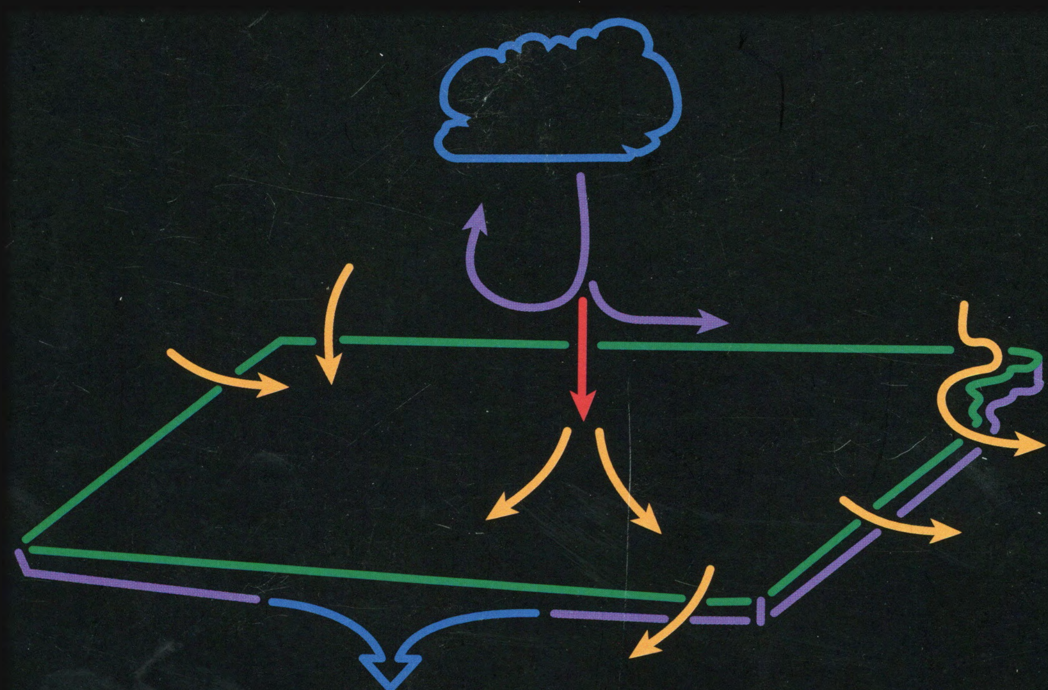
Bulletin 239

PERSPECTIVES ON Sustainable Development OF WATER RESOURCES IN KANSAS



MARIOS SOPHOCLEOUS, ED.

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Perspectives on Sustainable Development of Water Resources in Kansas

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Foreword

In the 1980's, much of the American environmental community rallied around the concept of "sustainable development," the idea of limiting resource use to levels that could be sustained over the long term. As a guiding philosophy, sustainable development quickly became popular, seen as something of a litmus test to judge the way resources should be exploited: any use that could be undertaken indefinitely met with approval under this concept, while those uses that could not be sustained were suspect.

It all seemed easy enough. Then people began grappling with the meaning of the phrase and came to realize the difficulties inherent in defining and adopting sustainability. Exactly what do people mean when they talk about sustainability? Is it possible to have a meaningful conversation about sustainable development of a nonrenewable resource? And how long can a resource be used before that use is considered "sustainable"? Ten years, a hundred years, geologic time? Do those amounts of time mean anything to most of us? Scientists realized that it might prove dauntingly difficult to quantify resources in order to determine how long their use could be sustained and to analyze the impact of resource use. In the essay *The Shaky Ground of Sustainable Development*, historian Donald Worster discusses sustainable development as it is applied to the science of ecology, writing that sustainable development "depends on the assumption that we can easily determine the carrying capacity of local and regional ecosystems" (Worster, 1993). Making those determinations is anything but easy in ecology, and apparently not much easier in many other scientific disciplines.

Shortly after the concept of sustainable development arrived in the environmental community, water-policy-makers in the ground-water management district of northwestern Kansas began discussing the concept of "zero depletion." This was the idea that water should be pumped from the aquifer at the same rate that it was replenished. If such a policy were enacted, depletion in parts of the Ogallala would go from the rate of several feet per year to zero, at least in theory. However, because recharge rates in western Kansas are low, a policy of zero depletion would require a drastic reduction in irrigation in the most seriously depleted portions of the Ogallala. Other ground-water management districts in the state were already applying standards of sustainability when they made judgments about allowing new wells to be drilled in their parts of the state. But this was the first time that an agency considered regulating existing water rights—wells that were already in place—with the goal of long-term, sustainable use of an aquifer. Zero depletion aroused considerable analysis, reaction, and discussion in northwestern Kansas and was applied eventually only to new wells.

Today the concepts of zero depletion or sustainable development are generally referred to in the hydrologic community as "safe yield." Safe yield has traditionally been defined as "the attainment and maintenance of a long-term balance between the amount of ground water withdrawn annually and the annual amount of recharge" (Sophocleous, 1997). While that definition seems simple enough, the following chapters demonstrate that, even when it comes to a renewable resource such as water, such a definition is fraught with difficulties and complexities. The definition does not explicitly recognize some of the inherent connections between ground water and surface water. It does not attempt to take into account the impact that pumping in one part of the hydrologic system may have on other parts of the system. Nor does it suitably address the question of time, the way yields change over long periods. It makes no mention of the complexities of characterizing the hydrologic system, or how the concept of sustainability might change in different hydrologic settings.

Just as the concept of sustainability required more subtle and detailed analysis in order to be meaningful, the concept of safe yield must be examined more carefully if it is to have any applicability to water issues. In organizing the following volume, and in writing several of the chapters, Survey hydrogeologist Marios Sophocleous is attempting to raise the level of discussions about the application of safe yield to water resources in Kansas. To do that he brought together ten of the state's water scientists, asking each to write about the issues of safe yield as applied to their particular scientific specialty. He then coordinated their efforts, constantly encouraging and cajoling. At times, working with these authors must have seemed a little like making water flow uphill—it can be done, but it takes time, energy, and constant maintenance.

Like any conversation, discussions about safe yield must be set in a context, and Sophocleous provides much of the necessary background, beginning the book with a description of hydrologic systems and water management in Kansas. Sophocleous and the other authors then discuss the concept of safe yield and its applicability in a variety of geologic and hydrologic settings and circumstances, such as confined aquifers and interconnected streams and aquifers. Other authors have contributed chapters that consider safe yield and surface water, water chemistry, and climate change. Two of the later chapters describe the complexity of hydrologic systems and the impact of agriculture on those systems.

Throughout the book, the authors analyze safe yield by using examples mainly from Kansas hydrologic settings. While this book will be of primary benefit to water users and policy-makers in the state, the Kansas case studies should prove instructive for areas throughout the Great Plains and the nation. Even more important, rather than limit these discussions to technical, sometimes mathematical examinations of the questions about safe yield, the authors have striven to make these chapters more accessible to water users, water regulators, and water-policy experts. For discussions about safe yield to have long-term impact, they must reach the people who are making, enforcing, and carrying out water policy. That is what this book attempts to do.

Regardless of what these concepts are called—sustainable development, zero depletion, or safe yield—they all attempt to address the feasibility of a long-term approach to resource use. The work of Sophocleous and the other authors is a first step in the process of analyzing these concepts as they apply to Kansas. This book will certainly not be the final comment about these issues, but it is an important contribution to discussions, and will undoubtedly inform future debates over water policy in Kansas. That is why the following chapters deserve a wide reading. And for attempting to bridge the gap between the scientific community and water users and policy-makers, Sophocleous and his fellow authors deserve the thanks of both groups.

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

Worster, D., 1993, The shaky ground of sustainable development; *in*, The Wealth of Nature, D. Worster, ed.: Oxford Press, p. 154

Rex Buchanan
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Preface

Water resources are essential to both economic development and the maintenance of natural systems. While water technically does not disappear but only changes form, the quality and quantity of water resources in any one place can be degraded or improved by a variety of human activities. Population growth, intensified land use, economic demands, and environmental degradation are exerting mounting pressures on the earth's soil, water, and other natural systems. The specter of possible changes in climate can only add to these pressures. Few areas of public policy are as contentious as the issues surrounding water management. Misconceptions and deficiencies in the dissemination of research findings to the local and regional levels add to these contentions.

The purpose of this volume is to contribute in educating Kansans and other people about water-resources sustainability issues so as to promote a better understanding of water resources in Kansas and more enlightened management of these resources. Knowing what we have, understanding how natural ecosystems work, and effectively communicating to decision-makers about environmentally sustainable practices are crucial if we are to ensure that the natural goods and services that we have enjoyed will continue to be available for both present and future generations. Although this effort has a Kansas focus with existing Kansas and U.S. Great Plains examples, it also stresses the universally applicable concepts on sustainability of water-resources systems. We attempted to make this work comprehensive within the hydrologic (scientific) realm of water-sustainability issues, and also cross-disciplinary with other scientific fields, but by design we do not specifically address socio-economic, political, legal, and ethical issues. This work is semi-technical, addressed to the educated layperson with a bachelor's level of education. We particularly aim at personnel in state and local management units who deal with water-resources issues on a regular basis. Each chapter stands by itself with no firm rigid formats, but with cross references and interconnections to other chapters. Boxed sections provide supplemental or more technical aspects, and a glossary provides easy-to-understand definitions.

Thus, Chapter 1 addresses the issue of "what we have" and the factors that control water resources in Kansas. It also covers how water is used in Kansas, what institutions are managing its water resources, and how they are managed. It also identifies the major water-related problems we face in Kansas. Chapter 2 addresses the hydrologic principles underlying the concept of safe yield, identifies its weaknesses, and outlines several examples of its use. This basic chapter was the catalyst for developing this entire volume. Chapter 3 expands on more recent developments of the evolving sustainability concepts, emphasizing the ecosystem management approach, and outlining the Kansas water-management experience. Chapter 4 addresses sustainability issues related to confined aquifers, with emphasis on the Dakota and Ozark aquifers of Kansas. Chapter 5 provides water-chemistry background and reviews pollutant pathways to aquifers as a basis for understanding the impacts of chemical compounds and processes on sustainable yield of aquifers. Chapter 6 addresses surface-water yield issues with emphasis on Kansas reservoirs. Chapter 7 presents an assessment of the effects of agricultural development on water yield in Kansas. Chapter 8 addresses the issue of climate change and its possible impact on sustainable water yield. Chapter 9 stresses the importance of recognizing and evaluating uncertainty in developing yield estimates. Chapter 10 is a concluding overview explaining why "safe yield" as traditionally defined is not sustainable and how to improve water-resources management. Finally, Chapter 11 presents a selective but rather comprehensive glossary of hydrology and sustainability-related terms in non-technical language.

This volume represents different perspectives on water-sustainability issues in Kansas by ten experienced scientists working in this state. We hope that these perspectives on sustainable development of water resources in Kansas will enhance public education and discourse, and enlighten managers and policy makers to making more informed and thus better decisions. The editor would appreciate feedback from the readers on any aspect covered in this volume, especially by pointing out errors, inaccuracies, and significant omissions so that these could be rectified in future editions of this or similar volumes. Figures throughout the book are used with permission of the publishers.

I would like to thank all participants in this volume for their willing cooperation and patience through the long process of multi-author coordination, review, and revision. I am particularly indebted to the Kansas Geological Survey (KGS) Associate Director Rex Buchanan for his continued support and participation in this project, as well as the KGS editor Marla Adkins-Heljeson for handling the editing and review processes. The chapters in this volume have undergone a double review process. The KGS internal review members consisted of (in alphabetical order) Marla Adkins-Heljeson, Rex Buchanan, Robert Buddemeier, and Marios Sophocleous. The external review members consisted of (in alphabetical order) Ernest Angino (University of Kansas, Lawrence, KS), Stanley Davis (University of Arizona, Tucson, AZ), Edwin Gutentag (Downey and Gutentag, LLC, Lakewood, CO), John Helgesen (U.S. Geological Survey–Lawrence, KS, office), Les Lampe (Black & Veatch Engineers–Architects, Kansas City, MO), William Mullican (Bureau of Economic Geology, Austin, TX), David Pope (Division of Water Resources, Kansas Department of Agriculture), and Adrian Visocki (Illinois State Water Survey, Champaign, IL). To all these and their staff, a note of gratitude is due for their volunteered, yet essential, service.

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Executive Summary[1]

Few issues of public policy are as contentious as those surrounding management of our environment and natural resources, such as water. This book analyzes the management concept of sustainable water development from a variety of hydrologic perspectives and describes its application to different hydrologic settings. The following summary is divided into four major sections—Kansas water resources, characterization of hydrologic systems, management of water-resources systems, and hydrologic impacts of agricultural development and climate change on water resources. Selected key conclusions and recommendations are highlighted in ***boldface italic type***.

Kansas Water Resources

A prerequisite for managing a region's water resources is knowing the quantity of suitable-quality water that can be developed. A hydrologic inventory or budget is needed to evaluate existing and potential development of dependable water supplies.

More than 98% of the water available for use enters the state of Kansas as precipitation. The statewide average annual precipitation is about 27 inches (68.5 cm). Evapotranspiration returns about 23.2 inches (59 cm) back to the atmosphere. Aquifer recharge uses approximately 0.9 inches (2.3 cm). Runoff to rivers that originate within the state represents approximately 2.6 inches (6.5 cm), and when combined with streamflow into the state from Nebraska and Colorado (equivalent to less than 0.4 inches or 1 cm), surface-water outflows to Missouri and Oklahoma account for almost 3 inches (7.5 cm). Annually, Kansans use about 1.6 inches (4 cm) of water. Ground-water use represents approximately 1.2 inches (3 cm) of that total (92% is used for irrigation), and surface-water use equals approximately 0.4 inches or 1 cm (75% is used by power plants).

Although the precipitation, evapotranspiration, and other factors in the water budget vary widely from year to year, the averages over several decades remain nearly constant. ***The evidence to date shows that the main water supply for Kansas—precipitation that falls on the state—has changed little in the last 150 years. What has changed is how water is used.***

In western Kansas, ground water provides almost all the water, but at the present level of water use, ***ground-water resources are being depleted***. Although the demand for water is continuously increasing, many areas in western and central Kansas are closed to further appropriations. In eastern Kansas, surface water is the principal water source; however, large withdrawals of ground water, which is closely coupled to the surface-water system, are obtained primarily from the alluvium of the Kansas River valley.

Kansas faces a number of water-availability and water-quality problems. Ground-water-level declines and streamflow reductions are especially significant in western Kansas. Saline-water intrusion, both natural and human-induced, affects surface- and ground-water systems. Pollution from non-point sources (mainly pesticides, fertilizers, and livestock), from point sources (waste-disposal sites), and from mining activities are other water-quality problems that affect water resources in the state.

Characterization of Hydrologic Systems

Stream-Aquifer Systems (Unconfined Aquifers)

Ground-water management and management of surface waters must be conceived as a combined system. ***Because of the interdependence of surface and ground water, changes to any part of the system have consequences for the other parts.***

Under natural conditions (prior to development by wells), aquifers are in a state of approximate dynamic equilibrium: over hundreds of years, wet times (in which recharge exceeds discharge) offset dry times (when discharge exceeds recharge). Discharge from wells disturbs this equilibrium by producing a loss of water from aquifer storage. The decline of ground-water levels around pumping wells located near streams captures some of the ground-water flow that would have, without pumping, discharged to the streams. In fact, at sufficiently large pumping rates, these ground-water-level declines can induce flow out of a body of surface water into the aquifer (a process known as induced recharge). The sum of these two effects leads to streamflow depletion. A new state of dynamic equilibrium can be reached with continued pumping only by an increase in recharge (induced recharge), a decrease in natural discharge, a loss of storage in the aquifer, or a combination of these.

Ground water pumped from the aquifer comes from two sources: aquifer storage and induced recharge of surface water. Storage refers to water that is naturally retained in the aquifer. Induced recharge is surface water that is added to the ground-water system mainly as a result of ground-water-level declines below the surface-water level. Initially, ground water pumped from the aquifer comes from storage, but ultimately it comes from induced recharge. ***The timing of the change from storage depletion to induced recharge is a key factor in developing***

[1]*The editor would like to thank Robert Sawin of the Kansas Geological Survey and the author-participants for their contributions in drafing this summary.*

water-use policies. Distinguishing between natural recharge and induced recharge to ascertain possible sustained yield is exceedingly difficult and is an area that needs further research.

Permanent streamflow or baseflow is usually a result of ground-water discharge. Thus, if ground-water pumping lowers the elevation of the water table below that of the stream bed, streamflow will be reduced or interrupted. On the other hand, streamflow may be the major source of recharge to some alluvial aquifers, so that ***streamflow regulation or diversion may alter the recharge characteristics, and therefore the sustainable yield, of the ground water in the area.*** Stream-aquifer interactions also are important in situations of ground-water contamination by polluted surface water and of degradation of surface water by discharge of low-quality ground water. ***Coordinated, combined use of surface- and ground-water resource (conjunctive use) and management are required to improve the reliability and value of both resources.***

Confined Aquifers

A confined aquifer is a porous and permeable geologic unit that is sandwiched between two relatively low-permeability layers (unconfined aquifers are only bounded by a low-permeability layer below). Because the confining layers above and below these aquifer systems are usually regionally extensive, the recharge and discharge areas for these systems may be hundreds of miles apart. ***Confined aquifer systems are more sensitive to development than unconfined systems because of their hydrogeologic properties, such as their much lower storativity.***

The issues surrounding the sustainability of water resources in confined systems are complex and involve both the quantity and the quality of ground water. These systems will not respond to development in the same manner as unconfined systems because of differences in the sources and amounts of recharge, and in the mechanisms that release ground water to pumping wells. Because of their greater average depth below the surface, confined systems are more likely to contain (or be connected to other aquifers that contain) unusable ground water. As a result, water quality can be a very important factor in determining the usability of the aquifer.

Sustainability of a confined aquifer system may be possible only in regions that are close to either the regional recharge/discharge areas or to areas of hydraulic connection with other aquifer systems. Management on the basis of sustainable yield may be more realistic in this part of the confined system for planning horizons on the order of a few decades. Ultimately, however, ***sustainability may not be a viable management concept for confined aquifers.***

The primary management tools to control declines in confined aquifers are well spacing, restrictions on the rates of withdrawal from the aquifer, and artificial recharge. Depletion of the aquifer will occur if production wells are too close together, or the rates of withdrawal from the aquifer are unregulated.

Water Chemistry

An essential consideration in development of an aquifer is the chemical quality of water produced because ***the quality of water limits its use***. In an undeveloped aquifer, ground water is, for the most part, at a chemical equilibrium with its surroundings because ground-water flow is generally very slow. ***Ground-water movement induced by pumping may change the ground-water chemistry***. One of the ways that ground-water chemistry may be affected is by ***recharge of contaminated surface water into unconfined aquifers***: surface water may contain incompletely processed sewage effluent, residual agricultural chemicals, or other undesirable chemicals. Another way is through ***mixing of poor-quality (for example, saline) water into unconfined or confined aquifers***: an aquifer containing good-quality water in hydraulic continuity with an aquifer containing poor-quality water may be affected by the poor-quality water.

All aquifers contain water that is chemically stratified. Pumping a well causes mixing of the stratified ground water, which may result in dissolution (corrosion) or precipitation (encrustation) of solids, sorption or desorption of metals or organics, ion exchange of cations or anions, and oxidation or reduction of redox elements that affect their mobility in ground water. In addition, fluctuation of the water table that results from pumping or pumping in concert with irrigation can change conditions in the unsaturated (soil) zone, the gateway to an aquifer. ***The unsaturated zone is an important chemical-buffer zone to aquifers***, the importance of which geochemists are only beginning to understand.

Ground-water use that results in deterioration of water quality may cause irreversible damage to an aquifer. ***Consideration of water-quality effects in sustainable yield assessments represents*** not just one more test of the "sustainability" of aquifer development, but ***an essential part of the evaluation.***

Management of Water Resources Systems

Misconceptions About Safe Yield

To protect ground-water supplies from overexploitation, some state and local agencies have enacted regulations and laws based on the concept of "safe yield." ***Safe yield is defined as the attainment and maintenance of a long-term balance between the amount of ground water withdrawn annually and the annual***

amount of recharge. Safe yield is a management concept that allows water users to pump only the amount of ground water that is replenished naturally through precipitation and surface-water seepage. As defined, ***safe yield ignores discharge from the system.***

Under long-term equilibrium conditions, the amount of recharge to an aquifer equals the amount of water discharged into a stream, spring, or seep. Consequently, ***if pumping equals recharge, the streams, marshes, and springs eventually dry up.*** Continued pumping in excess of recharge eventually depletes the aquifer (e.g., the Ogallala aquifer in parts of Kansas, Texas, and New Mexico). Thus, natural recharge should not be part of the well-field water budget unless natural discharge is also factored into the formula.

Policymakers are primarily concerned about aquifer drawdown and surface-water depletion; both are related to the rate and duration of pumping, location of the well, and aquifer properties. ***Natural recharge*** is unrelated to these parameters and ***is irrelevant to ground-water and surface-water depletion.*** Despite its irrelevance, natural recharge is often used in ground-water policy to balance ground-water use under the banner of safe yield. ***It is a misconception that the natural rate of recharge represents a safe rate of yield.***

Use of the traditional concept of "safe yield" of ground water persists today despite being repeatedly discredited in the scientific literature. Misconceptions about safe yield and its use in ground-water management lead to continued ground-water depletion, stream dewatering, and loss of wetland and riparian ecosystems.

Sustainable Systems

Safe yield has often been used as a guide for the sustainable use of a single product–the number of trees that can be cut, the number of fish that can be caught, the volume of water that can be pumped from the ground or river, year after year, without destroying the resource base. However, experience has repeatedly shown that a single-product goal is too narrow a definition of the resource, because other resources inevitably depend on, or interact with, or flow from the exploited product. We can maximize our safe yield of water by drying up our streams, but when we do, we learn that the streams were more than just containers of usable water.

A better approach would address the sustainability of the "system" and its water yield–not just the trees, but the whole forest; not just the fish, but the marine food chain; not just the ground water, but the running streams, wetlands, and all the plants and animals that depend on them. Such a holistic approach, however, is fraught with difficulty. We cannot use a natural system without altering it, and the more intensive and efficient the use, the greater the alteration.

Sustainable development of water resources refers to a holistic approach to development, conservation, and management of water resources, an approach that considers all components of the hydrologic system. It is inherently intergenerational because it implies that we must use the water resources in ways that are compatible with maintaining them for future generations. This intergenerational perspective constrains our management of water. The mechanisms to bring about these changes are not clear-cut and are still a matter of debate. The concept is a dynamic one and will be continually refined.

Although the ideas of sustainable yield have been around for many years, a quantitative methodology for the estimation of such yield has not yet been perfected. Since the 1980's, three-dimensional numerical models of the complete stream-aquifer hydrogeologic system have been employed to provide a predictive tool explaining the connection between well-field withdrawal and surface-water depletion.

Water-resource Management

In view of persistent declines in ground-water levels, especially in western Kansas, the Kansas Legislature in 1972 passed the *Kansas Groundwater Act* authorizing the ***formation of local groundwater management districts (GMD's)*** to help control and direct the development and use of ground-water resources. As a result of these ground-water level declines, especially since the mid-1970's, streamflows of western and central Kansas streams have been decreasing. In response to these streamflow declines, the Kansas Legislature passed the *minimum instream flow law* in 1982, which requires that ***minimum desirable streamflows (MDS) be maintained in different streams in Kansas.***

The three western GMD's (1, 3, and 4), which have the least precipitation and the highest rate of ground-water-level declines, adopted a *planned ground-water depletion policy* (although GMD 4 switched to a *zero-depletion policy* for new wells in 1990); the two GMD's in central Kansas (2 and 5), which have more precipitation and smaller rates of ground-water-level declines, adopted modified forms of "safe yield" or "sustainable yield" policies, thus attempting to maintain a balance between water-resource inputs and outputs.

Wise management of water resources needs to be approached not only from the standpoint of quantity and quality, but should also take into account the impact of ground-water exploitation on the natural environment, including human, ground-water, surface-water, and riparian ecosystems. ***This kind of integrated management approach is now taking hold in Kansas.*** The progressive evolution of Kansas water management from the establishment of local GMD's, and the progression of their policies, to the adoption of integrated resource planning and management by the Kansas Water Office and Division of Water Resources (Kansas Department of Agriculture) bodes well for the sustainable development of water resources in Kansas.

Water-resource management should be based on the best information we have today, but should be flexible enough for change and complexity because natural systems are inherently variable, "patchy," and complex. This also implies managing in a probabilistic and risk-assessment framework that recognizes the inherent unpredictability of nature. Instead of determining a fixed sustainable yield, managers should recognize that yield varies over time as environmental conditions vary.

Our understanding of the basic principles of soil and water systems and processes is fairly good, but our ability to apply this knowledge to solve problems in complex local and cultural settings is relatively weak. Additional lines of communication from the research fields to the water users in the field are required. Communication breakdowns probably account for the persistence of simplistic but misguided concepts such as conventional safe-yield management strategies. ***A strong public education program is needed to improve understanding of the nature, complexity, and diversity of ground-water resources, and to emphasize how this understanding must form the basis for operating conditions and constraints.*** This is the only way to positively influence, for the long term, the attitudes of the various stakeholders with water-resource interests.

Reservoir Yields

Yield is used to characterize the capacity of a water resource to serve as a long-term water supply. Yield determinations affect many facets of water policy. In Kansas, ***a yield estimate places an upper limit on the amount of water supply that can be marketed from a reservoir.*** This *de facto* rationing of water resources can have significant implications for entities in search of water supplies. Therefore, it can affect the larger regional water supply. Yield determinations also have corollary implications for policies pertaining to reservoir recreation, reservoir fisheries, and downstream streamflows and riverine habitat.

Reservoir yields depend primarily on inflows and reservoir storage. As such, ***reservoir yields decrease with time due to reservoir sedimentation.*** The loss of storage results in a loss of reservoir yield unless compensatory actions are taken. These measures can include augmentation of inflow, increasing the conservation storage capacity via structural or institutional means, or physically removing the accumulated sediments. ***Except for increasing the conservation storage via institutional means, these approaches (augmentation of inflow, structural increases in storage capacity, removal of bottom sediments) are generally not feasible due to economic, environmental, and political concerns.***

Uncertainty and Risk

Water-resources planners realize that knowledge of the hydrologic system is fraught with uncertainties, but decisions still must be made. Water-yield estimates are the result of a hydrologic-balance calculation, based on the initial stock of water, and all inflows and outflows to the system. These quantities vary with time and location and can only be estimated, and thus may carry significant uncertainty. All sources of uncertainty need to be recognized, and their impact on the variables, such as water yield, need to be evaluated. Because uncertainty and risk are companions, ***evaluating uncertainty allows the assessment of risks and the management of its consequences. Uncertainty needs to be incorporated into the analysis in a quantitative fashion, by means of probabilities.*** By doing this, decision makers can set policies that meet acceptable levels of risk.

Natural systems can never be perfectly known. Fortunately, uncertainty can be evaluated and policies adopted that minimize the risk of undesirable consequences, such as depleting an aquifer at a rate faster than desired. By recognizing uncertainty we can make the most of the available information, thus leading to better decisions.

Hydrologic Impacts of Agricultural Development and Climate Change on Water Resources

Agriculture

Over the last 150 years, most of the land area of Kansas (over 90%) has been changed by agricultural development. Sustainable crop production without irrigation has been a matter of developing management practices that increase the effectiveness of a limited water supply and protect the soil from excessive erosion. Adoption of conservation practices that decrease runoff and reduce evaporation losses have been important. In much of the state, the effectiveness of these practices has resulted in more efficient use of water for grain and forage production.

Since water use by agriculture is a consumptive use that results in evaporation of water from the land surface, ***more efficient irrigation practices mean that less water becomes runoff or ground-water recharge. As a result, with the development and adoption of ways to use water for agriculture more efficiently in Kansas, less water is***

available for non-agricultural uses, especially in the drier regions of the state. In the future, these effects will probably result in further decreases in the amount of water available for appropriation by other users. In the western half of the state in particular, streamflows have been reduced by up to 50% since 1950 by a combination of agricultural practices, including withdrawal of ground water for irrigation along streams. In the eastern half of the state, the effect has been limited because of the difference in climatic conditions.

Climate Change

A rapidly growing body of evidence suggests that we are entering a somewhat warmer and definitely more variable world. Sustainable water yields may or may not be reduced in the long-term average, but they will almost certainly be less reliable in the short term. Climate warming may increase demand for water at a rate even greater than that predicted on the basis of economic development. Present-day reservoirs, well fields, and water laws and rights are consistent with the climate-as-it-was. These rights and structures–or at least their present mode of operation–can not be expected to yield the same results in the now-and-future climate.

Sustainable yield depends on the assumption of basic stability of the hydrologic cycle: long-term consistency in precipitation and the flow of surface water and ground water, and factors such as temperature, wind, and sunlight that control evaporation and transpiration. Climate is subject to both natural and human-induced changes on scales ranging from local to global.

The local and regional hydrologic effects of global changes cannot be reversed or stabilized at a local level. ***Adaptation is the only near-term management option.*** Such adaptation will almost certainly require reconsideration of the concepts, as well as the present water quantities, associated with "safe yield" and ideas of sustainability.

Climate change will have uncomfortable results, but it need not be disastrous if action is taken now to prepare the state and its citizens to mitigate the worst effects of climate change and take advantage of possible benefits. Some of the possible approaches include:

- Recognition of the nature of the problem and of the need for advance preparation.
- Following a "no regrets" policy by doing things that have low present costs are desirable in any case, and prepare us for the expected future.
- Reassessing recent trends and projections related to water use and management, and using the climate statistics of the past 20–30 years to examine and predict the effects of variability.
- Establishing a mechanism for ongoing review of the rapidly changing field of climate change research and data, and its implications for state programs and economic prospects.
- Enhancing public information and education programs focused on sustainability, planning for change and decision making under conditions of uncertainty.

Contents

Selected Conversion Factors and Useful Data Relevant to Chapter 1

Multiply	By	To obtain
acre (ac)	4046.8564	square meters (m^2)
acre (ac)	0.40469	hectares (ha)
acre-foot (ac-ft)	325,851.4	gallons (gal)
acre-foot (ac-ft)	43,560	cubic feet (ft^3)
acre-foot (ac-ft)	1233.482	cubic meters (m^3)
acre-foot (ac-ft)	1.23348×10^{-6}	cubic kilometers (km^3)
billion gallons per day (bgd)	3,785,410	cubic meters per day (m^3/d)
billion gallons per day (bgd)	3.7854×10^{-3}	cubic kilometers per day (km^3/d)
centimeter (cm)	10	millimeters (mm)
centimeter (cm)	0.3937	inches (in)
cubic foot (ft^3)	7.48052	gallons (gal)
cubic foot (ft^3)	28.31685×10^{-3}	cubic meters (m^3)
cubic foot per second (ft^3/s or cfs)	0.02832	cubic meter per second (m^3/s)
cubic foot per second (ft^3/s or cfs)	28.31685	liters per second (L/s)
cubic foot per second (ft^3/s or cfs)	448.83117	gallons per minute (gal/min or gpm)
cubic foot per second (ft^3/s or cfs)	1.98347	acre-feet per day (ac-ft/d)
cubic kilometer (km^3)	1×10^9	cubic meters (m^3)
cubic meter (m^3)	8.107×10^{-4}	acre-feet (ac-ft)
cubic meter (m^3)	35.31467	cubic feet (ft^3)
cubic meter (m^3)	264.1721	gallons (gal)
curie (Ci)	3.7×10^{10}	disintegrations per second
foot (ft)	0.3048	meter (m)
feet per mile (ft/mi)	0.189394	meters per kilometer (m/km)
gallon (gal)	3.78541×10^{-3}	cubic meter (m^3)
gallons per minute (gal/min or gpm)	0.0631	liters per second (L/s)
hectare (ha)	10,000	square meters (m^2)
hectare (ha)	2.471	acres (ac)
inch (in)	2.54	centimeters (cm)
inch (in)	25.4	millimeters (mm)
kilometer (km)	0.62137	miles (mi)
liter (L)	0.001	cubic meter (m^3)
liter (L)	0.26417	gallons (gal)
meter (m)	3.28084	feet (ft)
microgram (μg)	0.001	milligram (mg)
mile (mi)	1.60934	kilometer (km)
mile (mi)	5280	feet (ft)
million acre-feet (MAF)	1.23348	cubic kilometers (km^3)
million acre-feet (MAF) per year	892.74	million gallons per day (MGD)
million gallons (Mgal)	3,785.41	cubic meters (m^3)
million gallons per day (MGD)	3.06888	acre-feet per day (ac-ft/d)
million gallons per day (MGD)	1,120.14	acre-feet per year (ac-ft/yr)
picocurie (pCi)	1×10^{-12}	curie (Ci)
square foot (ft^2)	0.0929	square meter (m^2)
square mile (mi^2)	2.58999	square kilometers (km^2)
square mile (mi^2)	258.9988	hectares (ha)
square mile (mi^2)	640	acres

Temperature

degrees Celsius (°C): T(°C)

degrees Fahrenheit (°F): T(°F)

$T(°C) = [T(°F) - 32]/1.8$

$T(°F) = [T(°C) \times 1.8] + 32$

Area of Kansas = 82,276 mi^2 = 52,656,640 acres = 213,094 km^2

CHAPTER 1

Water Resources of Kansas: A Comprehensive Outline

Marios Sophocleous

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Water Resources of Kansas: A Comprehensive Outline

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Preface

This chapter presents a compilation and synthesis of existing information from diverse sources. The material presented here is largely extracted from these sources almost verbatim in many instances, although several original contributions also are included. The major sources consulted are identified in each major chapter heading and listed in the selected references section. The subject matter is composed of five major parts: the physical environment, water use, water-related problems, water-resources management, and needed research. The selection and synthesis of the subject matter into a unified and complete whole is original. This chapter should provide readers with a comprehensive, general background on the water resources of Kansas. This, in turn, will form the basis for better appreciating the intricacies of sustainable development concepts to follow, as applied to Kansas conditions. (A selective unit-conversion table is included on page xiv for the benefit of the reader of this chapter.)

Introduction

A prerequisite for managing the water resources of a region is knowing the quantity of suitable-quality water that can be developed. A hydrologic inventory, or budget, defining water supply in terms of annual or seasonal precipitation and other inflows, water outflows, and storage inventories and their variabilities is needed to evaluate existing and potential development of dependable water supplies in any Kansas river basin. In terms of the hydrologic cycle for a particular basin under natural conditions (assuming no significant climatic trends or change), a balance must exist between the quantity of water supplied to the basin and the amount leaving the basin. The equation of hydrologic equilibrium (total inflow or supply or recharge equals total outflow or discharge) provides a quantitative statement of this balance. A perennial supply of water can be assured by not withdrawing more water than is available over the long term. This is true for either ground water or surface water. The concept of perennial or sustainable or safe yield of aquifers stems from the principle of renewability of the resources, as shown in the hydrologic cycle, and is based on an analogy to surface-reservoir operation.

Determining the water balance for a river basin or watershed serving individual towns or cities with water is in some ways like checking the financial balance of a household—it helps us to see where the expenditures are going and whether we can afford to spend more or whether to restrict expenditures. Existing information about water is often times rather spotty, and this makes it difficult to prepare a detailed day-to-day water budget for a basin serving most towns or cities with water. There is, however, enough information to prepare an approximate annual budget for the state as a whole.

The inputs of water (precipitation in the form of rainfall and snowfall) may be considered credit items; amounts of water withdrawn or depleted (including the flow of streams, evaporation from lakes, ponds, rivers, moist soil, and transpiration from plants) represent debit items. Whenever we do a water balance, we must also define the system, e.g., study area (the boundaries of which are conveniently chosen to simplify the analysis) and time period. For many situations in Kansas, we can conveniently use the state boundaries as the area of interest because over 98% of our water inputs come from precipitation falling onto the land surface. The precipitation input (fig. 1.0) averages approximately 118.7 million acre-feet (MAF; 146.4 km^3) or 27 inches (68.5 cm) over Kansas annually (U.S. Geological Survey, 1990). An acre-foot of water is the amount required to cover an acre to the depth of 1 ft (or about 325,850 gallons). If water were placed 1 ft deep over the entire state, the volume required would be 52.7 MAF (65 km^3). The annual flow of Kansas rivers that originates within the state amounts to approximately 11.3 MAF (13.9 km^3). Approximately 1.7 MAF per year (2.1 km^3/yr) comes to the state primarily from southeast Nebraska, and a much smaller portion from Colorado; approximately 13 MAF per year (16 km^3/yr) of streamflow leaves the state to Missouri and Oklahoma (fig. 1.0) and eventually reaches the Gulf of Mexico. Evapotranspiration averages about 102 MAF per year (126 km^3/yr; fig. 1.0) from the state (U.S. Geological Survey, 1990). Although the precipitation, evapotranspiration, and other factors in the water budget vary widely from year to year, the averages over several decades remain nearly constant. The main water supply for Kansas—precipitation that falls on the state—has changed little in the last 150 years (Flora, 1948; J. K. Koelliker, 1997, personal communication). What has changed is how water is used.

Water resources undergo constant change, even in their natural state without human development. Both long-term and short-term variations are caused by corresponding variations in climatically induced variations in precipitation and streamflow. To better understand the implications of developing dependable water supplies for Kansas, we need to know the factors that control Kansas water resources.

The major natural factors that control a region's water resources are climate, topography, and geology. Ecosystems, including humans, also affect water supplies. In this chapter, these factors are analyzed first as they affect Kansas, followed by a relatively brief analysis of how water is used in Kansas. With this information as background, we identify the various water-quantity and -quality problems of the state, including institutional and management issues. The various State, local, and Federal water-management agencies are briefly described, followed by a description of the way water is managed in the state. Finally, water problems and issues needing further study are identified.

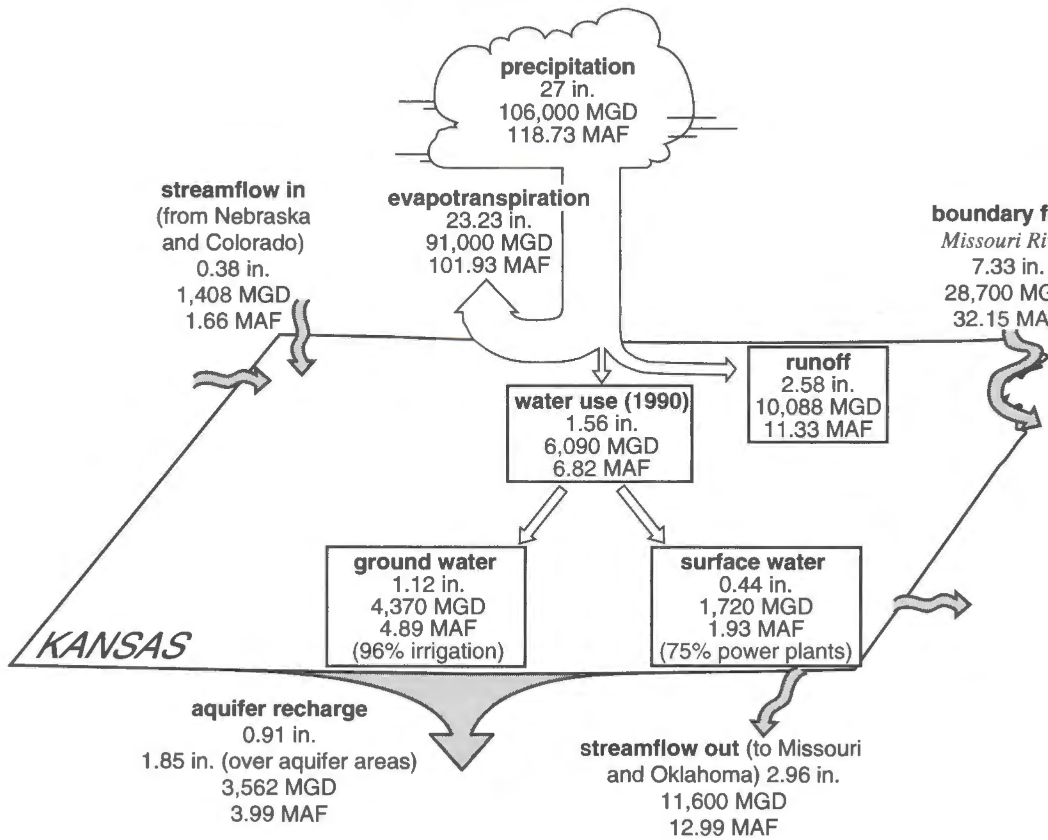


FIGURE 1.0—WATER-BUDGET COMPONENTS FOR KANSAS. VALUES are in inches (in.) per year, million gallons per day (MGD), and million acre-feet per year (MAF).

Part I. Physical Environment

Climate

Largely extracted from Goodin et al., 1995; Departmental Report 5-425, Kansas State University, 1978; Kansas Water Altas, 1967b, Kansas Water Resources Board; Water in Kansas, 1955, Kansas Water Resources Fact-Finding and Research Committee; Perry, 1993, U.S. Geological Survey, Circular 1120-E; U.S. Geological Survey, Water Supply Paper 2375; and Wetter, 1987.

Climate controls the amount of water that enters the surface-water and ground-water systems. Therefore the resulting surface- and ground-water hydrology also are included under this general heading.

Precipitation

SOURCES OF ATMOSPHERIC MOISTURE, PRECIPITATION, AND SNOWFALL

Located at midlatitudes in the heart of North America, Kansas has a distinct continental climate characterized by sizable monthly, seasonal, and year-to year variations in temperature, precipitation, cloudiness, and wind. The primary sources of moisture in Kansas are the Gulf of Mexico and the subtropical Atlantic Ocean, with the Pacific Ocean being a secondary source. The quantity and timing of the precipitation are, in part, a function of the state's distance from these moisture sources; this accounts for the precipitation variability across the state.

Kansas tends to receive less precipitation during winter than summer. During winter, most of the state's moisture comes from the northwest and west; this moisture originates over the Pacific Ocean and precipitates over the high mountain barrier of the Rocky Mountains. As a result, it is depleted by the time it reaches Kansas and therefore it is not a major source of precipitation in the area. During summer, southerly winds move moisture originating over the Gulf of Mexico into the state. Unlike the winds from the Pacific Ocean, these south winds do not encounter major mountain barriers (although the low Ouachita Mountains of eastern Oklahoma and western Arkansas intercept some of the moisture). The western part of the state is considerably farther from the Gulf of Mexico than eastern Kansas, and since there is a general tendency for moving air in the midlatitudes (the state lies in the zone of the prevailing westerlies, a zone famous for frequent cyclonic storms) to be deflected to the east, even the onshore southerly winds tend to shift eastwards as they move over the state. Thus, Kansas precipitation decreases toward the north and west. Occasionally, remnants of tropical cyclones, including hurricanes originating in the Gulf, move into the state and produce considerable precipitation.

Many of the storms in Kansas approach from the north and northwest, bringing air from colder source areas unable to supply much atmospheric moisture. These northern air masses confront the warmer humid air masses that invade the area from the south (Gulf) where the warm moist air is forced upward over the cold fronts, expand and condense into cloud droplets, and ultimately produce precipitation. Thus, warm moist air from the south is the major source of precipitation in Kansas. The general directions of movement and the relative quantities of moisture that enter Kansas are shown in fig. 1.1.

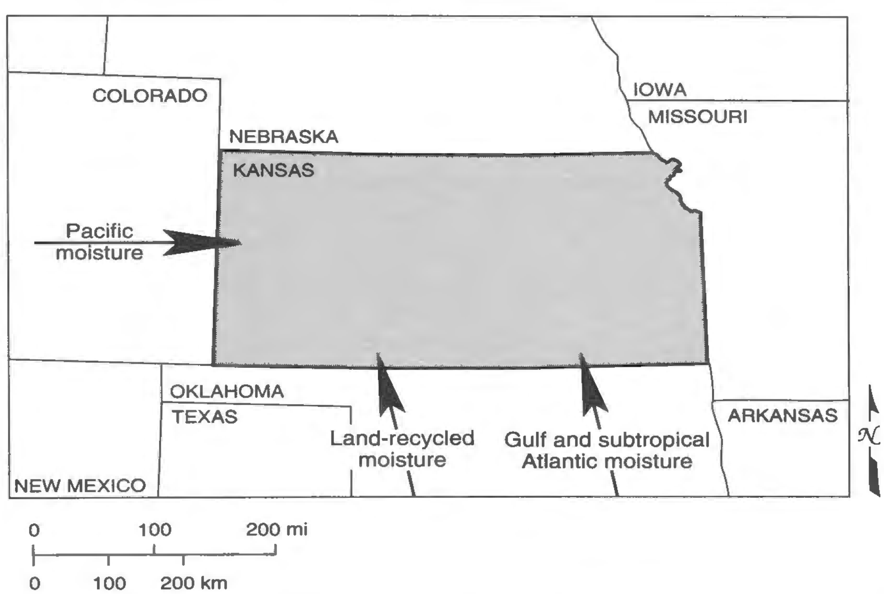


FIGURE 1.1—PRINCIPAL SOURCES AND PATTERNS OF DELIVERY OF MOISTURE INTO KANSAS (adapted from U.S. Geological Survey, 1991).

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean air mass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Because the Gulf of Mexico is the principal source of moisture for most of Kansas, the part of the state nearest the Gulf (i.e., southeastern Kansas) receives the most precipitation. Southeastern Kansas averages about 40 inches (101.5 cm) of precipitation annually, whereas areas along the western border of the state average 16 inches (40.5 cm) or less.

About 75% of the state's annual precipitation occurs from April to September (fig. 1.2), which is of great importance to farming. June is the wettest month, with precipitation for that 30-day period averaging 3 to 4 inches (7.5–10 cm) in the western third of the state, 4 to 5 inches (10–12.5 cm) in the middle third, and 5 to 6 inches (12.5–15 cm) over the eastern third. After September, precipitation declines sharply. Winters tend to be dry, particularly in the west. Normal precipitation for December and January, the driest months, is less than 0.5 inch (1.3 cm) per month over the western one-third of the state.

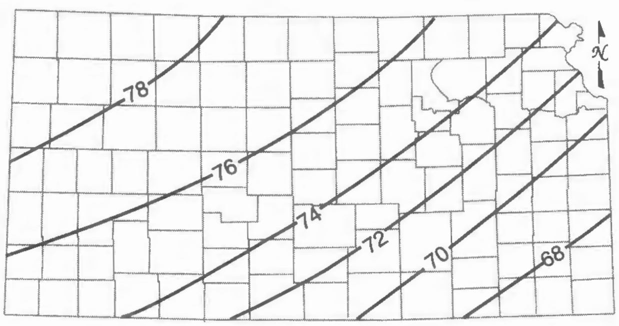


FIGURE 1.2—PERCENT OF ANNUAL PRECIPITATION RECEIVED FROM APRIL TO SEPTEMBER (adapted from KWRB, 1967B).

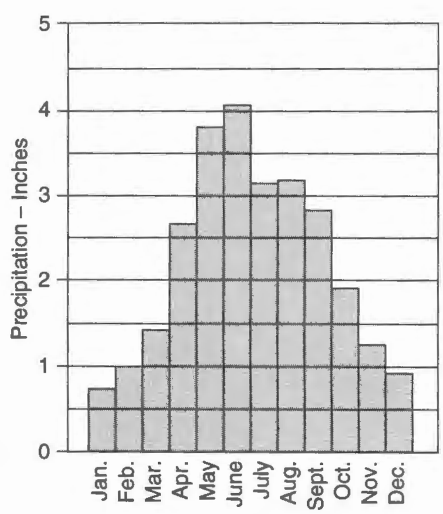


FIGURE 1.3—MEAN MONTHLY PRECIPITATION IN KANSAS DURING THE 1887-1945 PERIOD (adapted from Flora, 1948).

The mean monthly precipitation in Kansas is shown in fig. 1.3.

