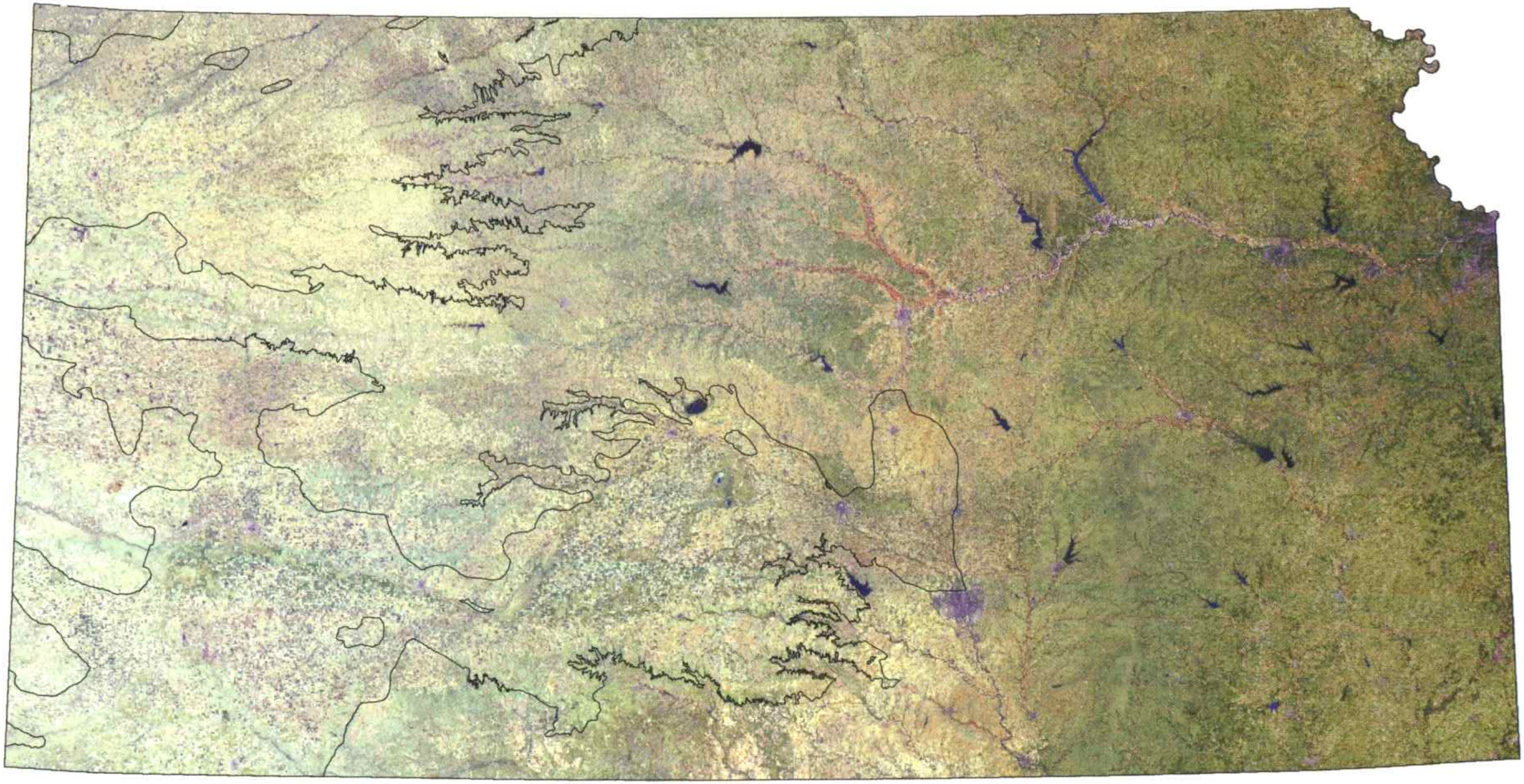
An Atlas of the Kansas High Plains Aquifer



by Jeffrey A. Schloss, Robert W. Buddemeier, and Blake B. Wilson, eds.

Educational Series 14
Kansas Geological Survey
2000

Educational Series 14

An Atlas of the Kansas High Plains Aquifer

by Jeffrey A. Schloss, Robert W. Buddemeier, and Blake B. Wilson, eds.

GIS Analysis and Map Production by J. A. Schloss and B. B. Wilson

Contributors (in alphabetical order):

R. W. Buddemeier
H. Cao
P. A. Macfarlane
C. W. McElwee
G. Misgna
J. Mosteller
J. A. Schloss
M. A. Sophocleous
B. S. Sorensen
M. A. Townsend
D. O. Whittemore
B. B. Wilson
J. J. Woods
D. P. Young

Kansas Geological Survey
Lawrence, Kansas 66047

2000

Cover: **Satellite image of Kansas superimposed with an outline of the High Plains aquifer.**

This image is a mosaic of 16 Landsat Thematic Mapper (TM) satellite images acquired during late summers of 1988 through 1993. The TM instrument records reflected and emitted energy from the earth in seven regions, or bands,of the visible and infrared portions of the electromagnetic spectrum. Although the images depicted here appear in natural color—vegetation appears green, water appears blue—they are actually a composite of two infrared and one visible bands. Infrared bands are used because they are less affected by atmospheric scatter from water vapor and other airborne particles than visible bands. The benefit is a high-contrast, haze-free image.

Image courtesy of the Kansas Applied Remote Sensing (KARS) Program, Kansas Biological Survey.

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

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

ISBN: 1-58806-316-X

Contents

Supplementary and Technical Appendices

Table

Figures

Introduction

R. W. Buddemeier
Kansas Geological Survey, Lawrence, Kansas

Boldface items refer to other sections; *italic* items refer to glossary definitions

The High Plains aquifer is a large (approximately 33,500 square miles of surface area) body of sands, gravels, silts, and clays. In western Kansas it generally is identical with the Ogallala formation, and the aquifer system originally was known as the Ogallala aquifer. However, the part of the aquifer extending into south-central Kansas (east of Ford County) currently is recognized as hydrologically similar but geologically different formations, and the combined aquifer system is referred to as the High Plains. Figure 1 illustrates the geographic extent of the saturated portion of the aquifer. Superimposed on the map of the physical boundaries of the aquifer are the counties (with abbreviated identifiers) and two important sets of administrative boundaries. The Groundwater Management Districts (GMDs) are responsible for managing the ground water within their boundaries, and the river basins provide the geographic basis for the development and implementation of the Kansas Water Plan. These are not the only relevant political boundaries; various types of districts (watershed, conservation, water assurance, local environmental protection, etc.) all have an effect on the water resource. However, a detailed enumeration of local entities is beyond the scope of this aquifer-scale description.

This atlas focuses on ground water and related water-resource issues in the High Plains aquifer in western and central Kansas. This region of the state largely depends on ground-water resources, which are, for the most part, fully appropriated and are declining in a number of areas. The western two-thirds of the state contrasts with eastern Kansas where precipitation and streamflow are more abundant, and the principal aquifer resources generally consist of alluvial deposits that have direct hydrologic connections to the streams. In eastern Kansas there generally is less stress on and competition for ground-water resources. In comparison, the High Plains aquifer of western and central Kansas encompasses a much larger area and contains a greater volume of ground water, much of which occurs independent of current streamflows. Due to the more arid environment, lack of dependable streamflow, and greater accessibility to ground water, a large proportion of the water-right development in Kansas has occurred within the High Plains aquifer region. The High Plains aquifer region has an integrated agri-business system based primarily on irrigation, and depends on ground-water resources which, for the most part, are nonrenewable under current water-use conditions. Kansas water policy and management practices thus must encompass a variety of environmental, economic, and hydrologic issues, of which meeting the water needs of western and central Kansas is among the most challenging.

The primary audience for this atlas is therefore the community of policy-makers, managers, and their technical support staff. At the same time, this information will be useful and of interest to both the general public and to researchers and analysts. To make the presentation as useful and authoritative as possible, it has been organized in a basic pattern of brief summary presentations of the various topics and results, accompanied by illustrative maps or figures. A standard format has been adopted that addresses for each topic:

- The subject and its definition;
- Its relevance or importance to understanding or managing the water resource;
- Key characteristics or features (with reference to the map or figure);
- Sources of information or data and how the product was prepared;
- Qualifications—limitations on the quality or use of the product; and
- References to related topics.

More detailed discussions of methods, uses, relationships, and other more technical background information are provided as appendices that are referenced to appropriate topics in the basic atlas entry, allowing readers to control the depth and level of detail at which they explore the topic while providing the information necessary for scientifically informed use of the products.

A **glossary** of hydrologic, geologic, and environmental terms has been provided; it is referred to at the first text appearance of some key terms, but also can be used independently as a dictionary to look up definitions of a wide range of other terms. Terms included in the glossary appear throughout the text in *italics*. References to other sections of the atlas appear in **boldface**.

The electronic version of this atlas <http://www.kgs.ukans.edu/HighPlains/atlas/> is a preliminary presentation of work in progress, subject to review, correction, and revision. While every effort has been made to ensure that it is accurate and informative, it is not appropriate for use in local, detailed, or highly quantitative analyses. It does not have official or regulatory status, and should not be used in place of maps that have been subject to technical review and/or official adoption.

Acknowledgments: This atlas of the High Plains aquifer in Kansas has been prepared by the Kansas Geological Survey under contract with the Kansas Water Office. The immediate purpose of the atlas is to provide technical information in response to a mandate by the Kansas Legislature to the Kansas Water Authority for a report on a range of water-resource issues relevant to Kansas. The atlas was developed in part with support from the Kansas Water Plan Fund.

The following contributions are gratefully acknowledged: Sharon Vaughn (program support and product development); Melany Miller (clerical and general office assistance); Mark Schoneweis (illustrations); Rex Buchanan, Marla Adkins–Heljeson, and Jennifer Sims (review, editing, and layout); and members of the HPAE Coordinating Council and their staffs and other external reviewers (review, advice, data, and information).

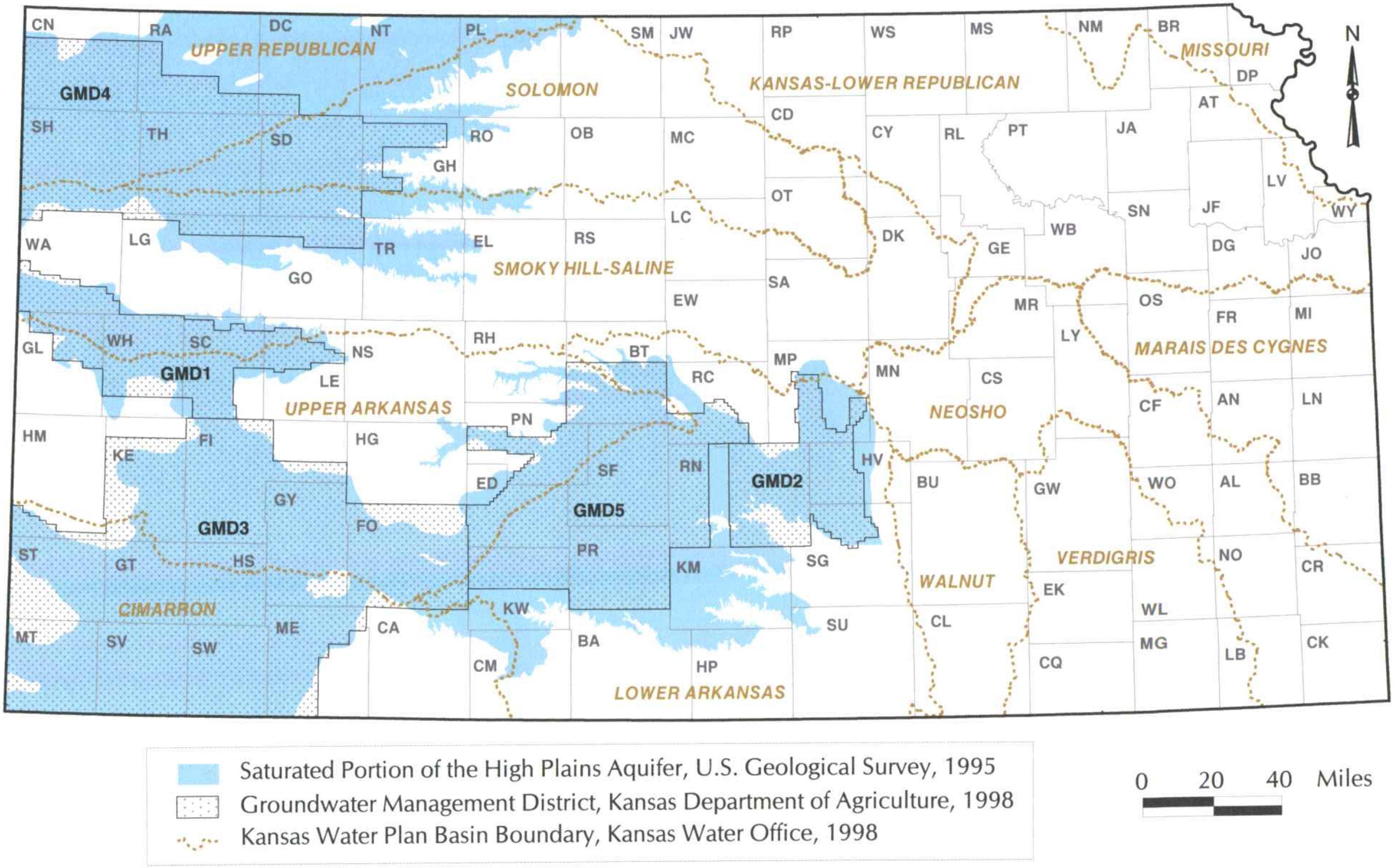


FIGURE 1—Location map showing High Plains aquifer extent, Groundwater Management Disrict boundaries, and Kansas Water Plan basin boundaries.

Surface Water in Kansas and its Interactions with Ground Water

M. A. Sophocleous[1] and B. B. Wilson[2]
[1]Kansas Geological Survey, Lawrence, Kansas, and [2]Kansas Water Office, Topeka, Kansas

Definitions: Surface water can be defined as all water on the surface of the land, including *runoff* moving across the land surface, streamflow in rivers, creeks, or other natural channels, ground water contributed through seeps or springs, and storage in lakes, ponds, or reservoirs. Streamflow rates usually are expressed in cubic feet per second (cfs), and these rates can be converted to streamflow volume by multiplying the rate by the time interval of interest, usually one year. Thus streamflow volume usually is expressed in acre-feet or in inches of runoff. One inch of runoff represents the volume of water required to cover the entire drainage area of a stream to a depth of one inch.

Relevance to understanding water resources: Approximately half the Kansas population is served by surface water. The distribution of surface *water rights* in the state is shown in fig. 2; Wyandotte County in eastern Kansas diverts the greatest amount of surface water. Because of high variabilities of streamflows, many municipalities and industries in the eastern third of Kansas depend on water stored in major reservoirs to meet current and future needs. Without the benefit of impoundments, flows in all but the largest Kansas streams would be almost zero for 30-day periods during moderate drought conditions.

Discussion: Surface water is distributed unevenly across Kansas mainly because of the state's climate. With few exceptions, western Kansas has little surface water. Ground water is the principal source of freshwater in most of this area. In contrast, ground water is not available in sufficient quantity in most of eastern Kansas, where surface water is the principal source of large supplies (fig. 2). To better manage the water resources of the state, Kansas is divided into 12 major river basins (fig. 3), a division based on the philosophy that areas drained by the same stream often have many similar water issues in common. Average annual rainfall ranges from 15 to 18 inches per year in far western Kansas to more than 40 inches per year in southeastern Kansas.

Although this climatically controlled rainfall variation is significant, average annual runoff across the state varies much more than the precipitation (figs. 4, 5). By comparison, the average runoff ranges from approximately 10 inches in the east (25% of precipitation) to 0.1 inch in the west (less than 0.6 of 1% of the precipitation), a 100-fold change in the runoff across the state.

Measured streamflow entering Kansas averages 1.7 million acre-feet annually. About 90% of this incoming streamflow is from southeastern Nebraska; the semi-arid High Plains of eastern Colorado contribute little runoff to Kansas. The flow in ungaged streams entering the state adds little to this total because most of the streams are dry except immediately following heavy rains. The precipitation falling over the state amounts to 118.7 million acre-feet in an average year, and about 13 million acre-feet per year leaves the state as streamflow. The streams annually accumulate 11.3 million acre-feet of runoff within the state. Figure 6 illustrates these water-budget components for the state of Kansas.

Few natural lakes occur in Kansas. The largest lakes in Kansas are the human-made impoundments formed behind dams built by the U.S. Army Corps of Engineers and the U.S. Bureau of Reclamation. These reservoirs store water for flood control, irrigation, municipal and industrial water supply, and other uses. Twenty-four major reservoirs have been built in the state, 17 by the Corps of Engineers and seven by the Bureau of Reclamation. The 24 reservoirs have a total storage capacity of 11 million acre-ft, of which 2.35 million acre-ft are available for conservation (water-supply) capacity to regulate surface-water supplies for sustained use in times of drought. Because of the high variability of streamflows, the State

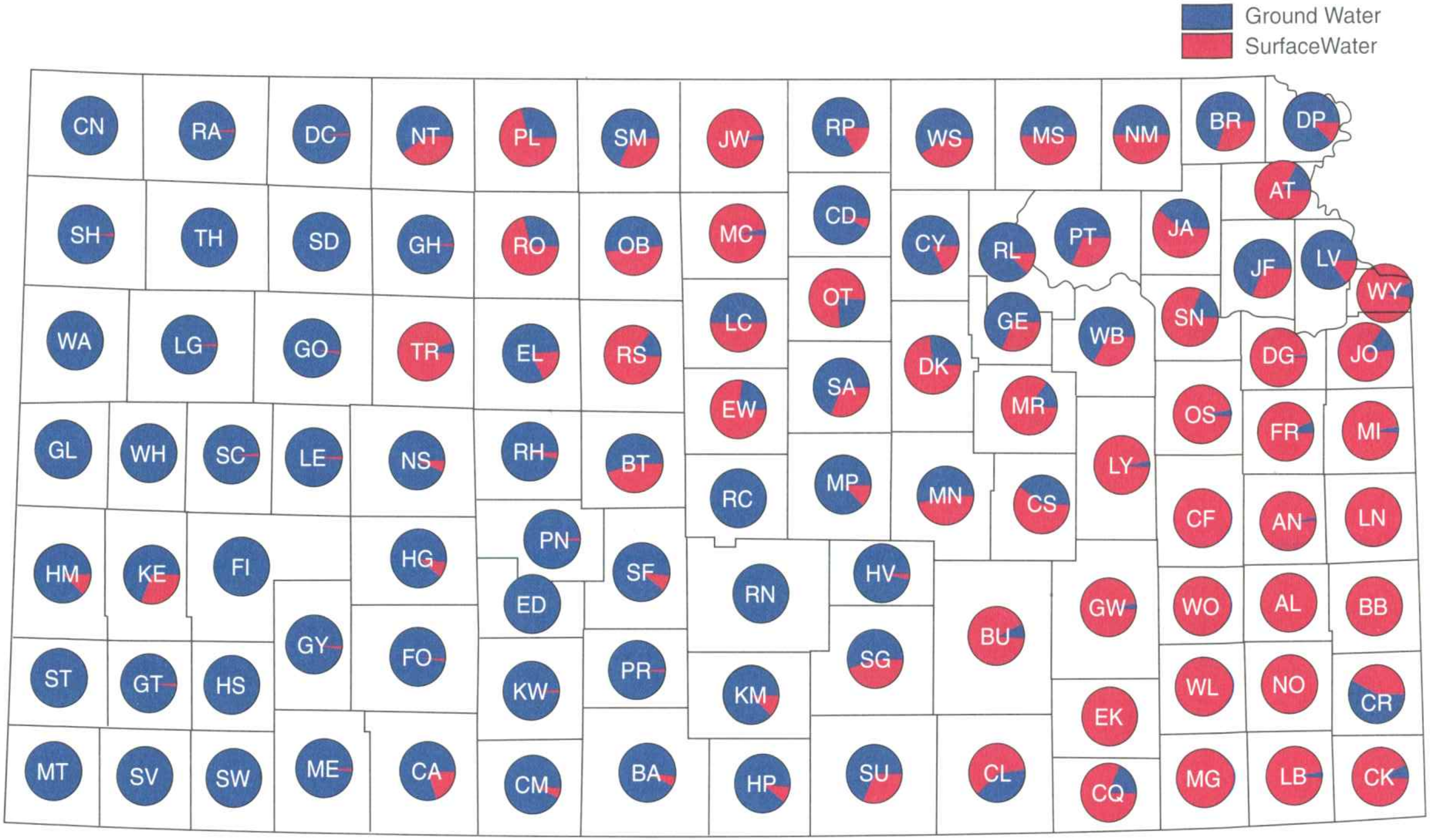


FIGURE 2—Proportion of surface- and ground-water rights for counties in Kansas, year 2000 data.

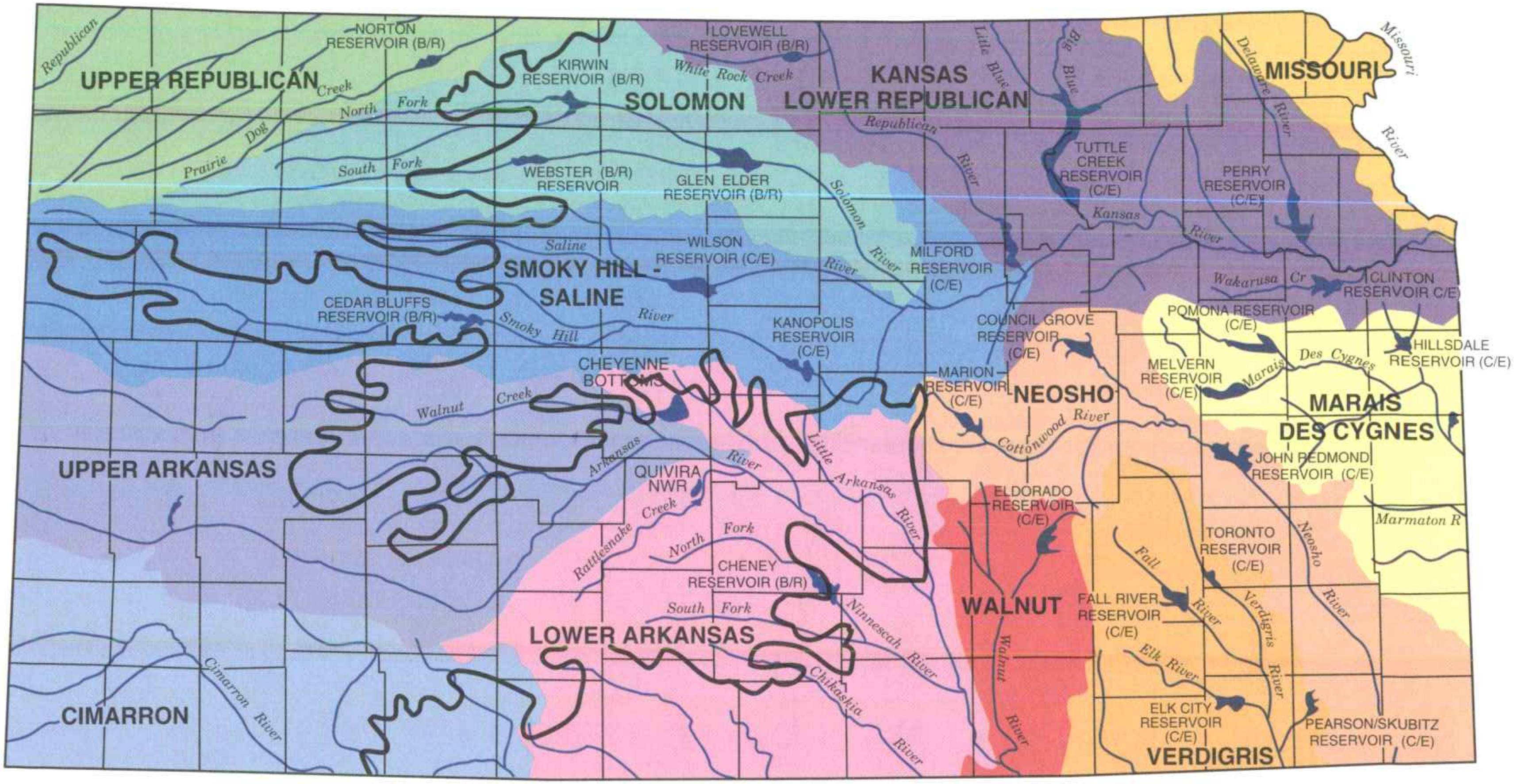


FIGURE 3—Kansas rivers and reservoirs (B/R = Bureau of Reclamation; C/E = Corps of Engineers) and major river basins. The two largest Kansas wetlands (Cheyenne Bottoms and Quivira National Wildlife Refuge, NWR) also are shown. The area west of the solid black line shows the extent of the High Plains aquifer in Kansas.

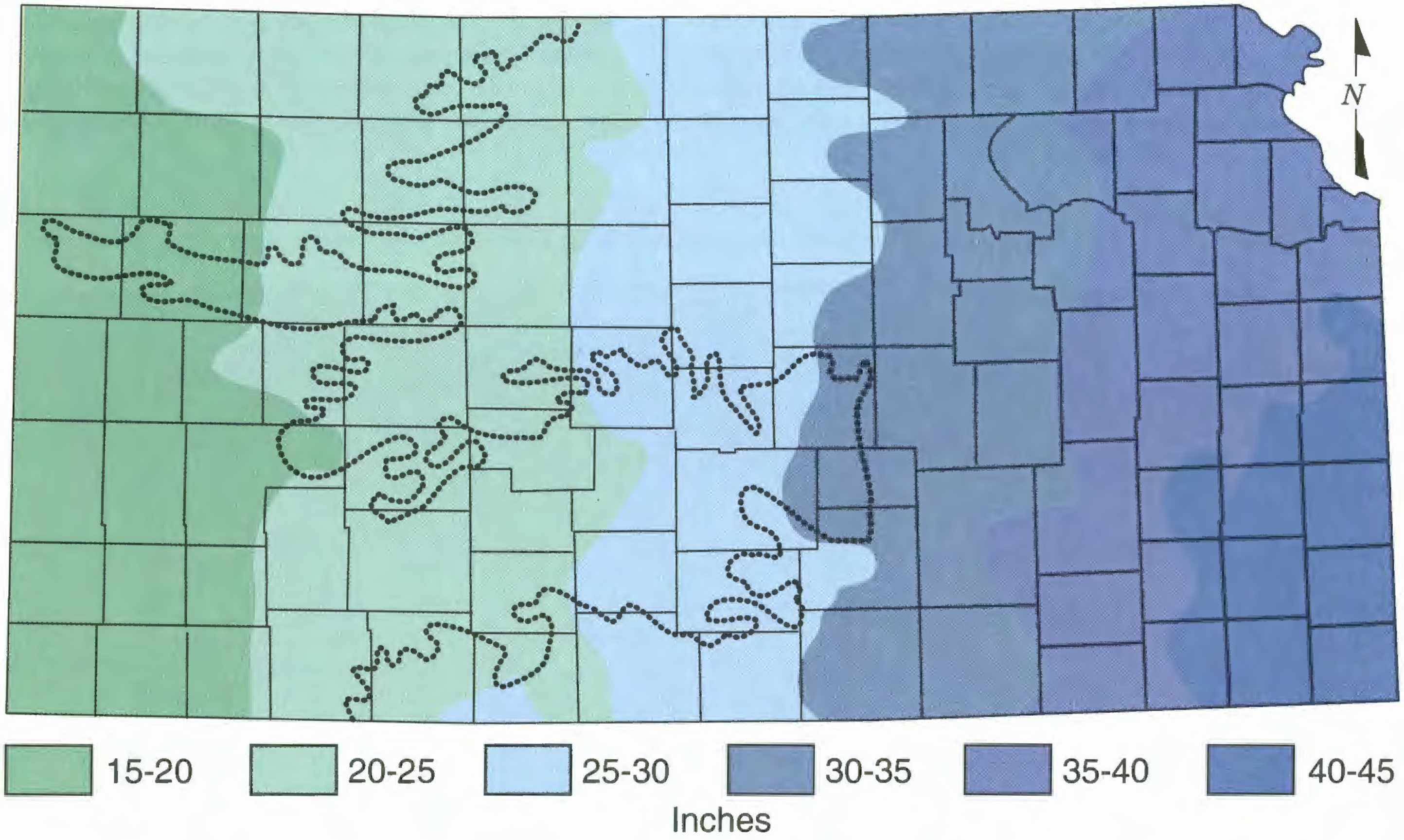


FIGURE 4—Normal annual precipitation (1961–1990) in Kansas. The area west of the dashed line shows the extent of the High Plains aquifer in Kansas (adapted from Goodin et al., 1995).

has contracted with the Federal government for water-supply storage in 12 of these reservoirs. The state makes water available to municipal and industrial water users through contracting procedures established by statute.

The two traditional methods of obtaining water in Kansas are the Water Appropriation Act (for water rights) and the Water Marketing Program, involving 12 Corps of Engineers reservoirs where the State currently owns storage. The Water Marketing Program in concert with the Water Assurance and Multipurpose Small Lakes Programs, all operated by the Kansas Water Office, provide surface-water supplies to approximately 61 Kansas communities, 68 rural water districts, and three public wholesale water-

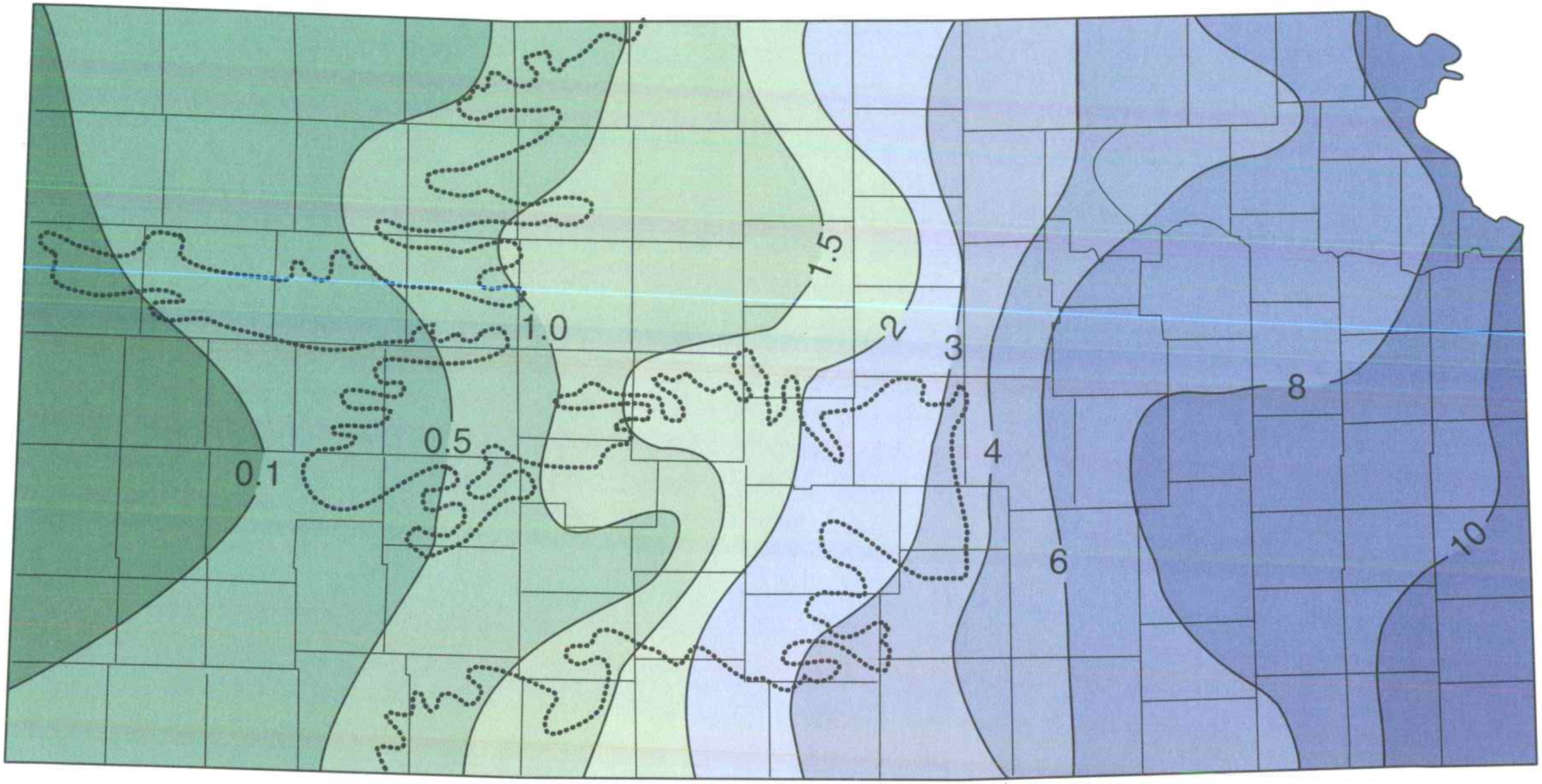


FIGURE 5—Mean annual runoff (in inches) in Kansas. The area west of the dashed line shows the extent of the High Plains aquifer in Kansas (adapted from Wetter, 1987).

supply districts, as well as to commercial and industrial water users. These surface-water supplies serve part or all of 29 Kansas counties.

Although the distinction between surface and ground water seems simple, they are connected in such a way that surface water can become ground water and vice versa, and such surface-/ground-water interactions generally are difficult to observe and measure. Aquifers often are fed partially by seepage from streams and lakes, and such surface-water bodies are known as *losing streams* or lakes (fig. 7A). In other locations, these same aquifers may discharge through seeps and springs to feed the streams, rivers, and lakes, and such water bodies are known as *gaining streams*, rivers, and lakes (fig. 7B). Many streams in Kansas gain water from such ground-water seepage, and this streamflow contribution from ground water is known as *baseflow*. Baseflow keeps the streams flowing during dry periods. For ground water to discharge into a stream channel, the altitude of the *water table* in the vicinity of the stream must be higher than the altitude of the stream-water surface. Ground-water pumping may lower the altitude of the water table in the vicinity of the stream, in which case ground-water seepage to the stream decreases; in cases of severe, extensive ground-water pumping, the water table in the vicinity of the stream may drop below the altitude of the stream-water surface, in which case the stream will lose water to the underlying aquifer. This seems to be happening in many regions of Kansas, but especially in western Kansas.

Many streams in western Kansas have experienced a progressive reduction in flow during the past three decades (fig. 8). Trends are most dramatic in the upper Arkansas, Cimarron, and Smoky Hill River basins, where a shift toward irrigated crop production has contributed to the lowering of the water table and significantly reduced baseflow contributions to streams from shallow aquifers.

Agricultural conservation practices also contributed to runoff reduction to streams. Declines in flow also exert a direct impact on surface-water quality by reducing the dilution base available to effluents from sewage-treatment plants and other pollution sources. Reductions in streamflow also aggravate problems associated with the intrusion of highly mineralized ground water, such as occurs in the Saline River and in Rattlesnake Creek. In an attempt to prevent streams from dwindling in quantity and quality because of declines in baseflow, water diversions, and pollution sources, the state established Minimum Desirable Streamflow (MDS) and Total Maximum Daily Load (TMDL) limits in selected streams in Kansas.

Data Sources and Methods: To evaluate surface-water supplies, continuous records of streamflow for a period of several years are necessary. Reasonable estimates of the quantity and variability of flow available can be made only from records of this nature. Stream-gaging stations have been maintained in Kansas for many years to collect the information needed for evaluation of the state's surface-water supplies. Streamflow information and water elevations currently are being collected from 143 complete-record stream-gaging stations and 19 lakes and reservoirs as the result of cooperative agreements between the U.S. Geological Survey and various State and Federal agencies. Near real-time water-level information is currently available on the Internet for stream-gaging stations and lakes (http://www-ks.cr.usgs.gov). Additional information on the water marketing, water assurance, and multipurpose small lakes programs can be found in the Kansas Water Office web page (http://www.kwo.org).

References

Angelo, R. T., 1994, Impacts of declining streamflow on surface water quality: 11th Annual Water and the Future of Kansas Conference Proceedings, Manhattan, KS, p. 1–2

Goodin, D. G., Mitchell, J. E., Knapp, M. C., and Bivens, R. E., 1995, Climate and weather atlas of Kansas—An introduction: Kansas Geological Survey, Educational Series 12, 24 p.

