GEOLOGIC FRAMEWORK AND SUBSURFACE HYDROLOGY CONTRIBUTIONS TO THE DAKOTA AQUIFER HOMEPAGE ON THE WORLD WIDE WEB AND VOLUME 1 OF THE DAKOTA CD-ROM

By

P. Allen Macfarlane
Geohydrology Section
Kansas Geological Survey

Kansas Geological Survey
Open-File Report 96-1c

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Introduction

During the summer of 1996, a project was undertaken to make information on the Dakota aquifer in Kansas available to the public and private sectors using CD-ROM and the World Wide Web media. Both the CD-ROM and the World Wide Web Site will carry the major results of the Dakota Aquifer Program arranged in three volumes. Volume 1 is an overview of the regional geologic framework, petrophysics, regional subsurface hydrology, and regional water quality of the Dakota aquifer system in Kansas and adjoining areas in southeastern Colorado and Nebraska. Volume 2 consists of more detailed point information in data bases, geophysical logs, and miscellaneous graphics and a collection of subregional maps. Volume 3 is a compendium of the annual reports, other Dakota-related reports, theses, and dissertations. Volume 1 will be organized in such a way so that any topic can be accessed in any order desired by the user. Regional-scale maps of the Dakota aquifer including the altitude of the top and bottom, the potentiometric surface, and water quality were developed as part of a contract with the Kansas Water Office. These maps and their associated geographic information system coverages are described more fully in Kansas Geological Survey Open-File Report 96-1b.

Volume 1 has information on the following topics:

- INTRODUCTION
  - Organization of the CD set
  - System and software requirements needed to use this set
- THE DAKOTA AQUIFER PROGRAM
  - Program description
  - Dakota aquifer extent in North America and in Kansas
- GEOLOGIC FRAMEWORK
  - Stratigraphy
  - Depositional environments
  - Sandstone body geometry and distribution
  - Characterization of sandstone body geometry and distribution
    - stratigraphic modeling
    - the Hodgeman County study
    - seismic methods

PETROPHYSICS
- Logging tools
- Log types
- Uses of the logs

SUBSURFACE HYDROLOGY
- Regional hydrostratigraphy
  - regional aquifer and aquitard units in western and central Kansas
  - hydraulic connections between regional aquifers
  - local aquifer and aquitard units in the Dakota aquifer system
- Steady-state regional flow systems
  - flow system hierarchies
  - sources of local and regional recharge
  - local and regional discharge areas of the Dakota aquifer
  - heat transport from the Denver basin
  - effects of local heterogeneity on flow and mass transport
- Water-resources development and management
  - history of water-resources development in the Dakota aquifer
  - sustainability of water resources from the confined Dakota aquifer
  - management of the coupled High Plains/Dakota system in Southwest Kansas
  - management of the Dakota aquifer in north–central Kansas
  - well-spacing requirements

WATER QUALITY
- Regional water quality in the Dakota aquifer
  - distributions of constituents
  - factors controlling constitiuent concentrations
- Effects of Dakota discharge on surface-water quality
- Assessment of water quality relative to water use

Volume 2 contains the following information:

GEOLOGIC FRAMEWORK
- Township-by-township type gamma-ray logs of the shallow subsurface for most of central and western Kansas
- Formation tops from the township-by-township type logs in tabular form
- Formation tops for the T. 16 S. and T. 11 S. geologic cross sections across western and central Kansas
- Gamma-ray logs used in the Hodgeman County study
- Formation tops from the Hodgeman County study
- Atlas of the subsurface hydrostratigraphy of southwestern Kansas
- Descriptions of the core samples collected from test-holes penetrating the Dakota aquifer

PETROPHYSICS
- Logging data in LAS format from Dakota Aquifer Program test holes

SUBSURFACE HYDROLOGY
- Water-level data used to generate the potentiometric surface map of the steady-state Dakota aquifer
- Hydrologic properties data for the Dakota aquifer
- Thermal logs of western and central Kansas

WATER QUALITY

Water quality data

Estimates of water quality in the Dakota aquifer from borehole geophysical log measurements of SP and resistivity

Volume 3 contains the following reports, theses, and dissertations (in chronological order):

Reports:

Macfarlane, P.A., Townsend, M.A., and Whittemore, D.O., 1988, Hydrogeologic assessment of the continued suitability of shallow underground disposal of oil-field brines in the Cedar Hills Ss., central Kansas: Kansas Geological Survey Open-File Report 88-39, 193 p.

Macfarlane, P. A., 1989, The impact of the regional ground-water flow system on water quality in the Dakota and overlying aquifers and surface waters in central Kansas. Kansas Geological Survey Open-File Report 89-30, 26 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 90-27, 302 p.

Macfarlane, P.A., Hamilton, V.J., Wade, A., and Meehan, T.J., 1990, The Dakota aquifer program: annual report, FY89, map plates 1 and 3–11: The Dakota Aquifer Program: Annual Report, FY89, Map Plates, Kansas Geological Survey, Open-File Report 90-27A, 1:500,000 scale.

Macfarlane, P.A., Whittemore, D.O., Townsend, M.A., Butler, J.J., Jr., Doveton, J.H., Hamilton, V.J., Chu, T.M., Wade, A., and Macpherson, G.L., 1991, The Dakota Aquifer Program: annual report, FY90: Kansas Geological Survey, Open-File Report 91-1, 42 p.

Macfarlane, P.A., Wade, A., Doveton, J.H., and Hamilton, 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, 73p.

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

Macfarlane, P.A., 1991, The Dakota aquifer in Kansas: Program with abstracts, University of Kansas, Lawrence, Kansas, 20 p.

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

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.

Macfarlane, P.A., Whittemore, D.O., Doveton, J.H., Chu, T., Smith, M., and Feldman, H., 1995, The Dakota Aquifer Program annual report, FY93: Kansas Geological Survey Open-File Report 94-1, 115 p.

Feldman, H.R., 1994, Road log and field guide to Dakota aquifer strata in central Kansas: Kansas Geological Survey Open-File Report 94-15, 30 p.

Macfarlane, P.A., 1994, Water and energy resources of the Dakota aquifer: workshop and clinic program and abstracts: Kansas Geological Survey and the Kansas Ground Water Association, Great Bend, Kansas, 37 p.

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

Macfarlane, P.A., 1995, The effect of river valleys and the Upper Cretaceous aquitard on regional flow in the Dakota aquifer in the central Great Plains of Kansas and southeastern Colorado: Kansas Geological Survey Bulletin 238, pp. 11–30.

Butler, J.J., Healey, J.M., and Macfarlane, P.A., 1995, Relationship between pumping-test and slug-test parameters: scale effect or artifact? Kansas Geological Survey Open-File Report 95-63, 27 p.

Theses and Dissertations

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

In order to take full advantage of the contents on the three CD volumes users will need to meet certain system and software requirements to run MOSAIC, a public-domain software. For the Macintosh: a hard drive with System 7.0 or later, 68020 or later processor, 6 MB RAM, and MACTCP2.02 or later. Other associated public-domain software that will be needed to display images, produce sound, and run the video clip include JPEGVIEW for JPEGs and GIFs, SPARKLE for MPEGS, and SOUNDMACHINE for audio input and output. For the IBM-compatible personal computers (386 or better): Windows 3.1x, Windows for Workgroups 3.1x, Windows NT 3.5x or better or Windows 95, an 80386SX co-processor in enhanced mode, and 4MB RAM.

An executable version of MOSAIC (v. 2.01 for the Macintosh or v. 2.0 for the IBM compatible personal computer) will be included in Volume 1 of the CD set.

The following is a compilation of the information provided by the author in 1997 to this project for use on the CD-ROM and the Dakota aquifer World Wide Web site.

EXTENT OF THE DAKOTA AQUIFER

The Dakota aquifer system and its equivalents extend across much of the central North American continent. Figure 1 is a map showing the Dakota extent in North America. The contiguous aquifer system extends northward from Kansas approximately to the Arctic Circle in Canada, southward into northeastern New Mexico and the Oklahoma panhandle, westward to the Rocky Mountain front, and eastward to western Iowa and Minnesota. Across the Continental Divide, the Dakota aquifer is present in many of the intermontane basins. In Kansas, the Dakota is present in most of the western two-thirds of the state. Figure 2 shows that the aquifer extends westward from Washington County in the north–central part of the state and northward from Morton County in southwestern Kansas. In all the Dakota is present in 59 of the 105 counties in the state.

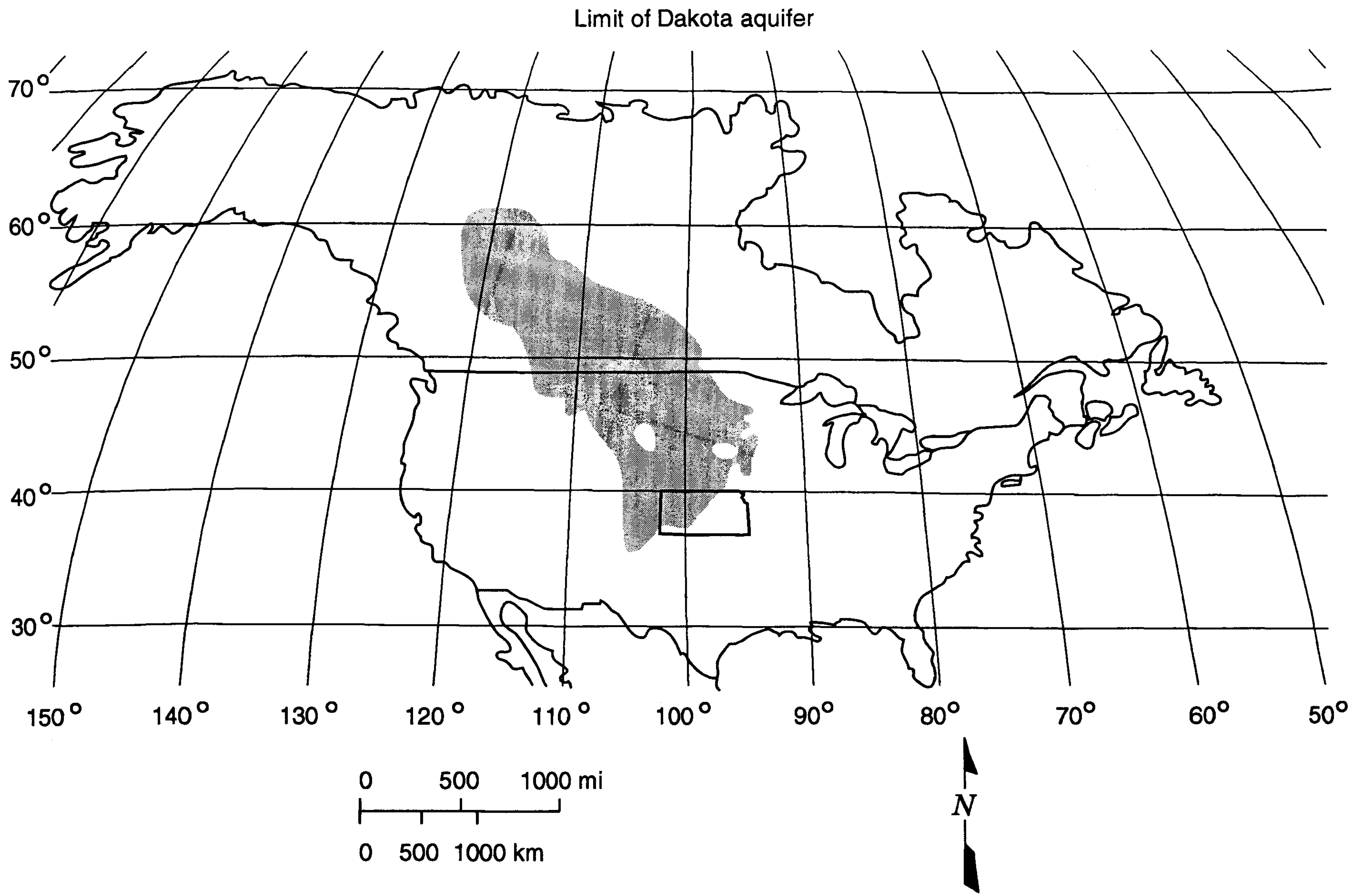

Figure 1. Extent of the Dakota aquifer in North America

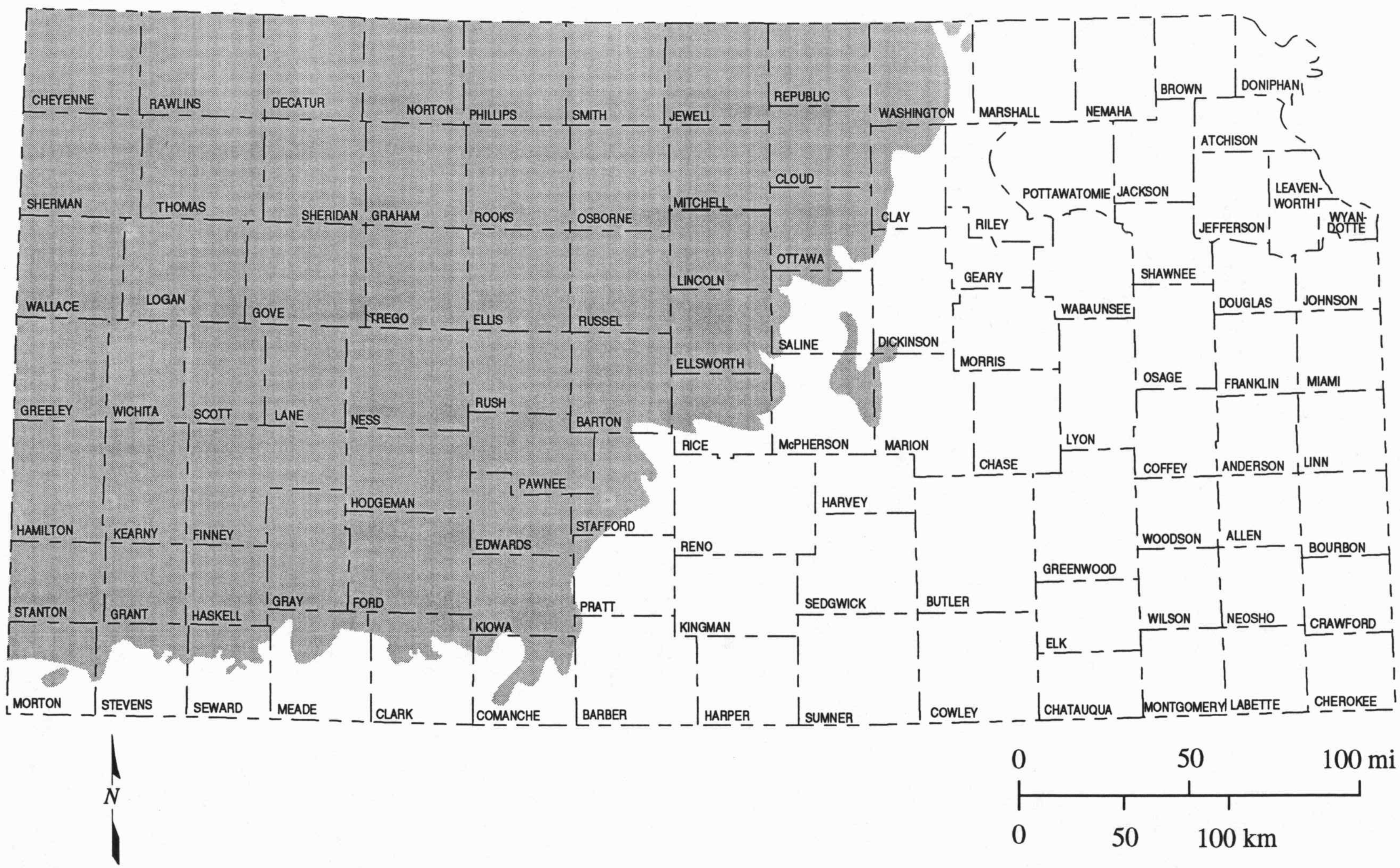

Figure 2. Extent of the Dakota aquifer in Kansas.

THE DAKOTA AQUIFER PROGRAM

More than eight years ago, state and local agencies recognized the localized depletion of near-surface sources of water in western and central Kansas and the need to identify other sources that might replenish available supplies. This focused the attention of the water agencies on the Dakota, a deeper and more complex sandstone aquifer system.

The Dakota has been used as a source of water for more than a century, but its hydrologic character has been poorly understood and the issues surrounding its use have been inadequately addressed. Little was known about either the quantity or the quality of ground water or the impact of regional or local development on the Dakota that could be used to guide regional or local planning until recently. There were also concerns related to human activity, such as the potential hazards of disposing oil-brine in shallow zones beneath the Dakota in central Kansas and the protection of usable ground-water resources in the Dakota.

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

During the planning stage it was recognized that a multidisciplinary effort was needed to understand the influence of the aquifer framework geology on the subsurface hydrologic system and water quality. As a result the backbone of the program is an integrated, interdisciplinary research strategy that incorporates elements of stratigraphy and sedimentology, petrophysics, subsurface hydrology, and water quality. Furthermore, the wide extent of Dakota in Kansas mandated a phased approach to the research to keep the size and scope of the investigations manageable. Thus the focus of the research has shifted with time from where the aquifer is shallow and currently under development (State FY90–94) to the deeper, undeveloped regions in northwest Kansas (State FY95–96). Each subregional project began with data-base development, progressed to the formulation of conceptual and mathematical models, and finally, applied the models to management issues with state and local agency input. Data-base development, mapping, data analysis, and mathematical modeling of the system were facilitated using state-of-the-art software packages.

STRATIGRAPHY

INTRODUCTION

The total thickness of sedimentary rocks above the Precambrian varies considerably across the study area ranging from less than 2,000 ft. in southeastern Colorado on the Sierra Grande and Apishapa uplifts to almost 7,000 ft. in the western Kansas basin. The strata range in age from Cambrian to the Holocene and consist of both consolidated and unconsolidated deposits that were deposited in marine and nonmarine environments. Periodic episodes of deposition, uplift, and erosion over geologic time and local variations in the rates of these processes are largely responsible for the observed variation in thickness of sedimentary strata in the study area. Table 1 shows the subdivision of the strata above the Permian Sumner Group into geologic units.

REGIONAL SEDIMENTARY ARCHITECTURE LITHOSTRATIGRAPHY OF THE DAKOTA AQUIFER

The Dakota aquifer is composed of the Cheyenne Sandstone, and the Dakota and Kiowa Formations, and is overlain by the Graneros Shale (Table 1). The Cheyenne Sandstone consists predominantly of cross-bedded, fine to medium sandstone with lenses of shale and conglomerate. It was deposited in fluvial to deltaic environments and rests unconformably on Permian and Jurassic rocks (Latta, 1946; Hamilton, 1994). The Cheyenne is variable in thickness, ranging up to 260 ft. (Merriam, 1957), but is typically less than 100 ft. thick, and tends to thicken into paleotopographic lows (Latta, 1946; Merriam, 1957; Hamilton, 1994). This basal Cretaceous unit has been termed the Plainview Member of the Purgatoire Formation on the basis of correlation to the type area in Colorado (Hamilton, 1994; Scott et al., in press).

The Kiowa Formation overlies the Cheyenne Sandstone, is an open-marine shale typically 100–150 ft. thick (Scott, 1970). The Kiowa also contains interbedded sandstone, siltstone, and shale deposited in open-marine, barrier-bar, nearshore, and deltaic environments (Franks, 1966, 1975; Scott, 1970). Where the Cheyenne is absent, the basal Kiowa lies directly on Permian and Jurassic rocks. In south–central Kansas outcrops of the contact between the Cheyenne and Kiowa have been described as both abrupt and unconformable (Franks, 1975). In other outcrop areas the contact is apparently conformable (Latta, 1946). In the subsurface, the transition from Cheyenne to Kiowa is commonly gradational with an upward increase in the proportion of shale, a decrease in sandstone bed thickness, and an increase in bed continuity. The Kiowa sandstones, as observed on subsurface data, are thickest near the base of the Kiowa (typically 30 ft. thick) and show coarsening-upward characteristics. These sand-rich deposits are interpreted to represent transgressive deltaic deposits. Locally, with an extensive log data base, some basal Kiowa deltaic sections can be laterally correlated to basal Cheyenne-type sandstones.

<table>
<tr><th>ERA</th><th>SYSTEM</th><th>SERIES</th><th colspan="3">ROCK STRATIGRAPHIC UNITS</th></tr>
<tr><td rowspan="2">Cenozoic</td><td>Quaternary</td><td></td><td colspan="3">Unconsolidated alluvial and eolian deposits</td></tr>
<tr><td>Tertiary</td><td></td><td colspan="3">Ogallala Formation</td></tr>
<tr><td rowspan="7">Mesozoic</td><td rowspan="6">Cretaceous</td><td>Upper Cretaceous</td><td>Colorado Group</td><td colspan="2">Pierre Shale
Niobrara Chalk
Carlile Shale
Greenhorn Limestone
Graneros Shale</td></tr>
<tr><td rowspan="5">Lower Cretaceous</td><td colspan="2" rowspan="2">Dakota Formation</td><td>Jansen Member</td></tr>
<tr><td>Terra Cotta Member</td></tr>
<tr><td colspan="2" rowspan="2">Kiowa Formation</td><td></td></tr>
<tr><td>Longford Member</td></tr>
<tr><td colspan="3">Cheyenne Sandstone</td></tr>
<tr><td>Triassic/Jurassic</td><td></td><td colspan="3">Dockum Group/Morrison Formation</td></tr>
<tr><td rowspan="2">Paleozoic</td><td rowspan="2">Permian</td><td>Guadalupian</td><td colspan="3">Big Basin Formation
Day Creek Dolomite
Whitehorse Formation</td></tr>
<tr><td>Leonardian</td><td>Nippewalla Group</td><td colspan="2">Dog Creek Formation
Blaine Formation
Flower Pot Shale
Cedar Hills Sandstone
Salt Plain Formation
Harper Sandstone
Stone Corral Formation</td></tr>
</table>

Table 1. Stratigraphy of the shallow subsurface of western and central Kansas.