The number of days per year with 0.01 inch (0.025 cm) or more of precipitation ranges from 53 in extreme southwest Kansas to 100 in the east-central and extreme southeast. Over parts of western Kansas less than 0.25 inch (0.6 cm) of precipitation falls on two-thirds of the days with measurable precipitation. Precipitation from such storms is usually of little benefit to crops due to high evaporation from the soil-surface layer during the growing season.

Annual precipitation varies greatly from year to year. In southwest Kansas, for example, normal yearly precipitation is about 19 inches (48 cm), but in one year out of three it is often less than 14 inches (35.5 cm) or more than 24 (61 cm). Once each 100 years on average, precipitation can be as low as one-half the annual average at a location or as much as twice the average. The variability tends to be greater in western and south-central Kansas than in the more humid eastern region. Over a long period, there may be consecutive sequences of several years of below-normal precipitation. Normal annual precipitation increases uniformly from about 17 inches (43 cm) along the western border to over 40 inches (101.5 cm) in the extreme southeast. Figure 1.4 shows average annual precipitation estimates for Kansas.

Annual snowfall averages near 10 inches (25 cm) in the south-central area of the state, increasing to 20-25 inches (51–63.5 cm) in the northeast and to 25-30 inches (63.5–76 cm) in the northwest.

STORMS AND RAINFALL INTENSITY

Practically all of the winter precipitation and much of the summer precipitation in Kansas occurs along the line of contact between cold air masses moving down from the northwest and warm, moist air moving up from the Gulf of Mexico. Spring and summer rainstorms tend to be (1) thunderstorms, which produce intense rains of short duration and cover relatively small areas or (2) storms that last for several days and cover thousands of square miles.

The graphic analysis of Kansas rainfall records, shown in fig. 1.5, reveals that the intensity of precipitation in a 50-year frequency storm (that is a storm which has a probability of being equaled or exceeded once in 50 years) can be expected to be about twice as great as for a 2-year frequency storm for durations of both 2 hours and 24 hours. [It must not be inferred that a 50-year-frequency storm, for example, can be expected to occur at regular 50-year intervals or that, having occurred once, it will not occur again for 50 years. Rather, over a long period of record of say 500 years, 10 such storms would have occurred; or, in any one year, there is a 2% (1/50) chance that a storm of this magnitude will occur.] The intensity increases from northwest to southeast. The series of maps depicts 2-hour and 24-hour duration maximum storms that have a chance of being equaled or exceeded every 2, 10, and 50 years. The 2-hour duration storms are related to thunderstorm activity, whereas the 24-hour duration storms are usually related to more general storms. The 2-year frequency gives an idea of the maximum amount of rainfall that might be equaled or exceeded on an average, once every other year during a 2- or 24-hour storm. The 10- and 50-year frequencies indicate the type of storm that could produce flooding. The maximum known rainfall for 2- and 24-hour storms occurs much less frequently than once in 50 years.

PRECIPITATION RELIABILITY

As mentioned earlier, Kansas is fortunate that, on an average, about 75% of the annual precipitation occurs during the crop-growing season. Although average values of precipitation are of interest for comparative purposes, the variations from the average are of much greater practical significance. Either too much rainfall in a short period of time or too little over a long period can be disastrous.

Graphic analyses have been made of the probable annual, seasonal, and monthly precipitation at five individual stations for the state (Colby, Garden City, Ellsworth, Horton, and Iola). The three maps in fig. 1.6 present annual amounts of precipitation that can be expected to be equaled or exceeded 10%, 50%, and 90% of the time. The 10% reliability means that there is a 10% chance of the amount being equaled or exceeded or, conversely, a 90% chance of the amount of rainfall being less; the 50% chance is one that has an equal chance of being more or less; the 90% reliability indicates that the amount can be expected to be equaled or exceeded 90% of the time or, conversely, that the rainfall will be less than the indicated amount 10% of the time.

Temperature

Strong solar radiation in summer and occasional surges of arctic air in the cold season combine to give Kansas a large annual range in temperature. In every year of record, the maximum temperature for the state has been

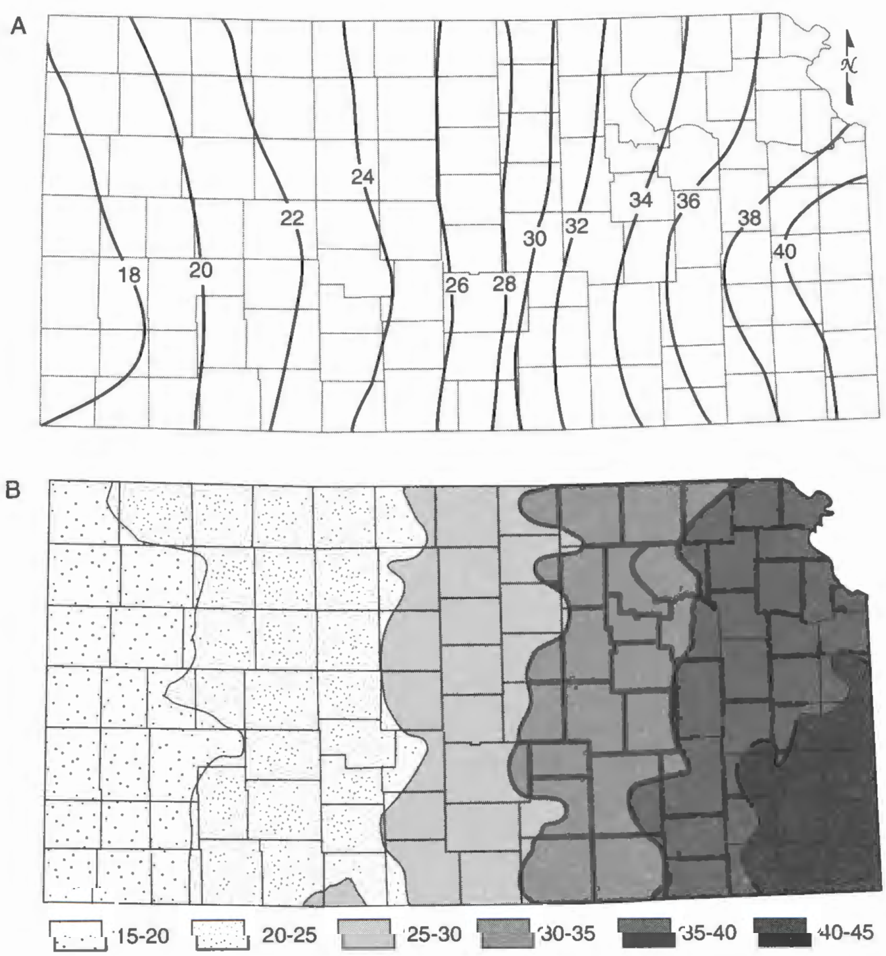


FIGURE 1.4—A) MEAN ANNUAL PRECIPITATION IN INCHES—1941-1970; B) MEAN ANNUAL PRECIPITATION IN INCHES—1961-1990. [A) adapted from Wetter, 1987; B) adapted from Goodin et al., 1995.]

above 100°F (37.8°C) and the low temperature has been below zero. The extremes of record are -40°F (-40°C) and 121°F (49.4°C). The relatively long warm season extends from about mid-April to mid-October. The three months of December through February make up the cold season, while March to mid-April and mid-October to late November are short transitional periods between winter and summer. In fall, winter, and spring, fair days are usually intermingled with short periods of stormy weather. Spring is the season with the most marked and rapid weather changes.

Temperature variations over the state are due primarily to elevation and latitude differences. Average temperatures in Kansas increase from north to south. The average annual temperature in Kansas ranges from about 58°F (14.4 °C) along the south-central and southeastern border to 52°F (11.1°C) in the extreme northwest as shown in fig. 1.7. Daily temperature ranges, on the average, amount to about 20°F (11.1°C) in the east and 30°F (16.7 °C) in the higher and drier elevations of the northwest.

Winter temperatures are considerably higher in south-central and southeast Kansas than in other sections. The normal minimum January temperature varies from 14°F (-10°C) in the northwest to 24°F (-4.4°C) in the extreme southeast. January maximum temperatures follow the same pattern, but regional differences are not as great. In summer, regional differences in temperature are not large. July normal minimum temperatures increase from northwest to southeast, ranging from around 61°F (16.1°C) to 69°F (20.5°C). July normal maximum temperatures only vary from 88°F (31.1°C) in the extreme northeast to about 95°F (35°C) in the south-central.

The growing season, the average length of time between the last killing frost in spring and the first in fall, ranges from 150 days in the northwest corner of Kansas to over 200 days in the southeast (fig. 1.8). Considerable variation occurs from year to year but even in years with shortened growing seasons, crops usually mature with little or no damage.

Winds

Winds are moderate to strong in all seasons. The windiest period is spring, when low-pressure storm systems frequent the area. The prevailing wind is southerly, but northerly winds are fairly common, particularly from December through March. During periods of dry weather in spring and fall, soil blowing can be a hazard in central and western Kansas. However, improved technology since the late 1940's has tended to minimize soil losses due to blowing. Winds average about 15 mph (24 km/hr) in the west and 10 mph (16 km/hr) in the east.

Evapotranspiration

The combined evaporation from the soil surface and transpiration from plants, called "evapotranspiration,"

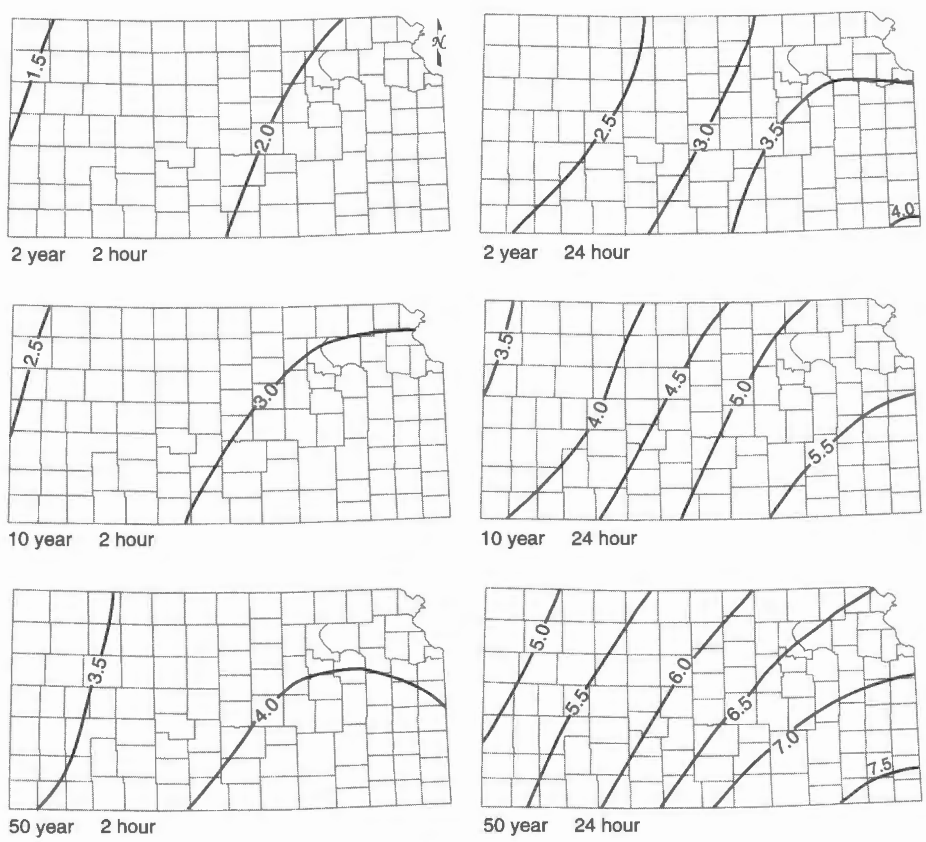


FIGURE 1.5—RAINFALL INTENSITIES IN INCHES IN KANSAS. See text for explanation (adapted from KWRB, 1967b).

represents the transport of water from the earth back to the atmosphere, the reverse of precipitation. Most of the state's precipitation is lost to evapotranspiration. The proportion that returns to the atmosphere at any point depends especially upon the temperature and is thus greatest in summer and least in winter. The proportion is also influenced by such variables as amount, duration, and intensity of rainfall; geology and topographic form; nature and density of the vegetative cover; porosity, moisture content, and other properties of the soil; and landscape modifications made by humans.

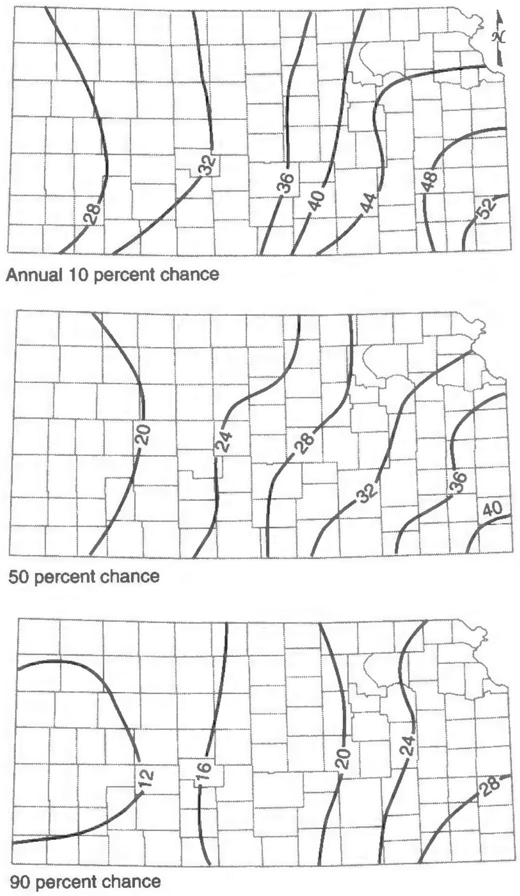


FIGURE 1.6—ANNUAL PRECIPITATION RELIABILITY (INCHES). See text for explanation (adapted from KWRB, 1967b).

The average annual rate of evapotranspiration throughout the state is shown in fig. 1.9, which can be compared to fig. 1.4 showing average annual precipitation. Figure 1.9 has been developed by subtracting the average annual runoff, as shown by stream gaging, from the average annual precipitation. This graph shows that evapotranspiration in Kansas is not controlled by temperature alone, for the rate is more than 30 inches (76 cm) at the eastern edge of the state and less than 18 inches (45 cm) in the southwest corner with the same average temperatures of 55°F (12.8°C). In regions of more plentiful water supply, the lines of equal rate of evapotranspiration would generally be parallel to the lines of equal temperature. In Kansas, however, some parts of the state do not have enough water to deliver to the atmosphere as rapidly as it can be absorbed. In other words, evapotranspiration is limited by the available supply at the land surface, and that in turn reflects the pattern of precipitation, decreasing to the west. This is clearly shown in fig. 1.10: more than 99% of the rainfall is returned to the atmosphere in 14 southwestern counties, and more than 95% is returned throughout the western half of the state. In eastern Kansas, an average of 85% of the rainfall is returned to the atmosphere.

The maximum amount of evapotranspiration that can occur in an area is governed by its climate. Temperature and wind are dominant factors. This maximum value, called potential evapotranspiration, varies across Kansas. Figure 1.11 shows values ranging from 44 inches (112 cm) per year in northeast Kansas to 68 inches (173 cm) in

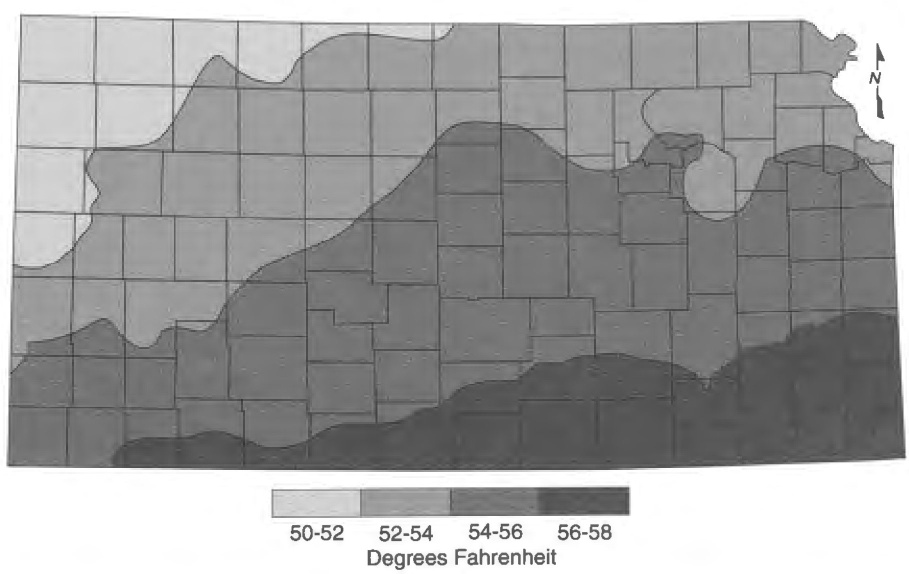


FIGURE 1.7—AVERAGE ANNUAL MEAN TEMPERATURE (1961-1990) in degrees Fahrenheit (adapted from Goodin et al., 1995).

southwest Kansas, as estimated using a) the modified Penman's equation for calculating potential evapotranspiration (ET_0) for a reference green-grass cover of uniform height completely shading the ground and not short of water (Lucas, 1982), and b) free-water surface or shallow-lake evaporation based on pan evaporation and other data (Farnsworth et al., 1982). Free water-surface evaporation is considered to be approximately equivalent to potential evaporation from a shallow water surface, and to potential evapotranspiration from a vegetative surface with an unlimited supply of water. The actual amount of evapotranspiration that can occur on an average, long-term basis will not exceed this potential. Appendix A contains the data sources and values on which fig. 1.11A is based, plus the average daily potential evapotranspiration (Penman ET_0) by month across Kansas, as calculated by the U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS) using the United Nations Food and Agriculture Organization (FAO)-recommended methodology (Doorenbos and Pruitt, 1977). In contrast to the above two estimates, the potential average annual evapotranspiration based on the empirical temperature-based Thornthwaite (1948, 1952) methodology shows values ranging from 27 inches (68.5 cm) per year in northwest Kansas to 33 inches (84 cm) in southeast Kansas (fig. 1.11C). These estimates are much lower than the previous two estimates, and they seem to be representing the land vegetative cover *consumptive* water use, i.e. the Thornthwaite estimates seem closer to actual evapotranspiration values than the other two estimates.

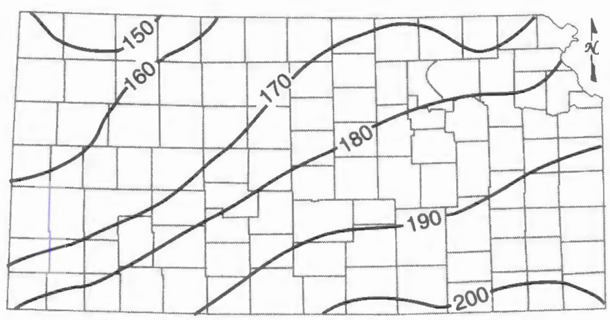


FIGURE 1.8—Average annual growing season (days) in Kansas (adapted from KSU, Agric. Exp. Sta., Dec. 1959, presented in Self, 1978).

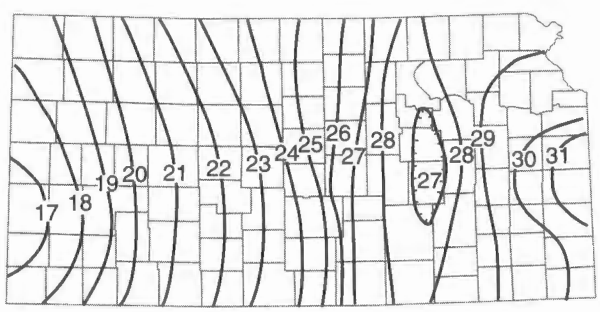


FIGURE 1.9—Mean annual evapotranspiration, inches; (precipitation minus runoff) [adapted from Wetter, 1987].

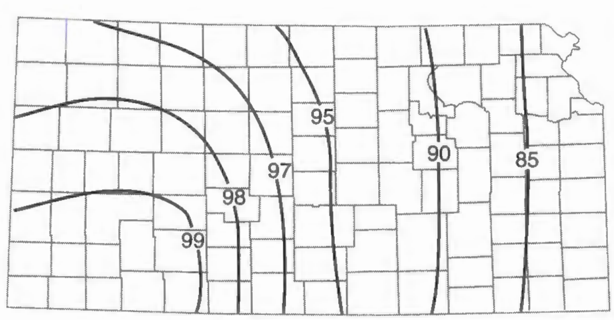


FIGURE 1.10—Mean annual evapotranspiration in percent of rainfall (adapted from Kansas Water Resources Fact-Finding and Research Committee, 1955).

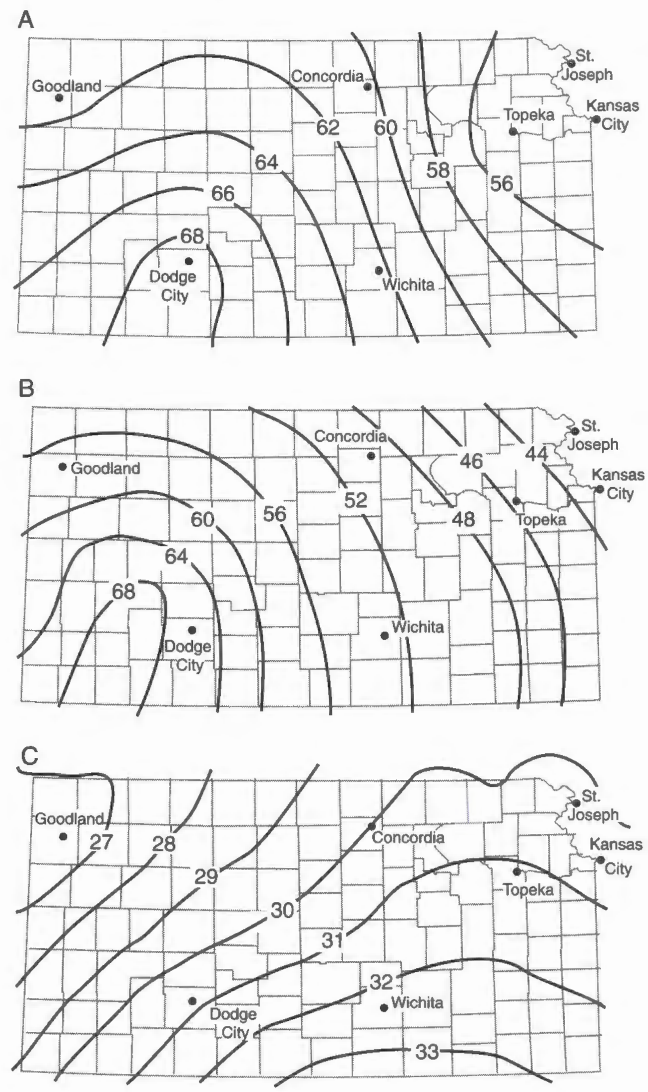


FIGURE 1.11—A) Annual (1979) Penman potential evapotranspiration, ET_0 (inches); B) Annual (1956-1970) free water surface evaporation (inches) [adapted from Farnsworth et al., 1982]; C) Potential average annual (1901-1930) Thornthwaite evapotranspiration (inches) [adapted from Wetter, 1987].

Figure 1.12A and B shows mean annual precipitation minus potential evapotranspiration estimated as per fig. 1.11 A and B, respectively, across Kansas. On average, a deficit of precipitation increases significantly to the west. This is dictated by climate; we can change it very little. Figure 1.12C shows the same quantities but is based on Thornthwaite's values. According to this figure, the eastern third of Kansas has positive values; on average, a surplus of precipitation exists in the east and a deficit in the west, which seems compatible with empirical evidence. The big differences in values in figs. 1.11 and 1.12 reflect the large uncertainties and difficulties in estimating potential evapotranspiration.

Surface Water and Runoff

Surface water is distributed unevenly across Kansas. With few exceptions, western Kansas has little surface water. Ground water is the principal source of freshwater in most of this area, but more ground water is being withdrawn than is being recharged. 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. About half of the population of Kansas is served by surface water.

The Kansas and Arkansas river systems are the state's major drainage ways (fig. 1.13). Other important rivers include the Big Blue, Cimarron, Marais des Cygnes, Neosho, Republican, Saline, Solomon, Smoky Hill, Verdigris, and Walnut rivers (shown in fig. 1.35). The Missouri River forms the boundary from the northeastern corner of the state southeasterly to Kansas City. The Kansas River basin (fig. 1.13) has a total area of 60,000 mi^2 (155,400 km^2) above its confluence with the Missouri River at Kansas City, and 34,500 mi^2 (89,355 km^2) of this total lie in Kansas. The Arkansas River drains an area of about 45,000 mi^2 (116,550 km^2) above the Oklahoma–Kansas state line (fig. 1.13) with about 20,000 mi^2 (51,800 km^2) of this total in Kansas. These totals do not include tributaries that join the Missouri River outside of Kansas or tributaries that join the Arkansas River below the Kansas state line.

The larger surface-water sources are in the central and eastern part of the state, whereas the major ground-water sources are in western Kansas. Average annual runoff across the state varies much more than the precipitation (fig. 1.14). By comparison, the average runoff ranges from approximately 10 inches (25 cm) in the east (25% of precipitation) to 0.1 inch (0.025 cm) in the west (less than 0.6 of 1% of the precipitation).

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 of ungaged streams entering the state adds little to this total since most of the streams are dry except immediately following heavy rains. The precipitation falling over the state amounts to 118.7 million acre-feet (146.4 km^3) in an average year, and about 13 million acre-feet per year (16 km^3/yr) leaves the state as streamflow. The streams annually accumulate 11.3 million acre-feet (13.9 km^3) of runoff within the state (fig. 1.0). The approximately 107.4 million acre-feet (132.5 km^3) of precipitation that does not become surface runoff is accounted for by evaporation, transpiration, ground-water recharge, storage in existing lakes and ponds, and by all other consumptive uses of surface water.

Conservation Practices and Runoff

The NRCS [previously the Soil Conservation Service (SCS)] Curve Number (CN) rainfall-runoff technique is a well-known method, widely used to estimate storm runoff

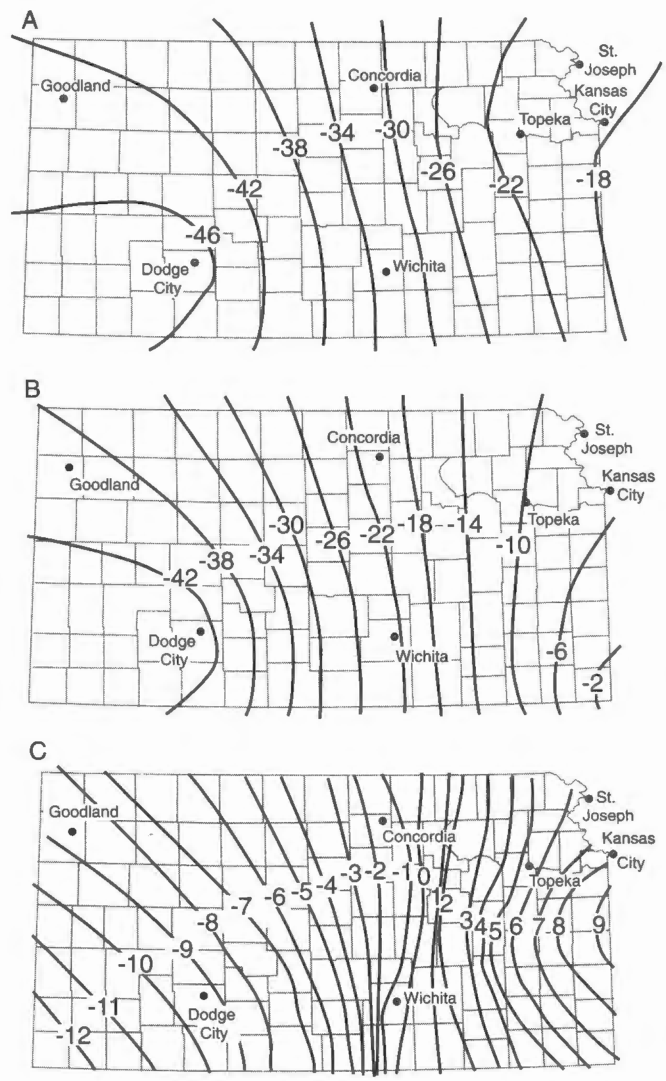


FIGURE 1.12—A) ANNUAL PRECIPITATION NORMAL MINUS PENMAN POTENTIAL EVAPOTRANSPIRATION, ET_0 (INCHES); B) Annual precipitation normal minus free water surface evaporation (inches); C) Mean annual precipitation minus Thornthwaite potential evapotranspiration (inches). [C) adapted from Wetter, 1987].

from watersheds with various kinds of soil and land use. The curve number is an empirical rating of the hydrologic performance of a large number of soils and vegetative covers throughout the United States. Runoff curve numbers for various combinations of soil, cover, and land-use practice are widely tabulated by the NRCS. Figure 1.15 is a graph of annual surface runoff versus annual precipitation for different runoff curve numbers (CN). It is a simple way of estimating changes in runoff through installation of conservation measures, changes in land use, and changes in agricultural-management practices. Curve-number reductions are translated directly into reductions in surface runoff. Table 1.1 is a standard table of NRCS curve numbers that can be used for various conservation practices. For example, if one changes the land-use condition or practice of a cultivated field from the category "no residue, no terrace" in table 1.1 to "storage-type terrace," then by noting the resulting change in CN from table 1.1, one could estimate the resulting change in annual runoff from that field from fig. 1.15.

TABLE 1.1—RUNOFF CURVE NUMBERS FOR USE IN KANSAS (antecedent moisture condition II) according to Natural Resources Conservation Service Field Manual, Kansas supplement.

Land Use or Cover[1]	Condition or Practice[1]	Hydrologic Soil Group[5] A	B	C	D
Miscellaneous[2]		72	82	87	89
Cultivated	Gradient Terraces	62	71	78	81
Cultivated	Storage Type Terraces[3]	40	60	67	70
Cultivated	No Residue, No Terrace	72	81	88	91
Cultivated	With Residue, No Terrace	66	77	84	88
Grassland	Poor Vegetative Cover	68	79	86	89
Grassland	Fair Vegetative Cover	49	69	79	84
Grassland	Good Vegetative Cover[4]	39	61	74	80

[1]Use estimated long-term land use and condition
[2]Includes roads, farmsteads, urban, etc. (about 3% for most rural areas)
[3]Includes flat pothole areas and other areas with significant storage
[4]Includes meadow and woodland
[5]Classification of soils by their hydrologic properties, four classes:

- •A: high infiltration, low runoff, as for sands and gravel, aggregated silts
- •B: moderate infiltration, as for moderately fine to moderately coarse-textured soils such as sandy loam
- •C: slow infiltration, as for fine-textured soil such as clay loam, soils low in organic content
- •D: very slow infiltration, such as swelling and plastic clays, and claypan

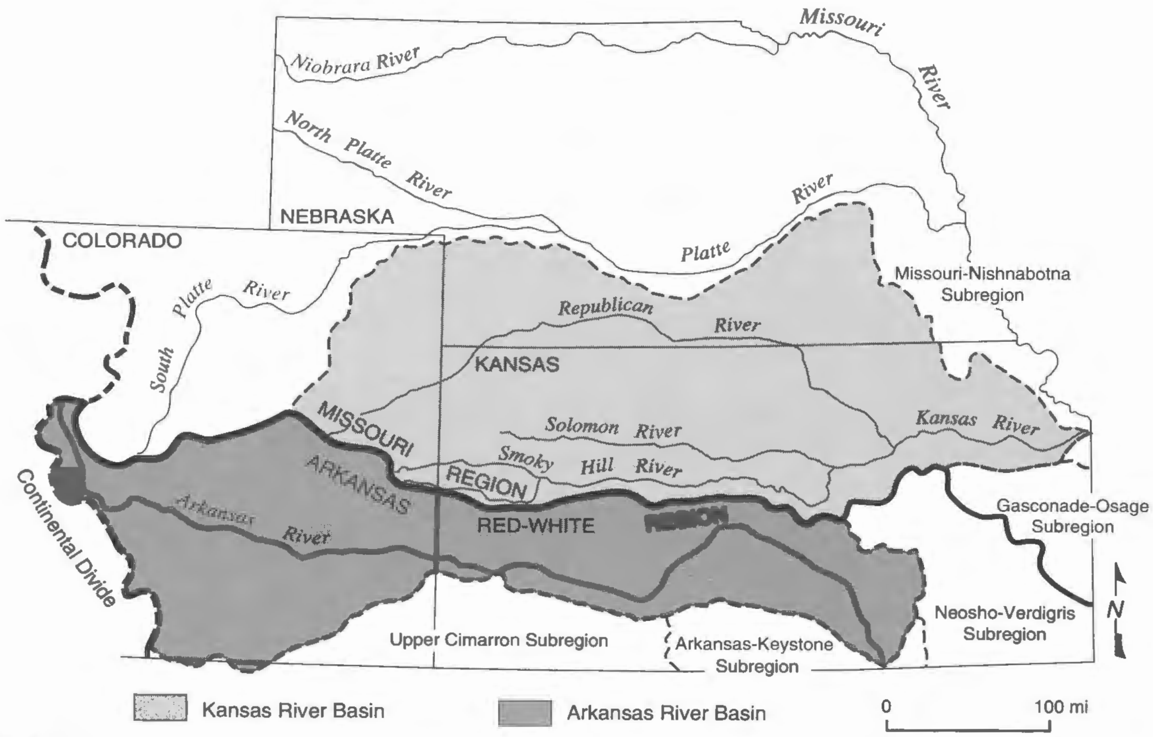


FIGURE 1.13—KANSAS AND ARKANSAS RIVER BASINS.

Figure 1.16, modified from work by Rawls et al. (1980) relates reduction in curve numbers to crop residue cover on the soil. Reducing the CN for a field results in reducing the amount of runoff from that field, as shown in fig. 1.15. In eastern Kansas, the terraces, ponds, planned grazing systems, and fields with conservation tillage hold back water that otherwise would have run off during or immediately following rains. Some of this water then drains slowly through the soil to the streams. This helps maintain some baseflow between rains and increases available surface-water supplies during normal and wet years.

In western Kansas good range-land management and conservation-farming methods (such as residue management, minimum tillage, no-till, storage-type level terraces, and flat-channel terraces) hold water where it falls. Crop production increases, but runoff decreases and, for all practical purposes, runoff stops entirely in average years in many areas. In western Kansas average annual runoff is only 0.5 inch (1.25 cm) or less, whereas precipitation averages about 20 inches (51 cm). During drier years, regardless of location within the state, conservation practices will decrease runoff. These practices are most effective at reducing runoff from small storms and have limited effect on runoff from large storms. During drier years, runoff is low to begin with and conservation practices hold back a greater portion of it; this in turn, is lost as evapotranspiration rather than becoming runoff or ground-water recharge. About 3% of total precipitation results in runoff and deep percolation. The remaining 97% leaves by evaporation and transpiration (evapotranspiration), as shown by fig. 1.17.

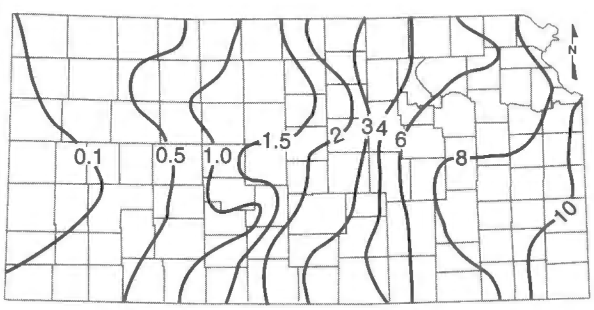


FIGURE 1.14—MEAN ANNUAL RUNOFF IN INCHES (adapted from Wetter, 1987).

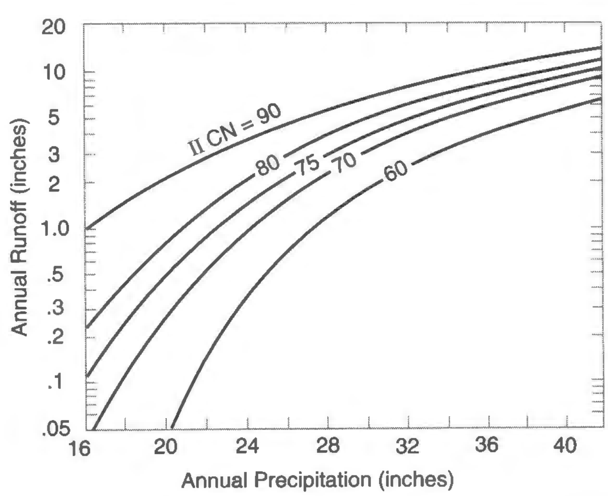


FIGURE 1.15—RUNOFF VS. PRECIPITATION IN KANSAS (adapted from Wetter, 1987).

Streamflow Frequencies

The annual runoff is made up of streamflows of various magnitudes and durations. A knowledge of those magnitudes and durations, their expected frequency of recurrence, and their chances of being equaled or exceeded is necessary for reliable evaluation of the adequacy and economic feasibility of water-supply and flood-protection projects.

FLOOD FLOWS

Experience indicates that overflows along most streams are inevitable. These overflows have created the floodplain areas adjacent to the streams. By occupying many of these floodplain areas, people risk damages from flooding. To prevent or minimize such flood damage, estimates are needed of the probable recurrence intervals for floods of various magnitudes.

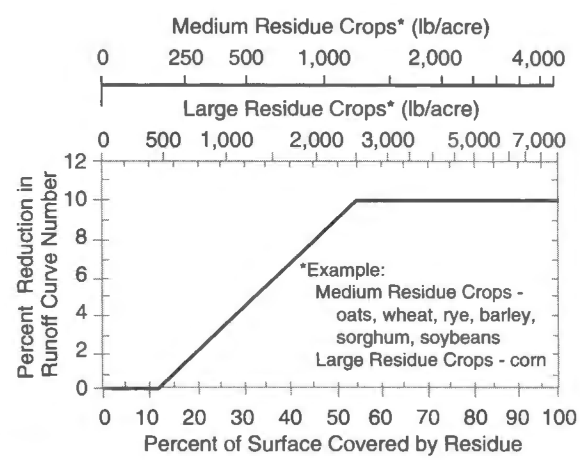


FIGURE 1.16—CROP RESIDUE EFFECT ON NATURAL RESOURCES CONSERVATION SERVICE (NRCS) RUNOFF CURVE NUMBER (adapted from Rawls et al., 1980).

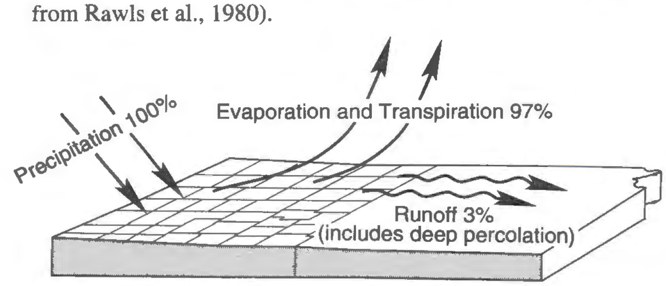


FIGURE 1.17—SIMPLIFIED WESTERN KANSAS HYDROLOGY (adapted from Wetter, 1987).

A **recurrence interval** is the average period of time in which the given runoff will be equaled or exceeded once. For example, a runoff peak discharge that has a five-year recurrence interval can be expected to be equaled or exceeded once every five years on the average. This is the same as saying that the peak discharge has a 20% chance of being equaled or exceeded once in any given year (100%/5 = 20%).

Some flooding occurs within the state almost every year. Although the pattern of recurrence of floods is quite irregular, most streams in the state can be expected to reach flood stage about once in two years on the average and to reach a stage of considerable flooding about once in five to 10 years on the average. Major destructive floods are likely to occur less often. Floods causing major damages can be expected to occur along many of the streams in the state about once in 50 years. However, the expected recurrence interval of floods as large as the Kansas River flood in 1951 cannot be adequately determined because streamflow records have not been kept long enough to indicate the recurrence interval.

The expected magnitude of floods having recurrence intervals of 10 and 50 years is shown in fig. 1.18 for drainage basins having an area of 500 mi² (1,300 km²). Several interesting comparisons can be drawn from these maps. The maps indicate that the ratio of the 50-year to the 10-year flood is about 2 to 1, whereas the maps on fig. 1.5 indicate that the ratio of the corresponding rainfalls is only about 1.3 to 1. A comparison of the 50-year flood to the two-year flood (not shown) would indicate a ratio of about 5 to 1, while the ratio of the corresponding rainfalls is only about 2 to 1. These comparisons indicate that the flood peak discharges have a greater variation than the rainfalls that produce the discharges. This variation is due to the infiltration capacity of the soil being exceeded by the rainfalls that have the greater recurrence intervals. In other words, as the infiltration capacity of the soil is exceeded by the precipitation, the runoff rate and amount increases.

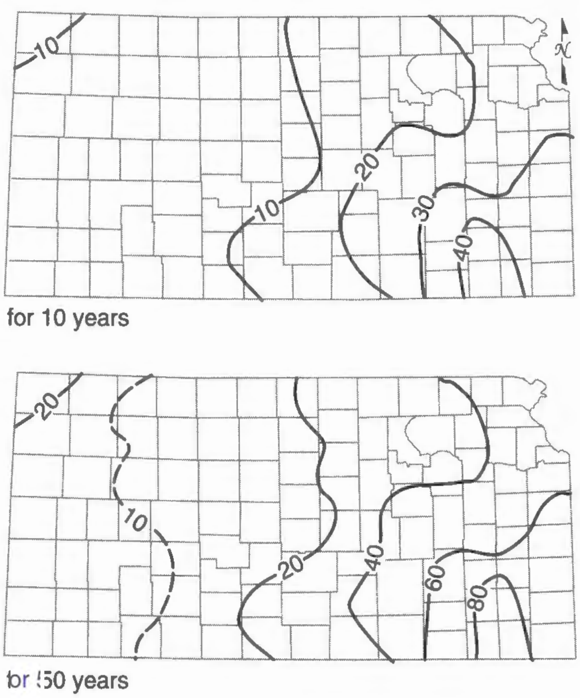


FIGURE 1.18—FLOOD-FLOW FREQUENCIES. Values are in thousands of cubic feet per second (cfs) for 500 mi² (1,300km²) of drainage area. See text for explanation (adapted from KWRB, 1967b).

The amount of discharge shown on the maps (fig 1.18) is to be expected only from basins having drainage areas of 500 mi² (1,300 km²). This 500-mi² (1,300-km²) area provides a common base for the lines of equal runoff and allows easy comparison of the probable high flows to be expected in different parts of the state. The flood peak discharges for basins having greater or smaller drainage areas are related to but not directly proportional to the size of the drainage basin.

LOW FLOWS

Low-flow frequency information is of major importance in providing answers to many water-supply and water-use questions. This information is necessary for the determination of the minimum water supply that can be provided directly from streamflow, the amount of storage needed to ensure a water supply of a given size, and the quantity of industrial and municipal wastes that can be adequately diluted by the stream.

The lowest average flows expected to be equaled or exceeded an average of once in two years from a drainage area of 500 mi² (1,300 km²) are shown in fig. 1.19. These flows are the lowest average flows to be expected during three different periods of consecutive days (120, 30, and 7 days) for a two-year recurrence interval. The maps indicate that the extent of the area in which zero flow can be expected increases as the number of consecutive days decreases, which means that short periods of no flow are more likely to occur than are long periods of no flow. This area of zero flow also increases considerably when the recurrence interval is increased only a few years.

Floods and Droughts

FLOODS

Floods in Kansas are caused by several different mechanisms, all dependent on a large flow of moist air from the south. One mechanism is a cool air mass from the north that becomes stationary over southern Kansas or

Oklahoma for several days. A frontal system is formed as warm, moist air moving northward from the Gulf of Mexico rises over the cooler, heavier air. Because the frontal system is stationary, rain can fall for several consecutive days. When the moisture supply is large, rainfall totals can be 10 to 15 inches (25–38 cm) over large areas.

Another flood-producing mechanism is the slow-moving, intense thunderstorm. These storms can produce local flash floods and result in extensive property damage and loss of life. The floods can be especially destructive in urban areas where drainage systems are not adequate to remove the runoff.

A third mechanism, although not common, involves dissipating tropical cyclones, including hurricanes, that move northward from the Gulf of Mexico carrying tremendous quantities of moisture. Occasionally, the remnants of hurricanes merge with frontal systems moving through the state. The combination can produce intense rainfall and severe flooding.

COMPARISON OF 1951 AND 1993 FLOODS

The flood of 1951 on the Kansas River is considered the largest flood in the Kansas River basin during the 20th century. It had a peak discharge of 510,000 ft^3/sec (14,440 m^3/sec) at De Soto, Kansas. The flood of 1903 ranks second, with an estimated peak discharge of 337,000 ft^3/sec (9,540 m^3/sec). Even if the state's reservoirs had not been in place, the 1993 flood is estimated to be about 266,000 ft^3/sec (7,530 m^3/sec; about 50% of the 1951 flood), thus ranking it third. Peak discharge, however, is only one way of ranking floods; another way is to compare flood volumes, or total amounts of flow through a river during a given period. This type of ranking is usually more consistent with the longer term, widespread climatic patterns that are responsible for the flooding. Instantaneous peaks greatly depend on storm intensities, timing, and direction of movement, which are critical in the development of large floods. However, total rainfall during the flooding period correlates closely with total flood volumes.

The total volumes of the floods of 1951 and 1993 are comparable because they occurred at nearly identical times of the year and the precipitation patterns also were quite similar. The total flood volume from April 1 to September 30, 1951, was 19,500,000 acre-ft (24.1 km^3) compared with 18,500,000 acre-ft (22.8 km^3) for the same period in 1993 (this includes the amount in flood-control pools on October 1, 1993). However, the timing of the flood discharges from the tributaries was different, in addition to the attenuating impact of the flood-control reservoirs throughout the Kansas and Missouri River basins, resulting in a much smaller flood peak discharge in 1993 than that of 1951.

DROUGHTS

In a semiarid region of variable precipitation, a drought can be difficult to define. Even in the eastern one-third of the state, where annual precipitation is much greater, dry periods of several weeks are frequent. **Meteorological drought** is defined by Palmer (1965) as "...an interval 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." **Agricultural drought**, a related concept, occurs only when available soil moisture is inadequate to meet evaporative demand by plants. **Hydrologic drought** refers to periods of below-normal streamflow. Widespread

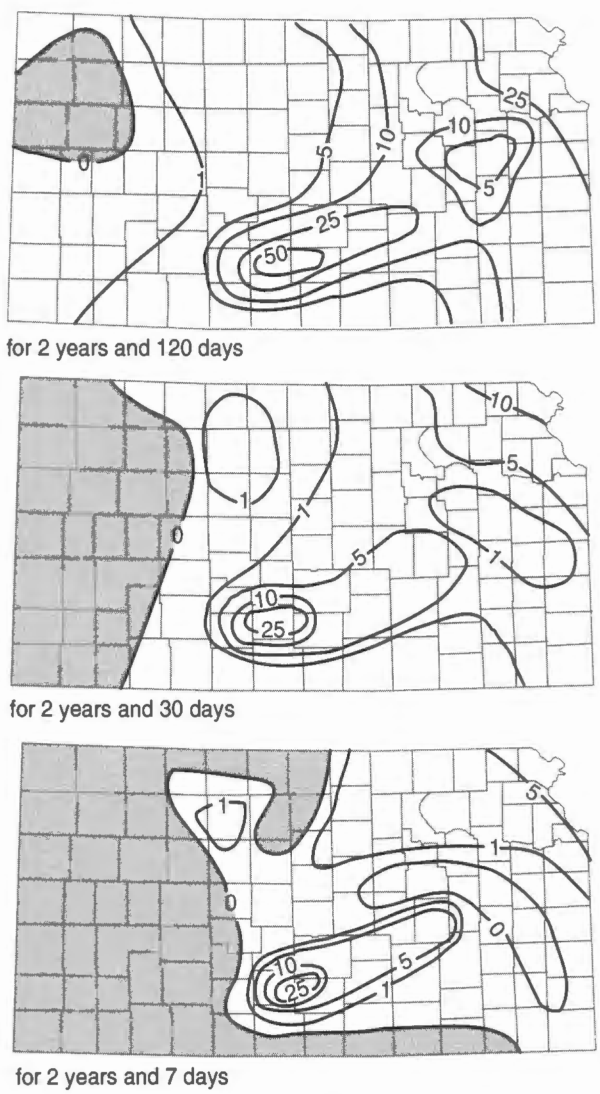


FIGURE 1.19—LOW-FLOW FREQUENCIES. Values are in cubic feet per second (cfs) for 500 mi^2 (1,300 km^2) of drainage area. See text for explanation (adapted from KWRB, 1967b).

drought affects Kansas when the area is dominated by high atmospheric pressure. The absence of significant vertical air movement within these high-pressure systems does not allow the convection necessary to produce clouds and precipitation. During periods of drought, the general circulation shifts the flow of moist air from the Gulf of Mexico farther east. Then Kansas is under an air flow that originates over the plateaus of Mexico, a hot and extremely dry region. Thus, little moisture is in the air to produce precipitation even by artificial means.