Sophocleous, M. A., 1998, Water resources of Kansas—A comprehensive outline; *in*, Perspectives on Sustainable Development of Water Resources in Kansas, M. A. Sophocleous, ed.: Kansas Geological Survey, Bulletin 239, p. 1–59

Wetter, L. H., 1987, Water conservation for more crop production in the Great Plains; *in*, Ground Water Quality and Agricultural Practices, D. M. Fairchild, ed.: Lewis Publishers, p. 13–34

Winter, T. C., Harvey, J. W., Franke, O. L., and Alley, W. M., 1998, Ground water and surface water—A single resource: U.S. Geological Survey, Circular 1139, 87 p.

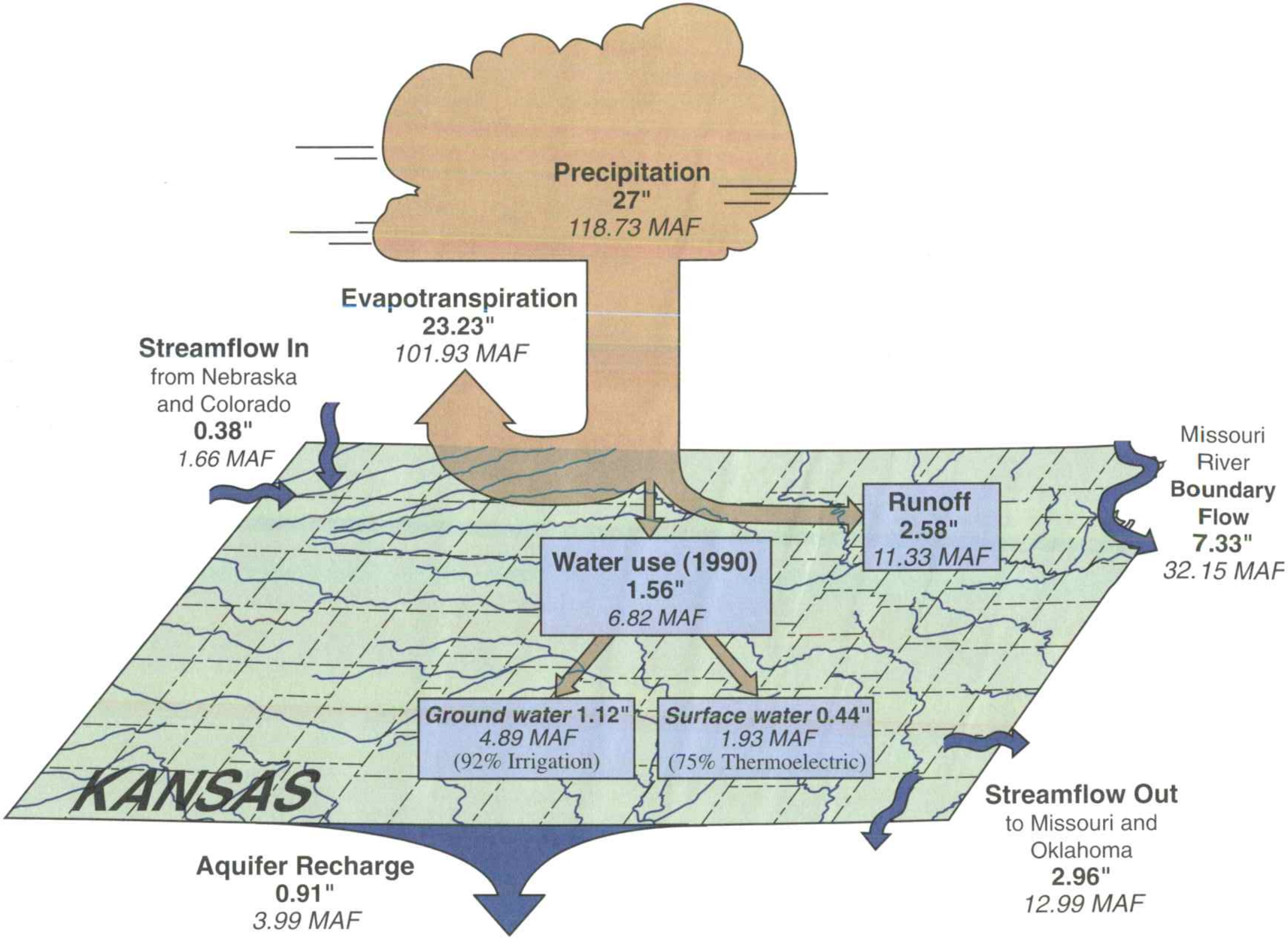


FIGURE 6—Water-budget components for Kansas. Values are in inches per year and million acre-feet per year (MAF). (Adapted from Sophocleous, 1998.)

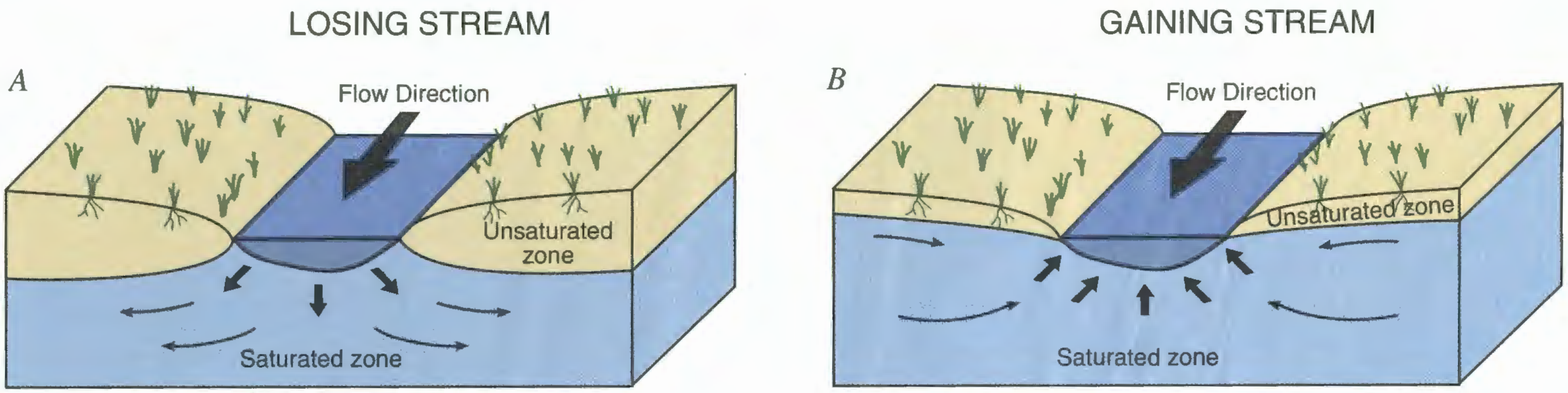


FIGURE 7—Interaction of streams and ground water. Losing streams (A) lose water to the ground-water system, whereas gaining streams (B) receive water from the ground-water system.

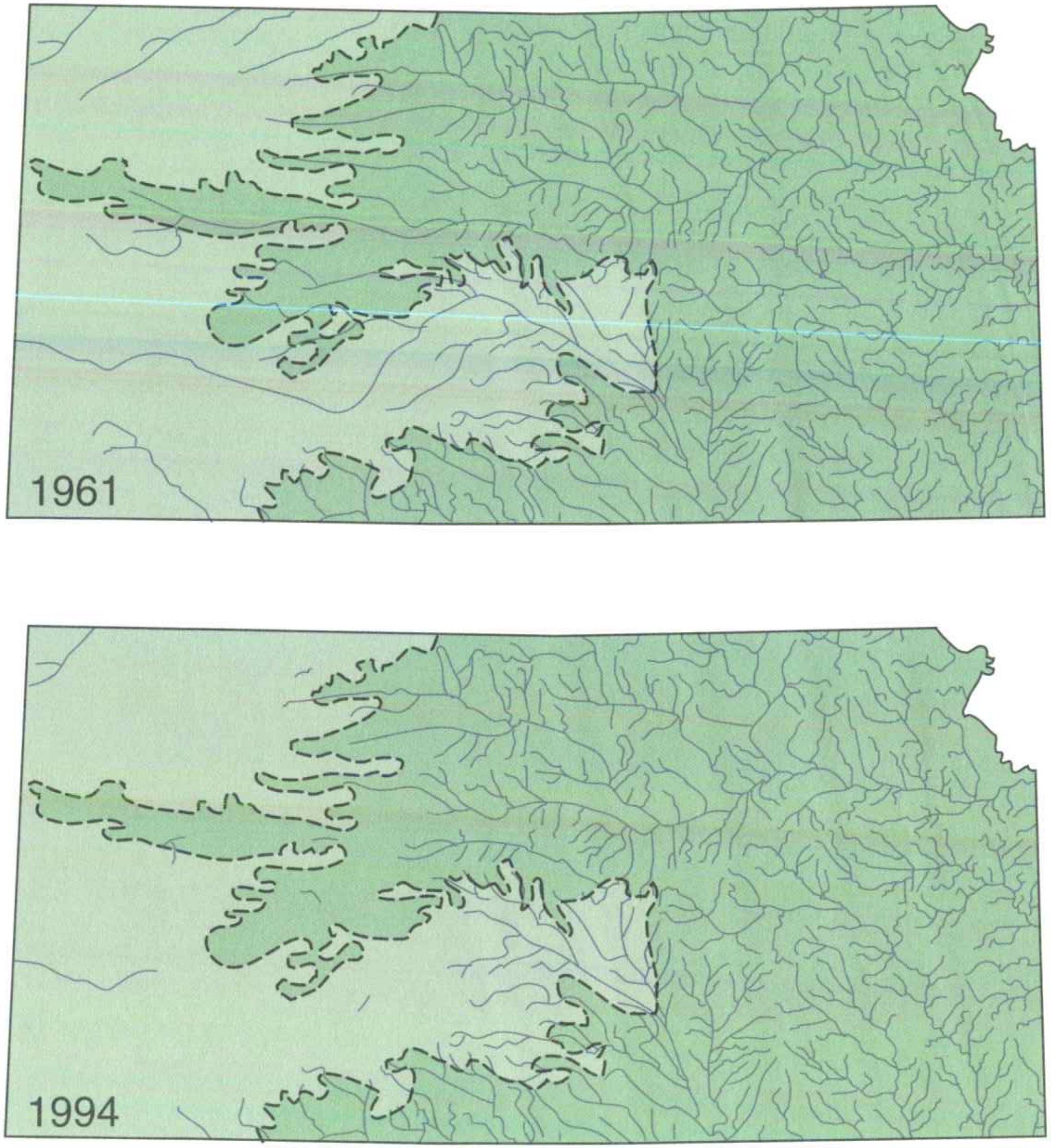


FIGURE 8—Major perennial streams in Kansas in 1961 and 1994. The area west of the dashed line shows the extent of the High Plains aquifer in Kansas (adapted from Angelo, 1994).

Aquifers of the High Plains Region

P. A. Macfarlane, G. Misgna, and R. W. Buddemeier
Kansas Geological Survey, Lawrence, Kansas

An *aquifer* is a body of rock or sediment that contains and yields enough water to be useful to humans. Its boundaries are defined by the land surface and/or by its borders with surrounding geologic formations, particularly if those borders do not contain or transmit water. The characteristics of aquifers are discussed in more detail in technical appendices on **aquifer types** (terminology and definitions), **saturated thickness**, and **ground-water storage and flow**.

The High Plains aquifer is the most important water resource in western and south-central Kansas, an area that lacks extensive surface water and has limited precipitation. The High Plains aquifer underlies approximately 33,500 square miles of 46 counties in western and south-central Kansas and is present in seven other states in the Great Plains region of the United States. Depth below land surface to the base of the aquifer is as much as 500 feet in parts of southwestern Kansas. This water source consists of Pliocene to late Holocene (approximately 5 million years ago up to present day)-age sediments deposited by eastward-flowing streams and by wind. These sediments consist of unconsolidated clay, silt, sand, and gravel in amounts that vary across the region. This aquifer formerly was referred to as the Ogallala aquifer in Kansas. However, the name has been changed because regional studies by the US Geological Survey have shown that other geologic units as well as the Ogallala form this aquifer. The purpose of this section is to identify the various aquifers in the region and describe their interaction with the High Plains aquifer.

Other aquifers are hydraulically connected to the High Plains aquifer. An aquifer is connected hydraulically to an overlying or underlying aquifer if water can move easily between them. Poor hydraulic connection exists when the aquifers are separated by low-permeability sediment or rock layers. In the extreme, an aquifer is isolated hydraulically from another if they are separated by thick, low-permeability sediment or rock layers. The other aquifers present in the High Plains region include the alluvial, the Dakota, and those within Permian rock units. The map (fig. 9) and cross sectional view (fig. 10) of the subsurface show the aquifer distributions in relationship to the High Plains aquifer.

The alluvial aquifers, which overlie the High Plains aquifer, consist of unconsolidated sediments deposited by rivers in the stream valleys (see fig. 9). In southwest Kansas, hydraulic connection between the Arkansas River alluvial aquifer and the underlying High Plains aquifer is poor because low-permeability clay layers inhibit the downward flow of ground water (see fig. 10). Thus, the upper Arkansas River alluvial aquifer is a perched aquifer. However, the Cimarron River alluvial aquifer is well-connected to the underlying High Plains aquifer because no clay layers are immediately beneath the alluvium to inhibit the flow of ground water between the aquifers.

The Dakota aquifer consists of sandstones that were deposited in ancient river valleys and along shorelines during the Cretaceous Period (approximately 100 million years ago) and underlies much of the western two-thirds of Kansas. In southwest and south-central Kansas, the Dakota underlies and is in good hydraulic connection with the High Plains aquifer (see figs. 9 and 10). To the north, a thick sequence of low-permeability shale and chalk hydraulically isolates the Dakota from the High Plains aquifer. As a result, the High Plains aquifer interacts very little if at all with the Dakota over most of its northern extent. Further information on the Dakota aquifer can be found at http://www.kgs.ukans.edu/Dakota.

The aquifers in Permian rocks consist of sandstones that were deposited along shorelines and in shallow bays during the Permian Period (approximately 250 million years ago) and underlie all of the western two-thirds of Kansas. In most areas, the water in these aquifers is too saline for human use. Where the Dakota is not present to separate them, these bedrock aquifer units are in good hydraulic connection with the overlying High Plains aquifer (figs. 9 and 10). This allows the upward movement of saltwater from the dissolution of naturally occurring salt in south-central Kansas Groundwater Management Districts (GMDs) No. 2 and No. 5, and beneath the Cimarron River valley in southwestern Kansas GMD3 (see **Regional Ground-water Quality Provinces** section).

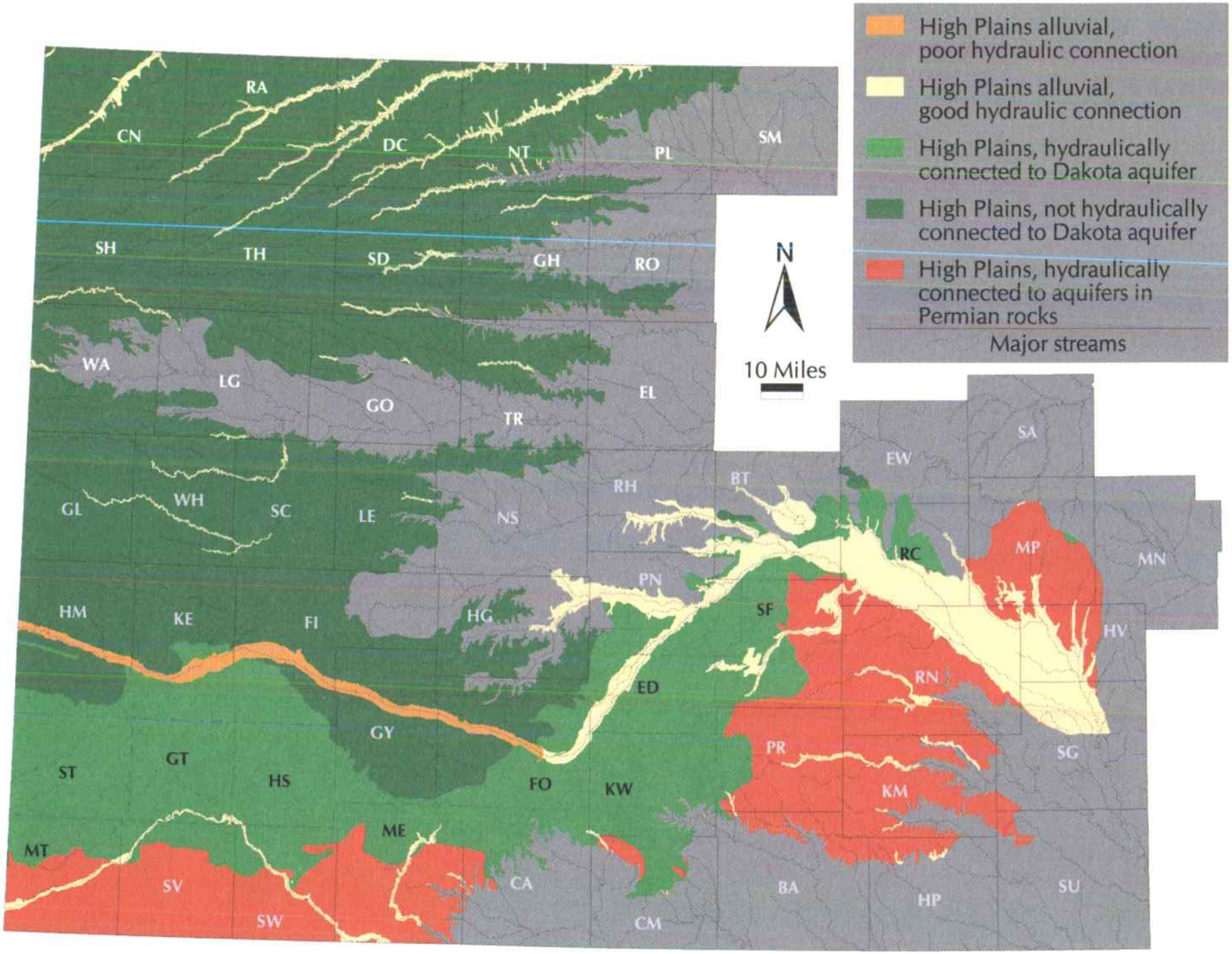


FIGURE 9—Map showing High Plains aquifer relationships.

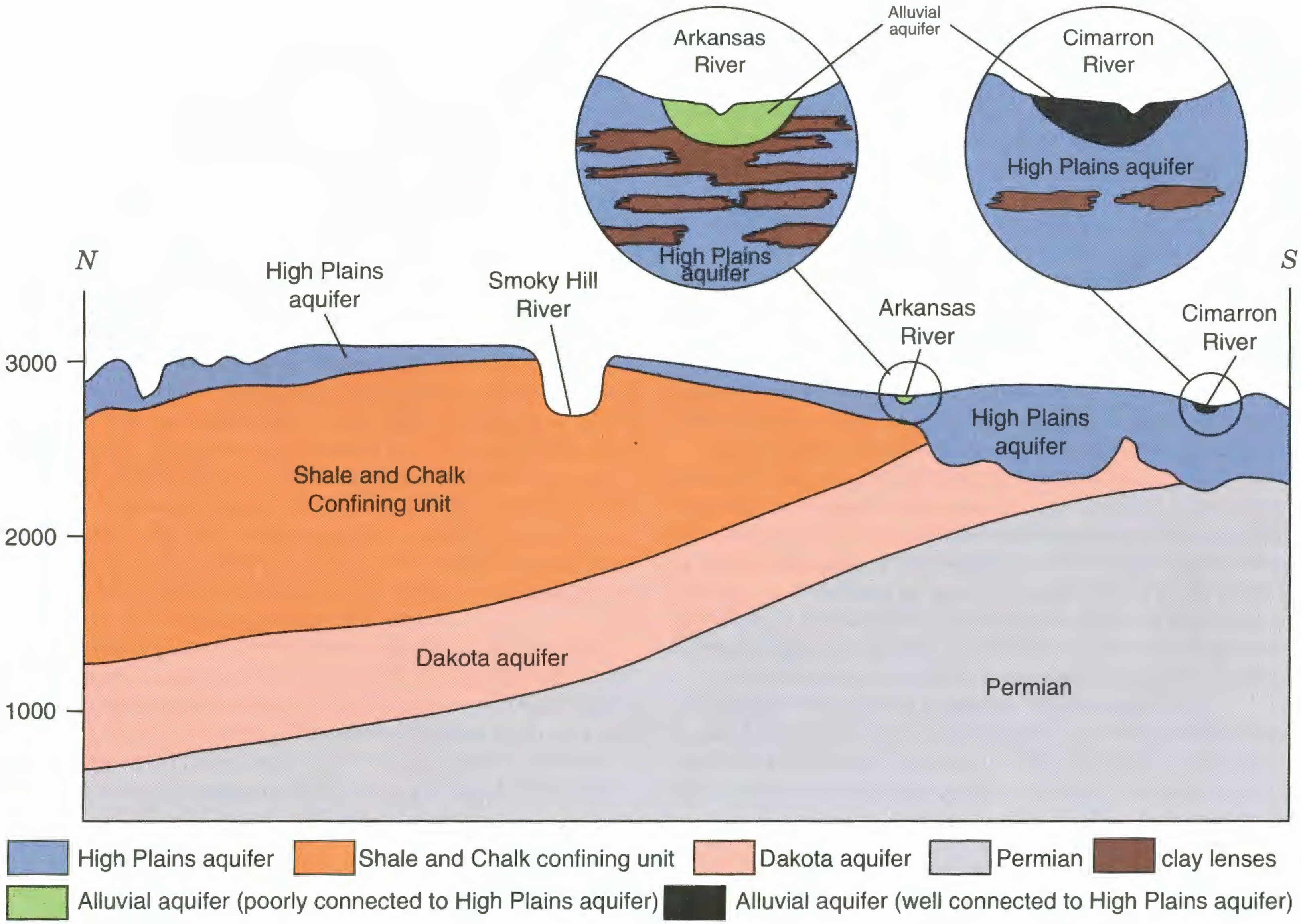


FIGURE 10—Cross sectional view of the area of the High Plains aquifer.

Predevelopment Saturated Thickness

J. A. Schloss and R. W. Buddemeier
Kansas Geological Survey, Lawrence, Kansas

Saturated thickness is the vertical thickness of the hydrogeologically defined *aquifer* unit in which the pore spaces are filled (saturated) with water. The predevelopment value is the estimated saturated thickness before the withdrawal of significant amounts of ground water and is taken as the starting point against which the amount and rate of any depletion is measured. It is commonly used as an indicator of available resources in setting management and use policies and regulations.

Relevance to understanding water resources: Saturated thickness is a key link between the measurements that can be made readily (of changes in *water-table* elevation) and the changes in resources available for use. The saturated thickness times the surface area times the *specific yield* is equal to the volume of potentially extractable water beneath a given area of land surface—for example, if the saturated thickness below an acre of ground is 100 feet and has a specific yield of 10%, the potential extractable water is 10 acre-feet (AF). Specific yield is difficult to determine with accuracy and precision, but for a given volume of the aquifer it is constant over time, and it commonly varies over space by less than a factor of about two. For these reasons, it is convenient and common to use the saturated thickness as an approximate indicator of the amount of water available and its rate of change.

Discussion: Figure 11 shows estimates of predevelopment saturated thickness for the parts of the High Plains aquifer for which adequate data are available. For comparison with the major hydrologic and administrative units (river basins, Groundwater Management Districts) of the state, see fig. 1. The 'blank' areas of the aquifer (inside the High Plains aquifer extent but not coded for saturated thickness) do not have an adequate number of data points and/or boundary definition to permit useful estimates by the techniques used. In western Kansas these are mostly fringe areas and are likely to be in the lowest (0–50 feet) category—an amount of saturated thickness not generally considered reliably useful for sustained high-volume pumping. This is reflected in the amount of water currently appropriated to water rights (see **Current Maximum Authorized Use**).

The original ground-water resources were unevenly distributed, in ways primarily controlled by *bedrock* topography and patterns of *recharge* and *discharge*. In southwestern Kansas, for example, the bedrock is deep beneath the surface and the thickness of the aquifer is the greatest. In terms of the **availability and accessibility** of the resource for human use, this uneven distribution of the resource does not always provide a good match with soil types, surface topography, or other features of the aboveground landscape that affect human water use and demand.

The distribution of the resource also suggests ways in which management-oriented subunits might be defined. In fringe areas of the aquifer, the saturated thickness is near or below the value needed to support high-volume pumping on a sustained basis; in the central ground-water 'basins,' the volume of water available allows managing over a longer time horizon, while intermediate regions (e.g., 50–100 feet of saturated thickness) represent areas that can sustain systematic ground-water usage in excess of the natural recharge for only a relatively short period of time.

Data sources and methods: Saturated-thickness estimates are based on point measurements of the bedrock elevation and of the water-table surface. Many locations where depth to bedrock has been recorded do not have water-level measurements and vice-versa, and many of the wells that were measured prior to the development of the aquifer (generally 1940–1950) are no longer accessible. Techniques have been employed to make use of as much of the available information on depth to bedrock and predevelopment water level as possible.

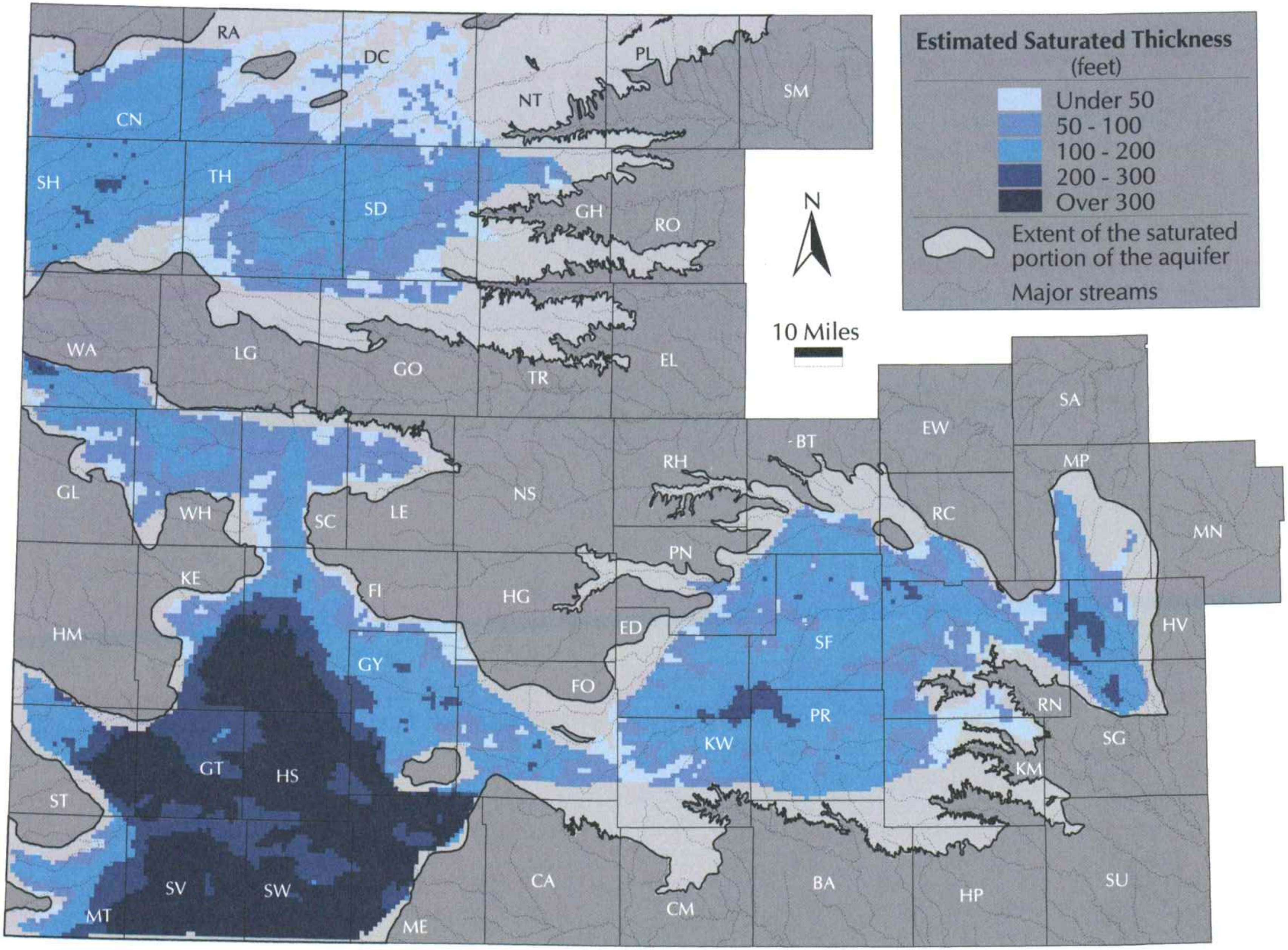


FIGURE 11—Map showing predevelopment saturated thickness for the High Plains aquifer in Kansas.

Qualifications (uncertainties, data needs, etc.): As with all maps in this atlas, this presentation is designed to provide general information only and is not intended to be used for regulatory or management purposes, or to replace or invalidate maps that have been adopted for those purposes. Major limitations restrict the precision with which we can define the predevelopment water table. Relatively few early measurements are available in many areas, and the available data represent a composite of measurements taken in different years and different seasons. This, in combination with the other factors shown in the **appendix on saturated thickness**, means that there is a rather substantial uncertainty (certainly of feet, perhaps tens of feet in some locations) in the absolute value of the predevelopment saturated thickness. However, measured changes in saturated thickness over more recent time periods are not affected by errors in the predevelopment estimate. Townships and sections typically are used for management applications, but these do not necessarily match either the natural scales or the distribution of ground water. The appendix on saturated thickness illustrates in cross sectional view some of the issues and uncertainties involved in determining saturated thickness and related variables, and the map in fig. 11 provides an image of the spatial distribution of the resource at a scale large enough to be unaffected by the known levels of uncertainty.

Current Saturated Thickness

J. A. Schloss and R. W. Buddemeier
Kansas Geological Survey, Lawrence, Kansas

Definition: *Saturated thickness* is the vertical thickness of the hydrogeologically defined *aquifer* in which the pore spaces of the rock forming the aquifer are filled (*saturated*) with water. The most current value is the best available estimate of the saturated thickness that would be observed if the present inventory of ground water were undisturbed by pumping. In practice, the measurements available for constructing such estimates are months to years old, so the "most current" estimates describe the situation of the past 1–3 years. However, in most areas the uncertainty in the estimates (discussed below under Qualifications) is greater than the average annual change, so a lag of a year or two in the results does not affect their potential use.

Relevance to understanding water resources: Saturated thickness is a key link between the measurements that can be made readily (of changes in *water-table* elevation) and the changes in resources available for use. The saturated thickness times the surface area times the *specific yield* is equal to the volume of potentially extractable water beneath a given area of land surface—for example, if the saturated thickness below an acre of ground is 100 feet and has a specific yield of 10%, the potential extractable water would be 10 acre-feet (AF) (see appendix on **ground-water storage and flow** [appendix 4]). Specific yield is difficult to determine with accuracy and precision, but it typically is constant over time and varies from place to place by not much more than a factor of two. Therefore, saturated thickness commonly is used as an indicator of available resources in setting water management and use policies and regulations.

Discussion: The map of current saturated thickness (fig. 12) shows estimates of the averaged 1997–99 saturated thickness for the High Plains aquifer at the center of every legal section (approximately every square mile) within the area for which adequate data are available. The data limitations are not as great as for the predevelopment case, but some of the fringe areas of the aquifer cannot be accurately characterized with the available data. The classification ranges are selected to permit easy visualization of the large range of values (see Qualifications section below). The results are grouped to indicate regional average values and cannot be used to make site-specific determinations about the resource. A saturated thickness of 30–50 feet is needed to support high-volume pumping (see appendix on **drawdown and pumping** [appendix 5]). For this atlas, a value of 30 feet has been used as the target for estimating **usable lifetime**. Anything less than 50 feet is considered a marginal area, or fringe, in terms of ground water usable for intensive pumping. The mapped results indicate the general distribution of the remaining ground-water resources, but the map (fig. 12) is most useful when compared to the map of **predevelopment saturated thickness** (fig. 11) or the map of **change in saturated thickness** (fig. 13). This provides a visual estimate of the change in the resource over time, and of the sustainability of past use. Groundwater Management Districts 2 and 5 in the eastern High Plains operate under safe-yield policies, with ground-water appropriations limited to an administratively adopted **recharge** value. These areas show little change, but the Ogallala Districts (1, 3, and 4) all have areas of substantial declines. However, the very large original inventory of ground water in southwestern Kansas makes this area still relatively 'water-rich' in spite of declines, while in other areas, such as west-central Kansas, a much larger proportion of the total aquifer area is now in the marginal (less than 50 feet) or intermediate (50–100 feet) saturated-thickness categories. Depletion causes the area of the usable aquifer to change much more rapidly than the total volume of water in storage. This change in the distribution of the relatively abundant resource affects the **accessibility and availability** of the resource for human use.

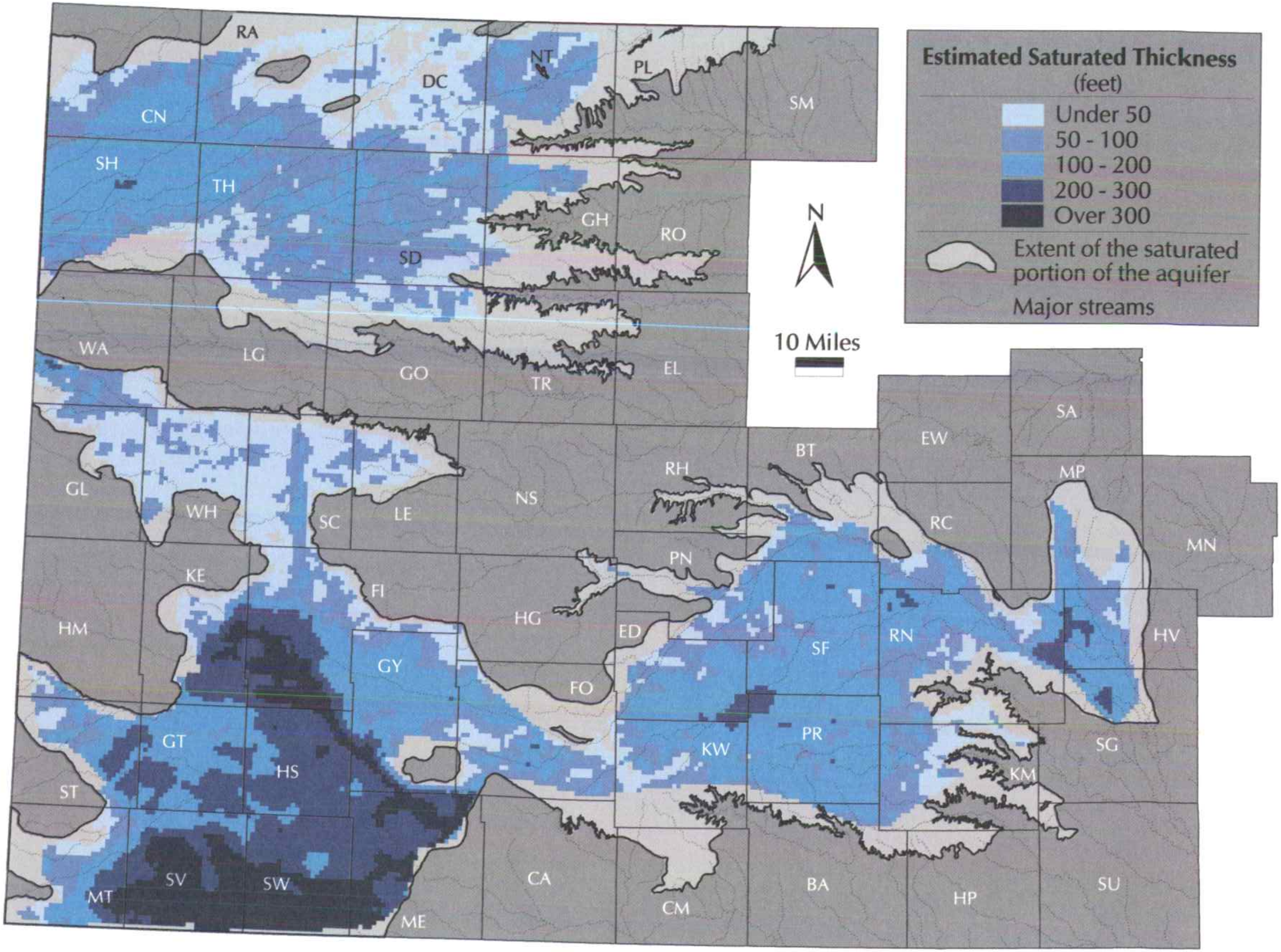


FIGURE 12—Map showing averaged 1997-99 saturated thickness for the High Plains aquifer in Kansas.

