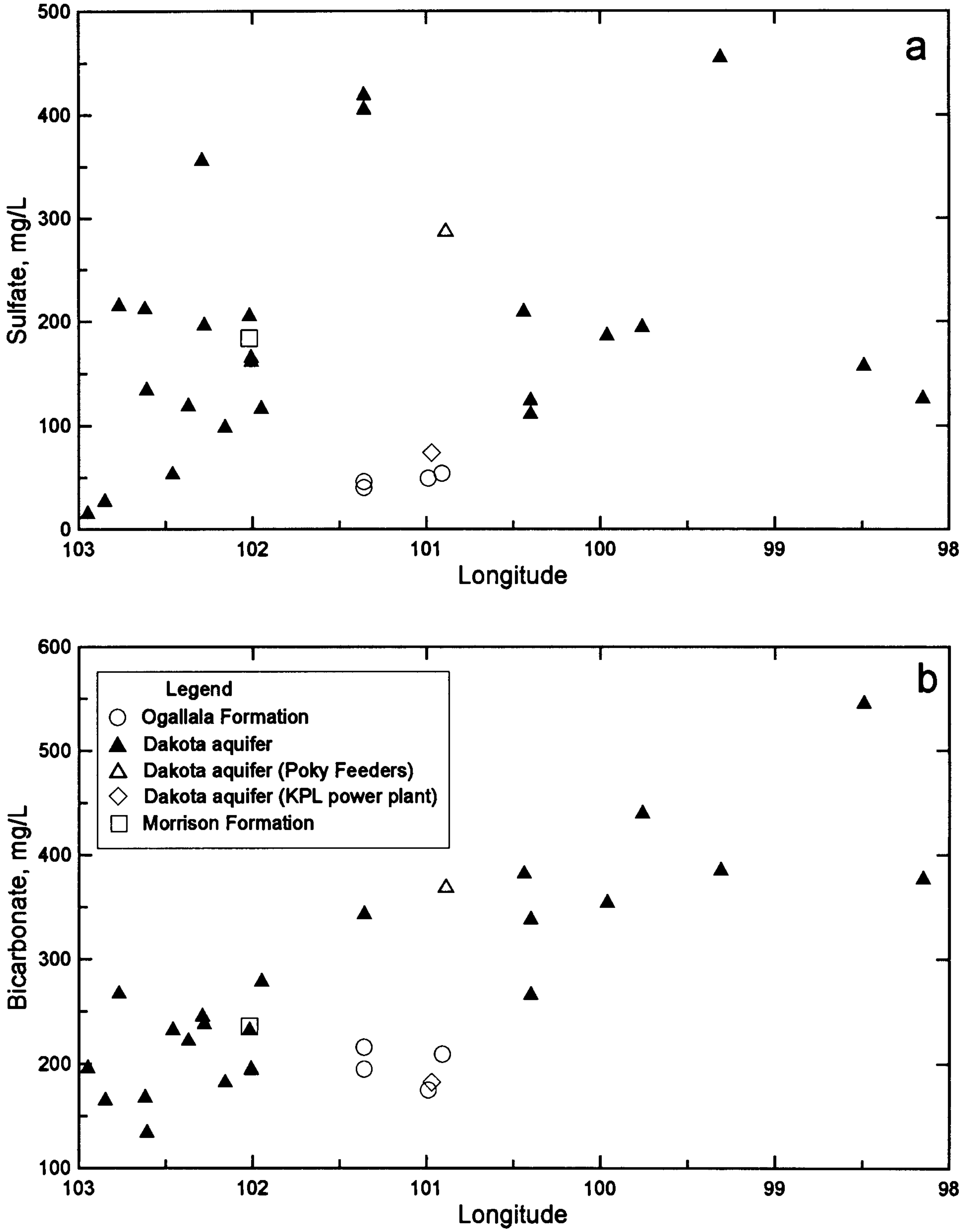

Figure 41. Distribution of Sulfate (a) and Bicarbonate (b) Concentrations along the Cross Section. The legend is the same for both figures.

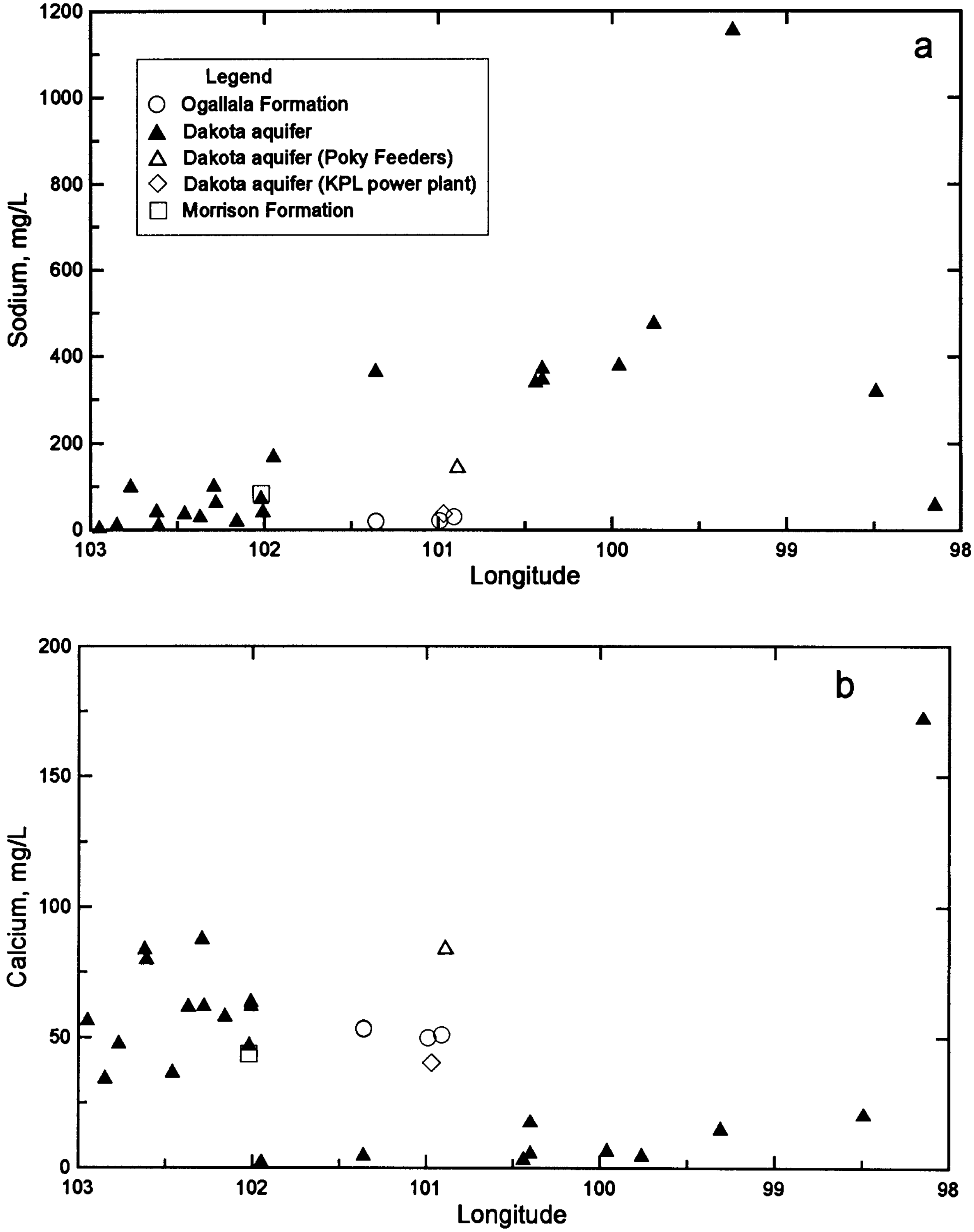

Figure 42. Distribution of Sodium (a) and Calcium (b) Concentrations along the Cross Section. The legend is the same for both figures.