Isolated sandstone bodies in the middle and upper Kiowa tend to be thin (less than 10 ft.) and laterally continuous for at least 10–20 mi. and are interpreted as shelf storm deposits.

The Longford Member of the Kiowa Formation originally was restricted to regressive siltstones, sandstones, and mudstones in the lower Kiowa in north–central Kansas (Franks, 1979). These facies were interpreted to have been deposited in lagoonal, estuarine, and fluvial environments (Franks, 1980). The term has since been extended to include a range of nearshore facies transitional between the Kiowa Formation and Cheyenne Sandstone throughout Kansas (Hamilton, 1994).

The Dakota Formation in Kansas lies between the Kiowa Formation below and Graneros Shale above (Table 1). The lower contact is erosional and separates the underlying marine to deltaic deposits from Dakota Formation terrestrial facies (Hamilton, 1994). Thick, cross-bedded unfossiliferous sandstone bodies in central Kansas have been described as marine barrier bars in the Kiowa Formation (Franks, 1979; Bayne et al., 1971). However, evidence in favor of interpreting them as fluvial deposits within incised valleys in the basal Dakota Formation includes concave-up erosional bases, abundance of clay pebbles, and the lack of marine fossils or bioturbation (Hamilton, 1989, 1994). The Dakota is generally 200–300 ft. thick in Kansas (Macfarlane et al., 1990) and consists of fluvial and deltaic/estuarine sandstone bodies encased in a matrix of alluvial plain to shallow marine claystone and siltstone deposits. Plant fossils and thick paleosols are common. In cores and on outcrop the sandstones are fine to medium, well sorted, and contain large-scale and small-scale cross-beds. These sandstone bodies are interpreted as fluvial channel deposits. Paleocurrent indicators throughout the Dakota Formation generally trend west to southwest (e.g., Siemers, 1976; Franks et al., 1959). Basal Dakota sandstone bodies thicken appreciably into paleotopographic lows on the unconformity reaching a maximum thickness of approximately 120 ft. In the lower half of the formation, sandstone beds are abruptly capped by fine-grained deposits or have a fining-upward succession. The Rocktown channel sandstone in the upper Dakota is a long-recognized outcrop expression of a channel sandstone in Russell County, Kansas. This channel contains cross-bedded, fine to coarse, fluvial sandstone in a discontinuous, narrow (1–2 mi. wide or less), sinuous belt that has been traced along a straight-line distance of 27 mi. (Rubey and Bass, 1925; Siemers, 1971, 1976). The upper Dakota fluvial complexes were transgressed and evolved into deltaic and estuarine environments (Siemers, 1976).

The lower Graneros Shale is composed of dark-gray silty shale with starved ripples, irregularly laminated siltstone and fine sandstone, thin-bedded sandstones, and bone and shell lags (Hattin and Siemers, 1987). The Graneros/Dakota contact appears transitional on outcrop and in shallow subsurface cores (Feldman, 1994; Gellasch and Hattin, 1994).

SEQUENCE STRATIGRAPHY

Rocks that constitute the Dakota aquifer are best understood within the framework of sequence stratigraphy (Hamilton, 1989, 1994; Coleman and Turbek, 1992). Sequence stratigraphic models for early Cretaceous rocks of the Western Interior seaway were initially developed along the Front Range in Colorado, where intertonguing of marine and continental rocks and deeply incised sequence boundaries provided key stratigraphic markers (Weimer and Land, 1972). The correlations of sequences on the western edge of the basin were subsequently extended throughout the Western Interior and into Kansas (Weimer, 1984) and then to the Texas Gulf Coast with the addition of biostratigraphic control (Scott et al., in press).

Following the models of Weimer (1984), Hamilton (1989, 1994), Coleman and Turbek (1992), and Scott et al. (in press), the units that make up the Dakota aquifer are divided into three sequences, the Cheyenne-Kiowa sequence, the Dakota J sequence, and the Dakota D sequence (Figures 1 and 2). A major Cretaceous unconformity lies at the base of the Dakota aquifer; Permian and Jurassic rocks were exposed and eroded prior to Cretaceous deposition. The oldest recognized Cretaceous sequence in Kansas is the Cheyenne/Kiowa sequence, which extends from the base of the Cheyenne Sandstone to the top of the Kiowa Formation. The Cheyenne Sandstone was deposited over the unconformable surface in fluvial and coastal-plain environments prior to transgression of the Kiowa sea into Kansas. The sharp contact between the Cheyenne Sandstone and Kiowa Formation is a transgressive surface of erosion that formed by shoreface erosion during the eastward migration of the shore line (Hamilton, 1994; Scott et al., in press). The overlying Kiowa Formation is a transgressive deposit that records widespread marine flooding of the Western Interior basin. The maximum extent of the Kiowa sea is not known because of post-Kiowa erosion, but Franks (1979) suggested that the distribution of nearshore facies in the type Longford Member indicates that the present eastward limit of the Kiowa Formation approximates the maximum extent of the transgression.

The Dakota J sequence extends from base of the Dakota Formation to the D unconformity near the middle of the Dakota Formation (Figures 1 and 2). A major drop in sea level resulted in subaerial exposure and erosion of Kiowa deposits. Thick, cross-bedded fluvial sands and alluvial-plain sediments were deposited within paleovalleys and then across the interfluves. Thick paleosols are common within the J section, and evidence of marine influence is lacking except in extreme western Kansas. The basal Dakota unconformity is correlated in central Colorado with the base of the J sandstone (Weimer, 1984). In the Denver basin this J sequence culminates upwards with the marine Huntsman Shale, which is present only locally in northwestern Kansas (Hamilton 1994).

Weimer (1984), Hamilton (1994), Coleman and Turbek (1992), and Scott et al. (in press) all have recognized a mid-Dakota sequence boundary in Kansas that correlates with the

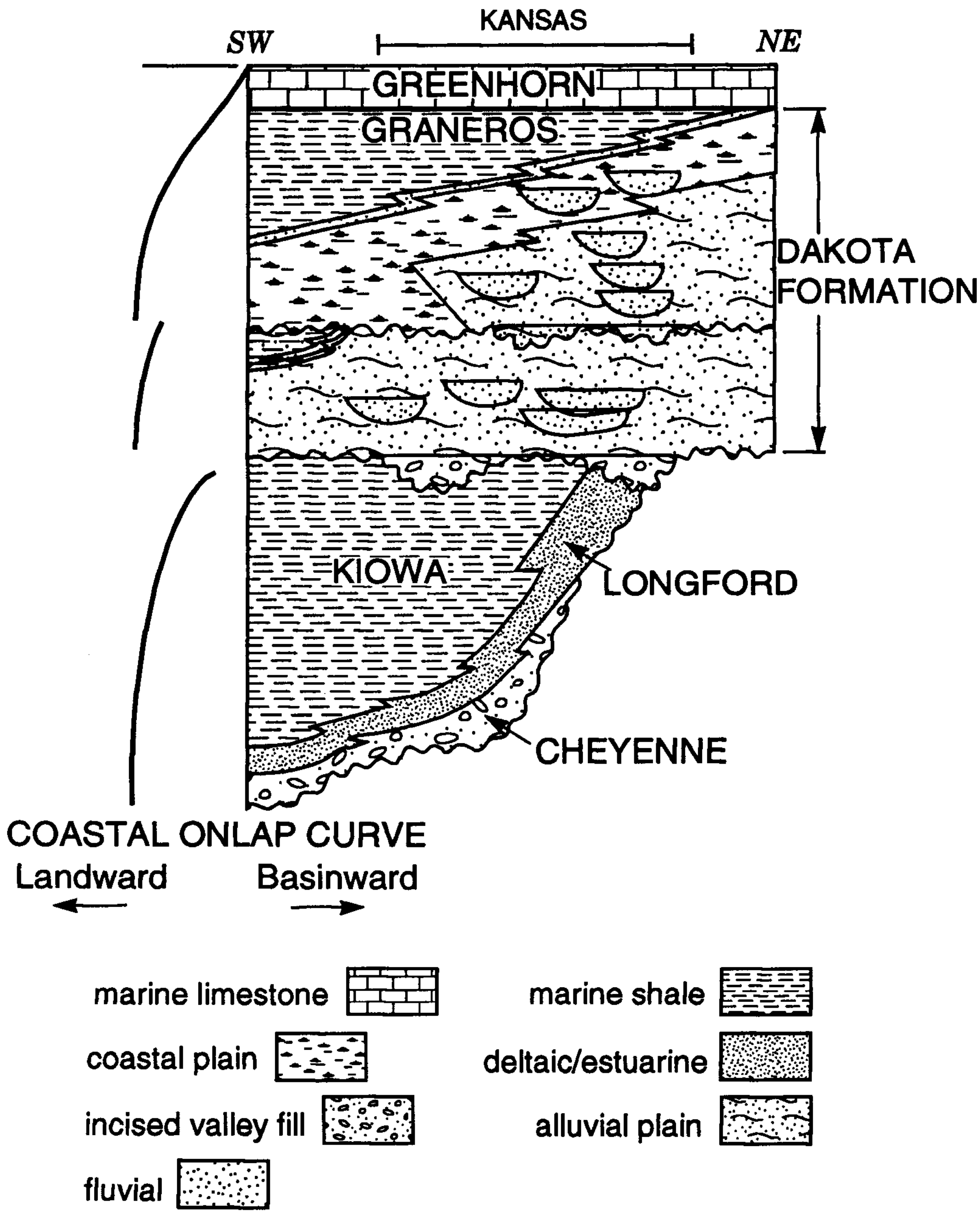

Figure 1. Regional cross section showing sequence stratigraphy of the Greenhorn Limestone and pre-Greenhorn Cretaceous deposits in Kansas and adjacent areas

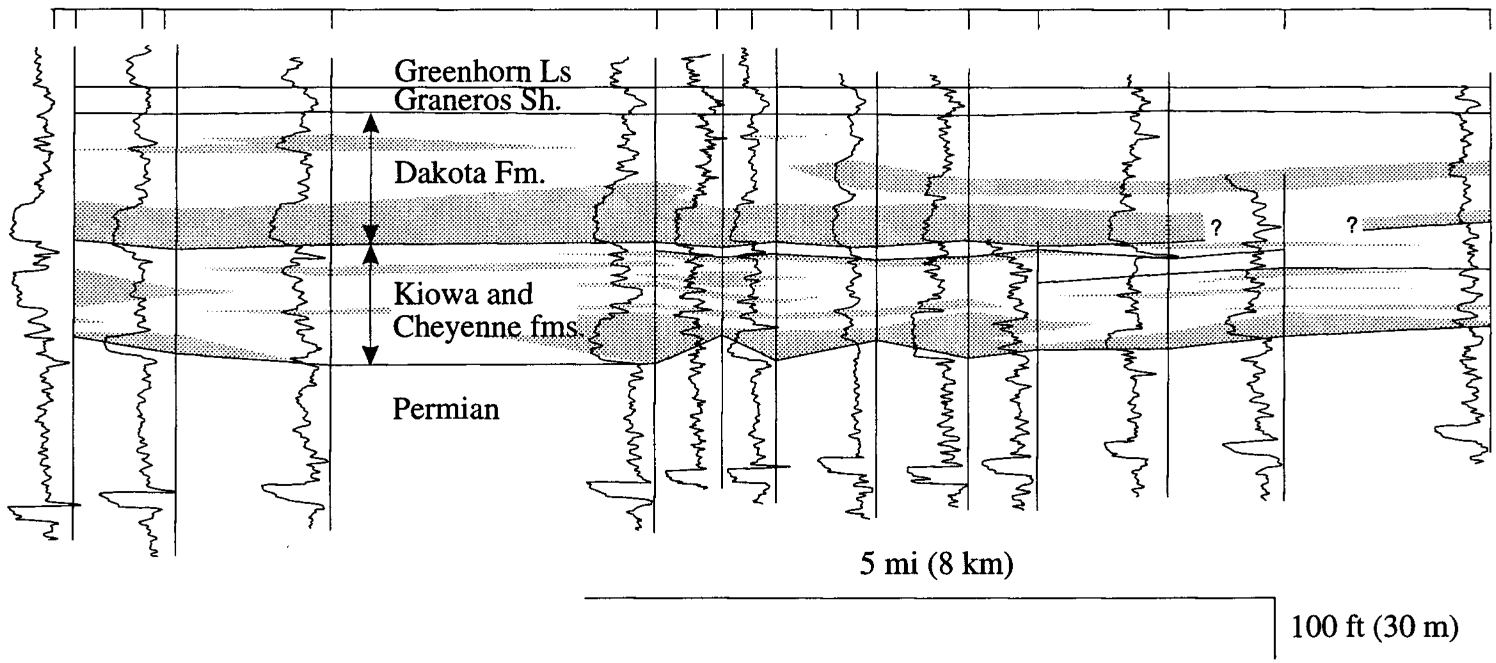

Figure 2. Gamma-ray cross section showing the subsurface stratigraphy and distribution of sandstone bodies in the Dakota, Kiowa, and Cheyenne Sandstone formations in northeastern Barton and western Ellsworth counties in Kansas. The basal Cretaceous surface is the base of the Kiowa-Cheyenne sequence. The contact between the Dakota and the Kiowa and Cheyenne Sandstone formations is the base of the J sequence. The base of the D sequence in the Dakota Formation can not be distinguished in this cross section.

unconformity between the D and J sandstones along the Front Range in central Colorado. In northwestern Kansas the boundary between the D and J sequences is placed at the unconformity between the Huntsman Shale below and fluvial facies above. The mid-Dakota sequence boundary is difficult to correlate across Kansas because of the lack of marine facies, but Hamilton (1989, 1994) identified the boundary in central Kansas at an upward abrupt change from meandering-stream deposits to braided-stream deposits. Associated with the braided river deposits are granules of chert and quartz that may indicate a lowering of base level (Hamilton, 1989). This sequence boundary has been identified in the Amoco Bounds #1 core from western Kansas as falling within a 30 ft. section of paleosols and overbank deposits (Hamilton, 1994; Scott et al. in press). The D sequence extends from the mid-Dakota sequence boundary to the unconformity at the base of the Carlile Shale (Hamilton, 1989) above the Graneros Shale.

Thick, clean, discontinuous fluvial channel sandstones were deposited above the D unconformity. In the upper Dakota, sandstone bodies are thinner and more laterally continuous, reflecting a transgressive deltaic/estuarine setting. In outcrop uppermost Dakota deposits show evidence of marine influence, including bioturbation and rare body fossils (Seimers, 1971; Gellasch and Hattin, 1994). The contact between the Dakota and overlying marine Graneros Shale has been interpreted as a transgressive surface of erosion (Hamilton, 1994).

VISUALIZATION OF REGIONAL STRATIGRAPHY

Geophysical logs are the continuous records of physical properties of rocks in boreholes drilled for hydrocarbons, minerals, or water. They are made by electrical, acoustic, and nuclear tools suspended on a wireline and winched upwards through the formations penetrated by the borehole. Most logging tools are run by the oil industry in both exploration holes and producing wells. Consequently, log analysis is a methodology geared mainly to the location of oil and gas. Fortunately, many of the rock properties that are used to characterize hydrocarbon reservoirs are also key parameters for aquifers. However, there are also some significant differences, so that adaptations of traditional methods of data analysis must be made with caution. The long history of oil exploration in Kansas has resulted in the recording of hundreds of thousands of logs across the state. The Dakota Aquifer Program has developed a large regional database of digital gamma-ray logs drawn from this library, which are being used for detailed mapping of inferred aquifer and aquitard units. This data base can be found on Volume 2 of this CD set.

Gamma-ray logs record natural gamma radiation, which can be attributed mainly to sources of potassium-40 and radioactive isotopes of the uranium and thorium families. The logs are conventionally recorded in API (American Petroleum Institute) units, which although arbitrary, do allow consistent comparisons between boreholes (Doveton, 1986). The sandstones of the Dakota aquifer have fairly low radioactivity since they consist mainly of quartz and water, with only minor amounts of clays, feldspars, and other accessory minerals (Franks, 1966). By contrast, the interbedded shales have moderate radioactivity caused by thorium adsorbed on the clay platelets, potassium in the composition of some clays, and variable amounts of uranium generally associated with organic matter and fixed under reducing conditions. Further details on the use of logs for determining the lithologic character of the subsurface can be found in the Petrophysics directory on this volume of the CD set.

Digital gamma-ray logs from wells along a lengthy east-west traverse along T. 16 S. in central and western Kansas were transformed to gray-level image strips, where the darkness intensity is a function of the natural gamma radioactivity of the logged formations. Under this system, sandstones and limestones appear as white or pale gray, while shales register as dark gray or black. When hung together on a common stratigraphic horizon (the top of the Graneros Shale) and arranged in correct geographic order, the result is a regional gray-level image of the subsurface geology of the Permian to Cretaceous sequence shown schematically in Table 1. In order to accentuate differences between the various lithologies, the gray levels were further converted to a range of false colors (Figure 3). Lighter colors were selected to represent low gamma-ray values and darker colors for high gamma-ray values. The major advantage of this approach is that the information is coded in a visual form that is close to a simulation of how the subsurface geology would actually appear, when making allowance for the vertical exaggeration. The immediacy of the image frees the observer to focus easily on structural and stratigraphic features of all kinds. In addition, gamma-ray-log cutoff criteria, discussed later in this paper, for aquifers and aquitards can be applied immediately in visual assessments of aquifer geometries.

The original version of the regional image required remedial processing to normalize the gamma-ray logs on which the image is based. Two stratigraphic units were selected to function as calibration standards: the Graneros Shale (Upper Cretaceous) as the "hot" standard (high gamma-ray values and darker colors) and the Stone Corral Formation (Lower Permian) as the "cold" standard (low gamma-ray values and lighter colors). The use of two different standards allows correction of random errors that involve both shift and stretch of the log with respect to its true scale. The choice of each was based on a geological perception that major local changes (at a scale less than the distance between section wells) would be fairly minor. Instead, the gamma-ray response of these units would be dominated by a regional trend but confounded by random measurement error.