Data sources and methods: Saturated-thickness estimates are based on point measurements of the *bedrock* elevation and of the water-table surface. Most of the data used are obtained from the annual water-level measurement program, which measures depth to water in about 1,350 wells each winter. The average values for the three most recent years are used instead of the most recent year alone; this reduces the effects of measurement uncertainty (see **drawdown appendix** [appendix 5]). Also, an individual well may not be measured in any one year. To make use of all of the information on bedrock elevation and water-level elevation, we calculate the differences between the water level and bedrock surfaces using a triangulation process to model the surfaces. The section-center values are then estimated from the difference between the elevations of the two modeled surfaces at that point. This process is fundamental to many water-resource calculation and mapping procedures and is described in more detail in the background information section on **bedrock** mapping (appendix 2).

Qualifications: As with all maps in this atlas, this presentation is designed to provide general information only and is not intended to be used for regulatory or management purposes, or to replace or invalidate maps that have been adopted for those purposes. The determination of current saturated thickness avoids some of the problems associated with estimates of predevelopment saturated thickness: more measurement points, of more consistent quality, with a more uniform distribution are used as a basis for the current saturated-thickness map (fig. 12), and the measurements for a given year are all made during the season of minimum evapotranspiration and pumping. However, the estimates still have significant uncertainties, in part because even the larger number of wells is less than would be necessary to see local variation. A significant additional feature is the potential failure of the measured well to achieve a water-table equilibrium after the pumping season (see **drawdown appendix** [appendix 5]). This, in combination with some of the natural factors shown in the **saturated-thickness appendix** (appendix 3), means that there is a rather substantial uncertainty (which may vary from a few tenths of a foot to several feet, depending on location) in the absolute value of the saturated thickness for any given year. The use of a three-year average reduces this uncertainty, because it is unusual for a well to exhibit the same bias year after year. Townships and sections typically are used for management applications, but these do not necessarily match the natural scales of the hydrologic processes, the data density, or distribution of ground water. Although the map is based on estimates made at the section level, the categories and the image of the spatial distribution of the resource are at a scale large enough to be insensitive to the known levels of uncertainty.

Change in Saturated Thickness

J. A. Schloss and R. W. Buddemeier
Kansas Geological Survey, Lawrence, Kansas

<u>Definition</u>: *Saturated thickness* is the vertical thickness of the hydrogeologically defined *aquifer* in which the pore spaces are filled (*saturated*) with water. Change in saturated thickness is the difference between the values of saturated thickness at two different times. It can be used to describe change at a particular place, but is more commonly used to describe average changes over a region of the aquifer. The change may be expressed as an absolute amount (e.g., "the saturated thickness in this region has decreased by a total of 50 feet") or as fraction or relative amount (e.g., "the saturated thickness has decreased by 25% of the predevelopment value"). It can be described as a single total value (feet or percent) or as a rate (e.g., "the water-table elevation [and therefore the saturated thickness] is declining by and average of 0.5 foot per year"). This section addresses both the absolute (feet) and relative (percent) changes in High Plains aquifer saturated thickness from the **predevelopment distribution** to the **present (1997–99) saturated thickness**.

<u>Relevance to understanding water resources</u>: Saturated thickness is a key link between the measurements that can readily be made (of changes in water-table elevation) and the changes in resources available for use. The saturated thickness times the surface area times the *specific yield* is equal to the volume of potentially extractable water beneath a given area of land surface—for example, if the saturated thickness below an acre of ground is 100 feet and has a specific yield of 10%, the potential extractable water would be 10 acre-feet (AF). Specific yield is difficult to determine with accuracy and precision, but it commonly varies from place to place by not much more than a factor of two and can be assumed to be constant over time. Therefore, change in saturated thickness often is used as an indicator of trends in available ground-water resources and trends in past water use.

<u>Discussion</u>: Two maps are presented: the first map (fig. 13) shows differences in feet between the **predevelopment** and the **1997–99 saturated thickness** estimates for the High Plains aquifer at the center of every legal section (approximately every square mile). The second map (fig. 14) shows the changes as a percentage of the predevelopment value. Because both predevelopment and current values are required to calculate change, these maps have missing data zones where either of the components currently are lacking. The absence of data does not mean either the absence of water or the absence of change, but simply that there is not a satisfactory basis for making the calculation.

The classification ranges portray the range of values and the probable magnitude of their significance (see **Qualifications** section). The results are grouped to indicate regional average values and cannot be used to make site-specific determinations about changes in the ground-water resource. Because of measurement uncertainties (see **drawdown appendix** [appendix 5]) and natural variations in saturated thickness (see **saturated-thickness appendix** [appendix 3]), long-term increases or decreases of a few feet are within the envelope of uncertainty and should not be treated as significantly different from zero. Although the total area showing an increase in saturated thickness is visually impressive, almost all these areas are either fringe areas of less than 50 feet of saturated thickness, in the lowest category of **authorized quantity**, in regions of poor **water quality**, or some combination. The increases, therefore, represent more or less natural variations in unstressed portions of the aquifer, and in most areas do not reflect an actual increase in water available for use under current conditions.

The results show that the absolute changes have been the greatest in southwest Kansas, but because of the large volume of water originally present, the percent changes in that area are not proportionately large. For areas that had marginal saturated thickness to start with, percent change based on the total predevelopment saturated thickness may be somewhat misleading. If something close to 50 feet of saturated thickness is required to support high-volume pumping, and the original saturated thickness was less than 100 feet, then a 50% change in the original total could actually represent 100% of the water available for high-volume pumping. The changes, relative and absolute, need to be interpreted in the light of the predevelopment and present saturated thicknesses.

In addition to affecting the **availability and accessibility** of ground water, changes in saturated thickness can have an impact on streamflow. Ground-water discharge makes up a component of the *baseflow* in most perennial streams and rivers of western and central Kansas. When the water table falls below the stream channel so that discharge no longer occurs, the stream changes from perennial to intermittent, with resulting changes in the availability of surface water and the nature of the stream and riparian ecosystems. This is illustrated in the section on **surface water** in Kansas and its interaction with ground water.

Sources and methods: Saturated-thickness estimates are based on point measurements of the *bedrock* elevation and of the water-table surface. The change in saturated thickness is simply the difference in elevation between two calculated water-table surfaces—the bedrock is the same for both and therefore disappears from the calculation. The values subtracted to determine change are those described in the sections on **predevelopment** and **current saturated thickness**.

Qualifications (uncertainties, data needs, etc.): As with all maps in this atlas, this presentation is designed to provide general information only and is not intended to be used for regulatory or management purposes, or to replace or invalidate maps that have been adopted for those purposes. The change in saturated thickness is a calculated difference between two water-table elevations that both have some inherent uncertainty; therefore, their difference necessarily will have uncertainties of its own. Readers should consult the qualifications sections of the entries for predevelopment and current saturated thickness. As is generally the case, larger absolute changes (tens or hundreds of feet) are more likely to be relatively accurate estimates than small differences.

An important consideration in understanding long-term changes (such as predevelopment to present—approximately half a century) is the recognition that the rate of change is not constant over time. The appendix on **decline rates** (appendix 6) plots the rates of change, by decade, for the Ogallala aquifer portion of the High Plains and for various subdivisions. It shows that the rate of water-level decline was substantially higher in the 1970's than in the 1980's and 1990's, but that the changes in rate occurred at different times in different areas. Change since predevelopment is a useful record of historic human impact on the aquifer, but not a particularly good basis for predicting the future. For that, more recent trends are probably more valid than the total long-term change (see **estimated usable lifetime**).

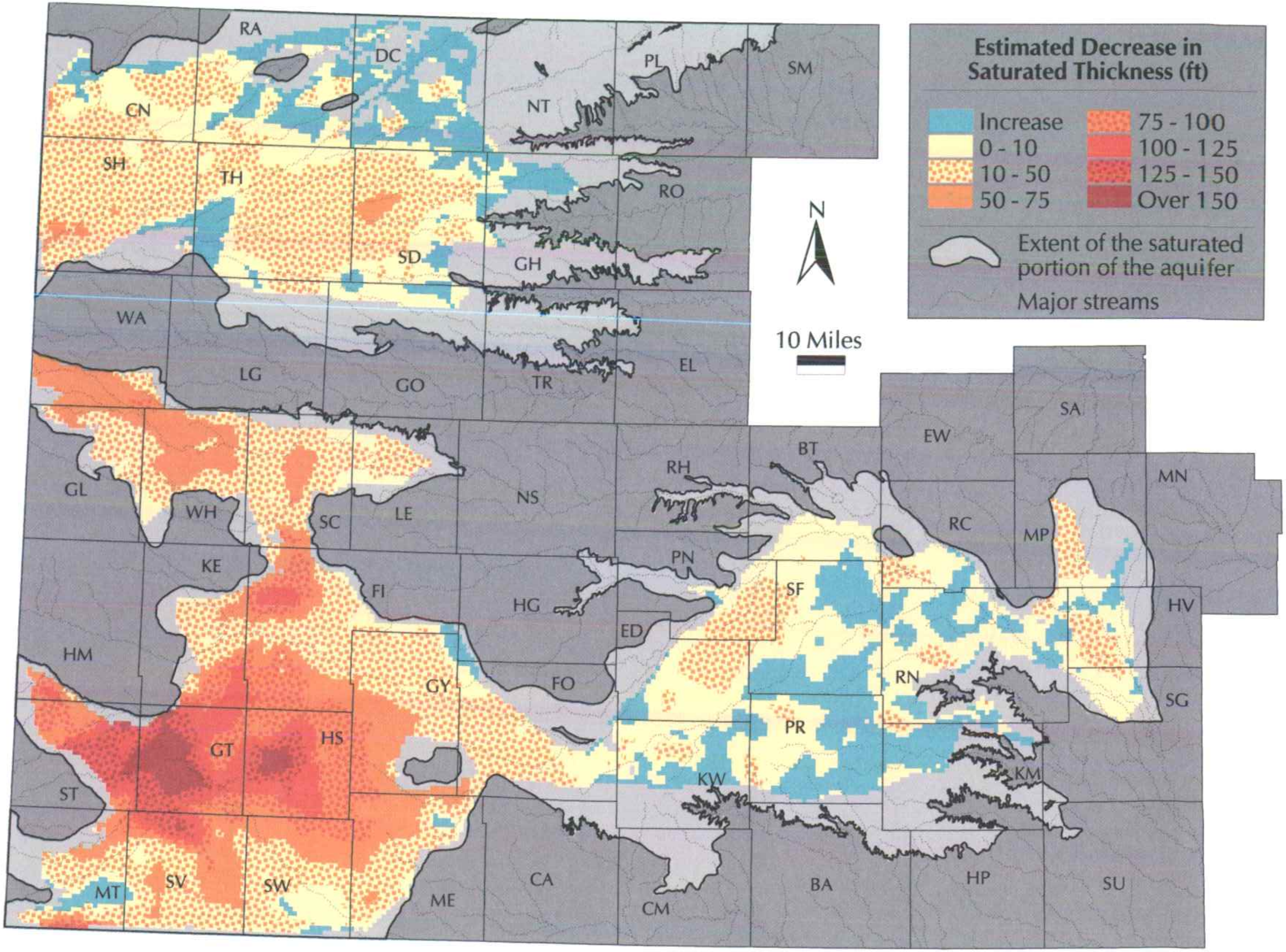


FIGURE 13—Map showing change in saturated thickness for the High Plains aquifer in Kansas, predevelopment to 1997–99.

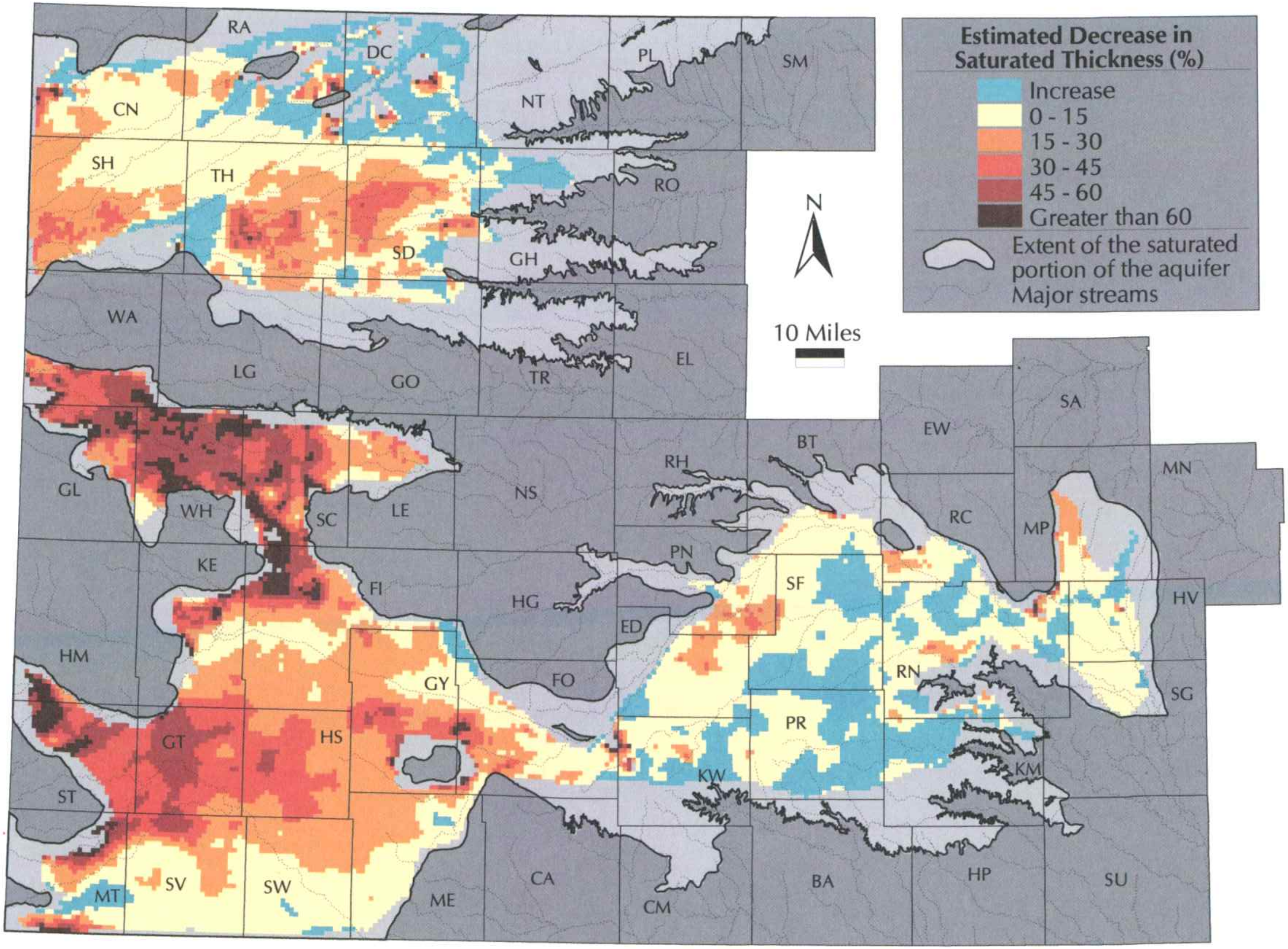


FIGURE 14—Map showing percent change in saturated thickness for the High Plains aquifer in Kansas, predevelopment to 1997–99.

Water in Storage

J. A. Schloss and R. W. Buddemeier
Kansas Geological Survey, Lawrence, Kansas

Definition: Water in storage is the volume of water, expressed in *acre-feet*, that underlies a given area of the land surface. It is the product of multiplying the *saturated thickness* (ST) and *specific yield* (SY) and represents the volume of water that could be recovered if that area of the aquifer were pumped dry. For example, a saturated thickness of 100 feet below an acre of ground in an aquifer with a specific yield of 10% represents 10 acre-feet (AF) of water.

Volume = Area × ST × SY

Relevance to understanding water resources: Water-right allocations, water use, pumping, and estimates of recharge all are expressed as some form of volume, or volume-based rate per unit time or unit area. It is useful to have a comparable volume estimate of the water in storage for comparisons and calculations. In a region where there is no surface discharge of ground water and lateral ground-water flow is either small or in approximate balance, a change in the volume of water in storage should be equal to the difference between extraction and net recharge (see **recharge** section and **ground-water storage and flow appendix** [appendix 4]).

Discussion: Water in storage is calculated using saturated thickness (which is determined from measurements of water-table and bedrock elevation), specific yield (which is estimated based on a limited number of aquifer tests), and surface area. Of these factors, only the saturated thickness is likely to change over time. The saturated thickness determined for any given time can be converted to volume in storage if the specific yield is known. The map of the predevelopment water volume in storage (fig. 15) is based on the saturated thickness values already determined and the specific yield (see appendix on **ground-water storage and flow** [appendix 4]). The darker blue areas of the map (fig. 15) represent the greater original reserves of ground water, and the light-colored areas show the regions least able to support use without careful management. The map of change in water storage (fig. 16) reflects withdrawals over time; comparing the maps shows that the regions with lower original storage (light blue on the predevelopment map [fig. 15]) and greater change (darker shades on the change map [fig. 16]) generally coincide with the areas showing the shortest **estimated usable lifetime**. Such areas are particularly noticeable along the Arkansas River corridor and in Wallace, Greeley, Wichita, Scott, and Finney counties.

Sources and methods: Saturated-thickness values were obtained as described in those sections of the atlas and the appendices cited. The U.S. Geological Survey (USGS) has prepared data bases and maps showing estimates of the distribution of specific yield and hydraulic conductivity in the High Plains aquifer. The saturated-thickness values at section centers were multiplied by the section-center specific-yield values obtained from the USGS data and then multiplied by the surface area for each section, giving results in units of acre-feet. These results were grouped into ranges of values and plotted in the accompanying maps.

Qualifications: These values should not be considered highly accurate estimates of available water and should not be used for developing detailed assessments or management policies. The uncertainties involved in determination of saturated thickness are discussed in those sections of the atlas; the specific-yield estimates are discussed in the information appendix on **ground-water storage and flow** (appendix 4). Because the specific-yield estimates are based on rather widely spaced data points and treat the aquifer as a single homogeneous layer, the volumes calculated should be considered regional estimates.

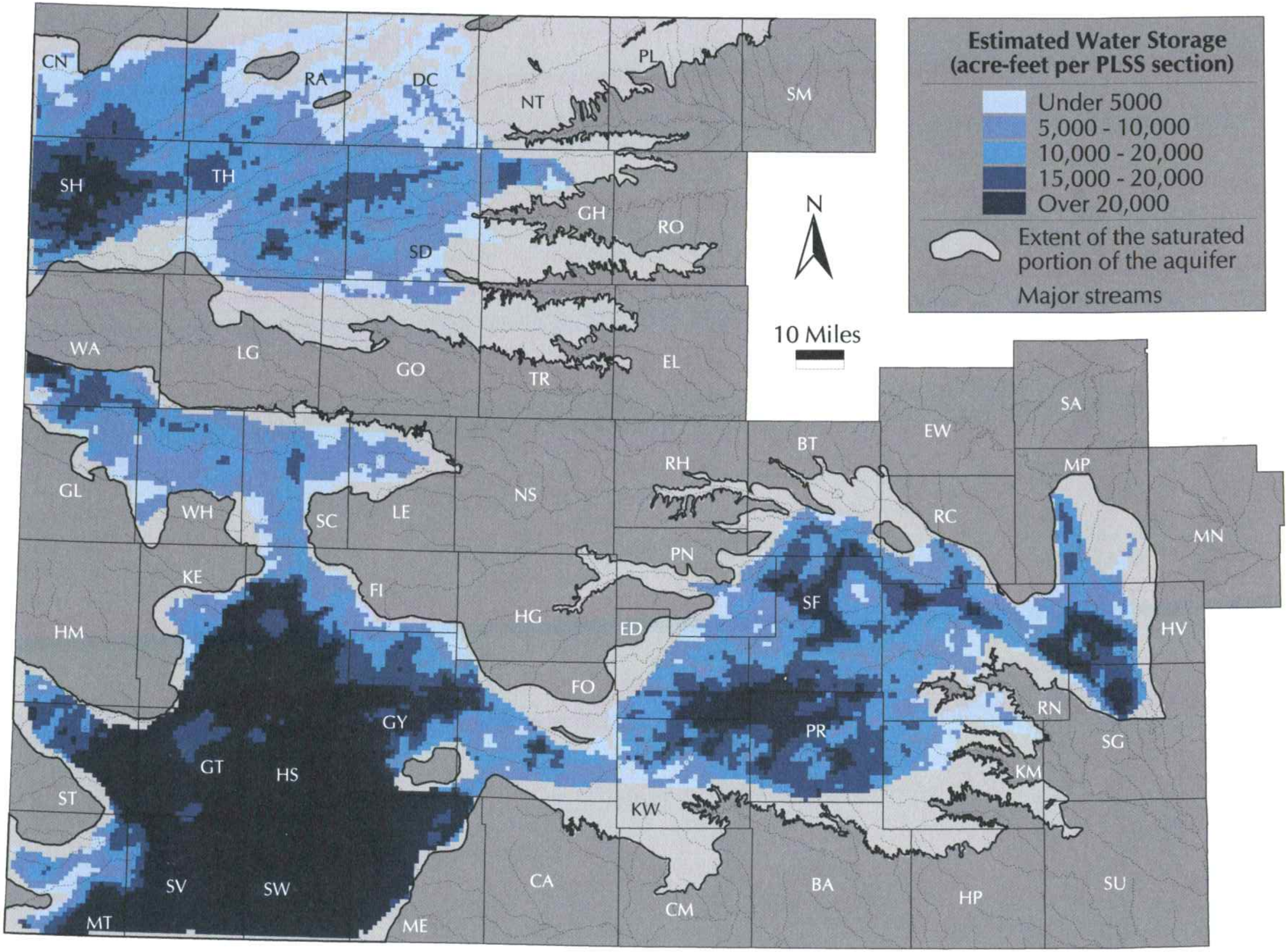


FIGURE 15—Map showing predevelopment water storage for the High Plains aquifer in Kansas.

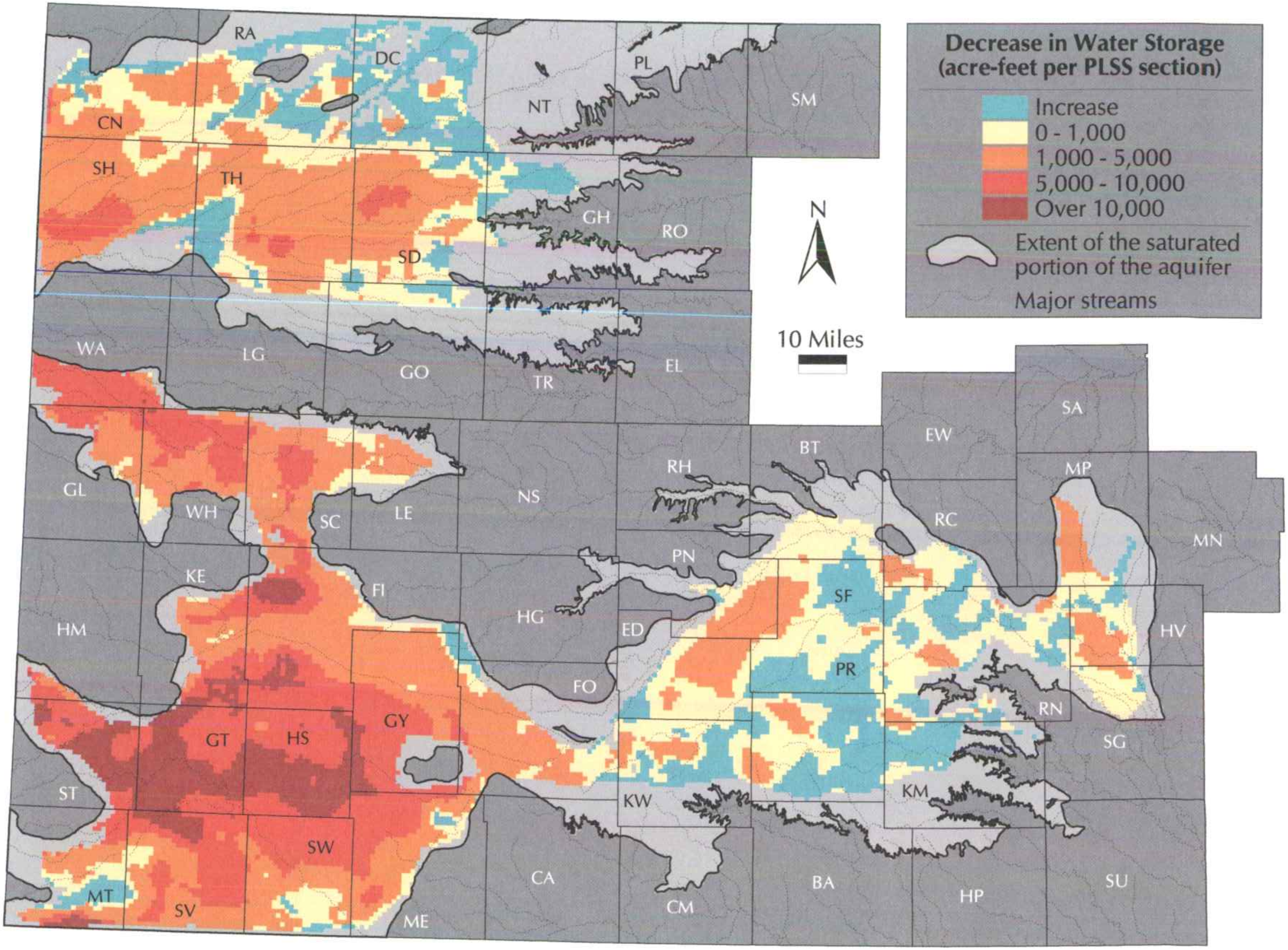


FIGURE 16—Map showing change in water storage for the High Plains aquifer in Kansas, predevelopment to 1997–99.

Ground-water Availability and Accessibility Provinces

C. D. McElwee and H. Cao
Kansas Geological Survey, Lawrence, Kansas

<u>Definitions</u>: General—Physical availability is the amount (volume) of water in storage beneath a given area of land surface. Accessibility is a function of *saturated thickness*, *depth to water*, and *hydraulic conductivity*, which is a measure of how easily water flows through or can be pumped from an *aquifer*. In order to combine and compare the effects of these different factors, this description uses normalized variables, which is simply a process of dividing all values of a particular map by the highest value observed, resulting in a common scale of zero to one. This standardizes and simplifies comparisons and calculations.

Specific—Availability is the normalized value of **water in storage**, presented in categories or intervals. Accessibility is zero if hydraulic conductivity or saturated thickness is zero and increases as these values increase. However, accessibility decreases as the depth to water increases. The basic definition of accessibility used here is the product of hydraulic conductivity and saturated thickness divided by the depth to water. In order to avoid the problems associated with dividing by numbers close to zero, the definition is modified by adding 1.0 to the normalized depth to water. This ensures that the accessibility function will range from 0 to 1. Provinces of ground-water accessibility are then defined based on selected ranges of values and displayed graphically on a map.

<u>Relevance to understanding water resources</u>: Clearly, if no water is available then we do not have a water resource. When volume in storage and hydraulic conductivity are both low, then an area will have low availability and accessibility. It is valuable to be able to rank a given area relative to another for ground-water availability. By using normalized current water-in-storage data and displaying high, medium, and low availability provinces, it is possible to see at a glance how various areas compare. Accessibility of an aquifer bears directly on the description of a water resource. If water is present but unable to move easily due to low hydraulic conductivity, the value of the water resource is considerably diminished. Water at a very great depth is not as valuable as water at shallow depths, due to increased pumping lift. The accessibility function that we have defined allows one to quickly evaluate the net effect of the three most important factors affecting accessibility: hydraulic conductivity, saturated thickness, and depth to water. Although strong similarities exist in the availability (fig. 17) and accessibility (fig. 18) maps, there can be important differences. For example, a very deep ground-water basin might have a large volume in storage (and therefore high availability), but if hydraulic conductivity is low and depth to water great compared to other areas, this water will be much less accessible.

<u>Discussion</u>: Ground-water availability and accessibility have been defined so that all values will be between 0 and 1. Color coding these ranges on the maps allows provinces of high, medium, and low availability and accessibility to be shown graphically. Because the same scale is used for the entire High Plains aquifer, it is possible to compare availability in one area to availability in any other area (fig. 17). The values selected for the range division in this presentation have been chosen for convenience in making visual distinctions on the maps; it is easy to redefine the classes to address specific questions or problems.

The values used for the availability ranges are: low (0.20–0.0), medium (0.45–0.20), and high (1.0–0.45). It should be emphasized that availability as defined here relates to the amount of water physically present and has no relation to regulatory availability. The Division of Water Resources of the Kansas Department of Agriculture and local Groundwater Management Districts (GMDs) have regulatory authority over and policies governing whether new water rights are granted in a given area.

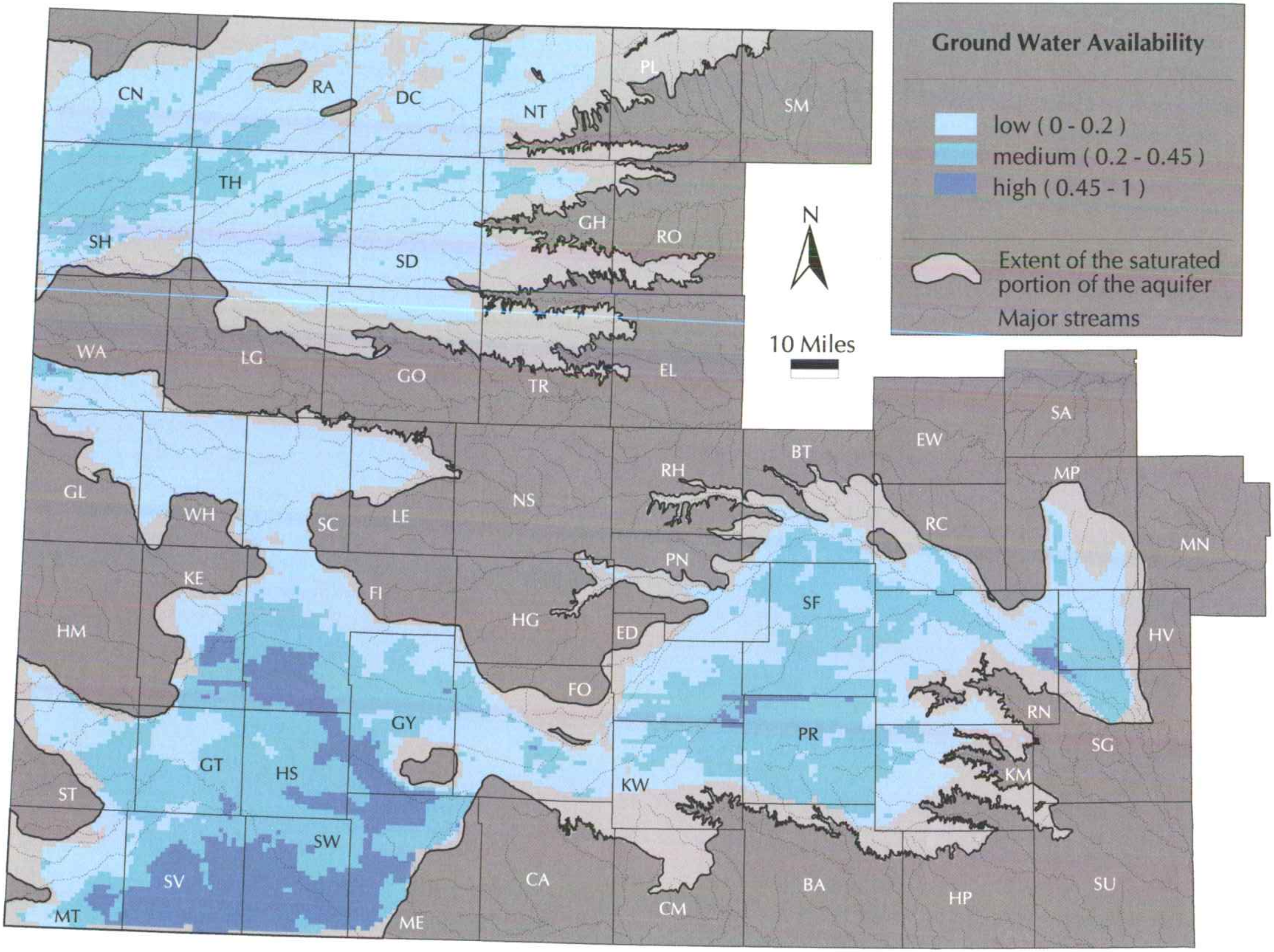


FIGURE 17—Map showing ground-water availability for the High Plains aquifer in Kansas.

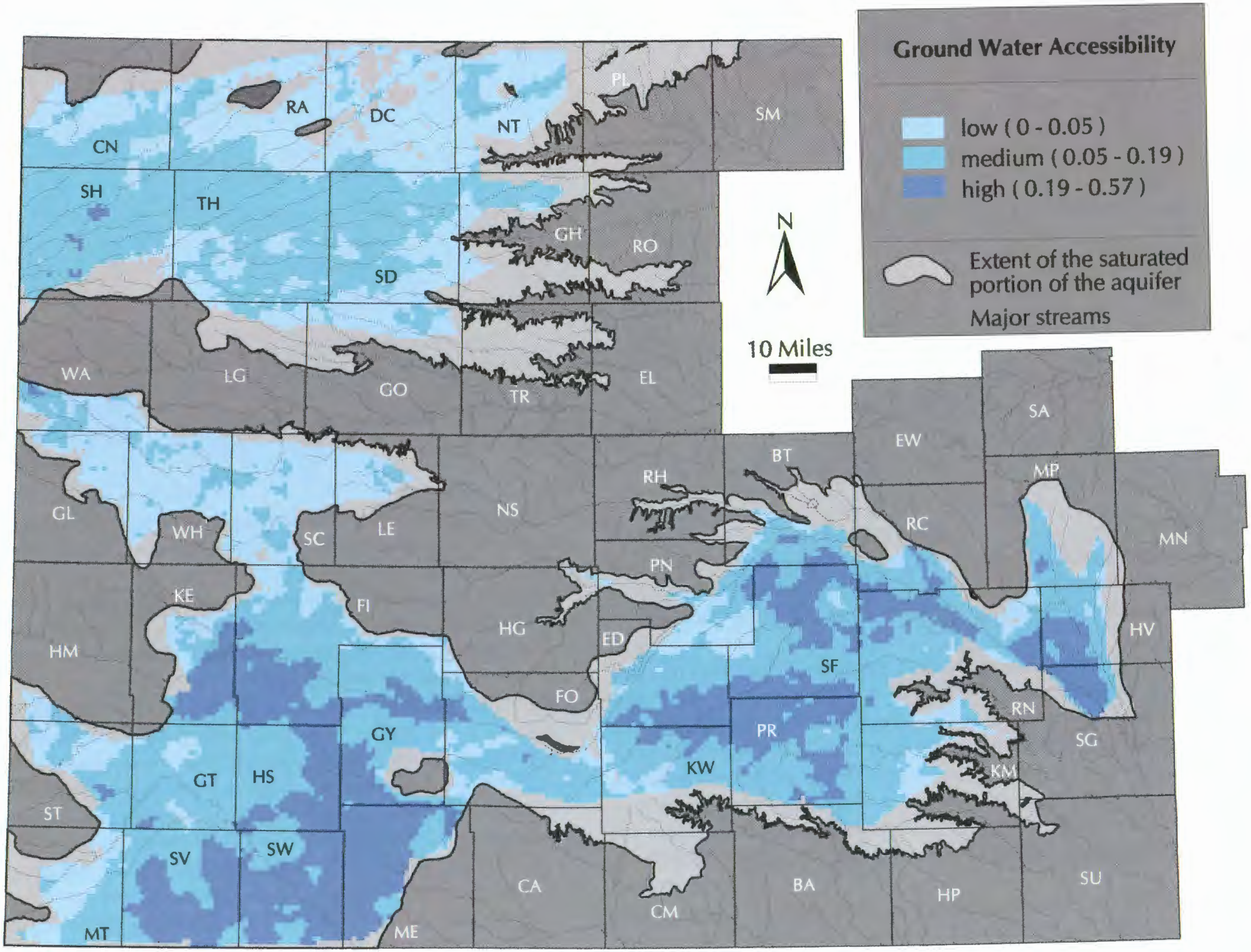


FIGURE 18—Map showing ground-water accessibility for the High Plains aquifer in Kansas.