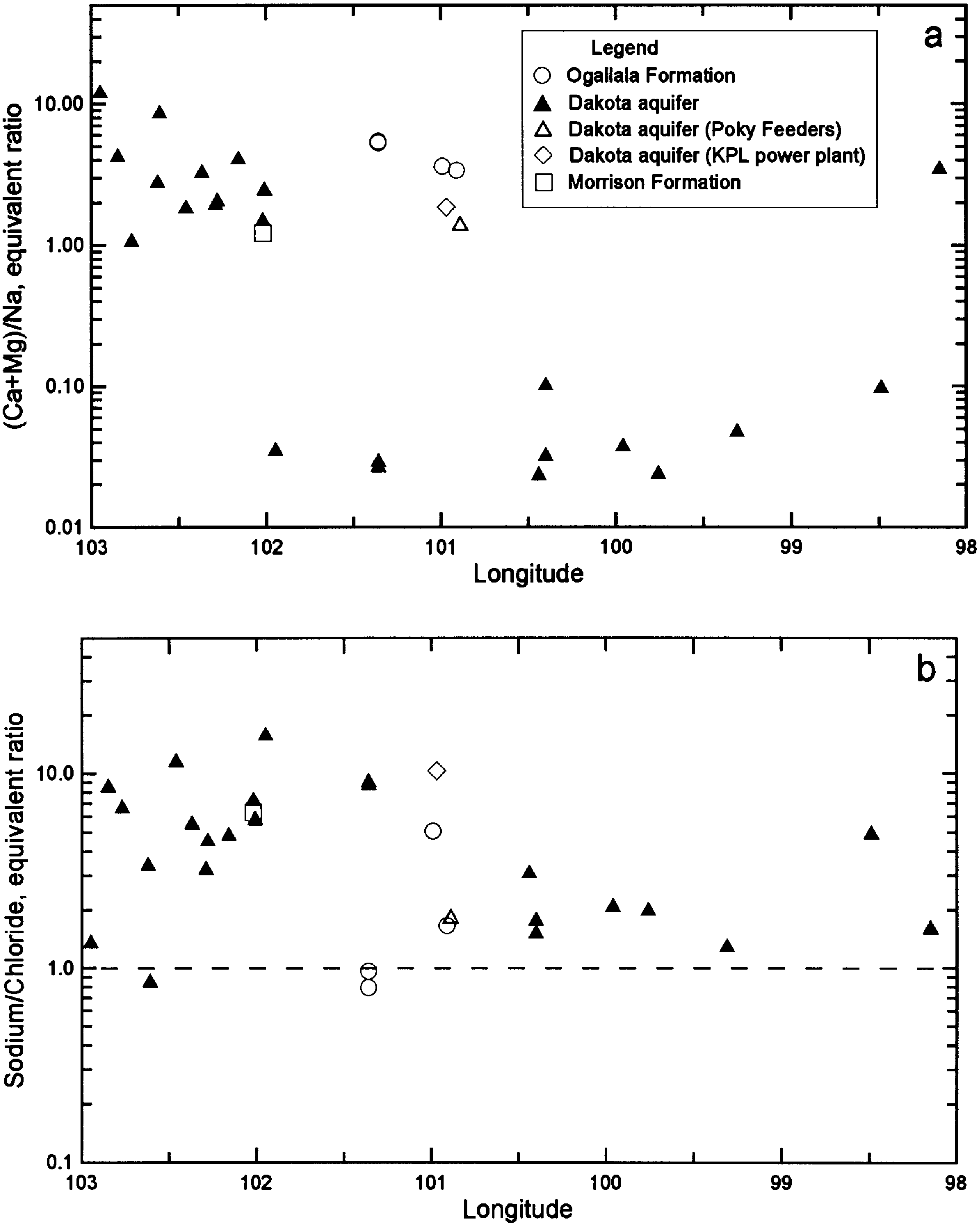

Figure 43. Equivalent Ratios of (Calcium plus Magnesium)/Sodium (a) and Sodium/Chloride (b) along the Cross Section. The legend is the same for both figures.