On the cross section in Figure 3, the Stone Corral Formation forms a distinct and continuous light-colored band at the base of the section. The Cedar Hills Sandstone (Table 1) is the most obvious feature in the overlying Permian as a thick wedge that subcrops at the base of the Cretaceous to the east. In the interval that includes the Dakota Formation, the Kiowa Formation, and the Cheyenne Sandstone, most of the strata register as blue, purple, and red bands

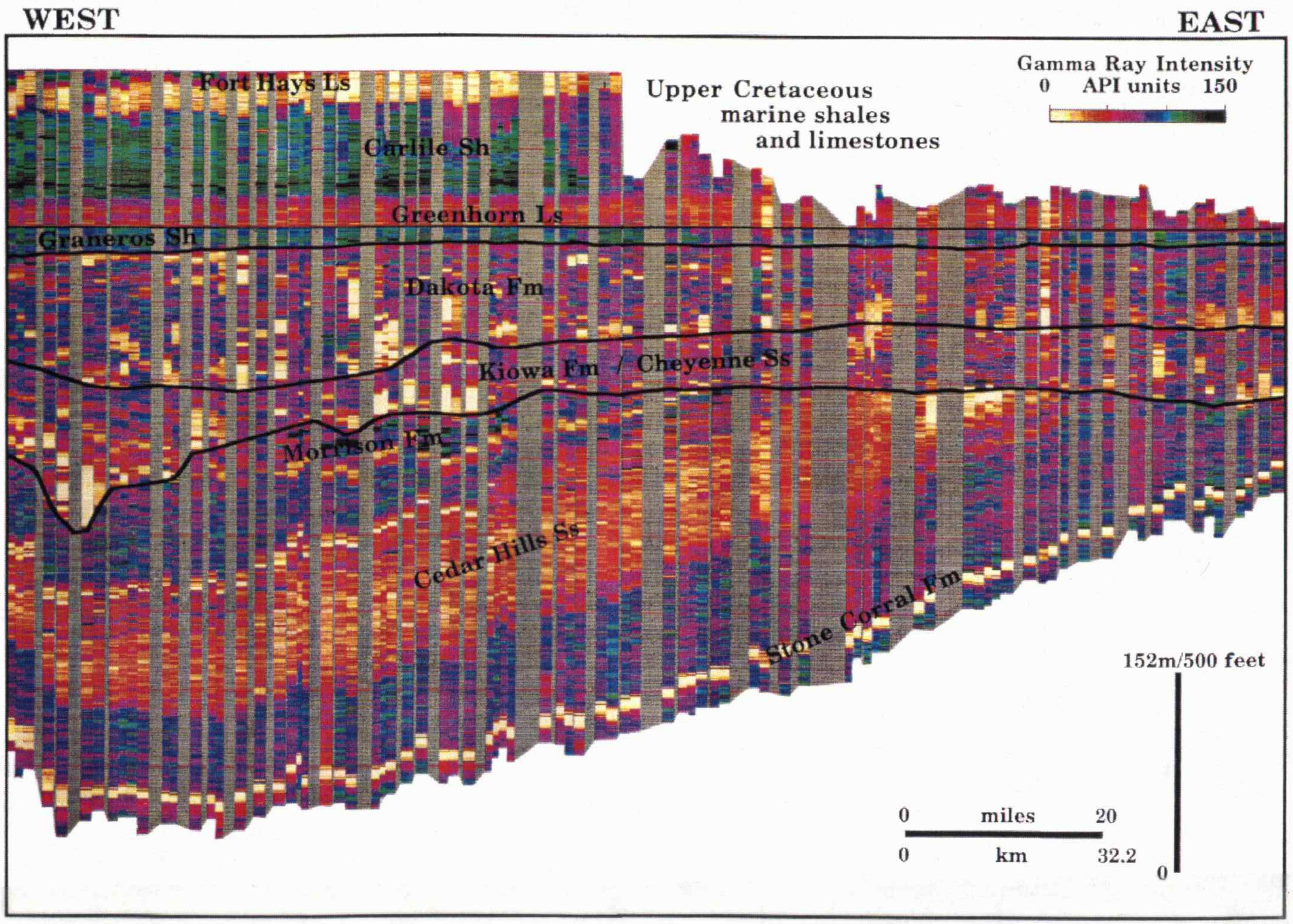

Figure 3. Colorized gamma-ray log intensity image of the Permian-Cretaceous section in western Kansas along Township 16. Each strip is a false-color rendition of a gray-level transformation of a gamma-ray log. Datum is the base of the Greenhorn Limestone.

on the cross section. This results from the shaly character of the mudstone that makes up most of the Dakota aquifer. In contrast, the sandstones register as light yellow to orange in the vertical section. Sandstones in the Cheyenne–Longford sequence appear to be traceable for considerable distances, and contrast with the rather patchy sandstone developments within the Dakota Formation. The patchiness is the expected outcome of the intersection of the east-west cross-section plane with the sinuous deposits of alluvial channel networks and the complex facies mosaics of the coastal and alluvial plains. The more shaly part of the marine transgressive sequence in the Upper Cretaceous above the Dakota Formation (Graneros Shale, Greenhorn Limestone, Carlile Shale in Table 1) shows as darker-colored blue, green, and black regional bands near the top of the section. The lighter orange to reddish-purple bands are chalky shales and limestones in the Greenhorn Limestone. At the very top, the chalky limestone of the Fort Hays Member, Niobrara Chalk, shows as a yellow to orange band in the western part of the cross-section.

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DEFINITION AND DELINEATION OF HYDROSTRATIGRAPHIC UNITS

A hydrostratigraphic unit can be defined as a part of a body of rock that forms a distinct hydrologic unit with respect to the flow of ground water (Maxey, 1964). In a review of the concept, Seaber (1988) redefined the term as "a body of rock distinguished and characterized by its porosity and permeability". Delineation of these units subdivides the geologic framework into relatively more or less permeable portions and thus aids in definition of the flow system. Table 1 shows the hydrostratigraphic column in comparison to the stratigraphic section above the Sumner Group in central and western Kansas. All of the regional aquitards consist largely of shale and are much less permeable than the regional aquifers by many orders of magnitude. As a result, the regional aquitards pose significant barriers to the vertical flow of ground water. By comparison the permeability contrasts between aquifers in Kansas are relatively small and do not significantly affect the regional flow of ground water.

Delineation of hydrostratigraphic units at the regional scale involves the application of: (1) lithostratigraphic and sequence stratigraphic concepts to the deposits in order to derive an overall conceptual framework of the strata where appropriate, (2) subsurface mapping using cores, driller's logs, and geophysical logs to define lithofacies, (3) laboratory testing of core samples of aquifer and aquitard units, (4) *in situ* hydraulic testing of aquifer and aquitard units, (5) generalizations about effective porosity and permeability comparisons between lithologies in the geologic framework, (6) limited information on the effect of geologic history including diagenetic processes and tectonics on the geologic framework and its properties, and (7) the results of previous research.

Gamma-ray and sample logs of boreholes drilled for hydrocarbon exploration and production, sample logs of test holes and water wells, and cores were used to delineate the subsurface stratigraphy and the major lithofacies in the study area. The gamma-ray log records the natural gamma-ray radiation that emanates from geologic media. The natural gamma-ray radiation is measured by a tool that is passed along the length of the borehole. The logs that were used to delineate the subsurface hydrostratigraphy were calibrated to a standard in API units.

On the gamma-ray logs formation tops were delineated using the shapes of the log traces and used to correlate the subsurface stratigraphy between boreholes to produce maps and cross sections of subsurface geology. The gamma-ray log was also used for distinguishing between clayey strata and non-clayey strata in the subsurface and thus to differentiate between shaley rocks and sandstones and limestones (Doveton, 1986). Owing their vertical and lateral lithologic continuity, a lithostratigraphic approach to correlation and subsurface mapping is adequate for many of the geologic units in the subsurface.

Table 1. Stratigraphy and hydrostratigraphy of the shallow subsurface in Kansas.

<table>
<tr><th>ERA</th><th>SYSTEM</th><th colspan="3">ROCK STRATIGRAPHIC UNITS</th><th>HYDROSTRATIGRAPHIC UNITS</th></tr>
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<tr><td rowspan="3">Paleozoic</td><td rowspan="3">Permian</td><td colspan="3">Undifferentiated Permian</td><td>Permian aquitard</td></tr>
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</table>

However, within the heterogeneous Dakota aquifer system a strictly lithostratigraphic approach to its hydrostratigraphy is not appropriate because it is difficult to recognize the physical continuity of the deposits locally. Sequence stratigraphy is the study of genetically related units that are packaged into sequences (Van Wagoner et al., 1990). Each sequence is bounded above and below by subaerial unconformities and their correlative conformities. Subaerial unconformities result from lowering of sea level and subaerial exposure of the former sea floor. The areal extent of each unconformity depends largely on the amount of sea level lowering. Each sequence, therefore, is formed by a single cycle of transgression and regression during which a wedge of sediment is deposited that generally thickens and is more marine basinward. Given similar conditions from sequence to sequence, predictable patterns of facies distributions are expected. Sequence stratigraphic models can be extended into areas of low data density in order to predict facies patterns. Facies distributions may be helpful in developing a framework within which to correlate hydraulic properties with lithology (Anderson and Woessner, 1992).

Hydraulic properties data from the subsurface come primarily from the major aquifer units, and are unevenly distributed and data on the aquitard units in Kansas and eastern Colorado are unknown. However, permeability is often a function of rock type. The permeability of sandstone, limestone, and shale each vary over three or more orders of magnitude (Freeze and Cherry, 1979), but their permeability ranges frequently do not completely overlap. On the other hand, effective porosity, the percentage of interconnected void space, is directly related to the textural fabric which is related to lithology (Domenico and Schwartz, 1990). The effective porosity and permeability are usually much higher in sandstones than they are in shales or siltstones. In the case of sandstone and limestone their permeability ranges may completely overlap but frequently the nature of the permeability and porosity distribution are sufficiently dissimilar to distinguish one from the other.

Knowledge of the geologic history of the area aids in the delineation of hydrostratigraphic units by providing a framework for determining the effects of diagenetic processes and tectonics and the redistribution or alteration of initial depositional porosity and permeability of the sediment. Diagenesis is the process that a body of sediment undergoes including all of the physical, chemical, and biological changes, during the process of lithifciation after its initial deposition (Gary et al., 1972). Processes associated with burial and cementation reduce pore space and effective porosity and permeability in sandstones and shales (Schwartz and Longstaffe, 1988). Tectonic activity may increase or decrease effective porosity as a result of the imposed stress fields or failure by fracturing and faulting (Means, 1976). Uplift and subsequent erosion may substantially change the distribution of effective porosity and permeability by volume expansion from unloading or, in the case of carbonates and strata containing evaporites, dissolution of portions of the geologic framework and the formation of solution channels and fractures (Schwartz and Domenico, 1990).

Delineation of hydrostratigraphic units is aided immensely by the results of previous regional investigations. The turn of the century investigations reported by Darton (1905, 1906) provided the first insights into the ground-water flow system in the Dakota aquifer in the central Great Plains. He recognized the Dakota as a distinct and important regional aquifer system. He also realized that the shale aquitard above the Dakota was leaky and not "impermeable" to vertical flow. Belitz (1985), Belitz and Bredehoeft (1988), and Helgeson et al. (1993) demonstrated that the shale aquitards significantly isolate the Dakota and underlying aquifers from the water table in the Denver basin. Robson and Banta (1987) recognized the Dockum as a distinct aquifer unit in southeastern Colorado but did not consider the Morrison an aquifer unit. To the east in southwestern Kansas, Kume and Spinazola (1985) found irrigation wells producing from Morrison and other overlying aquifer units and considered the Morrison to be an aquifer unit of local significance.

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REGIONAL DAKOTA AQUIFER HYDROSTRATIGRAPHY

The geologic units that form the Dakota aquifer in Kansas are the Dakota Formation, the Kiowa Formation, and the Cheyenne Sandstone (Table 1). These geologic units were deposited during the Cretaceous Period in alluvial valleys and in the coastal plain adjacent to the developing Western Interior seaway (Hamilton, 1994). The combined thickness of these units can range up to more than 700 ft in west–central parts of the state. However, not all of the units that constitute the Dakota contain aquifer-grade material that can yield water to wells. The amount of sandstone, considered to be the aquifer material, varies from less than 5% to more than 50% of the total thickness, even over distances of less than a mile. More information on the stratigraphy of these deposits can be found on this volume of the CD set in the Geologic Framework directory.

At the regional scale, the Dakota aquifer system consists of upper and lower units (Table 1; Figure 1). The upper aquifer unit consists entirely of the Dakota Formation and the shoreline deposits at the top of the Kiowa Formation and is approximately 300 ft thick. The lower aquifer unit consists of the Longford Member of the Kiowa Formation and the Cheyenne Sandstone and varies considerably in thickness up to 200 ft. These upper and lower regional aquifers are separated in western and parts of central Kansas by thick, marine shale in the Kiowa Formation, referred to as the Kiowa shale aquitard (Table 1). The thickness of the aquitard ranges up to more than 300 ft in parts of west–central and southwestern Kansas. The Kiowa shale aquitard is not present in much of central Kansas where it has been removed by erosion or was not deposited. Where it is not present the potential exists for direct hydraulic connection between the upper and lower Dakota aquifer. Figure 2 shows the extent of the Kiowa shale aquitard in Kansas.

HYDROLOGIC PROPERTIES

In most hydrogeologic investigations, the permeable nature of a natural porous medium to the flow of water is indicated by its hydraulic conductivity, expressed in L/T units. Sandstone hydraulic conductivities are derived from the results field tests involving either single or multiple wells and laboratory measurements of small samples from the outcrop or coring. Because of the variability of natural porous media, the hydraulic conductivity is a log-normally distributed parameter in most instances (Freeze and Cherry, 1979). The "average" value for the log-normal distribution is the geometric mean of the distribution.

Twenty-two reliable values of hydraulic conductivity from field hydraulic tests of wells in the Dakota aquifer of Kansas were found in the literature or were derived from field tests conducted for the Dakota Aquifer Program. Most of the values come from pumping tests where

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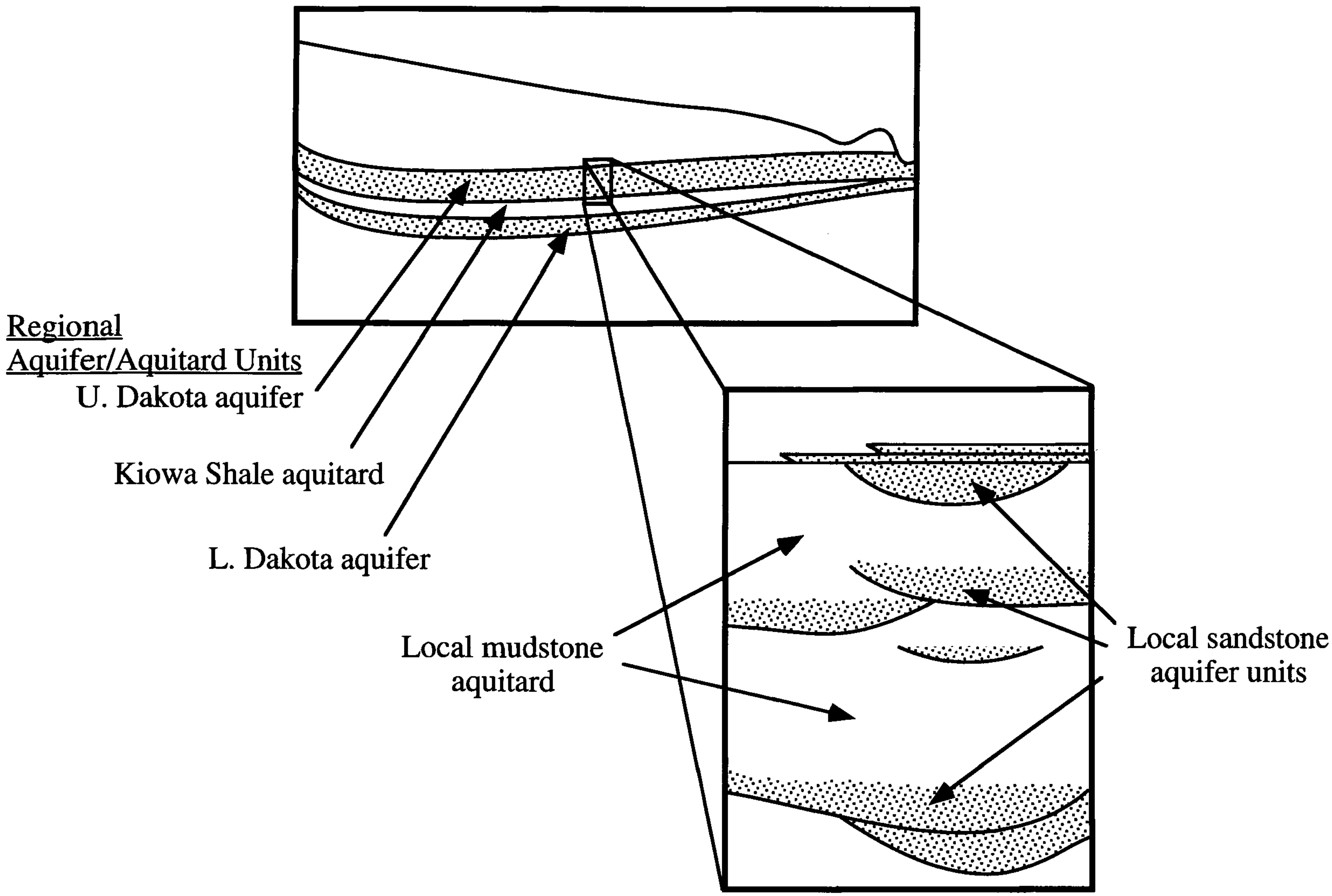

Figure 1. Regional and local aquifer/aquitard units of the Dakota aquifer system in Kansas.

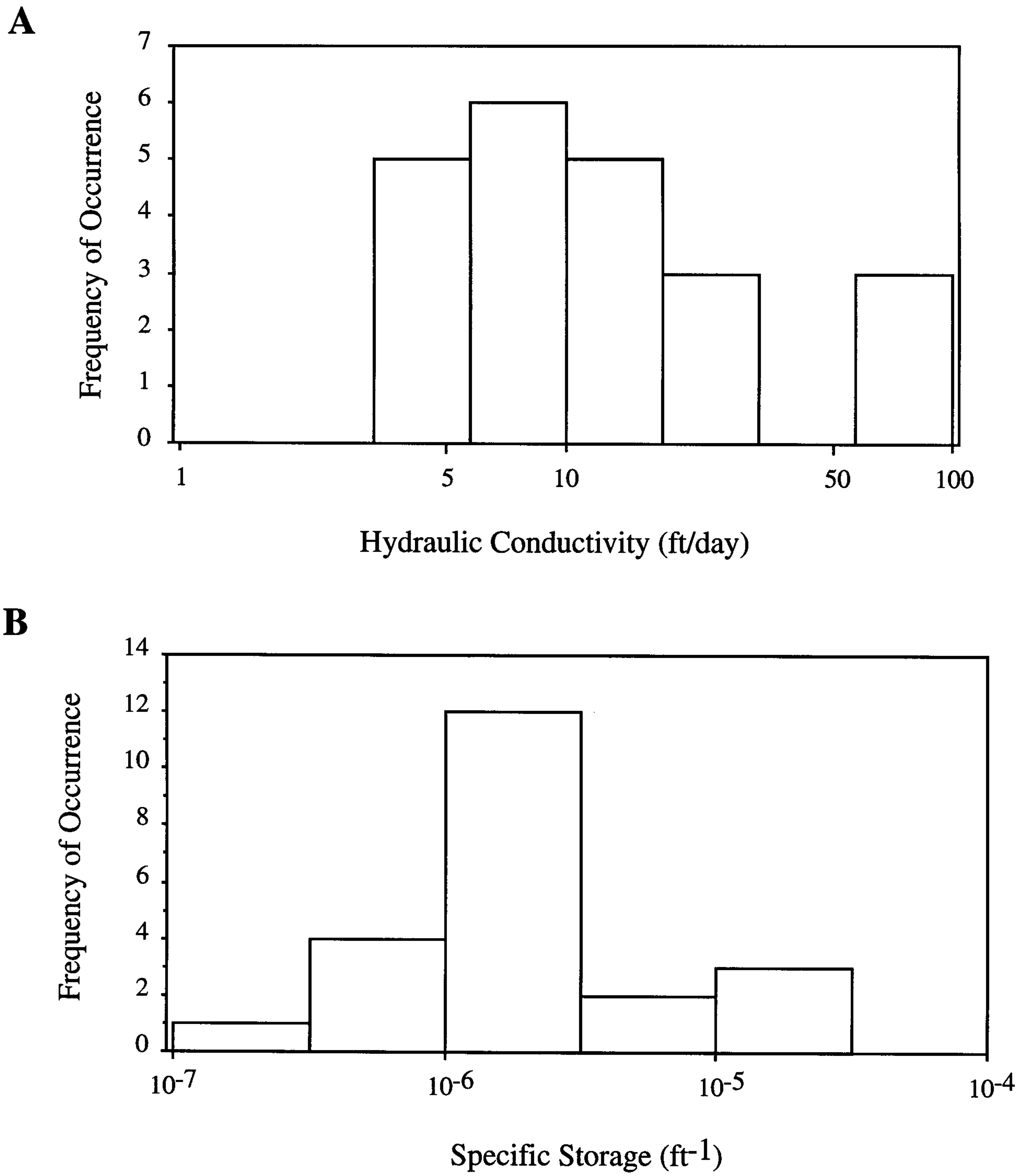

Figure 2. Distribution of hydraulic conductivity (A) and specific storage (B) values from 22 pumping tests of the Dakota aquifer in Kansas.

the Dakota aquifer is shallow in central and southwestern Kansas. The hydraulic conductivity data from the field hydraulic testing range from 3.6–88 ft./day with a geometric mean value of 12.5 ft/day (Figure 2A). The highest hydraulic conductivities are generally found in the outcrop or near the outcrop areas of the Dakota aquifer in central Kansas and the lowest values in southwestern Kansas.

In Figure 3 similar trends can be observed in the results from lab tests on core samples of the sandstones from the Dakota aquifer in central and northwest Kansas. Core samples of sandstone from central Kansas appear to be more permeable than core samples of sandstone from northwest Kansas. The test results suggest that hydraulic conductivity is generally highest in the better sorted and coarser sandstones. These sandstones are most common in the lower sections of thick, amalgamated, multi-story fluvial- and distributary-channel sandstone bodies found in central Kansas.

Direct field or laboratory tests on the mudstone matrix were not conducted in the Dakota Aquifer Program. However, Wade (1991, 1992) reported a mudstone vertical hydraulic conductivity of $2.2 \pm 0.6 \times 10^{-3}$ft./day from a pumping test of a thick sandstone aquifer in Washington County. Macfarlane et al. (1994) concluded from analysis of a pumping test in the confined Dakota of central Kansas, that the vertical hydraulic conductivity of the mudstone is considerably less than 0.001 ft/day, perhaps by several orders of magnitude. These results suggest that processes associated with erosion and unloading of the Dakota aquifer sediments may significantly increase the bulk vertical hydraulic conductivity of the mudstone matrix that surrounds the sandstone bodies of the Dakota aquifer.