The accessibility ranges have the same theoretical limit of 1.0, but in practice the observed maximum value for the index was much lower, so the useful numerical values of the ranges are not the same as for availability. For accessibility, the low range is 0.0–0.05, the medium range 0.05–0.19, and the high range 0.19–0.57 (the maximum value observed). The numerical ranges are displayed graphically on the map (fig. 18) by color coding. Again, because the same scale is used for the entire High Plains aquifer, it is possible to compare accessibility in one area to accessibility in any other area. As with availability, the ranges shown here can be modified and replotted to address specific considerations.

Data sources and methods: Ground-water availability and accessibility have no unique scientific definition. Availability and accessibility based on hydrologic principles and data available for the High Plains aquifer have been defined. The maps presented in this section are based on the amount of water in storage and the **saturated thickness** of the aquifer. In addition, a hydraulic-conductivity map produced by U.S. Geological Survey studies of the High Plains aquifer has been used in the accessibility calculations. The point values for depth to water at wells were used along with interpolation to produce estimates of the depth to water. These depth to water data were used in calculations for ground-water accessibility. All values were normalized by dividing by the largest value to ensure that all values will be between 0 and 1.

Qualifications: The limitations of the current water-in-storage data and the current saturated-thickness map (fig. 12) are discussed elsewhere in this atlas but apply equally well here because those maps are used in the availability and accessibility calculations. An unknown magnitude of uncertainty exists in the U.S. Geological Survey map for hydraulic conductivity. However, it is likely that the best available data at the time were used. The depth-to-water data used in the accessibility calculations could be improved by using more topographic control between measured wells.

As noted above, the values selected for the low-medium-high ranges were chosen for illustrative purposes and do not represent any specific management or economic considerations. The approach could easily be adapted to include such considerations.

Regional Ground-water-quality Provinces

D. O. Whittemore, M. A. Townsend, B. S. Sorensen, D. P. Young, and J. A. Schloss
Kansas Geological Survey, Lawrence, Kansas

Definitions: The regional ground-water-quality provinces are areas in the High Plains aquifer where the ground water has different ranges in the salinity or *total dissolved solids* (TDS) concentration and consists of different chemical types. The TDS concentration intervals range from fresh to saline water. The chemical-type provinces are based on the predominant chemical character of the ground water, i.e., the *major dissolved constituents* composing the total dissolved solids, specifically, *chloride* and *sulfate* for the province map.

Relevance to understanding water resources: The salinity of water is an important characteristic that determines its uses. Low salinities are generally desirable for all types of water use, including *public supply*, *domestic*, agricultural (both *stock* and *irrigation*), and *industrial* uses. In some cases, the particular constituents (such as chloride, sulfate, and the relative amounts of *sodium* to *calcium* and *magnesium*) can be a consideration for use where dissolved solids concentrations are high. The recommended or *secondary standard* of the U.S. Environmental Protection Agency (EPA) and the Kansas Department of Health and Environment (KDHE) for TDS in drinking waters is 500 *mg/L*, and for both chloride and sulfate concentrations is 250 mg/L. The general classification limit between freshwater and saline water is 1,000 mg/L.

Discussion: The map (fig. 19) shows the distribution of TDS concentration in the ground waters of the High Plains aquifer. The lowest TDS interval has an upper value of 500 mg/L, which is the secondary standard for drinking waters. The amount of data and the areas for waters with >1,000 mg/L are relatively small in comparison with that for less saline and freshwater. The TDS concentration of ground water varies substantially with depth at some locations in the High Plains aquifer. Except for the upper Arkansas River valley, the TDS generally increases with depth in the map areas showing high concentrations. The TDS data reflect the estimated concentration in the main portion of the aquifer.

Most of the ground water in the High Plains aquifer contains TDS concentrations less than 1,000 mg/L indicating that the water is fresh. A large portion of the freshwater has TDS contents less than 500 mg/L. Most of this water is of *calcium bicarbonate* type. Aquifer areas with high TDS concentrations include the eastern part of the *"Great Bend Prairie aquifer"* (Groundwater Management District No. 5) and the western portion of the *"Equus beds aquifer"* area (Groundwater Management District No. 2) in south-central Kansas. The source of salinity in this area is natural *intrusion of saltwater* (*sodium chloride* type water) from Permian *bedrock* underlying the High Plains aquifer. Ground waters in other areas also have elevated TDS content from intrusion of mineralized water from bedrock underlying the High Plains aquifer. Ground water in the *upper Arkansas River corridor* has high TDS concentrations from recharge of saline river water that flows into Kansas from Colorado. The water is of *sodium sulfate* type that has been largely generated by concentration of natural salts in residual water left after *evapotranspiration* losses in ditch irrigation systems. Natural evapotranspiration has produced elevated TDS ground waters of sodium sulfate type in the High Plains aquifer in parts of southern Scott and northwestern Finney counties.

Data sources and methods: The water-quality provinces map (fig. 19) is based on water samples collected from the aquifer over the last 30 years (from 1970 to the present). A large portion of the data is from the study of irrigation-water quality conducted by the Kansas Geological Survey (KGS) during 1974–1980 and published in KGS Chemical Quality Series 2, 4, 6–8, 10, and 11. Other data sets are KGS analyses of more recent samples of irrigation water collected by the *KDA*, chemical analyses in the QWdata

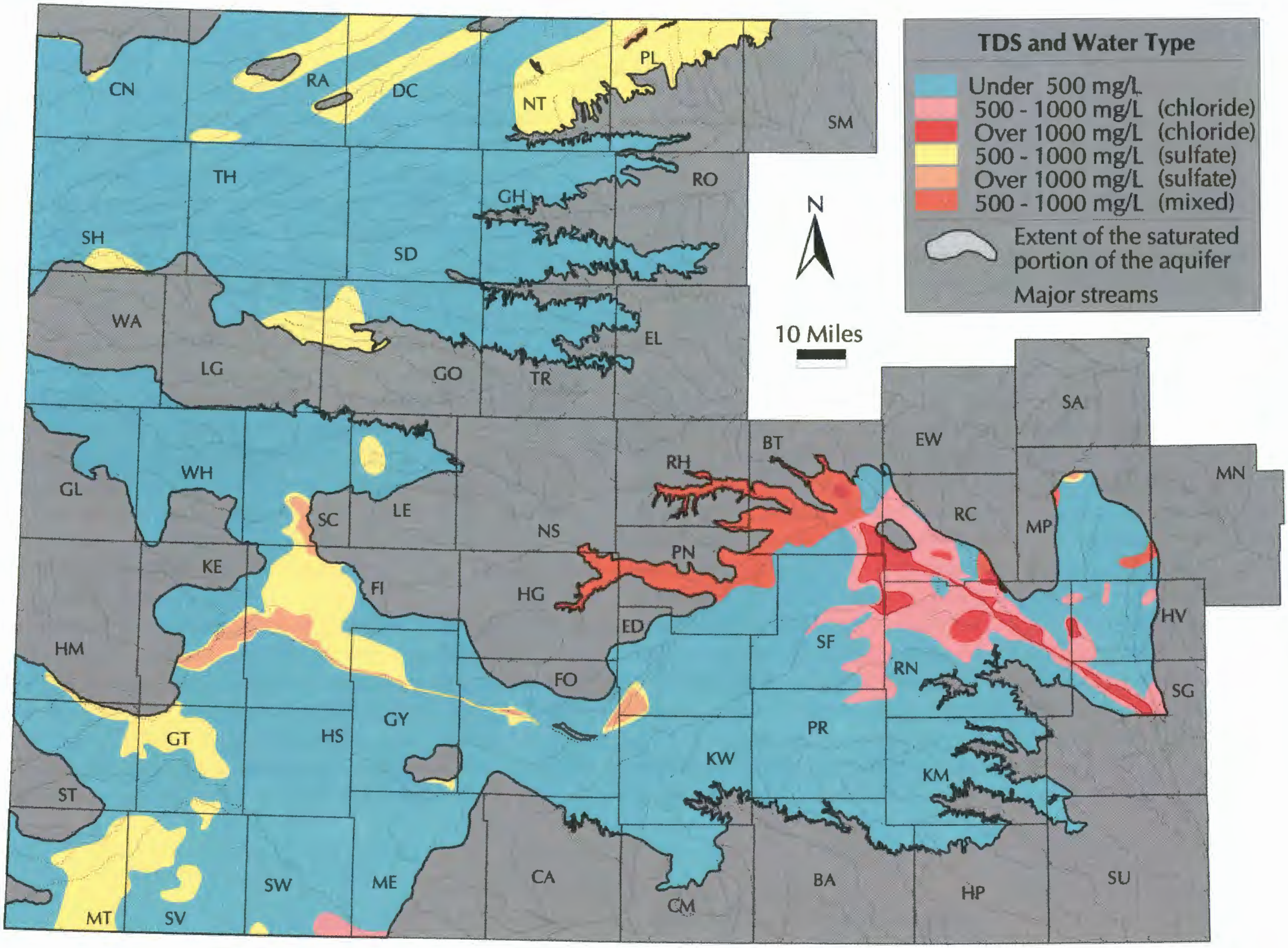


FIGURE 19—Map showing total dissolved solids (TDS) concentration and water-quality provinces of the High Plains aquifer in Kansas.

data base of the *USGS*, and chemical data in the STORET data base of the U.S. EPA from the present KDHE and past USGS sampling and analysis programs for monitoring ground waters. Where multiple samples for the same site exist, only the most recent data were used. Only the records in the QWdata data base with geologic codes present for units within the High Plains aquifer were used. Data for samples from the alluvial aquifer in Kearny, Finney, Gray, and Ford counties were not used to avoid confusion from the essentially two-aquifer system of the alluvial aquifer perched above the main part of the High Plains aquifer.

The TDS concentrations used to determine the water-quality provinces are primarily calculations of the sum of the major dissolved constituents, although some values are for measurement of the weight of salts remaining after a known volume of water was evaporated to dryness. When calculating the TDS sum, the *bicarbonate* concentration is multiplied by 0.4917 to represent the amount of *carbonate* that would be present in the mineral mass left if water were evaporated to dryness.

Qualifications (uncertainties, data needs, etc.): The map (fig. 19) is a generalized representation of the TDS concentration of the aquifer. It is not intended to show the detail of all high TDS locations in the aquifer. For example, isolated wells with greater TDS content from the surrounding areas were not always considered during map preparation. Therefore, the map does not show contamination sites of local extent, although it does represent larger areas of substantial contamination such as by infiltration of saline Arkansas River water. One of the largest uncertainties inherent in displaying water-quality data in a single map for an aquifer is the great range in quality with depth. As indicated above, the map represents the main portion of the High Plains aquifer from which larger-capacity wells draw water. In some cases, for example, in parts of the Great Bend Prairie, the areas on the map represent an average between TDS data for both the shallow and deep aquifers. Although data exist for TDS concentrations with depth for selected portions of the aquifer, the data are too limited to illustrate depth differences across the entire aquifer. Another uncertainty is the limited amount of data available for a shorter, recent time interval for the entire aquifer. Therefore, the last 30 years of data were used because it is more important to have points in areas that would otherwise have no data than to have points for a shorter time span with large spatial gaps of no information. Much of these data are for the period 1974–1980. Although many of the high TDS areas have natural sources, temporal changes are occurring in some areas impacted by human actions such as salt mining, oil production, irrigation, and waste disposal. This points to a need for more widely distributed sampling over a period of less than a decade.

Estimated Annual Ground-water Recharge

M. A. Sophocleous and J. A. Schloss
Kansas Geological Survey, Lawrence, Kansas

Definitions: Ground-water *recharge* is the replenishment of an aquifer with water from the land surface. It usually is expressed as an average rate of inches of water per year, similar to precipitation. Thus, the volume of recharge is the rate times the land area under consideration times the time period, and usually is expressed as *acre-feet* per year. In addition to precipitation, other sources of recharge to an aquifer are stream, lake or pond seepage, irrigation return flow (both from canals and fields), interaquifer flows, and urban recharge (from water mains, septic tanks, sewers, drainage ditches). Agricultural scientists use the term deep drainage to denote the downward flux of water below the plant root zone. Often this deep drainage flux is equated to recharge (that is, water reaching the water table). This will be true if no other losses of water occur below the root zone, such as subsurface lateral flows due to the make-up and orientation of geologic strata, absorption by sediments above the water table, and other causes, which may prevent the deep drainage from reaching the water table, especially when the water table is deep. Therefore, the deep drainage flux measured just beneath the root zone should be considered potential recharge. When the sole source of such potential recharge is precipitation, it usually is called potential natural recharge. Such potential natural recharge does not consider the other sources of recharge mentioned previously. In contrast to *natural recharge* (which results from natural causes), *artificial recharge* is the use of water to artificially replenish the water supply in an aquifer, as is done in the "Equus beds aquifer" with the Wichita recharge project.

Relevance to understanding water resources: If withdrawals exceed recharge, the water table in the aquifer will most probably decline. If this condition continues long enough, parts of the aquifer may be dewatered and become unusable as a source of water. In Kansas, the Division of Water Resources of the Kansas Department of Agriculture (DWR–KDA) uses existing estimates of precipitation-based annual recharge to determine "*safe yield*" quantities for different aquifers across the state. The quantity of recharge to an aquifer has been considered equivalent to the "safe yield" or quantity of water that could be removed from an aquifer on a sustainable basis. It is now understood that the "sustainable yield" of an aquifer is almost always appreciably less than recharge. This is because sustainable yield must also allow for adequate provision of water to sustain streams, springs, wetlands, and ground-water-dependent ecosystems (Sophocleous, 1997, 1998, 2000). Nevertheless, a sustainable-yield figure is derived from a recharge determination, and any sustainable-yield study will usually involve the determination of recharge as a first necessary step.

Discussion: The potential natural-recharge map (fig. 20) shows the annual amount of precipitation-based recharge in inches for western and central Kansas as estimated in the U.S. Geological Survey (USGS) Water Resources Investigations Report 87–4230 (Hansen, 1991). The Kansas study used a soil-moisture accounting model developed as part of the USGS Central Midwest Regional Aquifer System Analysis (CMRASA; Dugan and Peckenpaugh, 1985) to estimate the rate of recharge in western and parts of central Kansas. The results were combined with additional results from the CMRASA study to make a generalized map showing mean annual rate of recharge in Kansas. As can be inferred from this map, the distribution of annual recharge follows a similar pattern to that of annual precipitation across the state, that is, it progressively decreases as one moves westward across the state. The climatic conditions are such that not only is precipitation low in western Kansas, but most of it is lost to evaporation from the soil surface and transpiration from plants. More than 99% of the rainfall is returned to the atmosphere in 14 southwestern Kansas counties, and more than 95% is returned throughout the western half of the state, thus resulting in meager recharge to the High Plains aquifer in that region. (In eastern Kansas an average of 85% of the rainfall is returned to the atmosphere.) Thus, climatic conditions constitute a primary control on recharge, although vegetation and soils also influence recharge.

The administrative-recharge map (fig. 21) shows the amount of annual recharge, in inches, that is available for appropriation based on rules and regulations adopted by DWR–KDA. This map was created by interpolating values between the contours of the potential natural-recharge map (fig. 20), creating a digital gridded map, and overlaying on it the areas of special administrative recharge, such as the boundaries of the five Groundwater Management Districts (GMDs) and the DWR–KDA Unit Basins in south-central Kansas. In these areas, recharge standards have been set through some approach other than the use of the USGS map or similar data.

Data Sources and Methods: The USGS study employed a soil-moisture accounting model to estimate recharge based on soil, vegetation, and climate data (precipitation, temperature, and percent possible sunshine data). However, the basic data used in the USGS model, as well as the assumptions and limitations of that model application, are not presented in that report. Details on the methodology employed also are not reported, but the recharge model used was the same soil-moisture accounting model as the one used in the USGS CMRASA study to estimate the mean annual recharge in much of eastern and central Kansas. The CMRASA study is documented in the USGS Water Resources Investigations Report 85–4236.

Qualifications: Of all the factors in the evaluation of ground-water resources, the rate of recharge is one of the most difficult to derive with confidence. Estimates of recharge are normally subject to large uncertainties and spatial and temporal variability. For example, during the floods of 1973 and 1993, substantial areas in the Big Bend GMD 5 in south-central Kansas went from a net decline to a net increase in the water-table elevation as a result of these relatively rare extreme flood events.

The CMRASA recharge-estimation-model application covered an area of approximately 275,000 square miles in Nebraska, Colorado, Kansas, Oklahoma, and Texas, and employed monthly climatic data for a 30-year period (1951–1980) to derive mean potential-recharge estimates (Dugan and Peckenpaugh, 1985). Because of the simplifications made in the model, the USGS recharge estimates may be considered representative at the county level. As mentioned earlier, no stream seepage, irrigation return flow, or other sources of recharge were considered in this USGS analysis. In view of the above, caution should be exercised in attempting to apply the results to specific areas. Furthermore, these recharge estimates were not calibrated or statistically evaluated with empirically derived hydrologic data or ground-water-flow model simulations. Such tests are necessary for more detailed applications. The recharge estimates used by DWR–KDA are based on the previously mentioned and other USGS reports, as well as on Kansas Geological Survey studies. Actual field studies to determine recharge are lacking in many parts of Kansas, especially in western Kansas.

References

Dugan, J. T., and Peckenpaugh, J. M., 1985, Effects of climate, vegetation, and soils on consumptive water use and ground-water recharge to the Central Midwest regional aquifer system, midcontinent United States: U.S. Geological Survey, Water Resources Investigations Report 85–4236, 78 p.

Hansen, C. V., 1991, Estimates of freshwater storage and potential natural recharge for principal aquifers in Kansas: U.S. Geological Survey, Water Resources Investigations Report 87–4230, 100 p.

Sophocleous, M. A., 1997, Managing water-resources systems—Why "safe yield" is not sustainable: Ground Water, v. 35, no. 4, p. 561

________, 1998, Perspectives on sustainable development of water resources in Kansas: Kansas Geological Survey, Bulletin 239, 239 p.

________, 2000, From safe yield to sustainable development of water resources—The Kansas experience: Journal of Hydology, v. 235, no. 1–2, p. 27–43

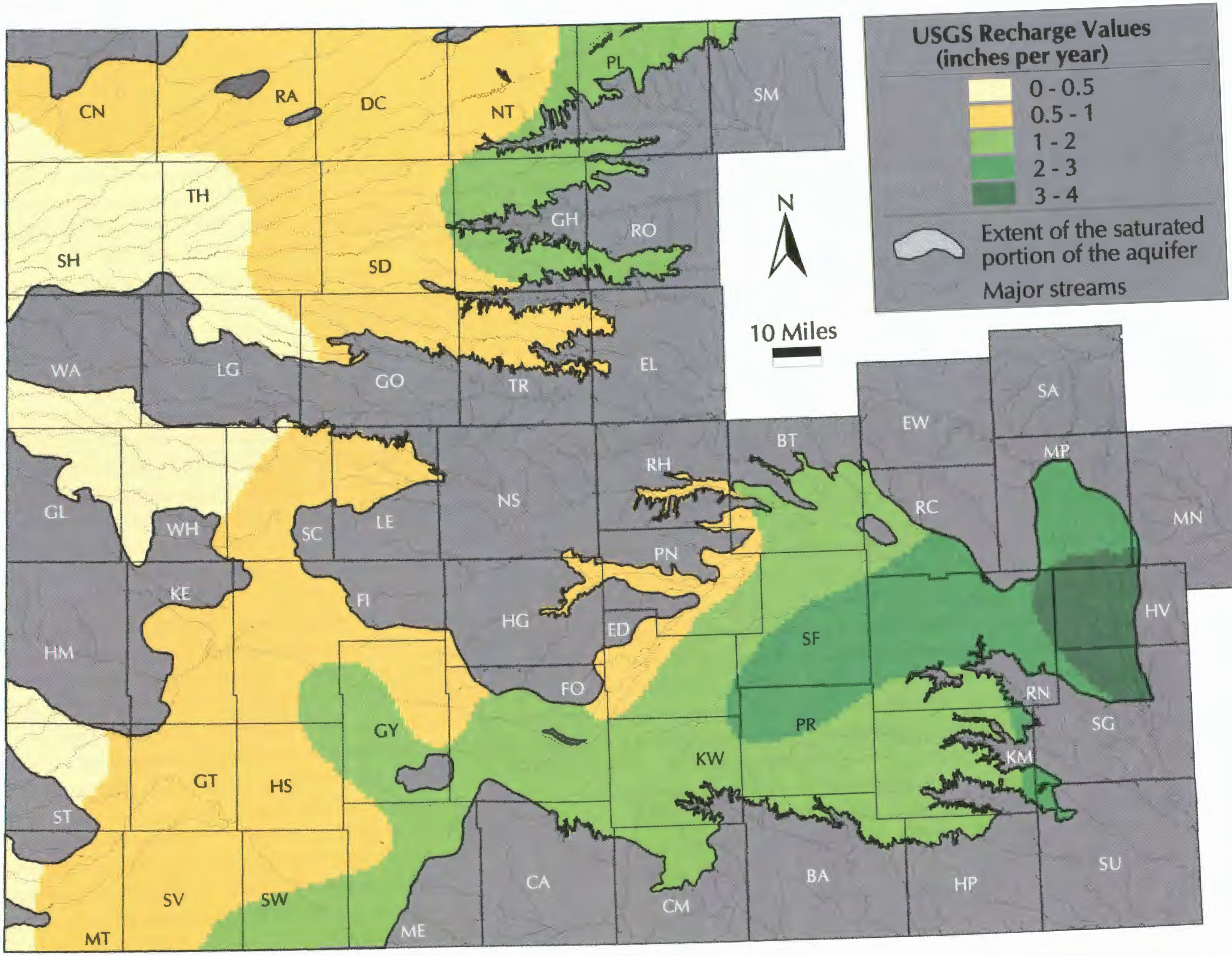


FIGURE 20—Map showing potential natural-recharge data for the High Plains aquifer in Kansas.

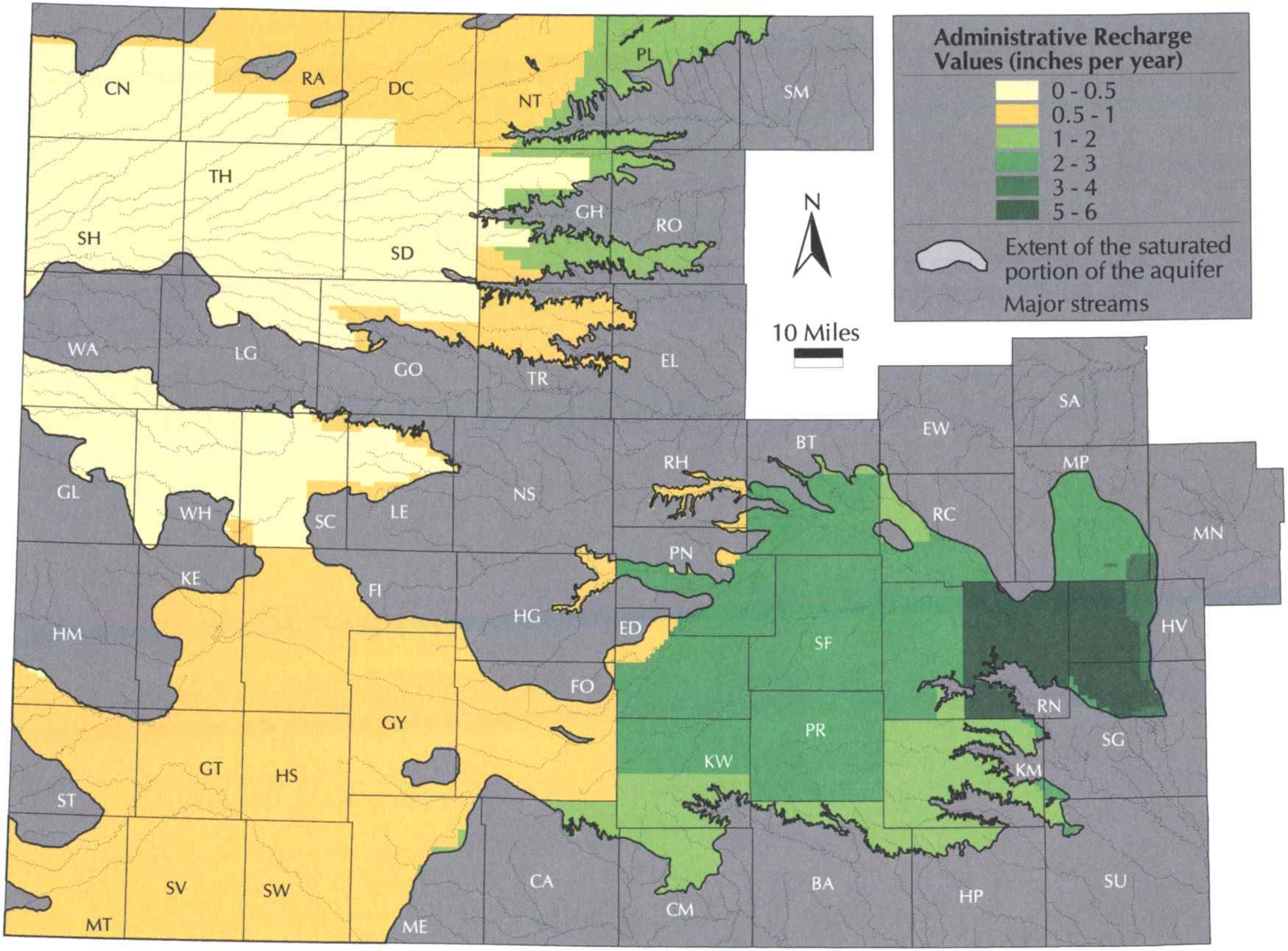


FIGURE 21—Map showing administrative-recharge data for the High Plains aquifer in Kansas.

Current Maximum Authorized Use

B. B. Wilson[1], J. A. Schloss[2], and R. W. Buddemeier[2]
[1]Kansas Water Office, Topeka, Kansas, and [2]Kansas Geological Survey, Lawrence, Kansas

Definition: Authorized use is the amount of water that is authorized to be pumped in a given year under water-right allocations. Each water-right permit or certificate allows the water-right holder a set quantity of water that can be used each calendar year. The quantity of water assigned to a water right depends on factors such as the location of the water right and whether the water right overlaps other senior water rights in either the point of water diversion or place of use (e.g., an irrigation-field boundary).

Relevance to understanding water resources: The amount of water that legally can be pumped from a given area is a key component in identifying areas of the High Plains aquifer that may be overdeveloped in terms of water rights. If the amount of consumptive water use authorized by ground-water rights is greater than the amount of water that is recharged naturally to the aquifer system, then the potential exists for aquifer resources to become stressed and to decline over time. Authorized quantity is one of the primary components of the Kansas Department of Agriculture's Division of Water Resources' (KDA–DWR) calculation of the local aquifer yield that is used as part of the review process to accept or deny water-right applications.

Discussion: Figure 22 shows how much water could be pumped each year. This is not the amount of water actually pumped (see sections on **water usage** and **percent of authorized quantity used**), but rather how much could be pumped if all water-right allocations pumped their full authorized quantity. Measured use in an area is typically somewhat less than the total use authorized for that area, due to climate, economic factors, and farm-management practices. The map of maximum authorized use (fig. 22) shows the amount of water, in acre-feet per township (approximately 36 square miles), that can legally be pumped from the ground water underlying that township in any given year. The distribution of water rights shows high concentrations of authorized use in areas of water availability, but other factors influence the distribution as well. The distribution of rights may reflect past as well as present patterns of water use, and the existence of soils and terrain suitable for irrigation also has influenced the distribution.

Because the amount of water that is authorized to be pumped under a water right may be changed as the water right progresses through the KDA–DWR's regulation and appropriation process, fig. 22 represents water-right conditions existing in late 1999. When a person or organization initially applies for a permit to appropriate water, the applicant lists how much water would be used based on the intended use and the amounts permitted at the proposed location of the well. Assuming the water-right application passes other rules and regulations, such as safe yield and well spacing, a set period of time is given to the water-right applicant to develop or perfect the water-right permit. This is the certifcation period (also referred to as the "perfection period") and generally lasts five years depending on the use made of water. After that time, the amount of water actually used during the perfection period, in addition to other factors, will determine how much water will be authorized to be used when the water right is finally certified. Generally, the authorized amount under the certified water right is less than the amount applied for. Once certified, the authorized quantity will not change unless there are other adjustments to the water right (for example, changes in the point of water diversion or place of use).

Sources and methods: The authorized quantity values were obtained from the KDA–DWR's Water Rights Information Systems data base and represent water-right conditions as of late 1999 for Vested and Appropriated ground-water rights. In the data base, the authorized quantity is assigned to water rights in one of three ways: by the water right itself, by the use made of the water, or by the point of water diversion. Several calculations were

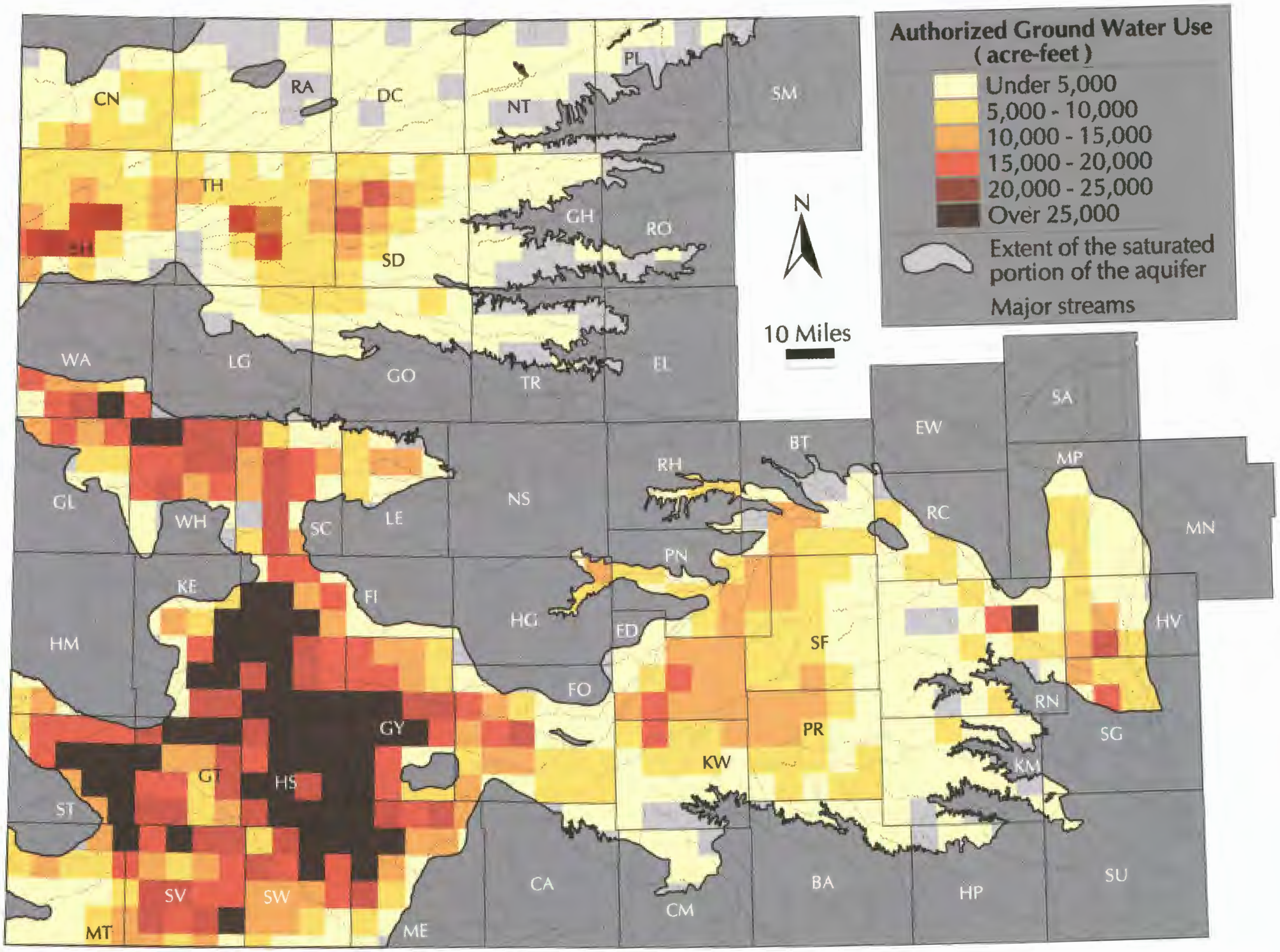


FIGURE 22—Map showing maximum authorized use of ground water in the High Plains aquifer in Kansas.

made to summarize these different types of entries into the total authorized quantity by Public Land Survey System (PLSS) township. The total amount of water authorized for each right that was stored by either water right or water use was divided by the number of points of diversion permitted under the water right. For every unique PLSS township, the prorated quantity for the points of diversion within the township was then combined with the quantities for the same township from water rights stored by point of diversion. This total is the maximum authorized quantity for the township.

Qualifications: Water rights in the state of Kansas can be extremely complex and dynamic. Due to restrictions, limitations, and/or special water-right conditions that exist for some water rights in Kansas, in combination with the potential for water rights to cross any spatial subunit (such as a PLSS section or township), it is impossible to precisely summarize the authorized quantity by any spatial subunits in a way that is completely accurate for both the total authorized use and the individual water rights. The steps outlined in the **Data Sources and Methods** (appendix 2) section of this report adequately represent the vast majority of the water rights in Kansas at the time of the calculation. This procedure provides a reasonably accurate estimate of the maximum possible total pumping at relatively large spatial scales (e.g., township size or larger). Domestic wells and other small withdrawals not subject to the appropriation process add a very small amount to the total withdrawal, but this volume is unlikely to be significant relative to either authorized or actual permitted use.

Water Usage

B. B. Wilson[1], J. A. Schloss[2], and R. W. Buddemeier[2]
[1]Kansas Water Office, Topeka, Kansas, and [2]Kansas Geological Survey, Lawrence, Kansas

Definition: Water usage represents the amount of water that was reported used each calendar year by water-right holders. All water-right holders are required by State law to complete and return a water-use report, whether any water was used or not, to the Kansas Department of Agriculture, Division of Water Resources (KDA–DWR). The State of Kansas is the only western state among those that follow the water-appropriation doctrine (first in time, first in right) that has a mandatory statewide water-reporting program. The KDA–DWR has archived water-use data since 1958; however, only since 1987 has the agency had the regulatory authority to enforce the mandatory reporting. Since that time, the KDA–DWR generally has a 99% return rate on water-use reports. In 1988, KDA–DWR, in conjunction with the Kansas Water Office, initiated a program to identify and correct potential inconsistencies on the reports. When an inconsistency is found, the water-right holder is contacted to further clarify the water-use report.

Relevance to understanding water resources: Water-use reports are the primary data set used to produce an estimate of the total amount of water used and to analyze a variety of water-use conditions each year. Because each water-use report is referenced to the actual ground-water well or surface-water pump that diverted the water, the amount of water used can be spatially quantified and then compared to other spatial features, such as changes in ground-water elevations, streamflows, or precipitation.

Discussion: The water-usage graph (fig. 23) shows the total amount of ground water reported used by water rights within the High Plains aquifer in comparison with the seasonal precipitation from 1990 to 1998. For water rights within the Kansas High Plains aquifer region, ground water consistently accounts for approximately 99% of the total reported use, and the average fraction of ground water used for irrigation is approximately 95% of the total. The graph also shows the inverse relationship between water use and seasonal precipitation that occurs between the months of March to October. As would be expected, when more precipitation occurs during the growing season, the need for supplemental water use, primarily irrigation, decreases.

Data Sources and Methods: The reported water-use information was obtained from the KDA–DWR Water Rights Information System for each year between 1990 and 1998, and represents only appropriated or vested water rights. The total amount of water reported used was summarized for all uses (irrigation, municipal, recreation, etc.) and sources (ground or surface water). Note that 1999 water-use reports will not have been processed through the quality-control program until almost the start of the 2001 calendar year.