Several severe droughts—determined by analysis of streamflow data—have occurred in Kansas since 1900. All affected the entire state. The most severe droughts were during 1929–1941 and 1952–57.

Topography

Largely extracted from KWRB, 1967b; O'Connor, 1981; and Self, 1978.

Topography also affects the state's water resources. When two areas have similar geology and climate, it is easy to depict a series of rainfall events in which runoff from nearly flat areas would be absent or nearly absent, but on steeply sloping land would be appreciable. Thus topography affects storm runoff and infiltration; it also affects the suitability of a site for a dam and surface-water impoundment.

The regional topography of Kansas is depicted in the geologic cross section shown on fig 1.20. In general, it is an eastward-sloping plain, with a slightly steeper slope in the western half and a somewhat more gentle slope in the eastern half. The surface of Kansas generally slopes upward from elevations of about 700–1,000 ft (210–300 m) above sea level in the east (the lowest point, 680 ft [207 m], is near Coffeyville where the Verdigris River leaves the state), to elevations exceeding 4,000 ft (1,220 m) in the west (highest point 4,039 ft [1,231 m] near the Colorado border in Wallace County north of the Smoky Hill River) (fig. 1.21). The difference between the lowest and highest points gives Kansas a total relief of 3,359 ft (1,024 m). If this total relief were condensed within a hundred miles of the eastern border of the state, Kansas would have a mountain range as high as most of the Blue Ridge of the Appalachian Mountains (Self, 1978). Instead, the elevation rises gradually from east to west at an average rate of approximately 10 ft per mile (1.9 m/km). In southeast Kansas, from the Verdigris River to the southeast corner of the state, the elevation also rises eastward toward the Ozark Plateau in Missouri at the rate of approximately 10 ft per mile (1.9 m/km).

Kansas lies in three major physiographic divisions of the United States. The extreme southeast corner of the state is in the Ozark Plateau Province of the Interior Highlands (as shown in fig. 1.22), whereas the remainder of the eastern part of Kansas is in the Central Lowland Province. The western area of the state is in the Great Plains Province of the Interior Plains. The provinces are further subdivided into smaller physiographic units. The physiographic divisions of the state are described in terms of their general topography.

Much of western and south-central Kansas has a relatively smooth surface and includes physiographic regions called the High Plains, the Great Bend Prairie, and the Wellington Plain (fig. 1.22). North-central and eastern Kansas include more hilly topography and encompass physiographic areas called the Smoky Hills, Red Hills, Flint Hills, the Glaciated Region, the Osage Cuestas, and Chautauqua Hills. In southeast Kansas are the gently undulating Cherokee Plains and the Ozark Plateau. Major streams generally flow from west to east.

As seen in the earlier illustrations showing precipitation and runoff, precipitation more than doubled from west to east and runoff increased more than 100 times, resulting in an average surface-water or stream discharge of 11.3 million acre-ft (MAF) per year (13.9 km^3/yr) from Kansas into Missouri and northeast Oklahoma. What a different perspective we would have about water supplies and water problems if the topography sloped from east to west, and we had about 11.3 MAF of surface water per year (13.9 km^3/yr) flowing from eastern Kansas to western Kansas!

Geology

Largely extracted from KWRB, 1967b; O'Connor, 1981; and U.S. Geological Survey, 1985.

Kansas water resources are also affected by the geology of the state (figs. 1.20 and 1.23). The geology of an area influences the quantity and quality of water that flows in its streams or can be obtained from wells in that area. The availability of ground water is directly related to the geology. The geology affects infiltration rates and the storage and transmission properties of aquifers. The geology affects the baseflow characteristics and the baseflow chemical quality of streams as well as the kind of sediment carried by the streams.

The rock formations exposed at the surface in Kansas are largely sedimentary, with only minor igneous intrusions in Woodson, Wilson, and Riley counties. The total thickness of sedimentary rocks ranges from about 1,000 ft (300 m) in eastern Kansas to more than 9,000 ft (2,700 m) in southwestern Kansas. The landscape in the state is a product of the geological processes operating since the Mississippian Period through the Holocene; these processes resulted in the deposition of glacial material, stream-laid deposits in the valleys, windborne deposits on the uplands and valley slopes, and marine deposits such as limestones as shown in the map and cross section (fig. 1.20). The surface and subsurface geology of the state varies considerably from one area to another because of the seas, glaciers, and rivers that at one time or another during a period of more than 300 million years exerted their influences on the surface of portions of Kansas. The geologic time chart (fig. 1.23) indicates the duration of the periods and the type of rock laid down.

Essentially all the fresh ground water in Kansas occurs in sedimentary rocks. The sedimentary rocks and thus the principal aquifers are divided into two major groups. The first group is the **unconsolidated** or loosely packed rocks such as the stream-laid deposits, or alluvium, the wind-laid deposits such as loess and dune sand, and glacial deposits of various kinds. Ground water is contained in the pore spaces in the rocks. Commonly 15–20% of a given volume of unconsolidated rock is drainable pore space, from which the water can be removed by gravity drainage and/or compressibility effects, and is the water available to a well. The second kind of sedimentary rocks are called **consolidated** rocks. These include limestone, dolomite, shale, sandstone, bedded salt, gypsum, anhydrite, and coal, and also are called bedrock. Ground water in the consolidated rocks is generally less free to

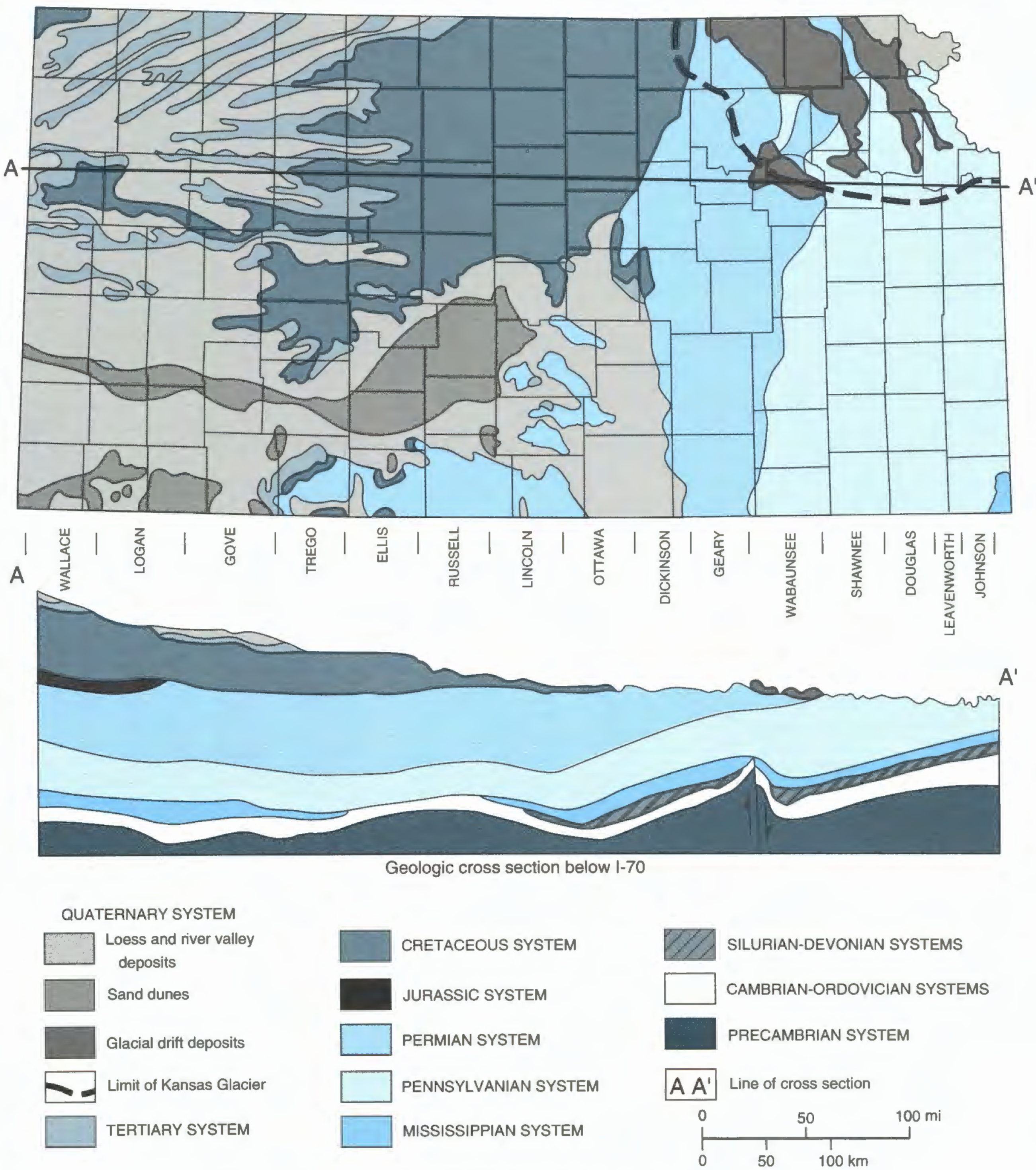


FIGURE 1.20—GENERALIZED GEOLOGIC MAP AND CROSS SECTION OF KANSAS (from Kansas Geological Survey, 1978).

move except in open fractures and joints. In sandstones, ground water moves through both pore spaces and fractures. In limestones, dolomite, and gypsum, it moves through solution cavities, joints, and fractures.

Characteristics of Major Bedrock and Unconsolidated Units

Figure 1.20 provides an overview of the major bedrock units in Kansas. The oldest and also some of the deepest freshwater occurs in the Cambrian–Ordovician

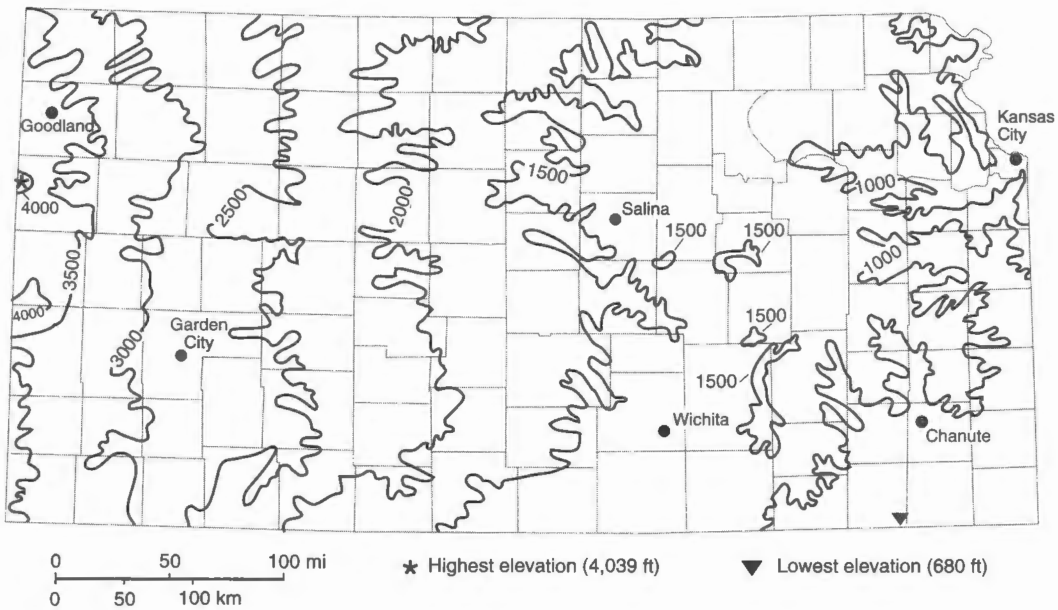


FIGURE 1.21—GENERALIZED ELEVATION MAP OF KANSAS. Contours in feet (adapted from Schoewe, 1949).

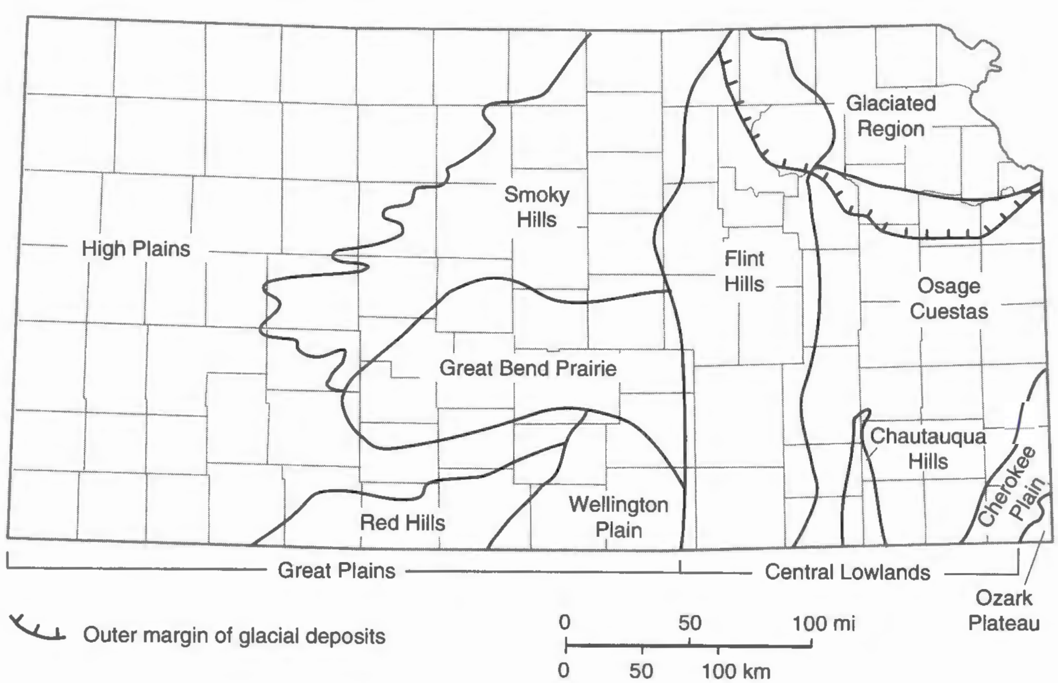
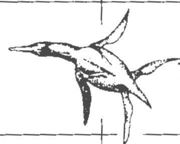
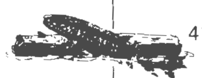
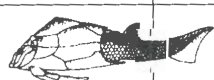
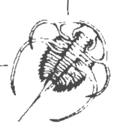


FIGURE 1.22—GENERALIZED PHYSIOGRAPHIC REGIONS OF KANSAS (adapted from Self, 1978).

KANSAS GEOLOGIC TIMETABLE

(Not scaled for geologic time or thickness of deposits)

ERAS	PERIODS	EPOCHS	EST. LENGTH (YEARS)*	DESCRIPTION	MILLION YEARS PAST
CENOZOIC	QUATERNARY	HOLOCENE	 10,000+	Early, the land was stable with some erosion. Glaciers moved into the northeast at least twice. Later the climate was dry. Sand dunes were formed by wind in the west. Volcanic ash was blown in from California, New Mexico, and Wyoming.	
		PLEISTOCENE	1,590,000		1.6
	TERTIARY	PLIOCENE	 3,700,000	Rocks found are part of the Ogallala Formation (sand, gravel, and porous rock), which contains a large quantity of ground water and occurs only in the western third of the state. No rocks were formed in eastern Kansas.	
		MIOCENE	18,400,000		
		OLIGOCENE	12,900,000		
		EOCENE	21,200,000		
		PALEOCENE	8,600,000		66.4
MESOZOIC	CRETACEOUS		 77,600,000	Much of the western half was covered by seas. Limestone, sandstone, and chalk formed from sea deposits. Fossils can be found in these rocks, which crop out in central and western Kansas.	144
	JURASSIC		64,000,000	Most rock in Kansas is underground in the west. A few small outcrops are found in the southwest corner.	208
	TRIASSIC		37,000,000	No rocks have been found in Kansas.	245
PALEOZOIC	PERMIAN		 41,000,000	Much of Kansas was covered by several seas. As they rose and fell, limestone, shale, and chert were deposited. The Flint Hills were formed. When the seas dried up, salt and gypsum were left behind. Salt, now underground, is mined in central Kansas. The Red Hills were formed from deposits of shale, siltstone, sandstone, gypsum, and dolomite.	286
	PENNSYLVANIAN		 34,000,000	For much of the period the land was flat. Seas and swamps came and went; coal formed in swamps from dead plants. Shale, limestone, sandstone, chert, and conglomerates were deposited. Two ridges of hills, the Nemaha uplift and the Central Kansas uplift, appeared; both are now buried. Pennsylvanian rocks are found at the surface in eastern Kansas.	320
	MISSISSIPPIAN		40,000,000	Repeated layers of limestone, shale, and sandstone indicate that seas rose and fell. Mississippian rocks are the oldest found at the surface and are in the southeast corner; elsewhere these rocks are only underground.	360
	DEVONIAN		 48,000,000	Seas covered Kansas during much of the period. Limestone, shale, and sandstone deposits are only underground.	408
	SILURIAN		30,000,000	Land was uplifted and seas disappeared. Limestone deposits are found only underground.	438
	ORDOVICIAN		 67,000,000	Seas covered parts of Kansas during much of the period. Dolomite and sandstone are only underground.	505
	CAMBRIAN		65,000,000	Early, the climate was dry and many rocks eroded. Later, parts of Kansas were covered by seas. Dolomite, sandstone, limestone, and shale are now underground.	570
PRECAMBRIAN			3,930,000,000	These rocks are the oldest on earth. In Kansas, they are only found deep below the surface and not much is known about them. Many are igneous and metamorphic and have gone through many changes.	4,500?

Eons not shown

* Decade of North American Geology, 1983 Geology Time Scale, Geological Society of America
Kansas Geological Survey, Lawrence, Kansas, 1996

FIGURE 1.23—Kansas geologic timetable (from Kansas Geological Survey, 1988).

rocks (570–438 million years past), consisting of sandstone and dolomite in four southeastern Kansas counties at depths of about 900–1,300 ft (270–395 m). Yields range from 100 to 1,000 gallons per minute (gpm; 6–63 L/sec). Mississippian rocks (360–320 million years past) yield some freshwater supplies to wells in parts of Cherokee County at depths generally less than 500 ft (150 m). Pennsylvanian rocks (320–286 million years past) in eastern Kansas are mostly shale and limestone, which yield meager ground-water supplies; however, Douglas Group sandstones locally yield 10–100 gpm (0.6–6.3 L/s) to wells at depths up to 500 ft (150 m). Permian rocks (286–245 million years past) locally yield 10–500 gpm (0.6–31.5 L/s) of freshwater from limestone aquifers in the Chase Group and gypsum aquifers in the Wellington Formation. Sandstones in the Permian red beds of south-central Kansas locally yield 10–100 gpm (0.6–6.3 L/s) of freshwater but in some areas yield highly mineralized water.

Minor amounts of water for irrigation are available from bedrock aquifers of southwestern Kansas, namely the **gypsum aquifer** in Upper Permian rocks (Morton County), the **sandstone aquifer** in Upper Jurassic or Triassic and Lower Cretaceous rocks (Finney, Grant, Morton, and Stanton counties), and the **chalk aquifer** in Upper Cretaceous rocks (Scott, Kearny, and Finney counties). These aquifers contain highly mineralized water and generally will not sustain large yields (Gutentag et al., 1981).

Unconsolidated rocks contain about 80% of our freshwater and consolidated rocks about 20%. About 400 million acre-feet (MAF) (493 km^3) of ground water is stored in both the consolidated and unconsolidated rocks. The unconsolidated deposits contain the most important and generally the most prolific aquifers. More than 600 ft (180 m) of saturated unconsolidated rocks are present in parts of southwestern Kansas where the Ogallala Formation is thickest, though the Ogallala underlies most of the western third of the state. In the Pleistocene (1.6–0.01 million years past), aquifers of the Great Bend Prairie of south-central Kansas and the Equus Beds of central Kansas, the maximum saturated thicknesses (the thickness of the rock formation that is saturated by water) are more than 200 ft (60 m). Parts of the glacial drift aquifer in northeastern Kansas have saturated thicknesses of 300 ft (90 m). Although not shown on fig. 1.20, the Kansas River valley, its major tributaries, and the Missouri River valley also have saturated thicknesses of 30-100 ft (9–30 m), which are capable of yielding quantities adequate for irrigation, industrial, and municipal use.

Principal Aquifers

Principal aquifers in Kansas consist of (1) unconsolidated gravel, sand, silt, and clay and (2) consolidated sandstone, limestone, and dolomite. Table 1.2 lists the aquifers, from youngest to oldest, and summarizes their characteristics; fig. 1.24 shows their areal distribution. The quality of ground water depends both on the substances dissolved in the water and on certain properties and characteristics that these substances impart to the water. To help readers appreciate the water quality of the principal Kansas aquifers, Appendix B includes three relevant tables (Heath, 1983). Table B1 contains information on dissolved inorganic substances that normally occur in the largest concentrations and are most likely to affect water use. Table B2 lists other characteristics of water that are commonly reported in water analyses and that may affect water use. Concentration limits for dissolved inorganic constituents for drinking water are presented in Table B3.

ALLUVIAL AQUIFERS

The Kansas River alluvial aquifer is an important source of water along the common border of the Osage Cuestas and Glaciated Till plains. The aquifer consists of unconsolidated fluvial deposits of Quaternary age and is unconfined. Large-diameter wells typically yield more than 500 gallons per minute (gal/min; 31.5 L/s). The water generally is a *calcium bicarbonate* type that is suitable for most uses. Concentrations of *iron* commonly exceed 0.3 milligrams per liter (mg/L), and concentrations of *manganese* can exceed 0.05 mg/L.

Wells developed in unconfined alluvial aquifers of the Arkansas, Republican, and Pawnee river valleys generally yield more than 500 gal/min (31.5 L/s). The water generally is a *calcium bicarbonate* type that is suitable for most uses. Locally, concentrations of dissolved solids greater than 500 mg/L, chloride greater than 250 mg/L, and nitrate greater than 10 mg/L can result from discharge of saline water from underlying bedrock, contamination from oil fields, and agricultural practices. Naturally occurring concentrations of selenium greater than 0.01 mg/L, and total or gross alpha radioactivity greater than 15 picocuries per liter (pCi/L) commonly are present in water from alluvial aquifers in the northern High Plains and Smoky Hills.

GLACIAL-DRIFT AQUIFER

The glacial-drift aquifer is a major source of water in northeastern Kansas. The aquifer consists of unconsolidated glacial deposits of Pleistocene age and generally is unconfined. Wells yield from 10 to about 500 gal/min. Shallow wells generally produce a calcium bicarbonate water that is suitable for most uses, but nitrate concentrations can exceed 10 mg/L. Deep wells can produce very mineralized water with concentrations of dissolved solids greater than 500 mg/L, sulfate and chloride greater than 250 mg/L, and iron exceeding 0.3 mg/L.

TABLE 1.2—AQUIFER AND WELL CHARACTERISTICS IN KANSAS AS SUMMARIZED BY THE U.S. GEOLOGICAL SURVEY (1985); (gal/min = gallons per minute; mg/L = milligrams per liter; ft = feet. Sources: Reports of the U.S. Geological Survey and Kansas agencies).

Aquifer name and description	Well characteristics: Depth (ft) Common range	Well characteristics: Yield (gal/min) Common range	Well characteristics: Yield (gal/min) May exceed	Remarks
Alluvial aquifers: Quaternary fluvial deposits of clay, silt, sand, and gravel. Generally unconfined.	10–150	10–500	1,000	Well yields in Kansas, Arkansas, Republican, and Pawnee river valleys exceed 500 gal/min. Wells in other valleys usually yield less than 100 gal/min. Locally, water from alluvial aquifers can have large concentrations of dissolved solids, chloride, sulfate, nitrate, iron, and manganese. Large concentrations of selenium and naturally occurring gross-alpha radioactivity sometimes occur in water from the northern part of the Great Plains.
Glacial-drift aquifer: Pleistocene glacial deposits of clay, silt, sand, and gravel. Generally unconfined.	10–300	10–100	500	Water from shallow wells generally a calcium bicarbonate type with less than 500 mg/L dissolved solids, but large concentrations of nitrate can occur. Water from deep wells can have large concentrations of dissolved solids, chloride, sulfate, iron, or manganese.
High Plains aquifer: Fluvial and eolian deposits of clay, silt, sand, and gravel of Cenozoic age. Generally unconfined.	10–450	500–1,000	1,500	Water generally a calcium bicarbonate type with concentrations of dissolved solids less than 500 mg/L, but large concentrations of fluoride and selenium can occur in the northern Great Plains. Provides water supplies for Dodge City, Garden City, Great Bend, Pratt, Hutchinson, McPherson, Wichita, and most other towns in the Great Plains.
Dakota aquifer: Dakota and Cheyenne sandstones of Cretaceous age. Generally unconfined.	20–200	10–100	1,000	Water quality variable. Calcium bicarbonate type water with less than 500 mg/L of dissolved solids produced where the aquifer is exposed. Sodium bicarbonate or sodium chloride type water with large concentrations of dissolved solids is produced west and north of the surface exposure. Large concentrations of iron occur in water from some wells. Some wells in Finney, Ford, and Hodgeman counties can yield more than 1,000 gal/min.
Chase and Council Grove aquifer: Limestones of Chase and Council Grove Groups of Permian age. Generally unconfined.	20–200	10–20	200	Water generally a calcium bicarbonate type with concentrations of dissolved solids less than 500 mg/L. Water from some wells can have large concentrations of sulfate. Wells in Butler and Cowley counties can produce water with large concentrations of dissolved solids. Concentrations of dissolved solids and chloride large west of the surface exposure, and water is not used.
Douglas aquifer: Channel sandstone of Pennsylvanian age. Generally unconfined.	5–400	10–40	100	Water ranges from a calcium bicarbonate type, with less than 500 mg/L of dissolved solids where the aquifer is exposed, to a sodium bicarbonate or sodium chloride type, with large concentrations of dissolved solids at depth or west of surface exposure. Concentrations of fluoride may be large.
Ozark aquifer: Weathered and sandy dolomites of Arbuckle Group. Cambrian and Ordovician age. Confined.	500–1,800	30–150	500	Water generally a calcium bicarbonate type with less than 500 mg/L of dissolved solids in the Ozark Plateaus and in extreme southeast corner of the Osage Plains. Sodium bicarbonate chloride or sodium chloride type water with large concentrations of dissolved solids is produced in rest of the Osage Plains. Hydrogen sulfide gas, or large concentrations of gross-alpha radioactivity or iron, can occur in water from some wells.

HIGH PLAINS AQUIFER

The High Plains aquifer is the most important and extensively used aquifer in Kansas. The aquifer consists of thick, unconsolidated fluvial and eolian deposits of Cenozoic age and generally is unconfined. The aquifer is present in most of western Kansas. Wells yield from 500 to about 1,500 gal/min (32–95 L/s). The water generally is a calcium bicarbonate type that is suitable for most uses. Concentrations of fluoride greater than 1.4 mg/L and selenium greater than 0.01 mg/L are present in some water from northern parts of the High Plains aquifer.

The term High Plains aquifer in Kansas refers to three, hydraulically connected but areally distinct aquifers: (1) the Ogallala aquifer (A in fig. 1.24), (2) the Great Bend Prairie aquifer (B in fig. 1.24), and (3) the Equus Beds aquifer (C in fig. 1.24). In general, the Ogallala Formation (comprising the bulk of the Ogallala aquifer) is made up of unconsolidated sand, gravel, silt, and clay deposited by streams that flowed east from the Rocky Mountains during the Pliocene Epoch. Erosion then removed the deposits between the mountains and the existing western border of the Ogallala so that no recharge is received from the mountains. The Great Bend Prairie and Equus Beds aquifers are also composed of silt, clay, sand, and gravel deposits left by streams flowing through central Kansas, but these deposits are generally younger (Pleistocene and Holocene) than those that make up the Ogallala.

Ground water in the High Plains aquifer is recharged by precipitation that falls on the area underlain by the aquifer and percolates downward to the water table. The amount of recharge varies widely depending on such factors as climate (precipitation and evapotranspiration), surface soils, vegetation, and land use.

The High Plains aquifer is underlain by various Cretaceous and Permian shales and sandstones. In northwestern and west-central Kansas, the shales are relatively impermeable and little hydraulic interchange takes place. Where the High Plains aquifer is underlain by the Dakota Sandstone aquifer in southwestern Kansas, however, significant hydraulic interchange takes place between the two aquifers. In southwestern Kansas along the Oklahoma border and in the Great Bend Prairie and Equus Beds area, the aquifers are underlain in some areas by Permian shales and sandstones that contain natural saltwater. This poor-quality water intrudes into the overlying freshwater aquifers and streams both naturally and in response to pumping, thus presenting a difficult management problem.

The High Plains aquifer yields water with the smallest concentrations of dissolved solids in Kansas; the median concentration of dissolved solids was 340 mg/L. Water from the High Plains aquifer typically is hard to very hard; only 25% of the samples had hardness concentrations less than 180 mg/L. Most concentrations of nitrate plus nitrite and fluoride do not exceed the drinking-water standards. Although samples from a few wells had large concentrations of chloride (the maximum for 773 samples was 440 mg/L), fewer than 10% of the samples contained more than 70 mg/L. Most of the water pumped from the High Plains aquifer is used for irrigation, but the aquifer also provides water for public supply and industrial use in the Wichita area and for many smaller cities and rural domestic users.

DAKOTA AQUIFER

The Dakota aquifer is a major source of water in north-central Kansas where the aquifer material is exposed

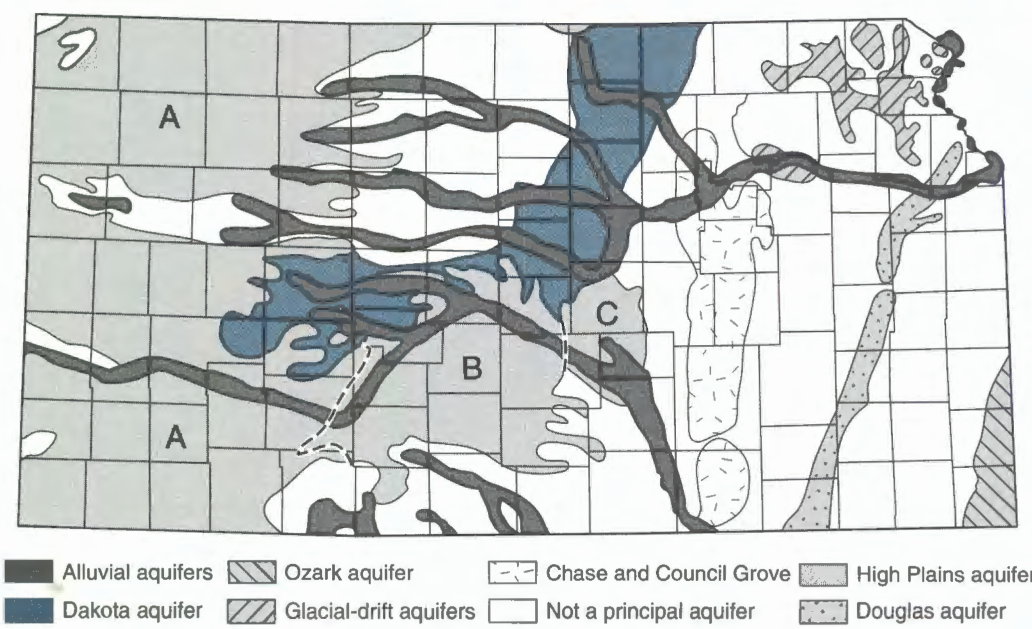


FIGURE 1.24—PRINCIPAL AQUIFERS IN KANSAS (adapted from U.S. Geological Survey, 1985). Dashed lines indicate approximate boundaries. A–Ogallala aquifer, B–Great Bend Prairie aquifer, and C–Equus Beds aquifer, all parts of the High Plains aquifer.

at or near the land surface. The aquifer consists of the Dakota and Cheyenne Sandstones of Cretaceous age. Wells yield from 10 to 100 gal/min (0.6–6.3 L/s) in the northeast to more than 1,000 gal/min (63 L/s) in the south. The water generally is a calcium bicarbonate type in areas where the aquifer is unconfined. However, sodium and chloride concentrations increase with depth, and the water is not used northwest of the area shown in fig. 1.24. Some wells yield water with concentrations of iron exceeding 0.3 mg/L.

CHASE AND COUNCIL GROVE AQUIFER

The Chase and Council Grove aquifer is a source of water where it is exposed in the Osage Plains. The aquifer consists of limestones of the Chase and Council Grove Groups of Permian age. The water from these aquifers generally is a calcium bicarbonate type that is suitable for most uses, although concentrations of sulfate exceed 250 mg/L locally. The water is very mineralized west of the area shown in fig. 1.24 (dissolved-solids and chloride concentrations exceed 500 mg/L and 250 mg/L, respectively) and is not used.

DOUGLAS AQUIFER

The Douglas aquifer is a source of water where it is exposed in the Osage and glaciated regions. The aquifer consists of channel sandstone of the Douglas Group of Pennsylvanian age. In these areas, wells yield from 10 to about 100 gal/min (0.6–6.3 L/s). The water generally is a calcium bicarbonate type that is suitable for most uses. Some wells produce water with fluoride concentrations that exceed 1.4 mg/L. As in the case of the Chase and Council Grove aquifer, west of the area shown in fig. 1.24, the water is not used because of its high mineral content.

OZARK AQUIFER

The Ozark aquifer is the major source of ground water in southeastern Kansas. The aquifer consists of weathered and sandy dolomites of the Arbuckle Group of Cambrian and Ordovician age, and is confined. The aquifer does not crop out in Kansas; at the shallowest point, it is 300 ft (90 m) below land surface. Wells yield from 30 to about 500 gal/min. The water generally is a calcium bicarbonate type that is suitable for most uses. Water in some wells contains excessive concentrations of iron (greater than 0.3 mg/L) and naturally occurring total or gross alpha radioactivity (greater than 15 pCi/L). In the Osage Plains, water from the Ozark aquifer becomes very mineralized with depth and toward the northwest, and hydrogen sulfide gas may be present. The water is not used west of the area shown in fig. 1.24.

Estimates of Freshwater Aquifer Storage and Natural Ground-water Recharge

A variety of estimates of freshwater (less than 1,000 mg/L total dissolved solids [TDS]) available in storage in all principal aquifers in Kansas exist. These estimates range from 380 MAF (469 km^3) by the Kansas Geological Survey (Hambleton, 1984), to 425.4 MAF (525 km^3) by the Kansas Water Resources Board (1967), to 590 MAF (728 km^3) by the U.S. Geological Survey (Hansen, 1991). The unconsolidated aquifers in Kansas (alluvial, glacial, High Plains) total approximately 300 MAF or 370 km^3 (KGS estimate 301 MAF or 371 km^3, U.S. Geological Survey estimate 292 MAF or 360 km^3), of which more than 90% is stored in the High Plains aquifer. The largest uncertainties are in the consolidated aquifers (from the Dakota to the Ozark and aquifers between those two). The Kansas Geological Survey estimate for freshwater (<1,000 mg/L TDS) in the consolidated aquifers in Kansas is 86 MAF or 106 km^3 (Hambleton, 1984), whereas the U.S. Geological Survey estimate is 297 MAF or 366 km^3 (Hansen, 1991). The U.S. Geological Survey estimate is probably inflated mainly because of the much larger freshwater aquifer thicknesses and storativity values employed in the U.S. Geological Survey calculations. In fact both U.S. Geological Survey and Kansas Geological Survey estimates are probably overestimated. For example, the latest data (P. A. Macfarlane, 1996, oral communication) indicate that the storativity values for the bedrock aquifers (Dakota and Ozark, for example) are of the order of 10^{-3} to 10^{-4} or lower, and that the sandstone thickness or permeable-formation thickness that is saturated with water of <1000 mg/L TDS is much less than reported in previous studies, which may have considered the entire formation thickness in freshwater-resource calculations.

Ground-water recharge is one of the most difficult and uncertain factors to measure in the evaluation of ground-water resources. Estimates of recharge based on precipitation range from 1% of precipitation for unirrigated land in western Kansas (Gutentag et al., 1981) to 10% in the Big Bend Groundwater Management District No. 5 (Sophocleous, 1992, 1993), to as much as 20% in the Equus Beds Groundwater Management District 2 (Williams and Lohman, 1949) in south-central Kansas, with most estimates less than 10% of precipitation. The U.S. Geological Survey (Hansen, 1991) estimated natural recharge from precipitation over the area of the state where the principal aquifers (fig. 1.24) have some saturated thickness and directly underlie the soil at land surface (such recharge area is estimated at 25.9 million acres or 10.5 million hectares) to be 3.99 MAF (4.92 km^3) or 1.85 inches (4.7 cm) per year (fig. 1.0) over that recharge area based on 1951–1980 climatic data. This estimate corresponds to less than 7% of the average annual precipitation in the state.

Human Impacts

Largely extracted from O'Connor, 1981; U.S. Geological Survey, 1996; and Walling, 1987.

Introduction

Human activity has modified parts of the natural hydrologic cycle. Figure 1.25 presents a simplified representation of the hydrologic cycle operating in an essentially natural drainage basin. Inputs of precipitation are distributed through a number of stores by a series of transfer processes and are output as channel flow, evapotranspiration, and deep leakage. An attempt has been made to point to the various ways in which this cycle could be modified through human activities by considering, first, modification of internal processes and secondly, additional moisture inputs. Bearing in mind the difficulties associated with any attempt to generalize the nature and extent of process modifications resulting from human impact, fig. 1.26 provides specific examples for a selection of processes. That figure illustrates some of the process modifications cited in fig. 1.25 and demonstrates that humans can profoundly influence the individual components of the hydrologic cycle. In addition, such modifications are clearly widespread occurrences, rather than isolated extremes.

Impacts on Kansas Streams and Aquifers

To conserve water from precipitation, individuals have built retention dams and applied such measures as stubble mulching and terracing that reduce soil erosion and retain more of the precipitation where it falls. Dams and reservoirs have been constructed to reduce flooding and provide water for conservation use and municipal, industrial, and irrigation uses. The Kansas Legislature, through the Kansas Water Office, has provided for inclusion of State-managed water supplies in nine eastern Kansas reservoirs.

In western Kansas, because aquifer recharge is so low (generally estimated to be less than 1/4 inch [0.63 cm] per year,) ground water is being *mined* in the Ogallala aquifer or removed much faster than it is replaced. The people of western Kansas have decided that the beneficial effects of mining the aquifer outweigh the detrimental effects. The long-term effects of this mining will create new problems. Already many streams in western Kansas have experienced a progressive reduction in flow during the past three decades. Trends are most dramatic in the upper Arkansas, Cimarron, and Smoky Hill river basins, where a shift toward irrigated crop production has helped lower the ground-water table and largely eliminated baseflow contributions to streams from shallow aquifers (see also Chapters 2 and 3). Proposed schemes for importation of

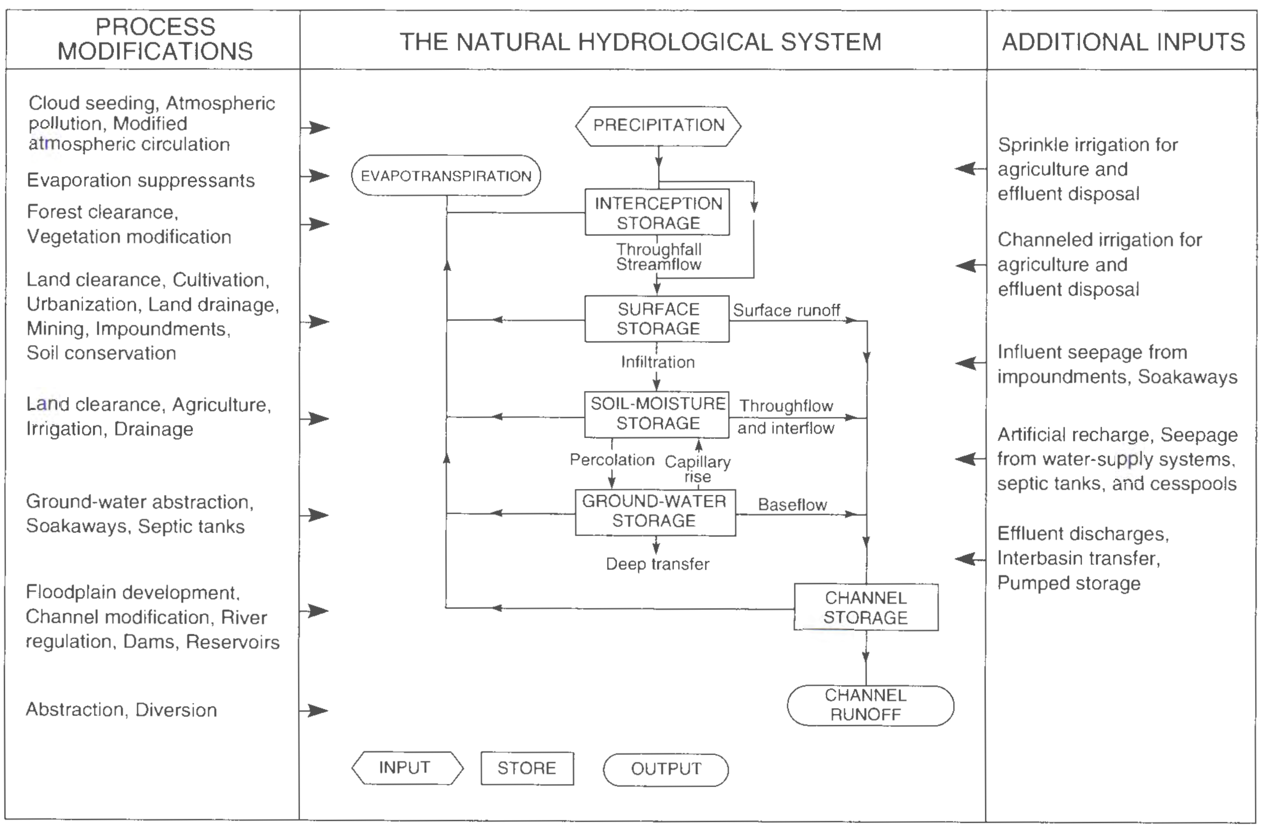


FIGURE 1.25—A SIMPLIFIED DIAGRAMMATIC REPRESENTATION OF THE HYDROLOGICAL PROCESSES OPERATING IN A DRAINAGE BASIN and some examples of human interference associated with process modifications and additional moisture inputs (from Walling, 1987).

water were being considered but a water source or sources and transfer plans that are politically and economically feasible have not been resolved.

Declines in streamflow exert a direct impact on surface-water quality by reducing the dilution base available to sewage-treatment plants and other pollution sources. In the face of such declines, contaminant loadings eventually begin to exceed the assimilatory capacity of streams. Reductions in streamflow also aggravate problems associated with the intrusion of highly mineralized ground water. In streams receiving significant baseflow contributions from saline aquifers, concentrations of chloride, sulfate, and other ions tend to increase as baseflow contributions from upstream or overlying freshwater aquifers decline. These circumstances render streams less valuable as sources of domestic and irrigation water and place a profound physiological stress on many native aquatic and semiaquatic species.

As reported in U.S. Geological Survey (1988), shallow aquifers have been contaminated locally by spills and by leaks from pipelines and storage tanks. Brines associated with oil and gas production have caused local contamination through leakage from brine-retention ponds and through interaquifer movement of brines via improperly abandoned wells or test holes. Contamination by chloride is associated with oil production in Harvey County, northwest of Wichita. Contamination of ground water from waste disposal has been identified chiefly in and near the

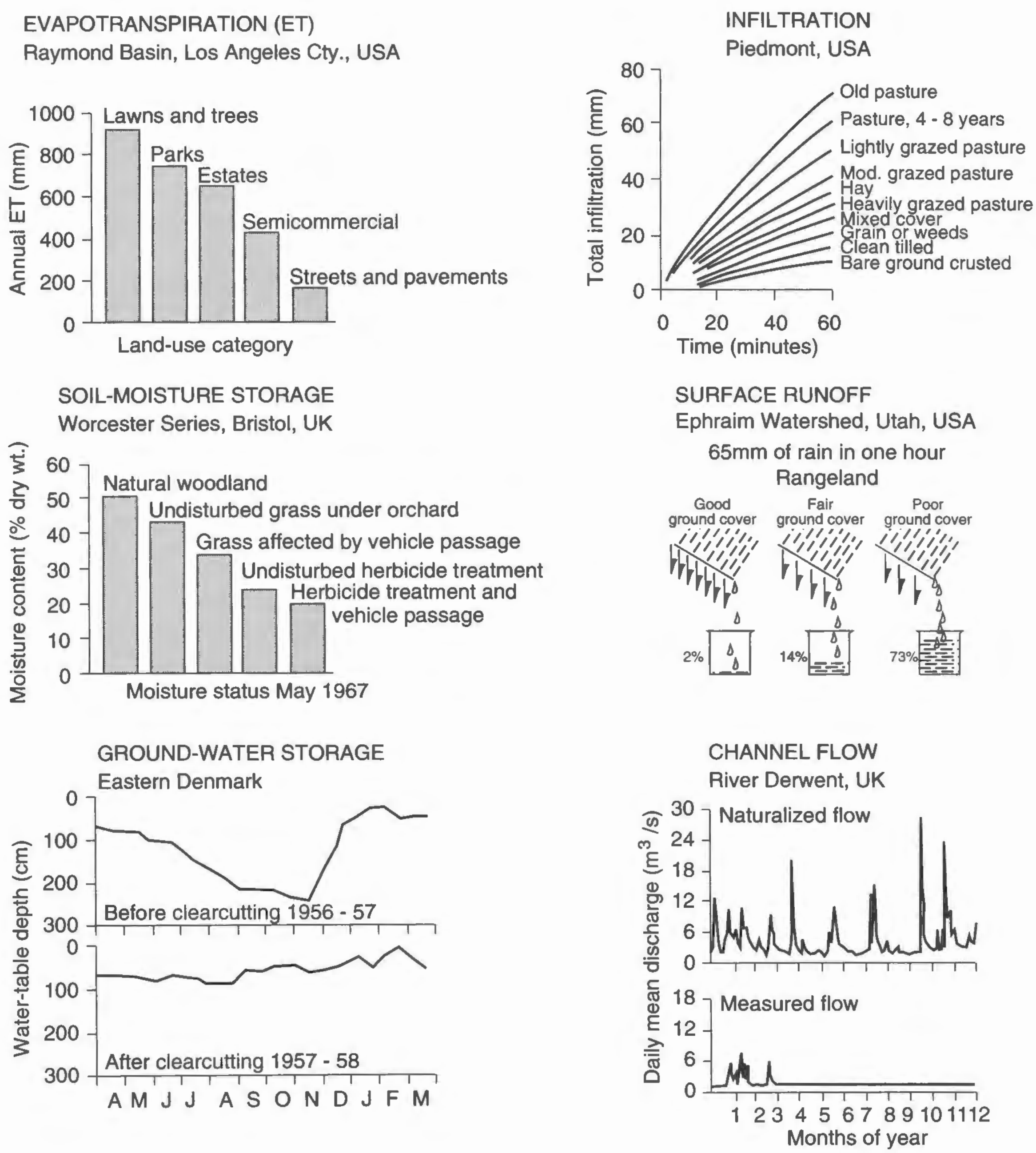


FIGURE 1.26—SOME EXAMPLES OF HUMAN IMPACT ON INDIVIDUAL HYDROLOGICAL PROCESSES (from Walling, 1987).

major population centers. Adverse effects from agricultural practices are being investigated by several State and Federal agencies. Pesticides have been detected in both surface and ground waters in several areas of the state (Carney et al., 1991; Koplin et al., 1994; Marc Anderson, Kansas Department of Agriculture, written communication, 1997). Additional human impacts on water quantity and quality are described in the section on "Kansas Water Resources Problems and Issues."