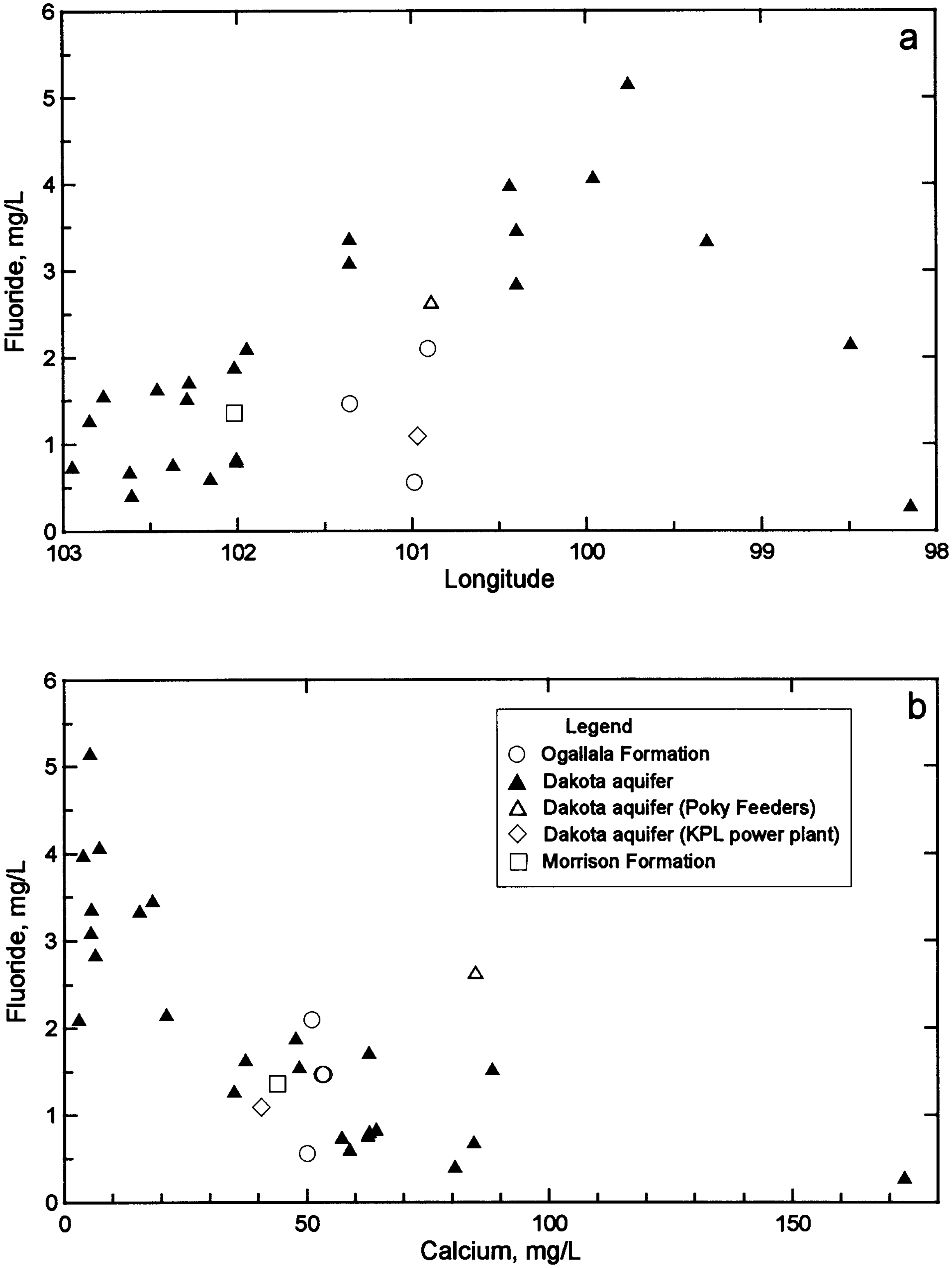

Figure 44. Distribution of Fluoride Concentration along the Cross Section (a) and Fluoride versus Calcium Concentration for the Same Waters (b). The legend is the same for both figures.

longitude (Figure 41a). The range in bicarbonate concentrations at a location along the flow path is generally much smaller than for sulfate.

Sodium concentration in Dakota waters (Figure 42a) follows a similar pattern as TDS along the cross section. In contrast, dissolved calcium (Figure 42b), and magnesium (Table 9) contents decrease appreciably from the local flow area of southeastern Colorado to the confined Dakota aquifer in western and central Kansas. The general inverse relationship between calcium plus magnesium and sodium is related to carbonate equilibria and cation exchange. Ground waters in southeastern Colorado initially derive calcium and magnesium from leaching of carbonate minerals concentrated in soils in an environment of greater evapotranspiration than precipitation. The aquifer is well flushed in this area, thus any previous saline water in the aquifer has been essentially all removed and sodium and chloride concentrations in the ground water are low. The flushing in the Dakota aquifer in southeastern Colorado has been extensive enough to also remove high sodium contents adsorbed on clays deposited in brackish or marine environments or subjected to later saltwater intrusion from underlying Permian strata. Thus, any former capacity to soften recharge waters has been largely removed and recharge, usually of calcium-bicarbonate chemical type, retains its higher calcium plus magnesium than sodium content. Additional calcium in the Dakota aquifer in the recharge area is probably obtained from calcite dissolution in the bedrock as well as dissolution of secondary gypsum. Secondary gypsum in the strata can be precipitated from locally high concentrations of sulfate derived from pyrite oxidation and high calcium from increased dissolution of calcite by the acidic solutions produced during the pyrite weathering.

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

Calcium and magnesium concentrations can become as low as a few mg/L each in the confined Dakota aquifer along the cross section in western Kansas (Table 9, Figure 42b). In contrast, the calcium concentrations in overlying Ogallala aquifer waters and in the Dakota water from the southern flow path are within the range of the Dakota aquifer waters in southeastern

Colorado. The even higher calcium content in the Poky Feeder well water than the Ogallala waters near the same longitude could reflect influence by calcium-sulfate waters from Upper Cretaceous shales and chalks and/or higher dissolved solids concentrations in Ogallala aquifer water in the Whitewoman Basin.

Figure 43a illustrates the decrease in calcium plus magnesium and increase in sodium concentrations along the Dakota flow path from southeastern Colorado into the confined aquifer in western Kansas. The change as indicated by the equivalent ratio is abrupt near the state line. The calcium plus magnesium/sodium ratio remains low along the northern flow path until the confining layer thins in central Kansas. Flushing of the saline water that intrudes from the underlying Cedar Hills Sandstone and removal of the high adsorbed sodium content on clays by recharge in the local flow area in central Kansas allows the return of the water type to calcium bicarbonate. The calcium plus magnesium/sodium ratio in the Ogallala Formation and Dakota waters near the southern flow path in western Kansas is within the same range as for the Dakota ground waters in southeastern Colorado and in the local recharge-discharge area in central Kansas. Calcium-sulfate type waters also occur in the local flow area in central Kansas as they do in southeastern Colorado. The origin of the water types is probably similar in the different areas.

The increase in sodium concentration in Dakota waters along the northern flow path (Figure 42a) is derived from both softening and increased intrusion of saltwater from the underlying Permian as the waters approach central Kansas. Although the sodium concentration is low in the recharge area of southeast Colorado, the sodium/chloride equivalent ratio is generally much greater than one (Figure 43b). The excess sodium could be either be remnants of adsorbed sodium released by exchange from Dakota sediments previously containing saline water or weathering of sodium containing minerals. The sodium/chloride ratio decreases along the flow path in Kansas as the salinity of the waters increases; the ratio is closest to the theoretical molar ratio of 1.0 for halite dissolution at the location with the highest chloride concentration. However, the cation exchange of calcium and magnesium for sodium results in maintaining an excess equivalent concentration of sodium concentration relative to chloride.

### *Distribution of constituents of concern for water use and water-quality assessment*

Flouride concentrations are less than 2 mg/L in the Dakota aquifer in recharge area of southeastern Colorado. After the waters flow into the confined portion of the aquifer, the dissolved fluoride content increases steadily to over the maximum contaminant level (MCL) of 4 mg/L for drinking waters. The fluoride concentration then decreases as increasing amounts of recharge from overlying units are able to enter the aquifer where the top confining bed thickness thins. The dissolved fluoride is low in the aquifer in the local recharge and discharge zone of outcropping Dakota rocks in central Kansas. Ground waters in the Dakota aquifer in southwestern Kansas where the overlying confining zone is thin or absent and in the Ogallala Formation have substantially lower fluoride concentrations than in the Dakota aquifer along the confined portion of the flow path.

The increase in the fluoride concentration along the northern flow path is primarily related to the simultaneous decrease in calcium concentration (Figure 42b) caused by the strong cation exchange (Figure 44a) within the confining zone. The inverse relationship of the fluoride to calcium content is illustrated in Figure 44b. The values for the Dakota aquifer fit a hyperbolic distribution (calcium times fluoride equals a constant) in Figure 44b as would be expected for the control on fluoride by dissolution or precipitation of minerals containing both calcium and fluoride. The most probable minerals are hydroxy apatite minerals with fluoride substituting for some of the hydroxyl ions.