Seasonal precipitation data were retrieved from the Hydrodata© software of Hydrosphere Data Products Inc., and are based entirely on National Climate Data Center (NCDC) weather stations. Only weather stations that contained monthly precipitation data from 1990 to 1998 for the months of March to October were selected. These months were used because they span the growing season, during which there can be a nearly direct trade-off between the amount of rain and the requirements for irrigation-water application. The total precipitation for the months of March to October was then summed for each station to represent seasonal precipitation. The weather station data were then interpolated into 1× 1-km precipitation grids across the High Plains aquifer region for each year, and the average precipitation value established.

Qualifications: The reported water-use data base maintained by the KDA–DWR is a very extensive and valuable data set. However, water-use data are reported in a variety of fashions and at various levels of accuracy. For example, some water usage is based on a metered amount while other usage is calculated based on the number of hours pumped and the rate of water flow reported by the water user. As such, the values presented in this report represent only an estimate of the total amount of water used each year. Domestic wells and other small uses of water not subject to the appropriation process are not included in these totals, but this volume of water is unlikely to be significant relative to either the authorized or permitted use.

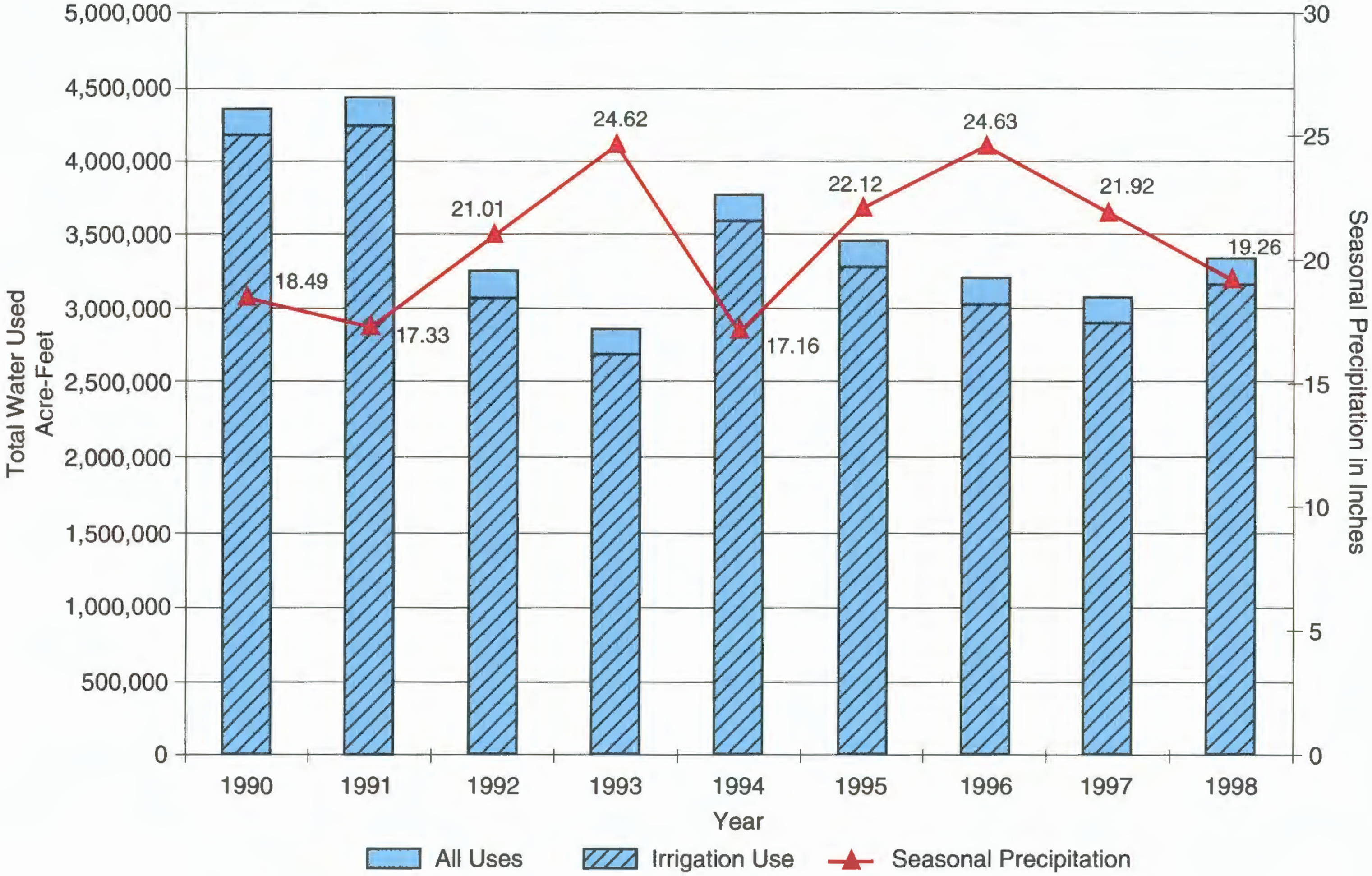


FIGURE 23—Total amount of ground water reported used and seasonal precipitation (March to October) in the High Plains aquifer in Kansas, 1990–98.

Percent of Authorized Quantity Used

B. B. Wilson[1], J. A. Schloss[2], and R. W. Buddemeier[2]
[1]Kansas Water Office, Topeka, Kansas, and [2]Kansas Geological Survey, Lawrence, Kansas

Definition: Percent of authorized quantity used compares the reported actual use of water with the amount that could have been used. Every water right has a set amount or authorized quantity of water that can be used each year. In addition, every water-right holder is required by State law to complete and return an annual water-use report that is used for, among other things, estimating the total amount of water used for that calendar year.

Relevance to understanding water resources: The percent of the authorized water quantity used is a measure of the total water-right activity, relative to total potential usage, that is occurring within the state. It can be used to identify locations where water rights are being used to their full extent, and to compare those locations with aquifer conditions elsewhere. A variety of factors influence the percentage of the authorized quantity actually used from year to year. These include economic conditions, farm-management programs, climate variations, and water **availability and accessibility**.

Discussion: The water-usage map (fig. 24) shows the average amount of ground water used expressed as a percentage of the maximum authorized quantity appropriated and is summarized by PLSS township using reported water-use data from 1990 to 1998. For water rights within the Kansas High Plains aquifer region as a whole, the average percent of the maximum authorized use of ground water is just over 50%.

Comparing this map (fig. 24) to the maps of Maximum Authorized Use (fig. 22), Actual Change in Saturated Thickness (fig. 13), Current 1997–1999 Saturated Thickness (fig. 12), and Potential Natural Recharge (fig. 20) reveals some interesting patterns. Both the relatively higher maximum authorized use and the percentage of that use in southwestern Kansas can be associated with the greater actual decline in saturated thickness for the same area. The relatively low percentage of use in west-central Kansas (the GMD1 area) is arguably a function of the current reduced saturated thickness of the aquifer in that area.

Data Sources and Methods: The reported water-use information was obtained from the KDA–DWR Water Rights Information System for each year between 1990 and 1998. Because each water-use report is tied to the point where water is diverted, the amount of water reported each year was summarized by PLSS township. For each township, the water usage from 1990 to 1998 was averaged. This averaged value was then divided by the total authorized quantity (see Current Maximum Authorized Use Map [fig. 24]) to get the average percent of the total quantity that was reported to have been used from 1990 to 1998.

Qualifications: The KDA–DWR currently does not maintain historic changes in a water right's authorized quantity. Because the amount of water authorized for use by a water right each year can change based on a variety of factors (combined with the fact that the number of water rights continue to grow each year), comparing current values to past reported water-use amounts can lead to incorrect assumptions. The procedure used to develop the data presented in this section of the atlas provides a reasonable estimate of the percent of the maximum authorized quantity based on the scale of the data presented on the map and the time period over which the data have been averaged.

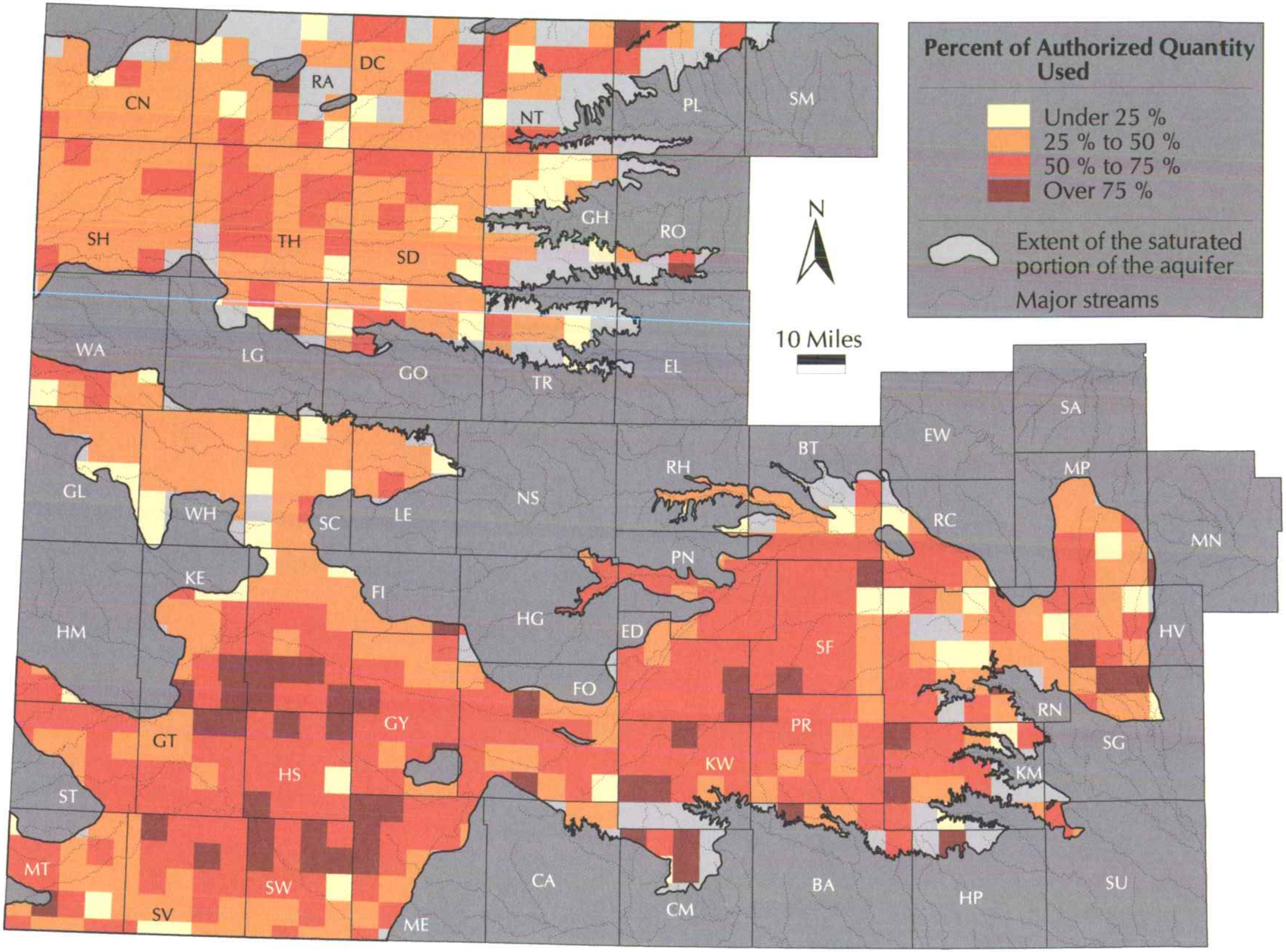


FIGURE 24—Map showing percent of maximum authorized ground-water quantity reported used, 1990–98.

Estimated Usable Lifetime

J. A. Schloss and R. W. Buddemeier
Kansas Geological Survey, Lawrence, Kansas

<u>Definition</u>: The estimated number of years remaining during which a region of the *aquifer* can sustain past levels of decline without significant impairment of existing uses can be described in various ways—"usable lifetime," "time to depletion," and so forth. Whatever the term used, the estimates are not predictions of aquifer depletion, but rather projections—what would probably happen if past rates and patterns of use continue into the future. For the calculations presented here, two scenarios are considered. One uses the average annual change in *saturated thickness* over the period between 1988 and 1998; the other uses the average annual change for the 1978–1988 period. These two time periods show a consistent linear trend in water level in most regions experiencing decline (see appendix on **estimated history of decline** [appendix 6]) although they represent significantly different climatic conditions. The decade of the 1990's has been significantly wetter than the 1980's, resulting in less water use and higher rates of recharge (see **water usage**). Other factors that may have contributed to the overall reduction in the rate of water-table declines in the 1990's include untimely climatic events, more efficient use of water, and increasing awareness that ground water is a limited resource. Usable lifetime is defined here as the number of years remaining until water-level declines reach the level where saturated thickness is 30 feet—an approximate value at which large-volume irrigation, municipal, or industrial pumping is likely to be impractical (see appendix on **drawdown and pumping** [appendix 5]), even though domestic and other low-volume wells can still function if they are completed at the base of the aquifer.

<u>Relevance to understanding water resources</u>: One of the most fundamental issues in understanding and managing natural resources is the question of whether or not resource exploitation is sustainable, and if not, how long, how much, or for what purpose the resource can be used. Quantitative depletion or lifetime estimates provide a consistent basis for comparing the remaining extent of the resource and the possible effects of changes in use or management. They also provide estimates of time periods and locations of the inevitable socioeconomic consequences of resource exhaustion (for example, a transition from irrigated to dryland agriculture). This type of estimate has several potential applications, with one major application being its use as a basis for defining aquifer subunits that can benefit from different management approaches, tailored to local needs and resource lifetimes.

<u>Discussion</u>: Both maps presented here use the average of the 1997, 1998, and 1999 saturated-thickness estimates to determine areas in which the resource has already been exhausted (saturated thickness 30 feet or less), and as a starting point for determining the number of years remaining in the aquifer's usable lifetime. The difference between the two maps comes from their use of water-level data from different time periods to calculate the trend in water-level change—the first map presented (fig. 25) uses the difference between the average water-levels from 1987–89 and from 1997–99 to establish a linear trend in water-level change based on a ten-year period. The second map (fig. 26) is based on water-level trends between 1977–79 and 1987–89. The water-level trends are then applied to the averaged 1997–99 saturated-thickness values to project the number of years it will take for the saturated thickness to reach the 30-feet mark. These maps should be used in combination with the maps of current saturated thickness (fig. 12), water in storage (fig. 16), and maximum authorized use (fig. 22) because the estimated usable lifetime calculated here will not exactly reflect the actual, on-the-ground situation for several reasons.

One fundamental issue is the use of the 30-feet value as an indicator of resource exhaustion (see **drawdown and pumping**). This would ultimately be a policy decision supported by, rather than detemined by, technical analysis, and the 30-feet example used here is only an approximation for the

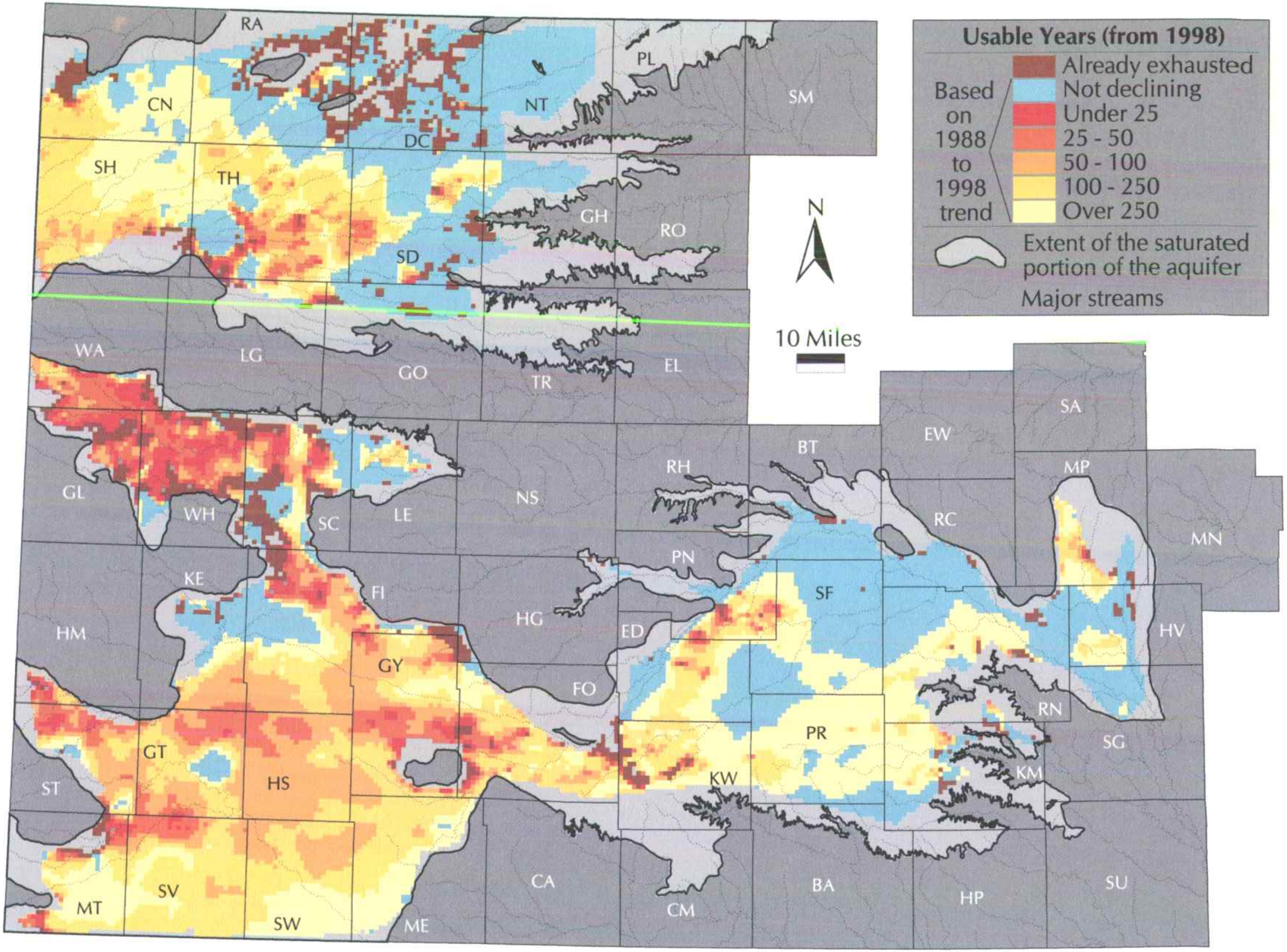


FIGURE 25—Map of estimated usable lifetime (1988–1998 trend) for the High Plains aquifer in Kansas.

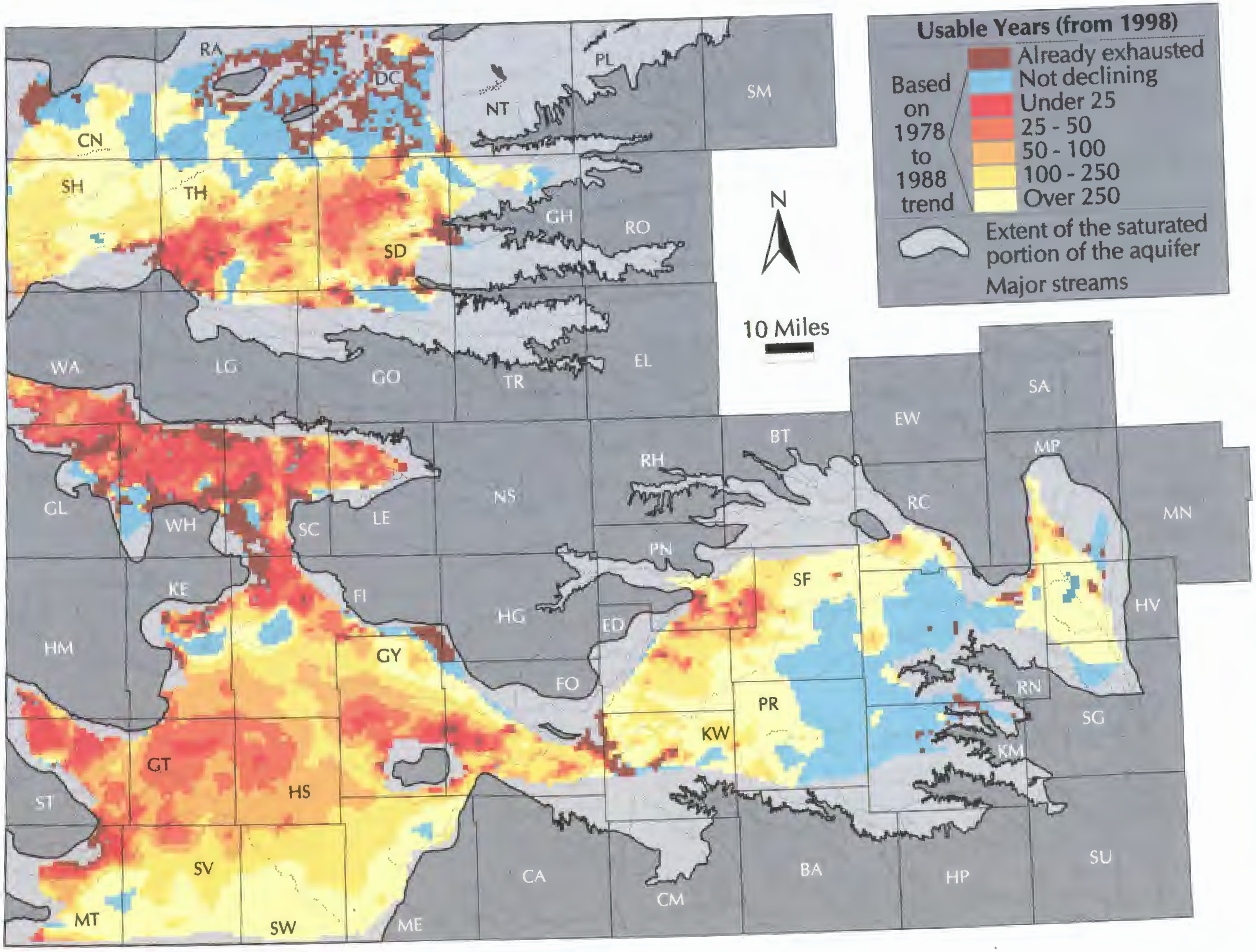


FIGURE 26—Map of estimated usable lifetime (1978-1988 trend) of the High Plains aquifer in Kansas.

purposes of illustration. Another fundamental issue is the inherent uncertainty in predicting the future of the climate (see **recharge**)—the results of using two different historically supported water-level trend scenarios illustrate this. A prudent approach might be to use an intermediate value for planning purposes, while recognizing the potential for significant variation. Other factors that could significantly change the predictions include changes in ground water or land use, and use of one of the many possible alternative methods for performing the calculations. For instance, water-level trends could be calculated for periods longer than ten years, or could be calculated as a 'best fit' for the entire water-level measurement history of each well instead of using three-year averages that are a decade apart. Most importantly, a very large area of the aquifer already has less than 100 feet of saturated thickness and has had this range of values for some time. The value of 30 feet has been identified by KWO, KDA–DWR, and KGS as a conservatively low estimate of the saturated thickness required for effective depletion. However, many of the more thinly saturated areas may already be experiencing reduced levels of pumping because of reduced **accessibility and availability** of the water, and some management units have used a value of 50 feet of saturated thickness as a criterion for deciding if water can be available for appropriation. These factors may contribute to long-estimated depletion times in some thinly saturated areas, without reflecting the important fact that the resource is already significantly depleted. The full range of possibilities for making predictions about aquifer response has yet to be explored, and the maps presented here are but two examples, selected to illustrate the differences when only one variable (the time period used to calculate the linear water-level trend) is altered. While the maps are fairly similar in appearance, the actual differences in annual water-level trend estimates at 1-mile section centers varied by almost 5 feet in some sections. Given that the maps use 25 years as the first class break for data display, the difference in annual trend (of nearly 5 feet per year or 125 feet over a 25-year period) can easily result in large local variations in predictions about the future of the resource.

The short time to depletion or usable lifetime values shown for much of GMD1 and for parts of northern GMD3 and southern GMD4 reflect a combination of low to moderate predevelopment **water in storage** and **saturated thickness** and relatively high levels of **authorized use**. Water rights and land use in these areas have been relatively stable over the past two decades, but this is not the case everywhere. For example, some areas in the Cimarron River basin in extreme southwestern Kansas have undergone recent development during the 1990's, so the rate of decline has been increasing rather than staying relatively constant. In this case, an estimate based on an assumed straight-line projection of the change over the whole decade will underestimate the actual rate of depletion, even if wet climatic conditions persist.

Adoption of different assumed values for effective depletion and projected withdrawal will change not only the estimate, but also the nature of the ultimate consequences. For example, a transition to high-efficiency, low-volume uses such as drip irrigation could substantially extend the life of the resource, but might ultimately result in nearly complete elimination of saturated thickness in some areas, with the resulting loss of water supplies available for municipal and domestic use, stockwatering, etc. (see discussion and illustration in the appendix on **drawdown and pumping**). It is also important to note that these estimates do not consider the increased costs of pumping, well replacement, etc., as water tables drop.

Sources and methods: The estimated usable lifetime is derived from determinations of the saturated thickness (see atlas sections and methods appendices for discussion of methods). The estimated bedrock elevation plus an additional saturated thickness of 30 feet is used to represent the target condition of effective depletion for high-volume pumping. The difference between the water-table elevations (which is identical to the change in saturated thickness) determined for averaged 1998 (1997–99) and 1988 (1987–89) conditions is used to calculate the average annual change in saturated thickness for each legal section (approximately 1 square mile) for which data are available:

[WL(1988) - WL(1998)]/10 years = Rate of Change in Saturated Thickness (feet per year)

The rate of change is then used to calculate the number of years required to reduce the 1998 saturated thickness to a total value of 30 feet:

[Saturated Thickness(1998) - 30 feet]/Rate of Change = Years Remaining Before Depletion

The process is then repeated using the 1978–1988 water-level difference to generate the second rate-of-change value.

Sections where the water-level trend calculations indicated rising water levels were grouped in the map classification labeled ‘not declining.’ Sections where the saturated thickness values averaged for 1997–99 were already 30 feet or less were grouped in the map classification labeled ‘already exhausted.’ The uncolored portions of the aquifer were areas where water-level data were inadequate to construct a satisfactory estimate; because most of these areas are near the fringe of the aquifer and have relatively low water-right development, it is likely that there is a high incidence of thinly saturated regions in these ‘no data’ areas. For the remaining sections (where the aquifer had more than 30 feet of saturated thickness and the water-level trend estimates indicated declining water-levels), the values are mapped as ranges of years, which reflects both the spatial variability of the resource and its use, and the uncertainty in the estimates. The use of values for legal sections is discussed under qualifications following.

Qualifications: These estimates are made for general assessment and planning purposes only and should not be interpreted as having any regulatory status, or used in place of more detailed, officially adopted maps used by water-management agencies. Values are calculated and plotted at the scale of legal sections (square miles), but the flow of ground water (see appendix on **flow and storage** [appendix 4]) will tend to smooth out the short-range variations shown on the map. Spatial variations in aquifer characteristics and water use make interpretation at larger scales, such as the township, more appropriate (for example, see **maximum authorized use**). The estimates are not meant to be a firm definition or prediction of aquifer depletion or usable lifetime, but rather an illustrative projection—a picture of the range of probable results if past use and climate patterns are extended into the future. The discussion section above addresses some of the implications of these assumptions in more detail.

Changes in Use Necessary for Sustainability

J. A. Schloss[1], B. B. Wilson[2], and R. W. Buddemeier[1]
[1]Kansas Geological Survey, Lawrence, Kansas, and [2]Kansas Water Office, Topeka, Kansas

Definition: For long-term sustainable use of a ground-water resource, average withdrawal must be no greater than average **recharge** (see discussion in recharge section for distinction between *safe yield* and *sustainable yield*). **Maximum authorized use** represents the amount of ground water that could legally be pumped from a given area. Reported use tends to be less than authorized use, as shown in the section on **percent of authorized quantity used**. If actual use is equal to actual recharge, then the resource use will be at 'safe yield.' The difference between estimated recharge and authorized use is therefore the maximum amount of change required to bring the use to, or close to, long-term sustainability. The difference between estimated recharge and actual use is a more realistic estimate of the change required to approach sustainability.

Relevance to understanding water resources: The **estimated usable lifetime** represents the future loss of benefit that will result from continued overexploitation of the resource; reduction in current authorized (or actual) use represents the forfeiture of present benefit required to ensure more extended or permanent use of the resource at some level. Enforcing changes in authorized quantities associated with water rights is the most certain but also the most disruptive way to achieve long-term sustainability. Use of education, incentives, and agreements to achieve further reductions of actual use within the framework of existing authorizations is a slower and less certain approach, but one that is likely to be more economically, socially, and politically acceptable.

Discussion: The maps of change required for sustainability (figs. 27 and 28) mirror to some extent the map of **current maximum authorized use** (fig. 22). Because large-scale recharge changes gradually across the region, and because actual pumping is related to authorized pumping, nonsustainability tends to track the amount and density of water rights. Because some recharge is assumed to occur everywhere, some level of sustainable use is possible throughout the aquifer system. The fraction, or percentage of use reduction required for sustainability is therefore lower in areas of low or moderate use than it is in regions with high densities of water rights. It is important to note that the apparent changes required in the 'safe yield' districts of the eastern High Plains are the result of using the natural-recharge map (fig. 20) as a basis rather than the administrative-recharge map (fig. 21). If the recharge values defined by regulation were used, there would be very few areas of apparent over-appropriation in Groundwater Management Districts 2 and 5.

The most striking feature of the two maps (figs. 27 and 28) is the very high percentage of reduction in authorized use required to match recharge. Overall, a lower percentage reduction in reported use is required. The difference is most noticeable in northwest Kansas and in regions close to the boundary of the saturated portion of the aquifer. Although reductions in actual use of a third to a half at the township level would bring extraction to the approximate magnitude of the recharge in some areas, the core irrigation regions in southwestern and western Kansas are pumping three to four times the estimated long-term recharge value. The differences in the authorized and reported use patterns shows the importance of scale in considering water-resource problems—because of the natural rates of ground-water flow and equilibration and the variability of ground-water systems (see technical appendices on **aquifer types and terminology** [appendix 1] and **ground-water storage and flow** [appendix 4]), the aquifer, basin, or district level is too large for assessing and managing the resource, and the legal section level is too small. Townships are awkward because they are political rather than natural hydrologic units, but their size is appropriate for addressing the nature of the resource and our knowledge of its characteristics.

Sources and methods: The maximum authorized use (acre-feet per township for the current year), the average reported use for the period 1990–98, and the maximum value of recharge (inches per year) from the natural-potential-recharge map intervals (fig. 20) were converted to the same units and calculated for each township. Recharge was subtracted from use so that a positive number represents the amount of over-use (or over-appropriation). This number was then divided by the actual use (or the authorized use) to express the reduction needed as a percentage of the total actual or authorized use. As with the other maps in this atlas, values were grouped into classes to indicate the approximate range of reductions required; because of uncertainties in the details of local recharge and in the way the authorized use was calculated at the township level, this provides a reasonable overview without spurious precision.

Qualifications: **Recharge** values are one of the more uncertain hydrologic parameters. Use of the maximum value from each recharge-class interval provides an estimated reduction that probably represents the lower end of the required reductions. However, given the uncertainties and the large and variable difference between authorized and actual use, it provides a useful estimate. The values presented here are estimates intended to provide general information on the scale of the problem and possible solutions. Although the authorized-use values (fig. 27) can be accurately determined, the reported-use values (fig. 28) are a reasonable approximation of actual use, and the recharge values are broad regional estimates that require refinement in order to establish actual local values of sustainable use. The values presented here are not specific recommendations, nor do they have any official standing in terms of policy or regulation.

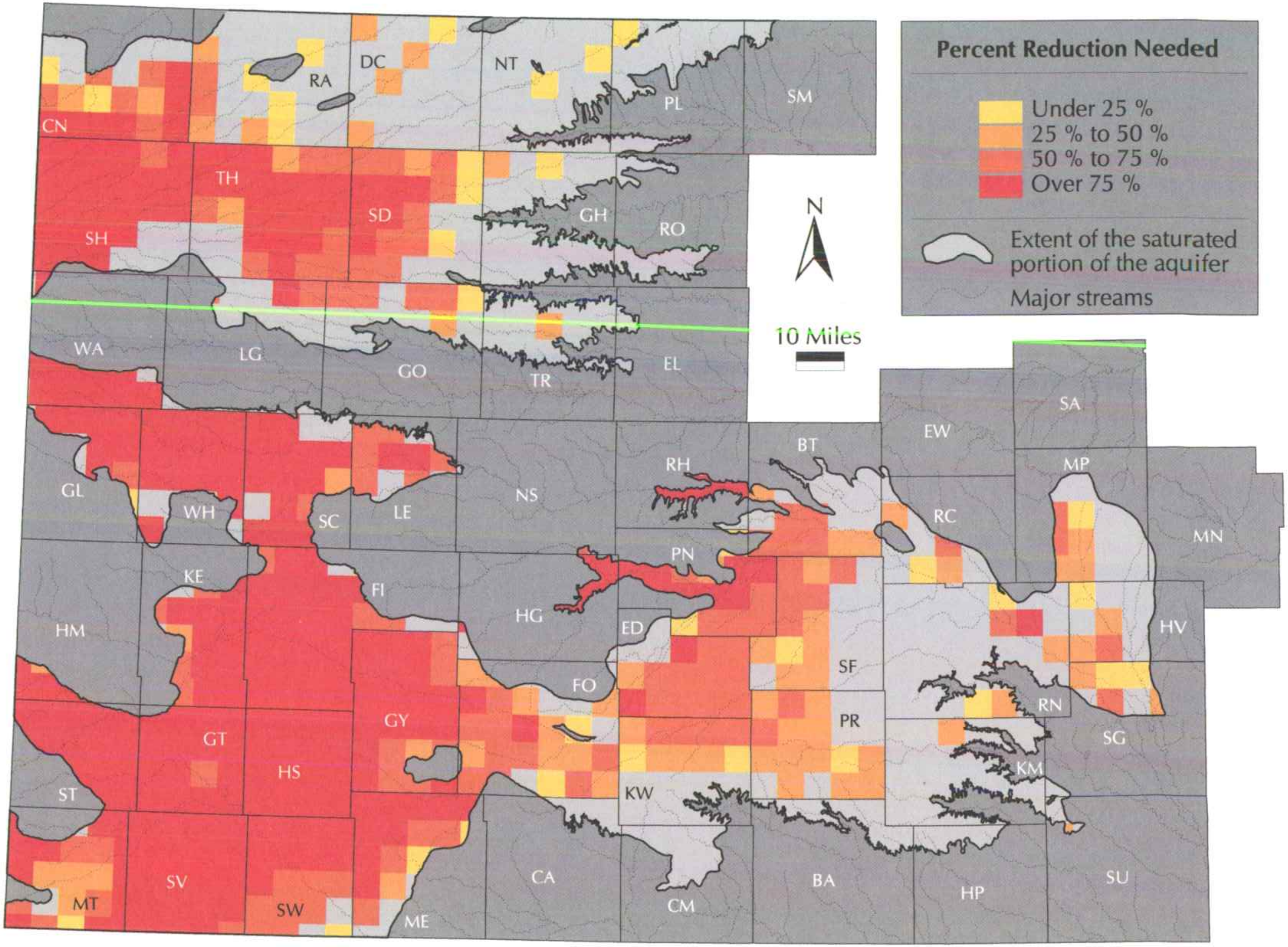


FIGURE 27—Map showing percent reduction in authorized ground-water use needed to meet sustainable yield in the High Plains aquifer in Kansas.