Impacts on Kansas Wetlands

According to U.S. Fish and Wildlife Service estimates, Kansas lost 405,600 acres (164,140 hectares), or 48% of its wetlands between the 1780's and 1980's (Dahl, 1990) In 1890, the State sold 12 major salt marshes in central Kansas, some more than 1,000 acres (405 hectares) in size. Many of these wetlands were drained and converted to agricultural uses shortly thereafter (Monda, 1992b). Draining and conversion to cropland have caused most of the wetland losses in Kansas; 40% of the losses occurred between 1955 and 1978 (Tiner, 1984). Most areas drained were shallow, vegetated wetlands such as the McPherson Valley Wetlands and the playa lakes. Only about 500 acres (200 hectares) remain of the original 9,000-plus acres (3,640-plus hectares) in the McPherson Valley wetlands (Wilson, 1992), and about 70% of the original playa lakes are gone according to the Kansas Department of Wildlife and Parks. Remaining wetlands, despite regulations protecting them, continue to be adversely affected by agricultural runoff of chemicals and sediment from surrounding croplands according to the Kansas Department of Wildlife and Parks (1991). Other causes of wetland loss include depletion of surface and ground water. Construction of flood-control structures and modifications to stream channels can result in drainage of wetlands or alteration of streamflows entering wetlands. Urban, industrial, and transportion-system development also can be detrimental to wetlands (Kansas Department of Wildlife and Parks, 1991).

The disappearance of nearly one-half of the state's wetlands has increased the importance of those that remain. Migratory birds formerly had access to many wetlands and to shallow, braided river channels throughout central Kansas for foraging and resting. Draining of these wetlands and the depletion of streamflows in major streams such as the Arkansas River have left only Cheyenne Bottoms (Barton County) and Quivira National Wildlife Refuge (mainly Stafford County) in central Kansas as major stopover places in the state (shown in fig. 1.35). Keeping those areas viable requires manipulation of the hydrologic system to ensure a consistent water supply.

Part II. Water Use

Water Use in Kansas

Largely extracted from U.S. Geological Survey, 1985, 1986, and 1990.

Water supplies in Kansas were generally considered adequate to meet the 1985 level of demand (U.S. Geological Survey, 1990), although streamflows in the eastern one-half of the state needed to be supplemented by storage during periods of less-than-average precipitation. Today, the demand for water is much greater, and many areas are closed to further appropriations, without having met the existing demand for irrigation water. Mineral concentrations in some streams during low flows are undesirably large, and reservoir releases must be scheduled to dilute the water and to ensure usability. Surface-water and ground-water withdrawals in Kansas for each decade since 1950 for various purposes and related statistics are given in table 1.3.

In western Kansas, ground-water provides almost all the water, but the present level of water use is not sustainable for the long term; only a few counties along perennial streams obtain any appreciable amounts of surface water. In eastern Kansas, surface water is the principal water source; however, large withdrawals of ground water are obtained primarily from the alluvium of the Kansas River valley.

Surface-water withdrawals by principal drainage basins are shown in fig. 1.27. The largest withdrawals were in the Missouri–Nishnabotna and the Kansas and Lower Missouri basins, both of which exceeded 200 Mgal/d (614 acre feet/day [AF/d] or 757,000 m^3/d) in 1985. In these basins large amounts of water were withdrawn for thermoelectric power generation. The Kansas and Lower Missouri basin also had large withdrawals (88 Mgal/d or 270 AF/d or 333,000 m^3/d) for public supply. Basins that extend into western Kansas, such as the Middle Arkansas, Smoky Hill, and Republican, are dominated by agricultural withdrawals.

Water in streams is used for several purposes such as recreation, wildlife, irrigation, and human consumption. The topography of Kansas does not lend itself to hydroelectric power generation; a single hydroelectric plant on the Kansas River at Lawrence generated only 0.03% of the state's power supply during 1985 (Solley et al., 1988).

Ground water supplied about 5.6 billion gallons per day (bgd) or 17,250 AF/d (21.2 million m^3/d) in 1980 and 4.4 bgd (13,413 AF/d or 16.7 million m^3/d) in 1990, representing 85% and 72% of the water used in Kansas, respectively. Public and rural systems provide ground water to almost 1.2 million people (about 49% of the state's population). More than 90% of the ground water withdrawn is used for irrigation. Ground-water withdrawals for each decade since 1950 for selected uses and related statistics are given in table 1.3.

Ground-water withdrawals from the principal Kansas aquifers are shown in fig. 1.28. Total withdrawals from the High Plains aquifer were 3,940 Mgal/d (12,093 AF/d or 14.9 million m^3/d) in 1985, which is more than six times the quantity of water withdrawn from the alluvial aquifers, the next-largest ground-water source in the state. Of the water withdrawn from the High Plains aquifer, 97.9% was used for agriculture, mostly for irrigation. Withdrawals from the alluvial aquifers in 1985 were 620 Mgal/d (1,903 AF/d or 2.3 million m^3/d), of which 74.8% was used for irrigation and 15.5% was used for public supply. In 1985, the Dakota aquifer supplied 140 Mgal/d (430 AF/d or 1.6 million m^3/d), 95.0% of which was used for agriculture.

Agriculture, primarily irrigation, accounted for 84.7% of the water used in Kansas during 1985 and for 68.9% during 1990, with thermoelectric power generation using 7.3% and 21.4% of the state's water during 1985 and 1990, respectively. The apparent decrease in amounts of irrigation water and irrigated acreage from the 1980's to the 1990's (table 1.3) is probably artificial, and reflects more accurate reporting in recent years than in the past, when estimates were based on appropriated amounts as opposed to reported use and reported irrigated acreage amounts. Public-water supplies accounted for about 5.6% of the 1985 freshwater withdrawals and for 6.1% of the1990 withdrawals. Major public-supply withdrawals were near the large population centers in Sedgwick County (Wichita) and along the lower Kansas River (Topeka and Kansas City).

Public Supply

Public supply is the water withdrawn, treated, and delivered to users by municipalities and Rural Water Districts. About 2 million people obtain their water for domestic use from public supplies. Public suppliers also furnished 30.0% of the water used for industrial and mining purposes. Total withdrawals for public supplies during 1985 (316 Mgal/d or 970 AF/d or 1.2 million m^3/d) and 1990 (373 Mgal/d or 1,145 AF/d or 1.4 million m^3/d) were almost equally divided between ground-water and surface-water sources (table 1.3) and constituted 5.6% of the total freshwater withdrawals in the state.

Domestic and Commercial

The self-supplied rural population of 453,000 people and a few dozen isolated commercial users withdrew 42 Mgal/d (130 AF/d or 0.16 million m^3/d) during 1985, which came almost entirely from ground-water sources.

Industrial and Mining

Industrial and mining activities during 1985 totalled 95 Mgal/d or 291 AF/d or 0.36 million m^3/d (table 1.3). Nearly all industrial users in the smaller cities, primarily food processors, obtain water from public supplies. Water for the light-aircraft manufacturers, chemical plants, and metal-fabrication activities in and near Wichita is self-supplied, mostly from ground-water sources. In the other major industrial area of the state, in and near Topeka and Kansas City, about one-half of the industrial water is self-supplied. Most of this self-supplied water is from surface-water sources, but a few industries have wells completed

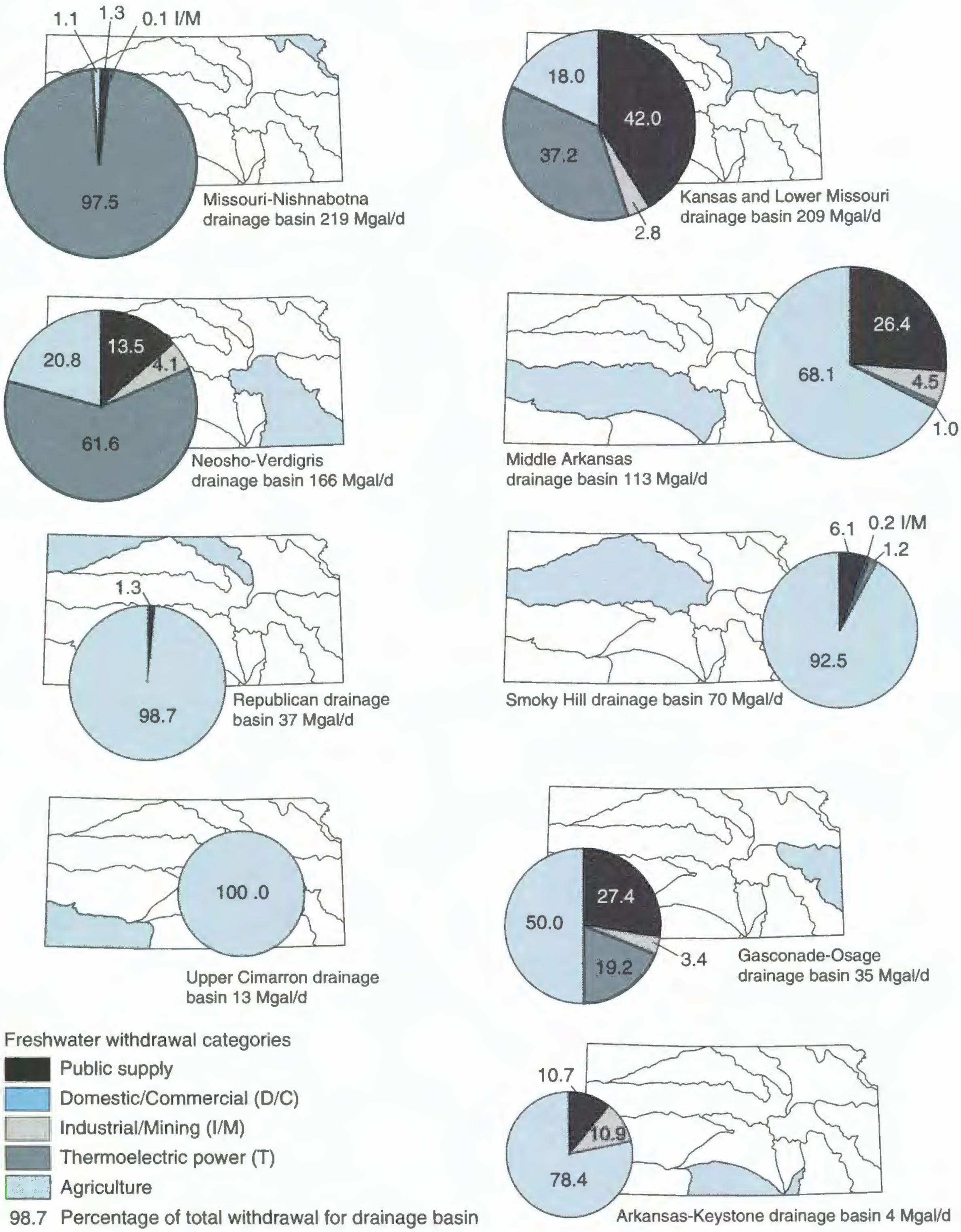


FIGURE 1.27—SURFACE FRESHWATER WITHDRAWALS BY CATEGORY OF USE AND HYDROLOGIC UNIT IN KANSAS, 1985 (from U.S. Geological Survey, 1990).

TABLE 1.3—GROUND-WATER AND SURFACE-WATER USE FOR KANSAS (figures may not add to totals because of independent rounding).

	Year	1950	%	1960	%	1970	%	1980	%	1985	%	1990	%
Population x1000		1905		2179		2249		2363		2451		2478	
Ground Water (MGD)		401	*68.3*	1230	*43.8*	3170	*82.9*	5620	*85.1*	4800	*84.7*	4370	*71.7*
Surface Water (MGD)		233	*31.7*	1580	*56.2*	630	*17.1*	980	*14.9*	866	*15.3*	1720	*28.3*
Total Water (MGD)		634		2810		3800		6600		5670		6090	
Per capita use (gpd)		330		1285		1700		2800		2310		2460	
Public Supply (MGD)	GW	75	*18.7*	120	*10.0*	130	*4.2*	140	*2.5*	158	*3.3*	176	*4.0*
	SW	60	*25.8*	81	*5.1*	120	*18.8*	150	*15.3*	158	*18.2*	197	*11.5*
	TL	135	*21.3*	200	*7.1*	250	*6.6*	290	*4.4*	316	*5.6*	373	*6.1*
Domestic and Livestock	GW	65	*16.2*	66	*5.5*	79	*2.5*	93	*1.7*	84	*1.8*	108	*2.5*
(MGD)	SW	15	*6.4*	28	*1.8*	51	*7.9*	50	*5.1*	26	*3.0*	31	*1.8*
	TL	80	*12.6*	94	*3.4*	130	*3.4*	142	*2.2*	110	*1.9*	139	*2.3*
Thermoelectric (MGD)	GW			23	*1.9*	38	*1.2*	46	*0.8*	12	*0.3*	13	*0.3*
	SW	N/R		510	*31.9*	220	*34.4*	300	*30.6*	403	*46.5*	1290	*75.0*
	TL			530	*18.9*	260	*6.8*	346	*5.2*	415	*7.3*	1300	*21.4*
Other (commercial /	GW	100	*24.9*	120	*10.0*	120	*3.9*	140	*2.5*	75.3	*1.6*	81	*1.9*
industrial / mining)	SW	95	*40.8*	60	*3.8*	37	*5.8*	41	*4.2*	19.3	*2.2*	5	*0.3*
(MGD)	TL	195	*30.8*	180	*6.4*	160	*4.2*	181	*2.7*	95	*1.7*	86	*1.4*
Irrigation (MGD)	GW	161	*40.1*	900	*75.0*	2800	*90.3*	5200	*92.9*	4470	*93.1*	3990	*91.5*
	SW	62	*26.8*	900	*56.3*	200	*31.3*	440	*44.9*	260	*3.0*	199	*11.6*
	TL	223	*35.2*	1800	*64.3*	3000	*78.9*	5600	*85.5*	4730	*83.4*	4190	*68.9*
Irrigated land (acres x 1000)		300		1000		1800		3400		2950		3110	

Abbreviations:GW - Ground Water; SW - Surface Water; TL - Total Water (GW+SW); gpd - gallons per day; MGD - million gallons per day; N/R - not reported; % - quantity as a percent of GW, SW, or TL use in particular category over total yearly use of GW, SW, or TL, respectively. To convert MGD to AF/day, multiply by 3.0693. To convert MGD to million m^3/d, multiply by 3,785.4.

Sources: U.S. Geological Survey Circulars 115 (1951), 456 (1961), 676 (1972), 1001 (1983), 1004 (1988), 1081 (1993).

in alluvial aquifers. The principal industrial activities in this area are food processing, metal fabrication, and chemical production. Very little mining activity occurs in Kansas; the small strip-mining operations for coal in southeastern Kansas get their water primarily from small streams in the area. Of the water withdrawn and delivered for industrial and mining use, 30.2% is consumed and 69.8% is returned directly to streams or to municipal sewage-treatment facilities.

Thermoelectric Power

About 7.3% (415 Mgal/d or 1,272 AF/d or 0.16 million m^3/d) of total withdrawals in 1985, and 21.4% (1,300 Mgal/d or 3,983 AF/d or 4.9 million m^3/d) in 1990 was used for thermoelectric power generation. Most of the water withdrawn by thermoelectric plants is used for condenser and reactor cooling. Most of the power plants in Kansas are in the eastern one-half of the state, where 96.9% of the water withdrawn for power generation was self-supplied from surface-water sources. A single nuclear power plant in Coffey County withdrew 2.1 Mgal/d (7,950 m^3/d) in 1985 and 22 Mgal/d (83,280 m^3/d) in 1990. All other power plants in the state burn fossil fuels. A total of 27,300 gigawatthours of electricity was generated. Consumptive use of water by thermoelectric generating plants is relatively small (10.4%).

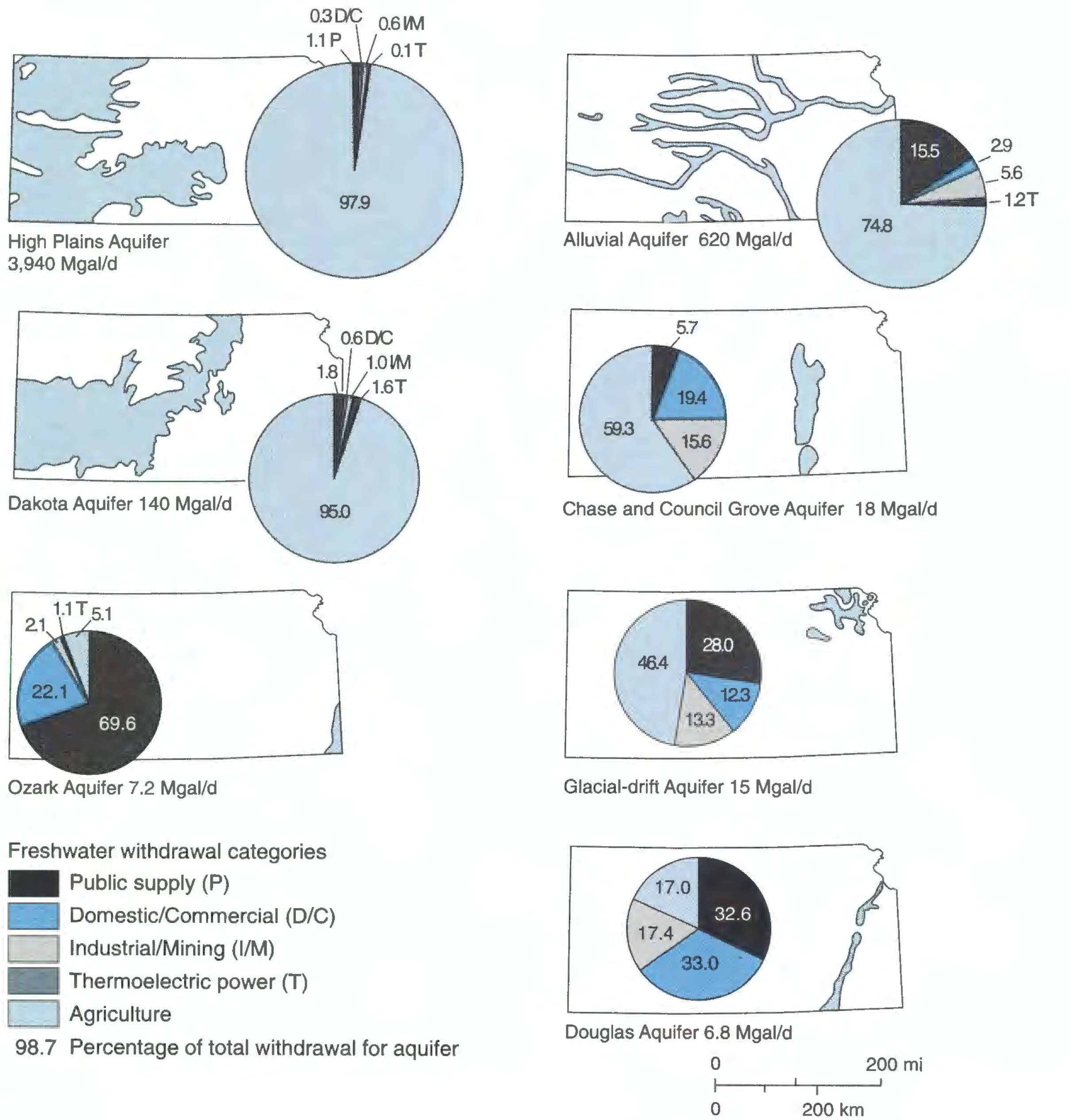


FIGURE 1.28—AQUIFER FRESHWATER WITHDRAWALS BY CATEGORY OF USE AND HYDROLOGIC UNIT IN KANSAS, 1985 (from U.S. Geological Survey, 1990).

Agricultural

Most of the 4,730 Mgal/d (14,492 AF/d or 17.9 million m^3/d) used by agriculture in 1985 (table 1.3) went to irrigation of nearly 3 million acres (1.2 million hectares) of crops in the western half of the state. Most of this water came from ground-water supplies, and represents 93.1% of the total freshwater withdrawals in the state. The widespread use of sprinkler irrigation (which applies little excess water to soil), combined with the practice of capturing runoff from flood irrigation and returning it to the soil, diminishes the return of irrigation water to the water table or streams. As a result, nearly all water withdrawn for irrigation is consumed.

Part III. Water-related Problems

Kansas Water-resources Problems and Issues

As identified by the Kansas District Office of the U.S. Geological Survey and Kansas State agencies. Largely extracted from KWRB, 1967b; Kansas Water Resources Fact-finding and Research Committee, 1955; Lampe, 1983; O'Connor, 1981; U.S. Geological Survey, 1984, 1985, 1988; and Woods et al., 1995.

Major water issues are summarized by category below. The letters and numerical subscripts identify issues shown on fig. 1.29; an asterisk (*) instead of a numerical subscript indicates that the issue is not shown on fig. 1.29.

Water-availability Issues

GROUND WATER—A_1 (fig. 1.29)

Ground water is being consumed much faster than it is replenished in parts of Kansas. Water levels in the High Plains (Ogallala) aquifer underlying western Kansas have declined as much as 150 ft (45 m) in parts of several counties during the last 30 years after widespread development of the aquifer as the principal source of irrigation water (Gutentag et al., 1984). In several areas, this aquifer is regulated by local Groundwater Management Districts and the Kansas Department of Agriculture, Division of

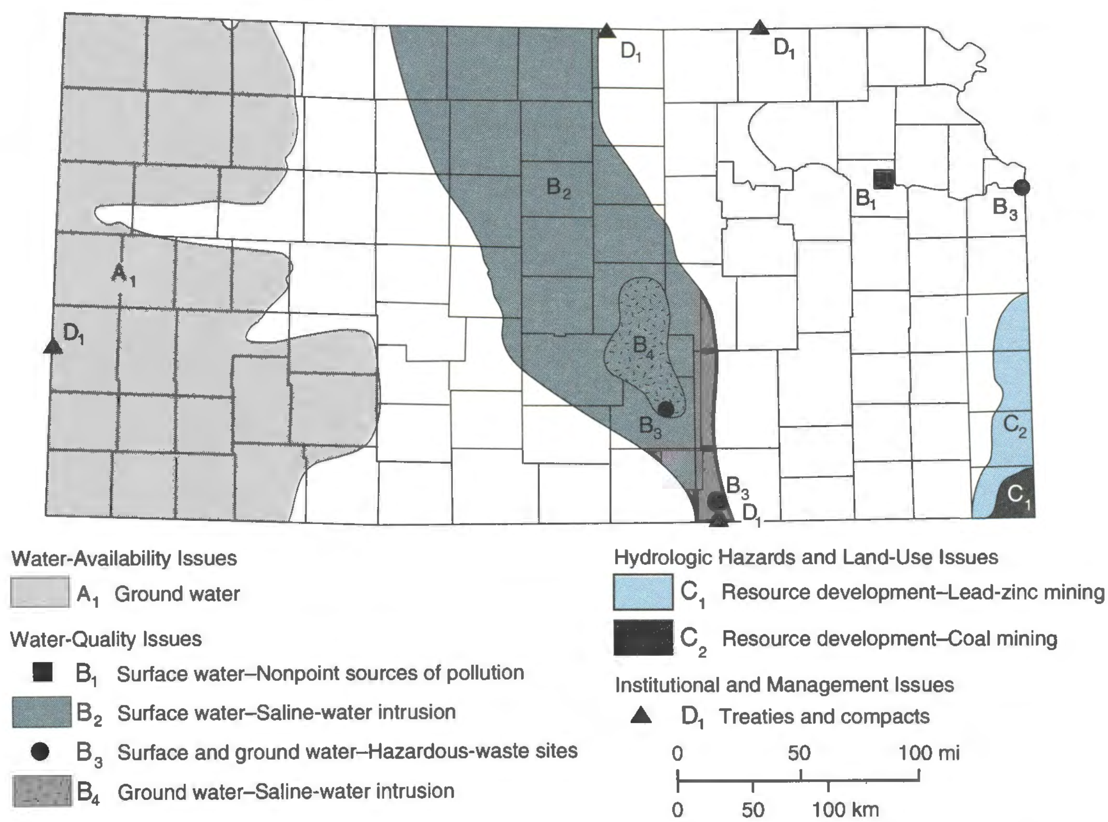


FIGURE 1.29—MAJOR WATER ISSUES IN KANSAS. See text for explanation (adapted from U.S. Geological Survey, 1984).

Water Resources. Additional areas are being considered for regulatory control. The Dakota aquifer, which underlies the High Plains (Ogallala) aquifer in western Kansas, is a potential source of additional water, and its hydrologic characteristics and water quality are being investigated by the Kansas Geological Survey. Because of concern about the effects of withdrawals of ground water from the alluvial stream-aquifer system along the Arkansas River in western Kansas from the state line to Dodge City, the State has restricted further development of the aquifer. Hydrologic-modeling studies show that this stream-aquifer system is sensitive to the quantity of flow in the Arkansas River.

Although ground water is withdrawn throughout the state, seven major pumping regions produce most of the water (fig. 1.30); the size of each circle shown in the figure is proportional to the amount of ground water pumped in each region. At locations 1 to 5 on fig. 1.30, water is withdrawn from the High Plains aquifer. These five pumping centers are Groundwater Management Districts (GMDs), which are political subdivisions of the State government, locally organized to manage ground-water resources. Location 6 is the Kansas River valley in northeast Kansas. At location 7, water is withdrawn from the Ozark aquifer in southeast Kansas. Ground-water withdrawals are estimated from water rights granted by the Kansas Department of Agriculture, Division of Water Resources. Estimates for pumping centers at locations 1 to 5 were provided by the GMDs for 1983 and reported in U.S. Geological Survey (1984). Estimates for pumping centers at locations 6 and 7 were obtained from unpublished data of the Division of Water Resources, Kansas Department of Agriculture and reported in U.S. Geological Survey (1984).

Approximately 710 million gallons per day (Mgal/d) or 2,179 acre-ft per day (AF/d) or 2.7 million m^3/d of water is withdrawn from the High Plains aquifer in region 1 in 1983 (fig. 1.30), representing the Western Kansas GMD1 which includes parts of Wallace, Greeley, Wichita, Scott, and Lane counties. The reported total irrigation water use for 1990 was 389,110 acre-ft or 0.48 km^3 (KWO/DWR, 1990). Because recharge is insufficient to replenish ground water withdrawn for irrigation, water levels had declined from 10 to 100 ft (3–30 m) by 1980 (Gutentag et al., 1984). A representative example of a well hydrograph in fig. 1.30 shows that the greatest rate of water-level decline occurred from about 1962 through 1975. Figure 1.31A shows generalized water-level and saturated-thickness changes from predevelopment to 1995 for the region.

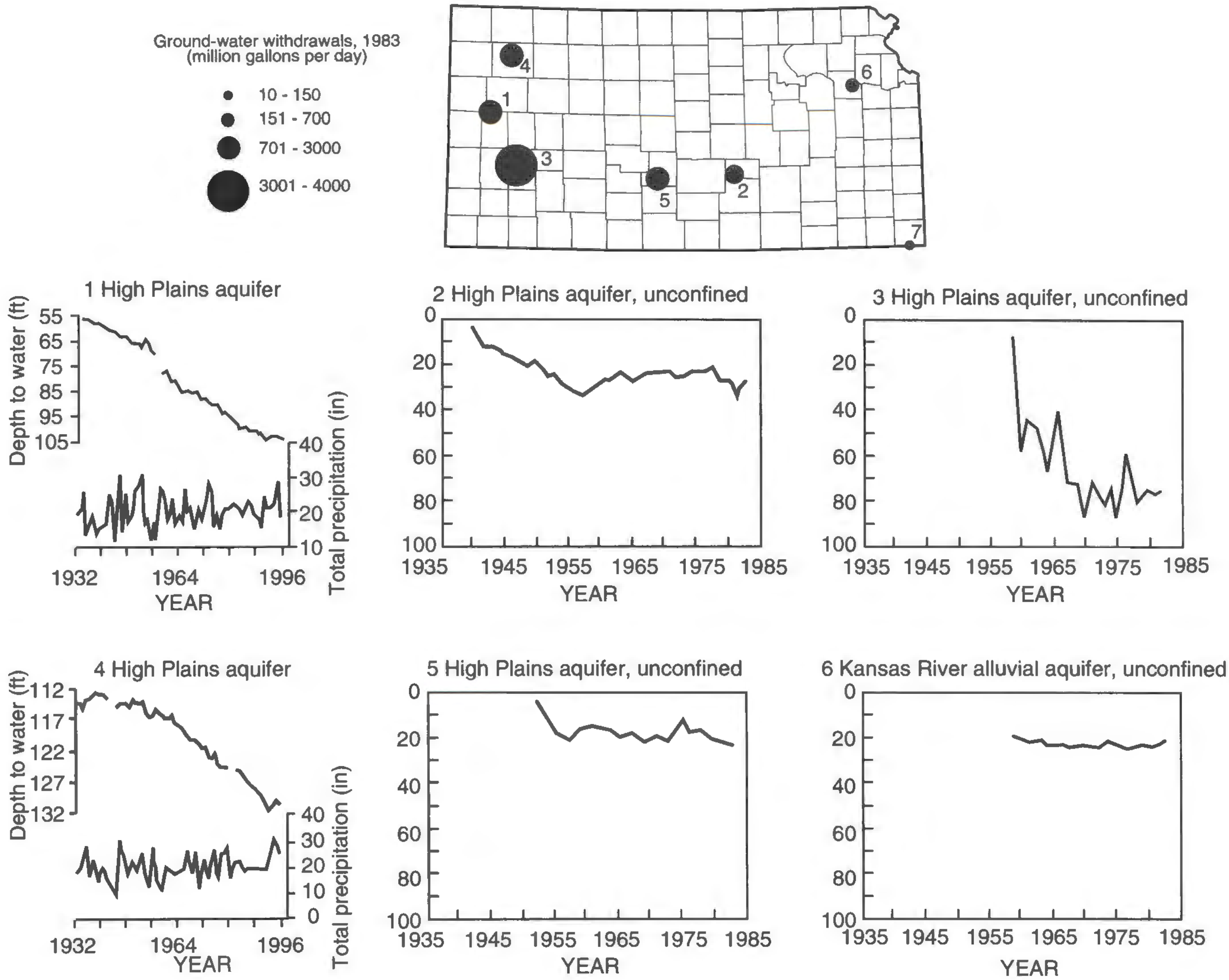
At location 2 (fig. 1.30), representing the Equus Beds GMD2, which includes parts of McPherson, Harvey, Reno, and Sedgwick counties, approximately 190 Mgal/d (583 AF/d or 0.72 million m^3/d) of water is withdrawn from the High Plains aquifer in 1983. The reported total irrigation water use for 1990 was 107,540 acre-ft or 0.13 km^3 (KWO/DWR, 1990). Although ground water is used extensively for irrigation and public supplies, recharge from precipitation generally prevented water levels from declining more than 10 ft (3 m) by 1980 (Gutentag et al., 1984). The largest decline, about 30 ft (9 m), occurred in the well field of the City of Wichita. A representative example of a well hydrograph from the Wichita well field (location 2, fig. 1.30) shows that the water level declined rather sharply from 1939 until 1957. The relative stability of water levels since about 1960 is primarily the result of decreased pumpage due to the increased use of surface water from Cheney Reservoir for public supplies. Figure 1.31B shows generalized water-level and saturated-thickness changes from predevelopment to 1995 for the combined GMD2 and GMD5 region.

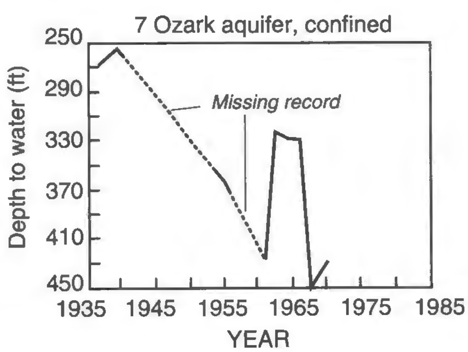
Approximately 3,300 Mgal/d (10,128 AF/d or 12.5 million m^3/d) of water is withdrawn from the High Plains aquifer at location 3 (fig. 1.30) in 1983, representing the southwestern GMD3, which includes Stanton, Morton, Grant, Stevens, Haskell, Seward, Gray, Ford, and parts of Hamilton, Kearny, Finney, and Meade counties. The reported total irrigation water use for 1990 was 2,551,837 acre-ft or 3.15 km^3 (KWO/DWR, 1990). Because precipitation is insufficient to replenish ground water withdrawn for irrigation, water levels had declined more than 150 ft (45 m) in parts of the area by 1980 (Gutentag et al., 1984). A representative example of a well hydrograph (location 3, fig. 1.30) shows that the greatest rate of decline occurred from about 1955 through 1970. Figure 1.31C shows generalized water-level and saturated-thickness changes from predevelopment to 1995 for the region.

Approximately 920 Mgal/d (2,824 AF/d or 3.48 million m^3/d) of water is withdrawn from the High Plains aquifer at location 4 (fig. 1.30) in 1983, representing the Northwest Kansas GMD4, which includes Sherman, Thomas, Sheridan, and parts of Cheyenne, Rawlins, Decatur, Graham, Wallace, Logan, and Gove counties. The reported total irrigation water use for 1990 was 514,487 acre-ft or 0.63 km^3 (KWO/DWR, 1990). Although ground water is withdrawn for irrigation in this area and precipitation provides little recharge, irrigation began later and has not developed as extensively as in other areas of the High Plains aquifer. Ground-water levels in this area had declined generally less than 50 ft (15 m) by 1980 (Gutentag et al., 1984). A representative example of a well hydrograph (location 4, fig. 1.30) shows that the greatest rate of water-level decline occurred from about 1970 through 1992. Figure 1.31D shows generalized water-level and saturated-thickness changes from predevelopment to 1995 for the region.

Approximately 910 Mgal/d (2,793 AF/d or 3.44 million m^3/d) of water is withdrawn from the High Plains aquifer at location 5 (fig. 1.30) in 1983, representing the Big Bend GMD5, which includes Stafford, Pratt, and parts of Kiowa, Edwards, Pawnee, Barton, Rice, and Reno counties. The reported total irrigation water use for 1990 was 570,888 acre-ft or 0.7 km^3 (KWO/DWR, 1990).

Ground water is used extensively for irrigation, but increased recharge and decreased pumping during wet years can raise water levels significantly, as indicated by a representative example of a well hydrograph (location 5, fig. 1.30). Ground-water levels in this area had declined generally less than 10 ft (3 m) by 1980 (Gutentag et al.,





WITHDRAWAL SITES			
No. on map	Geographic areas	Aquifer	Principal uses
1	Western Kansas, Ground-water Management District 1.	High Plains....	Irrigation, public supply
2	Equus Beds, Groundwater Management District 2.	High Plains....	Irrigation, public supply
3	Southwest Kansas, Ground-water Management District 3.	High Plains....	Irrigation, public supply
4	Northwest Kansas, Ground-water Management District 4.	High Plains....	Irrigation, public supply
5	Big Bend, Groundwater Management District 5.	High Plains....	Irrigation, public supply
6	Kansas River Valley, northeast Kansas.	Kansas River alluvial	Irrigation, Industrial
7	Southeast Kansas.	Ozark	Public supply

FIGURE 1.30—AREAL DISTRIBUTION OF MAJOR GROUND-WATER WITHDRAWALS AND GRAPHS OF ANNUAL DEPTH TO WATER IN SELECTED WELLS IN KANSAS (adapted from U.S. Geological Survey, 1985).

1984). However, declines of 25 ft (7.5 m) have been observed locally. Figure 1.31B shows generalized water-level and saturated-thickness changes from predevelopment to 1995 for the region.

Approximately 230 Mgal/d (706 AF/d or 0.87 million m^3/d) of water is withdrawn from the Kansas River alluvial aquifer at location 6 (fig. 1.30) in 1983, which includes the Kansas River valley in Geary, Riley, Wabaunsee, Pottawatomie, Shawnee, Douglas, Jefferson, Johnson, Leavenworth, and Wyandotte counties. Although ground water is used for irrigation and industrial supplies, significant amounts of recharge from precipitation and streamflow have kept water levels from declining significantly (location 6, fig. 1.30).

Approximately 14 Mgal/d (43 AF/d or 53,000 m^3/d) of water is withdrawn from the Ozark aquifer in location 7 (fig. 1.30) in 1983, which includes parts of Cherokee, Crawford, and Bourbon counties. Although the quantity of ground water withdrawn from this area is relatively small, recharge is limited because of confined conditions, and water levels have declined locally as much as 200 ft (60 m), based on predevelopment and 1980 potentiometric-surface maps (MacFarlane and Hathaway, 1987).

SURFACE WATER—A_* (not shown in fig. 1.29)

Because of the high variability of streamflows, many municipalities and industries in the eastern one-third of Kansas depend on water stored in major reservoirs to meet current and future needs. A concern to the State is its ability to deliver water released from upstream reservoirs to municipalities as much as 50 to 100 mi (80–160 km) downstream. The State is also concerned about providing dependable supplies to many communities in the southeast from small local reservoirs or via pipelines from large reservoirs in the region.

Water-quality Issues

SURFACE WATER—NONPOINT SOURCES OF POLLUTION—B_1 (fig. 1.29)

Pollution caused by sediment, nutrients, and organic and toxic substances originating from land-use activities and/or from the atmosphere, which are carried to lakes and streams by runoff, is known as *nonpoint source pollution*. Thus, storm runoff from urban areas may be a source of

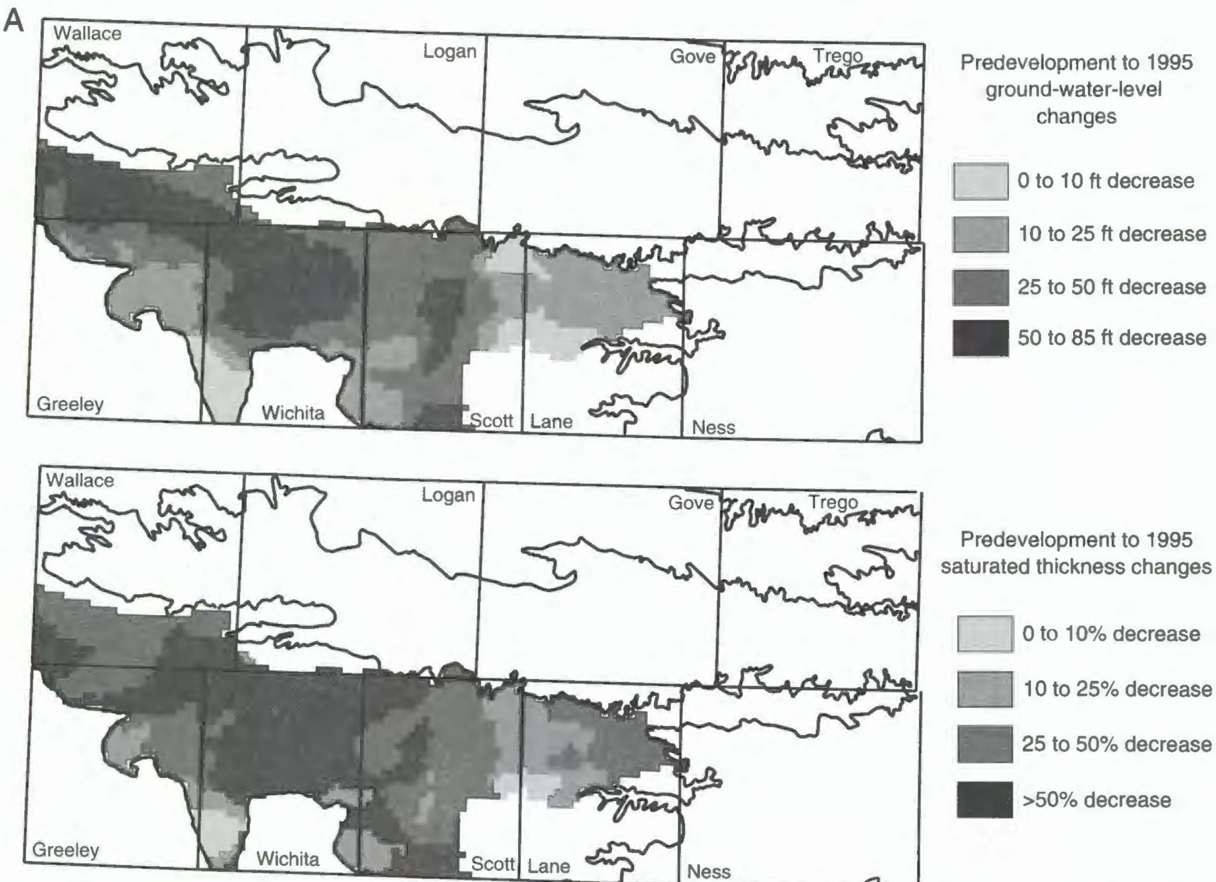


FIGURE 1.31—GROUND-WATER CHANGES IN A) THE GMD 1 AREA OF THE HIGH PLAINS AQUIFER IN WEST-CENTRAL KANSAS; B) the GMD 5 and GMD2 area of the High Plains aquifer in south-central Kansas; C) the GMD 3 area of the High Plains aquifer in southwest Kansas; and D) the GMD 4 area of the High Plains aquifer in northwestern Kansas (from Woods et al., 1995) .

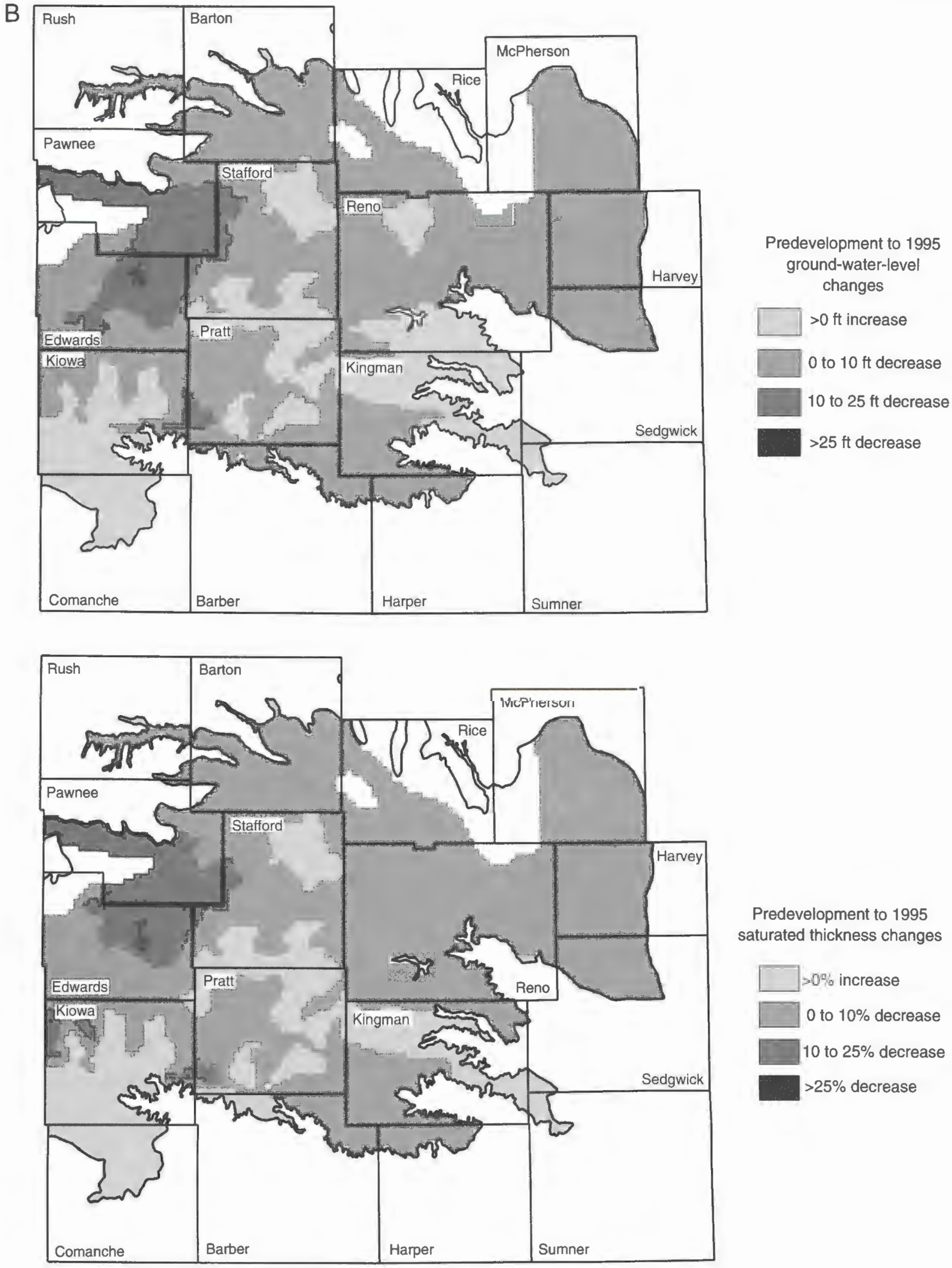


FIGURE 1.31 (continued)

stream pollution. In the Topeka area, for example, storm runoff from Shunganunga Creek basin transports large concentrations of suspended sediment and heavy metals, with the largest concentrations generally occurring during the initial part of the runoff from a storm (U.S. Geological Survey, 1984).

The herbicide atrazine is detected in Kansas surface waters more often than any other synthetic agricultural chemical. Detections in surface water are most common in the northeastern portion of the state, where extensive use of atrazine for row-crop production and higher levels of annual runoff combine to deliver substantial quantities of the material to nearby streams, lakes, and wetlands. The presence of atrazine in public or private drinking water supplies in excess of the maximum contaminant concentration of 3 parts per billion is a potential human health risk. While data are not yet considered conclusive, the data base is growing and suggests that atrazine in water supplies carries a health risk. The episodic occurrence (runoff events) of high concentrations of atrazine in lakes and streams may result in the gradual elimination of sensitive plant species and promote changes in the overall diversity and productivity of these ecosystems (Carney et al., 1991).