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

$$S_s = \rho g(\alpha + n\beta) \qquad \text{(eqn. 1)}$$

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

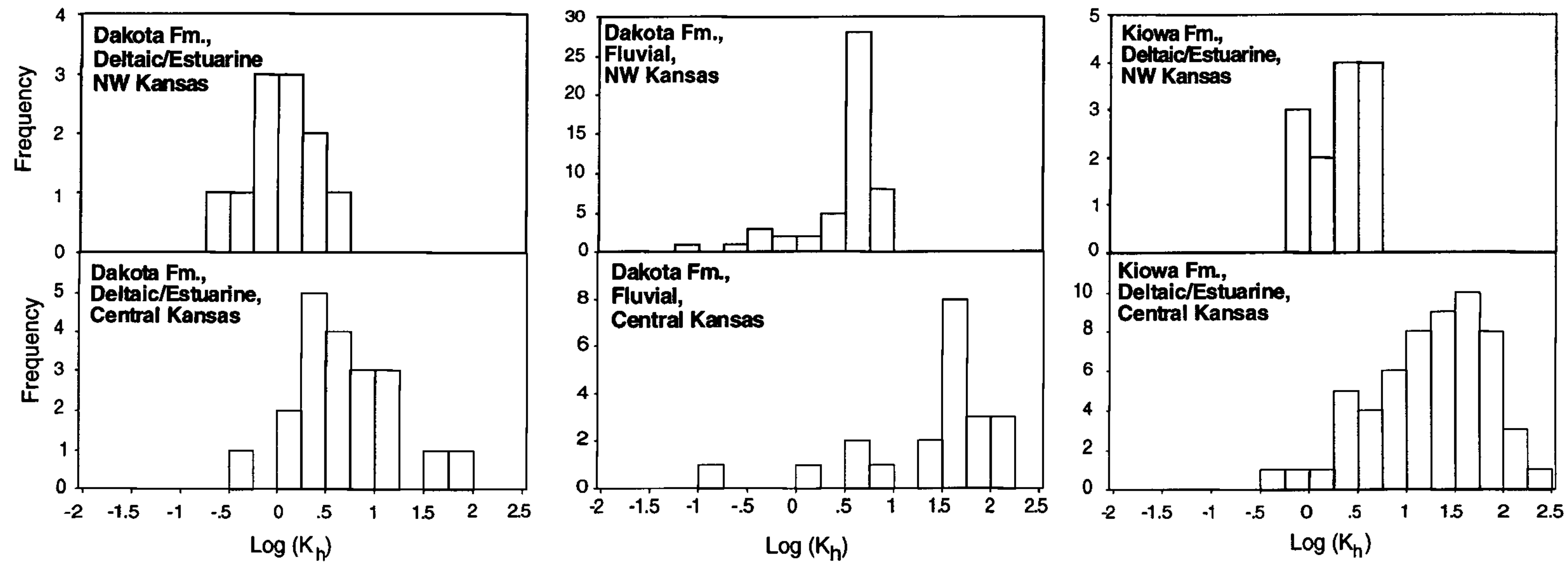

Figure 3. Histograms of horizontal hydraulic conductivity of fluvial and shoreface sandstones from the Dakota and Kiowa Formations in the KGS #1 Jones (central Kansas) and the #1 Beaumeister (northwestern Kansas).

Twenty-two reliable values of specific storage from field hydraulic tests of wells in the Dakota aquifer of Kansas were found in the literature or were derived from field tests conducted for the Dakota Aquifer Program. Most of the values come from pumping tests where the Dakota aquifer is shallow in central and southwestern Kansas. Values of specific storage range from 1.5×10^{-7} ft.$^{-1}$ up to 2.9×10^{-5} ft.$^{-1}$, which is within the expected range of values for confined sandstone aquifers. In Figure 2B the data appear to be log normally distributed with a geometric mean of 2.1×10^{-6} ft.$^{-1}$.

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LOCAL AQUIFER/AQUITARD UNITS WITHIN THE DAKOTA AQUIFER SYSTEM

The sandstone aquifers contained in these Cretaceous units occur as irregular, discontinuous bodies within the mudstone and generally occur in several, more or less distinct zones (Figure 1). The fluvial and distributary sandstone bodies are ribbon-shaped and are arranged in an approximately dendritic drainage pattern. Continuity and thickness are greatest along these paleoflow directions, which vary locally, but across the state trend generally to the northwest. The deltaic/estuarine upper Dakota Formation sandstone bodies are generally tabular and trend parallel to the paleoshoreline (Siemers, 1976). Physical connections between these sandstone bodies in this part of the section depends on the backstepping of the paleoshoreline as a result of progradation during transgression and the proximity of these sandstone bodies to underlying fluvial/distributary channel sandstones.

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

The high variability of the Dakota aquifer framework underscores the need to define hydostratigraphic units within the aquifer on basis of the scale and nature of the questions being asked (Figure 1). The aquifer/aquitard units defined at the regional scale would not be appropriate at the scale of the well field or well site, where the required level of detail in the results is much higher. At the local scale, perturbations of the flow field over some finite time period cause transient flow conditions in the vicinity of the well field or pumping well, and these propagate through the aquifer for some distance, mainly through the more permeable sandstones (Macfarlane et al., 1993). Thus the local hydrostratigraphy consists of sandstone aquifers confined within mudstone aquitards. The geometry of the sandstone bodies and their hydraulic properties become relatively important influences on ground-water flow that need to be evaluated

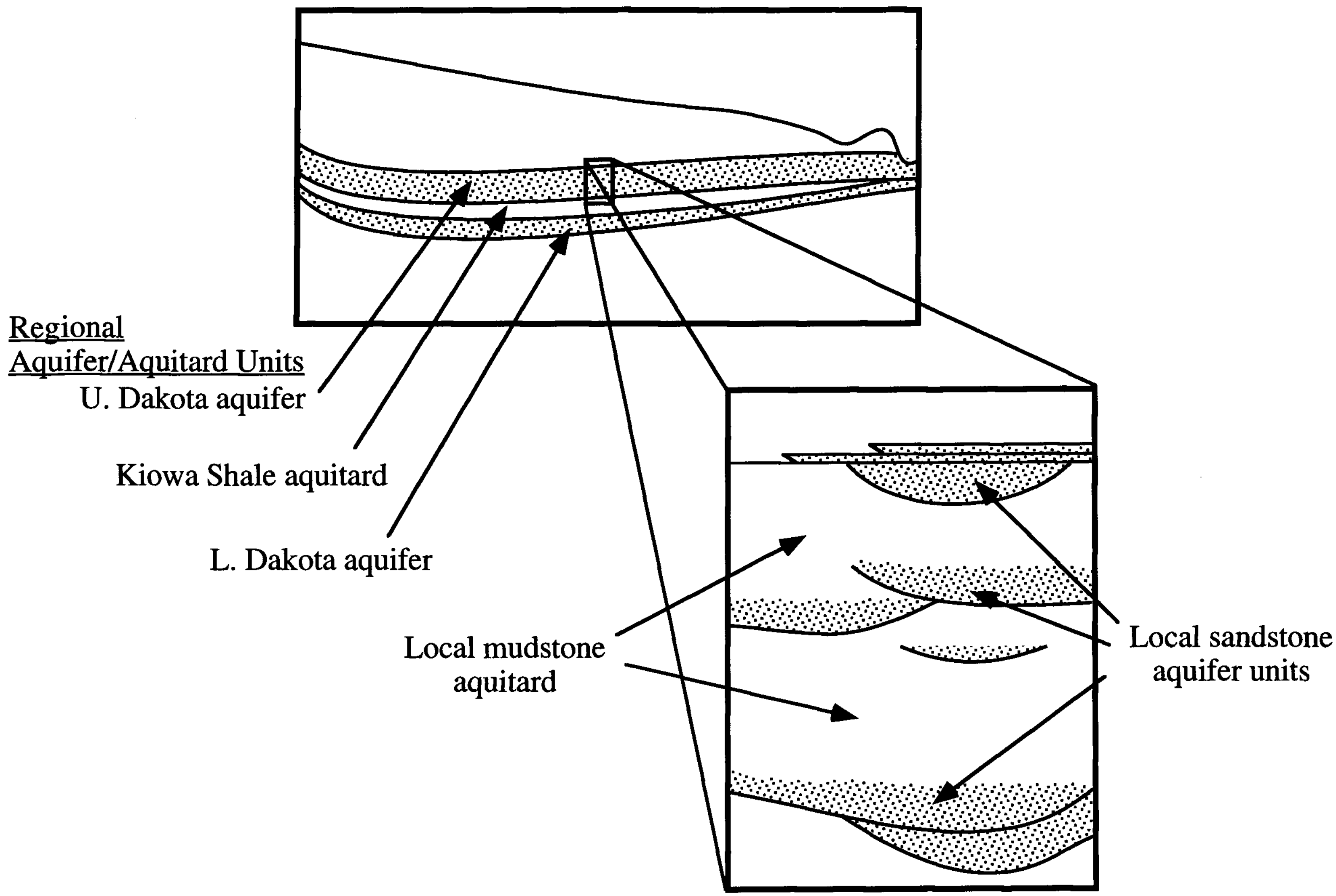

Figure 1. Regional and local aquifer/aquitard units of the Dakota aquifer system in Kansas.

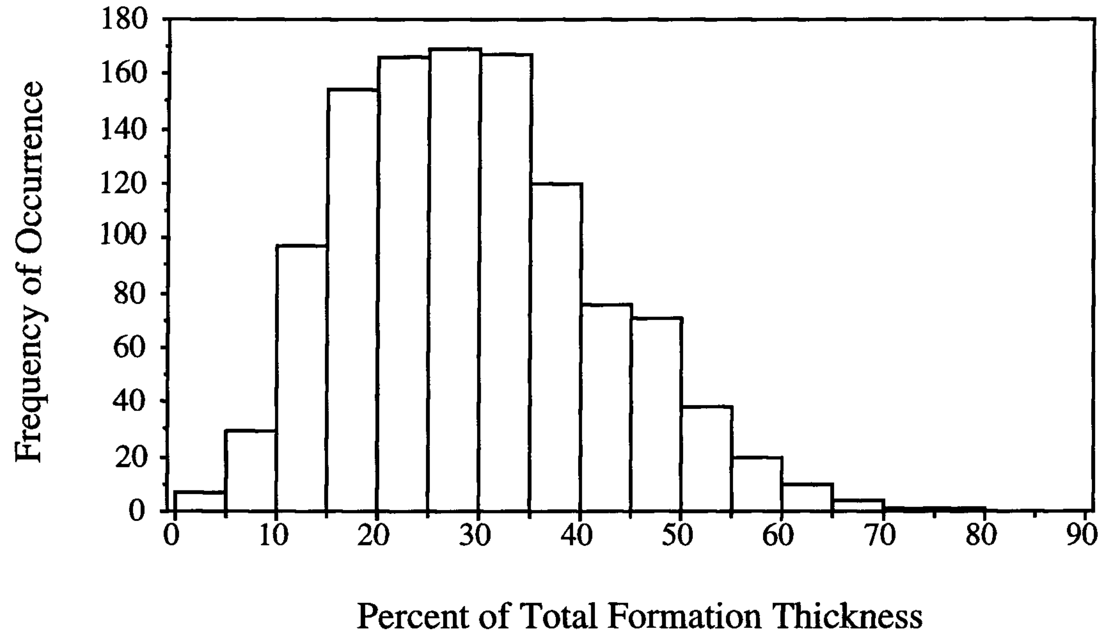

Figure 2. Sandstone proportion to total Dakota Formation thickness encountered by 1,131 oil and gas wells in southwestern Ellis County, Kansas.

to resolve issues related to the effect of withdrawals on the flow system. Regional subdivision of the deposits within the Dakota into sequences is useful for correlating and mapping discontinuous fluvial and deltaic/estuarine sandstone bodies in the subsurface, which are the local sources of water for pumping wells.

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OTHER SIGNIFICANT HYDROSTRATIGRAPHIC UNITS INFLUENCING THE DAKOTA AQUIFER SYSTEM

Over its extent in Kansas, the Dakota Formation is overlain by younger Upper Cretaceous bedrock units and Cenozoic unconsolidated deposits (Table 1, Figure 1). The Upper Cretaceous sequence consists of shale, chalk, and limestone belonging to the Graneros Shale, the Greenhorn Limestone, the Carlile Shale, the Niobrara Chalk, and the Pierre Shale (Hattin, 1962, 1965, 1975, 1982; Hattin and Siemers, 1987). The total thickness of this sequence generally increases to the west and north in Kansas up to more than 2,000 ft in the northwest corner of the state. These stratigraphic units form the Upper Cretaceous aquitard (Macfarlane, 1995). The Dakota is considered a confined aquifer system where it is overlain by the Upper Cretaceous aquitard (Figure 1). In most of southwest and most of south–central Kansas and much of southeastern Colorado, the Upper Cretaceous aquitard has been eroded and the Dakota is overlain by and hydraulically connected to the High Plains aquifer (Figure 1). In the river valleys of the central part of the state the Dakota aquifer is in hydraulic connection with the overlying alluvium which form the alluvial valley aquifers (Figure 1).

Westward dipping Jurassic and Permian rocks directly underlie the Dakota aquifer in Kansas (Hamilton, 1994). The subcrop of the Jurassic Morrison Formation beneath the Cretaceous is generally in the western part of the state, whereas the Permian subcrop is in the central part (Figure 2). In southwestern Kansas the Morrison consists mostly of sandstone and is a source of fresh water along with the Cheyenne Sandstone. Upper and lower Permian rocks consist of shale, siltstone, sandstone, and bedded salt with minor amounts of limestone and dolomite. Outside of southwestern Kansas, the Morrison, and the Permian and Pennsylvanian sequences form a thick regional aquitard. However, sandwiched within this aquitard is the Cedar Hills Sandstone aquifer which subcrops beneath the lower Dakota aquifer in central Kansas (Table 1, Figure 1). The Cedar Hills Sandstone aquifer consists of the Permian Cedar Hills Sandstone and the sandstones and shaly sandstones at the top of the underlying Salt Plain Formation.

Table 1. Stratigraphy and hydrostratigraphy of the shallow subsurface in Kansas.

ERA	SYSTEM	ROCK STRATIGRAPHIC UNITS		HYDROSTRATIGRAPHIC UNITS
Cenozoic	Quaternary	Unconsolidated alluvial and eolian deposits		Alluvial Valley & High Plains aquifers
	Tertiary	Ogallala Formation		
Mesozoic	Cretaceous	Colorado Group	Pierre Shale Niobrara Chalk Carlile Shale Greenhorn Limestone Graneros Shale	Upper Cretaceous aquitard
		Dakota Formation	Jansen Member	Upper Dakota aquifer
			Terra Cotta Member	
		Kiowa Formation		Kiowa shale aquitard
			Longford Member	Lower Dakota aquifer
		Cheyenne Sandstone		
	Triassic/Jurassic	Dockum Group/Morrison Formation		Morrison-Dockum aquifer
Paleozoic	Permian	Undifferentiated Permian		Permian aquitard
		Cedar Hills Sandstone		Cedar Hills Sandstone aquifer
		Undifferentiated Permian		Upper Permian-Pennsylvanian aquitard

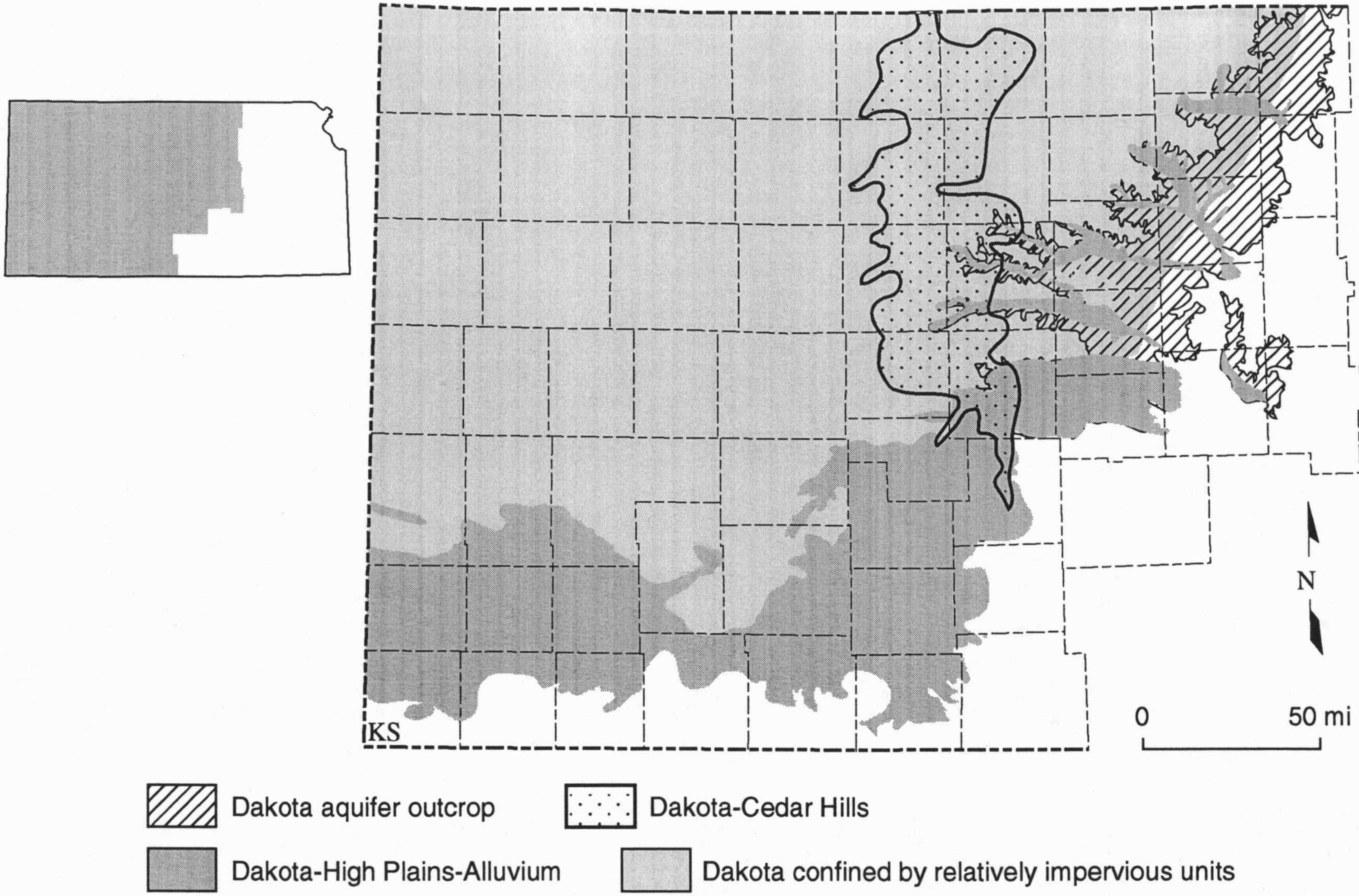

Figure 1. Extent of the Dakota aquifer in Kansas showing regions of hydraulic connection to other aquifers, where the Dakota is a near surface aquifer, and where it is confined by relatively impervious units.

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THE STEADY-STATE REGIONAL GROUND-WATER FLOW SYSTEM IN THE DAKOTA AQUIFER

INTRODUCTION

Without exception, ground water is constantly moving from points of recharge where it enters the subsurface hydrologic system to points of discharge where it exits back to the surface. The flowpaths taken by ground water are determined by the arrangement of aquifer and aquitard units and the land-surface topography (Freeze and Cherry, 1979). Some of the water only travels a short distance through the shallow subsurface from local recharge to local discharge areas. However, some of water travels a much longer distance from regional recharge to discharge areas through the deeper subsurface. All of the subsurface flowpaths from recharge to discharge areas taken together define a flow system that includes lateral flows within all of the aquifer units and across all of the aquitard units.

To define the pattern of moving ground water in a flow system, hydrogeologists use measurements of water-level elevation taken in wells scattered throughout the aquifer system. In most cases, the water-level elevation equals the hydraulic head in a well. The hydraulic head at any point in the flow system is a measure of the potential energy per unit weight of ground water at that point (Freeze and Cherry, 1979). The movement of ground water involves a loss of energy and is similar to the flow of water in river systems. Water naturally flows downhill from elevated regions of the continent (higher hydraulic head) to the sea (lower hydraulic head). In much the same way ground water moves from points of higher hydraulic head to points of lower hydraulic head in a flow system. Most of the hydraulic head data used to define the flow system come from the aquifer units. In a confined aquifer the hydraulic head is above the top of the aquifer unit whereas in an unconfined or water table aquifer unit, the hydraulic head is within the unit. Hydraulic head data are typically unavailable for the aquitard units. As a result, ground-water flow across the aquitards must be inferred from hydraulic head measurements in the adjacent aquifer units.

INFLUENCES ON THE FLOW SYSTEM

In the central Great Plains, the ground-water flow system in the Dakota aquifer is influenced primarily by regional and local topography and the Upper Cretaceous aquitard (Macfarlane, 1995). Hydrogeologists have long observed that the water table or the top of the saturation mimics the topography of the land surface. The land surface in the region slopes generally to the east and decreases in elevation from 5,000 ft. or more in eastern Colorado to 1,400 ft. or less in central Kansas. This results in an easterly flow of ground water across the region in all of the aquifer systems.

Due to its great thickness and extremely low permeability in the Denver basin of eastern Colorado, the Upper Cretaceous aquitard hydrologically isolates the flow system in the Dakota from the overlying water table. The aquitard is as much as 10,000 ft. thick in the deepest part of the basin adjacent to the Front Range of the Rocky Mountains. Here, the hydraulic heads in the Dakota aquifer are more than 2,500 ft lower than the elevation of the overlying water table (Figure 1). An aquifer is usually considered in good hydraulic communication with the overlying water table if there are only small head differences between them. The regional flow models of Belitz (1985) and Helgeson et al. (1993) have shown that the aquitard restricts the downward movement of recharge to the Dakota to near negligible levels.