As indicated before, the water from the Poky Feeders well appears to be a mixture of Dakota aquifer water with ground water from overlying Cretaceous bedrock and/or the Ogallala Formation. The fluoride and calcium contents of the Poky Feeders water are lower and much higher, respectively, than expected along the flow path for the Dakota aquifer. Simple mixing of two end points on Figure 44b would describe a straight line. If a fluoride concentration of near 4 mg/L and a calcium content of less than 10 mg/L were selected for the Dakota aquifer water at the Poky Feeders location, and a line drawn from that composition as represented on Figure 44b through the point for the actual water sampled from the well, the calcium concentration in the water mixing with the Dakota water in the well would need to be about 250 ± 50 mg/L. This could be possible if some of the overlying Cretaceous strata contained high-calcium waters derived from the dissolution of gypsum. The overlying Ogallala waters in the Whitewoman or Scott Basin in which Poky Feeders is located are also high in calcium (between 100 and 200 mg/L) (Hathaway et al., 1975). The dissolved solids contents of soils waters in the closed depression were probably concentrated by evapotranspiration and leached to the ground water. The Ogallala waters in parts of the basin are slightly saline and correspond to saline soils in the same area (Hathaway et al., 1975).

Dissolved nitrate concentrations in the Dakota aquifer range from less than detectable to several mg/L in the recharge area in southeastern Colorado (Figure 45a). The higher values probably derive from near-surface leaching of natural or human sources of nitrate, possibly entering the well along the annular zone around the casing if the well was gravel packed or not well sealed about the screened intervals in the Dakota strata. In general, if a well water contained detectable nitrate, the tritium concentration (Table 12) was above background (≤0.3 based on analytical error) for waters with an age greater than pre-European settlement in the region. Detectable tritium usually indicates the presence of some water affected by atmospheric

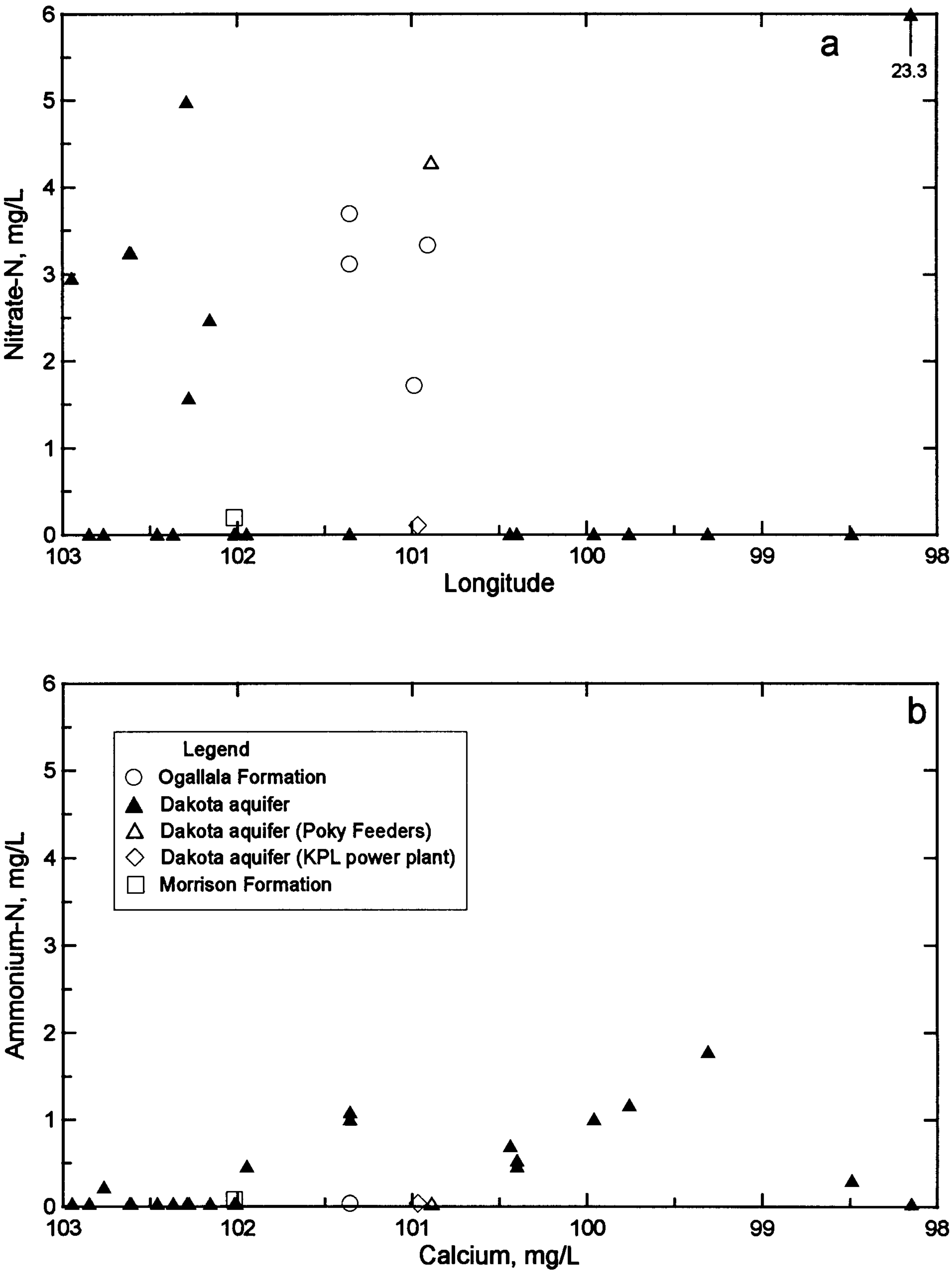

Figure 45. Distribution of Nitrate-N (a) and Ammonium-N (b) Concentrations along the Cross Section. The legend is the same for both figures. Ammonium ion was not determined in two Ogallala Formation samples.

testing of thermonuclear devices; the largest input of tritium from this source occurred during the 1960's. All of the Dakota aquifer waters in the confined portion of the northern flow path in Kansas except the Poky Feeders sample have undetectable nitrate content. The Dakota aquifer water at the eastern end of the cross section in the outcrop zone in central Kansas has a nitrate value exceeding the MCL of 10 mg/L for drinking water. The nitrate source is most likely related to anthropogenic sources or activities such as human or animal waste, fertilizer, or oxidation of organic nitrogen in cultivated soils. The well which yielded the high nitrate content is the shallowest of any represented on Figure 45.

The Ogallala well waters along the northern cross section contained a few mg/L nitrate which could represent surface leaching of both natural and anthropogenic sources of nitrate. The three samples with higher nitrate concentrations (representing two wells) had tritium levels greater than background, whereas the sample with the lowest nitrate had an undetectable tritium content. The Poky Feeders well water contained substantial amounts of both nitrate and tritium, indicating the effect of near-surface sources of nitrate and water. The well is located in a cattle feed lot.