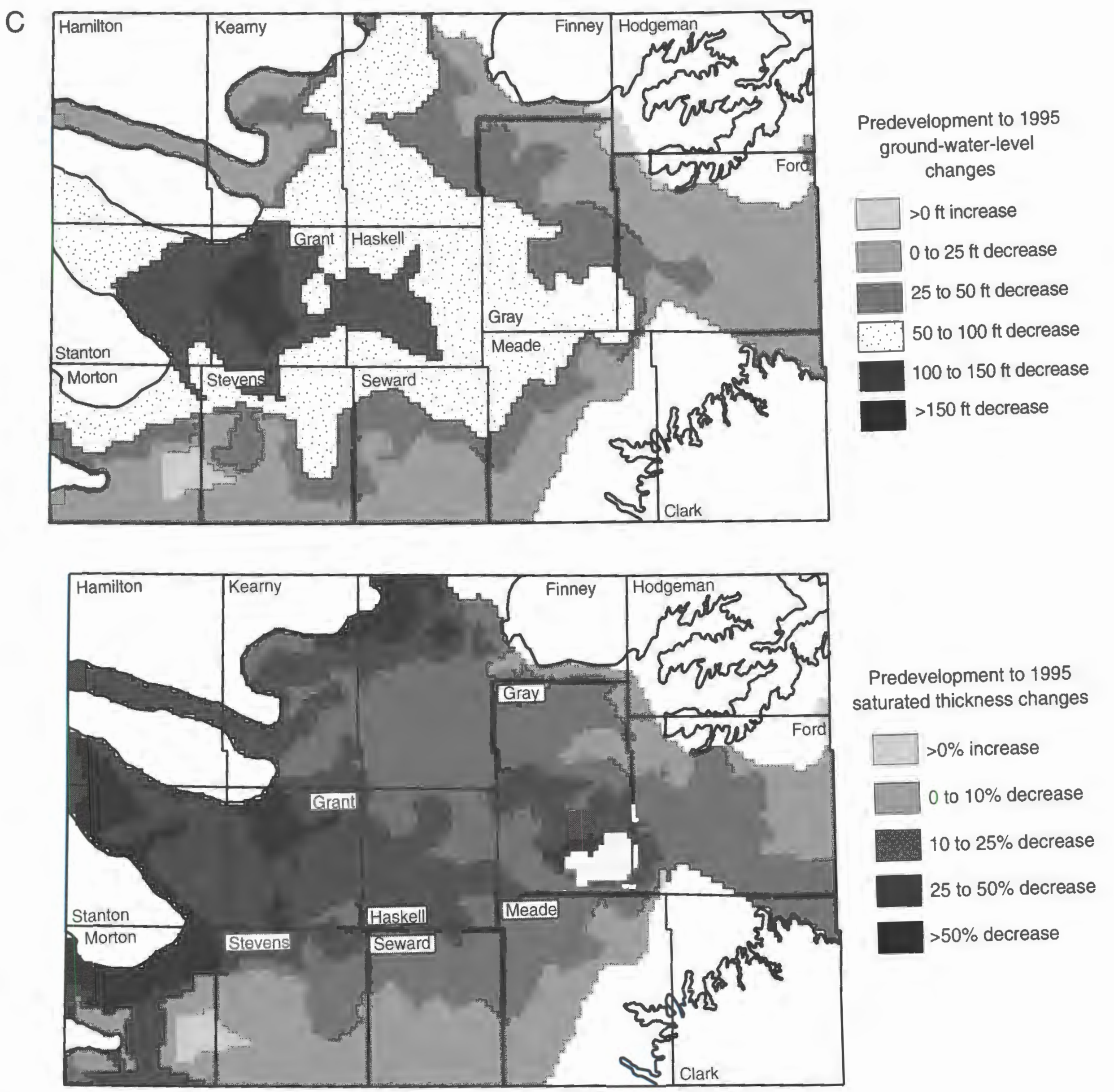


FIGURE 1.31 (continued)

SURFACE WATER—SALINE-WATER INTRUSION—B_2 (fig. 1.29)

Aquifers underlying central Kansas discharge saline water to streams. During low flows, the discharge of brine (chloride concentration about 60,000 milligrams per liter) from the Wellington aquifer upward through the alluvium to the Smoky Hill River near Salina causes a four-fold increase (from 250 to 1,100 milligrams per liter) in chloride concentration, which restricts the use of the river during low flows. Other major rivers affected by saline ground-water discharge include the Arkansas, Ninnescah, Saline, and Solomon.

SURFACE WATER—TRIHALOMETHANE—B*

Many public water-supply lakes in eastern Kansas are used for several purposes, including boating and fishing. Water in these lakes may contain undesirable concentrations of organic compounds resulting from the decay of vegetation. Subsequent water treatment with chlorine can form trihalomethane (a possible carcinogen) and other byproducts (Denne et al., 1984).

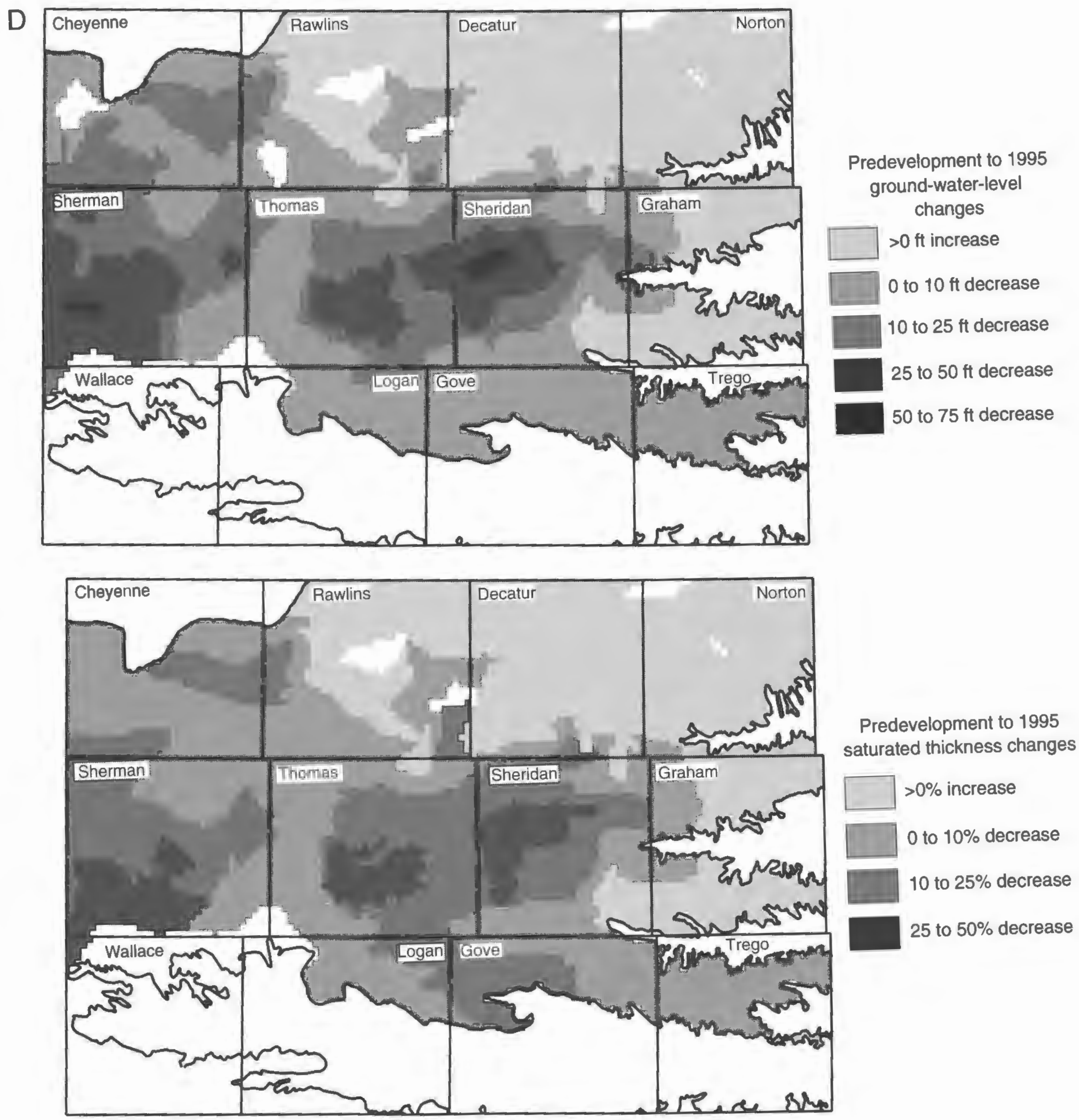


FIGURE 1.31 (continued)

SURFACE AND GROUND WATER—WASTE-DISPOSAL SITES—B_3 (fig. 1.29)

As of December 31, 1995, there were 11 Superfund (Comprehensive Environmental Response, Compensation, and Liability Act, CERCLA) sites, 525 "active" sites investigated by the Kansas Department of Health and Environment (KDHE, 1996) under the Resource Conservation and Recovery Act (RCRA), five Underground Injection Control (UIC) class I (most strictly regulated) industrial hazardous-waste disposal wells, and 37 nonhazardous Class I wells (Michael Cochran, Kansas Department of Health and Environment, oral communication, April 1997) in the state. (Class I injection or disposal wells are wells used to inject hazardous or nonhazardous liquid waste below a formation containing the lowermost underground source of drinking water located within one-quarter mile [400 m] of the well bore.) Figure 1.32A shows a number of these waste sites (as of 1986). Most of these sites involve disposal of industrial wastes. RCRA sites are concentrated near the major population and industrial centers of Wichita (Sedgwick County), Topeka (Shawnee County), and Kansas City (Johnson, Leavenworth, and Wyandotte counties). Wastes present at the CERCLA and RCRA sites include arsenic, chromium, lead, and other trace elements; petroleum products; volatile organic compounds (VOC); and agricultural chemicals. Areas of known and potential ground-water contamination from these sources are shown in fig. 1.32B. Ground water and soil are the most common contaminated media statewide. Fifty-eight contaminated sites involve a public water supply (KDHE, 1996). Figure 1.32C displays the number of contamination sites under active investigation by KDHE in each KDHE administrative district in the state, and also the Superfund sites as of December 31, 1995.

In addition to industrial waste-disposal sites, 104 active county and municipal landfills in Kansas were being monitored by the Kansas Department of Health and Environment as of 1986 (fig. 1.33A). However, a number of these were closed, so that only 24 municipal (subtitled D) and 33 small (exempt, see further below) landfills in Kansas remain today (Mark Duncan, Kansas Department of Health and Environment, oral communication, April 1997); these are shown in fig. 1.33B. Subtitle D of RCRA gives the U.S. Environmental Protection Agency the authority to establish minimum containment requirements for nonhazardous solid wastes. State of Kansas solid-waste regulations (KAR 28-29-104) require hydrogeologic site investigations, liner and leachate collection systems, and monitoring for municipal landfills. Small (exempt) landfills, which receive and dispose less than an annual average of 20 tons of municipal solid waste daily, are located in areas that receive less than or equal to 25 inches (63.5 cm) of average annual precipitation, and show no evidence of contamination, are exempt from the previously mentioned requirements specified in KAR 28-29-104.

Also shown in fig. 1.33A are 281 closed and abandoned landfills that were identified from county highway maps as of 1986. Few data are available to evaluate the effects of these closed landfills on local ground-water quality.

Disposal and management of oil and gas production wastes are regulated by the State, but such regulation is sometimes difficult to enforce, particularly where large areas are involved. Disposal of oil-field brines remains a potential source of contamination.

SURFACE AND GROUND WATER—UNDERGROUND PETROLEUM STORAGE TANK SITES AND SPILL SITES—B_* (not shown in fig. 1.29)

Regulation of petroleum storage tanks and corrective action on leaks from such tanks are major areas of responsibility of the Bureau of Environmental Remediation of the Kansas Department of Health and Environment. The Underground Petroleum Storage Tank Release Trust Fund (UST Fund) was established by the Kansas Legislature in 1989 to provide reimbursements to tank owners/operators for the costs of corrective action at leaking petroleum storage tank sites. A similar above-ground storage tank trust fund also was established. As of December 31, 1995, a total of 1,281 applications have been filed for UST Fund approval. During Federal fiscal year 1995, 279 underground storage tank sites (out of 608 investigated) were confirmed as leaking, and cleanup for 173 of these was initiated in the state (KDHE, 1996). During 1995, 1,132 spill sites were reported. The majority of spilled material was crude oil and brine (KDHE, 1996). The majority of spills affect only soil; however, many also affect surface water and, to a lesser extent, ground water.

AGRICULTURAL PRACTICES—C_* (not shown in fig. 1.29)

Relatively few studies have been conducted to determine the effect of irrigation on ground-water quality in Kansas. This probably reflects the likelihood that irrigation in most of Kansas is believed to be a minor ground-water-quality concern. Irrigation is not practiced extensively in the eastern one-third of the state, and water quality in the glacial-drift, Chase and Council Grove, Douglas, and Ozark aquifers is unlikely to be affected by irrigation. The Ozark aquifer also is protected by the great thickness of the overlying units.

Spruill (1985) attributed increased concentrations of calcium, sodium, sulfate, chloride, and dissolved solids in alluvial aquifers in north-central Kansas to irrigation return flows. However, analyses for pesticides for which primary drinking-water standards have been established indicated no contamination of ground water by these compounds in north-central Kansas.

Investigations by Bevans (1989) have detected herbicides in water from the High Plains aquifer in north-central Sedgwick County. These findings are of concern to

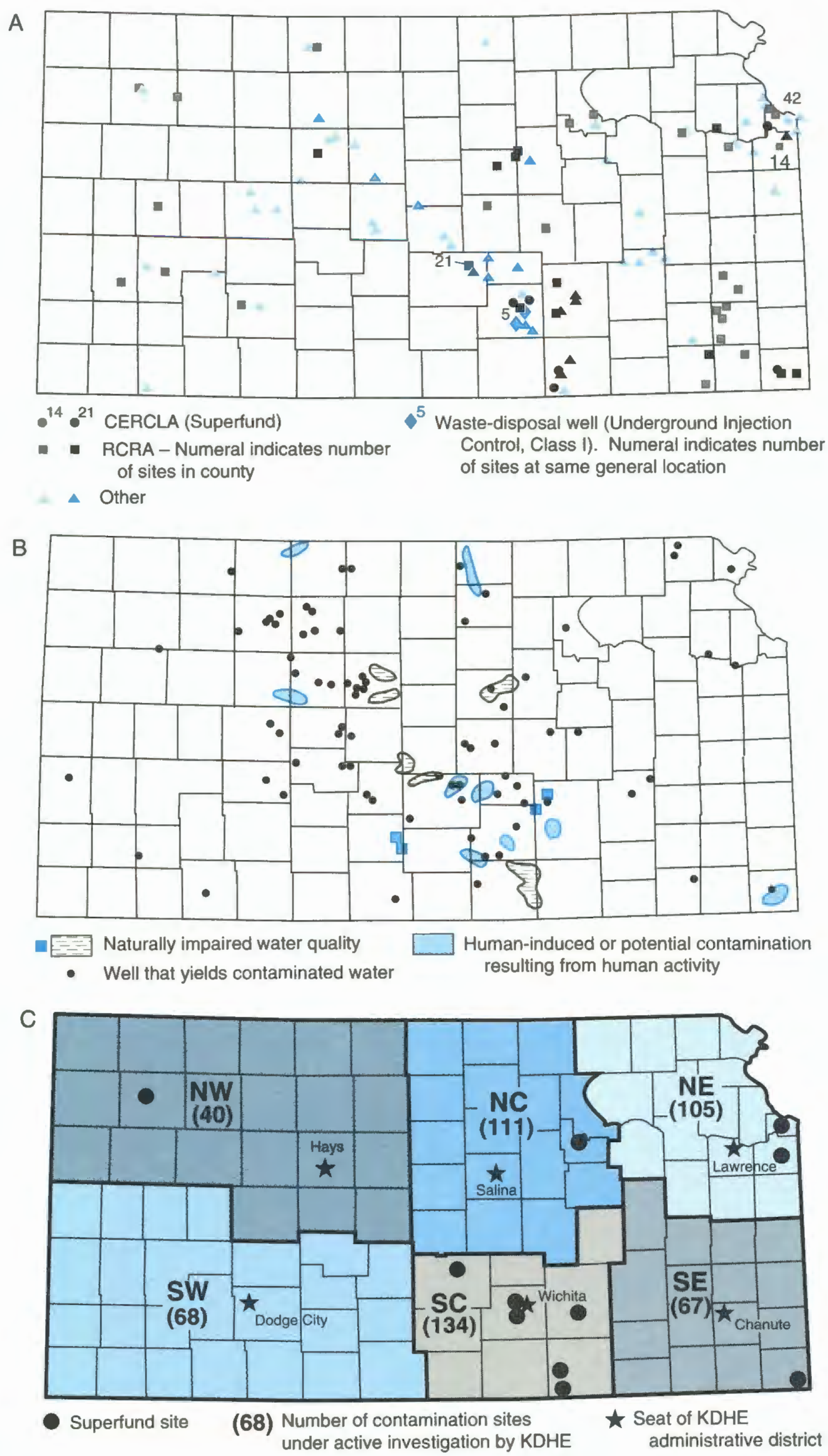


FIGURE 1.32—SELECTED WASTE-DISPOSAL SITES (A) AND AREAS OF NATURALLY INDUCED AND HUMAN-INDUCED GROUND-WATER-CONTAMINATION (B) AS OF 1986 IN KANSAS (adapted from U.S. Geological Survey, 1988). Kansas Department of Health and Environment (KDHE) administrative districts with the number of identified contamination sites under active investigation by KDHE, and with the Superfund sites as of the end of 1995 (C).

State and local officials because the City of Wichita uses water from this aquifer as a principal source of public supply.

The Division of Plant Health of the Kansas Department of Agriculture has been conducting yearly sampling of ground water from chemigation sites throughout Kansas. From 1987 to 1996, the Division of Plant Health has collected 590 water samples from chemigation sites in Kansas. Of this amount, 34 samples or 6% from 24 unique sites had contained at least one pesticide at a level at or above the Method of Detection Limit (i.e. the minimum concentration of a substance that can be measured and reported with 99% confidence that the analyte concentration is greater than zero); 77 samples or 13% from 72 unique sites had been determined to have nitrate-nitrogen (NO_3-N) levels at or above the Kansas Notification Level, KNL (i.e. the administrative level confirming that ground-water contamination does exist) of 10 mg/L; and 58 samples or 10% from 50 unique sites had been determined to contain sulfate levels at or above the KNL of 250 mg/L (Marc Anderson, Kansas Department of Agriculture, written communication, 1997).

Available water supplies in most of the irrigated areas of Kansas are almost completely appropriated, and irrigation is unlikely to increase greatly. However, the potential for additional contamination of ground water from agricultural practices remains. The movement of pesticides through the unsaturated zone is poorly understood, and investigations to determine their effect on ground-water quality continue. Declining water levels caused by withdrawals for irrigation also offer the potential for contamination of freshwater aquifers by underlying brines.

GROUND WATER—SALINE-WATER INTRUSION—B_4 (fig. 1.29)

Water quality in several unconsolidated aquifers is impaired by inflow of saline or briny water from underlying consolidated rocks (Hargadine et al., 1978). Locally, confined water that contains large concentrations of

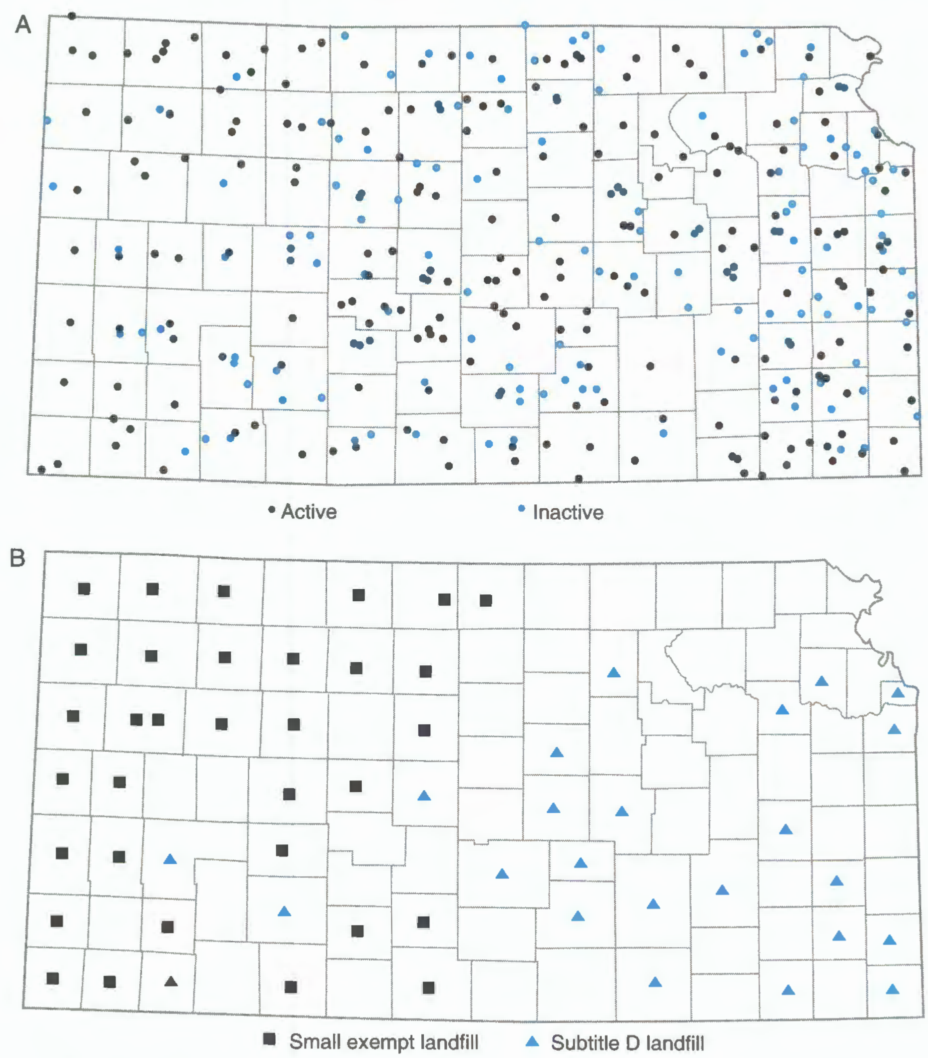


FIGURE 1.33—County and municipal landfill sites in Kansas as of 1986 (A), and as of April 1997 (B).

calcium, sodium, sulfate, and chloride is under higher hydraulic head than that in the overlying alluvium. In these areas, saline or briny water may move up through the confining layer and enter the alluvial aquifers. An example of such movement in the Smoky Hill River valley near Salina is shown in fig. 1.34. Water withdrawals from the alluvial aquifers may lower the hydraulic head in these aquifers causing upwelling of saline water and aggravation of the problem.

Some serious water-quality problems are associated with ground-water flow in Permian and Cretaceous rocks in different areas of the state. One of these areas is associated with the dissolution of the Hutchinson Salt Member of the Wellington Formation between Saline County on the north and Sumner and Cowley counties on the south. Natural ground-water circulation causes saltwater to discharge to the Smoky Hill River valley east of Salina and the Arkansas River valley in the vicinity of Geuda Springs, which causes increased salt content in the streams and the associated unconsolidated aquifers.

A second area of natural mineralized water discharge is from the Permian red beds in parts of Stafford, Reno, Pratt, Barber, Comanche, Clark, Meade, and Seward counties. The geohydrology of this flow system is not well understood, but ground water is believed to enter Permian red beds that include sandstone, bedded salt, gypsum, and anhydrite in southwest Kansas and to flow eastward and southeastward to discharge into streams and the unconsolidated aquifers that occur in those counties.

A third area of natural mineralized water discharge is from the sandstone beds in the Dakota and Kiowa Formations. This affects segments of the Smoky Hill, Saline, Solomon, and Republican rivers and the associated unconsolidated valley aquifers along the eastern edge of the Lower Cretaceous outcrop.

The "Equus beds," a principal unconsolidated aquifer in central Kansas, supplies much of the municipal water for the City of Wichita, and is increasingly used for irrigation. Increased pumpage may cause deterioration of ground-water quality by influx of underlying saline ground water or movement of more mineralized water from the Arkansas River into the alluvial aquifer.

Hydrologic Hazards

RESOURCE DEVELOPMENT—LEAD-ZINC MINING—C_1 (fig. 1.29)

Lead and zinc deposits in southeastern Kansas were mined in the past by underground methods; discharge from abandoned workings, mine tailings, and smelter sites has polluted some streams in the area including Short Creek, Spring River, and Tar Creek. In Short Creek, concentrations of as much as 28,000 micrograms per liter of dissolved zinc and as much as 300 micrograms per liter of dissolved cadmium have been detected (U.S. Geological Survey, 1984). Unaffected streams in the area typically have concentrations of less than 200 micrograms per liter of dissolved zinc and less than 1 microgram per liter of dissolved cadmium. An underlying aquifer that annually provides about 3 billion gallons (11.36 million m^3) to municipal- and rural-water users may also be polluted. The entire area of Cherokee County has been included in the EPA National Priorities List of hazardous-waste sites under CERCLA. Although the underlying Ozark aquifer probably has not been affected by mine drainage because it

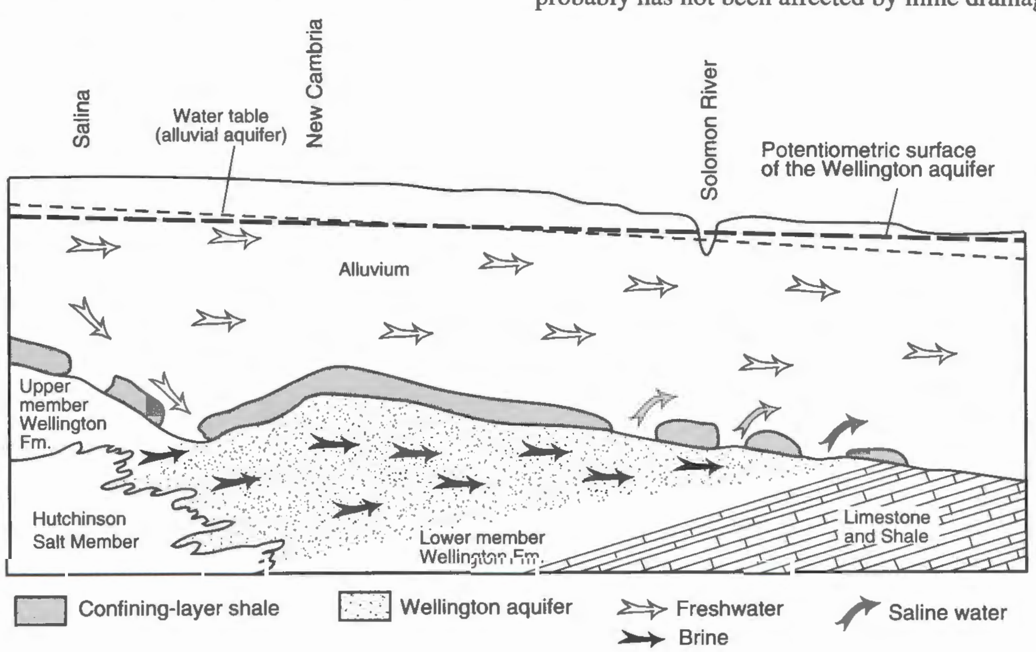


Figure 1.34—DIAGRAMMATIC SECTION ALONG THE SMOKY HILL RIVER VALLEY SHOWING PATTERNS OF GROUND-WATER FLOW THAT INTRODUCES SALINE WATER INTO THE ALLUVIAL AQUIFER (adapted from U.S. Geological Survey, 1988).

is deeply buried, the potential exists for contamination by leakage through drill holes and fractures.

RESOURCE DEVELOPMENT—COAL MINING—C_2 (fig. 1.29)

Coal has been mined in southeastern Kansas since about 1860. Originally the coal was mined by underground methods; however, because surface mining is less expensive, the deposits have been strip mined since about 1940. The underground mines and associated spoil piles, as well as some strip-mined areas, have been abandoned. Seepage from abandoned underground and strip mines has polluted nearby streams. Water in Brush and Little Cherry creeks, for example, sometimes has pH values of less than 4.0 as a result of discharges from underground mines. The average concentration of sulfate in area streams is related to the percentage of the basin that has been strip mined. The potential for localized pollution of aquifers by seepage of water from the abandoned mines also is present. The Kansas Mined-land Conservation and Reclamation Board, now replaced by the Kansas Department of Health and Environment Surface Mining Section, has prepared a plan to address these problems.

FLOODING—C_* (not shown in fig. 1.29)

Floodplain areas adjacent to the principal streams and rivers in Kansas are subject to occasional flooding that results in property damage and occasional loss of life. About 52% of the communities and 62% of the counties in Kansas have flood-prone areas, as defined by the Federal Flood Insurance Program of the U.S. Department of Housing and Urban Development.

EROSION AND SEDIMENTATION—C_* (not shown in fig. 1.29)

Sediment yields of streams generally increase from west to east across the state, ranging annually from less than 100 tons/mi^2 (40 tons/km^2) in semiarid southwestern Kansas to more than 5,000 tons/mi^2 (1,930 tons/km^2) in humid northeastern Kansas (Holland, 1971; Osterkamp, 1977; Bevans, 1982). Streambank erosion is a concern along the Kansas and Nemaha rivers, especially downstream from large reservoirs, in reaches where the channels have been straightened, and where sand is mined from the river channel.

Institutional and Management Issues

INTERSTATE COMPACTS—D_1 (fig. 1.29)

In all Kansas streams, some of the water may come from other states or may be going to other states. Such water becomes an interstate issue in states where water is in demand. Colorado is an example of a water-producing state from which some water flows to all five surrounding states where demand is great, and it has entered into compacts with all of them, including Kansas. At the other extreme is Louisiana, which receives runoff from one-third of the entire nation and has no need for a compact guaranteeing any specified quantity from any other state. In arid regions, compacts are generally beneficial to all states involved, because they recognize the rights of existing users but set limits on future development. In this way the interests of each state are protected regardless of the timing of development, and each state can plan soundly for the future.

The *Republican River Compact* was negotiated at Lincoln, Nebraska, on December 31, 1942; ratified by Colorado, Kansas, and Nebraska in February and March 1943; and approved by the Congress of the United States on May 26, 1943. The allocations of water specified in the compact are based on computations of average "virgin" water supply for each of 14 designated tributary basins above the lowest crossing of the Nebraska–Kansas state line, where the river enters Kansas for the final time. "Virgin water supply" was defined as the water supply within the basin that is undepleted by human activities. The Compact requires that, should the future computed virgin-water supply of any source vary by more than 10% from the allocations set forth in the Compact, the allocations shall be increased or decreased in relative proportions to the allocated virgin-water supply. Computations to determine if allocations vary by more than 10% are made by the Engineering Committee of the Republican River Compact and adjustments are made if needed. These data are published in an annual report.

The *Arkansas River Compact* was negotiated between the states of Colorado and Kansas on December 14, 1948, to equitably divide and apportion the waters of the Arkansas River and help resolve disagreements and head off future arguments. It specifies the operation of the conservation pool of the John Martin reservoir at Caddoa, Colorado, which has a conservation capacity of 395,000 acre-feet (487.23 million m^3). During a five-month winter storage period (November 1 to March 31), all inflow to the reservoir is to be stored, except that Colorado users may demand release of an amount equivalent to the natural inflow up to 100 cubic feet per second (cfs) or 2.83 m^3/s. All Compact waters stored in John Martin are apportioned 60% to Colorado and 40% to Kansas. These waters are generally released during April 1 through October 31. There is no allowance of credits or debits for or against either state. The releases from John Martin Reservoir to which Kansas is entitled shall be satisfied by an equivalent in stateline flow.

In 1985, Kansas filed suit against Colorado for failing to live up to terms of the Compact. In its case, Kansas claimed that Colorado reduced the river's flow in three ways. First, Colorado was claimed to be keeping too much water in Trinidad Reservoir, a lake in south-central Colorado on the Purgatoire River, a tributary of the Arkansas. Second, Colorado was claimed to be storing and using too much of the Arkansas River flow into

Pueblo Reservoir. Third, Colorado was claimed to let farmers drill about 1,500 "post-Compact irrigation wells," that is, wells drilled after the 1948 agreement, in the Arkansas River alluvium. Those wells, Kansas claimed, were taking away huge amounts of water that would have been recharging the river. The Special Master hearing the case submitted a final report in July 1994. The Supreme Court reviewed the report and in May 1995, Chief Justice William Rehnquist wrote the opinion that upheld the Special Master's view that the Kansas complaints about Trinidad and Pueblo reservoirs were not relevant. But Rehnquist agreed with the Special Master that those post-Compact wells were a problem. Having determined that Colorado was at fault, the trial has moved into its next phase, one to determine remedies for the current problem and compensation for the past. The phase is likely to last several years and will determine a way for Colorado to deliver Kansas' share of water as agreed upon in the compact. Colorado must also reimburse Kansas for the water—however much that is—that it should have delivered.

The State of Kansas and the State of Nebraska are member states of the *Big Blue River Compact.* The Compact was approved by each state on January 25, 1971. The Compact requires that minimum mean daily flows be maintained at the Kansas–Nebraska stateline on the Big and Little Blue rivers during the months of May through September each year. Gaging stations at Hollenberg, Kansas, and Barneston, Nebraska, are the stateline stations for recording flows. The Compact contains specific procedures that may be implemented to maintain minimum stateline flows. The Compact also requires that studies be made to determine the effects of pumping of wells on the flows of the Big and Little Blue rivers at the Kansas–Nebraska stateline.

Kansas and Oklahoma are member states of the *Arkansas River Basin Compact* which was entered into on March 31, 1965. The Compact apportions specific new conservation storage capacities by subbasin within the state of Kansas plus an additional capacity equal to the new conservation storage constructed in said subbasins in Oklahoma. The Cimarron subbasin is excluded from this provision as new conservation storage is limited in each state by specific provisions. New conservation storages are computed by the Engineering Committee of the Compact and published annually.

RESERVOIR STORAGE DEVELOPMENT

There are few natural lakes in Kansas. Of these, most are in sinkholes, formed by collapse of the underlying geologic formations. Some, however, have been created on the floodplain of major streams when a river changed its channel and left an oxbow lake behind. Some are natural depressions filled with water. These natural lakes are not large. The largest natural lake in Kansas is about 3 mi (4.8 km) northeast of Inman in McPherson County and has a surface area of about 130 acres (52.5 hectares) and a maximum depth of less than 10 ft (3 m).

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.

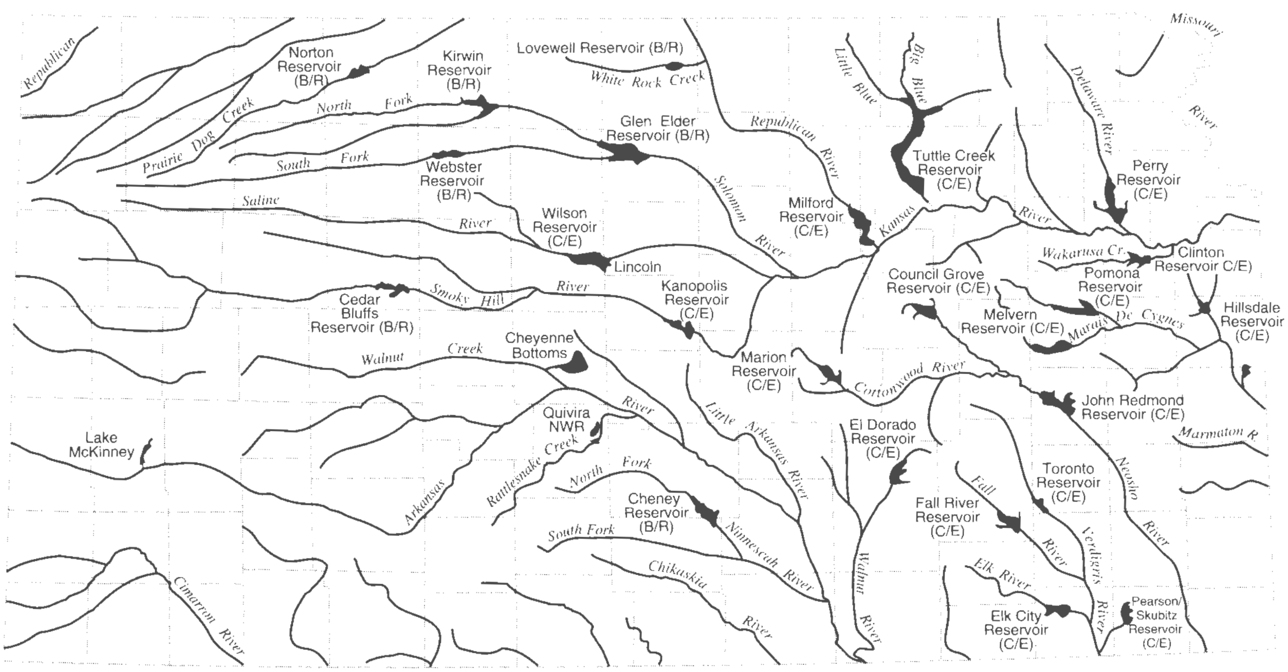


FIGURE 1.35—KANSAS RIVERS AND RESERVOIRS. The two largest Kansas wetlands (Cheyenne Bottoms and Quivira National Wildlife Refuge) also are shown. B/R–Bureau of Reclamation, C/E–Corps of Engineers.

Twenty-four major reservoirs have been built in the state (fig. 1.35), 17 under the auspices of the Corps of Engineers and seven under the Bureau of Reclamation. The State has contracted with the Federal government for water-supply storage in nine of these reservoirs; the total 2% drought yield (i.e. a yield that has a 1/50 chance of occurring) in these nine reservoirs is 305 million gallons per day (935 AF/d or 1.15 million m^3/d). In addition, storage in Tuttle Creek Reservoir may be reallocated from purposes of navigation and maintenance of water quality to water-supply purposes. This could add several hundred million gallons per day to the State water supply and storage program.

The effectiveness of storage facilities in providing a sustained yield is limited by their ability to retain the surplus water and release it to supplement deficiencies.

TABLE 1. 4—BASIC INFORMATION ON MAJOR KANSAS RESERVOIRS (from Lampe, 1983).

Name	Watercourse	Completion Date	County	Total Storage (1,000 acre-feet)	Long Range Yield (million gallon day)	Long Range Purpose of Project*
Pearson/Skubitz	Big Hill Creek	1980	Labette	40.6	7.1	1,2,4,5
Cedar Bluff	Smoky Hill River	1951	Trego	377.0	23.7	1,2,3,5
Cheney	North Fork Ninnescah River	1965	Sedgwick, Kingman, and Reno	243.3	33.0	1,2,5
Clinton	Wakarusa River	1979	Douglas and Shawnee	397.2	23.3	1,2,4,5
Council Grove	Neosho River	1964	Morris	114.0	9.7	1,2,4,5
El Dorado	East Branch Walnut Creek	1977	Butler	236.2	20.8	1,2,4,5
Elk City	Elk River	1966	Montgomery	291.0	28.4	1,2,4,5
Fall River	Fall River	1949	Greenwood	259.0	10.0	1,2,4,5
Glen Elder	Solomon River	1969	Mitchell and Osborne	963.8	59.8	1,2,3,4,5
Hillsdale	Big Bull Creek	1981	Miami	160.0	22.3	1,2,4,5
John Redmond	Neosho River	1964	Coffey and Lyon	644.8	47.2	1,2,4,5
Kanopolis	Smoky Hill River	1948	Ellsworth	450.0	58.8	1,2,3,4,5
Kirwin	North Fork Solomon River	1955	Phillips	314.5	25.9	1,3,5
Lovewell	White Rock Creek	1957	Jewell	92.2	11.4	1,3,5
Marion	Cottonwood River	1968	Marion	146.5	12.3	1,2,4,5
Melvern	Marais des Cygnes River	1974	Osage	367.0	27.9	1,2,4,5
Milford	Republican River	1967	Geary, Dickinson, Riley, and Clay	1,160.0	128.6	1,2,4,5
Norton	Prairie Dog Creek	1965	Norton	134.7	9.7	1,2,4,5
Perry	Delaware River	1969	Jefferson and Atchison	770.0	79.5	1,2,4,5,6
Pomona	110 Mile Creek	1963	Osage	246.5	14.2	1,2,4,5
Toronto	Verdigris River	1960	Woodson and Greenwood	195.3	9.9	1,2,4,5
Tuttle Creek	Blue River	1963	Riley, Marshall, and Pottawatomie	2,346.0	226.2	1,2,4,5,6
Webster	South Fork Solomon River	1956	Rooks	260.7	17.3	1,3,5
Wilson	Saline River	1965	Russell and Lincoln	775.0	55.8	I,2,3,4,5,6

*1 - Flood Control 2 - Municipal and Industrial 3 - Irrigation 4 - Streamflow Regulation 5 - Recreation, Fish and Wildlife 6 - Navigation

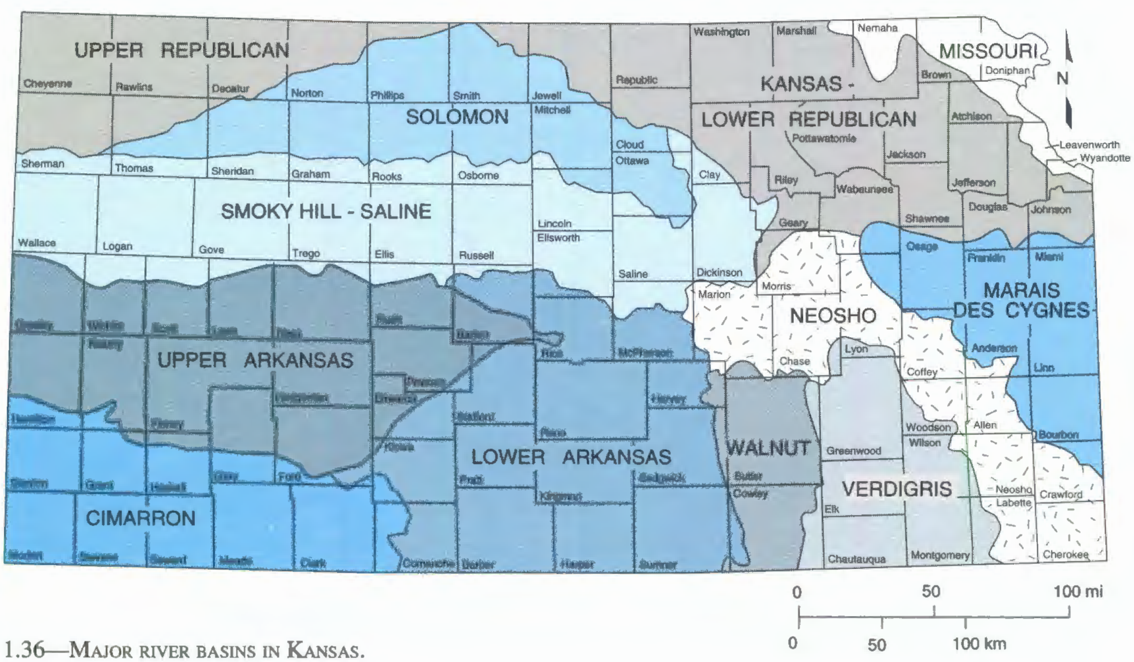


FIGURE 1.36—MAJOR RIVER BASINS IN KANSAS.

Some reservoirs are naturally incapable of holding water long enough to ensure a sustained yield, but most of the limitations on storage are human-made regulations that do not permit water to be held so long or prevent it from being withdrawn. The reservoirs and their functions are indicated in table 1.4. The 24 reservoirs have a total storage capacity of 11,000,000 acre-feet (13.57 km^3) of which 2,350,000 acre-feet (2.9 km^3) are available for conservation capacity to regulate surface-water supplies for sustained use.

Part IV. Water-resources Management

Water-management Agencies—Responsibilities for Planning and Management

Largely extracted from Lampe, 1983; and U.S. Geological Survey, 1986, 1988, 1990, and 1993.

Kansas has five State agencies and one type of local State government unit with major responsibilities for managing surface and ground water. In addition, Federal water projects are managed by the U.S. Army Corps of Engineers and the U.S. Bureau of Reclamation. Management decisions are based on hydrologic data collected by the U.S. Geological Survey in cooperation with several Federal, State, and local agencies. Responsibilities of individuals and State, Federal, and local agencies include both planning for judicious use of water resources and managing the existing facilities and resources to best fit these plans. One commonly overlooked point of paramount importance is that the role of government water agencies is to enable private water users to make the best possible use of the resource. Individual farmers, cities, industries, fishermen, boaters, and so forth—in other words, all water users—are ultimately responsible for judicious utilization of water resources. The purpose of government agencies is to promote that process.

State and Local Agencies

The *Kansas Water Office (KWO)* is the water-planning, policy, and coordination agency for the state and the marketing agent for water from State-owned storage in Federal reservoirs (Kansas Statutes Annotated, KSA, 74-2605 et seq.). It prepares State plans for water-resource management, conservation, and development. A new process of water planning was developed and implemented during 1983 and 1984, culminating in a new Kansas Water Plan. Because the planning process is continuous, the Kansas Water Plan is modified and updated frequently.

The *Kansas Water Authority* (KSA 74-2605 et seq.) is responsible for advising the Governor, Legislature, and Director of the Kansas Water Office on water-policy issues. Twelve local River Basin Advisory Committees, created in 1985, are responsible for advising the Kansas Water Authority on needs and courses of action within the river basins (fig. 1.36).

The Kansas Department of Agriculture, *Division of Water Resources (DWR)*, administers laws related to water rights, conservation, and use of water resources, including appropriation of surface water and ground water. Enacted during 1945, the Kansas Water Appropriation Act (KSA 82a-701 et seq.) operates on the principle of prior appropriation. The date of application for a permit establishes the priority to continue the use of water during periods of shortage. Allocation, storage, and diversion of water in the Republican, the Big Blue, and the Arkansas River basins are affected by Interstate Compacts with Colorado, Nebraska, and Oklahoma. The Division of Water Resources and the five local Groundwater Management Districts have authority to instigate controls on withdrawals in areas where ground-water quantity or quality is deteriorating. The Kansas Department of Agriculture also regulates and monitors the use of agricultural chemicals.

The *Kansas Department of Health and Environment (KDHE), Division of Environment*, has regulatory authority over matters dealing with water pollution (KSA 65-161 et seq., KSA 55-1003 et seq., KSA 82a-1035 through 1038, and KSA 82a-1201 et seq.). The KDHE is responsible for developing water-quality-management plans, monitoring waste-disposal sites, monitoring public-water supplies, licensing well drillers, and responding to emergency water-contamination problems.

The KDHE, Division of Environment, has the primary responsibility for administering provisions of Federal water-pollution-control statutes. The Division of Environment is responsible for protecting drinking-water supplies, regulating wastewater discharges, control of nonpoint-source pollution, and mined land. The Division also monitors and assesses the quality of the state's surface- and ground-water resources and establishes water-quality standards.

The KDHE, Division of Environment, prepares a biennial water-quality-assessment report that is submitted to the U.S. Congress and the EPA pursuant to section 305(b) of the Federal Clean Water Act. In preparing the report, the Division relies extensively on physical and chemical monitoring conducted at its network of fixed and rotational stations, lake and reservoir surveys, a stream-macroinvertebrate sampling network, effluent-quality monitoring, effluent-toxicity testing, fish-tissue monitoring (a cooperative venture with Region VII of the EPA), and special investigations. Since the early 1970's, water-quality monitoring conducted by the KDHE has increased substantially in terms of the number of sites sampled and the substances monitored.

The Kansas nonpoint-source pollution-control program is a relatively recent State water-quality-management initiative. The 1987 amendments to the Federal Clean Water Act require states to assess water-quality effects of nonpoint-pollutant sources and to develop a corrective-action program. The Kansas program also seeks to protect existing undamaged water quality. The KDHE is responsible for maintaining and coordinating the nonpoint-source pollution-control program among numerous State, Federal, and local agencies.

The *Kansas Corporation Commission (KCC)* has a mandate (KSA 55-115 et seq.) to protect fresh ground-water supplies from adverse effects from mineral-development activities. The KCC enforces regulation of oil and gas exploration and production, with a statutory mandate [Kansas Statutes Annotated (KSA) 55-115 and the following] to protect the quality of fresh ground-water supplies. It also is responsible for locating and plugging abandoned oil and gas wells (KSA 55-1003 and the following).