However, away from the basin center in Kansas and southeastern Colorado, the Upper Cretaceous aquitard thins from more than 2,000 ft in northwest Kansas toward its extent in central and southwestern Kansas. As a result, its control on the flow system in the Dakota aquifer diminishes toward the outcrop/subcrop belt. Within the last 10 million years, differential uplift and intense local dissection of the High Plains surface have created considerable local and regional topographic relief. Incisement is a common feature of the drainage in the Arkansas River basin in southeastern Colorado, and southern Kansas and the Smoky Hill, Saline, and Solomon River systems in north–central Kansas. Many of these river systems have cut down through the aquitard and into the geologic units that constitute the Dakota aquifer system. Consequently, the head difference between the Dakota and the overlying water table is less than 1,000 ft. in most of western and central Kansas and southeastern Colorado where the confined aquifer is relatively shallow (Figure 1). Here, local topographic relief is an important influence on ground-water flow in the Dakota aquifer (Figure 2).

Geologic processes have also played an active role in changing the boundary conditions of the flow field and the hydraulic properties and composition of the hydrostratigraphic framework (Kreitler, 1989). Periods of deposition, erosion, and tectonic activity associated with the Laramide Orogeny at the close of the Cretaceous Period and cycles of erosion and deposition that occurred in the Quaternary have undoubtedly induced significant changes in the flow system over time. These geologic processes would have changed the elevation and configuration of the regional water table and pore pressures in low permeability porous media. As a result, it is possible that an overprint of a more recent flow system on an older one is being maintained while the regional system is adjusting to a new steady-state condition. However, it is believed that if the flow system is still adjusting to a new equilibrium configuration, the changes in hydraulic head caused by the adjustments are relatively minor in comparison to the large hydraulic head differences in the aquifer systems between eastern Colorado and central Kansas.

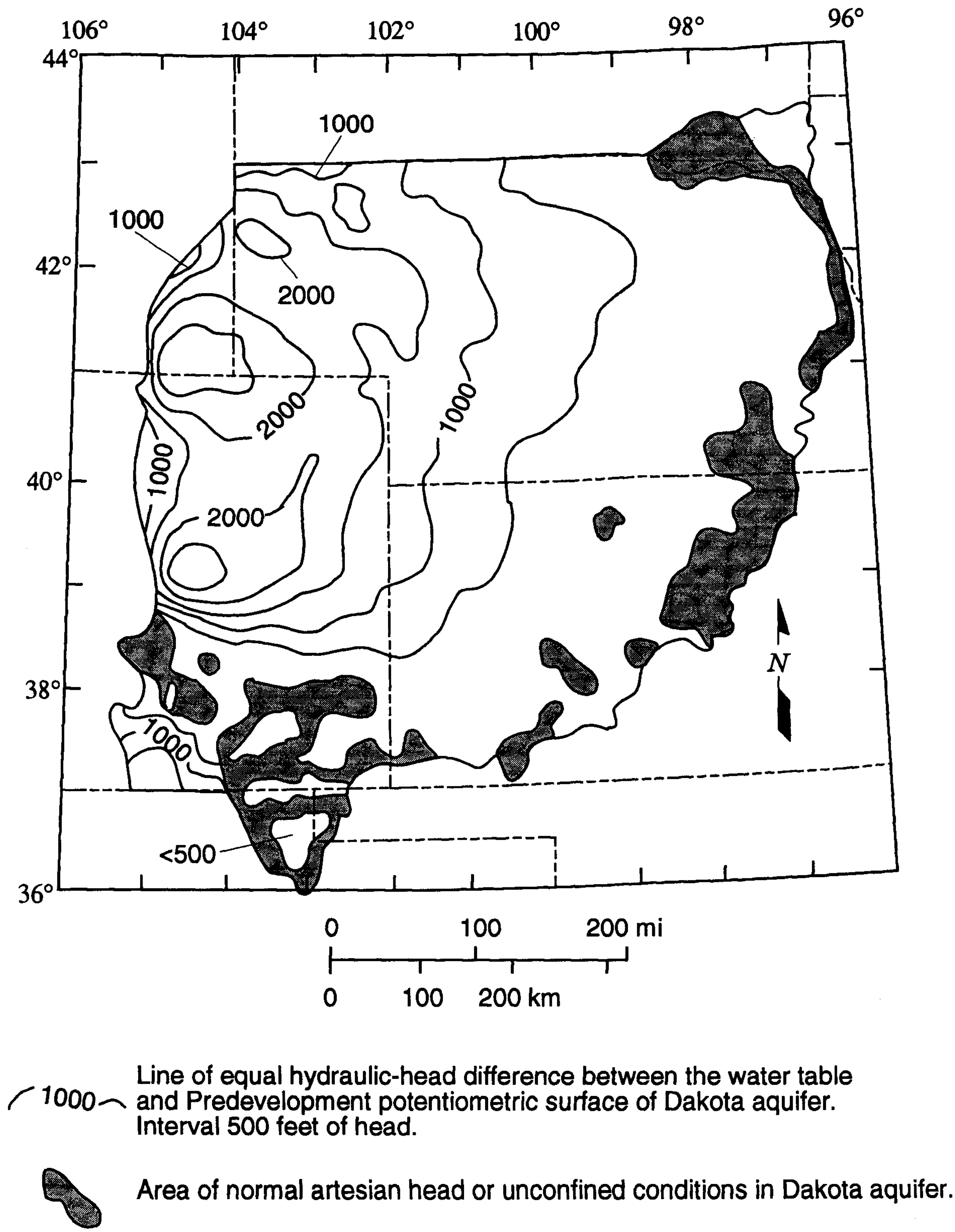

Figure 1. The hydraulic head difference between the Dakota aquifer and the overlying water table in the Denver basin and adjacent areas to the east. Modified from Helgesen et al. (1993)

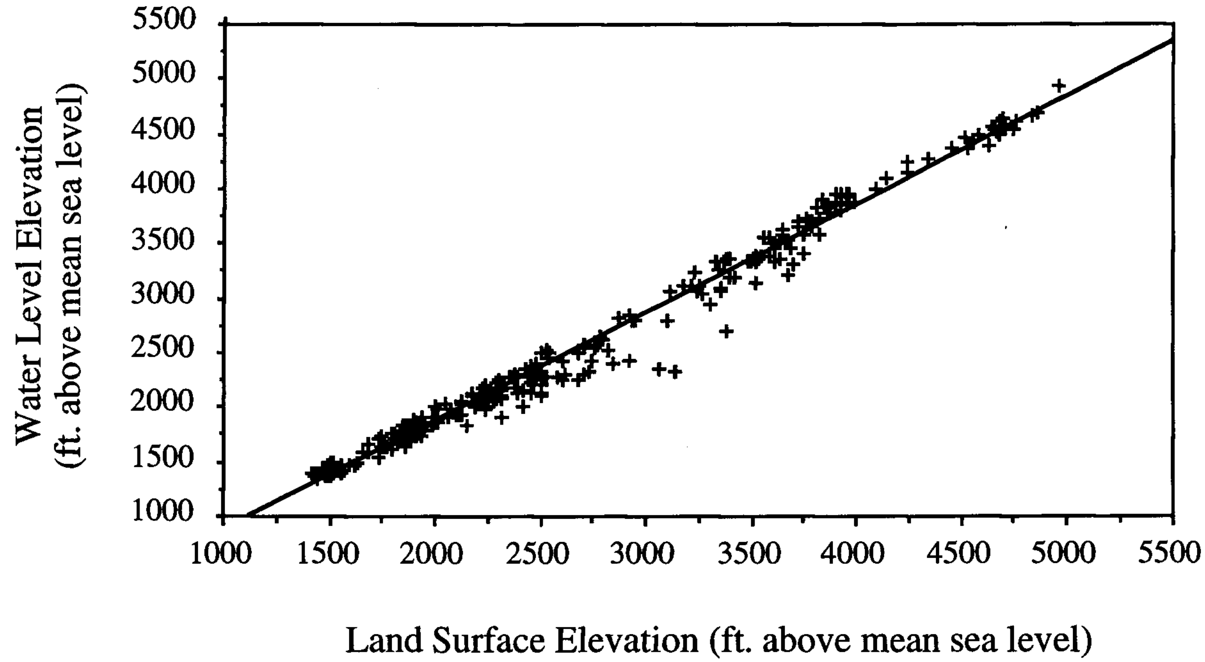

Figure 2. Water-level elevation vs. land-surface elevation in the confined Dakota aquifer, southeastern Colorado and western and central Kansas. The slope of the best-fit line from regression is 0.993 which is signifcant ($p = 0.001$). The larger negative deviations of the data from the fitted line indicate the greater influence of the Upper Cretaceous aquitard on the flow system between 3,000 ft. and 3,700 ft. land surface elevation.

STEADY-STATE GROUND-WATER FLOW IN THE DAKOTA AQUIFER

Figure 3 is a potentiometric surface map of the Dakota aquifer in Kansas and extreme southeastern Colorado as it might have appeared in the early 1900s. The water-level data used to produce the map come from records of the earliest wells drilled in the region. Because the aquifer is shallower nearer the outcrop/subcrop region, the data are more numerous in this region than in areas to the north where the Dakota is much deeper and water-resources development of the aquifer has been minimal. As a result the map accuracy is much better in southwestern and central Kansas than it is in northwest Kansas where there are only a few scattered measurements. Another factor limiting map accuracy is that the data used to assemble the map are not all from the same time period. Many of the water-level measurements were made in wells that were installed in the 1940s through the 1960s. This is because development of water resources in the Dakota began at different times in different places. To limit the amount of introduced error, only the earliest measurements taken in any one area were used to generate the equipotentials on the potentiometric surface map.

The Dakota potentiometric surface map in Figure 3 shows that the hydraulic head in the Dakota aquifer is higher to the south of the Arkansas River than elsewhere to the north and east. On the map the equipotentials are arranged concentrically around a hydraulic head maximum and decrease rapidly to the north and east of this region. This indicates northeastward flow away from an area of recharge to the Dakota aquifer. The total recharge from precipitation depends on the downward movement of water below the root zone to the water table or seepage into exposed bedrock outcrops. Within this recharge area in southeastern Colorado a part of the Dakota aquifer underlies and is hydraulically connected to the High Plains aquifer. The total amount of seepage downward into the Dakota from the High Plains depends on the hydraulic connection between the two aquifers and the hydraulic head gradient. In Figure 4, most of the recharge to the Dakota is intercepted by local shallow flow systems that discharge back to the surface drainage within the recharge area (Macfarlane, 1995). Consequently, the age of ground water in this part of the system is generally less than 10,000 yrs (Macfarlane et al., 1995).

Locally in this part of the Arkansas River valley, some wells tapping the Dakota flowed at the surface where the potentiometric surface was above land surface. McLaughlin (1954) outlined an area where flowing artesian wells were concentrated in the Bear Creek drainage north of Walsh, Colorado, and referred to this part of the drainage as the Walsh artesian area. Darton (1906) outlined a large part of the Arkansas River valley where flowing artesian conditions existed from Syracuse, Kansas, up river to the vicinity of Pueblo, Colorado.

Only about 10% of the infiltrated water entering the aquifer moves downdip from the recharge area south of the Arkansas River into the confined Dakota in western Kansas and southeastern Colorado (Figure 3 and 4; Macfarlane, 1995). Within the confined aquifer, the

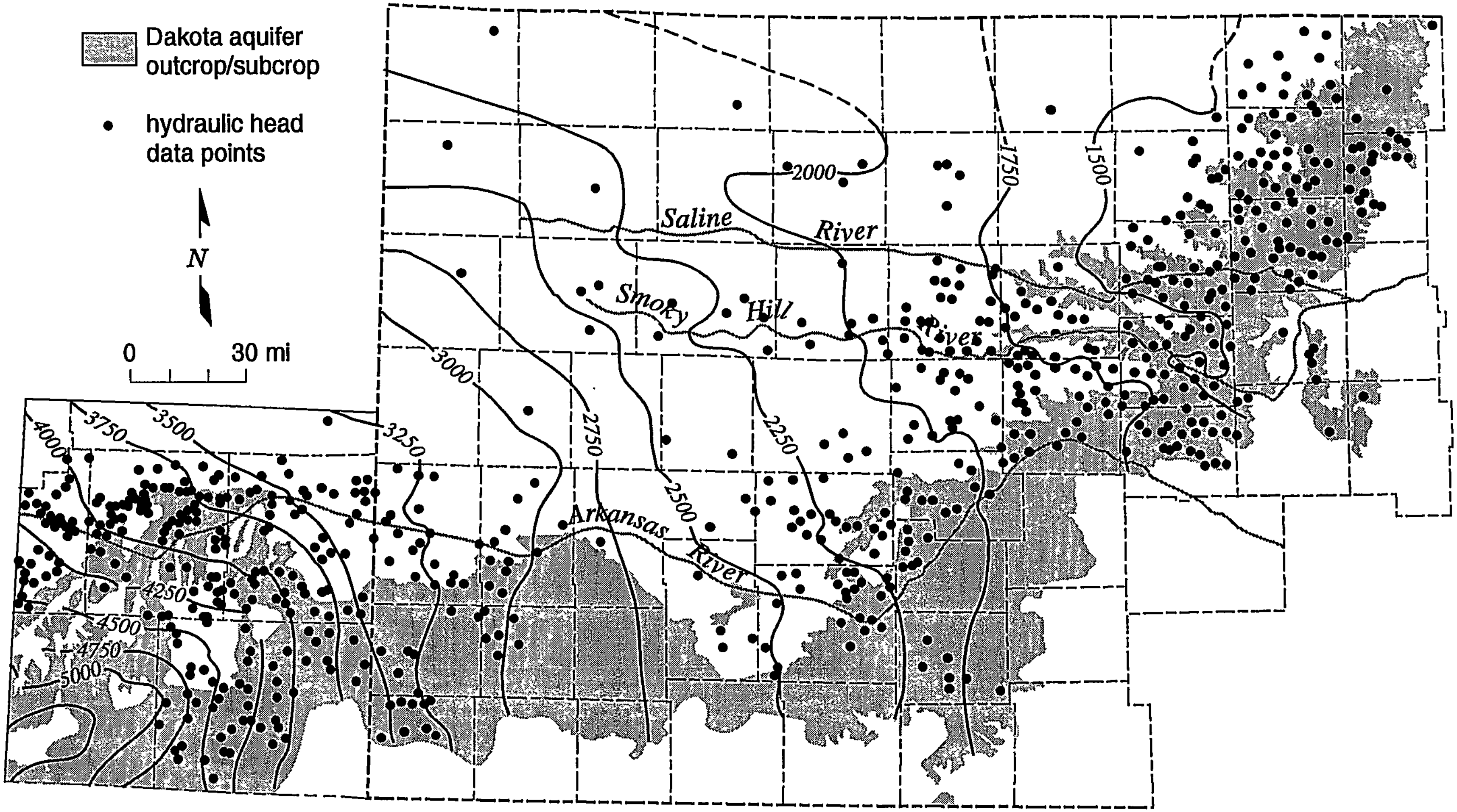

Figure 3. Elevation in feet above mean sea level of the predevelopment potentiometric surface of the Dakota aquifer in southeastern Colorado and western Kansas. The shaded area shows the area of outcrop, primarily in central kansas, and subcrop beneath Pleistocene and Tertiary deposites in southwestern Kansas and southeastern Colorado. Hydraulic head data are from the U.S. Geological Survey's Central Midwest Regional System Analysis Program.

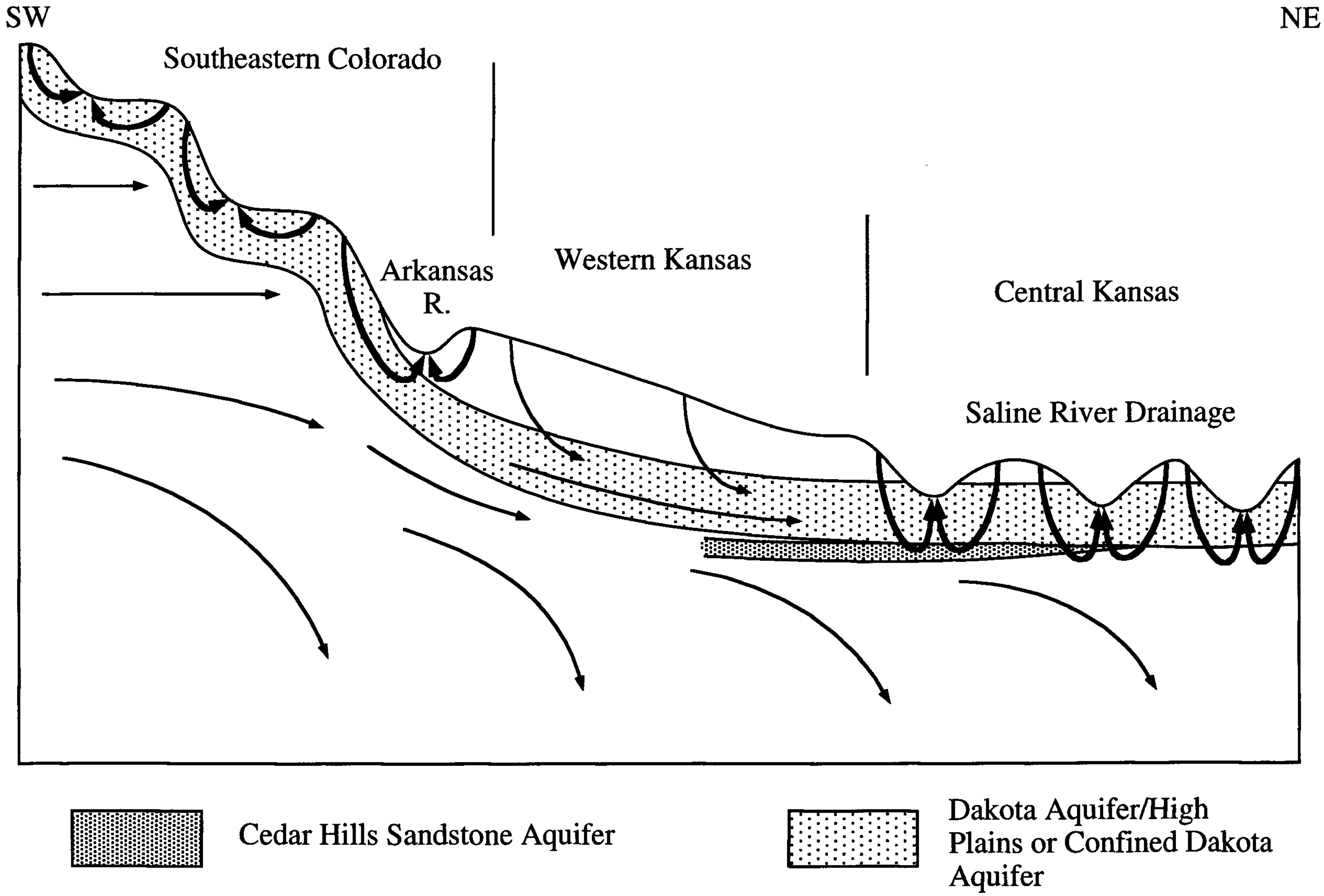

Figure 4. A conceptual model of ground-water flow through the confined Dakota aquifer from the regional recharge area in southeastern Colorado to the regional discharge area central Kansas. The trrace of the cross-section is shown on Figure 3. Most of the recharge to the Dakota aquifer is routed back to the surface by local flow systems in central Kansas and southeastern Colorado.

ground-water moves slowly northeastward towards the regional discharge area in central Kansas due to low aquifer transmissivity (Macfarlane, 1993). Over most of western Kansas, the vertical hydraulic conductivity of the overlying Upper Cretaceous aquitard is very low, on the order of 1 x 10^{-7} ft/day or less (Macfarlane, 1993; Belitz and Bredehoeft, 1988). Freshwater recharge to the confined Dakota is negligible, less than 0.1% of the lateral flow within the aquifer (Figure 5). Most of the freshwater recharge to the confined Dakota enters where the aquitard is relatively thin and dissected near the outcrop/subcrop areas. Here, the vertical hydraulic conductivity is two to three orders of magnitude higher and recharge from overlying sources may amount to as much as 10% of the lateral flow within the aquifer (Smith and Macfarlane, 1994; Smith, 1995). In central Kansas, an additional source of recharge to the Dakota comes from the underlying Cedar Hills Sandstone where both aquifers are hydraulically connected (Figure 4). The total recharge from this source amounts to less than 1% of the lateral flow in the upper Dakota aquifer.

Because of the low flow rates in the confined Dakota, variable rates of recharge from overlying sources, and the range in flow path lengths, the age of ground water ranges from 10s to 100s of thousands of years nearer the outcrop/subcrop belt and may exceed a million years in far northwest Kansas (Macfarlane et al., 1995). Acting over time spans of millions of years, the cumulative flow moving downdip from the recharge area in southeastern Colorado has flushed the salinity from a large part of the confined aquifer in Kansas and in southeastern Colorado (Whittemore and Fabryka-Martin, 1992; Smith, 1995; Macfarlane et al., 1995). It is believed that in northwest Kansas, the lateral flow of ground water has not been sufficient to remove the remnant salinity within the confined aquifer (Figure 6). The fresh-saltwater transition is a narrow band that cuts across the northwest corner of the state. To the northwest of the transition, total dissolved solids concentrations exceed 10,000 mg/L. In central Kansas, the total dissolved solids concentrations of the brines moving upward from the Cedar Hills Sandstone exceed 20,000 mg/L (Figure 6). Freshwater recharge from overlying sources has been insufficient to depress the fresh-saltwater interface much below the top of the upper Dakota aquifer (Smith, 1995).