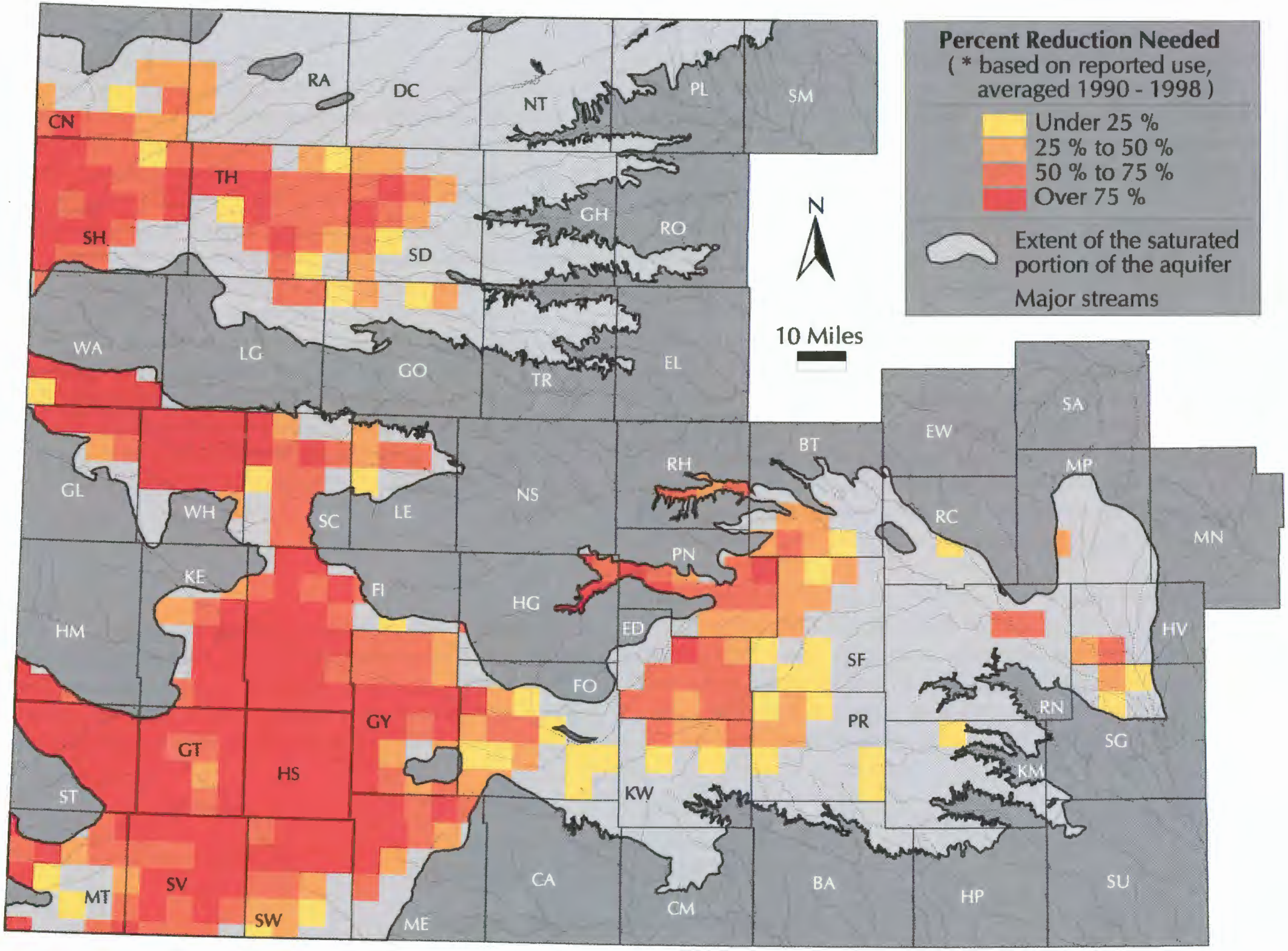


FIGURE 28—Map showing percent reduction in reported ground-water use needed to meet sustainable yield in the High Plains aquifer in Kansas; reduction needed based on reported use, averaged 1990–98.

High Plains Aquifer Atlas—Information Appendix 1

Aquifer Types and Terminology

R. W. Buddemeier, P. A. Macfarlane, and G. Misgna
Kansas Geological Survey, Lawrence, Kansas

Ground-water terminology can be confusing, in part because often many different terms are used in describing the same phenomenon, and the same term can be used with different meanings. This section provides a brief summary of the general issues and an indication of the way the terms are used in this atlas, with sections on terminology, internal structure, and aquifer type.

Terminology

What is an *aquifer*? The word literally means 'water bearer' and refers to a layer of rock or sediment that contains enough accessible water (see appendix on **ground-water flow and storage** [appendix 4]) to be of interest to humans. Water in an aquifer is stored between the grains of rock. Aquifers can be either consolidated rock (such as sandstone) or unconsolidated (such as the sands and gravels that make up the High Plains aquifer). The variety of reasons for human interest create some of the differences in definition: a person seeking a municipal or irrigation well that can pump a thousand gallons per minute has a different perspective from a domestic well user who can be content with ten gallons per minute, and both have a very different perspective than a scientist interested in the migration of fluids over geologic time. Yet, all can and do call the objects of their attention 'aquifers.' In keeping with the major uses of the Kansas High Plains aquifer, we use the term to mean a body that can supply pumped ground water at rates at least adequate for domestic water supplies and that contains primarily potable water.

And what is not an aquifer? Two other common terms used are *aquitard* (which retards ground-water flow) and *aquiclude* (which excludes ground-water flow). These terms also are relative for the same reasons used as examples in the case of 'aquifer.' A number of similar or synonymous terms exist for these features; aquicludes also are known as *confining* or impermeable layers, and aquitards as semi-confining or leaky impermeable layers.

AQUIFER NAMES: Aquifers are often named for the geologic formation in which they occur—Kansas examples include the Ogallala and the Dakota aquifers. However, the geologic formation may not be uniformly water-bearing—the Dakota is a good example, having a greater volume of relatively impermeable units than of actual aquifer units (see the Kansas Geological Survey web site on the Dakota aquifer at http://kgs.ukans.edu/Dakota). Aquifers (especially smaller units) are often identified by the way they were formed (e.g., *alluvial aquifers* are water-deposited, and *glacial-drift* aquifers are deposited by glacial action). Because aquifer function is defined by continuity and characteristics rather than by the origin of the materials, large aquifer systems may be composed of several geologic formations. The High Plains aquifer is such a composite; in western Kansas it consists of the Ogallala Formation, which in eastern Ford County grades into the more recent but very similar deposits of the "Great Bend Prairie aquifer" and "Equus Beds aquifer." The alluvial stream and river-channel deposits on the surface of the High Plains units (which also are alluvial in origin) usually also are considered part of the High Plains aquifer system when there is a good hydraulic connection between them. See also aquifer types on the next page.

Internal Structure

Alluvial material is deposited from water (usually flowing water)—rapidly moving water transports and deposits coarse material (gravel and sand), which turns into permeable aquifer deposits when buried, while floodplains and lake bottoms may have thick layers of relatively impermeable silts and clays. The dimensions of alluvial features may range from a few feet to many miles in lateral extent, and from vanishingly thin to hundreds of feet in thickness. This accounts for the spatial variability of properties within an alluvial aquifer unit, and for the common complaint that "we do not have enough data." When the zone of influence of a single well is on the order of a mile (see appendix on **drawdown and pumping** [appendix 5]) and the aquifer properties can vary significantly at both smaller and larger scales, precise and accurate prediction of behavior is not possible without intensive—and expensive—field studies.

The aquifer cross section (fig. 10) illustrates some of the features common in alluvial deposits. Laterally extensive clay layers can lead to 'confined aquifer' or 'perched aquifer' characteristics.

One of the ways to deal with the problem of spatial variability is being pursued by the Survey's High Plains Aquifer Evaluation Project—this is to use intensively studied or well-characterized areas as case-study sites to see how detailed information can be related to or predicted from the more general information usually available. Understanding these relationships does not provide the same level of knowledge as real measurements would, but it does improve the odds of making a valid estimate when faced with questions where data are sparse.

Aquifer Types

The High Plains, like most Kansas aquifers, is an unconsolidated, unconfined aquifer. Other terms similar to 'unconfined' are 'water table,' or '*phreatic*,' aquifer. Some deeper water-bearing units like the Dakota aquifer contain consolidated (e.g., sandstone) layers and may be separated from the surface by confining layers impermeable enough so that the deep water can be under pressure. Breaches in the confining layer may result in a spring or *artesian well* flowing at the surface.

The cross section (fig. 10) illustrates the occurrence of a rather extensive clay layer within the water-table aquifer below the Arkansas River. If such layers are large enough and impermeable enough, the water beneath them is said to be 'locally confined' or 'semi-confined,' and the water on top of them is said to be 'perched.' Effectively, the layer divides the aquifer into two unconnected regions, which are not in flow or pressure equilibrium. Such regions occur in the High Plains; for example, areas in south-central Kansas (southwestern GMD5 and northwestern GMD2) and along the Upper Arkansas River Corridor (see Kansas aquifer section) display confined behavior. In such areas the usual relationships between water-table elevation and change and the underlying water resource are not valid, so it is important to recognize the differences for effective management and monitoring.

High Plains Aquifer Atlas—Information Appendix 2

Bedrock Data Sources and Data-processing Methods

J. A. Schloss
Kansas Geological Survey, Lawrence, Kansas

This section describes the data sources used to derive estimates of the elevation of the bedrock underlying the High Plains aquifer in Kansas, and gives an overview of the data-processing methods used to combine these data into a three-dimensional surface that was used to generate the estimates.

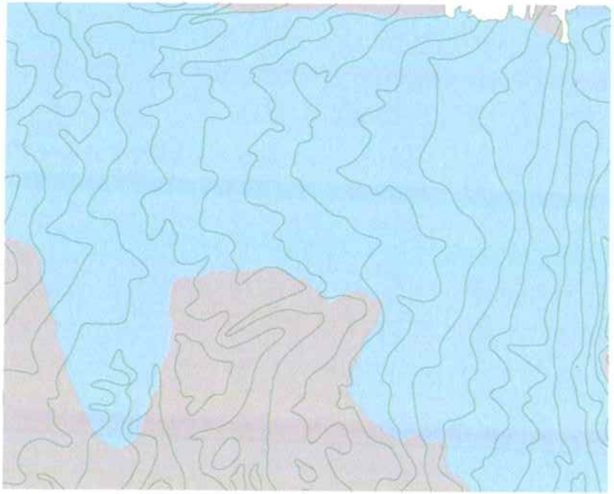


FIGURE 29—This figure shows a sample of the contours of the base of the High Plains aquifer used as input to the bedrock surface. These contours were produced by the U.S. Geological Survey (USGS) and are the primary source of input data to these estimates of bedrock elevation. The light-blue areas in the figure are within the saturated portion of the aquifer and the gray areas are defined as thinly or nonsaturated. These distinctions come from another data layer produced by the USGS that delineates the extent of the High Plains aquifer. This layer defining the extent of the aquifer is used throughout this atlas..

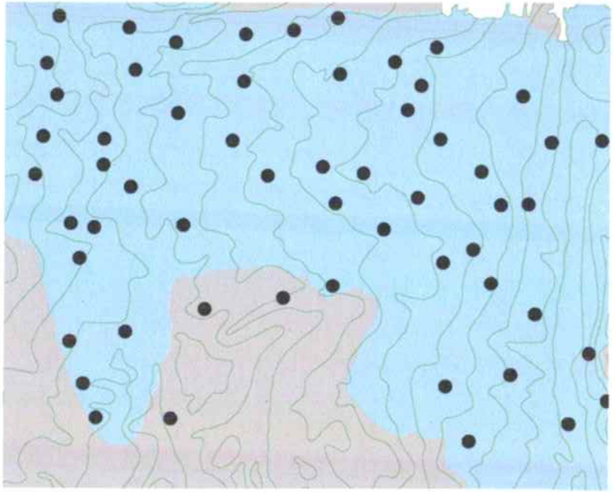


FIGURE 30—To include as much information as possible, data were added from the KGS Oracle™ data base for all wells that had a value for depth to bedrock. Because the contours describe the base of the aquifer in terms of altitude instead of depth, the altitude of the bedrock surface at each well was calculated by subtracting the depth to bedrock from the altitude of the land surface. These points serve as a secondary source of input to the estimates of bedrock elevation.

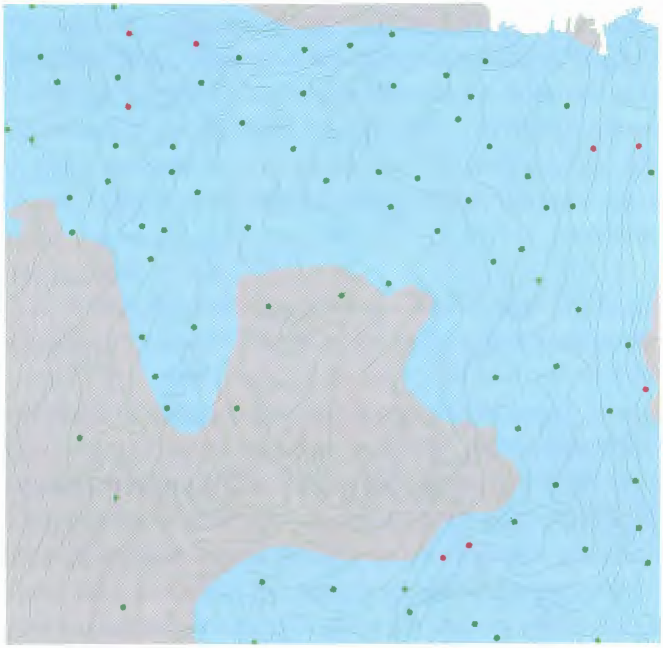


FIGURE 31—To honor the locations of the contours and points as much as possible, the bedrock data at the points were evaluated with respect to the contours, and some points were found to be in disagreement with the contours. All points were then flagged to be included or excluded from the surface model. In this figure, those colored green were used and those in red were ignored.

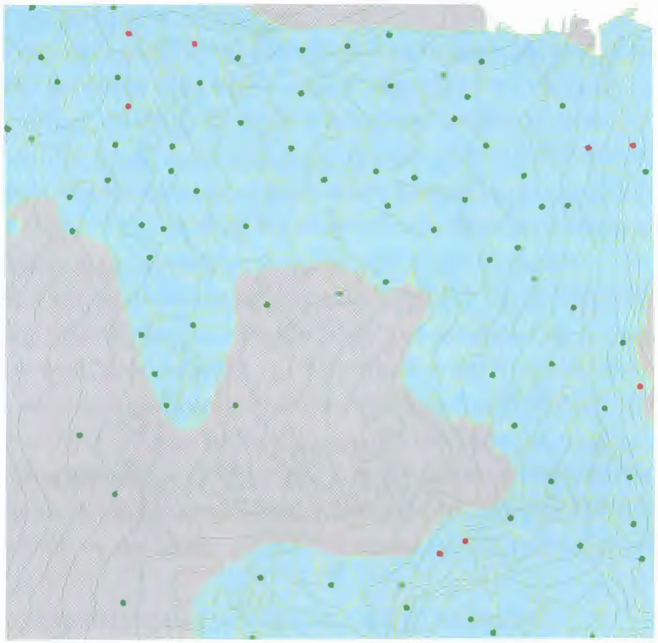


FIGURE 32—Once the input features were prepared, they were combined to create a model of the bedrock surface that would best honor the data from both sources. This image illustrates the density of the surface model (shown in yellow) that was created and how it "connects" to every contour line and every included point.

High Plains Aquifer Atlas—Information Appendix 3

Saturated Thickness—Concepts and Measurement

R. W. Buddemeier
Kansas Geological Survey, Lawrence, Kansas

A Close-up Definition—

The detailed figure following (fig. 33) shows the rock and pore spaces in a volume of the aquifer. It gives an exaggerated illustration of saturated and unsaturated zones in an aquifer and how those relate to the upper and lower boundaries and to saturated thickness. See the appendix section on **ground-water storage and flow** (appendix 4) for how this relates to *porosity*, *specific yield*, and water volume. In the unsaturated, or vadose zone, addition of water by *recharge* from the surface causes the water content to rise until it reaches the field capacity of the soil—the concentration of water at which gravity-driven drainage flow occurs.

Under natural conditions, the elevation of the boundary between the unsaturated and saturated zones—the water table—fluctuates as a function of recharge, discharge, and *evapotranspiration*. These variations can be surprisingly large, in part because of the effect of porosity in amplifying the elevation change due to recharge. If the effective porosity of the aquifer is 17%, for example (a common value in the High Plains), recharge of 2 inches of free-standing water will cause the water table to rise by approximately 1 foot.

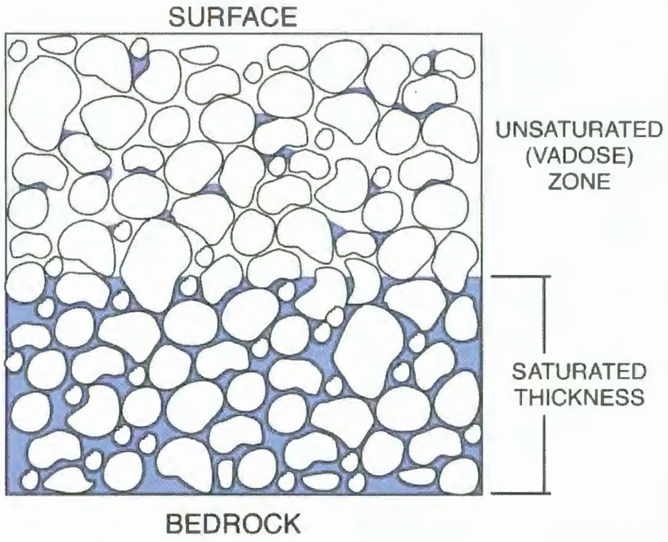
The figure following (fig. 34) illustrates the idea of saturated thickness—that volume of the aquifer in which the pore spaces are completely filled (saturated) with water. At a particular point, the local saturated thickness is the difference in elevation (or depth) between the water table and the bedrock surface (the base of the aquifer). However, bedrock and water-table elevations are often measured at different points, and because both vary over space, the saturated thickness at any given point usually must be estimated from what is known about the two surfaces rather than on observed values. This is often a more useful measure of the actual amount of underground water than observations at a few specific points, because it provides good estimates for a whole region instead of precise measurements at very limited locations.

Natural Condition—No Ground-water Pumping

The elevation of the water table varies over time even under natural conditions. Seasonal and year-to-year variations in recharge result in fluctuations, and where the water table is shallow the evapotranspiration of plants can have very significant effects during the growing season. Estimates of saturated thickness therefore depend on the times, places, and numbers of measurements taken. Uncertainties in the absolute value will be at least several feet and perhaps tens of feet, but adoption of a standard set of assumptions and measurement protocols can provide an estimate that is useful as a baseline for comparison regardless of its accuracy.

Human modification of the land surface, and especially ground-water pumping and/or stream diversion, have even greater short-term and long-term effects on the water table and saturated thickness. For a discussion of the effects of pumping on short-term water-table elevation changes, see the appendix on **drawdown and pumping** (appendix 5). Long-term effects are addressed in the atlas section on **change in saturated thickness**, and in the appendix on **decline rates** (appendix 6).

FIGURE 33 (opposite)—Saturated and unsaturated zones in an aquifer composed of coarse, unconsolidated material. In the saturated zone, all the pore spaces are filled with water. In the unsaturated (also known as the vadose zone), some water is usually present, but the amount is variable and it always is less than the field capacity.



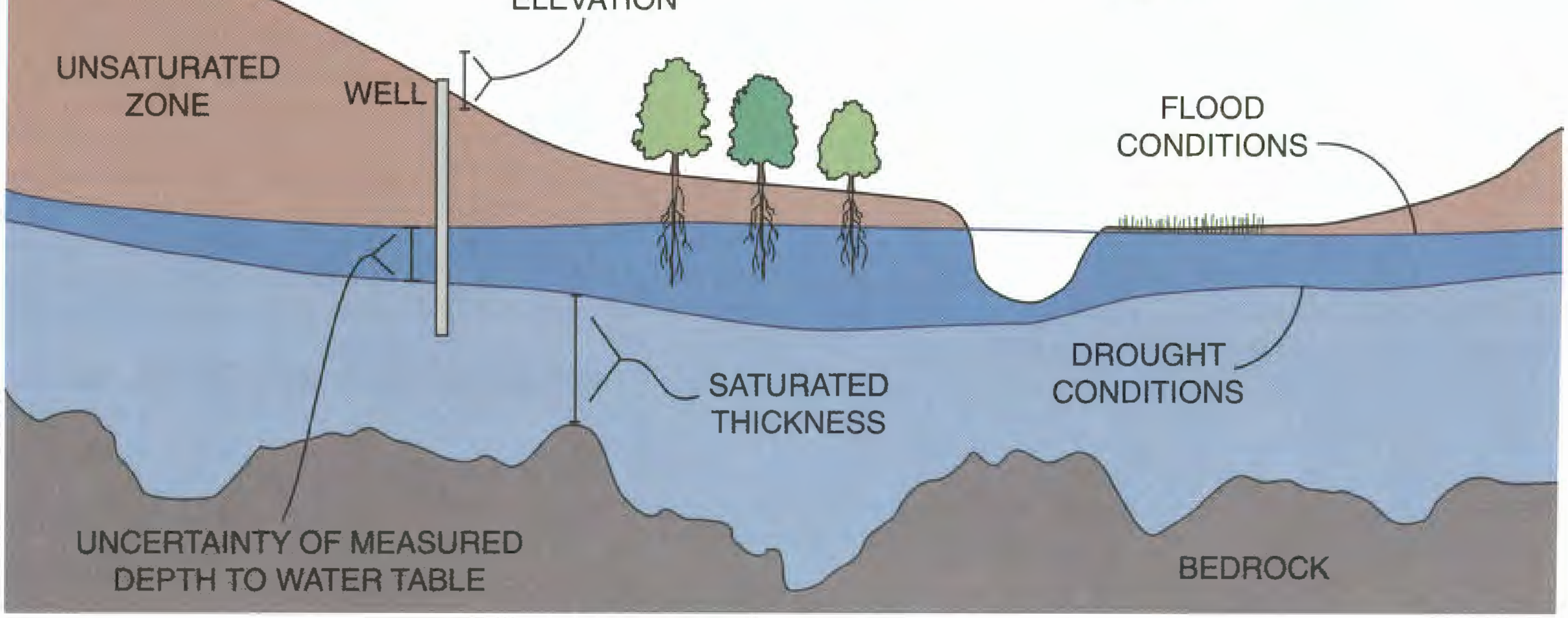


FIGURE 34—Saturated thickness in cross section—the light-blue area represents the average volume of permanent saturation, and the dark-blue area is the range of variation of its upper limit, which is affected by topography, recharge, discharge, and the effects of vegetation.

High Plains Aquifer Atlas—Information Appendix 4

Ground-water Storage and Flow

R. W. Buddemeier and J. A. Schloss
Kansas Geological Survey, Lawrence, Kansas

Ground-water Storage, Porosity, and Specific Yield

Ground water occupies the cracks and pore spaces between rocks and mineral grains below the land surface. In the saturated zone, essentially all the pores are filled with water. If a volume of saturated aquifer material is completely dried, the water volume removed reflects the total *porosity* of the material, or the fraction of pore space within the total volume of solids plus open spaces. This number can be surprisingly large; some minerals and rock formations can have total porosities in excess of 50%. In the unsaturated, or vadose zone there can be significant amounts of water present, but the voids are not completely filled (see appendix on **saturated thickness** [appendix 3]).

However, some of the pore spaces may be too small or too poorly connected to permit the water they contain to flow out easily. The effective porosity can be thought of as the volume of pore space that will drain in a reasonable period of time under the influence of gravity. Effective porosity is always less than total porosity, sometimes (as in the case of clays) much less. "Good aquifers" tend to have values of effective porosity in the range of 10–30%, although examples of higher and lower values can be found. Figure 35 illustrates the relationship among the types of porosity and the volume of water in storage.

A characteristic closely related to effective porosity is the specific yield of the aquifer, which is the volume of water per unit volume of aquifer that can be extracted by pumping. Although there are some technical distinctions, effective porosity and specific yield can be thought of as equivalent for most nontechnical purposes.

Specific yield (*SY*) is clearly an important factor in water availability and is the factor that is used to convert saturated thickness (*ST*) to the actual volume of ground water available:

$$\text{Volume} = \text{Area} \times ST \times SY$$

Figure 35 compares the water available for extraction with the total water and aquifer volumes.

At any given location, the porosity of the formation remains essentially constant, but the volume of water in storage, the average local porosity, and the specific yield all vary with changes in saturated thickness (water-table elevation). Some of this variation can be explained (and quantitatively predicted) on the basis of straightforward physical principles, but some of it is due to local variations in the aquifer structure. This hydrogeologic variability is difficult to predict or measure with detailed accuracy.

The U.S. Geological Survey (USGS) has prepared maps and electronic coverages showing estimates of the distribution of specific yield for the High Plains aquifer, which have been adapted for use in this project.

Ground-water Flow and Hydraulic Conductivity

Ground-water flow is very slow compared to surface-water movement. A rough average number often used for natural flow in the High Plains aquifer is a foot per day. This is thousands of times slower than river flow (typically measured in feet per second), and means that a 'parcel' of ground

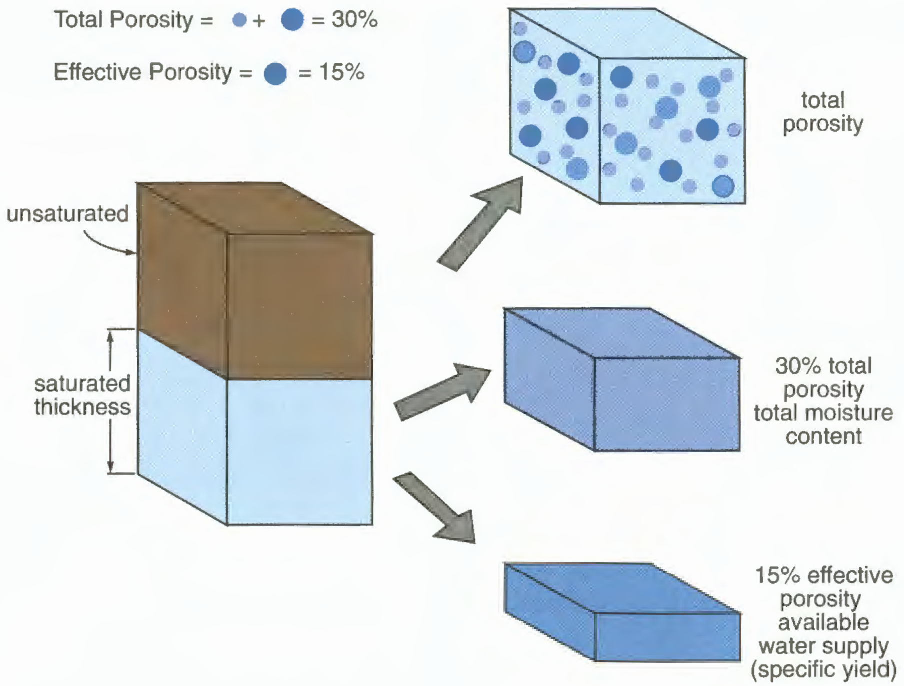


FIGURE 35—A schematic illustration of an aquifer in which the total porosity in the saturated zone is 30%, half of which is tightly held in small pores or mineral associations, and half of which is in large pores that drain relatively easily. The latter fraction can be pumped out and is the effective porosity or specific yield. Illustration not to scale.

water takes over a decade to move a mile, and about a century to cross a township. This natural time scale underscores the importance of long-term planning and management and helps explain why resource depletion or contamination cannot be quickly or easily rectified.

Ground water, like surface water, flows 'downhill' in the direction determined by the slope of the water table. Its rate of flow is determined by the steepness of the slope and an aquifer characteristic called *hydraulic conductivity*. In a porous medium, flow is described by Darcy's Law, an equation that relates the rate of flow to the slope (or gradient) of the water table and the characteristics of the aquifer. This law is illustrated in fig. 36, and is written as

$$Q = A \times K \times G,$$

where Q is the volume flow of water (for example, in cubic feet per day—also called *flux*), A is the cross sectional area of the aquifer through which the horizontal flow is occurring, G is the gradient or slope of the water table in the direction of flow (difference in elevation divided by horizontal distance), and K is the hydraulic conductivity—a constant of proportionality that describes how easily water flows through the medium. The term *permeability* is closely related to hydraulic conductivity; in strict scientific usage they have slightly different definitions, but for water in unconfined aquifers they are essentially the same.

Like specific yield, the hydraulic conductivity is related to but not solely determined by the porosity of the aquifer. All of these characteristics may show considerable variation over a variety of spatial scales. Because both specific yield and hydraulic conductivity are typically measured from tests on individual wells, their determination is relatively expensive and applies to the scale of the zone of influence of the well—which is much larger than local variations in the aquifer, but very small compared to the whole aquifer, basin, etc.

Qualifications: The USGS maps are a valuable source of aquifer information and represent the only consistently prepared whole-aquifer assessment of these properties. As with all such descriptions, they suffer from scarcity of data; measurements must be extrapolated much more

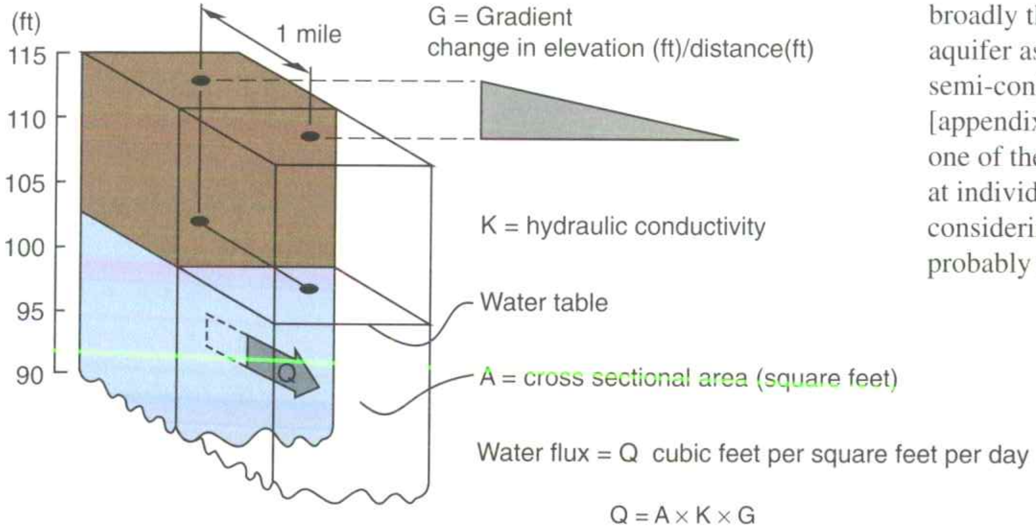


FIGURE 36—Illustration of the factors governing flow in ground-water systems—the head gradient, or slope of the water table, the hydraulic conductivity of the aquifer, and the area through which flow can occur.

broadly than would be ideal. In addition, the analyses necessarily treat the aquifer as a single homogeneous layer, while it is known that in some areas semi-confining layers (see appendix on **aquifer types and terminology** [appendix 1]) causes vertical stratification. Unless the location is close to one of the measurement sites, use of these coverages to describe the aquifer at individual locations could be quite misleading. However, when considering averages at the spatial scale of townships and larger, the data probably represent a significant improvement over "best guess" values.

High Plains Aquifer Atlas—Information Appendix 5

Water-table Drawdown and Well Pumping

R. W. Buddemeier
Kansas Geological Survey, Lawrence, Kansas

Withdrawal of a thousand gallons per minute (a common pumping rate for high-volume wells) is an unnaturally rapid change in a ground-water system (see appendix on **ground-water storage and flow** [appendix 4]) and results in some major perturbations of the *water table*. Initially, water level drops very rapidly in the immediate vicinity of the well. This lowering of the water table is known as *drawdown* and may amount to many tens of feet. This is why thinly saturated zones are unsuitable for high-volume pumping even if substantial water is present—the *saturated thickness* must be large enough so that the pump can remain completely submerged at maximum drawdown.

As pumping continues, the rate of local drawdown decreases and eventually stabilizes as the withdrawal is compensated for by inflow of ground water from the surrounding area. As this happens, the measurable decline in the water table spreads outward. When the ground-water system has adjusted to the pumping, the resulting pattern of water-table depression is sometimes referred to as steady-state drawdown; this feature is illustrated in fig. 37. The pattern of water-table distortion is called the *cone of depression*, and the area over which the depression can be detected is called the *zone of influence* of the well. This zone of influence can easily have dimensions of a mile or more, depending on the characteristics of the aquifer.

When pumping ceases, lateral inflow continues, and the water table gradually recovers toward an equilibrium value. This recovery is fastest where the depression is greatest and slows as equilibrium is approached. Figure 37 indicates some aspects of the recovery process—in particular the fact that it make take months for full recovery to occur.

This rapid distortion and slow recovery is one of the major complications involved in making accurate estimates of water-table (and therefore saturated-thickness and volume-of-water) changes over time. Even though water levels are measured annually in the winter when irrigation pumping has been at a minimum for some months, it is probable that full recovery of the water table never occurs, and some pumping does occur outside of the normal spring-summer growing season. For example, municipal supply wells, well maintenance and testing, 'pre-irrigation,' and irrigated winter-wheat production may all result in local pumping close to the winter measurement period. A water-level measurement made near a recently pumped well may be significantly affected, which is one of the reasons why water-level change estimates (see the **usable lifetime** section and the appendix on **estimated history of decline** [appendix 6]) are constructed from multi-year averages. Highly accurate, short-term measurements of change in a large, variable system are extremely difficult.

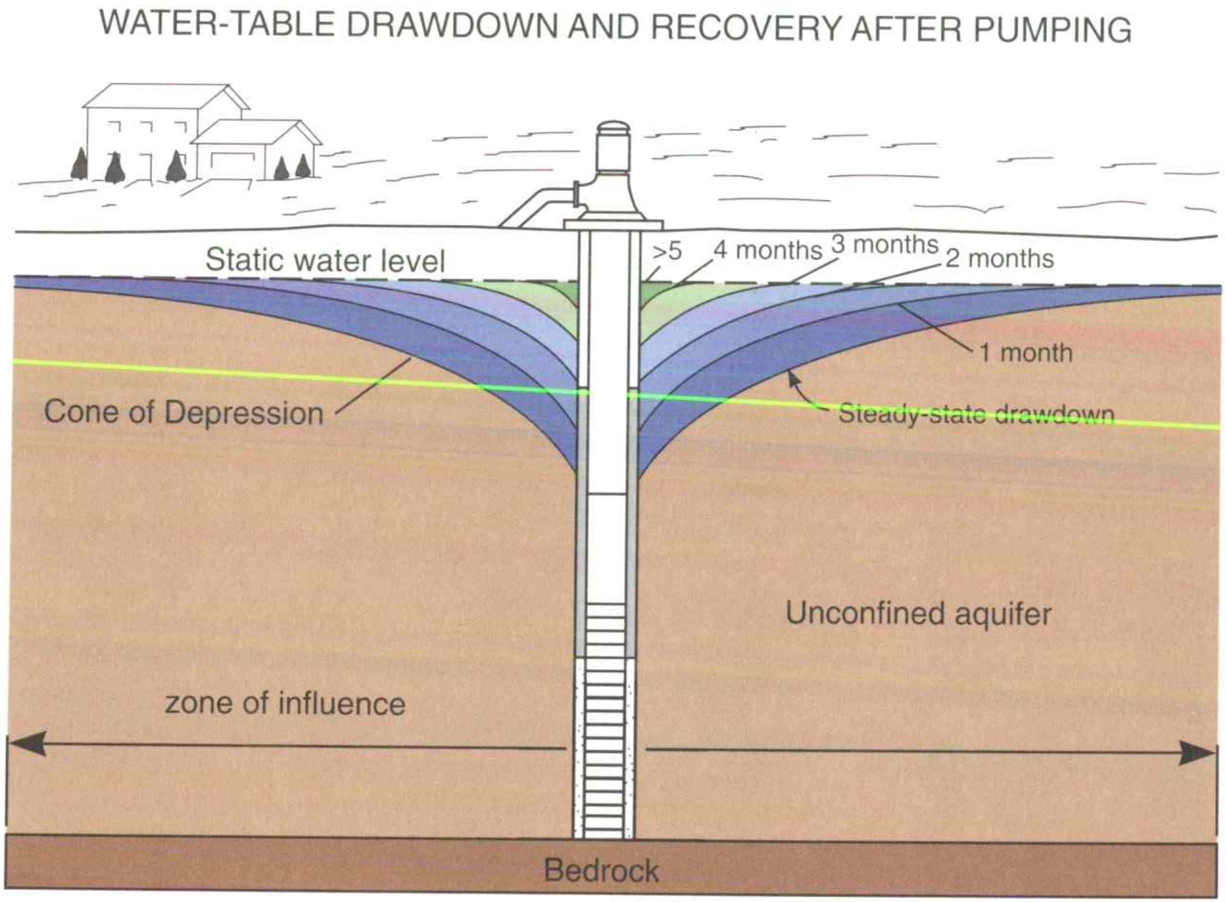


FIGURE 37—Simplified drawing of drawdown and recovery terms and processes. The figure is not to scale and is intended to represent the basic concepts, not the relative or absolute magnitudes. Drawdown near the well can be a number of tens of feet, and the zone of influence can be greater than a mile.