The *State Conservation Commission* administers the following assistance programs that affect surface water: State aid to Conservation Districts, Water Resources Cost-Share Program, State assistance in construction of water-shed dams, and administration of a Small Lakes Program. Also, it is responsible for regulating the reclamation of sand and gravel pits and limestone quarries.

Other State agencies involved in water-resources planning and management include the Department of Wildlife and Parks, the Cooperative Extension Service, and the Kansas Water Resources Research Institute, which operates jointly out of Kansas State University and The University of Kansas.

Groundwater Management Districts (GMD), locally managed political subdivisions of the state, have been formed as a result of the Groundwater Management District Act of 1972 (KSA 82a-1020, et seq.). Five GMDs

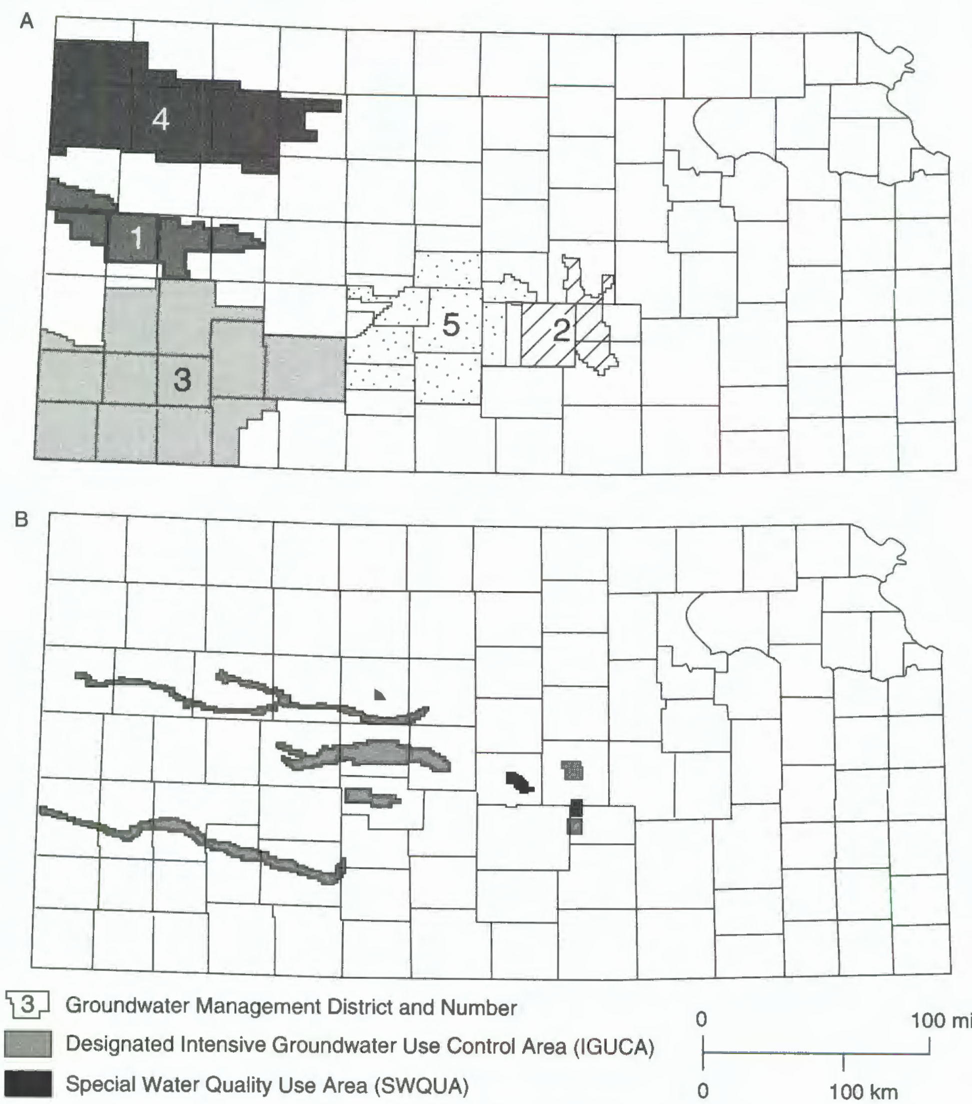


FIGURE 1.37—GROUNDWATER MANAGEMENT DISTRICTS (A), AND CONTROL AREAS OF GROUND-WATER WITHDRAWAL IN KANSAS (B).

operate in Kansas (shown in fig. 1.37A): District 1, west-central Kansas (GMD1); District 2, Equus beds (GMD2); District 3, southwest Kansas (GMD3); District 4, northwest Kansas (GMD4); and District 5, Big Bend (GMD5). Each district is charged with managing ground-water resources within its boundaries.

Federal Agencies

Federal agencies that have been most strongly involved in water planning in Kansas are the U.S. Army Corps of Engineers; the Bureau of Reclamation; and the Natural Resources Conservation Service, formerly the Soil Conservation Service. Other agencies, such as the Environmental Protection Agency and the Fish and Wildlife Service, have been involved to a lesser degree.

Responsibilities of the *Corps of Engineers* in Kansas are divided almost equally by a geographical partition between the Kansas City District and the Tulsa District. The area served by the Kansas City District includes the drainage basins of the Republican, Smoky Hill, Big Blue, Kansas, Delaware, and Marais des Cygnes rivers. The area served by the Tulsa District is the Arkansas River drainage basin, including tributaries such as the Cimarron, Little Arkansas, Neosho, and Verdigris rivers. Locations of existing or authorized Corps of Engineers reservoirs in the state are shown in fig. 1.35 and labeled C/E. The functions of the reservoirs are indicated in table 1.4.

The *Bureau of Reclamation* has traditionally focused on irrigation, which is the primary purpose of the seven reservoirs the Bureau has built in Kansas (fig. 1.35), labeled B/R. Irrigation districts have been formed below most of these reservoirs, as well as along the Republican River in north-central Kansas. While several of the irrigation districts have been developed as planned, others have suffered a variety of problems including organizational struggles, inability to meet repayment schedules, and reduced water supplies caused by reservoir sedimentation and lower-than-anticipated inflows.

The *Natural Resources Conservation Service* (NRCS), through its State office in Salina, has promoted soil- and water-conservation efforts throughout the state by encouraging construction of farm ponds, terracing to retain runoff on fields, and conservation tillage practices and by providing technical and financial assistance to conservation districts, watershed districts, and individual farmers. One of the NRCS programs with a large potential for both soil and water conservation and for providing water supplies to small municipalities is the small reservoir program established by PL 566.

Water-resources Management in Kansas

Largely extracted from Kansas Administrative Regulations, and Buchanan and Buddemeier, 1993; and U.S. Geological Survey, 1990, 1991.

Overview of Some Laws and Regulations Related to the Use of Water Resources

The administration of laws related to water rights, conservation, and use of water resources, including the appropriation of water, is the responsibility of the Chief Engineer, Division of Water Resources (DWR), Kansas Department of Agriculture. The Kansas Water Appropriation Act, originally enacted in 1945 and subsequently amended several times, dedicates all waters of the state to the beneficial use of the people of the state, subject to regulation in the manner provided by the Act (Irvine, 1996).

Except for domestic use, a permit to appropriate water is required for all uses of water. The date of application for a permit establishes the priority to continue the use of water during periods of shortage. An application for a permit to appropriate water may be approved if it is filed in good faith, if it is in the proper form, if the quantity and rate of use are reasonable for the intended purpose, and if use of the water will not impair existing water rights nor "prejudiciously or unreasonably affect the public interest."

A right to use water is "perfected" by the actual use of water in accordance with the terms, conditions, and limitations of the permit. Water users also are required to submit an annual water-use report to the DWR. The holder of a water right may change the point of diversion, the place of use, or the type of use by filing an application and receiving approval from the DWR.

Applications for permits to appropriate water received after April 12, 1984, are considered junior to any minimum desirable streamflow (MDS) requirements that have been established for the same source of supply pursuant to law. As of 1996, MDS requirements have been established for 23 Kansas rivers and streams.

The Kansas State Water Plan includes 12 river-basin (fig.1.36) plans and sections on management, conservation, quality, fish, wildlife, and recreation. The planning process in Kansas is continuous, and the State Water Plan is updated annually. Before being submitted to the Governor and the Legislature, the Kansas Water Plan must be approved by the Kansas Water Authority, a policy board that has members appointed to represent various water interests and agencies. Twelve local River Basin Advisory Committees are responsible for advising the Kansas Water Authority and the Kansas Water Office on needs and courses of action within the river basins. Policy recommendations in the State Water Plan are implemented through the legislature by passing new, or amending existing, statutes and by authorizing funding for specific programs and projects.

In 1983, the Kansas Legislature enacted the Kansas Water Transfer Act. This act requires the filing of an application with the Chief Engineer by any person wishing to transfer a quantity of water in excess of 2,000 acre-ft (2.47 million m^3) per year a distance of 35 mi (56 km) or more from the point of withdrawal to the ultimate place of use. Approval of a water transfer is a thorough procedure requiring a formal hearing and approval by an interagency panel. The panel considers the costs and benefits to the State of the water transfer, the alternative sources of water available to the applicant, the current and future needs of the area of origin, and the effects on the environment, the economy, and the public health and welfare of the proposed transfer. The applicant also must have an acceptable conservation plan.

In general, most streams and aquifers in the western part of the state are considered to be fully developed, and, because of decreased streamflows and declining ground-water levels, little or no additional water is being appropriated. In the eastern part of the state, surface water is available during periods of normal or greater-than-normal streamflow, but direct-flow water rights usually are not considered to be dependable during a drought unless they can be supplemented from storage. As a result of limitations on the availability of the state's water, Kansas has evolved from developing water for use to conserving and managing water.

In response to water-management concerns, the Kansas Legislature has allowed the organization of several types of local water districts to provide for local input into the conservation and management of water. Since the mid-1970's, five Groundwater Management Districts have been organized in the western and south-central parts of the state (fig. 1.37A). The boundaries of these districts conform primarily to the boundaries of the High Plains aquifer (fig. 1.28). Each district is required to develop a management program and may recommend rules and regulations to the Chief Engineer to implement policies related to the conservation and management of ground water. Examples of policies and regulations adopted within the districts include mandatory metering, well-spacing restrictions, water-use and water-wastage restrictions, and programs related to protecting the quality of ground water.

In 1978, the Chief Engineer was given the authority to designate Intensive Ground-water Use Control Areas (IGUCAs) in the state. Control areas may be established where water levels have declined excessively, where the rate of withdrawal of ground water exceeds the rate of recharge, where preventable waste of water is occurring, where unreasonable deterioration of water quality is occurring, or where other conditions exist that require regulation in the public interest. In designating such an area, the Chief Engineer may order corrective control provisions, such as closing the area to further appropriation of water, limiting the total amount of withdrawal from the area, decreasing the permissible amount of withdrawal of ground water, or any other controls necessary to protect the public interest. By 1996, eight Intensive Ground-water Use Control Areas (IGUCAs) had been designated (fig. 1.37B) by the Chief Engineer for water-quantity and water-quality problems. In addition, two Special Water Quality Use Areas (SWQUAs, which are variants of IGUCAs) have been designated by the Chief Engineer in Rice (around Lyons) and Harvey (around Burrton) counties (fig. 1.37B).

In 1986, the Kansas Legislature enacted the Water Assurance Program Act. This act allows public water suppliers and industrial water users located downstream from a Federal reservoir to organize a Water Assurance District (WAD). A district may contract with the State for the use of State-controlled storage in the reservoir so that water may be released during periods of low flow, ensuring that its water needs are met. This program is intended to help manage the storage and use of water in several major river basins in the eastern part of the state. Public suppliers and industrial users also may enter into contracts with the state to purchase water directly from storage under the State Water Marketing Program administered by the Kansas Water Office. The price of water is based on the cost to capitalize the State's investment and pay for administration of the program. A surcharge of 2.5 cents per 1,000 gallons (3.79 m^3) is added for future water development (U.S. Geological Survey, 1990). Protection of releases of water for the Water Assurance Districts or the Marketing Program from unlawful diversion is the responsibility of the Division of Water Resources.

In 1986, the State implemented legislation that requires conservation plans to be prepared by water users in certain situations. Members of Water Assurance Districts and water-transfer applicants must prepare a conservation plan, and water users seeking to purchase water through the Water Marketing Program may be required to develop and implement such a plan in accordance with State-approved guidelines. In addition, the Chief Engineer may require conservation plans from anyone filing an application for a permit to appropriate water after July 1, 1986.

Statewide Water Appropriations Outside the Groundwater Management Districts

The approval of any new application to appropriate ground water or surface water for beneficial use in an area outside of a Groundwater Managment District, with the exception of domestic or temporary use, is done according to the following "safe yield" criteria: (a) For unconfined aquifers, the total quantity of water already authorized for beneficial use in a 2-mi (3.2-km) radius circle with the proposed point of diversion (i.e. proposed well) as the center, plus the quantity of water requested, must not exceed a predetermined percentage of the amount of calculated recharge occurring within the above-mentioned 2-mi (3.2-km) radius circle. The amount of calculated recharge for an unconfined aquifer in Kansas is generally based on results reported in the U.S. Geological Survey Water-Resources Investigations Report 87-4230 (Hansen, 1991), in which recharge was estimated using a water-balance computer model including soil, vegetative, and climatic data. A few exceptions or modifications to this procedure are listed in Kansas Administrative Regulations (KAR) 5-3-11. The percentages of calculated recharge which are considered available for appropriation by the Chief Engineer are listed for various river basins in KAR 5-3-11, and are generally grouped into three categories, i) 100%, ii) 75%, and iii) 50%, depending on the estimated amount of baseflow contributed to streams within the region of interest and the sensitivity of the stream to that baseflow contribution. The more significant and important the baseflow contribution to a stream, the less the percentage of calculated recharge that is available for additional appropriation.

(b) For confined aquifers (such as the Dakota aquifer) no firm procedure has been established, and each situation is dealt with on a case by case basis using the best available hydrologic information (KAR 5-3-14). Some minimum spacing requirements have to be met however, as is the case with all nondomestic and nontemporary wells (K.A.R. 5-4-4). For the confined portion of the Dakota aquifer, the established spacing between wells is 4 mi (6.4 km), whereas for the unconfined portion of the Dakota aquifer it is 0.5 mi (0.8 km). For all other aquifers, the spacing for nondomestic and nontemporary wells is 0.25 mi (0.4 km).

(c) For surface water, the rate and quantity of water available for appropriation is made so as to satisfy senior domestic rights from the stream, all other senior water rights and permits, and to meet minimum desirable streamflows, assurance district target flows, and Division of Water Resources target flows where applicable (KAR 5-3-15).

Ground-water Appropriations within the Groundwater Management Districts (GMDs)

Under the authority of the Groundwater Management District Act (K.S.A. 82a-1020 et seq.), each district has developed its own distinct management plan in cooperation with the Chief Engineer, Division of Water Resources, Kansas Department of Agriculture. The ultimate goal of each management plan is to conserve and prolong the life of the aquifer. Management is achieved, in part, through review of all applications to appropriate water filed with the Division of Water Resources. The districts review such applications and make relevant recommendations to the Chief Engineer, who, in turn, approves, modifies, or denies the applications to use water. Each application to appropriate ground water must meet the appropriate district's criteria before a recommendation for approval of a permit is made to the Chief Engineer. Thereupon the Chief Engineer reviews the application and recommendations of the Management District and makes the final decision as to whether a permit shall be issued.

The three western districts (1, 3, and 4) have the greatest number of large-capacity wells and the highest rate of water-level decline, but the least precipitation. Each of these districts has adopted a plan (planned depletion policy) that will allow a specific portion of the aquifer to be depleted over a period of 20-25 years (KAR 5-21-4; 5-23-4). For example, the Southwest Kansas GMD3 allows a maximum rate of depletion of 40% of the aquifer saturated thickness underlying the area of consideration in 25 years. However, the Northwest Kansas GMD4 switched to a "zero depletion" policy in 1990 for new wells according to which the total appropriation within the area of consideration (i.e. the 2-mi [3.2-km] circle) is not allowed to exceed the calculated total average annual recharge received by the aquifer underlying the area of consideration (KAR 5-24-2).

The districts to the east (2 and 5) are not as heavily developed and have more precipitation. These eastern districts have adopted a "safe yield" or "sustainable yield" management plan according to which all existing prior appropriations and vested rights, plus the portion of natural discharge to a stream within the 2-mi (3.2-km)-radius circle, are not allowed to exceed the calculated amount of recharge in each district or in portions of each district (as is the case with GMD2). The natural discharge to a stream (baseflow) is determined to be the rate of flow in the stream that is equaled or exceeded 90% of the time. Artificial points, known as "baseflow nodes," are located in the channel of a stream for the purpose of protecting a proportional amount of the baseflow when evaluating a new application to appropriate water from a proposed point of diversion (i.e. well) located within 2 mi (3.2 km) of the node (KAR 5-22-7; 5-25-4). These "baseflow nodes" are spaced 1,320 ft (0.25 mi [0.4 km]) apart along the channel, which is the minimum spacing between permanent, nondomestic wells.

Water-management Implications

At present, State and local policies indicate that aquifers should be managed on a sustained or safe-yield basis. In practical terms, safe yield can be defined as the pumping rate that is compatible with the hydrogeologic environment from which the water is taken. This need for compatibility implies that yield must be viewed in terms of a balance between the benefits of ground-water pumpage and the undesirable changes that will be induced by such pumpage. The most common change that results from pumping is lowered water levels beyond acceptable limits. However, many major Kansas ground-water resources were over-allocated in terms of pumping rights before safe-yield policies were in place. State and local agencies and water users are grappling with the issues of how to deal with the situation. Permanent streamflow is usually a result of ground-water discharge, so that if ground-water pumping lowers the elevation of the water table below that of the stream bed, streamflow will be reduced or interrupted. On the other hand, streamflow may be the major source of recharge to some alluvial aquifers, so that streamflow regulation or diversion may alter the recharge characteristics, and therefore the safe yield, of the ground water in the area. For example, in 1991 and 1992, the State's DWR held hearings concerning streamflow in Wet Walnut Creek (which provides some of the water for Cheyenne Bottoms Wildlife Area). The DWR eventually decided that streamflow was being lowered because of ground-water pumping for irrigation, created an IGUCA, and limited pumping on existing wells. This was an historic recognition in Kansas of the relationship between streamflow and ground water.

Water-resource management also must consider other needs and values, among them water quality, flood control, wildlife habitat, and recreation. The conflicts between the multiple uses are well expressed by the concept that for flood control a reservoir should be empty, for water supply it should be full, and for recreation the level should remain constant. Ground-water issues come into play most strongly with respect to biological habitat concerns. Wetlands and marshes, like the baseflow of streams, are generally related to ground-water discharge. They are, therefore, vulnerable to water-table fluctuations as well as surface-water balance, and concerns about the major wetlands habitats of central Kansas (Cheyenne Bottoms and Quivira Marsh, fig. 1.35) have sparked interest in the water budgets of those areas.

It should be kept in mind, however, that the legal process, not social or scientific policy, determines how water is allocated to different interests. Very often, cases reduce to senior water-rights versus junior water-rights. Older rights, quite simply, give their owner the priority for access to water when supplies are limited (first in time, first in right). In the case of Wet Walnut Creek, again, the rights to water flowing into the stream (and eventually to Cheyenne Bottoms) were older, or more senior, than rights for pumping ground water. Thus, the case was decided not on the desirability of maintaining streamflow for the sake of Cheyenne Bottoms, but on the legal issue of the age of the right to acquire water.

Water management is a complex and difficult process and will become more so if demands increase while available resources decrease. Fortunately, Kansans have taken a forward-looking step in creating the Kansas Water Plan. The Kansas Water Office (under the direction of the Kansas Water Authority) is responsible for centralized planning and coordination for all water-related issues, while leaving intact the specific responsibilities of existing State water agencies. Much of the water-resources planning for Kansas is currently accomplished on the basis of the state's 12 major drainage basins (fig. 1.36), a division based on the philosophy that areas drained by the same stream often have many similar water issues in common.

This current approach to water planning and regulation in Kansas attempts to avoid the problems inherent in dealing with an integrated system (the hydrologic cycle) on a piecemeal and patchwork basis, while still retaining local control and the advantages of specialized expertise.

Water Management During Floods and Droughts

Planning water-management functions before and during floods and droughts requires coordination among various governmental agencies. The water-management functions involve three areas of responsibility: (1) floodplain management to decrease loss during floods, (2) flood-forecast and warning systems, and (3) planning efficient use of water resources during droughts. As population densities in Kansas change, the priorities of the water-management functions also change to meet the need for protection of life and property and to meet demands on water resources during periods of deficient supply.

FLOODPLAIN MANAGEMENT

Floodplain-management programs in Kansas are regulated by the Division of Water Resources, Kansas Department of Agriculture. Cities and counties have the authority to establish floodplain regulations to ensure the protection of people and structures within the designated floodplain zones (Kansas Statutes Annotated [KSA] 12-705). The statutes define a floodplain as the area adjacent to a watercourse that would be inundated by a flood having a 100-year recurrence interval (KSA 12-734). Generally, the delineation of a floodplain zone for a community coincides with zones identified through the National Flood Insurance Program, which is implemented by the Federal Emergency Management Agency. The Chief Engineer, Division of Water Resources, maintains the authority of review and approval before adoption of all resolutions, ordinances, or regulations that pertain to the establishment of or changes in existing floodplain zones (KSA 12-734). The Chief Engineer is responsible for ensuring that proposals are consistent with the following minimum standards: (1) no human habitation of the floodplain unless protected against floods having a 100-year recurrence interval; (2) flood-proofing of all new or reconstructed existing structures to the altitude of a flood crest having a 100-year recurrence interval; and (3) no structure, encroachment, or other use, not otherwise prohibited in the floodplain, that would raise the altitude of a flood crest more than 1 ft (0.3 m) so as to cause an undue restriction of floodflows within the floodplain (KSA 12-735).

Mitigation of flood damage is the responsibility of the Division of Emergency Preparedness of the Adjutant General's office. A postflood requirement is the formulation of a set of recommendations that would lessen the effect of future floods. These recommendations are contained in a Mitigation Plan prepared by the Division of Emergency Preparedness with assistance from other State and Federal agencies.

FLOOD-WARNING SYSTEMS

The reliability and timeliness of flood forecasts are important to the safety of lives and property. Reliable forecasts can facilitate a rapid return to normal operations after flood threats have passed.

The primary flood-warning systems in Kansas are operated by the National Weather Service River Forecast Centers in Kansas City, Missouri, and in Tulsa, Oklahoma. The Kansas City office is responsible for the upper Missouri River basin, which includes the Kansas and Marais De Cygnes River basins in Kansas (fig. 1.36). The Tulsa office is responsible in part for the Arkansas River and its major tributaries in Kansas. River forecasts are prepared primarily from meteorological data from the various National Weather Service Forecast Offices and meteorological and hydrologic data from other agencies including the U.S. Army Corps of Engineers, the U.S. Bureau of Reclamation, the U.S. Geological Survey, and local agencies. The River Forecast Centers review and process the data to determine the anticipated runoff and then combine the estimated runoff with existing river flows to forecast future flows at selected locations within the network. The timeliness of the data is important to the speed with which a forecast can be made. Advanced technology in automated recording and rapid communication permit information to be obtained promptly through use of radar and satellite imagery and telemetry.

Although several local flood-control projects in the state use forecast data in specific operations, two Kansas cities—Great Bend and Overland Park—have developed ongoing data-collection and reporting systems that contribute information to local and municipal forecast systems. Because of the small areal distribution of urban drainage networks in those cities and the extremely short response times of these small urban basins, rapid data collection and dissemination and forecast computations are critical.

WATER-USE MANAGEMENT DURING DROUGHTS

Droughts can be defined by the nature of the water deficit. In Kansas, droughts are classified as either from meteorological (rainfall) deficits, agricultural (soil-moisture) deficits, or hydrologic (streamflow) deficits. Water management in Kansas mitigates the latter two types of droughts or deficits. Agricultural deficits are mitigated by conservation techniques or supplemental irrigation, whereas the legal institutions of the state primarily address hydrologic deficits and water supply.

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 (Jordan, 1983, table 1.1, p. 32–44). As such, natural streamflow is an unreliable supply to meet present-day demands. As a result, more than 70% of the water used in Kansas comes from ground-water sources (table 1.3) and is used mostly for irrigation (table 1.3).

Institutional management of water during droughts in Kansas takes two forms—appropriation of surface and ground water and use of stored water. Water-appropriation rights are issued for the diversion and beneficial use of water under the Water Appropriation Act by the Division of Water Resources of the Kansas Department of Agriculture. Under State law, allocation of water during drought is based on the priority date specified at the time the water right is filed. A water right does not guarantee water, only the user's place in priority relative to other users. Water management under this law is by reaction, whereby the holder of a water right must file a complaint if that water right is impaired. After receipt of the complaint, the Division of Water Resources investigates the impairment and takes subsequent regulatory action. Hence, during a drought, extensive field investigation and regulation are required.

The other legal method of obtaining water during droughts is the use of reservoir storage. Recognizing the dependence of the user on surface water in eastern Kansas, the state used the Federal Water Supply Act of 1958 to develop water-supply storage in some of the 24 Federal reservoirs. Numerous cities also have developed storage on small tributaries to meet local needs. The Kansas Water Office manages the Water Marketing Program, which sells water to cities and industries from nine U.S. Army Corps of Engineers' reservoirs in eastern Kansas. The program is intended to provide reliable water supplies during droughts.

During droughts, many downstream users, including irrigators, divert releases made from reservoir storage that is dedicated for maintenance of water quality. Because the State treats such releases as natural flow, the users are in compliance with their water rights. However, as streamflows become dependent on such releases, users are vulnerable to any alteration in those releases. Drought-simulation exercises conducted by the Kansas Water Office have confirmed the users' vulnerability when relying on water rights supplemented by water-quality-maintenance releases (T. C. Stiles, Kansas Water Office, oral communication, 1986).

Stream-aquifer Management in Kansas[1]

Kansas, in 1945, adopted the prior appropriation doctrine intrinsic to U.S. Western water law. Basically, the principles are that all water is dedicated to the people of the state for use as regulated by the State (that is, a land owner does not hold any title to water on or under his or her property — the reverse of the riparian doctrine of the eastern United States which Kansas more or less observed prior to 1945). The basic principle is "first in time, first in right." In addition, as Kansas was late adopting the appropriation doctrine, rights established prior to 1945 were given special status (they are called "vested rights"). Only a court of law can determine priority among vested rights. In Kansas, unlike some western states, there is no differentiation between surface-water and ground-water rights. That means there is no constraint about administering ground-water rights to protect surface-water rights (or vice versa).

Ground-water and surface-water systems are closely interrelated. The next two chapters (2 and 3) outline the nature of this interconnection and the reasons why both need to be managed together as a single system. In the early 1980's, it became apparent that ground-water pumping was causing significant depletions of baseflow in some streams in western Kansas. This realization along with the growth of environmental awareness in the Kansas public caused two major thrusts. The first was administrative. The Chief Engineer closed three basins in northwest Kansas to further appropriations of water primarily because ground-water pumping in the alluvial valleys was excessive and was causing declines in baseflows (i.e. in the ground-water contributions—seepage—to streams). The second activity was in the water-planning arena. Out of the State Water Plan came an amendment to the Appropriation Act that established Minimum Desirable Streamflows (MDS) for a number of Kansas streams in the early 1980's. Before MDS were established, protection of instream flows in Kansas was not considered possible, as rights are for the diversion of water for beneficial uses. MDS essentially required the Chief Engineer to withhold from appropriation sufficient water to meet target flows specified in the law.

Since the establishment of MDS, Kansas has administered ground-water rights for MDS protection and has continually considered MDS when considering applications to appropriate water. Administratively, the Kansas Water Office requested protection of streamflows for MDS in 1992 in the Republican River. The agreed plan was to provide early notice to water-right holders junior to MDS (MDS has a priority similar to each water right in the state) that their water right would be curtailed in the following year. The reasoning was twofold: 1) The Jenkins stream-aquifer interaction graphical procedure (see below) indicated that summer restrictions on ground-water use would produce minimal improvements in streamflow and 2) curtailing ground-water users (predominately irrigators) at that critical time would have ruined their crops. So, all junior right holders were notified that their use was curtailed for the next year to allow the aquifer to recover and to prevent further effect to the stream if the drought continued. This allowed them time to alter cropping plans to dryland conditions. Junior users were curtailed until about July 4 when significant flows (which later became general flooding) occurred.

When evaluating applications to appropriate water in those areas with established MDS, Jenkins analysis is generally performed to evaluate the impact of the proposed diversion on streamflow. A brief description of the Jenkins procedure follows (Jenkins, 1970): When field conditions approach certain assumed conditions, the depletion in flow of a nearby stream caused by pumping a well can be calculated readily by using dimensionless curves and tables. Stream depletion means either direct depletion of the stream or reduction of ground-water flow to the stream. Computations using this procedure can be made of (1) the rate of stream depletion at any time during the pumping period or the following nonpumping period, (2) the volume of water induced from the stream during any period, pumping or nonpumping, and (3) the effects, both in rate and volume of stream depletion, of any selected pattern of intermittent pumping. In the past few years, most of the basins with significant ground-water resources and MDS have been closed to all further appropriation or have had more comprehensive management rules established, which has curtailed the use of the Jenkins stream-depletion graphical procedure.

A derivative of this effort was used a few years later in the creation of the first Water Assurance District (WAD) in eastern Kansas. As mentioned previously, WADs are created on river systems with large reservoirs to assure municipal and industrial users of a reliable surface-water supply during drought (by proper management of the reservoirs). In the Kansas River WAD, the Chief Engineer determined that certain ground-water users ought to be members of the WAD because they received significant benefits from reservoir releases. This analysis was based on the Jenkins procedure, and all appropriations within 0.25 mi (0.4 km) of the bank of the river and with rights to more than 1,000 acre-feet (1.23 million m^3) of ground water were made members of the WAD.

In 1992, an Intensive Groundwater Use Control Area (IGUCA) was created by the Chief Engineer along Walnut Creek (fig. 1.37). Development of ground water in the Walnut Creek alluvial valley appears to have reduced streamflows critically and senior surface water rights could no longer be used reliably. Rather than administer rights, the Chief Engineer (under statutory authority in the GMD Act) after a long and difficult public hearing, established the IGUCA and restricted the use of ground water significantly. The experience in Kansas is that water users generally prefer "sharing the shortage" to strict administra-

[1] *Matt A. Scherer, Kansas Department of Agriculture, Division of Water Resources (personal communication, 1996).*

tion according to priority. In this case, the restrictions were significant— vested ground-water rights were unaffected, but irrigation rights after 1945 but prior to 1965 were reduced from about 18 inches (46 cm) to about 13 inches (33 cm) and rights after 1965 were reduced to about 5 inches (12.7 cm). Other types of use, municipal, stockwatering and industrial, took about a 10% reduction (these are all minor uses in this valley).

A final, and the newest, concept is an adjustment to the management policies in two GMDs (GMD2 and GMD5). Both GMDs operate on a "safe yield" basis with the total amount that may be appropriated in a 2-mi (3.2-km) circle around the proposed diversion limited to the long-term average annual recharge calculated for the circle. Thus the quantity already appropriated within that 2-mi (3.2-km) circle plus the quantity proposed under the new application must be less than the long-term average annual recharge (which is equated to "safe yield"). One flaw, of course, is that there is, in the long-term, no water left for the stream. While this is partially mitigated by the fact that actual use is virtually always less than what is appropriated, the management rule does not recognize the impact of ground-water pumping on streamflow. To alleviate this concern, GMD2 has implemented "streamflow nodes" on a major stream in the GMD, and GMD5 has recently (1996) obtained approval of new regulations by the State to implement such nodes on several streams in the district. The concept is to prorate the baseflow (usually estimated as the 90% probable low-flow value on a monthly basis–from flow-duration curves) to a series of phantom wells (streamflow nodes) located on the stream's centerline at 0.25-mi (0.4-km) intervals. Each of these nodes has an annual quantity of water assigned to it, equal to its prorata share of the assumed baseflow, which is considered its "appropriation" for 2-mi (3.2-km) circle computations. If there are nodes in a 2-mi (3.2-km) circle, they are each treated as water rights for purposes of determining whether or not a new application should be approved.

DWR is also attempting to develop comprehensive basinwide management programs in areas of Kansas with significant problems because of the development of ground water (these problems generally show up first as impacts on surface water).

Part V. Needed Research

Problems and Issues Needing Further Study

Largely extracted from Buchanan and Buddemeier, 1993; and Council of Water Research Directors, 1995.

Among the critical areas where improved understanding will help us to make the most effective use of our limited water supply are the following:

1) Understanding the water budgets of the major basins of Kansas. Variations in climate and changes in land and water use produce the observed effects on declining streamflow, reservoir storage, and ground-water levels in Kansas. The magnitude and trend in the variations and changes should be examined for causal relationships with the declines in order to determine planning and management actions that are appropriate to each basin or aquifer system. Historic patterns in land and water use affecting water runoff and infiltration, as well as sediment filling of reservoirs, should be compared to current practices and physical environment for explaining observed water-budget changes and predicting future trends. Results should be compared among the different major basins in the state to determine differences in their impact on water budgets, thereby providing information for planning and management appropriate to the geographic area. Defining sustainable yields of major basins is a complex problem that needs further research.
2) Stream-aquifer interactions: We need a much better understanding of the dynamics of ground-water discharge and recharge in stream-aquifer systems. The relationship between recharge and streamflow needs to be studied over a range of time scales and water levels to provide an information base for managing the combined resource on a long-term basis. Some of the questions involve alteration of the hydrologic character of the system. High rates of flow and floods can act to scour out a stream channel, so human control or reduction of streamflow may result in a gradual reduction of the permeability of the channel and change the coupling of the ground water and surface water. Quantification of ground-water contributions to streamflow (baseflow), definition of minimum streamflow requirements to maintain the capacity of streams to accept discharged contaminants, quantification of phreatophyte impacts, maintenance of ecosystem functions, and satisfaction of water quality and quantity requirements are subjects of needed research.
3) Water-quality issues: Water quality can be a problem because of natural factors or because of artificially introduced contaminants. Kansas faces both types of problems.

   a) Mineral intrusion: The salt beds and brine-containing aquifers that are near the surface in much of central Kansas represent a special problem for water supply and management. Freshwater heads and flow rates can often be maintained at a level adequate to either keep the underlying saltwater from discharging or to dilute it to tolerable levels when it does discharge. However, managing this sort of balanced system requires a detailed understanding of the hydrology, geology, and geochemistry of multiple interacting aquifers. It is a challenging research problem, but the issues are important. A substantial fraction of the irrigated agriculture and municipal water supplies of south-central Kansas are vulnerable to salt problems, and aquifers tend to have a "memory" effect—a temporary introduction of brine into a freshwater aquifer may leave behind long-term residual contamination. Marginal-quality water inventory and assessment for possible uses are needed.

b) Human-induced contamination: The so-called point sources of ground-water contamination (landfills, industrial discharge, underground storage tanks, injection wells, etc.) are gradually being brought under regulatory control. This will reduce some of the problems in the future, but improved methods for locating and predicting the movement of contaminant plumes resulting from past practices are still needed. As attention turns to the nonpoint sources of pollution (such as agricultural chemicals or urban runoff), we find that we need a greatly improved understanding of how both water and contaminants move through the unsaturated zone and mix into the ground water. Such studies can improve our understanding of the recharge process as well as of pollution-related mechanisms. Direct land-use impacts on water quality and quantity, and appropriate management measures to address these issues, are needed. The impacts of irrigation and the use of nutrients and other agricultural chemicals on soil and water salinization also need attention.

4) Improving Water-use Efficiency: Traditional approaches to water-use efficiency focus on questions such as how to maintain crop yields with less water per acre, or the same quality of urban life with less water consumption per capita. With a limited water supply and growing demand, these questions take on even greater importance; however, a new suite of issues must also be considered. Improvements in overall efficiency will need to include consideration of qualitatively appropriate use (e.g., opportunities to use poorer quality water to conserve good water for critical applications), and the potential impacts of water-quantity conservation measures on long-term water-quality trends.

5) Deep-aquifer characterization: Deep aquifers, such as the Dakota, the Ozark, and other consolidated aquifers represent the next available source of ground water once shallower aquifers are depleted. In some areas, these deep aquifers are already being used. In some areas they provide avenues for the flow of saltwater that mixes with and degrades freshwater in the deep or shallower aquifers. The extent, hydrologic characteristics, and distribution of water quality in these aquifers needs to be much better known locally to understand both their water-resource potential and the safe yield at which they can be developed.

6) Regional-scale hydrology: Hydrologic observations are made at a very local scale, but our climate and budgetary insights work best at a very large scale. The National Research Council (1991) has identified the link between local-scale (watersheds or sites) and continental-scale hydrologic systems as one of critical importance. This focus on dimensions typical of aquifers or river basins is particularly relevant to the Kansas approach to water planning based on river basins. It is also critical to the future of water planning, because this is the scale of understanding required to link global or regional climate-change effects to local water resources.

The Kansas State Water Research Agencies have recently prepared a white paper on research and data needs for Kansas with special emphasis on unmet needs and new issues (Council of Water Research Directors, 1995).

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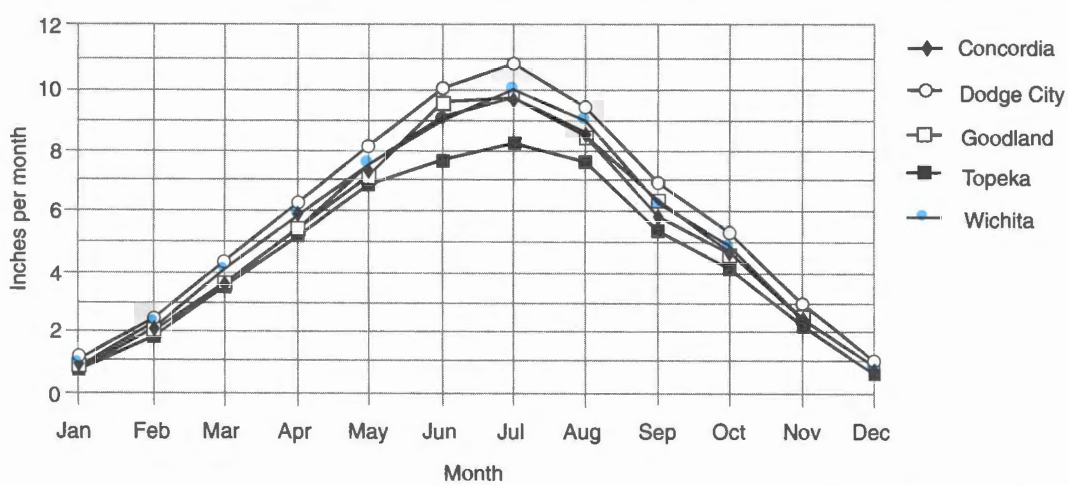
Appendix 1.A—Potential Evapotranspiration (Penman ET_0) Values for Kansas



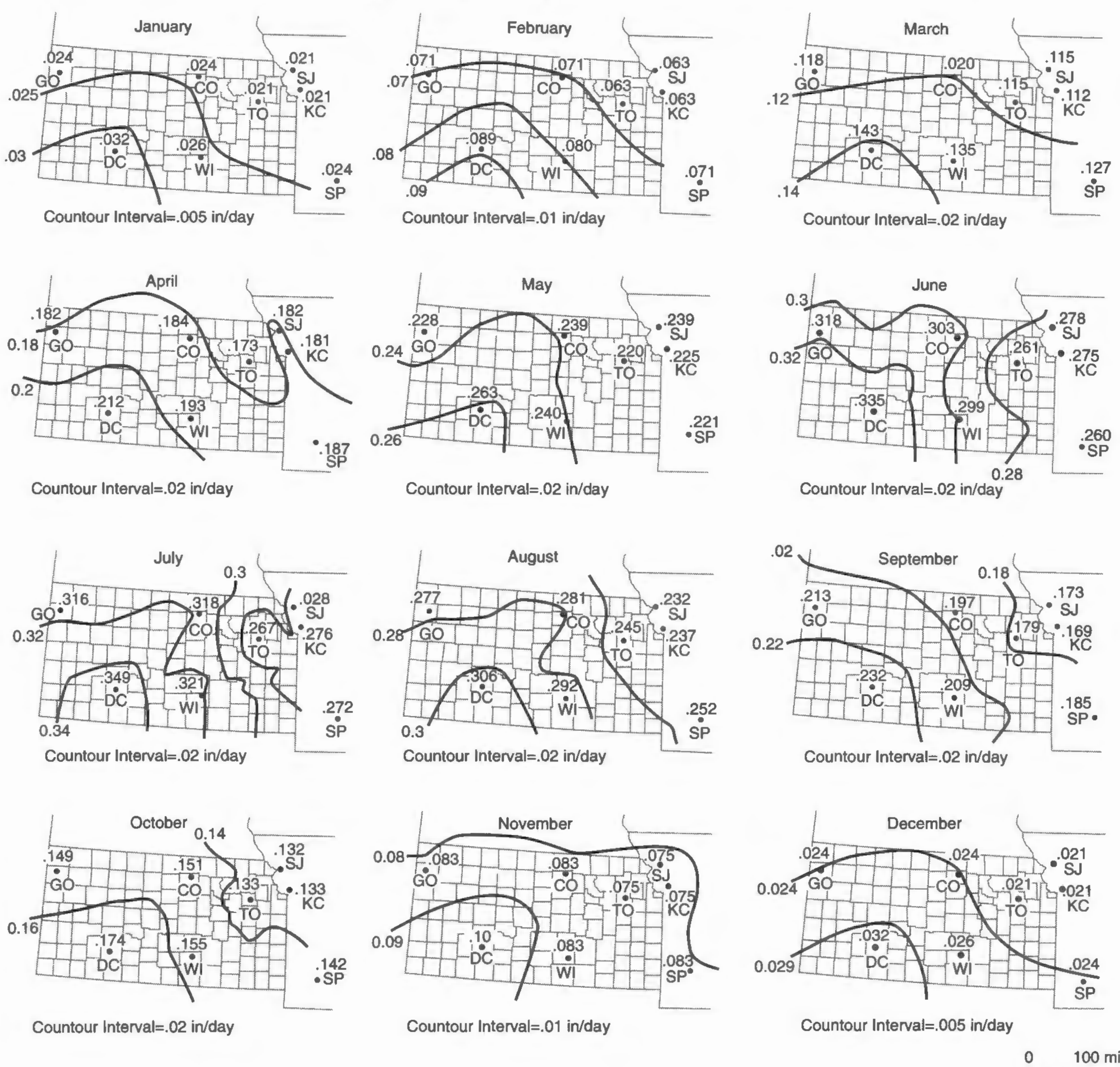
Data from table 1A.1 on following page.

Appendix 1.A cont'd.

TABLE 1A.1—PENMAN'S ET_0 AMOUNTS IN INCHES, BASED ON NOAA CLIMATOLOGICAL DATA–ANNUAL SUMMARIES FOR 1979.

Location in or near to Kansas	*Values from USDA, SCS (1981) for March–October*								*Remaining months are estimates by J. K. Koelliker*				
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Dodge City	1.00	2.50	4.43	6.36	8.15	10.05	10.82	9.49	6.96	5.39	3.00	1.00	69.16
Goodland	0.75	2.00	3.66	5.46	7.07	9.54	9.80	8.59	6.39	4.62	2.50	0.75	61.12
Wichita	0.80	2.25	4.19	5.79	7.44	8.97	9.95	9.05	6.27	4.81	2.50	0.80	62.81
Concordia	0.75	2.00	3.72	5.52	7.41	9.09	9.86	8.71	5.91	4.68	2.50	0.75	60.90
Topeka	0.65	1.75	3.57	5.19	6.82	7.63	8.28	7.60	5.37	4.12	2.25	0.65	54.07
Springfield, MO	0.75	2.00	3.94	5.61	6.85	7.80	8.43	7.81	5.55	4.40	2.50	0.75	56.39
St. Joseph, MO	0.65	1.75	3.57	5.46	7.41	8.34	8.65	7.19	5.19	4.09	2.25	0.65	55.20
Kansas City, MO	0.65	1.75	3.47	5.43	6.98	8.25	8.56	7.35	5.07	4.12	2.25	0.65	54.52
Average % of total	1.3	3.4	6.3	9.2	12.0	14.8	15.8	14.1	10.0	7.7	4.1	1.3	100.00

Penman's ET_0 Average Daily Estimates by Month in Inches/day



Adapted from NRCS, Midwest National Technical Center's (Lincoln, Nebraska) 12 midwestern state maps. See also Lucas (1982).

Appendix 1.B—Interpretive Water-quality Tables

TABLE 1.B1—NATURAL INORGANIC CONSTITUENTS COMMONLY DISSOLVED IN WATER THAT ARE MOST LIKELY TO AFFECT USE OF THE WATER (adapted from Heath, 1983).

Substance	Major natural sources	Effect on water use	Concentrations of significance (mg/L)[1]
Bicarbonate (HCO_3) and carbonate (CO_3)	Products of the solution of carbonate rocks, mainly limestone ($CaCO_3$) and dolomite ($CaMgCO_3$), by water containing carbon dioxide. Soils and rocks containing limestone, dolomite, and gypsum ($CaSO_4$). Small amounts from igneous and metamorphic rocks.	Control the capacity of water to neutralize strong acids. Bicarbonates of calcium and magnesium decompose in steam boilers and water heaters to form scale and release corrosive carbon dioxide gas. In combination with calcium and magnesium, cause carbonate hardness.	150 - 200
Calcium (Ca) and magnesium (Mg)	Soils and rocks containing limestone, dolomite, and gypsum ($CaSO_4$). Small amounts from igneous and metamorphic rocks.	Principal cause of hardness and of boiler scale and deposits in hot-water heaters.	25 - 50
Chloride (Cl)	In inland areas, primarily from seawater trapped in sediments at time of deposition; in coastal areas, from seawater in contact with freshwater in productive aquifers. Dissolution of salt beds.	In large amounts, increases corrosiveness of water and, in combination with sodium, gives water a salty taste.	250
Fluoride (F)	Both sedimentary and igneous rocks. Not widespread in occurrence.	In certain concentrations, reduces tooth decay; at higher concentrations, causes mottling of tooth enamel.	0.7 - 1.2[2]
Iron (Fe) and manganese (Mn)	Iron present in most soils and rocks; manganese less widely distributed.	Stain laundry and are objectionable in food processing, dyeing, bleaching, ice manufacturing, brewing, and certain other industrial processes.	Fe > 0.3, Mn > 0.05
Sodium (Na)	Same as for chloride. In some sedimentary rocks, a few hundred milligrams per liter may occur in freshwater as a result of exchange of dissolved calcium and magnesium for sodium in the aquifer materials.	See chloride. In large concentrations, may affect persons with cardiac difficulties, hypertension, and certain other medical conditions. Depending on the concentrations of calcium and magnesium also present in the water, sodium may be detrimental to certain irrigated crops.	69 (irrigation), 20 - 170 (health)[3]
Sulfate (SO_4)	Gypsum, pyrite (FeS), and other rocks containing sulfur (S) compounds.	In certain concentrations, gives water a bitter taste and, at higher concentrations, has a laxative effect. In combination with calcium, forms a hard calcium carbonate scale in steam boilers.	300 - 400 (taste) 600 - 1,000 (laxative)

[1] A range in concentration is intended to indicate the general level at which the effect on water use might become significant.
[2] Optimum range determined by the U.S. Public Health Service, depending on water intake.
[3] Lower concentration applies to drinking water for persons on a strict diet; higher concentration is for those on a moderate diet.

TABLE 1.B2—CHARACTERISTICS OF WATER THAT AFFECT WATER QUALITY (from Heath, 1983).