Ammonium ion concentrations are undetectable in nearly all the Dakota aquifer waters in the recharge area of southeastern Colorado (Figure 45b). In contrast, ground waters in the confined Dakota aquifer along the northern cross section in Kansas have detectable ammonium ion contents which exceed the level of 0.1 mg/L suggested by the Kansas Department of Health and Environment (KDHE) for drinking waters. The ammonium ion levels then decrease to below detection at the eastern end of the cross section in the outcrop zone. Where nitrate concentrations are detectable, ammonium ion contents are undetectable and vice versa. Some sites also have undetectable concentrations of both nitrate and ammonium ion. The inverse relationship between the two constituents and the location of the undetectable nitrate and detectable ammonium ion along the flow path indicate the presence of a chemically reducing environment in the confined portion of the Dakota aquifer. In the recharge zone, the system is oxidizing enough to limit the ammonium ion concentration. The undetectable ammonium ion concentration in the Poky Feeders water probably results from oxidation of the small amounts expected during mixing with oxygenated near-surface ground water.

Many of the metals and semi-metals determined by the KGS for Dakota aquifer waters along the cross section were also analyzed by the LLNL for the same metals. For some metals the values agreed relatively closely based on higher analytical error expected for the very low levels present. However, concentrations obtained by the LLNL were generally lower than those from the KGS for chromium, cadmium, mercury, and lead. The LLNL used an isotope dilution method that is more sensitive than the analytical method used by the KGS.

During fiscal year 1993, the KDHE adopted the revisions in drinking water standards established by the US EPA. The MCL's were changed for a few metals or semi-metals. The MCL's for chromium and selenium were raised, whereas the MCL for cadmium was lowered. Based on the revised standards for constituents for which MCL's previously existed, none of the Dakota waters sampled along the cross section contained metals or semi-metal concentrations exceeding the drinking water standards if the LLNL values for cadmium and lead are accepted as more correct. If the cadmium and lead values of the KGS were accepted as correct, then 1 and 4 samples would exceed the cadmium MCL and lead treatment standard, respectively. The reason for the higher KGS values for these metals is unknown at this time.

The KDHE adopted the EPA drinking-water MCL's for four additional trace metals in fiscal year 1993. The metals and the MCL's are antimony (6 µg/L), beryllium (4 µg/L), nickel (100 µg/L), and thallium (2 µg/L). None of the Dakota aquifer waters analyzed for the latter three of these metals contained concentrations exceeding the MCL's. Two of the Dakota aquifer waters in Kansas slightly exceeded the MCL for antimony. The LLNL did not determine antimony, thus there is no comparison to assess whether the isotope dilution method would give lower concentrations.

The US EPA has proposed an MCL 20 µg/L for uranium in drinking water. One of the Dakota ground waters in southeastern Colorado and the Poky Feeders well water in Kansas exceeded 20 µg/L (Table 12). The higher uranium content in the Poky Feeders water may derive from some water entering the well from the Cretaceous bedrock overlying the Dakota aquifer and/or the Ogallala Formation. The evapotranspiration concentration of the near-surface water in the Whitewoman or Scott Basin in which the Poky Feeders well is located would also concentrate uranium. One water from the recharge area of the Dakota aquifer in southeastern Colorado and the water from the Dakota outcrop area at the eastern end of the cross section in central Kansas exceeded the current standard of 15 pCi/L for adjusted gross alpha radioactivity. The adjusted gross alpha is represented by the gross alpha minus uranium in pCi/L in Table 12. None of the Dakota ground waters contained more than the 50 pCi/L MCL for gross beta radioactivity in drinking water. The current MCL for combined radium-226 and radium-228 is 5 pCi/L. Two waters from the Dakota aquifer in southeastern Colorado and one from Kansas exceeded the radium standard. The ground water with high radium in Kansas was from the well in the outcrop zone in central Kansas; the same well water in Kansas with the high gross alpha radioactivity. The MCL's proposed by the US EPA for radium-226 and radium-228 are 20 pCi/L for each constituent, values at least 4 times higher than the current values. If these standards are accepted, only one Dakota water in southeastern Colorado would exceed the MCL for radium-226.

## Coupled Geochemical and Mass Transport Modeling of Ground-Water Systems in North-Central Kansas

### *Modeling of ground-water flow and water quality using HYDROGEOCHEM*

The coupled flow and reaction model HYDROGEOCHEM, which was previously selected as the most appropriate for modeling ground-water flow and water quality interactions in the Dakota aquifer, was purchased in early 1993. The package obtained included the software and a users' manual. The initial modeling approach selected involved first a simulation of the ground-water flow field with HFLOW, the flow module of HYDROGEOCHEM. Next, selected chemical reactions were simulated with EQMOD, the chemical-reaction module of HYDROGEOCHEM, to determine the range of solute concentrations appropriate for the hydrogeologic system to be modeled. The last step comprised running the coupled model HYDROGEOCHEM. In the process of adapting the software to the model tasks, inadequacies in the documentation were discovered. Description of input and output was insufficient for immediate use or adaptation of the program to the modeling needs. There were also some errors detected during testing of the program.

The output format of the HFLOW program was substantially altered to conserve memory space and be more readable. The program was also modified to include message displays in both computer screen and output file formats to provide for easier detection of problems occurring during simulation runs. Errors in the program were corrected as needed for current use.

The EQMOD module of HYDROGEOCHEM was modified to include additional or alternative approaches to chemical computations. The B-dot method for calculating activity coefficient was added to the EQMOD program. The modification allows the program to handle solutions with ionic strength up to about 1 M. The database for the B-dot method was taken from SOLMINEQ.88 and is only good for temperatures of 0-50 °C with low pressure, conditions sufficient for the Dakota aquifer study. The EQMOD module uses the mole fraction of exchanging species in ion-exchange reaction calculations. The program was modified to perform calculations based on equivalent ratios because this approach is generally used more often in such computations. Both of the modification were verified by comparing the results with SOLMINEQ.88.

Selected physical-chemical assumptions used in the model were examined. For example, constant ion-exchange capacity (CEC) is the only available approach for exchange calculations in the program. Bolt (1979) indicates that the constant-capacity ion-exchange model should be good enough for soil with clay minerals as its primary sources of CEC. Clays are expected to be the main control on CEC in the Dakota aquifer, thus the approach appears valid for the simulations.

The coupled model was also modified to improve handling of a convergence problem. The input and output formats were adjusted to adapt to the modifications made in the program. This allows a much easier determination of the meaning of the data displayed in the output file. Additional output messages were incorporated to provide information for detecting possible problems. More work is still need to improve the convergence scheme for complicated chemical reactions.