High Plains Aquifer Atlas—Information Appendix 6

Estimated History of Decline in Saturated Thickness of the Ogallala Portions of the High Plains Aquifer, Groundwater Management Districts, and River Basins

J. J. Woods, J. A. Schloss, J. Mosteller, and R. W. Buddemeier
Kansas Geological Survey, Lawrence, Kansas

The Ogallala aquifer is the western portion of the High Plains aquifer (from the Colorado border to approximately the eastern boundary of Ford County, Kansas). This portion of the aquifer has the lowest **recharge** and the greatest **changes in saturated thickness**, and in most areas is managed under "programmed depletion" rather than "safe yield" policies. Under a separate contract, the Kansas Geological Survey has calculated the average rate of change in saturated thickness in the Ogallala aquifer as a whole, and in the Groundwater Management Districts and the portions of the river basins (fig. 1) overlying the aquifer. Two different approaches were used: one employed data from those wells that had 30 years of measurement record (fig. 38), and the other used all available measurements over the past eleven years (fig. 39a-c).

Although neither of the methods of determination were identical to the calculations used to produce the maps in this atlas (see note on methods and qualifications, below), the general agreement among the results validates the overall findings and provides an adequate comparison of the rates of change at different periods of time.

Water-level Changes Determined from Wells with Long-term Records

Results: The figures show three major results: (1) rates at which the various regions of the aquifer are declining have generally slowed substantially between the 1969–1979 and 1989–1999 periods; (2) the changes in the 1979–1989 decade are not consistent across the various subunits; and (3) the pattern and amount of change observed is strongly dependent on the region considered.

Methods and qualifications: The estimates in these figures were produced by averaging the ten-year changes in wells that had measurements in each of the years defining the endpoints of the decades. This method results in more precise individual values, but a much smaller number of wells—and therefore greater uncertainty as to how well their average represents the behavior of the overall region. In other words, only wells measured in the winters of 1969, 1979, 1989, and 1999 were used, but all of each well's winter measurements were used in calculating the average for each year.

Another cautionary note also is expressed in the section on **estimated usable lifetime**; rates of decline may change either because the resource is being used more sustainably—or because there is not enough left to use. Rate-of-decline figures needed to be considered in the context of the amount and distribution of the remaining resource; decreasing use in a fringe area (e.g., with 50 feet of saturated thickness or less) could mask more serious declines in the remaining resource if only averages are considered.

Short-term Water-level Changes Determined from All Available Well Records

Table 1 following presents the average rate of water-level (expressed as depth to water) change over the period 1989–1999, based on all available well data for a given region. The trends were analyzed (see Methods and Qualifications, below) and used to project the values expected in 2010.

These values are expected to be similar to those obtained in the previous section on water-level changes determined from wells with long-term records for the 1989–1999 decade (see right-hand column in fig. 39a). The general patterns are similar, but differ significantly in detail. Both methods find an average rate of decline of over a foot per year for southwestern Kansas GMD3 and the Cimarron basin, and agree on the small declines for the Solomon and Upper Republican basins. However, fig. 39a shows a significant decline for the Smoky Hill–Saline basin and for northwestern Kansas GMD4, whereas table 1 does not. Compared to table 1, fig. 39a underestimates the declines in the Upper Arkansas basin, western Kansas GMD1, and the Ogallala aquifer as a whole.

These values can then be compared with the usable-lifetime estimates. The usable-lifetime estimates are systematically different because they take into account saturated thickness, whereas the estimates discussed here simply address change in the elevation of the water table. The usable-lifetime maps show the greatest concentration of "hot spots" in GMD1, followed by the Smoky Hill–Saline basin and the Upper Arkansas basin. These findings, especially for the Smoky Hill–Saline basin, tend to generate very different management and planning perspectives than the values shown in table 1 and fig. 39a.

These differences can be resolved and explained by further analysis, but they point out the importance of developing clear, consistent measures of resource status and changes that take into account both hydrologic principles and the patterns of use.

Methods and Qualifications: The data for each region were averaged for each year (1989–1999) and analyzed for trends; where a statistically significant change occurred, the "significance" column has a "yes." All significant trends were tested for best fit, and in all cases it was found that a linear trend line was better than any non-linear fit. The trend lines were then extrapolated to the year 2010 and an estimated value determined for that year.

These estimates make use of all available data rather than a limited subset of wells as is the case in the results reported in the previous section utilizing wells with long-term records. This should make the results more

TABLE 1—Average water levels by region and trends of change over the past eleven years, projected to 2010.

Region	Average depth to water (ft), 1999	Average rate of change (ft/yr)	Projected depth to water (ft), 2010	Significance
Upper Republican	132.81	0.326	136.40	yes
Solomon	111.12	0.003	111.15	no
GMD4	131.37	-0.171	129.49	no
Smoky Hill–Saline	126.43	0.142	128.00	no
GMD1	133.09	0.836	142.29	yes
Upper Arkansas	112.09	1.181	125.08	yes
GMD3	155.59	1.594	173.12	yes
Cimarron	182.77	1.340	197.50	yes
Ogallala aquifer	135.29	0.900	145.19	yes

reliable, but the scale of the determinations in both cases is excessively large compared to the distribution of the resource and its uses. Averages therefore tend to smooth out the very real differences within regions and paint the depleted, endangered, and relatively "safe" parts of the aquifer with the same brush. These results tend to support the need for developing appropriate techniques for classifying management and planning subunits of the larger regions. The challenge inherent in this is that our data bases put limits on the degree of local detail or precision that we can apply at smaller scales.

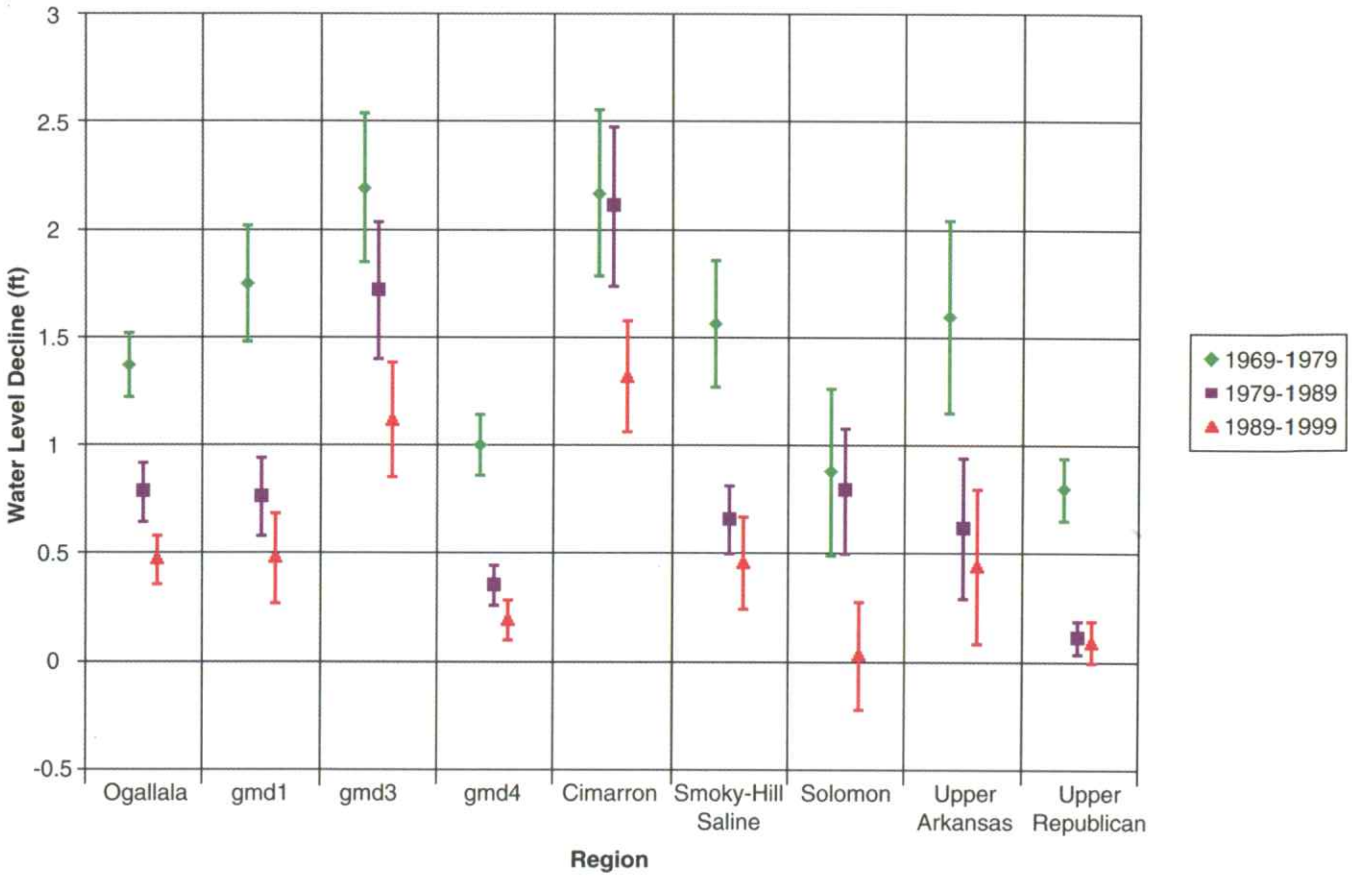


FIGURE 38—Average annual rates (ft/yr) of water-level change by region for the past three decades (1969–1979, 1979–1989, and 1989–1999). The central points are the average values, and the vertical lines represent an uncertainty of one standard deviation—the range that can be expected to include about 66% of all of the measurements for that period and region.

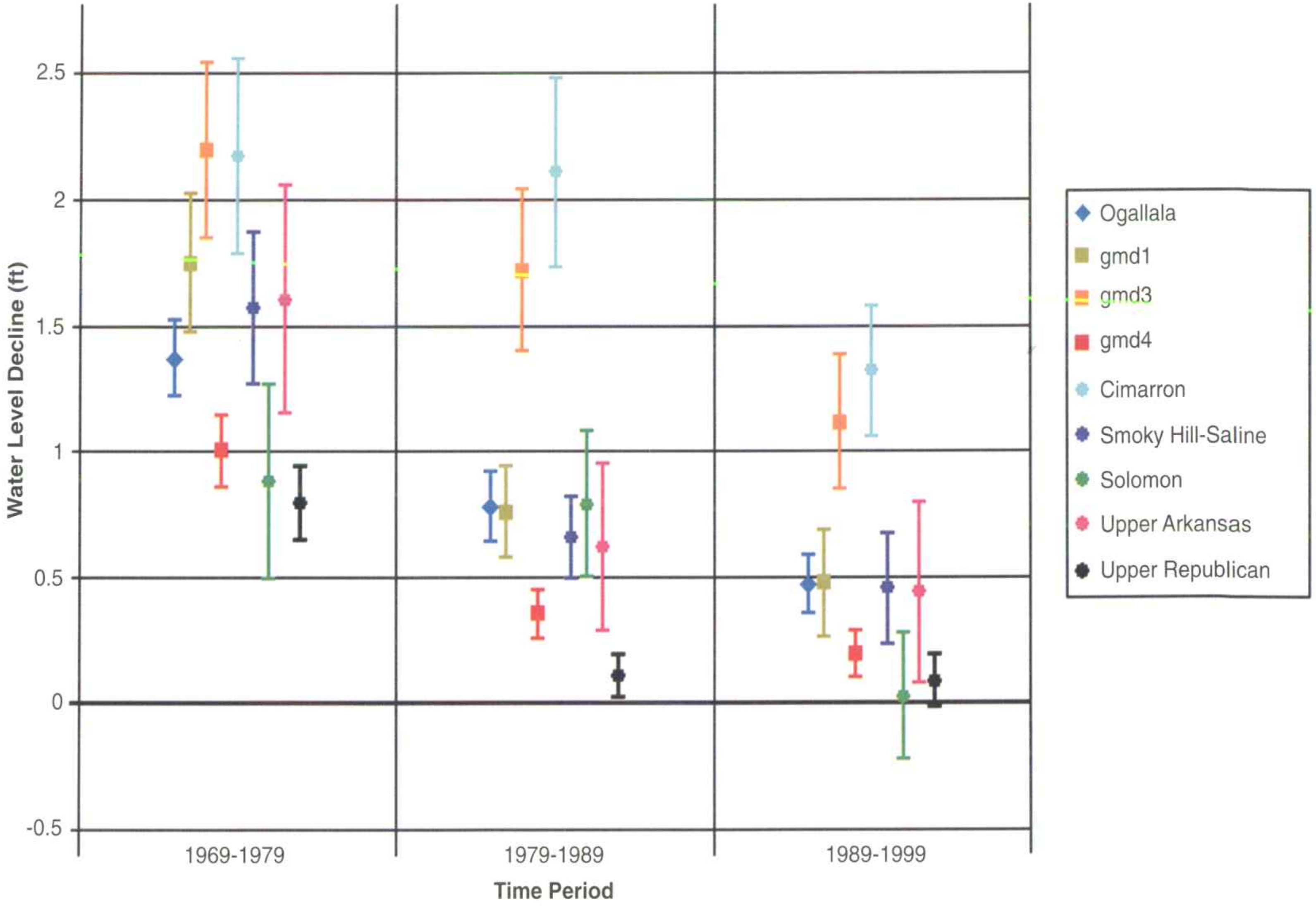


FIGURE 39a— Time series of average annual water-level decline rates (ft/yr) for the Ogallala aquifer regions. Data of fig. 39a replotted to show time course of change. For presentations of the data in figs. 39b and 39c separated by GMDs and basins, see http://www.kgs.ukans.edu/HighPlains/atlas/wldecfig.htm.

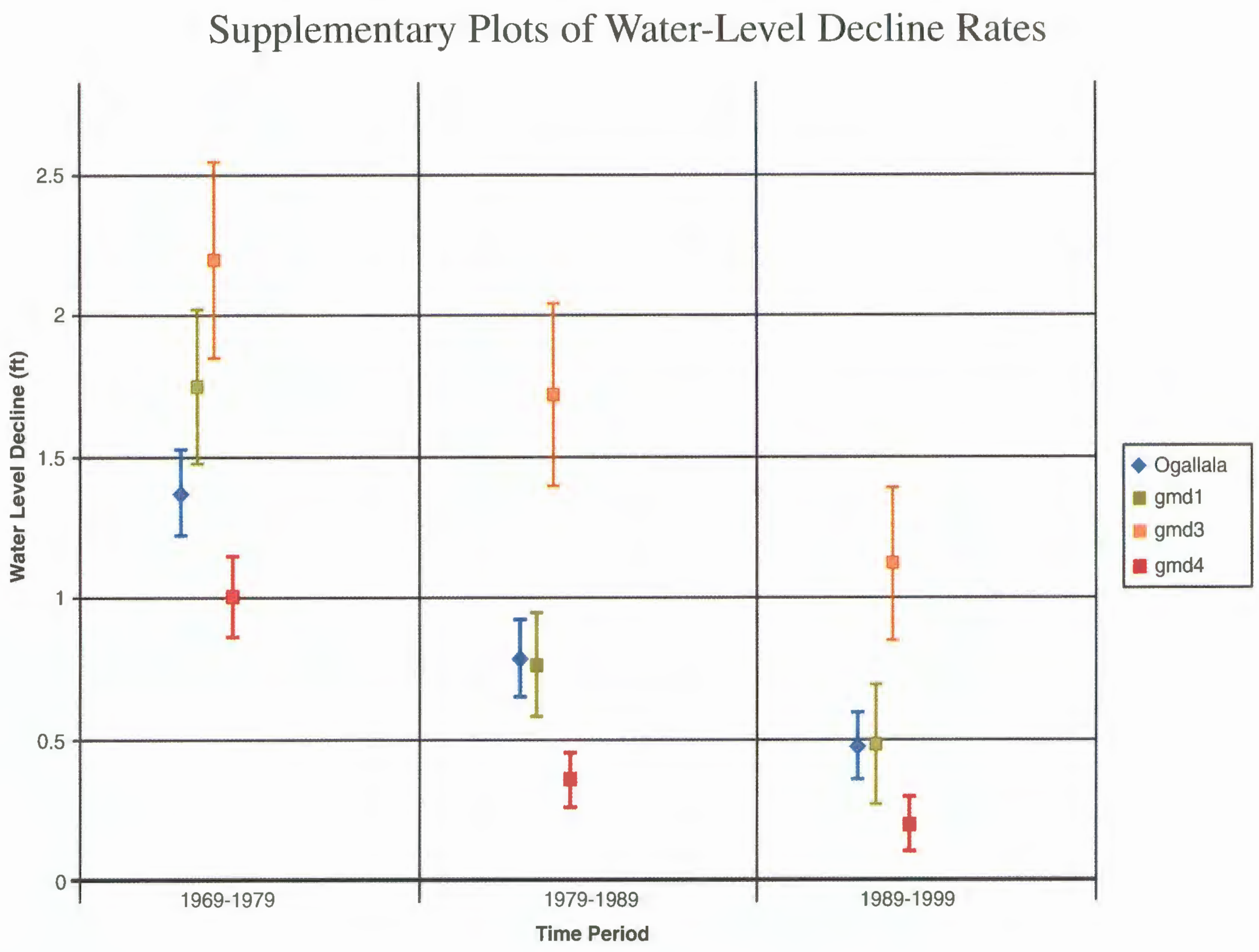


FIGURE 39b—Annual rate of decline (ft/yr) by decade for the Ogallala aquifer and Groundwater Management Districts (see introductory map [fig. 1] for location of regions).

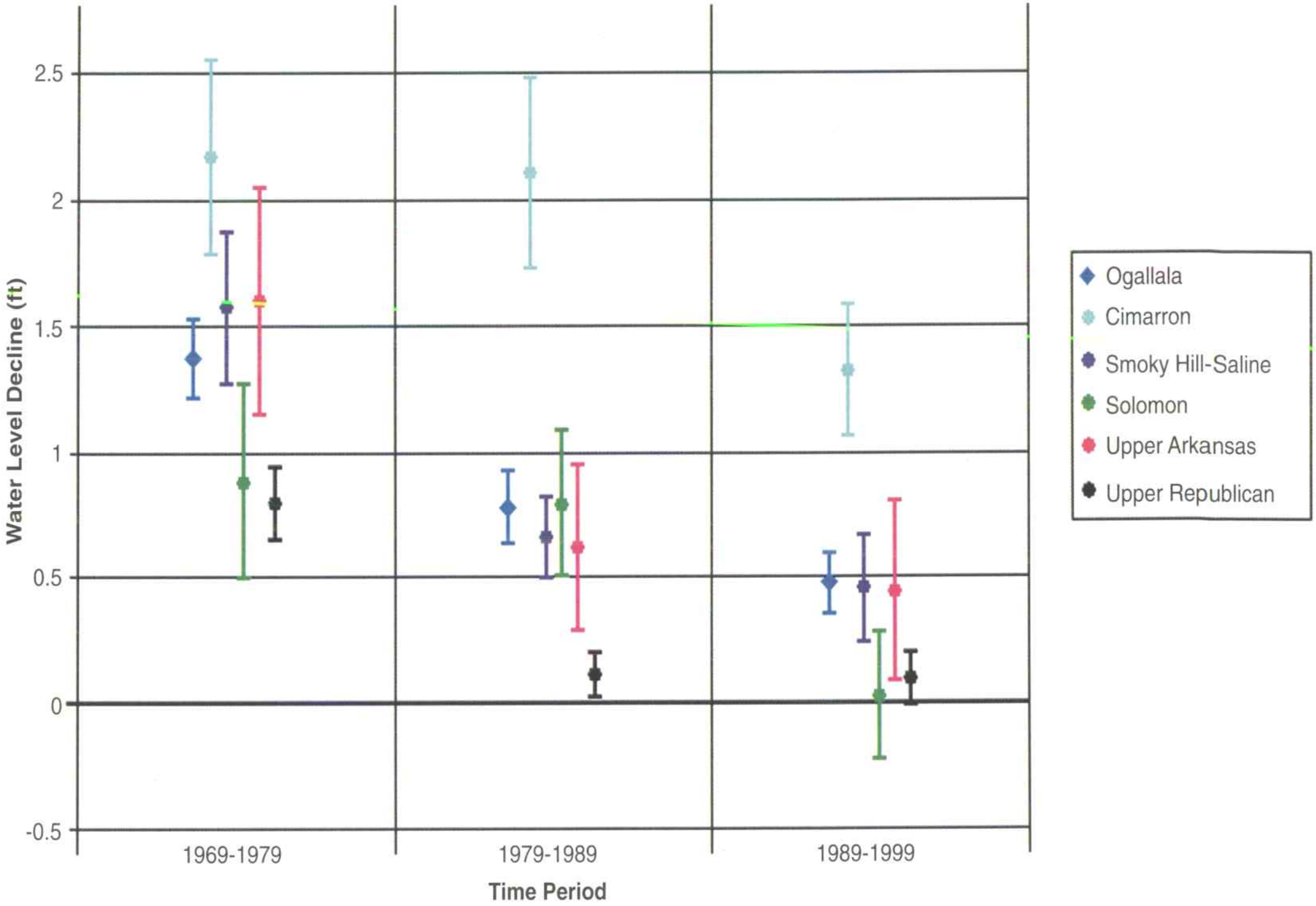


FIGURE 39c—Annual rate of decline (ft/yr) by decade for Ogallala aquifer and river basin areas (see introductory map [fig. 1] for location of regions).

High Plains Aquifer Atlas—Information Appendix 7

Glossary

A

ACRE-FOOT—The volume of water necessary to cover one acre to a depth of one foot. Equal to 43,560 cubic feet or 325,851 gallons, or 1,233 cubic meters.

ADJUDICATION—Judicial process to determine the extent and priority of the rights of all persons to use water in a river or aquifer system.

AGRICULTURAL DROUGHT—*See* DROUGHT.

ALLUVIAL AQUIFER—An aquifer formed by material laid down by physical processes in a stream channel or on a floodplain.

ALLUVIAL PLAIN—A level, gently sloping, or slightly undulating land surface produced by extensive deposition of alluvium, usually adjacent to a stream that periodically overflows its banks.

ALLUVIUM—Unconsolidated clay, silt, sand, or gravel deposited during Recent geologic time by running water in the bed of a stream or on its floodplain.

ANALYTICAL MODEL—Model that uses closed-form mathematical solutions to the governing equations applicable, for example, to ground-water flow and transport processes.

APPROPRIATION—Under Kansas law, this is the right to use water for a beneficial use or the acquisition of such a right gained through the process of diverting water and putting it to a beneficial use.

APPROPRIATIVE RIGHTS—Appropriative water rights, generally found in western states, are created by diversion of water and putting it to beneficial use. Appropriative water rights have a priority based on the date of first usage. In times of shortage, junior appropriators are cut off while senior appropriators receive their full allotment.

AQUICLUDE—An impermeable layer of rock that does not allow water to move through it. Some shales, for example, have such low permeability that they effectively form an aquiclude.

AQUIFER—A geologic formation (or one or more geologic formations) that is porous enough and permeable enough to transmit water at a rate sufficient to feed a spring or a well. An aquifer transmits more water than an aquitard. Sandstone beds and the Ogallala Formation are some of the best water-producing layers in Kansas and are used extensively for private and municipal water supplies.

AQUIFER (HYDRAULIC) DIFFUSIVITY—Ratio of aquifer transmissivity to storativity (or hydraulic conductivity to specific storage); it indicates how fast a transient change in head will be transmitted throughout the aquifer system.

AQUIFER SYSTEM—Heterogeneous body of interbedded permeable and poorly permeable material that functions regionally as a water-yielding unit; it comprises two or more permeable beds separated at least locally by confining beds that impede vertical ground-water movement but do not greatly affect the regional hydraulic continuity of the system; includes both saturated and unsaturated parts of permeable materials.

AQUIFER YIELD—Maximum rate of withdrawal that can be sustained by an aquifer. *See* YIELD.

AQUIFUGE—Body of earth material which is impervious to water and unabsorbtive.

AQUITARD—A part of a geologic formation (or one or more geologic formations) that is of much lower permeability than an aquifer and will not transmit water at a rate sufficient to feed a spring or for economic extraction by a well.

ARID—Said of a climate characterized by dryness, variously defined as rainfall insufficient for plant life; less than 10 inches (254 mm) of annual rainfall.

ARTESIAN AQUIFER—An aquifer in which ground water is confined under pressure significantly greater than atmospheric pressure. This pressure, called artesian pressure, generally is due to the weight of water at higher levels in the same zone and is sufficient to cause water to rise above the level of the aquifer in a well or natural fissure. An artesian aquifer is bounded above and below by confining beds of less-permeable rock. *Synonym*: confined aquifer.

ARTESIAN GROUNDWATER—*See* CONFINED GROUND WATER.

ARTESIAN WELL or ARTESIAN SPRING—A well or spring that taps ground water under pressure beneath an aquifuge or aquiclude so that water rises (though not necessarily to the surface) without pumping. If the water rises above the surface, it is known as a flowing artesian well.

ARTIFICIAL RECHARGE—Deliberate act of adding water to a ground-water aquifer by means of a recharge project, also the water so added. Artificial recharge can be accomplished via injection wells, spreading basins, or in-stream projects.

ATMOSPHERE—(1) The gaseous portion of the planet. (2) Standard unit of pressure representing the pressure exerted by a 29.92-inches (760-mm) column of mercury at sea level at 45 degrees latitude and equal to 14.696 pounds per square inch (psi) or 101.325 kilopascals (An).

AVAILABLE MOISTURE (OR MOISTURE)—Portion of water in a soil that can be absorbed by plant roots. It is the amount of water released from a wet soil between field capacity and the permanent wilting percentage.

B

BANK STORAGE—Change in storage in an aquifer resulting from a change in stage of an adjacent surface-water body.

BASEFLOW (OR BASE FLOW)—Streamflow derived mainly from ground-water seepage into the stream.

BASEFLOW NODE—Artificial point located in the channel centerline of a stream for the purpose of allocating a proportional amount of the baseflow to be considered when evaluating a new application in Kansas Groundwater Management Districts 2 (Equus Beds) and 5 (Big Bend) to appropriate water from a proposed point of diversion located within 2 miles of the node.

BASE LEVEL—In general, the lowest point in the water table in a given area. Water in the area flows toward this destination by gravity and hydrostatic pressure.

BASE MAP—A map that shows only essential geographic references (such as roads, towns, section lines, etc.) on which additional information is plotted: for example, a topographic map on which geologic information is recorded.

BASIN—*See* DRAINAGE BASIN.

BASIN YIELD—Maximum rate of withdrawal that can be sustained by the complete hydrogeologic system in a basin without causing unacceptable declines in hydraulic head anywhere in the system or causing unacceptable changes to any other component of the hydrologic cycle in the basin. *See* YIELD.

BED—A layer of rock in the earth. Also the bottom of a body of water such as a river, lake, or sea.

BEDROCK—The solid rock that underlies any unconsolidated sediment or soil. Limestone and sandstone are common types of bedrock in Kansas. Most Kansas bedrock is in formations of Cretaceous age or older.

BENEFICIAL USE—Use of water, such as domestic, municipal, agricultural, mining, industrial, stockwatering, recreation, wildlife, artificial recharge, power generation, or contamination remediation, that provides a benefit. Water rights not put to beneficial use are subject to forfeiture. Historically, very few uses of water have been declared nonbeneficial by courts.

BICARBONATE—The anionic constituent HCO_3 that has a single negative charge as dissolved in water. Nearly all of the alkalinity in water is composed of bicarbonate. An alkalinity value (reported as mg/L $CaCO_3$) for a water can be converted to the equivalent bicarbonate concentration in mg/L by multiplying by 1.219.

BOUNDARY CONDITION—Mathematical expression of a state of the physical system that constrains the equations of the mathematical model.

BRACKISH WATER—*See* SALINE WATER.

BRINE—Highly salty water, commonly with more than 10,000 milligrams per liter of chloride. In parts of Kansas, ground water may be naturally salty. Brine also is regularly produced along with oil in Kansas.

C

CALCITE—The mineral calcium carbonate ($CaCO_3$). It is the main component of limestone and one of the most common minerals in Kansas.

CALCIUM—The element Ca that occurs as a cation with a double positive charge when dissolved in water; the major dissolved constituent constituting hardness in water.

CALCIUM-BICARBONATE TYPE—The most common chemical type of freshwater in Kansas; the constituents with the largest concentrations in this type of water are calcium (Ca) and bicarbonate (HCO_3).

CALIBRATION (model application)—Process of refining the model representation of the hydrogeologic framework, hydraulic properties, and boundary conditions to achieve a desirable degree of correspondence between the model simulation and observations of the ground-water system.

CAPILLARY FRINGE—Unsaturated zone immediately above the water table containing water in direct contact with the water table.

CAPILLARY POTENTIAL—*See* SOIL-WATER POTENTIAL.

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

CARBONATE—The anionic constituent CO_3 that has two negative charges as dissolved in water or present in a mineral.

CERTIFICATION—The process whereby a permit to appropriate water is completed into final form based on the completion of the diversion work and past application of water to the proposed use in accordance with the approved water-right application. A certified water right has a legal, State-issued document that establishes a priority date, type of beneficial use, and the maximum amount of water that can be used annually.

CHLORIDE—The anionic form of the element chlorine (Cl) that has a single negative charge as dissolved in water.

CLAY—A very fine grained material, smaller than silt (clay has a diameter of less than 1/256 mm). Clay is formed by the weathering and breaking down of rocks and minerals.

CONE OF DEPRESSION—A cone-shaped depression in the water table around a well or a group of wells. The cone is created by withdrawing ground water more quickly than it can be replaced.

CONFINED AQUIFER—An aquifer that is bounded above and below by confining layers. Because of the pressure created in a confined aquifer, the water level in a well drilled into a confined aquifer will rise above the top of the aquifer and, in some instances, above the land's surface.

CONFINED GROUND WATER—Ground water lying beneath an aquiclude or an aquifuge. Confined ground water is artesian if the water levels in wells are above the top of the aquifer.

CONFINING BED—A layer of relatively impermeable (i.e., incapable of transmitting fluids) material overlying an aquifer.

CONGLOMERATE—Rock that consists of nonsorted, cemented particles usually containing sand and gravel. Resembles concrete.

CONJUNCTIVE OPERATION OR USE—Operation of a ground-water basin in coordination with a surface-water system. Often the purpose is to artificially recharge the basin during years of above-average precipitation so that the water can be withdrawn during years of below-average precipitation, when surface supplies are below normal.

CONSERVATION—Management of water resources so as to eliminate waste or maximize efficiency of use.

CONSERVATION STORAGE—Storage of water in a reservoir for later release for useful purposes such as municipal and industrial water supply, water quality, or irrigation.

CONSUMPTIVE USE—Use that makes water unavailable for other uses, usually by permanently removing it from local surface or ground-water storage as the result of evaporation and/or transpiration. Does not include evaporation losses from bodies of water.

CONTACT SPRING—A type of gravity spring whose water flows to the land surface from permeable rocks that are underlain by less-permeable rocks, preventing the downward movement of water.

CONTAMINANT PLUME—Zone of polluted ground water downgradient from a point source of pollution.

CUBIC FOOT PER SECOND (cfs)—Rate of discharge representing a volume of one cubic foot (28.317×10^{-3} m^3) passing a given point during 1 second. This rate is equivalent to approximately 7.48 gallons (0.0283 m^3) per second.

CURRENT METER—Device for measuring water velocity consisting of a propeller that turns at a rate dependent on the water velocity.

D

DARCY's EQUATION or LAW—Formula stating that the flow rate of water through a porous medium is proportional to the hydraulic gradient. The factor of proportionality is the hydraulic conductivity.

DEAD-STORAGE RESERVES—*See* GROUND-WATER STORAGE RESERVES.

DEPLETION TIME—Time indicating how long it would take the watershed or the ground-water system to dry out if surface runoff or ground-water replenishment (recharge) were stopped from the instant t onward and if outflow was maintained at the rate it had at that instant. The depletion time is defined as $V(t)/Q(t)$, where $V(t)$ equals volume of water stored and $Q(t)$ equals outflow at time t. Depletion times of surficial waters usually are of the order of hours to weeks. They may run into months or years if the river basin includes large lakes. Depletion times of aquifers are usually of the order of tens to hundreds, and often thousands of years. As a consequence, rivers react quickly to precipitation and to the abstraction of water, whereas ground-water systems react very sluggishly to these events.

DEPTH TO WATER—The depth of the water table below the earth's surface.

DISCHARGE—Movement of ground water from the subsurface to the land surface, usually from a spring or to a marsh, river, or stream.

DISCHARGE AREA—An area where ground water is lost naturally from an aquifer through springs, seeps, or hydraulic connection to other aquifers. The water leaving the aquifer is called discharge.

DISSOLUTION—*See* SOLUTION.

DIVERSION—Physical removal of surface water from a channel. Also the act of bringing water under control by means of a well, pump, or other device for delivery and distribution for a proposed use.

DIVIDE (DRAINAGE DIVIDE)—Boundary between one drainage basin and another.

DOMESTIC USE—Water used for drinking and other purposes by a household such as from a rural well.

DOWNGRADIENT—In reference to the movement of ground water, the "downstream" direction from a point of reference (e.g., a well).

DRAINAGE AREA—Of a stream at a specified location is that area, measured in a horizontal plane, enclosed by a topographic divide from which direct surface runoff from precipitation normally drains by gravity into the stream above the specified location.

DRAINAGE BASIN—Hydrologic unit consisting of a part of the surface of the earth covered by a drainage system made up of a surface stream or body of impounded surface water plus all tributaries. The runoff in a drainage basin is distinct from that of adjacent areas. A river basin is similarly defined.

DRAWDOWN—Lowering of the ground-water surface or the piezometric pressure caused by pumping, measured as the difference between the original ground-water level and the current pumping level after a period of pumping.

DROUGHT—(1) Iinterval of time, generally of the order of months or years in duration, during which the actual moisture supply at a given place rather consistently falls short of the climatically expected or climatically appropriate moisture supply (meteorological drought); (2) a condition that occurs only when available soil moisture is inadequate to meet evaporative demand by plants (agricultural drought); (3) a period of below-normal streamflow (hydrological drought).

E

EFFLUENT—Any substance, particularly a liquid, that enters the environment from a point source. Generally refers to wastewater from a sewage-treatment or industrial plant.

EFFLUENT STREAM—Stream or reach of a stream whose flow is being increased by inflow of ground water. A gaining stream.

ELEVATION HEAD—*See* HYDRAULIC HEAD.

EPHEMERAL FLOW—When water flows in a channel only after precipitation.

EQUUS BEDS—The sediments containing an important source of ground water in parts of Harvey, McPherson, Reno, and Sedgwick counties. The Wichita municipal well field is located in the Equus Beds.

EVAPORATION—Process of liquid water becoming water vapor, including vaporization from water surfaces, land surfaces, and snow fields, but not from leaf surfaces. Compare with transpiration.

EVAPOTRANSPIRATION—A collective term for water that moves into the atmosphere from evaporation from land or water and from transpiration from plants.

F

FIRM YIELD—*See* SAFE YIELD.

FLOODPLAIN—Land bordering a stream, built up of sediments from overflow of the stream and subject to inundation when the stream is at flood stage.

FLOW-DURATION CURVE—Graph of stream discharge versus the percentage of time that the flow exceeds that stream discharge.

FLOWING ARTESIAN WELL—*See* ARTESIAN WELL.

FLUX—Refers to the rate of flow; it is the quantity of material or energy transferred through a system or a portion of a system in a unit time and is called mass flux. If the moving matter is a fluid, the flux may be measured as volume of fluid moving through a system in a unit time and is called volume flux. For most applications, we desire to know the flux per unit area of a system rather than the flux of the entire system; the flux per unit area is called the flux density.

FLUX DENSITY—*See* FLUX.

FREE GROUND WATER—Unconfined ground water whose upper surface is a free water table.

FRESHWATER—Water containing only small quantities (generally less than 1,000 milligrams per liter) of dissolved materials.

G

GAGING STATION—Site on a stream, lake, reservoir, or other body of water where direct systematic observations of hydrologic data are obtained.

GAINING STREAM—A stream that receives ground-water discharge from the zone of saturation.

GRAVEL PACK—Coarse sand and gravel placed in the annular space between the borehole and the well casing in the vicinity of the well screen. The purpose of the gravel pack is to minimize the entry of fine sediment into the well, stabilize the borehole, and allow the flow of ground water into the well.

GRAVITATIONAL POTENTIAL—*See* SOIL-WATER POTENTIAL.