The potentiometric surface map in Figure 3 indicates that the hydraulic head in the Dakota aquifer is lower in north–central Kansas than elsewhere. Beneath most of the river valleys, the hydraulic head in the Dakota is higher than the water level in the streams and may be higher than the land-surface elevation. This suggests that ground water in the Dakota is moving toward these river valleys from elsewhere in the region and discharging to streams or to the surface along the sloping valley sides. In the outcrop areas, the flow system in the Dakota is influenced by both regional flow from the confined Dakota to the west and local flow systems that result from local topographic relief. These local systems are replenished by infiltration of local recharge which may be discharged from the aquifer a short distance away. Also, pumping

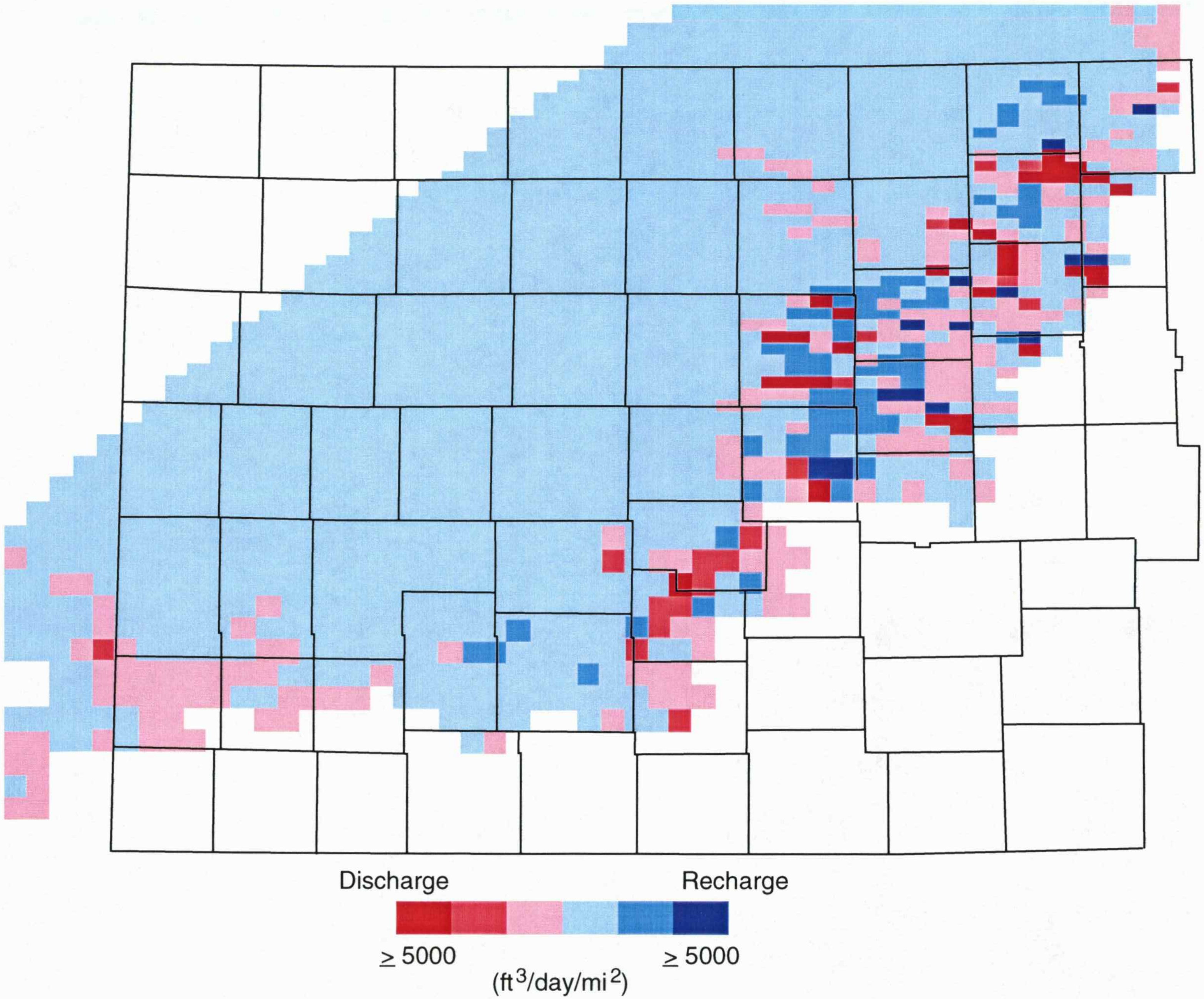

Figure 5. Recharge and discharge from the Dakota aquifer in units of $ft^3/day/mi^2$

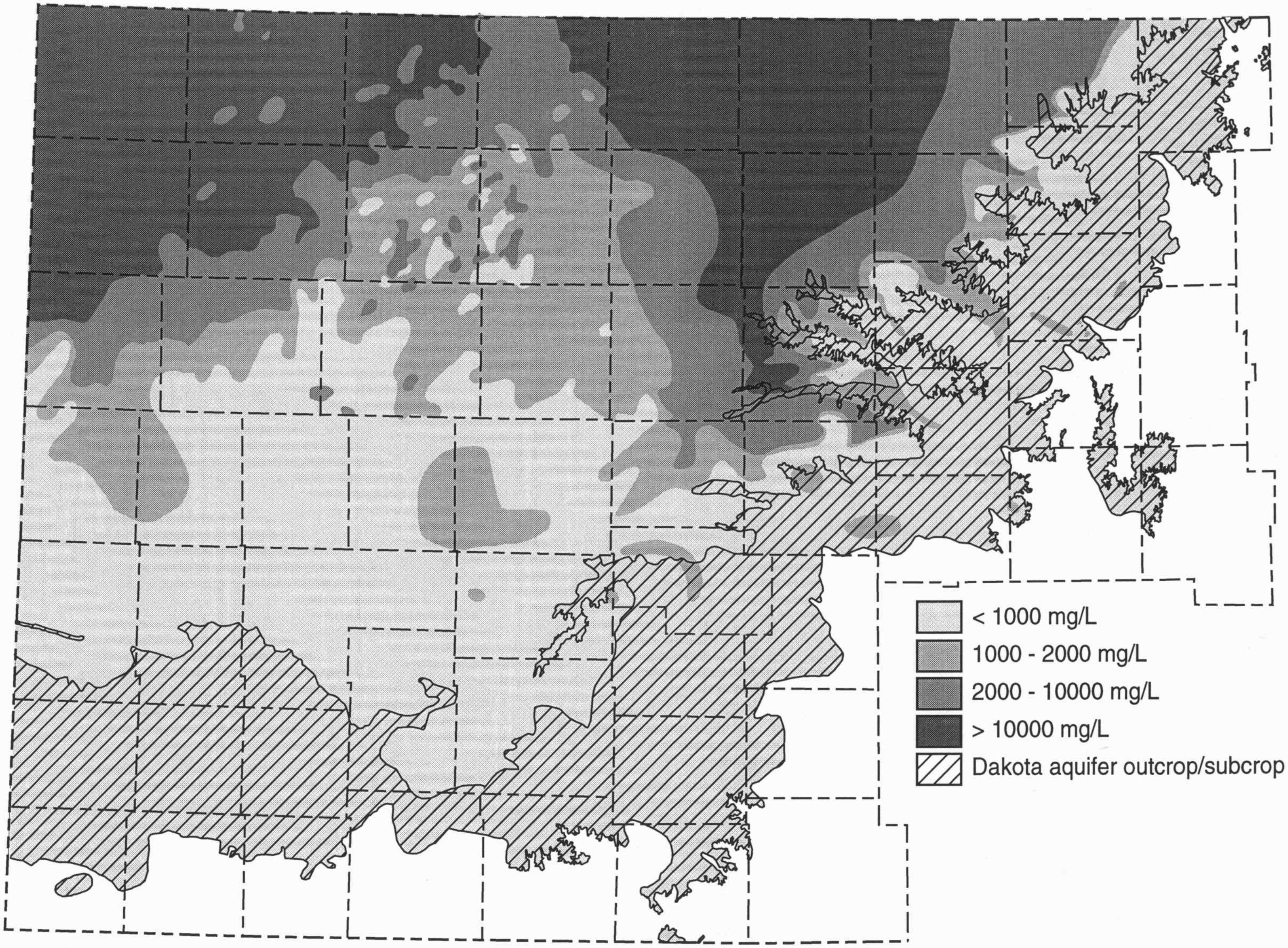

Figure 6. Distribution of total dissolved solids (TDS) concentrations in ground waters in the upper Dakota aquifer in western and central Kansas. Water less than 1000 mg/L TDS is defined as fresh. Water with 1000-2000 mg/L TDS is usable for many purposes but is less desirable than freshwater. A concentration of 10,000 mg/L TDS is defined in the state regulations of the Kansas Corporation Commission as the upper limit of usable water; above 10,000 mg/L a water is classified as unusable or mineralized.

test results suggest that the Dakota is generally more permeable in this region than it is to the west. Computer simulations of the steady-state flow system indicate that the flux of fresh water through outcrop/subcrop belt is at least four times higher than in the confined aquifer to the west (Macfarlane and Smith, 1994; Wade 1992). In the Washington County area, Wade (1992) estimated the annual recharge to the Dakota to be on the order of 0.25 in. where it is unconfined. As a result, fresh and saline water springs and seeps can be found in the river valleys. Salt marshes associated with discharge to surface water are common features in the Saline, Solomon, and Republican River valleys of central Kansas (Figure 7). During low flow periods when baseflow constitutes the bulk of stream discharge, the chloride concentration of surface waters escalates rapidly (Figure 8). Elsewhere, the freshwater is discharged from the upper Dakota to the Arkansas, Pawnee, and Wet Walnut drainages (Smith and Macfarlane, 1994). In southwestern Kansas where the Dakota is directly beneath the High Plains aquifer, model simulations show that the Dakota and the High Plains behaved largely as a single, coupled system prior to development.

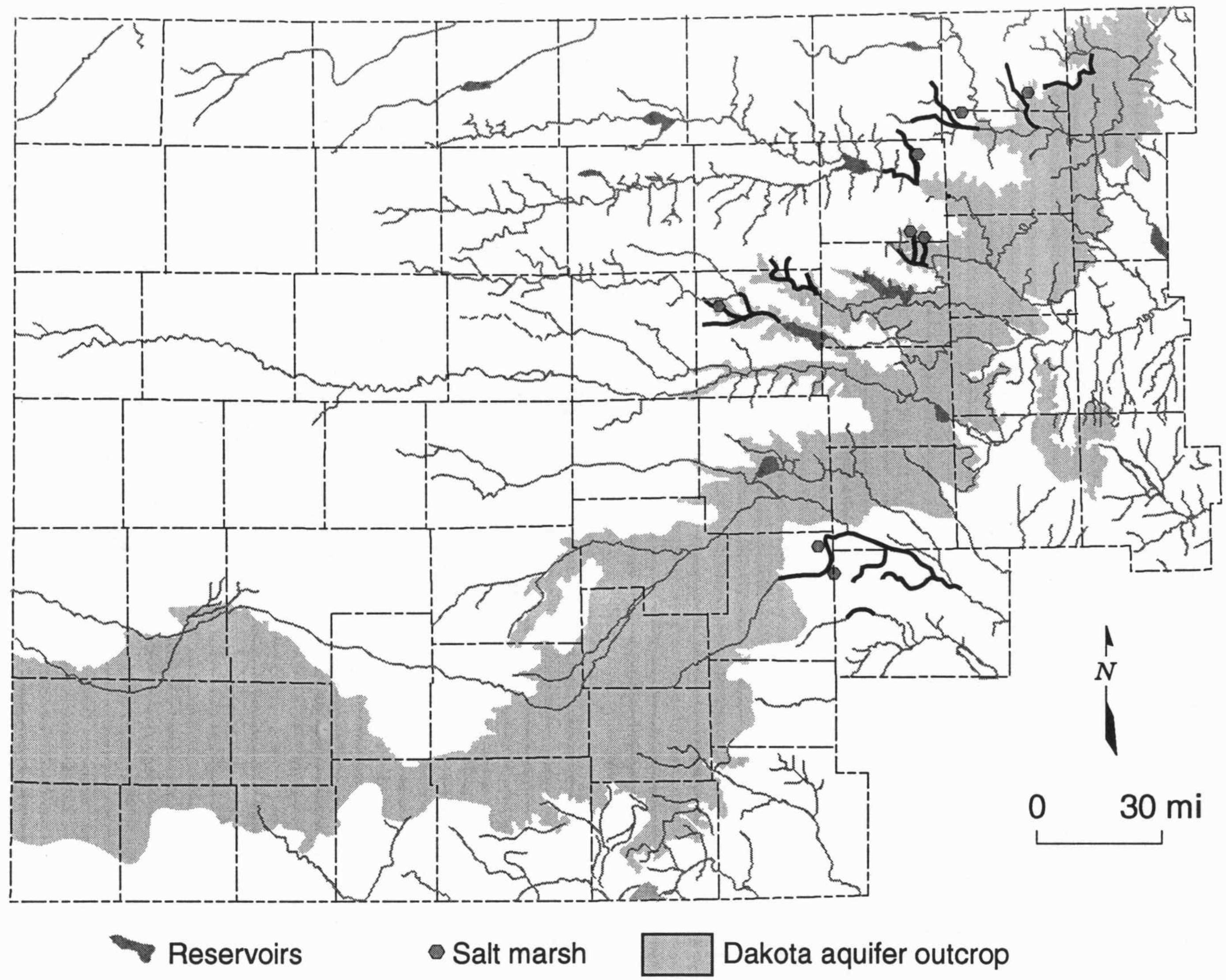

Figure 7. Location of salt marshes in central Kansas. Many of these features are associated with discharge from the Dakota aquifer

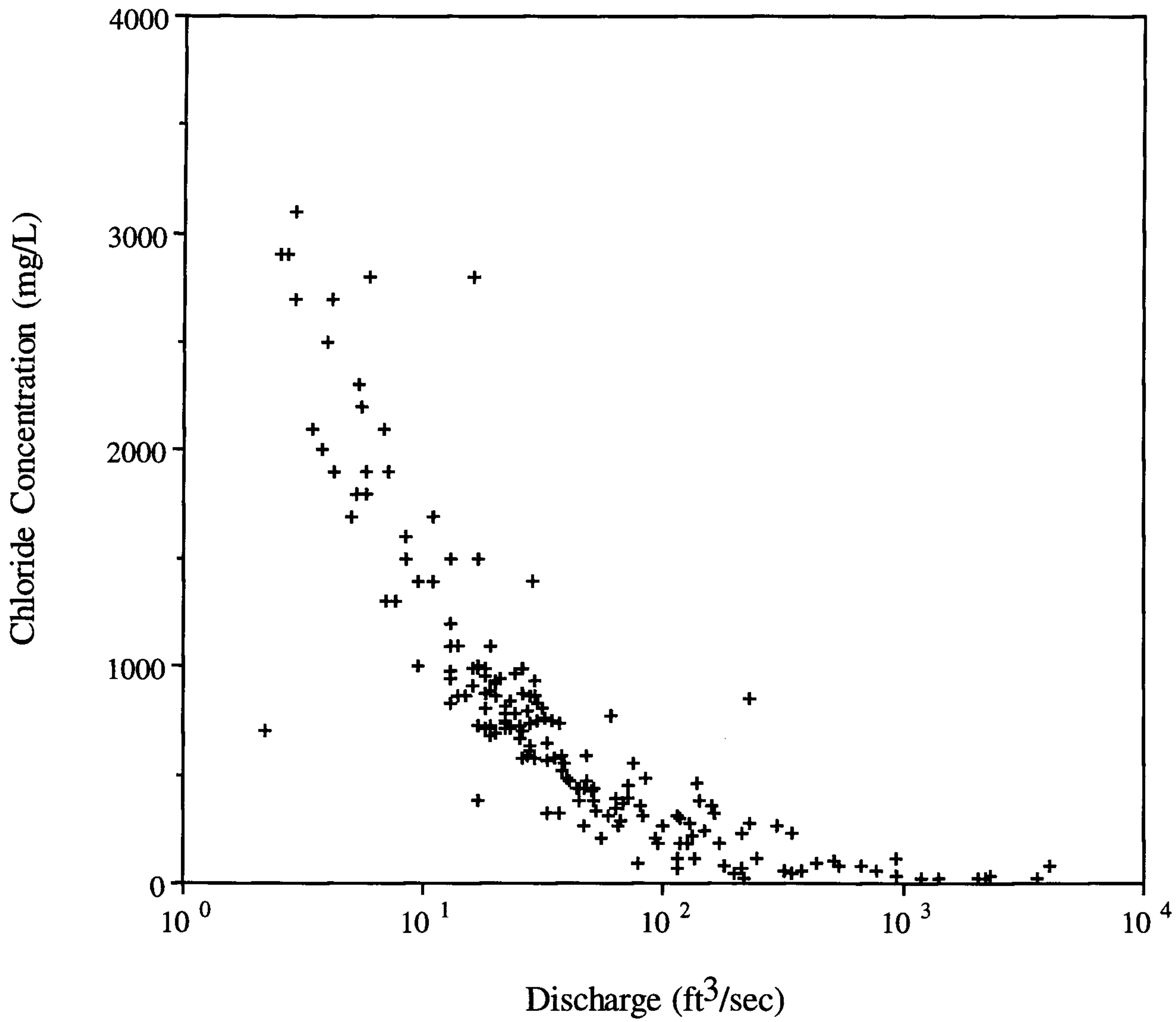

Figure 8. Stream discharge vs. chloride concentration at the Saline River gaging station north of Russell, Kansas.

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A BRIEF HISTORY OF WATER-RESOURCES DEVELOPMENT

In his reconnaissance of the Great Plains, Darton (1905, 1906) found widespread use of the Dakota for drinking water, steam locomotives, and non-irrigated agriculture. Flowing wells were very common in the Arkansas River valley of southeastern Colorado, in much of South Dakota, and parts of southeastern North Dakota and northeastern Nebraska in the Missouri River valley at that time (Darton, 1905; Haworth, 1913). The artesian pressure within the aquifer in these areas was sufficient that many of the wells produced an adequate supply of fresh water without the use of a pump.

In the Arkansas River valley of southeastern Colorado, the depths of these flowing artesian wells ranged from more than 1,000 ft at Pueblo and Fowler, Colorado, to 300 ft at Coolidge, Kansas. Darton (1906) found considerable artesian pressure in many of the wells he visited. He estimated that in some cases if the well casing were extended up into the air, the water levels would rise from a few feet up to 150 ft above land surface. Flow rates ranged from less than one up to more than 100 gallons per minute.

Figure 1 is a photograph of one of the flowing artesian wells visited by Darton in the early 1900s. The water levels in the first flowing artesian Dakota wells at Coolidge, Kansas, in 1885 were estimated to be almost 20 ft above land surface. In the early 1900s local well owners could expect flows from wells tapping the Dakota aquifer to range from 25 to 75 gallons per minute in the Arkansas River valley between Coolidge and Syracuse. Later in the 1930s and early 1940s, the flow rates from these wells decreased to 30 gallons per minute or less in this same stretch of the valley.

Many of the wells that Darton (1906) inventoried in the Arkansas River valley did not flow naturally to the surface. Water levels were generally 75 ft or less below land surface eastward of Lamar, Colorado. Darton reported that some of the artesian pressure had been lost due to pumping and unregulated, year-round discharge from the flowing artesian wells. If a well did not flow naturally under artesian pressure, steam- or wind-power was needed to bring water to the surface. Well yields were reported to range from 25 to 80 gallons per minute. Now, the flowing artesian wells that once were commonplace in the Arkansas River valley are rare where historic development was heaviest.

On the basis of a handful well-drilling reports from across western and central Kansas, Haworth (1913) outlined an area where the Dakota is shallow and could be practically used for water supply. This area included most of the Arkansas River drainage above Great Bend, Kansas and a portion of the Cimarron River basin. Haworth also observed freshwater springs emanating from the hillsides in central Kansas. He reported that they were fed locally by the Dakota

The photo in Figure 1 is not available at this time aquifer where it is at the surface, but did not report on their use by the local population for water supply.

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

In the late 1970s, a regional study of the Dakota aquifer by the Kansas Geological Survey estimated that 80–95 million acre-ft of water with a total dissolved solids concentration of less than 3,000 mg/L could potentially be withdrawn from the Dakota. However, it was recognized that development of water resources for irrigation of crops could be limited due to the complexity of the Dakota.

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

In north–central Kansas at about this time, limited use of the Dakota aquifer for irrigating crops in southwestern Washington and adjacent Cloud and Republic counties also began and has continued to the present. The only guidelines applied to this development stipulated a well spacing of one mile between these high-yield wells.