Ground-water flow and chemical transport was simulated in a profile across the Republican River Valley at Concordia using the coupled model. Construction of the model grid for the alluvial aquifer along the profile was based on the many drilling logs available for the area. Field and laboratory tests of hydrogeological parameters are also available for the alluvial aquifer system in the vicinity of the profile (Bayne et al., 1959; Fader, 1968; and Fishel, 1948). However, only few data are available for the Dakota aquifer near the profile. Due to the lack of geological and hydrogeological information for the underlying Dakota aquifer, the bedrock aquifer was assumed to be uniform. The Dakota was divided with two hydrologic units, the upper Dakota Formation and the basal sandstone unit of greater permeability, based on Wade's (1992) study in the same vicinity.

A numerical steady-state flow field of the Concordia profile was obtained based on the available data for the system. The heterogeneity of the alluvial aquifer was incorporated into the grid profile based on geological information. However, the hydrogeological properties are not necessary coincident with the generalized geologic descriptions in the drilling logs. Laboratory data (Fishel, 1948) indicate that a few percent difference in the fine-grained particles in the matrix can cause orders of magnitude differences in the hydraulic conductivity. The five or six water-level measurements for different dates in the Concordia profile only provide an estimate of the water-table surface and are not sufficient for a very accurate calibration of the simulated flow field. The water table in the system will respond to any change of hydraulic conductivity at any part of the same vertical column, i.e., the water table at a certain horizontal distance will response to the change of hydraulic conductivity below it, whether the changes occur near the water table or at the bottom of the profile. This restricts the significance of a sensitivity analysis for the hydraulic conductivity of any particular layer.

The coupled model will include computation of the main aqueous species $Ca^{2+}$, $Mg^{2+}$, $Na^+$, $H^+$, $CO_3^-$, $SO_4^{2-}$, and $Cl^-$, the aqueous complexes $OH^-$ (decomposition of water), $HCO_3^-$, $H_2CO_3$, $CaSO_4$, $MgSO_4$, and $NaSO_4^-$, precipitation and dissolution of calcite, and cation exchange of $Na^+$, $Mg^{2+}$, and $Ca^{2+}$. Model results have been obtained for the transport of the main aqueous species and complexes alone and accompanied by precipitation of calcite. Simulation with cation exchange currently in progress. More effort is also needed to find a solution for the convergence problem.

The model with aqueous complexing and precipitation of calcite indicates that calcite precipitates when the Dakota aquifer water containing a high pH and a low calcium concentration mixes with the neutral pH and more calcium rich ground water in the alluvial aquifer. The high pH water in the Dakota aquifer derives from combined effects of cation exchange and calcite dissolution within the sandstone on the south side of the Republican River. The calcite precipitation occurs in the mixing zone directly below the boundary of the alluvial aquifer with the Dakota aquifer on the south side of the river. A small amount of calcite precipitation also occurs where the high TDS water from the bottom of the Dakota aquifer on the north side of the river meets the high pH Dakota water from the south. The precipitation of calcite may explain some of the occurrences of calcite-cemented sandstone found in the Dakota outcrop area (Swineford, 1947). The calcite precipitation might also affect the local flow system by decreasing the permeability of parts of the bedrock. However, the permeability change cannot be simulated with the coupled program.

A series of FORTRAN programs were written to process pre- and post-modeling data. The programs include the transformation of data formats between graphic programs and model output files. Each program extracts a different data set from the output file. The functions assist in visual modification of the node coordinates and allow quick inspection of the model results on a routing basis. Another program calculates the water budget for specific cases to check whether the boundary conditions selected for the model are appropriate. One problem is that Yeh (1980) uses the conventional method of calculating the Darcian velocity in the finite-element model, i.e., taking the derivatives of the computed pressure field. This causes discontinuities in the velocity field at nodal point and element boundaries. This might cause a mass-balance error of up to 30% if the pressure field is not linearly distributed.

### *Laboratory determination of the cation exchange capacity of Dakota aquifer sediments*

In order to accurately simulate cation exchange in the coupled flow and transport model, valid values of cation exchange capacity (CEC) are needed. Although some CEC data exist in the literature for sandstones, silts, and shales, no data are available for the Dakota aquifer. Therefore, samples of Dakota aquifer sediments were analyzed for CEC to allow selection of appropriate input values for the coupled model.

Representative samples of Dakota aquifer sediments were taken from different depths of the KGS #1 Jones core. The samples were ground to pass a #60 mesh sieve (250 mm). Each sample was split into two separate bags for checking the error of duplicate analyses. Each split sample weighed a little more than 100 g. The samples were sent to the Soil Test Laboratory of the Kansas State University for analysis of bulk cation exchange capacity (CEC). The laboratory uses a common analytical method involving saturation of the exchange sites with a solution of ammonium acetate (Chapman, 1965). The results are listed in Table 14.

Except for the Kiowa marine shale sample, the CECs of the Dakota aquifer sediments range from 5 to 80 meq/kg, with an average of 32.1 meq/kg. There is no significant difference between the CECs of the Dakota Formation and the Longford Member of the Kiowa Formation. However, the CECs for samples of grain sizes coarser than fine sand are in a range of 5 to 37 meq/kg with an average of 17.3 meq/kg. An x-ray diffraction study of these sediment samples was conducted by other staff of the Kansas Geological Survey to determine their clay mineralogy. The investigation indicates that kaolinite is the dominate clay mineral in the Dakota aquifer (P. Hoth, personal communication). This result is compatible with previous studies (Plummer et al., 1954, 1963; and Plummer and Romary, 1947). Relative differences in the amount of organic matter in the sediments (based on visual inspection) do not appear to correlated with the CEC values. High illite content in the Kiowa marine shale is the probable reason for its relatively high CEC.

Table 14. Cation exchange capacity of Dakota aquifer sediments collected from KGS #1 Jones core. The first digits in the sample identification number indicate the sample depth in the core. The second set of digits in the sample ID indicates the number of the split sample. Detailed geological description of the core is in Macfarlane et al. (1991) and Combes and Feldman (1993).

| Sample ID | Geologic formation | Sample description | CEC meq/100 g |
|---|---|---|---|
| 71-1<br>71-2 | Dakota Fm | Fine sandstone, rare pyrite concretions, plant debris | 3.7<br>3.6 |
| 81-1<br>81-2 | Dakota Fm | Fine sandstone, plant debris, iron | 3.5<br>3.4 |
| 122-1<br>122-2 | Dakota Fm | Mudstone to siltstone, abundant hard brown sand-sized grins, probably weathered pyrite | 5.4<br>5.1 |
| 154-1<br>154-2 | Dakota Fm | Silty fine sandstone, poor sorted, many plant debris | 4.4<br>4.4 |
| 172-1<br>172-2 | Dakota Fm | Medium sandstone, clean, well sorted, pyrite crystals scattered | 2.0<br>1.9 |
| 200-1<br>200-2 | Dakota Fm | Fine to medium sandstone, clean, well sorted | 0.52<br>0.57 |
| 284-1<br>284-2 | Longford Mbr of Kiowa Fm | Sandy shale, red-filled crusts and root tubes, paleosols | 5.3<br>4.9 |
| 319-1<br>319-2 | Longford Mbr of Kiowa Fm | Mudstone with sand-sized pyrite crystals | 7.8<br>9.2 |
| 354-1<br>354-2 | Longford Mbr of Kiowa Fm | Fine sandstone with thin clay lamina | 0.86<br>0.90 |
| 418-1<br>418-2 | Longford Mbr of Kiowa Fm | Fine sandstone, clean, well sorted | 0.55<br>0.57 |
| 435-1<br>435-2 | Longford Mbr of Kiowa Fm | Medium to fine sandstone, glauconite up to 10%, pyrite concretions | 1.1<br>1.0 |
| 470-1<br>470-2 | Kiowa Fm | Dark gray marine shale | 32.8<br>32.8 |
| 475-1<br>475-2 | Permian | Green siltstone | 6.1<br>5.9 |