GREAT BEND PRAIRIE—The area south of the big bend in the Arkansas River; the region includes Stafford and Pratt counties and parts of Barton, Edwards, Kingman, Kiowa, Pawnee, Rice, and Reno counties.

GROUND WATER—Underground water that generally is found in the pore space of rocks or sediments and that can be collected with wells, tunnels, or drainage galleries, or that flows naturally to the earth's surface via seeps or springs.

GROUND-WATER BASIN—Geologically and hydrologically defined area that contains one or more aquifers that store and transmit water and will yield significant quantities of water to wells.

GROUND-WATER-FLOW MODEL—Application of a mathematical model to represent a site-specific ground-water-flow system.

GROUND-WATER-FLOW SYSTEM—Set of ground-water-flow paths with common recharge and discharge areas. Flow systems are dependent on both the hydrogeologic characteristics of the soil/rock material and landscape position. Areas of steep or undulating (hummocky) relief tend to have dominant local-flow systems (discharging in nearby topographic lows such as a pond or stream). Areas of gently sloping or nearly flat relief tend to have dominant regional-flow systems (discharging at much greater distances than local systems in major basin topographic lows or oceans.)

GROUND-WATER HYDROGRAPH—*See* HYDROGRAPH.

GROUND-WATER MINING—Pumping ground water from a basin at a rate that exceeds safe yield, thereby extracting ground water that had accumulated over a long period of time.

GROUND-WATER OVERDRAFT—Pumpage of ground water for consumptive use in excess of safe yield.

GROUND-WATER STORAGE—(1) Quantity of water in the saturated zone, or (2) water available only from the storage as opposed to capture.

GROUND-WATER-STORAGE RESERVES—Sum of live and dead storage reserves; live storage reserves are situated above the aquifer outlet or discharge area and can be depleted by natural discharge drainage and also recovered by pumping; dead storage reserves can be recovered only by pumping after the live reserves have been exhausted.

H

HARD WATER—*See* HARDNESS.

HARDNESS—(1) Water-quality parameter that indicates the level of alkaline salts, principally calcium and magnesium, and expressed as equivalent calcium carbonate ($CaCO_3$). Hard water is commonly recognized by the increased quantities of soap, detergent, or shampoo necessary to lather. (2) In mineralogy, the degree of hardness of a mineral is an aid in identification. Geologists have assigned numbers to the hardness of several minerals; in this hardness scale, softer minerals are assigned a low mineral and the harder minerals a higher number.

HEAD—*See* HYDRAULIC HEAD.

HEAD LOSS— *See* HYDRAULIC HEAD.

HECTARE (ha)—One hectare equals 2.47 acres. One square kilometer equals 100 hectares. One square mile equals 259 hectares.

HETEROGENEOUS—Material property that varies with the location within the material. *See also* HOMOGENEOUS.

HIGH PLAINS AQUIFER—In Kansas, three hydraulically connected but distinct aquifers: the Ogallala, Great Bend Prairie, and Equus Beds aquifers. In general, the Ogallala Formation is made up of unconsolidated sand, gravel, silt, and clay deposited by streams that flowed east from the Rocky Mountains during the Miocene Epoch. The Great Bend Prairie and Equus Beds aquifers also are composed of silt, clay, and gravel deposits left by streams flowing through central Kansas, but these deposits are generally younger (Pleistocene and Holocene) than the Ogallala. In some areas, these aquifers are in contact with each other and thus form one continuous aquifer.

HOMOGENEOUS—Material is homogeneous if its hydrologic properties are identical everywhere.

HYDRAULIC CONDUCTIVITY—Factor of proportionality in Darcy's equation relating flow velocity to hydraulic gradient having units of length per unit of time. A property of the porous medium and the fluid (water content of the medium.

HYDRAULIC CONTINUITY—Property of the rock framework on a given time scale whereby a change in hydraulic head in any point of the region can cause a head change in any other point of the same region by means of pressure transfer through the rock pores and within a time interval measurable at that time scale.

HYDRAULIC GRADIENT—Slope of the water table or potentiometric surface. The change is static head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

HYDRAULIC HEAD or (STATIC) HEAD—Height that water in an aquifer can raise itself above an (arbitrary) reference level (or datum) and is generally measured in feet. When a borehole is drilled into an aquifer, the level at which the water stands in the borehole (measured with reference to a horizontal datum such as sea level) is, for most purposes, the hydraulic head of water in the aquifer. This term defines how much energy water possesses. Ground water possesses energy mainly by virtue of its elevation (elevation head) and of its pressure (pressure head). *See also* HYDROSTATIC HEAD. When ground water moves, some energy is dissipated and therefore a head loss occurs.

HYDRAULIC POTENTIAL—*See* SOIL-WATER POTENTIAL.

HYDRAULICALLY CONNECTED—A condition in which ground water moves easily between aquifers that are in direct contact. An indication of this condition is that the water levels in both aquifers are approximately equal.

HYDROGEOLOGY—The study of ground water and its relationship to geology. Also sometimes known as geohydrology.

HYDROGRAPH—Graph showing stage, flow, velocity, or other characteristics of water with respect to time. A stream hydrograph commonly shows rate of flow; a ground-water hydrograph shows water level or head.

HYDROLOGIC BUDGET OR BALANCE—Accounting of the inflow to, outflow from, and storage in a hydrologic unit such as a drainage basin, aquifer, soil zone, lake, or reservoir; the relationship between evaporation, precipitation, runoff, and the change in water storage, expressed by the hydrologic equation.

HYDROLOGIC CYCLE—The complete cycle that water can pass through, beginning as atmospheric water vapor, turning into precipitation and falling to the earth's surface, moving into aquifers or surface water, and then returning to the atmosphere via evapotranspiration.

HYDROLOGIC EQUATION—Equation that balances the hydrologic budget.

HYDROLOGICAL DROUGHT—*See* DROUGHT.

HYDROLOGY—The study of the characteristics and occurrence of water, and the hydrologic cycle. Hydrology concerns the science of surface water and ground water, whereas hydrogeology principally focuses on ground water.

HYDROSTATIC HEAD—Height above a standard datum of the surface of a column of water or other liquid that can be supported by the (hydro) static pressure at a given point.

HYDROSTATIC PRESSURE—Pressure exerted by water at any given point in a body of water at rest.

I

INDUCED INFILTRATION OR INDUCED RECHARGE—Recharge to ground water by infiltration, either natural or human-made, from a body of surface water as a result of the lowering of the ground-water hydraulic head below the surface-water level.

INDUSTRIAL USES—Water used for a wide range of purposes by industries, including cooling water for electrical-power generation, manufacturing, food preparation, washing of wastes, etc. The quality needed ranges substantially depending on the use.

INFILTRATION (SOIL)—Movement of water from the ground surface into the soil.

INFLUENT STREAM—Stream or reach of stream that loses water into the ground. Also known as a losing stream.

INJECTION WELL—Well used for injecting water or other fluid into a ground-water aquifer. *See also* ARTIFICIAL RECHARGE.

INORGANIC—Not made of or derived from living matter. Minerals are inorganic.

INSTREAM USE—Use of water that does not require withdrawal or diversion from its natural watercourse; for example, the use of water for navigation, recreation, and support of fish and wildlife.

INSURGENCE—A sinkhole opening that permits flowing surface water to be captured and transported underground, to later reemerge as a spring (resurgence). Includes piracy openings.

INTERBASIN TRANSFER—Physical transfer of water from one watershed to another.

INTERFLOW—*See* UNDERFLOW.

INTERMITTENT FLOW—Surface water flowing only during periods of seasonal runoff.

INTERRUPTED FLOW—Water flowing alternatively on the channel surface in some stream stretches and disappearing underground in others.

INTRINSIC PERMEABILITY—Quantitative measure of fluid-transmitting ability of a porous medium that is related to the size and interconnectedness of the void openings. *See also* PERMEABILITY.

INTRUSION OF SALTWATER—The movement of saltwater from bedrock into the overlying aquifer, as in the High Plains or alluvial aquifer. The source of the saltwater is dissolution of rock salt in Permian rocks in the subsurface.

IRRIGATION USE—Water applied to the soil surface by center pivots, ditches, or other means, or to the soil subsurface by tubes to add to the water available for plant growth.

ISOTROPIC—Said of a medium whose properties are the same in all directions. *See* ANISTROPY.

J

JUNIOR APPROPRIATOR—Holder of a surface- or ground-water right that was acquired subsequent to other water rights on the same stream or aquifer.

K

KANSAS WATER APPROPRIATION ACT—Act that established the general principle that all water within the state is dedicated to the use of the people of the state subject to the control and regulations of the state as set forth in the act. The law provides that water appropriated must be put to beneficial use, and that among appropriators, the first one in time should be the first in right. This act was enacted on June 28, 1945.

KARST—A terrain or type of topography generally underlain by soluble rocks, such as limestone, gypsum, and dolomite, in which the topography is chiefly formed by dissolving the rock; karst is characterized by sinkholes, depressions, caves, and underground drainage.

KARST WINDOW—A sinkhole by which an underground stream can be observed and studied.

KDA—Kansas Department of Agriculture. The main offices of the KDA, including the Division of Water Resources, are in downtown Topeka.

KDHE—Kansas Department of Health and Environment. The main offices of the Division of Environment and laboratories of KDHE are currently at Forbes Field in Topeka.

L

LACUSTRINE—Pertaining to or formed in a lake or lakes.

LIMESTONE—Composed mainly of calcium carbonate ($CaCO_3$), it is one of the most common rocks in the state. Like most of the rocks found at the surface in the state, it is a sedimentary rock.

LITHOLOGY—(1) The description of rocks on the basis of physical characteristics, such as color and mineral composition. (2) The physical character of a rock.

LIVE STORAGE RESERVES—*See* GROUND-WATER-STORAGE RESERVES.

LOCAL FLOW SYSTEM—*See* GROUND-WATER-FLOW SYSTEM.

LOESS—Nonstratified sediment composed of silt-sized particles deposited by the wind. These windblown dust deposits were derived from glacial materials. Loess is found throughout Kansas but is especially common in the northeastern and northwestern parts of the state.

LOSING STREAM—A stream that contributes water to the zone of saturation, recharging the ground water.

M

MAGNESIUM—The element Mg that occurs as a cation with a double positive charge in water; along with calcium, it constitutes hardness in water.

MAJOR DISSOLVED CONSTITUENTS—The substances in largest concentration that are dissolved in typical Kansas waters are calcium, magnesium, sodium, bicarbonate, chloride, sulfate, and silica, although nitrate can sometimes be a major constituent.

MARINE—Relating to the sea. Native to or formed by the sea.

MASS FLUX—*See* FLUX.

MATHEMATICAL MODEL—Mathematical equations expressing the physical system and including simplifying assumptions. The representation of a physical system by mathematical expressions from which the behavior of the system can be predicted.

MATRIC POTENTIAL—*See* SOIL-WATER POTENTIAL.

MAXIMUM CONTAMINANT LEVEL (MCL)—Maximum level of a contaminant allowed in water by Federal law. Based on health effects and currently available treatment methods.

MESIC ENVIRONMENT—Habitat with a moderate amount of water.

METEOROLOGICAL DROUGHT—*See* DROUGHT.

METEOROLOGY—*See* ATMOSPHERE.

METRIC TON—1,000 kilograms (kg). One metric ton = 1.1 U.S. (or short) ton.

MICROMHOS PER CENTIMETER (mmhos/cm)—*See* SPECIFIC CONDUCTANCE.

MILLIGRAMS PER LITER (mg/L)—Milligrams of a substance dissolved in one liter of water. The value is essentially the same as a part per million in freshwater because one liter of distilled water weighs one million milligrams (one kilogram).

MINERAL INTRUSION—Movement of water from an aquifer containing mineralized or salty water into a freshwater stream, lake, or aquifer.

MINIMUM DESIRABLE STREAMFLOWS (MDS)—Under Kansas water law, streamflows that maintain or preserve instream uses of water quality, fish, wildlife, aquatic life, recreation, and aesthetics from unacceptable stream depletions by future consumptive appropriations. Minimum desirable streamflows will not be preferred to vested and senior appropriation rights filed prior to their enactment nor will they be maintained through all drought conditions.

MINING—As it pertains to water, the process, deliberate or inadvertent, of extracting ground water from a source at a rate so that the ground-water level declines persistently, threatening actual exhaustion of the supply.

MISFIT RIVER—River that appears to be too small for its present valley. This may be because its head waters have been captured and so are reduced, a change of climate has occurred and the amount of water has decreased, or the valley has been enlarged by glaciation. Sometimes known as an underfit river.

MODEL—Assembly of concepts in the form of mathematical equations that portray understanding of a natural phenomenon.

MODELING—Investigative technique that uses a mathematical or physical representation of a system or theory that accounts for all or some of its known properties. Models are often used to test the effects of changes of system components on the overall performance of the system.

MONITORING WELL—Nonpumping well used primarily for drawing water-quality samples; also for measuring ground-water levels.

N

NATURAL RECHARGE—Naturally occurring water added to an aquifer. Natural recharge generally comes from snowmelt and precipitation or storm runoff.

NONCONSUMPTIVE USE—Use that leaves the water available for other uses. Examples are hydroelectric power generation and recreational uses.

NONPOINT SOURCE—Source of water pollution that originates from a broad area, such as agricultural chemicals, applied to fields, or acid rain.

NORMAL—Average value of a meteorological variable (such as precipitation or temperature) over a fixed period of years, usually recognized as standard. In the United States, 30-year normals are frequently used.

NUMERICAL METHODS—Set of procedures used to solve the equations of a mathematical model in which the applicable partial differential equations are replaced by a set of algebraic equations written in terms of discrete values of stated variables at discrete points in space and time. There are many numerical methods. Those in common use in ground-water models are the finite-difference method, the finite-element method, the boundary-element method, and the analytical-element method.

NUMERICAL MODEL—Model that uses numerical methods to solve the governing equations of the applicable problem.

O

OBSERVATION WELL—Nonpumping well used primarily for observing the elevation of the water table or the piezometric pressure; also to obtain water-quality samples. *See* MONITORING WELL.

OPEN SYSTEM—System in which energy and matter are exchanged between the system and its environment, for example, a living organism. Compare closed system, isolated system.

OSMOTIC POTENTIAL—*See* SOIL-WATER POTENTIAL.

OUTPUT—Modeling, all information that is produced by the computer code.

OVERDRAFT—(1) Pumping of ground water for consumptive use in excess of safe yield; (2) the condition of a ground-water basin where the amount of water withdrawn exceeds the amount of water captured over the basin over a period of time. The use of water in excess of the perennial yield.

P

PARTS PER BILLION (ppb)—Micrograms per liter; one-one thousandth of milligrams per liter.

PARTS PER MILLION (ppm)—*See* MILLIGRAMS PER LITER.

PERCHED WATER TABLE—Water table of a relatively small ground-water body lying above the general ground-water body.

PERCHING HORIZON—A relatively impermeable (i.e., incapable of transmitting fluids) lens or layer of clay or bedrock in otherwise permeable sediments that slows or prevents the downward movement of water.

PERCOLATION—Laminar-gravity flow through unsaturated and saturated earth material.

PERENNIAL FLOW—Year-round flow.

PERENNIAL YIELD—Maximum quantity of water that can be withdrawn annually from a ground-water supply under a given set of conditions without causing an undesirable result.

PERFECT (verb)—Under Kansas water law, the actions of a water user to bring an appropriation right into final form by the completion of diversion works and application of water to the proposed use in accordance with the approved water-right application.

PERMEABLE—Permeability is a measure of the ease with which a fluid will move through a porous material (e.g., sand and gravel or rock). A geologic unit is permeable if ground water moves easily through it.

PERMEABILITY—(1) Ability of a material (generally an earth material) to transmit fluids (water) through its pores when subjected to pressure or a difference in head. Expressed in units of volume of fluid (water) per unit time per cross section area of material for a given hydraulic head; (2) description of the ease with which a fluid may move through a porous medium; abbreviation of intrinsic permeability. It is a property of the porous medium only, in contrast to hydraulic conductivity, which is a property of both the porous medium and the fluid content of the medium.

pH—Measure of the relative acidity or alkalinity of water. Defined as the negative log (base 10) of the hydrogen ion concentration. Water with a pH of 7 is neutral; lower pH levels indicate an increasing acidity, while pH levels above 7 indicate increasingly basic solutions.

PHREATIC—Indicating the water-saturated zone below the water table. The phreatic zone is the area of the subsurface that is saturated with water.

PHREATIC ZONE—Same as zone of (ground-water) saturation. Was originally used to designate water in the upper part of the zone of saturation.

PHREATOPHYTE—Plant whose roots generally extend downwards to the water table and customarily feed on the capillary fringe. Phreatophytes are common in riparian habitats. Term literally means "well" plant or water-loving plant. Common examples in Kansas are salt cedar, cottonwoods, and willows.

PIEZOMETER—Small-diameter well open at a point or short length in the aquifer to allow measurement of hydraulic head at that point or short length.

PIEZOMETRIC PRESSURE—Pressure corresponding to the height to which water would rise in an observation well penetrating an aquifer.

PIEZOMETRIC SURFACE—Surface defined by a pressure head and position (elevation above a standard datum, such as sea level). For an unconfined aquifer, it is equal to the elevation of the water table. For a confined aquifer, it is equal to the elevation to which water would rise in a well penetrating and open to the aquifer. This term is now replaced by potentiometric surface.

PLANNING HORIZON—Range of time during which the system under study has to be operated. An aquifer with negligible annual recharge containing a million acre-feet (1.2335 km^3) of recoverable ground-water stocks has a zero sustainable yield if the planning horizon is infinite. For a 100-year-time (planning) horizon, the same aquifer has a 10,000 acre-foot sustainable yield; for a 10-year horizon, a 100,000 acre-foot sustainable yield.

PLUVIAL—Pertaining to precipitation.

POINT OF DIVERSION—Point at which water is diverted or withdrawn from a source of water supply.

POINT SOURCE—Source of pollution that originates from a single point, such as an outflow pipe from a factory.

POROSITY—Fraction of bulk volume of a material consisting of pore space. Porosity determines the capacity of a rock formation to absorb and store ground water.

POROUS—Geologically, this term describes rock that permits movement of fluids through small, often microscopic openings, much as water moving through a sponge. Porous rocks may contain gas, oil, or water.

POTENTIAL EVAPOTRANSPIRATION (PET)—Maximum amount of soil evaporation and transpiration from a well-irrigated crop for a given set of environmental conditions.

POTENTIAL GRADIENT—*See* SOIL-WATER POTENTIAL.

POTENTIOMETRIC SURFACE—Imaginary surface representing the static head of ground water and defined by the level to which water will rise in a well. The water table is a particular potentiometric surface.

PRECIPITATION—Water in some form that falls from the atmosphere. It can be in the form of liquid (rain or drizzle) or solid (snow, hail, sleet).

PRESSURE HEAD—*See* HYDRAULIC HEAD.

PRIOR APPROPRIATION—Doctrine for prioritizing water rights based upon dates of appropriation (“first in time, first in right”). Common for allocating water rights in the western United States.

PUBLIC SUPPLY—Water used for drinking and other purposes supplied to many people by a system operated by a city, housing unit, industry, etc.

Q

R

RATING CURVE—Plot of discharge as a function of gage height. Data for a rating curve are obtained by current meter measurements of discharge.

RECHARGE—The replenishment of ground water in an aquifer. It can be either natural, through the movement of precipitation into an aquifer, or artificial—the pumping of water into an aquifer.

RECHARGE AREA—A geographic area where water enters (recharges) an aquifer. Recharge areas usually coincide with topographically elevated regions where aquifer units crop out at the surface. In these areas infiltrated precipitation is the primary source of recharge. The recharge area also may coincide with the area of hydraulic connection where one aquifer receives flow from another adjacent aquifer.

REGIONAL-FLOW SYSTEM—*See* GROUND-WATER-FLOW SYSTEM.

REGULATED FLOW—Surface flow downstream from a dam or other flow-control structure.

RESERVOIR CAPACITY—Amount of water a surface reservoir is capable of storing.

RESERVOIR STORAGE—Water stored in a surface reservoir.

RESIDENCE TIME—Size of any specific reservoir or pool of mass (e.g., carbon) divided by the total flux of mass into or out of that pool.

RESURGENCE—A speleologic term for spring or the exit of ground water to the surface. Often refers to the downstream cave opening. An opening where flowing surface water enters the subsurface is known as an insurgence.

RETURN FLOW—Part of water that is not consumed and returns to its source or another body of water.

RETURN PERIOD—*See* RECURRENCE INTERVAL.

RIPARIAN—Of, or pertaining to, rivers and their banks.

RIPARIAN HABITAT—Natural home of plants and animals occurring in a thin strip of land bordering a stream or river. Dominant vegetation often consists of phreatophytes.

RIPARIAN RIGHTS—Surface-water rights assigned on the basis of land ownership along a stream reach common in the western United States.

RIVER BASIN—*See* DRAINAGE BASIN.

RISK ASSESSMENT—Evaluation of the potential for exposure to contaminants and the associated hazard.

RIVERINE SYSTEM—Entire river network, including tributaries, side channels, sloughs, intermittent streams, etc.

RUNOFF—Drainage or flood discharge that leaves an area as surface flow or as pipeline flow, having reached a channel or pipeline by either surface or subsurface routes. Generally, surface water entering river, lakes, or reservoirs.

S

SAFE YIELD—(1) Rate of surface-water diversion or ground-water extraction from a basin for consumptive use over an indefinite period of time that can be maintained without producing negative effects; (2) the annual extraction from a ground-water unit which will not, or does not, [i.] exceed the average annual recharge; [ii.] so lower the water table that permissible cost of pumping is exceeded; [iii.] so lower the water table as to permit intrusion of water of undesirable quality; or [iv.] so lower the water table as to infringe upon existing water rights; (3) the attainment and maintenance of a long-term balance between the amount of ground water withdrawn annually and the annual amount of recharge; (4) the maximum quantity of water that can be guaranteed from a reservoir during a critical dry period. Synonymous to firm yield.

SALINE WATER—Water containing more than 10,000 parts per million (ppm) of dissolved solids of any type. Brackish water contains between 1,000 and 10,000 ppm of dissolved solids.

SALINITY—The total quantity of dissolved salts in water, usually measured by weight in milligrams per liter (mg/L) or parts per million (ppm). The upper limit for freshwater is 1,000 mg/L; natural seawater has a salinity of approximately 35,000 mg/L.

SALTWATER INTRUSION—Movement of saltwater into freshwater aquifers.

SAND—A rock fragment or mineral particle smaller than a granule and larger than a coarse silt grain. Its diameter ranges from 1/16 to 2 mm.

SANDSTONE—Rock formed by the compaction and/or cementing of sand. Cement (matrix) material can be calcite, hematite (FeO_2), or other materials.

SATURATED THICKNESS—The vertical thickness of an aquifer that is full of water. The upper surface is the water table. The height of the hydrogeologically defined aquifer unit in which the pore spaces are filled (saturated) with water. For the High Plains aquifer and similar unconfined, unconsolidated aquifers, the saturated thickness is equal to the difference in elevation between the bedrock surface and the water table. The predevelopment saturated thickness is based on the best available estimate of the elevation of the water table prior to human alteration by ground-water pumping.

SATURATED ZONE—That portion of soil or an aquifer in which all of the pore space is filled with water.

SECONDARY STANDARD—The maximum concentration recommended for a substance in water for a particular use. An example of secondary standard for drinking water is 250 mg/L chloride that is based mainly on taste.

SEDIMENT—Rock or other material that has been worn or broken into small pieces. Sediment is often carried from its original location by wind or water and deposited in other areas.

SEEP—A discharge of water that "oozes out of the soil or rock over a certain area without distinct trickles or rivulets" (from H. Bouwer, 1978, Groundwater Hydrology: New York, McGraw–Hill, 480 p.).

SEMIARID—Said of a type of climate in which there is slightly more precipitation (10–20 inches [254–508 mm]) than in an arid climate, and in which sparse grasses are the characteristic vegetation.

SENIOR APPROPRIATOR—Owner of a surface-water right whose right was acquired prior to other rights holders on the same stream.

SENSITIVITY—In model application, the degree to which the model result is affected by changes in a selected model input representing hydrogeologic framework, hydraulic properties, or boundary conditions.

SHALE—Rock that is often impervious to water (will not allow water to move through it) but rather soft, brittle, and easily eroded. Shale is the result of compaction of silt or mud. Much of the Permian and Pennsylvanian strata in Kansas consists of various shales, often brightly colored.

SILT—A rock fragment or mineral particle with a diameter of 1/16 mm to 1/256 mm, smaller than a very fine sand grain and larger than coarse clay.

SIMULATION—In ground-water-flow modeling, one complete execution of a ground-water-modeling computer program, including input and output.

SINK (SINKHOLE)—A depression in the surface of the earth caused by solution and/or collapse of rock. A sink is an entry point for water into cave and spring systems. All sinks will carry water into the subsurface.

SODIUM—The cationic form of the element sodium (Na) that has a single positive charge as dissolved in water.

SODIUM CHLORIDE TYPE—Water in which the constituents with the largest dissolved concentrations are sodium (Na) and chloride (Cl). Sodium chloride type water is usually derived from dissolution of rock salt (the mineral halite with the composition NaCl).

SODIUM SULFATE TYPE—Water in which the constituents with the largest dissolved concentrations are sodium (Na) and sulfate (SO_4). Also, calcium usually is present in substantial concentrations in this type of water, but the calcium is limited from being at higher levels due to the solubility limits of minerals such as calcite ($CaCO_3$) and gypsum ($CaSO_4 \cdot 2H_2O$).

SOIL MOISTURE—Water in the root zone.

SOLUTE-TRANSPORT MODEL—Application of a model to represent the movement of constituents dissolved in ground water.

SOLUTION—Geologically, the action of the dissolving of rock by water or the term to describe the water that dissolves the rock. Limestone dissolves in acidic solutions; gypsum can be dissolved in pure water. On dissolving the rock, the water becomes a calcite solution (the calcite may later be redeposited).

SPECIFIC CONDUCTANCE—Measure of the ability of water to conduct an electrical current, expressed in micromhos per centimeter at 250°C. Specific conductance is related to the type and concentration of ions in solution and can be used for approximating the dissolved-solids content of the water. Commonly, the concentration of dissolved solids (in milligrams per liter) is about 65% of the specific conductance (in micromhos/cm). This relation is not constant from supply to supply, and it may even vary in the same source with changes in the composition of the water.

SPECIFIC DISCHARGE—For ground water, the rate of discharge of ground water per unit area measured at right angles to the direction of flow.

SPECIFIC RETENTION—Ratio of the volume of water that a given body of rock or soil will hold against the pull of gravity to the volume of the body itself. It is usually expressed as a percentage. Compare with field capacity.

SPECIFIC STORAGE—Volume of water released from or taken into storage per unit volume of the porous medium per unit change in head. It is the three-dimensional equivalent of storage coefficient or storativity, and is equal to storativity divided by aquifer saturated thickness.

SPECIFIC YIELD—The quantity of water given up by a unit volume of a substance when drained by gravity.

SPRING—A place where ground water flows naturally from the earth into a body of surface water or onto the land surface, at a rate sufficient to form a current.

STAGE—Elevation of stream surface above a defined datum, usually mean sea level.

STEADY-STATE FLOW—Characteristic of a flow system where the magnitude and direction of specific discharge are constant in time at any point.

STOCHASTIC—In subsurface fluid flow, consideration of subsurface media and flow parameters as random variables.

STOCHASTIC MODEL—In subsurface fluid flow, a model representing ground-water parameters as random variables.

STOCHASTIC PROCESS—Process in which the dependent variable is random (so that prediction of its value depends on a set of underlying probabilities) and the outcome at any instant is not known with certainty.

STOCK USE or STOCKWATERING—Water used for drinking by livestock.

STORATIVITY or STORAGE COEFFICIENT—Volume of water released per unit area of aquifer and per unit drop in head. Storage coefficient is a function of the compressive qualities of water and matrix structures of the porous material. A confined aquifer's ability to store water is measured by its storage coefficient. Storativity is a more general term encompassing both or either storage coefficient and/or specific yield.

STORM-CURVE NUMBER—*See* CURVE NUMBER.

STREAM HYDROGRAPH—*See* HYDROGRAPH.

STREAM REACH—Specific portion of the length of a stream.

STREAMFLOW—Discharge that occurs in a natural channel. A more general term than runoff, streamflow may be applied to discharge whether or not it is affected by diversion or regulation.

SUBLIMATION—Transition of water directly from the solid state to the gaseous state, without passing through the liquid state; or vice versa.

SUBSURFACE WATER—All water below the land surface, including soil moisture, capillary fringe water in the vadose zone, and ground water.

SULFATE—The anionic constituent SO_4 that has two negative charges as dissolved in water.

SURFACE WATER—Water found at the earth's surface, usually in streams or lakes.

SURFACE-WATER DIVERSION—*See* DIVERSION.

SUSTAINABLE DEVELOPMENT—Economic and social development that increases the welfare of current generations without affecting adversely the welfare of future generations; for example, future generations have economic opportunities that are at least as large as earlier generations.

SUSTAINABLE YIELD—Volume of ground water that can be extracted annually from a ground-water basin without causing adverse effects.

T

TERRACES—In geologic terms, these are flat broad benches of land that lie above the immediate floodplain of a stream. Terraces represent a prior floodplain level of the stream.

TOTAL DISSOLVED SOLIDS (TDS)—The total quantity of minerals (salts) in water, usually measured by weight in milligrams per liter (mg/L) or parts per million (ppm).

TRANSITION CURVE or GROWTH CURVE or RESPONSE CURVE—Graph indicating the fraction of ground-water pumpage derived from ground-water storage or a surface-water source plotted against time.

TRANSMISSIVITY—Flow capacity of an aquifer measured in volume per unit time per unit width. Equal to the product of hydraulic conductivity times the saturated thickness of the aquifer.

TRANSPIRATION—Vaporization of water given off by plants.

TURNOVER RATE—Fraction of the total amount of mass (e.g., carbon) in a given pool or reservoir that is released from or that enters the pool in a given length of time. The turnover rate of carbon is often expressed as gigatons carbon (GtC)/year.

U

UNCONFINED AQUIFER—An aquifer that is not bounded above by an aquitard; water levels in wells screened in an unconfined aquifer coincide with the elevation of the water table.

UNCONFORMITY—Contact between rock layers representing a break or interruption in the deposition process, which creates a gap in the geologic record.

UNDERFIT RIVER—*See* MISFIT RIVER.

UNDERFLOW—(1) Ground-water flow within a streambed below a surface stream; (2) lateral movement of water through the soil zone, also known as interflow.

UNSATURATED ZONE—Also known as the vadose zone, this is the area of soil or rock just above the water table.

UPCONING—The upward movement of ground water from a deeper to shallower position in the aquifer, usually induced by pumping a well or discharge to the surface.

UPGRADIENT—In reference to the movement of ground water, the "upstream" direction from a point of reference (e.g., a well).

UPPER ARKANSAS RIVER CORRIDOR—The valley of the Arkansas River from the Colorado–Kansas state line to eastern Ford County. The corridor includes the area irrigated by Arkansas River water.

USGS—United States Geological Survey. The Kansas District of the USGS collects data and conducts research on water resources, and its main office is in Lawrence, Kansas.

V

VADOSE—Indicating the area below the earth surface but above the water table. Includes all ground water above the water table. In caves vadose water forms stalactites and other dripstone speleothems. Vadose-cave streams carve trenches and canyons and vertical pits as the water table lowers with time.

VADOSE ZONE—Unsaturated (not completely filled with water) zone lying between the earth's surface and the top of the ground water. Also known as unsaturated zone and zone of aeration.

VESTED RIGHT—Right to continue the use of water having actually been used for a beneficial use on or before June 28, 1945, when the Kansas Water Appropriation Act became effective.

VOID—Pore space or other openings in rock. The openings can be very small to cave size and are filled with water below the water table.

VOLATILE ORGANIC COMPOUND (VOC)—Organic chemical that volatilizes (evaporates) relatively easily when exposed to air.

VOLUME FLUX—*See* FLUX.

W

WATER BALANCE—A mathematical construction that shows the amount of water leaving and entering a given watershed or aquifer.

WATER DEMAND—Amount of water used over a period of time at a given price.

WATER FLUX—A volume of water per unit area per time.

WATER QUALITY—Physical, chemical, and biological characteristics of water and how they relate to it for a particular use.

WATER POTENTIAL—*See* SOIL-WATER POTENTIAL.

GLOSSARY SOURCES

Many of the glossary terms included here are from the glossary appearing on the web pages of *GeoKansas*, the educational web site of the Kansas Geological Survey, at www.kgs.ukans.edu/Extension/home.html. The following reference list is from that glossary.

Buchanan, R. C., and Buddemeier, R. W., compilers, 1993, Kansas Ground Water—An Introduction to the State's Water Quantity, Quality, and Management Issues: Kansas Geological Survey, Educational Series 10, 44 p.

Buchanan, Rex C., and McCauley, James R., 1987, Roadside Kansas—A Traveler's Guide to Its Geology and Landmarks: Lawrence, Kansas, University Press of Kansas, 365 p.

Buchanan, Rex, McCauley, Jim, and Sawin, Bob, 1996, Field Trip to the Kanopolis Lake Area: Kansas Geological Survey, Open-file Report 96–41, 17 p.

Evans, Catherine S., 1988, Glossary; *in*, From Sea to Prairie—A Primer of Kansas Geology: Kansas Geological Survey, Educational Series 6, 60 p.

Goodin, D. G., Mitchell, J. E., Knapp, M. C., Bivens, R. E., 1995, Climate and Weather Atlas of Kansas—An Introduction: Kansas Geological Survey, Educational Series 12, 24 p.

Jackson, Julia A., editor, 1997, Glossary of Geology (Fourth Edition): Alexandria, Virginia, American Geological Institute, 769 p.

Oceans of Kansas Paleontology: http://www.oceansofkansas.com/index.html (accessed 3/31/99).

Sophocleous, Marios, 1998, Selective Glossary of Hydrology and Environmental Sustainability-related Terms; *in*, Perspectives on Sustainable Development of Water Resources in Kansas, Marios Sophocleous, ed.: Kansas Geological Survey, Bulletin 239, 239 p.

Young, James, and Beard, Jonathan, 1993, Caves in Kansas: Kansas Geological Survey, Educational Series 9, 47 p.

WATER RIGHT—Any vested or appropriation right under which a person may lawfully divert and use water. It is a real property right appurtenant to and severable from the land on or in connection with which the water is used; such water right passes as an appurtenance with a conveyance of the land by deed, lease, mortgage, will, or inheritance.

WATERSHED—The area drained by a single stream or river. The Arkansas River watershed, for example, includes that area from which water eventually flows into the Arkansas River.

WATER TABLE—A fluctuating demarcation line between the unsaturated (vadose) zone and the saturated (phreatic) zone that forms an aquifer. It may rise or fall depending on precipitation (rainfall) trends. The water table is semiparallel to the land surface above but is not always a consistent straight line. Because of impervious beds of shale, etc., local water tables can be perched above the area's average water table.

WATER TRANSFER—Legal change in a water right reflecting some combination of a change in ownership of diversion, place of use, and/or type of use to another.

WATER USE EFFICIENCY (WUE)—Ratio of crop biomass accumulation or yield to the amount of water used in evapotranspiration.

WATER VAPOR—Water present in the atmosphere in gaseous form; the source of all forms of condensation and precipitation. Water vapor, clouds, and carbon dioxide are the main atmospheric components in the exchange of terrestrial radiation in the troposphere serving as a regulator of planetary temperatures via the greenhouse effect. Approximately 50% of the atmosphere's moisture lies within about 1.84 km of the earth's surface, and only a minute fraction of the total occurs above the tropopause.

WATER YEAR—Twelve-month period of which the U.S. Geological Survey reports surface-water supplies. Water years begin October 1 and end the following September 30, and are designated by the calendar year in which the water year ends.

WELL—A vertical excavation into an underground rock formation.

WELL SCREEN—A slotted section of pipe usually placed in the borehole adjacent to the main aquifer unit or units that supplies the well with water.

WELL YIELD—Maximum pumping rate that can be supplied by a well without drawing the water level in the well below the pump intake. *See* YIELD.

WETLAND—Land with a wet spongy soil, where the water table is at or above the land surface for at least part of the year.

X

Y

YIELD—Amount of water that can be supplied from a reservoir, aquifer, basin, or other system during a specified interval of time. This time period may vary from a day to several years depending upon the size of the system involved.

Z

ZONE OF AERATION—*See* VADOSE ZONE.