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Well-Spacing Regulations

The Effect of Well Pumping on the Dakota Aquifer

Ground water in the surrounding aquifer moves toward the well when the pump is turned on. As water is removed from the well by pumping, the hydraulic head in the well and in the aquifer adjacent to the well screen is decreased. This causes ground water in the aquifer to move laterally toward the well. The drawdown is the decline of water level (or hydraulic head) observed in wells screened in the aquifer being pumped. Under ideal conditions of a relatively uniform regional aquifer, such as the High Plains aquifer, the area experiencing drawdown around the pumping well is nearly circular in plan view. The amount of drawdown is a maximum at the pumping well and diminishes to zero some distance away. The region affected by drawdown from pumping is referred to as the cone of depression (Figure 1). The size of the cone of depression and the drawdown will increase until there is a balance between the pumping rate and the flow in the aquifer moving radially toward the well from all directions. If the rate of water production greatly exceeds the radial flow moving toward the well the cone of depression will grow continuously and the aquifer around the well will eventually be depleted. The movement of water toward the well is governed by the aquifer permeability and thickness.

The Dakota aquifer is not a uniform regional aquifer, but consists of hydraulically connected and isolated permeable sandstone bodies that are finite in size and encased in relatively impervious mudstone. Because the mudstones effectively do not yield water, the edges of these sandstone bodies are hydrologic barriers to flow depending on the rate and duration of pumping. This reduces the rate of recharge moving laterally toward the developing cone of depression or zone of influence. As a result, the zone of influence can extend out from the well along the length of these elongated sandstone bodies for several miles or more and may extend into other hydraulically connected sandstone bodies. However, in the direction perpendicular to the long axis of the sandstone body, this zone may only extend to the edge of the aquifer. In some cases this may be less than a mile away (Figure 2). These boundaries affect the well by accelerating the rate of drawdown increase with time. The lower water levels may necessitate lowering the pump in the well, which increases energy costs associated with water production.

If two pumping wells in the Dakota aquifer are spaced even a few miles apart and are withdrawing water from the same sandstone body, their zones of influence will likely overlap and coalesce (Figure 3). When this occurs, the total recharge moving laterally into each well's zone of influence from the adjacent aquifer is reduced, creating an impairment. Impairment results when one well diminishes the supply of water available to another nearby well. The immediate impact of this impairment is to increase the drawdown in both wells. If both wells continue pumping for longer periods of time, it may cause local depletion of the aquifer. This is

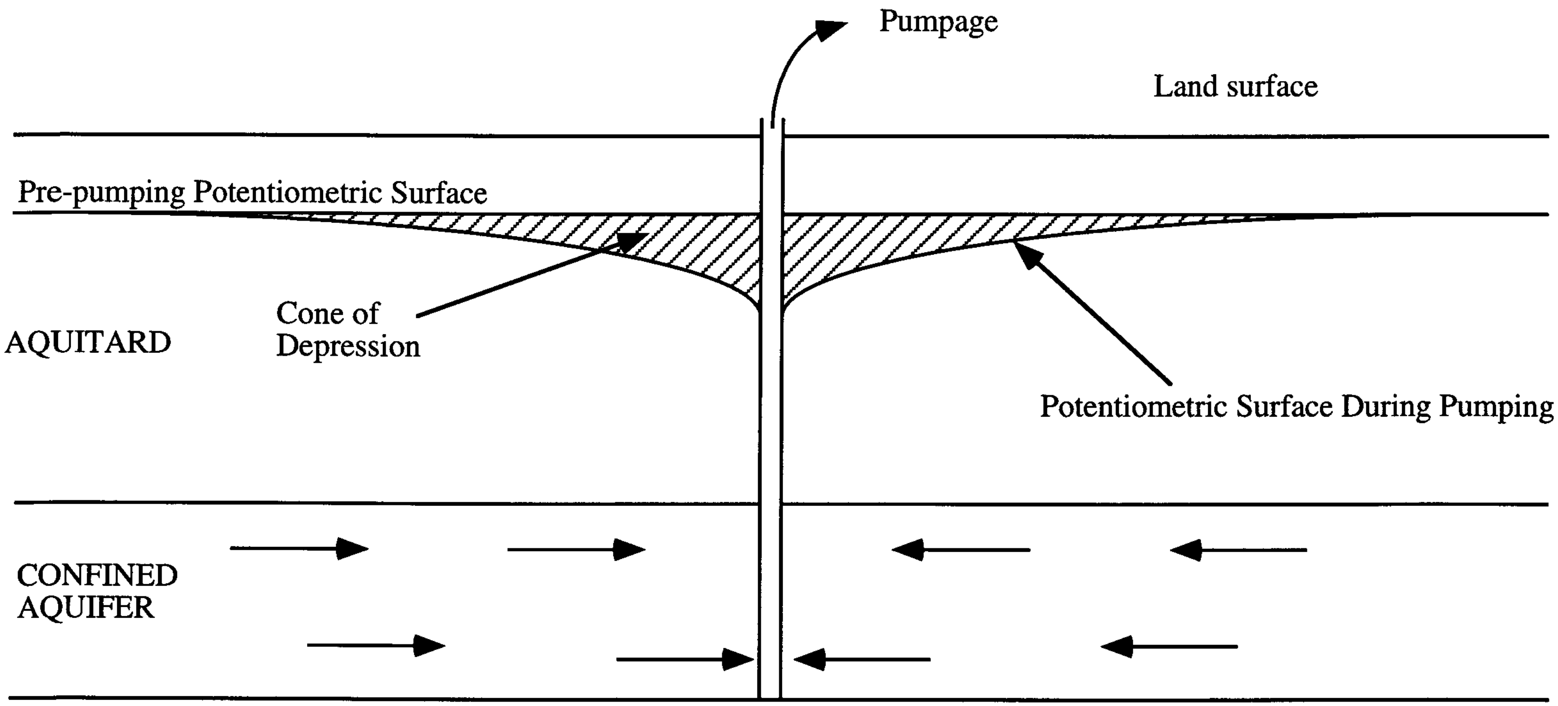

Figure 1. The cone of depression that results from pumping water out of a confined aquifer. Pumping decreases the fluid pressure in the aquifer, thereby also decreasing the hydraulic head in the aquifer.

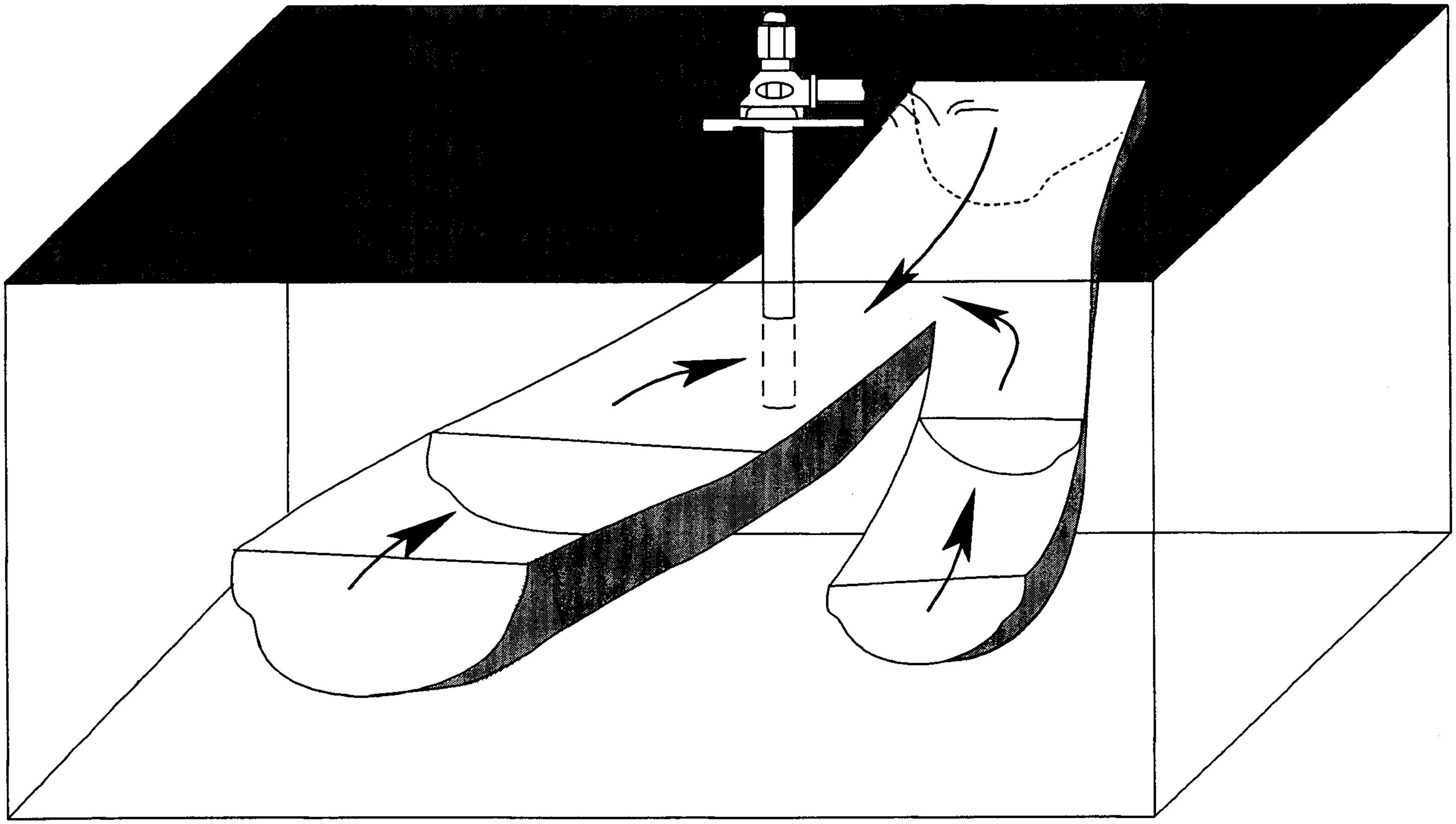

Figure 2. Schematic showing the flow of water to a pumping well screened in a sandstone body. Notice how the flow is "channelized" or restricted and not uniformily distributed as it would be in the Ogallala aquifer.

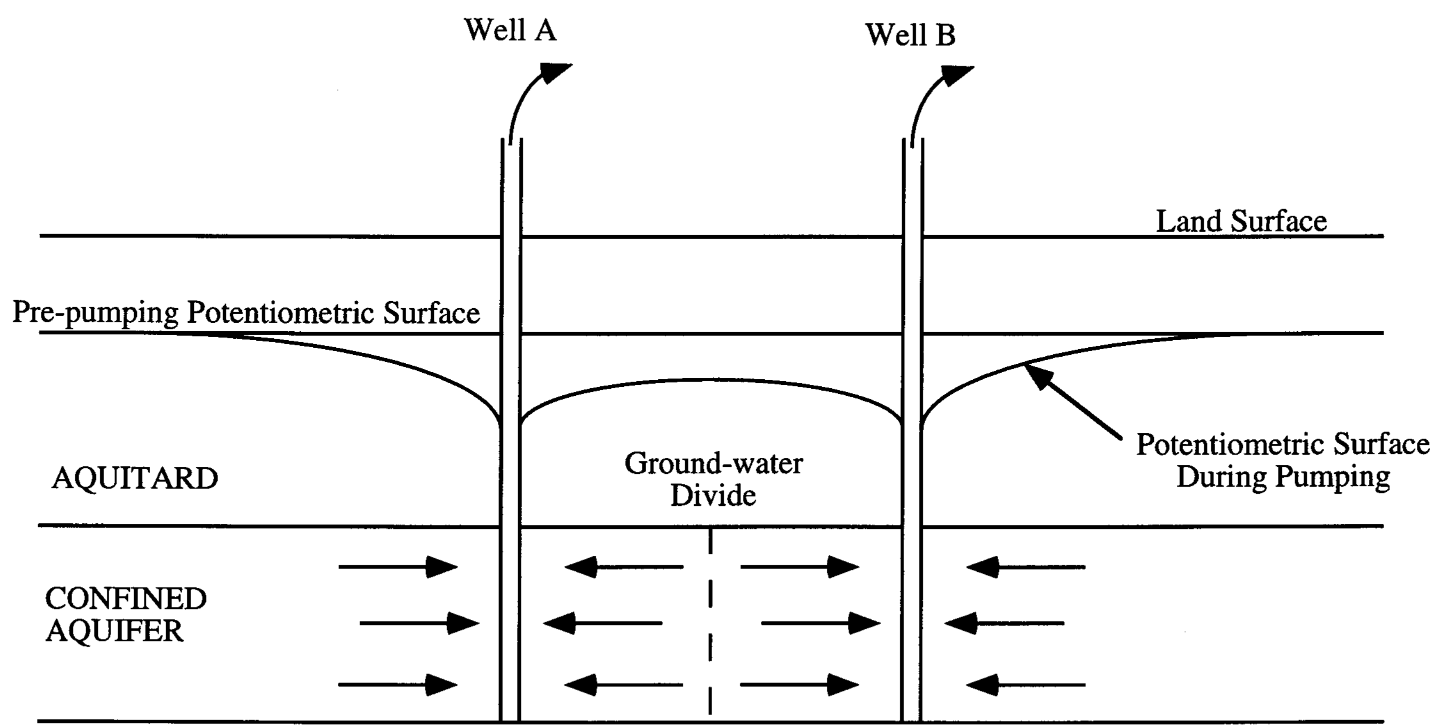

Figure 3. The mutual interference that develops when pumping wells are spaced too closely together in a confined aquifer. Note how the drawdown is greater at the ground-water divide between the wells than at the same point outboard from each well.

most likely to happen where the pumping wells are located far away from sources of recharge or a discharge area.

The pumping effect on hydraulic head is transmitted through an aquifer much faster than the actual movement of water. However, pumping does move water and can induce the movement of saline water in the aquifer into a supply well. Water withdrawn from a well will be preferentially derived laterally from the most permeable layers in a sandstone. Some water may also be derived vertically as leakage from overlying units. However, if pumping occurs at a great enough rate or over a long enough period of time, the stress may be sufficient to cause upward movement of saline water from the bottom of a sandstone below which there is a great salinity increase. Pumping stress can also move water laterally from near the edge of sandstone bodies where water in the confined aquifer can be more saline in finer grained sediments. In addition, long-term pumping near lateral zones of freshwater to saltwater transition could obtain higher salinity water from the transition zone. Decreasing the rate of withdrawal could decrease the amount of saline water drawn from below and laterally if leakage from above the sandstone is relatively important. However, upconing and lateral movement of salinity from nearby sandstone boundaries and saltwater transition zones could eventually cause slow increases in TDS concentrations if the leakage rate from above is relatively low.

Division of Water Resources and Groundwater Management District Spacing Requirements

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

In Southwest Kansas GMD #3, the hydrogeology and use of the Dakota are sufficiently varied across the District that a variable well spacing is appropriate. Figure 4 shows the generalized hydrogeology of the District in cross section. Beneath the unconsolidated High Plains aquifer the bedrock units are slightly tilted to the north. In the northern part of the

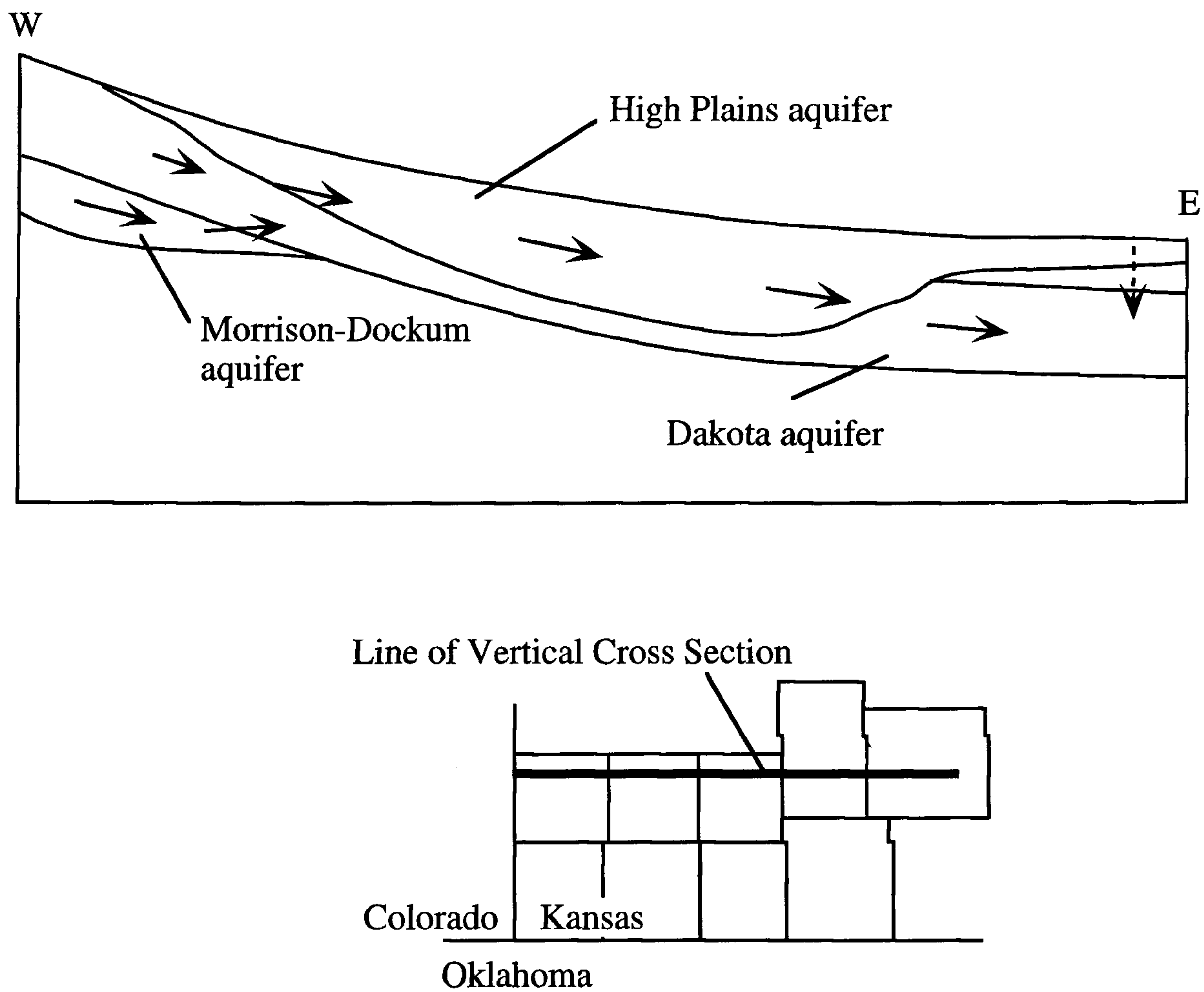

Figure 4. Ground-water flow in the Dakota, Morrison-Dockum, and High Plains aquifers in southwestern Kansas.

Cretaceous aquitard is present and the Dakota and High Plains aquifers are separate systems. In the southern part of the District where the Upper Cretaceous aquitard is not present, the Dakota thins to the south due to erosion and is hydraulically connected to the overlying High Plains aquifer. As a result, the boundary separating the High Plains from the Dakota is an irregular surface. Within this part, the upper Dakota aquifer is not present near the southern extent of the Dakota aquifer system. To the south, the Kiowa Shale aquitard provides a local separation between the lower Dakota and the High Plains aquifers. Elsewhere in the southern part of the District, the lower Dakota is hydraulically connected to the overlying High Plains aquifer. Where both aquifer systems are hydraulically connected, the spacing for wells in the Dakota withdrawing more than 500 acre-ft/yr is 2,300 ft, the same as it is for High Plains aquifer wells. Wells withdrawing less water can be placed more closely together.

Water Supply Suitability Areas of the Dakota Aquifer in Kansas

Introduction

In many areas of western and central Kansas, the water resources in shallow aquifers and surface waters will be inadequate to meet future demands for water. Because the only other available source of water for these areas is the Dakota aquifer, proactive management plans must be formulated to prevent overdevelopment.

The Dakota is a highly variable aquifer system in Kansas. Some parts of the aquifer contain abundant quantities of fresh water at shallow depths. Elsewhere, the aquifer is much deeper in the subsurface and may contain unusable ground water with salinities (the sum of the dissolved constituents in the water) that exceed 10,000 mg/L. In some areas, well pumping in the Dakota may allow saltwater to move upward into shallower, fresher aquifers or induce freshwater recharge into the Dakota from other aquifers. In other areas, ground-water withdrawals may cause the eventual depletion of the aquifer. To insure its continued use the Dakota is best managed by taking into account this high degree of natural variability and the variable response of the aquifer system to pumping.

From our research on the Dakota aquifer, the Kansas Geological Survey (KGS) proposes the recognition of distinct water supply suitability areas in the Dakota aquifer based on local conditions in the aquifer or its response pumping by wells. Information on these proposed suitability areas may be useful for managing existing wells and planning new wells or wellfields in the Dakota aquifer in Kansas. Groundwater management districts, basin advisory councils, state water agencies and other agencies may find this concept useful in the development of water-management plans and policies.

Water Supply Suitability Areas

The highly variable conditions in the Dakota aquifer system, and the impact of pumping, suggests that the strategies used to manage Dakota water resources should vary from region to region. A water supply suitability area is defined by the KGS as a region of the Dakota aquifer in which the hydrologic and water-quality characteristics, and the impacts of pumping on the hydrologic system, are relatively uniform. The proposed boundaries between suitability areas mark significant changes in these characteristics or the response of the hydrologic system to pumping.