## LIAISON ACTIVITIES WITH FEDERAL, OTHER STATE, AND LOCAL AGENCIES AND THE PUBLIC

During FY93 the Kansas Geological Survey consulted with and provided information on the Dakota aquifer to several federal, other state, and local agencies and the public. In FY93 the Survey worked on the Dakota aquifer with the U.S. Geological Survey (USGS) through cooperative arrangements between agencies primarily in southwestern Kansas. Both agencies have also been actively working with Groundwater Management District 3 in southwestern Kansas to implement research plans that meets the needs of the District. In this past year the USGS was primarily responsible for assembly of the subregional management model of the coupled High Plains/Dakota aquifer system in southwest Kansas. The USGS also provided analytical support in support of the water quality being undertaken by the Program. The USGS provided analytical support for determination of radioactive and stable isotope concentrations through a cooperative arrangement with the KGS. Lawrence Livermore National Laboratory (LLNL) cooperated with the KGS on research directed to geochemical characterization of recharge and flow in the Dakota aquifer system. The KGS and LLNL conducted a joint ground-water sampling trip in FY 1993 along a flow path of the Dakota aquifer from western to central Kansas. The Texas Bureau of Economic Geology and the KGS shared data in FY 1993 for a joint sampling trip in FY 1992 as part of a project to determine interactions among the Dakota and other aquifers in the Great Plains.

The KGS provided information to the Kansas Corporation Commission for the City of Hays on the source of salinity in ground waters obtained from test wells in the Dakota aquifer as a part of the city's search for additional supplies of ground water for municipal use. Samples were received at the end of FY 1993 from the new water-supply wells which Hays installed in the Dakota aquifer. The wells were run for a limited period to examine the response of the aquifer relative to water quantity and quality and to test the functioning of desalinization technology to decrease salinity and provide supplementary municipal water supply. Other cooperative work was conducted with Ground Water Associates for the City of Russell on the source of salinity in ground waters in test wells drilled in Russell County. Some of these samples were received during the end of FY 1993 and analyses and geochemical identification of salinity source were not completed until FY 1994. The results and interpretation for ground waters from the City of Hays supply wells and the Russell County test holes in the Dakota aquifer will be given in the FY 1994 report.

The Dakota aquifer program also consulted with and gave briefings to the Interagency Dakota Technical Committee during FY93. Short briefings were also given to all of the basin planning committees in the western and central part of Kansas and other groups.

# RELATIONSHIP OF THE FY93 DAKOTA AQUIFER PROGRAM TO FUTURE RESEARCH DIRECTIONS

The overall objectives of the Dakota aquifer program in FY90–94 are to (1) 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) develop conceptual models of ground-water flow and assess water-planning and regulatory scenarios in FY92-94. On the basis of a review of the data on the Dakota aquifer, the region under development was subdivided geographically into southwestern, south–central, and north–central subareas of investigation. Up-to-date information in these subregions is insufficient to determine how past development has affected this source of water and to project the effects of future water-resources regulatory and planning policies.

To accomplish the FY92–94 goal, two objectives were formulated: (1) integrate the findings from previous years' research and (2) develop two- and three-dimensional numerical models of the Dakota and adjacent aquifers in southeastern Colorado and southwestern and central Kansas to simulate the flow of water, transport of solutes, and chemical reactions along the flow path.

Under the second objective, these simulations can 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 use of these models will be carried out in phases. In phase one (FY92–93), computer models of the ground-water flow system were used to determine the factors controlling the ground-water flow system, such as the arrangement of aquifer and aquitard units, and the effect of topography, and to estimate the amount of recharge to and discharge from the aquifer. The results of this modeling effort have formed a backdrop for subsequent efforts to understand the evolution of water chemistry in the Dakota using geochemical models. In FY93-94 (phase 2) the program emphasis has begun to shift toward the simulation of water-resources management options in the area of the Dakota aquifer currently under development in southwest Kansas.

In FY94, the research direction of the program will begin to shift to the deeper subsurface of northwest Kansas. Little is known about the Dakota in this part of the state because of its considerable depth below surface. As a result, most of the program's attention during its last two years will be focused to the north and west of the developed aquifer, especially in Greeley, Hamilton, Kearny, Wichita, Scott, and Lane counties in southwest Kansas and in Jewell, Smith, and Phillips counties in northern Kansas. Concerns in northwest Kansas are generally related to the quality of ground water in the Dakota aquifer. To address these concerns, the program emphasis will be on data collection from monitoring sites constructed in the Dakota aquifer in these fringe areas and the estimate of water quality from the vast library of borehole geophysical logs at KGS. A preliminary analysis in FY89 indicated considerable potential for water-resources development in parts or all of Lane, Scott, Wichita, and Gove counties.

## SUMMARY

During FY93 a wide diversity of research and research support activities were completed, continued, or initiated to further the goals of the Dakota aquifer program in southeastern Colorado and southwestern and central Kansas. In the area of the program emphasizing the geologic framework the, work continued to obtain core samples of the Mesozoic part of the section at the Stanton County monitoring site. In the area of the program emphasizing geohydrology the following tasks were completed or initiated: (1) completion of the hydrologic testing of the Stanton county monitoring site; (2) assembly and initial calibration of a three-dimensional regional steady-state model of the Dakota aquifer for Kansas and adjacent parts of southeastern Colorado; (3) assembly of a subregional model of the coupled Dakota/High Plains aquifer system in southwestern Kansas; and documentation and report writing on the development of the ARC-MOD interface. Finally, in the area of research support, the FY92 Dakota aquifer program annual report was completed and published as KGS Open-File Report 92-1.

During FY90-94 the overall objective of the Dakota aquifer program is 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. The progress made during the FY93 program has provided much new information that is being used to update existing data bases and to construct three-dimensional simulations of the Dakota and hydraulically-connected aquifers in southeastern Colorado and Kansas in FY92-94. In FY94 these simulations will be used to evaluate various management options for the Dakota aquifer in Kansas.

# REFERENCES CITED

Alger, R.P., 1966, Interpretation of electric logs in fresh water wells in unconsolidated formations: 7th Ann. SPWLA Symp., Paper CC, 25 p.

Anderson, M.P., and Woessner, W.W., Applied groundwater modeling simulation of flow and transport: San Diego, Academic Press, 381 p.

Archie, G.E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: Trans. AIME, v. 146, pp. 54–62.