Characteristic	Principal cause	Significance	Remarks
Hardness	Calcium and magnesium dissolved in water.	Calcium and magnesium combine with soap to form an insoluble precipitate (curd) and thus hamper the formation of a lather. Hardness also affects the suitability of water for use in the textile and paper industries and certain others and in steam boilers and water heaters.	USGS classification of hardness (mg/L as $CaCO_3$): 0-60: Soft; 61-120: Moderately hard; 121-180: Hard; More than 180: Very hard.
pH (or hydrogen-ion activity)	Dissociation of water molecules and of acids and bases dissolved in water.	The pH of water is a measure of its reactive characteristics. Low values of pH, particularly below pH 4, indicate a corrosive water that will tend to dissolve metals and other substances that it contacts. High values of pH, particularly above pH 8.5, indicate an alkaline water that, on heating, will tend to form scale. The pH significantly affects the treatment and use of water.	pH values: less than 7, water is acidic; value of 7, water is neutral; more than 7, water is basic.
Specific electrical conductance	Substances that form ions when dissolved in water.	Most substances dissolved in water dissociate into ions that can conduct an electrical current. Consequently, specific electrical conductance is a valuable indicator of the amount of material dissolved in water. The larger the conductance, the more mineralized the water.	Conductance values indicate the electrical conductivity, in micromhos, of 1 cm^3 of water at a temperature of 25 °C.
Total dissolved solids	Mineral substances dissolved in water.	Total dissolved solids is a measure of the total amount of minerals dissolved in water and is, therefore, a very useful parameter in the evaluation of water quality. Water containing less than 500 mg/L is preferred for domestic use.	USGS classification of water based on dissolved solids (mg/L): Less than 1,000: Fresh; 1,000-3,000: Slightly saline; 3,000-10,000: Moderately saline; 10,000-35,000: Very saline; More than 35,000: Briny.

TABLE 1.B3—MAXIMUM CONCENTRATIONS OF INORGANIC CONSTITUENTS ALLOWED IN DRINKING WATER (data from the Environmental Protection Agency, 1993).

Constituents	Concentration (mg/L)
Arsenic	0.05
Barium	2.0
Cadmium	0.005
Chromium	0.1
Lead	0.015
Mercury	0.002
Nitrate (as N)	10.0
Selenium	0.05
Silver	0.1
Adjusted gross alpha radioactivity	15 (pCi/L)

CHAPTER 2

On the Elusive Concept of Safe Yield and the Response of Interconnected Stream-aquifer Systems to Development

Marios Sophocleous

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Introduction

The time has passed when abundant supplies of water were readily available for development at low economic, social, and environmental cost. According to Hufschmidt (1993), we are now entering the period of a "maturing water economy" with increasing competition for access to fixed supplies, a growing risk of water pollution, and sharply higher economic, social, and environmental costs of development. It should be understood that most of the available water in western states, including Kansas, has been developed, and that future water management is going to depend heavily on sustaining existing supplies. The great challenge facing the world today is to cope with the impact of economic growth on environmental processes. The concept of *sustainable development* emerged during the late 1980's as a unifying approach to concerns over the environment, economic development, and the quality of life. The World Commission on Environment and Development (1987), better known as the Brundtland Commission, defined sustainable development as ". . . development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Water is not only essential to sustain life, but it also plays an integral role in ecosystem support, economic development, community well-being, and cultural values. How all these values, which sometimes conflict, are to be prioritized, which are to be sustained, and in what fashion, are still unresolved questions (Gleick et al., 1995). The concept of sustainable development is intended to provide a framework within which the environment can be properly managed to support economic development while providing adequate resources for the future. This has lent weight to arguments for *proactive* rather than reactive environmental policies. However, despite the progress which has been made in defining the goals of sustainable development, the mechanisms to bring about these changes remain abstract. The challenge of the 1990's is to turn the principles of sustainable development into achievable policies that lead to positive changes in this direction. Science can assist by exploring the implications of different interpretations of sustainability. Although science cannot say that one particular interpretation is the "correct" one for society, sustainable solutions will have to be based on fundamentally sound hydrologic analyses and related technology.

A *perennial* supply of ground water or surface water can be assured if no more water is withdrawn than enters the system over the long term. To evaluate existing and potential development of dependable water supplies in a given area, a *hydrologic budget* is needed—a statement of the balance between the water that enters the area during a given period of time and the water that goes into storage within its boundaries, is consumed, or flows out during that period. The hydrologic budget or balance may be expressed as follows:

$$\text{Inflow} = \text{Outflow} \pm \Delta\text{Storage}$$

Because changes in storage (Δ *Storage*) become insignificant over a long period for most natural or sustainably managed systems, the hydrologic budget expresses the overall balance between inflow and outflow. However, independent evaluation of all the inflow and outflow items of the hydrologic budget is frequently impossible. Application of the hydrologic balance equation requires good scientific judgment, adequate hydrologic data, and careful analysis of the geology and hydrology of the particular area.

To protect ground-water and surface-water supplies from overexploitation, State and local agencies in Kansas and other states have enacted regulations and laws based on the sustainability concept of "safe yield." *Safe yield* as traditionally defined is the attainment and maintenance of a long-term balance between the amount of ground-water withdrawn annually and the annual amount of recharge. However, as we will show, with this definition even safe-yield exploitation eventually causes a significant loss of ground-water reserves and decline in streamflows in streams hydraulically connected to the aquifer under development.

Although human factors often play an overriding role in resource exploitation (Ludwig et al., 1993), analysis of the human and socio-economic problems in water-resources management is beyond the scope of this chapter. The main objective of this exposition is to highlight the hydrologic fundamentals underlying the concept of safe yield especially as it relates to stream-aquifer systems. These hydrologic principles lead to the following two basic conclusions.

1) Originally, all water withdrawn in any ground-water development comes from aquifer storage, but ultimately it is derived from *induced recharge* from pulling waters directly from surface-water bodies. This transition period to dependence on induced recharge is highly variable and particular to each case, and is a key to developing water-use policy. Ground-water storage and induced recharge are the two sources of water to balance artificial ground-water withdrawals. Because natural recharge is balanced by natural discharge, it does not enter the development water account. Despite its irrelevance, natural recharge is often mistakenly used in ground-water policy to balance ground-water use, ostensibly representing a safe rate of yield.

2) Ground-water management cannot be conceived of separately from management of surface waters. It cannot be said too strongly that surface water and ground water together form the indivisible water-resource system as illustrated by the hydrologic cycle. (The coordinated use of ground and surface waters to maximize benefits from both resources is known as *conjunctive use.*) Therefore the importance of integrated water-resource management, hydrologic understanding, and public education as the basis for establishing operating conditions and constraints on water-resource development needs to be stressed.

Safe Yield: Origins and Ground-water Yield Analysis

Origins

Principles of safe yield in ground-water development derive from water-reservoir engineering studies. An essential feature of any water-supply development is that a minimum quantity of water must be provided at all times. Precipitation and stream discharge vary from month to month and from year to year. During certain times of the year, a stream may carry minimal amounts of water, while following heavy rains the same stream may become a raging torrent. To deal with this variability in discharge, surface-water reservoirs are constructed to store excess water from periods of high flows for use during periods of drought. Regardless of the size of the storage reservoir or the ultimate use of the water, the major function of reservoirs is to stabilize flow over time.

One of the most important aspects of reservoir design is the study of the relationship between yield and capacity (Linsley and Franzini, 1972). *Yield* is defined as the amount of water that can be supplied from the reservoir during a specified interval of time. This time period may vary from a day to several years depending upon the size of the reservoir. Since yield depends upon inflow, it varies from year to year. *Safe* or *firm yield* is defined as the maximum quantity of water that can be guaranteed from a reservoir during a critical dry period. Because this quantity is often based on the lowest natural streamflow on record, there is a finite probability that a drier period may occur, with a yield even less than the safe yield. Thus, yield must always be considered in probabilistic terms.

Standardized techniques exist for the development of reservoir storage-yield relationships. *Mass curves* or *Ripple diagrams* (fig. 2.1), which are cumulative plots of reservoir inflow on the vertical (y-axis) against time on the horizontal (x-axis), permit simple graphical evaluations of reservoir yield (Linsley and Franzini, 1972) and are widely used in surface-water engineering design. Given this widespread and standardized use of the reservoir-yield term in surface-water-supply problems, hydrogeologists sought to define the term for ground-water use as well. Ground water was visualized as a large reservoir that was drawn upon to supply water needs during periods of low recharge. Lowering of the water table during dry periods is not necessarily evidence that the safe yield has been exceeded, but a continuing decline during periods of abundant water warns of excessive withdrawals.

Ground-water Yield Analysis

The objective of many ground-water-resource studies is the determination of how much water is available for pumping, that is, determination of the maximum possible pumping compatible with stability of the ground-water supply. The term *safe yield* as an indicator of this maximum use rate has had an interesting evolution since first introduced. Lee (1915) first defined safe yield as . . . "the limit to quantity of water which can be withdrawn regularly and permanently without dangerous depletion of the storage reserve." Meinzer (1920) defined safe yield as . . . "the rate at which water can be withdrawn from aquifer for human use without depleting the supply to such an extent that withdrawal at this rate is harmful to the aquifer itself, or to the quality of the water, or is no longer economically feasible." The "dangerous depletion" spoken of by Lee takes on economic overtones in Meinzer's definition, and both speak of permanency of withdrawals. Meinzer's definition was expanded by Conkling (1946), who described safe yield as ". . . the annual extraction from a ground-water unit which will not, or does not—1. exceed the average annual recharge; 2. so lower the water table that permissible cost of pumping is exceeded; or 3. so lower the water table as to permit intrusion of water of undesirable quality." A fourth condition, the protection of existing water rights, was added by Banks (1953). Thus, the concept of safe yield, as now understood, ambiguously encompasses hydrologic, economic, quality, and legal considerations. Todd's (1959) compact definition of safe yield as . . . "the amount of water which can be withdrawn from (a ground-water basin) annually without producing an undesired result" does not clarify the situation.

Methods of determining safe yield (Conkling, 1946; Todd, 1959; ASCE, 1987) are generally based on mass conservation considerations expressed in the hydrologic-balance equation. The Hill method is shown in fig. 2.2A; it is merely a plot of annual pumping versus average water-level change and allows identification of the pumping amount associated with zero water-level change. Figure 2.2B illustrates the Harding method in which retained flow (surface inflow minus outflow) is plotted against average water-level change, the zero-change in water level again designating safe yield (Ingerson, 1941).

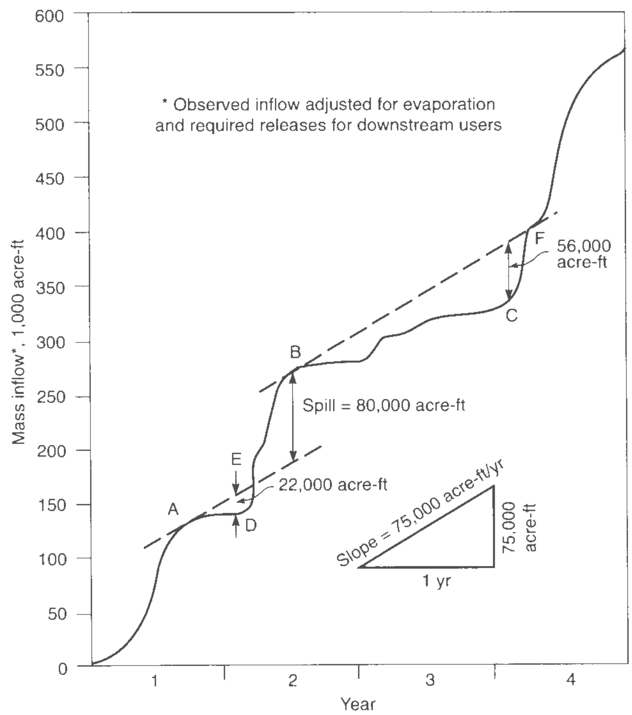


FIGURE 2.1—Use of a mass curve to determine the reservoir capacity required to produce a specified yield. The slope of the mass curve at any time is a measure of the inflow rate at that time. Demand curves representing a uniform rate of demand are straight lines having a slope equal to the demand rate. Demand lines drawn tangent to the high points of the mass curve (A, B) represent rates of withdrawal from the reservoir. Assuming the reservoir to be full wherever a demand line intersects the mass curve, the maximum departure between the demand line and the mass curve represents the reservoir capacity required to satisfy the demand. The vertical distance between successive tangents represents water spilled over the spillway. Mass curves are also used to determine the yield which may be expected with a given reservoir capacity. In this case, tangents are drawn to the high points of the mass curve (A, B) in such a manner that their maximum departure from the mass curve does not exceed the specific reservoir capacity. The slopes of the resulting lines indicate the yields which can be attained in each year with the specified storage capacity. Adapted from Linsley and Franzini (1972).

The zero water-level change method defines safe yield as the average amount of pumpage over a long period of time, provided the ground-water-storage elevation is the same at the beginning and end of this long period of pumping (fig. 2.2C).

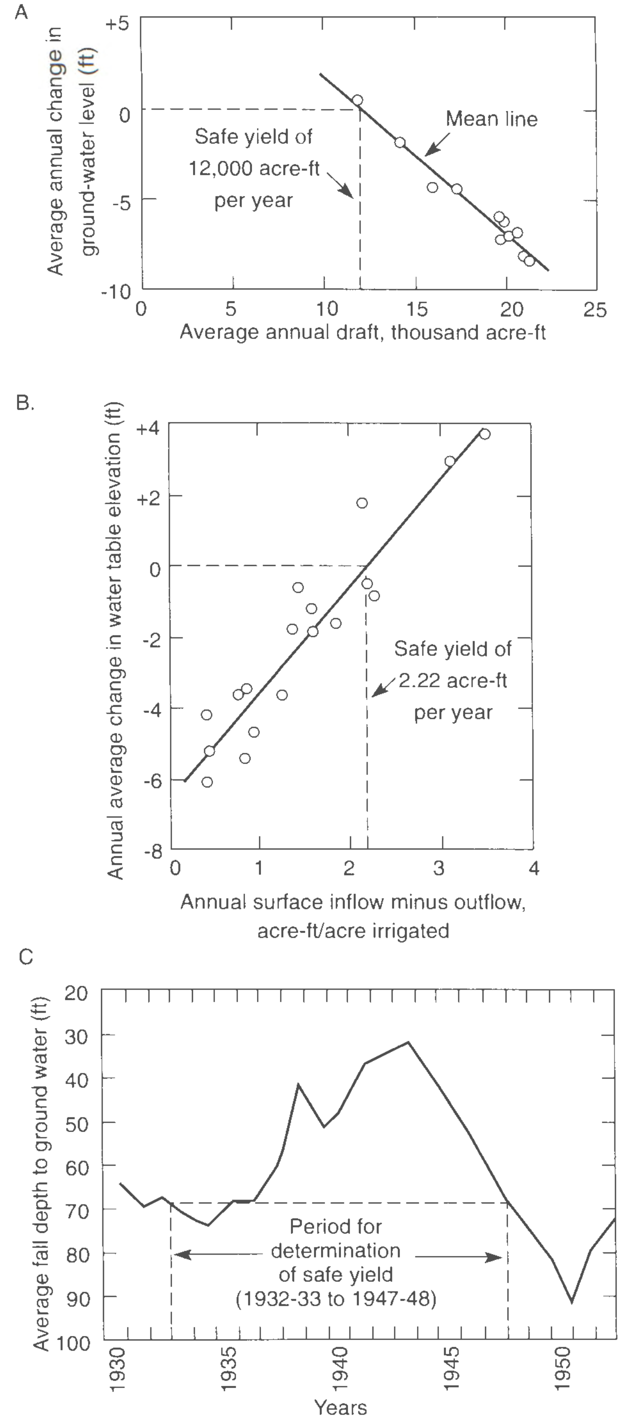


FIGURE 2.2—Determination of safe yield. A) Hill Method for the Pasadena basin, Los Angeles County, California (after Conkling, 1946). B) Harding Method for the Tule River–Deer Creek area, San Joaquin Valley, California (after Ingerson, 1941). C) zero net ground-water fluctuation for South Santa Clara Valley, California (after Haley et al., 1955). Adapted from Todd (1959).

Hydrologic Fundamentals Underlying the Concept of Safe Yield

To determine whether or not a desired quantity of water can be withdrawn from a given aquifer requires an adequate knowledge of the geologic framework and its plumbing system, plus a thorough knowledge of the hydrologic principles described in this section. These hydrologic fundamentals form the basis for understanding the intricacies of the safe-yield concept.

Source of Water Derived from Wells

Our present quantitative approach to ground-water problems is based upon the hydrologic principles concisely stated by Theis (1940). According to Theis, the essential factors that determine the response of aquifers to development by wells are:

1) Distance to, and character of, the recharge;
2) Distance to the locality of natural discharge; and
3) Character of the cone of depression in the aquifer, which depends upon the values of aquifer transmissivity (*T*) and storativity (*S*).

Under natural conditions, prior to development by wells, aquifers are in a state of approximate dynamic equilibrium: over hundreds of years, wet years in which recharge exceeds discharge offset dry years when discharge exceeds recharge. Discharge from wells upsets this equilibrium by producing a loss from aquifer storage; a new state of dynamic equilibrium is reached when there is no further loss from storage. This can only be accomplished by an increase in recharge (natural or artificial), a decrease in natural discharge, or a combination of the two.

Two possible conditions may exist in the *recharge area*. The potential recharge rate may seasonally (or even uniformly) exceed the rate at which water can flow laterally through the aquifer. The water table stands at or near the surface in the recharge area. The aquifer becomes overfull, and available recharge is rejected. In such locations, more water is available to replenish the flow if use of ground water by means of wells can increase the rate of underground flow from the area.

On the other hand, the potential recharge rate may be less than the rate at which the aquifer can carry the water away. The rate of recharge in this case is governed by (1) the rate at which water is made available by precipitation or by the flow of streams, or (2) the rate at which water can move vertically downward through the soil to the water table and thus escape evaporation. In recharge areas of this latter type, none of the recharge is rejected by the aquifer.

If water is rejected by the aquifer in the recharge area under natural conditions, then pumping of wells may draw more water (induced recharge) into the aquifer. On the other hand, no matter how great the normal recharge, if under natural conditions, none of it was rejected by the aquifer, then there is no possibility of balancing the well discharge by increased recharge, except by the use of artificial recharge (such as water spreading or well injection).

Figure 2.3 indicates diagrammatically the difference between the two conditions. Near the mountain border where the water table is close to the surface, vegetation uses ground water, and streams maintain their courses. This is the area of rejected recharge. If the water table in this zone is lowered, ground-water recharge will increase by decreasing the amount of transpiration and surface-water runoff. In the remainder of the area there is some recharge by rainfall, but the water table is so deep that

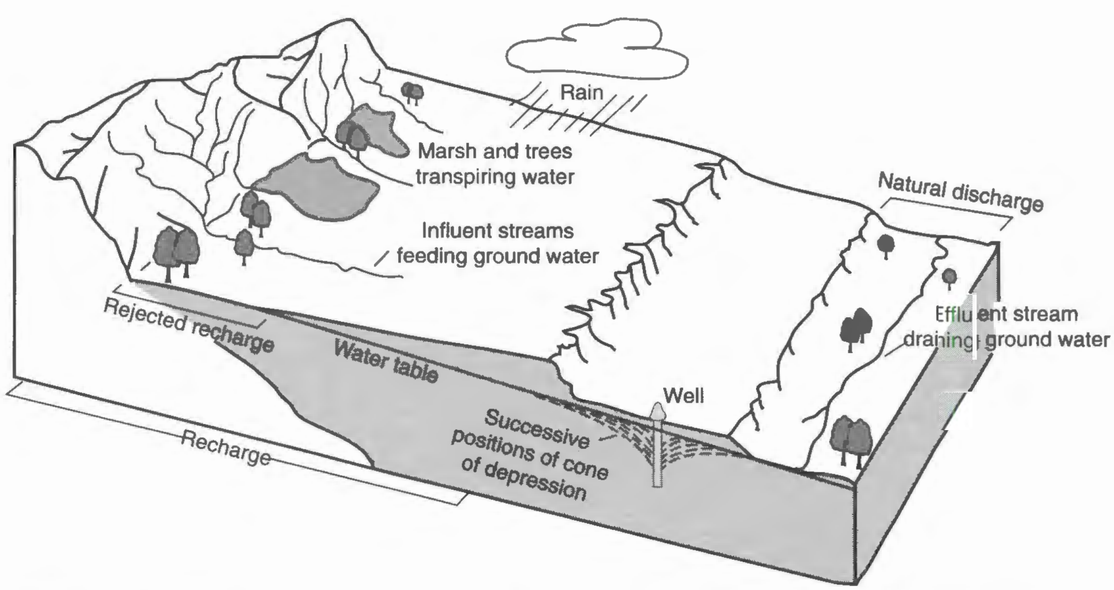


FIGURE 2.3—FACTORS CONTROLLING THE RESPONSE OF AN AQUIFER TO DISCHARGE BY WELLS. Adapted from Theis (1940).

comparatively small changes in its level will not affect the amount of recharge. Recharge is not rejected here, and when the water table is lowered by pumping, no more water will seep downward to the ground-water body.

The normal amount of recharge to the aquifer is sometimes assumed to be the measure of the possible yield of the aquifer to wells. The theory is that if the wells pump an amount equal to the recharge, then the *natural discharge* will be stopped. Although under some conditions, especially where the wells are located close to the area of natural discharge, this may be at least approximately true; in general, wells are not able to stop all the natural discharge from an aquifer in the form of river baseflow, springs, or seepage. Whether the natural discharge or the recharge can be affected without too great a lowering of water level in the pumping area depends on the conditions of flow in the aquifer. To prevent the natural flow of water out of the aquifer, it would be necessary to lower the water levels everywhere between the wells and the areas of natural discharge so that, by Darcy's law, flow is towards the wells. Fig. 2.4 presents a schematic diagram of possible aquifer recharge-discharge mechanisms.

The above statements can be put in simple equation form (Lohman, 1972). Under predevelopment conditions, a steady state or equilibrium condition prevails in most ground-water systems, and over a reasonable period of time natural recharge is equal to the natural discharge. We can write the following expression for the system as a whole

$$R \approx D \text{ or } R - D \approx 0, \qquad \text{(eq. 2.1)}$$

where R and D are the natural recharge and discharge rates, respectively.

After development, we can write the following expression

$$(R + \Delta R) - (D + \Delta D) - Q + dV/dt = 0, \qquad \text{(eq. 2.2)}$$

where ΔR is the change in the mean rate of recharge, ΔD is the change in the mean rate of discharge, Q is the rate of withdrawal from wells due to development, and dV/dt is the rate of change in storage in the system (V is the volume of water stored in the system).

Denoting the increase in recharge $\Delta R = r$ and the decrease in discharge $\Delta D = -d$, eq. (2.2) can be rewritten as

$$(R + r) - (D - d) - Q + dV/dt = 0. \qquad \text{(eq. 2.2a)}$$

From eqs. (2.1) and (2.2a), we can obtain

$$r + d - Q + dV/dt = 0. \qquad (2.3)$$

If dynamic equilibrium can be reestablished, there will be no further withdrawals from storage, so that $dV/dt = 0$, for which case we say that the system reached a *steady state* condition, and eq. (2.3) becomes

$$r + d = Q, \qquad \text{(eq. 2.4)}$$

where the sum $(r + d)$, i.e. the decrease in discharge, d, plus the increase in recharge, r, is called *capture*.

Capture may occur in the form of pulling waters directly from streams (induced recharge), intercepting the ground-water discharge into streams, lakes, and the ocean, or from reducing evapotranspiration (ET) derived from the saturated zone in the riparian and other areas where the water table is near the ground surface. After a new artificial withdrawal from the aquifer has begun, the head in the aquifer will continue to decline until this new withdrawal is balanced by capture. The ultimate production of ground-water from wells depends on how much the rate of recharge and/or discharge can be changed, i.e. how much water can be captured.

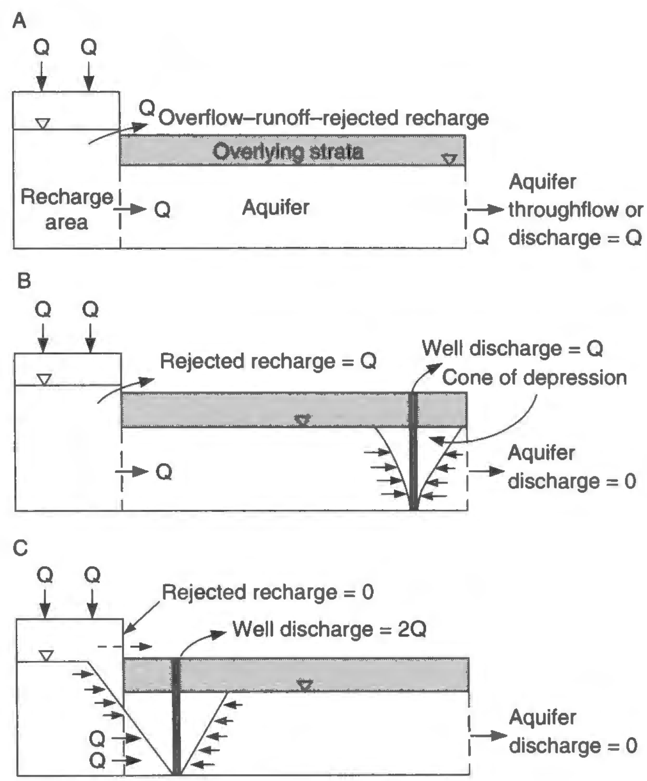


FIGURE 2.4—SCHEMATIC DIAGRAM OF POSSIBLE AQUIFER RECHARGE-DISCHARGE MECHANISMS. (A) Aquifer-recharge area under natural conditions. Potential recharge rate is $2Q$, although the infiltration capacity of the recharge area is limited to Q so the remaining Q becomes rejected recharge such as runoff. The Q that is not rejected flows through the aquifer to the discharge area. (B) As (A), but a well located near to the discharge area intercepts the aquifer discharge which is reduced to zero. (C) The well is now located so that the cone of depression reaches the area of rejected recharge. As a result of the steeper hydraulic gradient, the flow through the aquifer will be increased and rejected recharge will be reduced (in this example to zero). By this means the yield of a well or aquifer may be increased, although streamflow may be decreased so the net gain to a conjunctive use scheme could be negligible. Adapted from Hamil and Bell (1986).

Depletion of Surface Water by Wells

The hydrologic factors that must be considered in any effort to manage the water resources of a ground-water basin and administer water rights in interconnected stream-aquifer systems are further highlighted below. Consider a stream-aquifer system such as an alluvial aquifer discharging into a stream. A new well drilled at some distance from the stream and pumping the alluvial aquifer will cause a cone of depression to form. The cone will grow as water is taken from storage in the aquifer until a source of capture is encountered. Eventually, however , the periphery of the cone will arrive at the stream (fig. 2.5). Then a difference will be produced between the head of the water in the stream and the head just inside the edge of the cone of depression. Water will either start to flow from the stream into the aquifer or cease to flow from the aquifer into the stream. The cone will continue to expand with continued pumping of the well until an equilibrium is reached in which induced recharge balances the pumping. Because the stream is the source of recharge, the cone will expand until its periphery along the stream is long enough, and the head gradient is sufficient, to cause a flow from the stream into the cone that is equal to the rate of pumping from the well. The length of time before an equilibrium is reached depends on several variables, including the distance between the well and the stream.

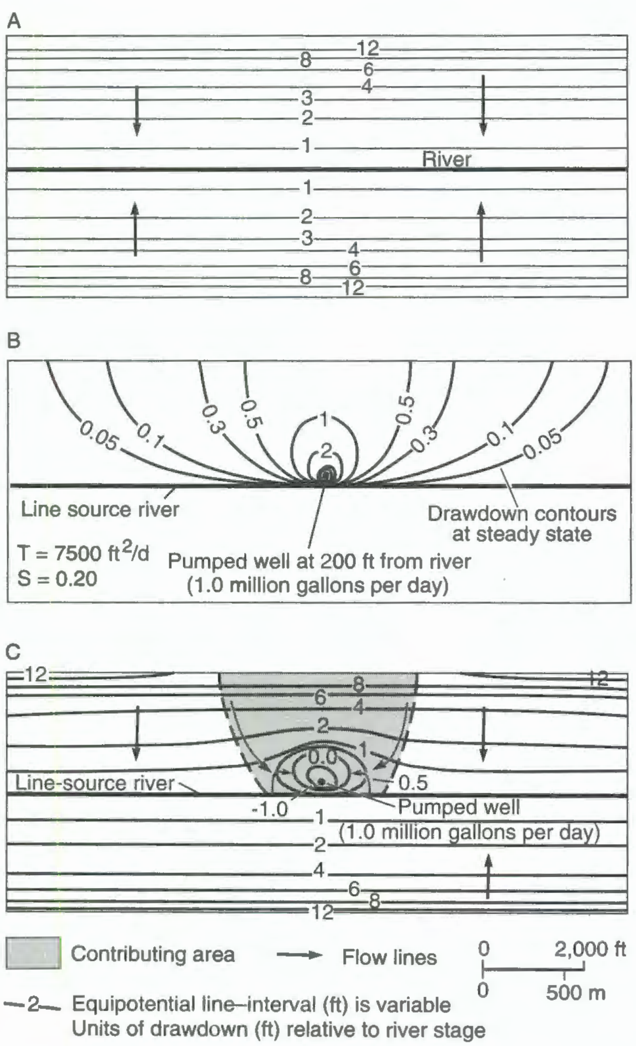


FIGURE 2.5—BIRD'S-EYE VIEW OF WATER-TABLE CONTOURS AND CONTRIBUTING AREA TO WELLS NEAR A RIVER. (A) Natural condition before pumping. (B) Water-table drawdown due to pumping well. (C) Well intercepts water that was flowing to the river and also extracts flow from the river. The contributing area of the well (shaded area) results from superposition of (A) and (B). The river in all cases above is treated as a constant head line-source of water. Adapted from Morrissey (1989).

Once the well's cone has reached an equilibrium size and shape, all of the pumping is balanced by flow diverted from the stream. Eventually there is no difference in their impact on stream flow between a well withdrawing ground water, as described, and a pump diverting streamflow at the same rate. A crucial point, however, is that before equilibrium is reached (before all water is coming directly from the stream), the two situations are not the same (DuMars et al., 1986). Until the perimeter of the cone reaches the stream, the volume of the cone represents a volume of water that has been taken from storage in the aquifer, over and above the subsequent diversions from the river (provided compaction effects can be neglected). It is this volume that may be called *ground-water depletion.*

Thus, ground-water sources include ground-water storage and induced recharge of surface water. Ground-water storage is relatively large. Variation in supply is not a consideration until the decline in water level becomes an economic, environmental, or political problem. Diversions from wells, however, are physically linked to surface depletions in the form of induced recharge from the surface streams. Since the 1980's, three-dimensional numerical models of the complete stream-aquifer hydrogeologic system have been used for water-rights purposes (Balleau, 1988). These models provide a predictive tool explaining the connection between well-field withdrawal and surface-water depletion at particular sites.

The timing of effects on adjacent streams caused by ground-water withdrawals depends upon the *aquifer diffusivity*—how fast a transient change in head will be transmitted throughout the aquifer system, expressed as the ratio of aquifer transmissivity to storativity, T/S—and the distance from the wells to the stream. This distance is the major factor in determining the rate at which surface supplies are affected (Balleau, 1988). For radial flow of ground water, a tenfold increase in distance from the surface-water body causes a hundredfold delay in the response time, whereas a change in diffusivity is linearly proportional to the response time. Generally, if the wells are distant from the stream, it will take tens or hundreds of years before their influence on streamflow is felt.

TABLE 2.1—SOURCES OF WATER (surface-water depletion and ground-water storage) supporting ground-water withdrawals as predicted by 3-D ground-water models in New Mexico (adapted from Balleau, 1988).

Author	Distance to surface water (miles)	Geologic units	Time period (years)	Well-field drawdown (feet)	Source of water (percent of withdrawal)	
					Ground-water storage	Surface-water depletion
Billings and Assoc. (1984)	1 to 7	Permian limestone	11	30	37.6	62.4
Faust et al. (1984)	4 to 20	Tertiary volcanics	34	600	54.3	45.7
Hearne (1980)	1 to 10	Tertiary sediments	50	300	88.8	11.2
HGC (1982)	15 to 20	Jurrassic sediments	30	2300	98.4	1.6
HGC (1983)	12	Permian sediments	50	138	96.8	3.2
Lyford et al. (1980)	40	Jurassic and Cretaceous sediments	47	3900	99.2	0.8
Peterson et al. (1984)	12	Tertiary sediments	100	200	49.6	50.4
Kernodle et al. (1987)	1 to 8	Tertiary sediments	72	60	25	75

When a working hydrogeologic model is available, the effects of ground-water usage can be quantified in terms of the availability of the surface supply to serve prior water demand. With ground-water development, the total system yield available to support beneficial uses increases until surface-water depletion approaches the magnitude of the ground-water development. The duration of the net benefit may be months or millenia depending upon two factors: diffusivity and distance. Table 2.1, compiled by Balleau (1988), shows the variable time period for ground-water pumpage to be balanced in part by surface-water sources as predicted in some recent three-dimensional ground-water models. As shown in the last column (surface-water depletion), the expanded yield of the total system reduces the reliable supply of surface water.

Spatial and Temporal Scales in Water-resource Development

One can study the flow of fluids through geologic media at a variety of scales (Freeze, 1983). At one end of the spectrum is the microscopic study of the physics of flow in individual pores and capillaries. At the next level are studies on the scale of a representative elementary volume, where porous-media properties rather than capillary properties first came into play. Yet another level is available at the scale of laboratory experiments involving flow through columns and sand tanks. Moving out of the lab and into the field, the smallest unit of study is probably a single well. We can move up another level to the analysis of ground-water conditions at a single engineering site, perhaps a sanitary landfill, an earth dam, or a well field. Also, one can conduct ground-water studies at a regional scale, where analyses are carried out on the scale of aquifers, or aquifer-aquitard (low-permeability layer) systems, or entire ground-water basins (see further below).

The concept of yield can also be applied on several scales (Freeze and Cherry, 1979). *Well yield* can be defined as the maximum pumping rate that can be supplied by a well without drawing the water level in the well below the pump intake. *Aquifer yield* can be defined as the maximum rate of withdrawal that can be sustained by an aquifer. *Basin yield* can be defined as the 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. If one considers the effects of well interference, it is clear that if all wells in an aquifer pump at their well yield it is likely that the aquifer yield will be exceeded. If one considers the effects of leakage across aquifer-aquitard systems, it is clear that if all aquifers are developed to the limits of their aquifer yield, the basin yield will probably be exceeded.

The hydrologic inventory relating precipitation to yield becomes useful only when it is applied to an appropriately defined region. Studies of surficial waters refer to a *watershed* (or *catchment*) or *river basin* characterized by the property that the addition or subtraction of water in any part of it influences streamflow and river stages further downstream. A watershed can easily be mapped, and all points in it are, in principle, accessible for observations and measurements. The region appropriate for ground-water studies should comprise a *ground-water basin*—the underground equivalent of a river basin—consisting of one aquifer or several interconnected aquifers that are surrounded by impermeable rocks on all sides, except in areas through which natural replenishment and outflow are affected. If water is added to or abstracted from these aquifers at any point, water levels and the pattern of ground-water flow in the entire region are changed. The identification of a ground-water basin is more problematic because it is not necessarily related to topographic or geologic features visible at the surface. Because ground water is accessible to observation only in isolated points, information about a ground-water system has to be pieced together from measurements at these points with the aid of geologic reasoning, the theory of flow in porous media, and other techniques. (A fundamental block to progress in using most hydrologic data is our relatively poor knowledge of how to interpolate between measurement points.) Watersheds and ground-water systems perform identical functions in the hydrologic cycle. They convey water from higher elevations to lower ones and hold a certain volume of water in transient storage.

The relationships between the different components of a hydrologic inventory are complex in both time and space, especially the dynamics of hydrologic systems that are composed of both surface streams and aquifers. The complexity of the stream-aquifer interactions emerges from two major factors. In the first place, flow in open channels, including streams and rivers, occurs in a time frame that is expressed in meters per second, while movement of water in aquifers is measured generally in velocities that are several orders of magnitude smaller. The *depletion time* indicates how long it would take the watershed or the ground-water system to dry out if surface runoff or ground-water replenishment were stopped from the instant t onward and if outflow were 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 are usually 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 generally react very sluggishly to these events.

As infiltration feeding ground-water recharge increases, overland flow feeding surface runoff decreases. As water tables flatten, gradients decrease, and discharge to streams as baseflow decreases. If ground-water basins are developed to their maximum yield, the yields of surface-water components in the basin will be reduced (Freeze, 1983). In addition, the stochastic aspects of streamflows and the uncertainty connected with the areal extent of the physical characteristics of aquifers contribute to the complexity of stream-aquifer interactions.

The evolution of hydrologic science has been in the direction of ever-increasing scale, from small catchment to large river basin to the earth system, and from storm event to seasonal cycle to climatic trend. Inevitably, increased scale brings increased complexity and increased interaction with allied sciences.

Ground-water Mining, Natural Recharge, and Planning Policy

Balleau (1988) described the transition of ground-water development from storage depletion to induced recharge. Every ground-water development, whether from a local river bed or a continental-scale flow system, begins with 100% withdrawal from storage. The timing of the change from storage depletion (mining) to induced recharge from surface-water bodies is a key to developing water-use policy. The shape of the transition curve for a two-dimensional system is shown in fig. 2.6A in nondimensional form based on Glover's (1974) tabulation, where the percent of ground-water withdrawal derived from ground-water storage is plotted against dimensionless time. Although dimensionless time may seem esoteric on first encounter of the term, it is a very convenient way to represent, in one curve, multiple values of aquifer diffusivities (T/S), multiple distances between wells and streams (x), and multiple times. Thus, for example, all three transition curves of fig. 2.6B, representing three different distances between the pumping well and stream, are collapsed into the single curve of fig. 2.6A when the time axis (days) is transformed to a dimensionless time axis $[4(T/S)t/x^2]$. The general shape of the transition or

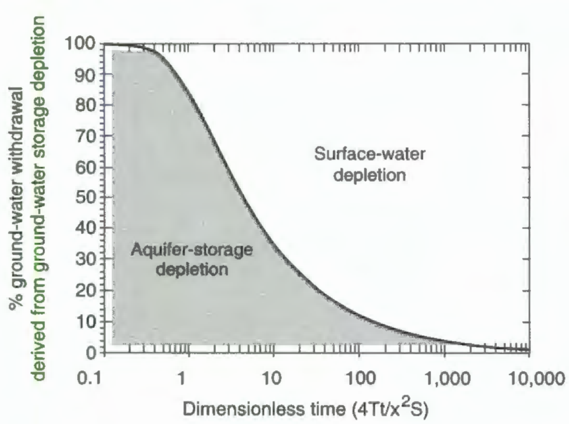


FIGURE 2.6(A)—TRANSITION OF SOURCES OF WATER TO WELLS FROM RELIANCE UPON GROUND-WATER STORAGE TO INDUCED RECHARGE OF SURFACE WATER. Adapted from Balleau (1988).

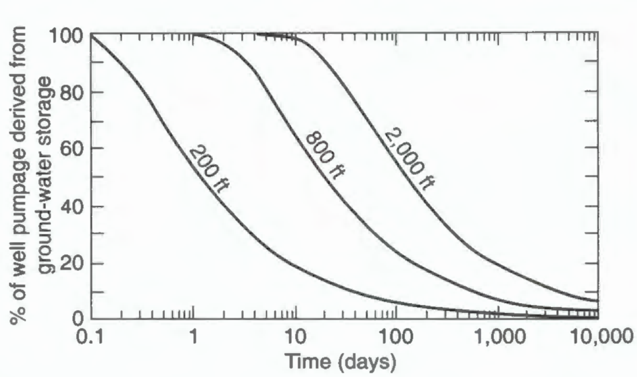


FIGURE 2.6(B)—TRANSITION OR GROWTH CURVES FOR WELLS LOCATED AT THREE DIFFERENT DISTANCES FROM A STREAM BASED ON GLOVER'S (1974) ANALYTICAL SOLUTION.

TABLE 2.2—EXAMPLES OF RATES OF TRANSITION FROM GROUND-WATER MINING TO INDUCED RECHARGE (adapted from Balleau, 1988).

	Time on transition curve of fig. 2.6A			
Sources of water	**Example A[a]**	**Example B**	**Example C**	**Example D**
Mining phase	1 second	1 day	1 week	1 year
90 percent storage	2 seconds	2 days	2 weeks	2 years
50 percent storage	12 seconds	12 days	3 months	12 years
10 percent storage	6 minutes	11 months	6.5 years	340 years
Induced recharge phase	2 hours	23 years	160 years	8,350 years

[a]The hydrologic parameter T/Sx^2 (aquifer diffusivity/distance squared) ranges over seven orders of magnitude in examples A–D.

growth curve is retained in systems with appreciably different boundaries and parametric values (Bredehoeft et al., 1982, fig. 4.8, reproduced as fig. 2.10 here; Faust et al., 1984, fig. 15).

The rate at which dependence on ground-water storage converts to dependence on surface-water depletion is highly variable and is particular to each case. Table 2.2 illustrates a broad range of rates of transition from ground-water mining to induced recharge. The initial and final phases of the growth curve on fig. 2.6A, representing mining and induced recharge, are separated in time by a factor of nearly 10,000; for example, one week of mining implies a transition to steady induced recharge 8,000 weeks or 160 years later. The curve is disproportionately steep in the early transition toward induced recharge. In example C (table 2.2), storage provides 90% of the source of water after two weeks and only 10% after 6.5 years. Full reliance on indirect recharge, above 98%, takes an extremely long time. The distinct category of ground-water mining depends entirely upon the time frame (Balleau, 1988). *All ground-water developments initially mine water, and ultimately do not.* (Boxed section 2.4, later on, provides additional examples of transition curves from full reliance on aquifer storage to full reliance on induced recharge of surface water.)

Administration of ground water has been governed by the concepts of safe yield versus mining, and the idea of impairment of existing water rights in a water supply. The eventual reduction in surface-water supply as a result of ground-water development, and the distinction between natural recharge and induced recharge, complicates the administration of water rights. *Natural recharge* is that water moving through the ground-water system under boundary conditions imposed by natural topography, geology, and climate. *Induced recharge* is surface water added to the natural ground-water system in response to such artificial boundary conditions as those imposed by pumping wells, drains, recharge basins, or reservoirs. As discussed above, induced recharge and ground-water storage are the two sources of water to balance artificial ground-water withdrawals. Natural recharge balances natural discharge and does not enter the artificial water account. Natural recharge is already generally relied upon at its downstream discharge point as the reliable baseflow of springs, wetlands, and rivers. Thus, natural recharge should not be part of the well-field water budget and should be irrelevant to the magnitude of an artificial ground-water development (Balleau, 1988).

The effects of ground-water development that concern policymakers are primarily aquifer drawdown and surface-water depletion (Balleau, 1988). Both are fundamentally related to pumping rate, aquifer diffusivity, location, and time of pumpage. The natural recharge rate is unrelated to any of these parameters. Despite its irrelevance, natural recharge is often used in ground-water policy to balance ground-water use based ostensibly on a steady state (Balleau, 1988). As we will also show in the next section, pumping at the natural recharge rate does not lead to a stable, non-declining level of ground-water development. *It is a misconception that the natural rate of recharge represents a safe rate of yield.* Another example of the environmentally "unsafe" impacts of safe yield in areas outside the immediate area of development is presented in boxed section 2.1 following.

Boxed section 2.1: Environmental aspects of safe yield (based on Prokopovitch, 1990).

The traditional definition of safe yield often ignores considerations outside the immediate area of development but from an ecological/environmental standpoint, such restrictions are too narrow. Development of an aquifer means modification of conditions in its outflow-discharge area. For example, agricultural pumping in an aquifer system in southwestern Nevada in the vicinity of the Death Valley National Monument endangered several species of an endemic desert fish (*Cyprinodon* species), which inhabited several local waterholes fed by this aquifer system.

Fig. B2.1-1 illustrates an example of "unsafe" results of such so-called safe-yield development (Prokopovitch, 1990). The development area has two aquifers—the upper one, unconfined (*U*), and the lower one, confined (*C*). A ground-water development in the district "*D*" includes pumping from the unconfined aquifer (*pu*) and the artesian flow from the confined system (*pc*). The development is based on a safe yield of both aquifers and causes no decline in either the free water table or the piezometric head. Reduction of the original natural outflow from the unconfined zone, however, results in the degradation and aging of a swampy area and reduced outflow from the confined horizon into a saltwater basin (*B*), results in a saltwater intrusion (*In*) into the originally freshwater aquifer (*C*), salt poisoning of vegetation in area (*T*), and ecological changes in area (*E*) that originally was inhabited by brackish organisms due to the dilution of salty water by fresh underwater outflow (*O*). Hence, the yield was "safe" for a developing area but was not so safe for other distant areas. Attempts should be encouraged in environmental impact statements to analyze as much as possible the impact of the safe yield outside the area of development, particularly within areas of the natural discharge of aquifers.

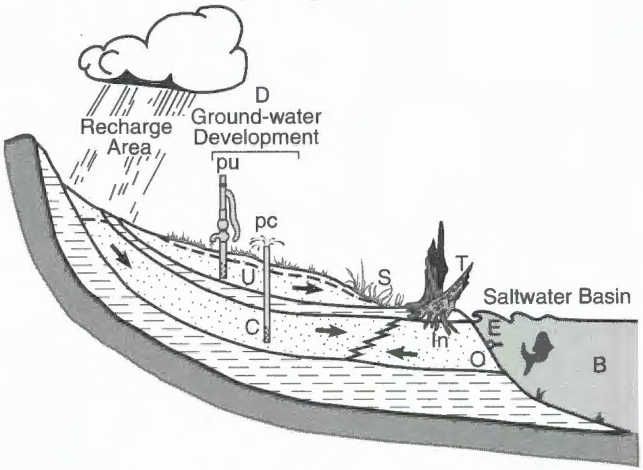


FIGURE B2.1-1—A theoretical example of "unsafe" impacts of a development of two aquifers systems under "safe yield" conditions. Adapted from Prokopovitch (1990).

Criteria for the Regional Exploitation of Ground Water

The advantages and dangers of ground-water over-exploitation (or mining) in a semiarid or dry region are not easily grasped. *Preservationists* may assert that it is unwise to endanger an irreplaceable water resource for the sake of temporary gain. *Economists* may argue that it makes no sense to keep sitting on the huge wealth represented by ground water in storage while restricting oneself to the very frugal "yearly income" represented by an estimated sustained yield.

As we have previously mentioned, definitions of "safe yield" are based on the premise that the rate of ground-water withdrawal is less than or, at most, equal to the rate of natural replenishment. It is usually concluded that safe-yield exploitation leaves the reserves of ground water intact. However, simple considerations show that *even safe-yield exploitation eventually causes a significant loss of ground-water reserves.* Ground-water storage reserves may be divided into 1) *live storage reserves* which are situated above the outlet or discharge zone and can be depleted by natural discharge drainage and can also be recovered by pumping (see fig. 2.7), and 2) *dead storage reserves* which can be recovered only by pumping after the live reserves have been exhausted.

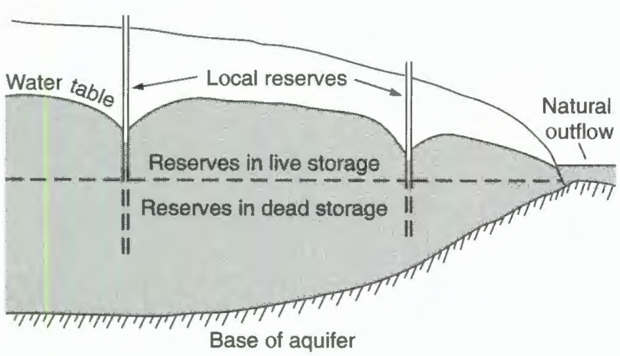


FIGURE 2.7—Classification of ground-water reserves. Adapted from Mandel and Shiftan (1981).