For the Dakota aquifer, it is not appropriate to establish suitability areas with permanent, fixed boundaries because the boundaries between some of these areas are not well defined and may change as new information becomes available. Locally, the Dakota remains a relatively unknown aquifer system in Kansas in comparison to the High Plains and other shallow aquifers. Also, the rate and intensity of development may necessitate the adjustment of these boundaries. The KGS is not suggesting the creation of regulatory bodies to manage each of these suitability areas. Rather, it is our intent that these suitability areas be incorporated into the formulation of policies and plans by the existing local and state water agencies. With the recognition of these suitability areas, it may be possible for these agencies to more fully address the issue of sustainability of the hydrologic system, which includes both surface and ground waters.

Description of the Water Supply Suitability Areas of the Dakota Aquifer

Figure 1 shows the location of the six Suitability Areas of the Dakota aquifer in Kansas. The following describes the important features of each suitability area.

Suitability Area I

Suitability Area I encompasses the region where the Dakota and the High Plains aquifers are hydraulically connected in southwestern and south–central Kansas (Figure 1). Where the High Plains aquifer's saturated thickness is greatest, the depth below the surface to the top of the Dakota aquifer is more than 500 feet. In western Stanton, western Morton, and southern Hamilton counties, the High Plains aquifer is absent or is very thin and the Dakota aquifer is the primary shallow aquifer. Ground water in the upper Dakota aquifer is fresh throughout this suitability area. However, ground-water chemical quality is variable in the lower Dakota aquifer because of the small amount of freshwater recharge that passes through the Kiowa shale aquitard. Ground-water salinities may exceed 2,000 mg/L (a value too high for human consumption but usable for livestock) in these parts of the suitability area. Nearer the Kansas-Colorado border and the Dakota's southern extent in southwestern Kansas, the lower Dakota contains fresh water because of its proximity to the regional recharge area in southeastern Colorado and local recharge from the High Plains aquifer. In this suitability area, the Dakota is used for drinking, industry, and agriculture, including irrigation. Water-level declines in the Dakota from previous development are less than 50 ft in Suitability Area I.

Because the Dakota and the High Plains aquifers are hydraulically connected, they behave as a single system in this suitability area. The water-management policies developed for one of the aquifers will eventually have an impact on the other. Consequently, it is appropriate to consider both aquifer systems in policy development.

Suitability Area II

In Suitability Area II the Dakota aquifer is confined by the Upper Cretaceous aquitard and is adjacent to the area where the Dakota is hydraulically connected to the High Plains aquifer

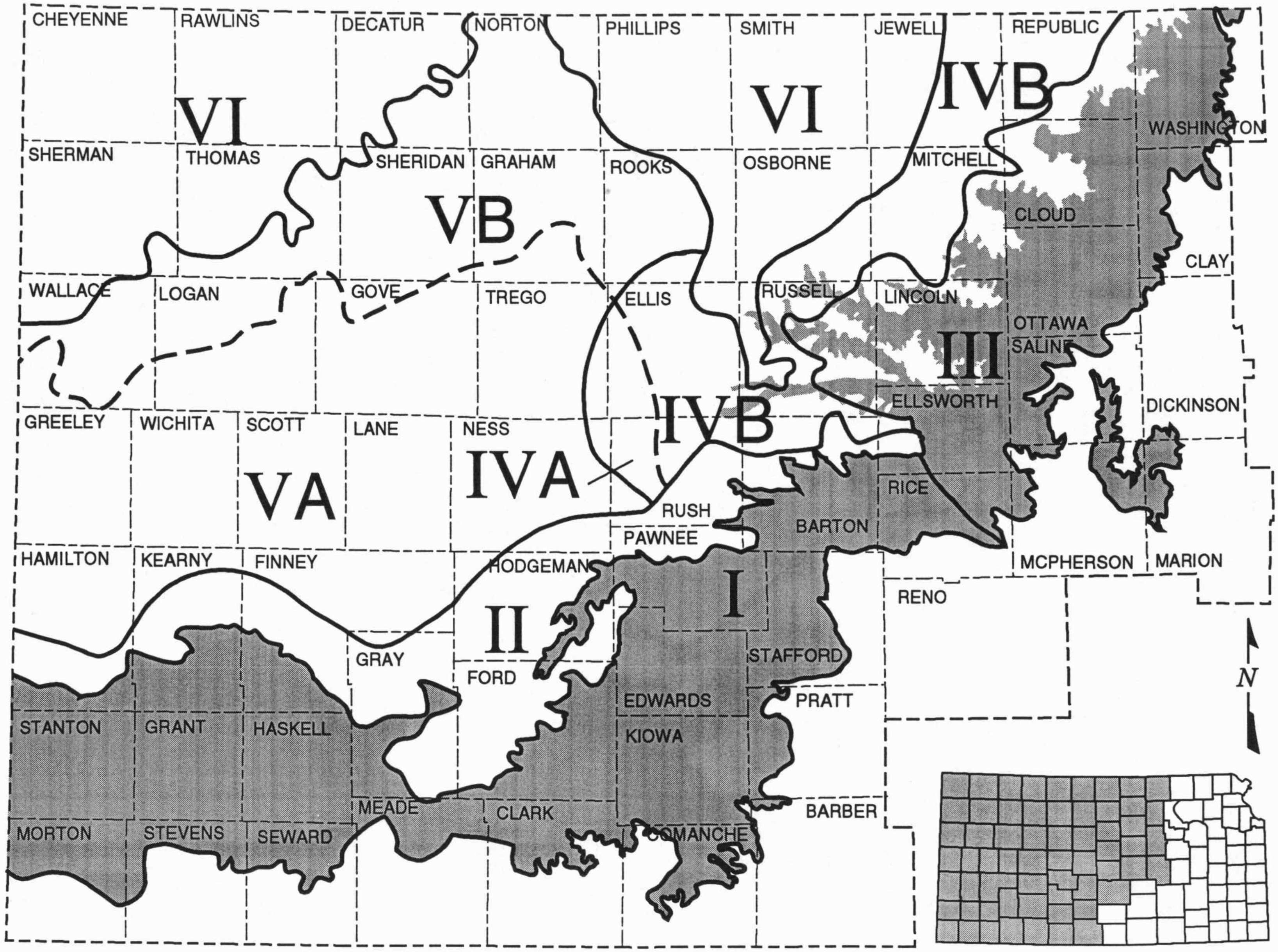

Figure [illegible]. Water supply suitability areas of the Dakota aquifer in Kansas. The dashed line is the 1500 mg/L isocon for ground water in the Dakota.

in Suitability Area I (Figure 1). The depth below the surface to the top of the Dakota aquifer is less than 400 ft over most of this suitability area. Because the aquitard is thin, recharge from overlying sources contributes significantly to the upper Dakota aquifer, but is less than the amount that is being withdrawn by pumping. Ground water in the upper Dakota is fresh (less than 1,000 mg/L) over most of the region. Ground-water salinity in the lower Dakota is believed to be less than 5,000 mg/L in the western half and more than 5,000 mg/L in the eastern half of the area. The upper Dakota is used for drinking water, industry, and agriculture, including irrigation. Use of the Dakota for irrigation is more common in Hodgeman and Ford counties. Water-level declines from previous water-resources development are generally less than 50 ft. Pumping wells in the Dakota aquifer in Suitability Area II may increase recharge from the High Plains aquifer into the Dakota aquifer in Suitability Area I.

Suitability Area III

In the eastern part of Suitability Area III, the Dakota is a shallow unconfined aquifer or is in contact with stream/aquifer systems (Figure 1). In the western part of the suitability area, the Dakota is confined and the Upper Cretaceous aquitard is thin and relatively pervious. The depth below the surface to the top of the Dakota aquifer in the western part of this suitability area is generally less than 150 ft. The maximum recharge rates are on the order of a few tenths of an inch per year where the Dakota is unconfined. Ground-water quality in the upper part of the Dakota is locally variable where the salinity has not been flushed from the aquifer by freshwater recharge. In the unconfined regions, ground water in the upper part of the Dakota is mostly fresh. Salinity generally increases with depth in the lower part of the aquifer where the Dakota is confined and near some of the major streams that cross central Kansas. In this suitability area, the Dakota is used for drinking water, industry, and agriculture, including irrigation. Irrigation use is concentrated primarily in southwestern Washington, southeastern Republic, and northern Cloud counties. Water-level declines from development in Suitability Area III are believed to be less than 20 ft.

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

Suitability Area IV

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

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

Suitability Area V

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

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

Suitability Area VI

In Suitability Area VI, the Dakota is a confined aquifer and contains saline or "mineralized" ground water as defined by state statute. State statutes define mineralized ground water as water containing more than 5,000 mg/L chloride or more than 10,000 mg/L total dissolved solids. Mineralized ground water is considered undesirable for most uses except oil and gas operations (such as secondary recovery) and is not protected by state and local regulations. In the northwest part of Suitability Area VI, the Dakota receives negligible freshwater recharge from overlying sources, flow rates are very low, and the depth to the top of the Dakota exceeds 1,500 ft. In the central part, vertical and lateral flow rates through the aquifer are higher and the top of the aquifer is less than 500 feet deep. However, the flow of freshwater through aquifer has been insufficient to flush the salinity from the aquifer where it is hydraulically connected to the Cedar Hills Sandstone.

Summary

The Dakota is a major aquifer system in Kansas and may become an important source of water in areas where shallower aquifers are inadequate. However, unlike other major shallow aquifer systems in Kansas, conditions in the Dakota are highly variable. Consequently, delineation of water supply suitability areas within the aquifer on the basis of hydrology, water quality, and the impact of pumping is an important first step in proactive policy development to prolong the use of this water resource.

Sustainability of the Dakota Aquifer

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

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

Water budgets are useful for examining the flow of water between the various compartments within the hydrologic cycle or a ground-water flow system. Under pre-development conditions within an aquifer, there is a dynamic equilibrium between recharge and the discharge or outflow from an aquifer (Figure 1A). There is also water in storage within the pores of the aquifer framework and under these conditions, the total volume in storage remains relatively constant.

With the introduction of pumping wells, the volume of water in each of these three catagories changes depending on the location of the pumping wells in the aquifer with respect to sources of recharge and discharge, the rates of withdrawal, and the characteristics of the aquifer. All of the water withdrawn by a pumping well in a confined aquifer comes either from storage or capture (Figure 1B). Initially, all of the water produced by the well comes from storage in the aquifer adjacent to the well. As the well continues to pump, more and more of the aquifer experiences water-level declines. Given enough time, these declines propagate to either the recharge or the discharge area, or both, producing "capture" (Figure 1C). When this happens, additional recharge enters or discharge from the aquifer system is decreased, resulting in an additional source of water added to the aquifer to balance the withdrawal. Capture is the sum of

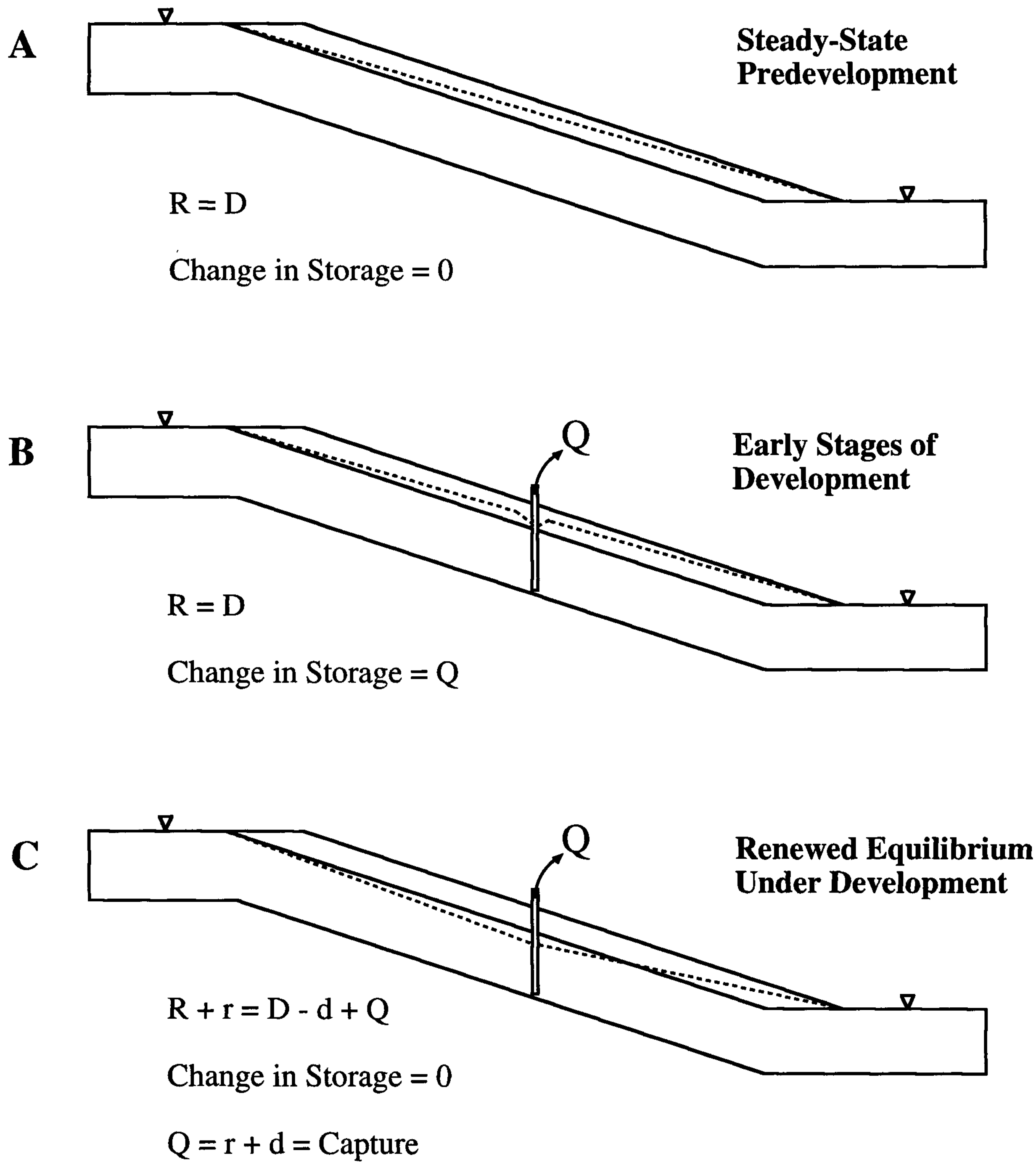

Figure 1. Changes in the water budget of a confined aquifer caused by water-resources development. The dashed line represents the trace of the potentiometric in the cross section. Under the steady-state, pre-development phase recharge (R) is balanced by discharge (D) from the aquifer with no change in storage. In the early stages of development the water produced by wells comes entirely from storage. Once the the potentiometric surface has been lowered sufficiently to increase the hydraulic gradient near the recharge or discharge area, additional recharge (r) or reduced discharge (d) or both may occur, generating capture. In this later stage of development, the water produced by wells comes entirely from capture and there is no further loss of storage and a new equilibrium condition is created. The time required to generate significant capture depends on the diffusivity (the ratio of hydraulic conductivity to specific storage) of the aquifer.

the increase in recharge and the decrease in discharge that results from the pumping. As the well continues to pump, more and more of the water produced by the well is replaced by capture. The additional recharge coming from the recharge area may result from reduced local discharge to streams in the recharge area or from another hydraulically-connnected aquifer. The generation of capture by pumping does not create any "new" water, but is merely a re-allocation of the amounts in the total hydrologic budget for a region. All other things being equal, the proportion of added recharge to or decreased discharge from the aquifer will depend on whether the well is located closer to the source of the recharge or the discharge area. Eventually, a new dynamic equilibrium occurs when the amount of water withdrawn is balanced by capture. At this point, the hydraulic heads in the aquifer approach stability at levels that are lower than they were during pre-development (Figure 2).

In the confined part of the Dakota aquifer, the effects of development will be pronounced. The distance from recharge to discharge areas is up to several hundred miles away in the Dakota in northwest Kansas. If the production wells are more than approximately 20 mi away from sources of recharge or discharge the generation of capture is unlikely within a 20 yr time frame. Even where the High Plains aquifer is present, significant amounts of additional freshwater recharge to the confined Dakota are unlikely because of the low vertical hydraulic conductivity and thickness of the overlying aquitard. Hence, all of the water withdrawn from the aquifer will come from storage. Meaningful management plans in this part of the system should be premised on an acceptable rate of water-level decline within the planning period and not on the premise of sutained yield.

Depletion of the confined aquifer is likely if production wells are spaced too closely together and the rates of withdrawal from the aquifer are unregulated. Computer simulations to assess the effects of pumping have demonstrated that in the confined upper Dakota aquifer, coalescing cones of depression from multiple pumping wells spaced from 1 to 4 mi apart form quickly after pumping begins. After 10 yrs, larger drawdowns than would be expected from a single pumping well are produced and a much larger area of the aquifer is affected by the withdrawals. Taking into account the heterogeneity of the Dakota, a well spacing of 20 mi in an east-west direction and 5 mi in a north-south direction is recommended to avoid mutual interference problems.

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

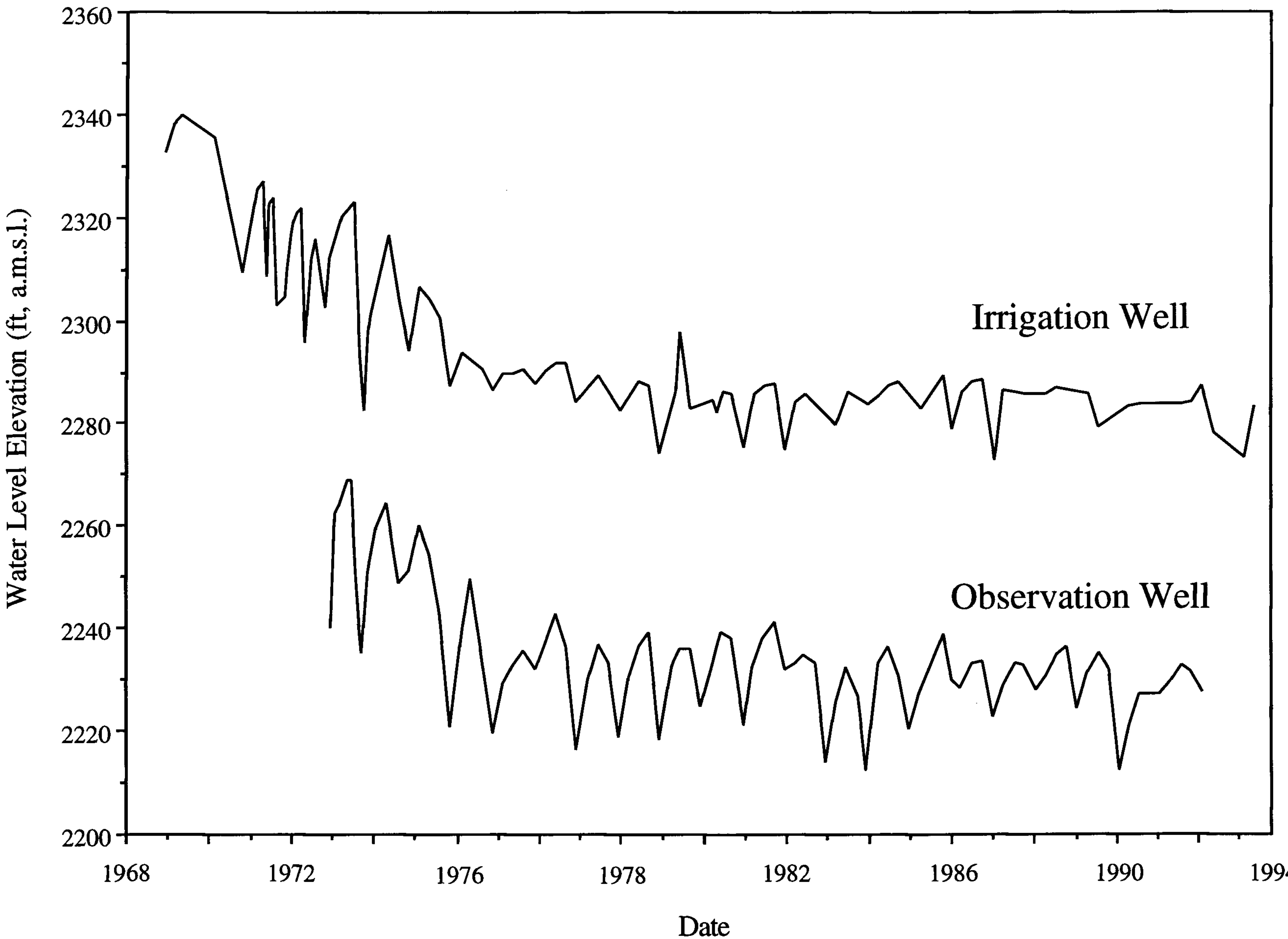

Figure 2. Hydrographs of a production well and an observation well in the upper Dakota aquifer of Ford County, Kansas. The wells are approximately 6 miles apart. Water-level declines during the early phase of development induce flow into the Dakota aquifer from the High Plains aquifer eventually creating a new equilibrium within the aquifer.

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

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

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

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

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