Bayne, C. K., Walters, K. L., and Plummer, N., 1959, Geology and Ground-water resources of Cloud County, Kansas: Kansas Geological Survey Bulletin 139, 144 p.

Bentley, H.W., Phillips, F.M., and Davis, S.N., 1986, Chlorine-36 in the terrestrial environment: *in* Fritz, P., and Fontes, J.C., eds, Handbook of Environmental Isotope Geochemistry, Volume 1B, New York, Elsevier Science, pp. 422–475.

Bolt, G. H., 1979, Soil chemistry, B. Physico-chemical models: Developments in Soil Sciences 5B, Elsevier Scientific Publishing Company, New York, 479 p.

Chapman, H. D., 1965, Cation exchange capacity: *in* Black, C. A., et al. (ed.) Methods of soil analysis: Agronomy 9, America Society of Agronomy, Inc., Madison, Wisconsin, p. 891-901.

Collier, H.A., 1993, Borehole geophysical techniques for determining the water quality and reservoir parameters of fresh and saline water aquifers in Texas - volume I: Texas Water Development Board Report 343, 414 p.

Combes, J. and Feldman, H. R., 1993, Valley fill deposits of the Cretaceous Dakota sequences comprising a major aquifer system in Kansas: *in* Archer, A. W., Feldman, H. R., and Lanier, W. T. (ed.) Incised paleovalleys of the Douglas Group in northeastern Kansas: field guide and related contributions: Kansas Geological Survey Open-file Report 93-24, p. 16.1-16.6.

Cooper, J.B., and Davis, L.V., 1967, General occurrence and quality of ground water in Union County, New Mexico: State Bureau of Mines and Mineral Resources, Ground-Water Report 8, 168 p.

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

Darton, N.H., 1906, Geology and underground water resources of the Arkansas valley in eastern Colorado: U.S. Geological Survey Professional Paper 52, 90 p.

Dutton, A. R., 1994, Sources and ages of ground water in unconfined and confined aquifers beneath the U.S. High Plains: Final Technical Report, prepared for U.S. Geological Survey Award No. 14-08-0001-G1885, Bureau of Economic Geology, Austin, TX, 43 p.

Fader, S. W., 1968, Ground water in the Republican River area, Cloud, Jewell, and Republic counties, Kansas: Kansas Geological Survey Bulletin 188, 27 p.

Fishel, V. C., 1948, Ground-water resources of Republic County and northern Cloud County, Kansas: Kansas Geological Survey Bulletin 73, 194 p.

Gutentag, E.D., Lobmeyer, D.H., and Slagle S.E., 1981, Geohydrology of southwestern Kansas: Kansas Geological Survey Irrigation Series 7, 73 p.

Hallenburg, J.K., 1984, Geophysical logging for mineral and engineering applications: Tulsa, Oklahoma, PennWell Books, 254 p.

Hathaway, L. R., Magnuson, L. M., Carr, B. L., Galle, O. K., Waugh, T. C., 1975, Chemical quality of irrigation waters in west-central Kansas: Kansas Geological Survey Chemical Quality Series 2, 46 p.

Helgeson, J.O., Leonard, R.B., and Wolf, R.J., 1994 Aquifer systems underlying Kansas, Nebraska, and parts of Arkansas, Colorado, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming--hydrology of the Great Plains aquifer system in Nebraska, Colorado, Kansas, and adjacent areas: U.S. Geological Survey Professional Paper 1414-E, 161 p.

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

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

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

Macfarlane, P.A. and Whittemore, D.O. Chu, T., Butler, J.J., Jr., Wade, A., Coleman, J., Doveton, J.H., Mitchell, J., and Kay, S., 1992, The Dakota Aquifer Program: annual report, FY91: Kansas Geological Survey, Open-file Report 92-1, 93 p.

Macfarlane, P.A., 1993, The effect of topographic relief and hydrostratigraphy on the upper part of the regional ground-water flow system, southeastern Colorado and western and central Kansas with emphasis on the Dakota aquifer: Ph.D. thesis, University of Kansas, Lawrence, KS, 197 p.

Mazor, E., and Nativ, R., 1992, Hydraulic calculation of groundwater flow velocity and age: examination of the basic premises: Journal of Hydrology, 138, pp. 211-222.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 586 p.

McLaughlin, T.G., 1954, Geology and groundwater resources of Baca County, Colorado: U.S. Geological Survey Water Supply Paper 1256, 232 p.

Orzol, L.L., and McGrath, T.S., 1992, Modifications of the U.S. Geological Survey modular, finite-difference, ground-water flow model to read and write geographic-information-system files: U.S. Geological Survey Open-File Report 92-50, 191 p.

Plummer, N., Edmonds, C. S., and Bauleke, M. P., 1963, Test-hole exploration for light-firing clay in Cloud and Ellsworth counties, Kansas: Kansas Geological Survey Bulletin 165, Part 3, 47 p.

Plummer, N. and Romary, J. E., 1947, Kansas clay, Dakota Formation: Kansas Geological Survey Bulletin 67, 241 p.

Plummer, N., Swineford, A., Runnels, R. T., and Schleicher, J. A., 1954, Chemical, petrographic, and ceramic properties of four clays from the Dakota Formation in Kansas: Kansas Geological Survey, Bulletin 109, Part 10, p. 153-216.

Prudic, D.E., 1989, Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model: U.S. Geological Survey Open-File Report 88-729, 113 p.

Robson, S.G., and Banta, E.R., 1987, Geology and hydrology of deep bedrock aquifers in eastern Colorado: U.S. Geological Survey Water-Resources Investigations Report 85-4240, 6 sheets.

Silva, P., and Bassiouni, Z., 1981, a new approach to the determination of formation water resistivity from the SP log: 22nd Annual SPWLA Symp., Paper G, 14 p.

Stullken, L.E., Watts, K.R., and Lindgren, R.J., 1985, Geohydrology of the High Plains aquifer, western Kansas: U.S. Geological Survey Water-Resources Investigations Report 85-4198, 86 p.

Swineford, A., 1947, Cemented sandstones of the Dakota and Kiowa formations in Kansas: Kansas Geological Survey Bulletin 70, Part 4, p. 57-104.

Wade, A., 1992, Ground-water flow systems and the water-resources potential of the Dakota aquifer in a two-county area in north-central Kansas: Unpublished master thesis, Department of Geology, University of Kansas, 158 p.

Wang, H.F., and Anderson, M.P., 1982, Introduction to ground-water modeling finite difference and finite element methods: San Francisco, W. H. Freeman and Co., 237 p.

Whittemore, D.O., and Fabryka-Martin, J., 1992, Halogen geochemistry of Cretaceous sandstone aquifers of North America: *in* Kharaka, Y.K., and Maest, A.S., eds., Proceedings of the 7th International Symposium on Water-Rock Interaction, Rotterdam, Netherlands, A.A Balkema Publishers, pp. 855–858.

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

Yeh, G. T., 1980, Computation of the velocity field and mass balance in the finite-element modeling of groundwater flow: *in* Symposium on modeling and low-level waste management, Denver, Colorado, Dec. 1980.