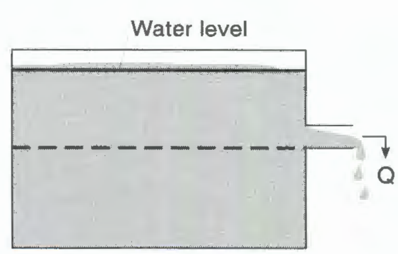


FIGURE 2.8—Unicell model for the simulation of spring flow. Adapted from Mandel and Shiftan (1981).

The essence of the process is as follows. In the natural state, ground-water reserves and water levels adjust themselves so that a state of equilibrium is maintained between replenishment and discharge of the aquifer. In safe-yield exploitation, ground-water reserves and water levels must eventually adjust themselves so that an equilibrium is established between replenishment on the one hand and exploitation plus reduced discharge on the other. *During the transition from natural to artificial equilibrium, a part of the ground-water reserves is unavoidably lost.*

Mandel and Shiftan (1981) analyzed the process of transition with the aid of a highly simplified model, the *unicell model*. The unicell model is a tank with vertical walls filled with sand or some other porous material and provided with a spout above its bottom (fig. 2.8). The sand is saturated with water to a certain depth and the discharge issuing from the spout is observed. The relation of the unicell model to the natural prototype is shown in fig. 2.7. (A karstic limestone aquifer with very large transmissivities, draining through a well-defined spring, is the best natural approximation to this model.)

Assuming that pumping (Q) and replenishment (R) are constant and that pumping is smaller than replenishment, we obtain the following asymptotic expression from the unicell model and mass balance considerations (Mandel and Shiftan, 1981):

$$D(t) = (R - Q) + Qe^{-t/t_0}, \qquad \text{(eq. 2.5)}$$

where $D(t)$ is the time-varying rate of natural discharge through the outlet, e is the special number, whose natural logarithm is equal to 1, and whose value is approximately 2.718, that appears as the base in most exponential functions, and t_0 is the *depletion time*, which indicates how long it would take the ground-water system to dry out if ground-water replenishment were stopped from the instant t onward and if outflow were maintained at the rate it had at this instant (i.e. $t_0 = V(t)/D(t)$).

Figure 2.9 shows numerical results, based on the unicell model (eqn. 2.5), calculated for a medium-sized aquifer by Mandel (1977). The postulated final equilibrium state is approached only after about 150 years. During this time the live reserves run to "waste" in this model.

The last term on the right-hand side of eq. 2.5 is outflow in excess of the final quasi-steady equilibrium outflow rate, D_S ($=R-Q$). Integration of that asymptotic expression (Mandel and Shiftan, 1981) yields the volume of water ($\Delta V = t_0 Q$) that is lost through natural discharge until the final equilibrium state is established—in other words, the live reserves.

If pumping equals natural replenishment ("safe yield" attainment), the entire live storage reserve will be lost, natural discharge will be stopped, and the water level will be stabilized at the elevation of the outlet. Continued pumping in excess of replenishment also will eventually deplete the reserves in dead storage until the aquifer practically dries up. If a recharge boundary is present (such as lake, reservoir, or perennial stream), an equilibrium state will be attained when the influx through the boundary equals excess pumping. Dynamic drawdowns created by wells near the outlet will decrease natural discharge almost immediately. As a consequence, the time of transition will be prolonged and the loss of reserves will be delayed. The reverse will happen if wells are situated at a large distance from the outlet.

Over-exploitation, in excess of the "safe yield," provides increased water supplies for a limited time. Overexploiting an aquifer in this model means that ground-water reserves are being recovered that, under safe-yield conditions, would either be "lost" through outflow or remain in storage. Two principal kinds of over-exploitation, exploitation of live storage reserves and mining, can be distinguished according to the degree of reserve depletion they entail (Mandel, 1977). Although in practice it is difficult to say exactly when the live storage reserves are gone and when mining starts, in broad outline the distinction is quite clear.

The exploitation of live storage reserves implies that the process of transition to an equilibrium state commensurate with the safe yield is speeded up but that the water resource is not "damaged." Figure 2.9 also illustrates this type of over-exploitation, in which the unicell model previously analyzed is exploited at the constant rate of 225 million cubic meters per year—approximately 182,000 AF/yr—(i.e. 225 ÷ 90 = 2.5 times its assumed safe yield of 90 million cubic meters per year—approximately 73,000 AF/yr) during the first 25 years. Figure 2.9 shows that the aquifer approaches its final equilibrium state at the end of this period. If ground-water abstraction is reduced to the safe yield from then onwards, no harmful effects, in terms of additional water-level declines, will be observed.

The practical implication is that development of the area is advanced by almost one generation. The period of 25 years is long enough to plan and implement alternative

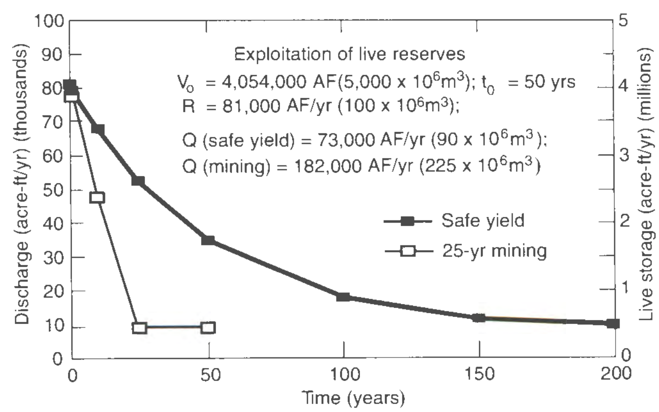


FIGURE 2.9—DEPLETION OF RESERVES BASED ON THE UNICELL MODEL UNDER SAFE-YIELD EXPLOITATION (darker line) and 25-year mining policy (lighter line).

water supplies so as to compensate for the eventual reduction of ground-water supplies. On the negative side of the ledger, it will be difficult to impose the required reduction of ground-water abstraction because water users, feeling no ill effects, will not be easily convinced that restrictions are necessary.

The unicell model assumes that wells are far removed from the natural outlet and the geometry of the outlet remains constant. The unicell model also assumes uniform (average) parameters and uniform stresses throughout the basin (i.e. it is a *lumped-parameter model*).

As we have seen in the unicell model example, previous attempts to consider the optimal rate of pumping over time for a ground-water basin have used a simplified model for the ground-water system which assumes that drawdowns in response to withdrawals are uniformly distributed through the basin. However, large differences in drawdown commonly occur in developing ground-water systems. These differences throughout the basin lead to great variations in water costs and perhaps to localized economic and hydrologic failure.

To illustrate the influence of the dynamics of a ground-water system, Bredehoeft et al. (1982) chose a rather simple, yet realistic, system for analysis. Consider a closed intermontane basin of the sort one might find in the western states. Under predevelopment conditions the system is in equilibrium: *phreatophyte* (plants that withdraw their water supply from the saturated zone) evapotranspiration in the lower part of the basin is equal to recharge from the two streams at the upper end (fig. 2.10).

Pumping begins in the basin, and, for simplicity, is assumed to equal the recharge. In this example two assumptions about the hydrology are made:

1) Recharge is independent of the pumping in the basin, a typical condition, especially in the arid west.
2) Phreatophyte use decreases in a linear manner as the water levels in the vicinity decline by 0.3 to 1.5 m (1–5 ft). Phreatophyte use of water is assumed to cease when the water level is lowered 1.5 m (5 ft) below the land surface.

The geometric and hydrologic parameters assumed for the system are shown in table 2.3. The system was simulated mathematically by a finite-difference approximation to the equations of ground-water flow. One-thousand years of operation were simulated. Stream recharge, phreatophyte-water use, pumping rate, and change in storage for the entire basin were graphed as functions of time. Two development schemes were examined: case 1, in which the pumping was more or less centered within the valley, and case 2, in which the pumping was adjacent to the phreatophyte area (fig. 2.10).

The system does not reach equilibrium until the phreatophyte-water use (the natural discharge) is entirely salvaged (captured) by pumping, i.e. phreatophyte water use equals zero because eventually the plants die (we define equilibrium as $dV/dt = 0$). In case 1, phreatophyte-water use is still approximately 10% of its initial value at year 1,000 (fig. 2.11). In case 2, it takes 500 years for the phreatophyte-water use to be completely captured.

In both cases, for the first 100 years, nearly all of the water comes from storage. Obviously, as the system approaches equilibrium, the rate of change of the volume of water removed from storage also approaches zero. If the aquifer were thin, it is apparent that wells could go dry long before the system could approach equilibrium.

This example illustrates three important points (Bredehoeft et al., 1982):

1) The rate at which the hydrologic system can be brought into equilibrium depends on the rate at which the discharge can be captured.
2) The placement of pumping wells in the system significantly changes the dynamic response and the rate at which natural discharge can be captured.
3) Some ground water must be mined before the system can be brought into equilibrium.

An additional example of the dynamic response of a ground-water basin to development, which provides additional insight into the concept of safe yield, is presented in boxed section 2.2 following.

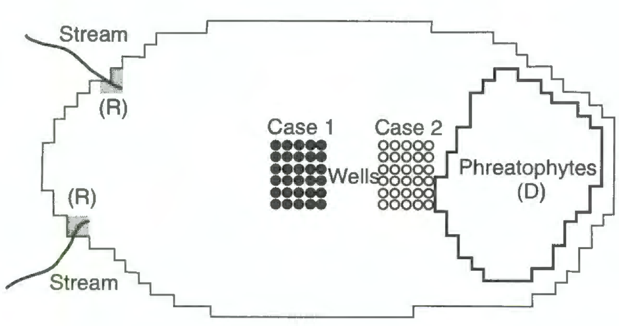


FIGURE 2.10—SCHEMATIC MAP OF AN INTERMONTANE BASIN SHOWING AREAS OF RECHARGE (R), DISCHARGE (D), AND TWO HYPOTHETICAL WATER-DEVELOPMENT SCHEMES, CASE 1 AND CASE 2. Adapted from Bredehoeft et al. (1982).

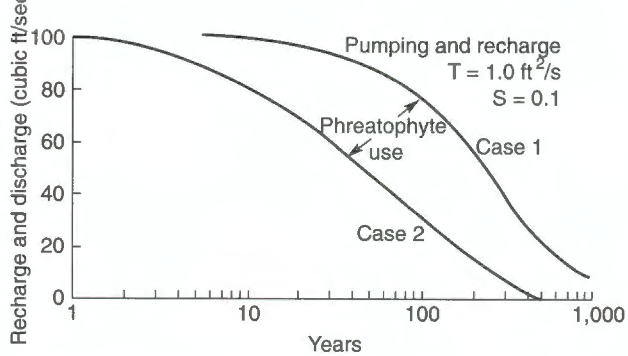


FIGURE 2.11—PLOT OF THE RATE OF RECHARGE, PUMPING, AND PHREATOPHYTE USE VERSUS TIME. Adapted from Bredehoeft et al. (1982).

TABLE 2.3—AQUIFER PARAMETERS EMPLOYED IN THE BREDEHOEFT ET AL. (1982) EXAMPLE.

Basin dimensions	50 × 25 miles (80×40 km)
Aquifer	
Hydraulic conductivity (*K*)	0.5×10^{-3} ft/sec (0.15×10^{-3} m/sec)
Storage coefficient (*S*)	0.1
Initial saturated thickness	2,000 ft (610 m)
Phreatophytes	
Area	172 miles^2 (445 km^2)
Average use (annual)	100 ft^3/sec (2.8 m^3/sec)
Recharge	
Area	7 miles^2 (18 km^2)
Average recharge rate	100 ft^3/sec (2.8 m^3/sec)
Development	
Area	30 miles^2 (78 km^2)
Average pumping rate	100 ft^3/sec (2.8 m^3/sec)

Variability and Ambiguity of Safe Yield

As mentioned previously, the concept of safe yield stems from the principle of renewability of the ground-water resource. To many people, safe yield has come to mean an annual rate that the water user can count upon from an aquifer, and it is easily confused with water rights. However, the location of wells with respect to areas of recharge and discharge, the character of the aquifer, the potential sources of pollution, and many other factors are involved in estimates of the maximum feasible withdrawal from an aquifer. A number of closely spaced wells will cause much more rapid decline of local water levels than the same number of wells more widely dispersed. In some basins the quantity of water in the aquifer governs the safe yield; in others, especially in confined aquifers with recharge areas distant relative to pumping centers, the rate of flow towards the wells is the limiting factor (see also Chapter 4). Any change in conditions, such as changes in land use, or economics (for example, resulting in the importation of new water supplies) would require calculation of a new yield. Changes in vegetation may affect surface infiltration and subsequent percolation to the water table. Urbanization of an area would be expected to reduce recharge. Changes in the use of ground water, such as from irrigation to municipal or industrial use, may also change the safe yield.

Clearly, no unique and constant value can be attached to safe yield. The determination of safe yield by any of the available methods briefly discussed is based on existing or assumed conditions. However, one should consider also those conditions that would prevail in the future when estimating the yield that will be extracted from the aquifer. The safe yield of an aquifer, in some instances, can be substantially augmented by engineering controls (ASCE, 1987). For example, more water can be made available through artificial recharge by spreading or injection wells, or by lowering ground-water levels to reduce evapotranspiration, to capture rejected recharge, or to capture surface water from streams. The level of water production quantified by the phrase "safe yield" (perennial yield) is fixed at any point in time only in the sense that no more money may be available for engineering construction, or that legally no more water may be obtained from any source. Should these constraints be changed, for example, by the importation of water and the utilization of underground storage, the safe yield could be increased. Thus, the first and foremost drawback of the conventional safe-yield approach is the lack of an unambiguous quantitative definition. Once it is recognized that an equilibrium can be established in the aquifer at different levels of development and annual withdrawals, the need for other approaches upon which to base operation decisions becomes obvious (Bear and Levin, 1967). In the next section, two such alternative approaches will be illustrated.

A significant problem with most definitions of ground-water safe yield is the failure to address impacts of ground-water exploitation on related surface water, and on areas of the natural discharge of aquifers which might be outside the area of development as mentioned earlier.

Thus, considerable dissatisfaction with the term "safe yield" has been expressed. Certainly, few would deny the term safe yield is something less than satisfactory (Mann, 1963). Especially in litigation, the connotation that extractions beyond a certain annual rate will result in a condition which is unsafe, unduly dramatizes the situation. From this standpoint, a more innocuous expression such as "sustained yield" (McGuinness, 1951) or "perennial yield" (Parker, 1951; Williams and Lohman, 1949; Kazmann, 1956) is preferable. Thomas (1951), Kazmann (1956), and others have suggested abandonment of the term because of its indefiniteness, because it is often misinterpreted by laypersons as implying a fixed underground water supply, and because it may depend more on the particular well location rather than on general aquifer characteristics.

Boxed section 2.2: Transient hydrologic budgets and safe yield of a ground-water basin (based on Freeze, 1971; and Freeze and Cherry, 1979).

Some authors have suggested that the safe yield of a ground-water basin be defined as the annual extraction of water that does not exceed the average annual ground-water recharge. This concept is not correct. As pointed out by Bredehoeft and Young (1970), major ground-water development may significantly change the recharge-discharge regime as a function of time. Clearly, the basin yield depends both on the manner in which the effects of withdrawal are transmitted through the aquifers *and* on the changes in rates of ground-water recharge and discharge induced by the withdrawals. In the form of a transient hydrologic budget for the saturated portion of a ground-water basin,

$$Q(t) = R(t) - D(t) + dS/dt \qquad \text{(eq. B2.2-1)}$$

where $Q(t)$ = total rate of ground-water withdrawal
$R(t)$ = total rate of ground-water recharge to basin
$D(t)$ = total rate of ground-water discharge from basin
dS/dt = rate of change of storage in saturated zone of basin.

Freeze (1971) examined the response of $R(t)$ and $D(t)$ to an increase in $Q(t)$ in a hypothetical basin in a humid climate where water tables are near the surface. The response was simulated with the aid of a three-dimensional transient analysis of a complete saturated-unsaturated system. Figure B 2.2-1 is a schematic representation of his findings. The diagrams show the time-dependent changes that might be expected in the various terms of eq. B2.2-1 under increased pumpage. Let us first look at the case shown in fig. B2.2-1(A), in which withdrawals increase with time but do not become excessive. The initial condition at time t_0 is a steady-state flow system in which the recharge, R_0, equals the discharge, D_0. At times t_1, t_2, t_3, and t_4, new wells begin to tap the system and the pumpage rate Q undergoes a set of stepped increases. Each increase is initially balanced by a change in storage, which in an unconfined or water-table aquifer takes the form of an immediate water-table decline. At the same time, the basin strives to set up a new equilibrium under conditions of increased recharge, R. The unsaturated zone will now be induced to deliver greater flow rates to the water table under the influence of higher gradients in the saturated zone. Concurrently, the increased pumpage may lead to decreased discharge rates, D. In fig. B2.2-1(A), after time t_4, all natural discharge ceases and the discharge curve rises above the horizontal axis, implying the presence of induced recharge from a stream that had previously been accepting its baseflow component from the ground-water system. At time t_5, the withdrawal, Q, is being fed by the recharge, R, and the induced recharge, D; and the water table has undergone significant decline. Note that the recharge rate attains a maximum between t_3 and t_4. At this rate, the ground-water body is accepting all the infiltration that is available from the unsaturated zone under the lowered water-table conditions.

In fig. B2.2-1(A), steady-state equilibrium conditions are reached prior to each new increase in withdrawal rate. Figure B2.2-1(B) shows the same sequence of events under conditions of continuously increasing ground-water development over several years. This diagram also shows that if pumping rates are allowed to increase indefinitely, an unstable situation may arise where the declining water table reaches a depth below which the *maximum* rate of ground-water recharge R can no longer be sustained. After this point in time the same annual precipitation rate no longer provides the same percentage of infiltration to the water table. Evapotranspiration during soil-moisture-redistribution periods (following the end of rainfall events) now takes more of the infiltrated rainfall before it has a chance to percolate down to the ground-water zone. At t_4 in fig. B2.2-1(B), the water table reaches a depth below which no stable recharge can be maintained. At t_5, the maximum available rate of *induced* recharge is attained. From time t_5 on, it is impossible for the basin to supply increased rates of withdrawal. The only source lies in an increased rate of change of storage that manifests itself in rapidly declining water tables. Pumping rates can no longer be maintained at their original levels. Freeze (1971) defines the value of Q at which instability occurs as the *maximum stable basin yield*. To develop a basin to its limit of stability would, of course, be foolhardy. One dry year might cause an irrecoverable water-table drop. Production rates must allow for a factor of safety and must therefore be somewhat less than the maximum stable basin yield.

The discussion above emphasizes the important interrelationships between ground-water flow and surface runoff. If a ground-water basin were developed to its maximum yield, the potential yields of surface-water components of the hydrologic cycle in the basin would be reduced. It is now widely recognized that optimal development of the water resources of a watershed depends on the conjunctive use of surface water and ground water. Young and Bredehoeft (1972) and Bredehoeft and Young (1983) describe the application of digital computer simulations to the solution of management problems involving conjunctive ground-water and surface-water systems.

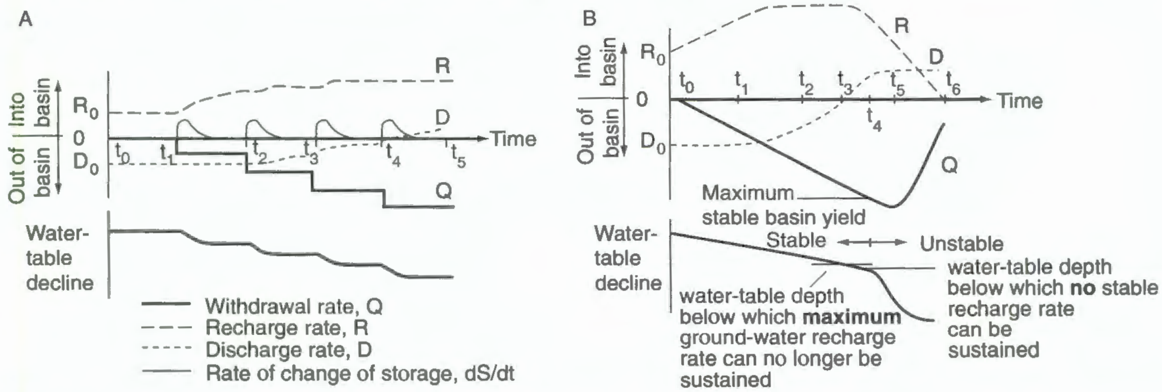


FIGURE B2.2-1—SCHEMATIC DIAGRAM OF TRANSIENT RELATIONSHIPS BETWEEN RECHARGE RATES, DISCHARGE RATES, AND WITHDRAWAL RATES (after Freeze, 1971).

Sustainable Development

A simplified procedure for estimating the sustained yield of an aquifer based on the unicell lumped-parameter model was summarized by Mandel and Shiftan (1981) in the following six steps:

1) Determine average annual replenishment.
2) Identify the most stringent constraint, i.e, the first unacceptable effect that will occur when water levels are lowered.
3) Find the quantitative relation between water-level elevations and the occurrence of this unacceptable effect. In many cases, it is possible to confine attention to certain key locations that are especially sensitive to water-level changes.
4) Define minimal water levels for the whole aquifer or for the above-mentioned key positions.
5) Compute the rate of natural outflow that will occur when a quasi-steady state of flow commensurate with minimal water levels is established.
6) The sustained yield is the difference between (1) and (5).

An example of this procedure is presented in the Appendix of this chapter.

For a *distributed system*, representing areal variation in processes and parameters, a suitable hydrologic basis for a ground-water planning policy aimed at determining the magnitude of possible development would be a curve as in fig. 2.6A, coupled with a projected pattern of drawdown for the system under consideration (Balleau, 1988). The level of ground-water development is calculated using specified withdrawal rates, well-field locations, drawdown limits, and

Boxed section 2.3: Example calculations for determining aquifer safe yield based on a distributed model (MODFLOW) (based on Balleau and Mayer, 1988).

Lohman (1972) discussed safe yield and the sources of water derived from well fields using a series of five example aquifer types. He discussed in conceptual terms the setting, sources of water, operation of the systems in terms of mass-balance, and the limitations on each. His conceptual model is extended below to illustrate quantitatively the rate of change of water sources in the types of systems that he discussed. The three-dimensional aquifer model program MODFLOW of McDonald and Harbaugh (1988) is used to calculate the drawdown and depletion rates for five example flow systems following Lohman's description. Four of the aquifers are presented here:

1. Valley of large perennial stream in humid regions.
2. Valley of ephemeral stream in semi-arid region.
3. Southern High Plains.
4. Artesian basin.

Lohman's figures of the above four aquifer types are reproduced as parts (A) in figs. B2.3-1 through B2.3-4 for illustration of the geometry of each aquifer system. Additional input required for the three-dimensional simulations, particularly withdrawal rates and anisotropy, is illustrated in parts (B) of figs. B2.3-1 through B2.3-4. In each case a well field was specified in the model to produce at practical rates from each system. Withdrawal was simulated at a constant rate except at the Southern High Plains example where a constant drawdown with declining yield was simulated. The sources of water to each system also are outlined. Generally, the surface sources were simulated as an amount available to be captured from perennial streams, springs, or from reduction of evapotranspiration. The example aquifers do not represent any specific field conditions, but are intended to demonstrate the general behavior of a variety of generalized ground-water systems under development.

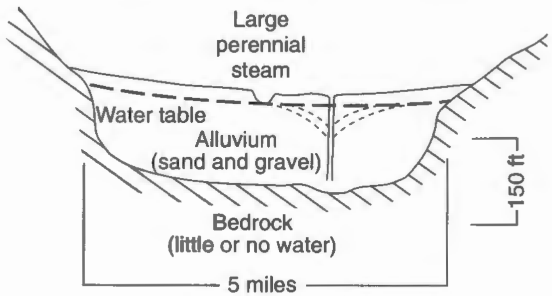
Calculated curves displaying the transition from full reliance on aquifer storage to full reliance on induced recharge of surface waters are given in parts (C) of figs. B2.3-1 through B2.3-4. The shape of the curves is generally reminiscent of that on fig. 2.6 for a two-dimensional radial-flow system. The curves show the importance of selecting a suitable planning horizon when evaluating the effect of a ground-water withdrawal. As seen on table B2.3-1, the phase during which more than 98% of the withdrawals are derived from aquifer storage ranges from 9 hours to 33 years after initiation of withdrawals in these four examples. The 98% induced recharge phase ranges from 4 to 9,400 years. The results suggest that a ground-water policy based either on equilibrium conditions or on a mining strategy should be thoroughly examined for its physical and economic effects through the years. *Both arid and humid regions may require this type of information before the effects of a water plan are fully understood.*

TABLE B2.3-1—DURATION OF SOURCES OF WATER FROM STORAGE AND FROM INDUCED RECHARGE IN FOUR EXAMPLE AQUIFER SYSTEMS.

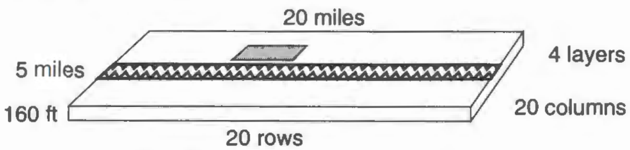
Aquifer System	Duration of Storage Phase[a]	Time of Induced Recharge Phase
Large Perennial Stream	9 hours	4 years
Ephemeral Stream	310 days	375 years
Southern High Plains	33 years	2,900 years
Artesian Basin	1 year	9,400 years

[a] The storage phase is defined as the period when >98% of withdrawals are derived from aquifer storage. The induced recharge phase is the period when <2% of withdrawals are derived from aquifer storage.

A) Development of ground water from valley of large perennial stream in humid region



B) Large perennial stream aquifer model



AQUIFER PROPERTIES:	WITHDRAWAL:	SOURCES OF WATER:
K = 200 feet/day Anisotropy = 0.005 S_y= 0.10 S_s= 0.0000025 Layers = 40 feet x 4	Net from 6 model cells in layer 3 produce 18 cfs (13,000 AF/yr)	1. Aquifer storage; Max drawdown 9.25 ft at 10 years. 2.Perennial stream, 0.25 mile wide throughout a 20-mile reach (1,170,000 AF available).

Surface-water source — Well field

C) Large perennial stream-aquifer system transition from reliance on aquifer storage to surface-water depletion

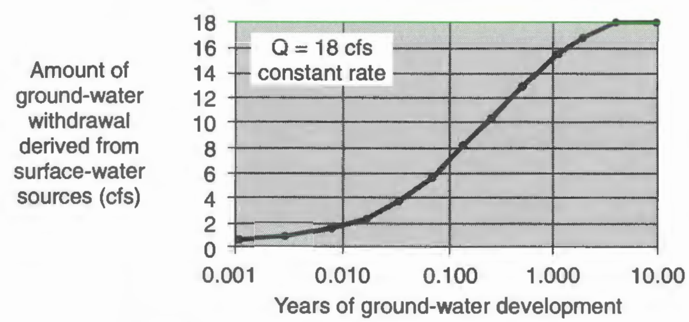
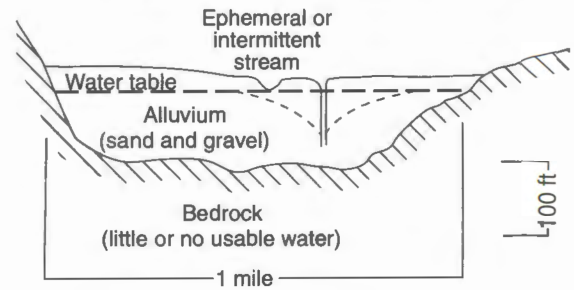
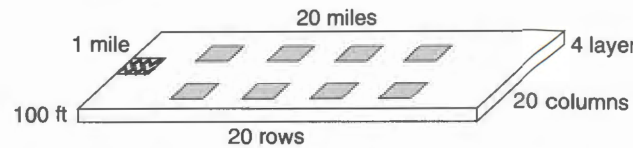


FIGURE B2.3-1

A) Development of ground water from valley of ephemeral stream in semiarid region



B) Ephemeral stream aquifer model



AQUIFER PROPERTIES:	WITHDRAWAL:	SOURCES OF WATER:
K = 200 feet/day Anisotropy = 0.01 S_y= 0.10 S_s= 0.000002 Layers = 25 feet x 4	Net from 8 model cells in layer 3 produce 3.52 cfs (2548 AF/yr)	1. Aquifer storage; Max drawdown 87 ft at 1000 years. 2. Ephemeral stream with a 1-mile reach (26,500 AF available).

Surface-water source — Well field

C) Ephemeral stream aquifer system transition from reliance on aquifer storage to surface-water depletion

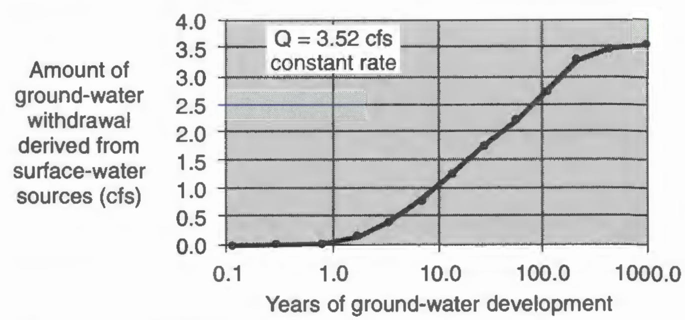
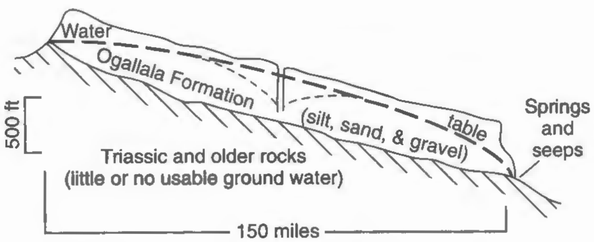
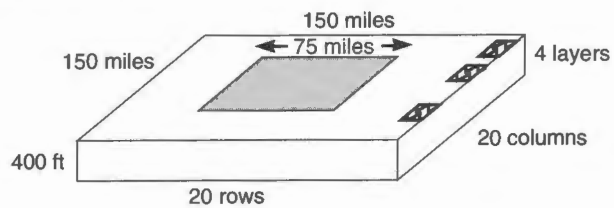


FIGURE B2.3-2

A) Development of ground water from southern High Plains of Texas and New Mexico



B) Southern High Plains aquifer model



AQUIFER PROPERTIES:

K = 40 feet/day
Anisotropy = 0.01
S_y= 0.10
S_s= 0.000002
Layers = 100 feet x 4

WITHDRAWAL:

Constant drawdown of 300 ft in 75 sq. mi. area. Yield decreasing from layer 3 from 810 cfs at 100 years to 86.8 cfs at 10,000 years.

SOURCES OF WATER:

1. Aquifer storage; max drawdown 300 ft at 1000 years.

2. Springs in discharge area (68,780 AF available).

Surface water source — Well field

C) Southern High Plains aquifer system transition from reliance on aquifer storage to surface-water depletion

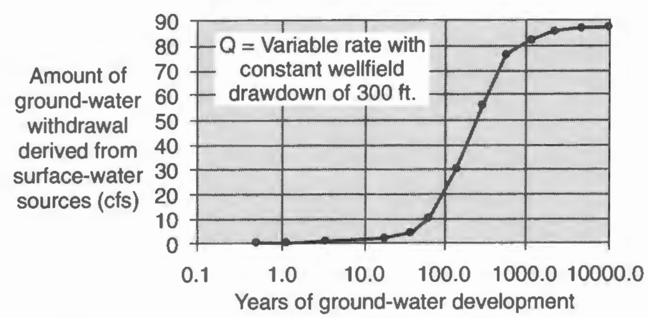
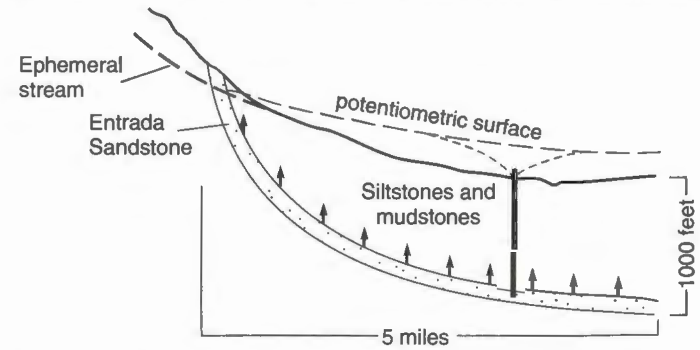
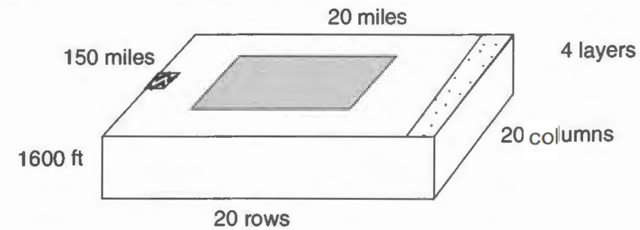


FIGURE B2.3-3

A) Development of ground water from the Grand Junction artesian basin, Colorado



B) Artesian basin aquifer model



AQUIFER PROPERTIES:

K = 40 feet/day
Anisotropy = 0.01
S_y= 0.10
S_s= 0.000001
0.00000033
0.000001
Layers = 4 - 50 feet
900 feet
150 feet
500 feet

WITHDRAWAL:

Net from 30 model cells in layer 3 to produce 0.30 cfs (217 AF/yr).

Well field
Surface water source
Evapotranspiration

SOURCES OF WATER:

1. Aquifer storage; Max drawdown 9 ft at 10,000 years.

2. Evapotranspiration of 1.0 cfs in a diffuse area of 20 sq. mi (724 AF/yr).

C) Artesian basin aquifer system transition from reliance on aquifer storage to surface-water depletion

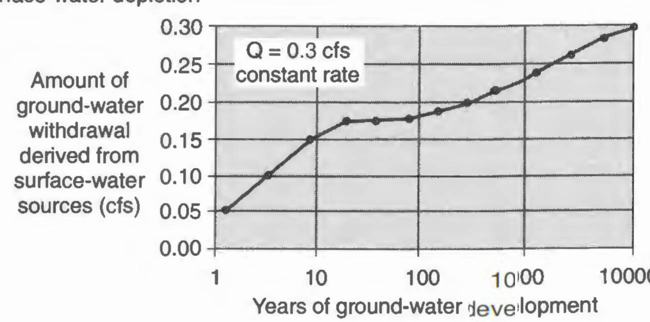


FIGURE B2.3-4 (Adapted from Balleau and Mayer, 1988; and Lohman, 1972.)

a defined planning horizon. Ground-water models such as those in table 2.1 are capable of generating the transition curve for any case by simulating the management or policy alternatives in these terms. A specified withdrawal rate, well distribution, and drawdown of water levels to an economic or physical limit are used in the model to project the sources of water from ground-water storage and from surface-water depletion throughout the area of response. The area of response is not known in advance of such a projection. A planning-horizon must be defined to assess which phase of the transition curve will apply during the period of the plan. The withdrawal rate selected in this way relies first on aquifer storage and secondly on the potential for induced recharge. The plan can contain explicit physical and economic limits on drawdown and induced recharge rates, but the analysis is unrelated to the initial natural recharge.

The ultimate limit on ground-water withdrawal is equal to the yield of the induced-recharge phase, but this limitation is of little interest if it applies only after several thousand years. Induced recharge, of course, implies the reduction of supplies for existing uses of the captured surface water. Such concerns may lead policy-makers to avoid major ground-water development. Example calculations of the effects of well-field development on a variety of aquifer systems is presented in boxed section 2.3 on p. 76–77.

Examples of Various Stages of Development from the High Plains Aquifer

The Southern Ogallala and the Kansas Great Bend Prairie Aquifers

The High Plains aquifer spans parts of eight states from Texas to South Dakota (fig. 2.12). In Kansas, the High Plains aquifer consists of the Ogallala (western Kansas), the Great Bend Prairie, and the Equus Beds aquifers (south-central Kansas). Pumpage from the High Plains aquifer, principally for irrigation, has increased steadily since the early 1930's. According to Gutentag et al. (1984), by 1978, pumpage from about 170,000 wells reached approximately 28 billion cubic meters (23×10^6 acre-ft), making the High Plains aquifer the most heavily pumped ground-water system in the United States. In their overview of ground-water problems in the High Plains, Kromm and White (1992) stated the following pertinent observations:

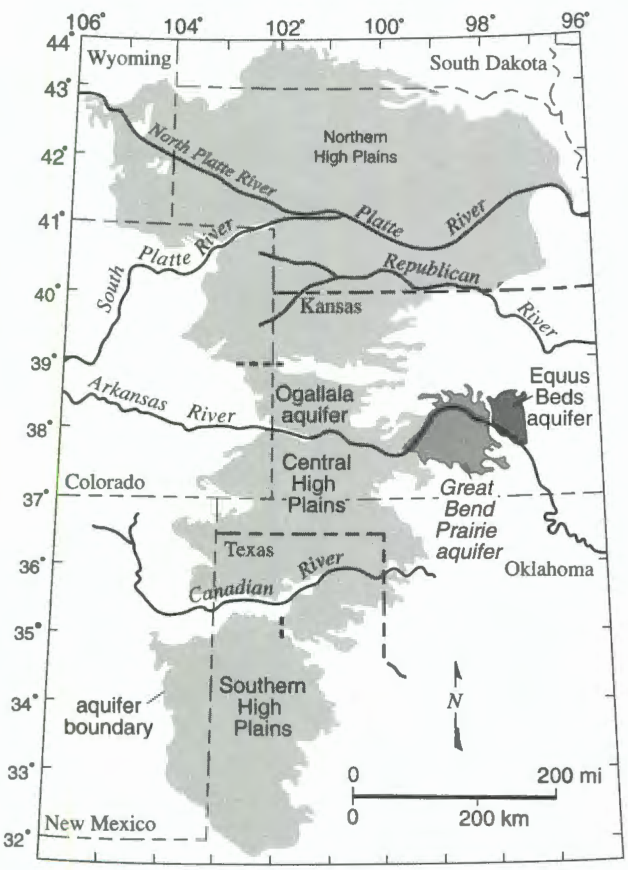


FIGURE 2.12—THE HIGH PLAINS AQUIFER AND ITS KANSAS COMPONENTS.

> Ironically, while our nation's farmers are confronting agricultural surpluses, low crop prices, reduced land values, and foreclosures, we are systematically mining a virtually nonrenewable resource to produce more in a time of plenty. At the national scale it might seem prudent to conserve High Plains ground water for future generations, but at the individual or local level, irrigated agriculture is often perceived as necessary for survival. In many cases, farmers may decide to irrigate not only to protect themselves from drought and to increase yields but also because their neighbors are pumping from an aquifer with a relatively short life expectancy. They may have to decide whether to take advantage of the availability of water now or perhaps forego the opportunity to irrigate forever since the declining aquifer makes the water more costly each year. Likewise, the decision to revert to dryland farming often has little to do with the perceived need to conserve water but instead results from the economic reality that continued irrigation is simply less cost-effective.

In the southern High Plains (i.e. the Ogallala aquifer of Texas and New Mexico), pumpage from the aquifer far exceeds the natural recharge rate, and this has caused a large decline of the water table. Maximum declines (more than 60 m or 200 ft) have occurred in Texas. A large area where declines exceed 15 m (50 ft) exists in eastern New Mexico, the western panhandle of Texas, and western Kansas. Figure 2.13 shows ground-water budgets for the High Plains aquifer for predevelopment, and 1960–1980 conditions. Note that pumpage currently exceeds natural recharge by more than 30 times, and that depletion of ground-water storage occurs at a rate about 14 times greater than the rate of natural recharge. The principal effect of these declines has been a permanent (long-term) dewatering of the aquifer that amounts to about 5% of the drainable water stored in the aquifer prior to development (Gutentag et al., 1984). The volume of aquifer dewatered has been greatest in Texas and Kansas. An economic side effect of the declining water table has been decreased well yields and greater pumping lifts.

The nature of ground-water-flow systems can be dramatically altered by large-scale development. As we mentioned before, large-scale pumping from wells and accompanying changes in hydraulic gradients can cause increases in recharge rates and decreases in discharge to streams. Note that recharge to the High Plains aquifer system has increased twenty-fold since predevelopment (fig. 2.13), according to Luckey et al. (1986). Most aquifer discharge is now from pumping wells rather than by natural discharge as streamflow or evapotranspiration. However, in the semiarid west, low precipitation and very low recharge rates cause flow through aquifers to be very small under natural conditions. Under large-scale ground-water development, pumping rates are commonly far in excess of the predevelopment recharge rates, and opportunities for diverting ground-water discharge (mostly ET) are limited. Much of the withdrawal from the High Plains is used for irrigation, and irrigation return flow is the dominant aquifer-recharge mechanism. Thus, ground-water circulation is significantly increased (Johnston, 1989). As a result of the significant ground-water development and consequent regional ground-water-level declines, a number of streams changed from perennial to intermittent throughout the southern and central High Plains. An example of such impact on streams from the Kansas High Plains will be shown in the concluding section of this chapter (fig. 2.15).

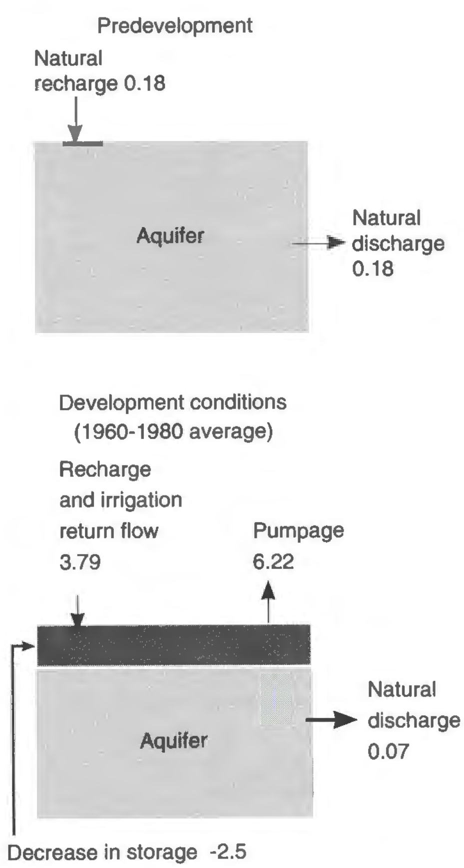


FIGURE 2.13—COMPARISON OF PREDEVELOPMENT AND PRESENT-DAY GROUND-WATER BUDGET FOR THE SOUTHERN PORTION OF THE HIGH PLAINS AQUIFER. (All values in billion gallons per day.) Adapted from Johnston (1989).

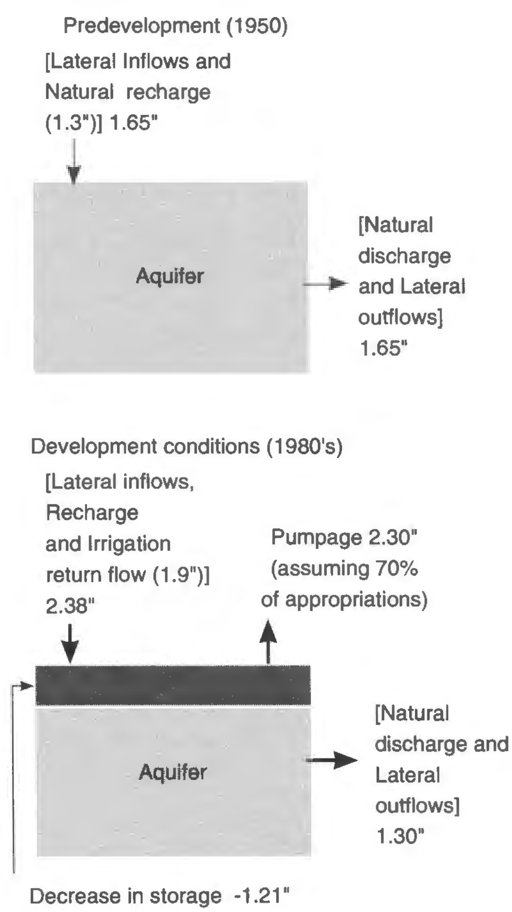


FIGURE 2.14—COMPARISON OF PREDEVELOPMENT AND PRESENT-DAY GROUND-WATER BUDGETS OF THE LOWER RATTLESNAKE CREEK BASIN PORTION OF THE GREAT BEND PRAIRIE AQUIFER. (Values are in inches per year.) Derived from Sophocleous and Perkins (1993).

Boxed section 2.4: Equus Beds aquifer and the City of Wichita: A case study of integrated resource planning from Kansas (based on Warren et al., 1995).

Water resources are often subject to competing uses as well as competing policy goals. Perceptions of scarcity and rising costs and prices intensify conflicts about water resources. Integrated resource planning (IRP) provides a means of addressing competing, conflicting, or segregated goals. No single planning solution will resolve all these issues at once, but in a world of increasingly scarce resources, coordinating institutional responses and trying to address multiple goals simultaneously makes better sense than continuing the discounted processes that exist today (Beecher, 1995).

Since the 1980's, the city of Wichita, Kansas, has known that its current water resources are inadequate to meet water needs beyond 2010 (Warren et al., 1995). To accommodate its future water requirements, the city explored the possibility of importing water from an existing reservoir more than 160 km (100 mi) away. However, high front-end development costs and significant social, environmental, and political opposition to use of the distant water resource caused the city to reevaluate locally available water resources.

In 1992, the city commissioned an engineering study of area water sources. The study, based on integrated resource-planning (IRP) principles, evolved into Wichita's current plan for water-resource planning and development. Developed with numerous State and local agencies and citizen inputs, this holistic plan has proved environmentally, socially, and economically acceptable to the community.

Key elements of Wichita's plan (Warren et al., 1995) include:

- water conservation to help control customer demand and water use;
- evaluation of existing surface-water and ground-water sources to determine their capacity and condition, methods of enhancing their productivity, and ways to protect their quality;
- evaluation of nonconventional water resources for meeting future water needs;
- optimization of all available water resources to enhance water supply;
- pursuit of application for conjunctive water resource use permit with State agencies;
- evaluation of the effects of using different water sources on water supply, delivery, and treatment facilities with consideration of risk and reliability; and
- communication with key stakeholders including regulatory agencies, other water users, and the public.

The city's existing water-supply system consists of two principal water-supply sources (fig. B2.4-1)—the Equus Beds aquifer well field 26 km (16 mi) northwest of the city, and Cheney Reservoir 32 km (20 mi) west of the city. The E & S well field near the city's water plant in north-central Wichita is also used to meet short-term peak water needs. Raw water is pumped from these sources through pipelines to the water plant at the confluence of the Little Arkansas River and the Arkansas River.

Although two major rivers run through Wichita, these have historically not been used because intermittent flows preclude the availability of a reliable supply and there were no suitable dam sites in the area watersheds. The Arkansas River drainage also has undesirable high levels of total dissolved solids with high chlorides, which is a primary concern in both the surface water and alluvial ground water.

Wichita historically has used ground water on a first-priority basis because of its excellent quality; 60% of the raw water originates from the Equus Beds well field. Most of the remaining 40% is surface water from Cheney Reservoir. Raw water from the E & S well field is blended with higher-quality ground water and intermittently used to help meet maximum-day water demands in the summer.

The Equus Beds aquifer is located within Groundwater Management District 2 (GMD2). The average annual withdrawal from the aquifer is 194 million cubic meters (157,000 acre-ft) with 55% by irrigators, 39% by Wichita and other municipalities, and 6% by industry. The city's current water rights include an annual use of 49 million cubic meters (39,934 acre-ft). Since the 1950's, water levels in the Equus Beds aquifer have dropped 6-12 m (20–40 ft) because of ground-water pumping in excess of natural aquifer recharge rates. In 1975, GMD2 was formed to manage the aquifer by limiting ground-water withdrawals to annual recharge from precipitation (estimated at 81-152 mm/year—3.2-6 in/year) and to protect the water quality in the aquifer. Because of the lower ground-water levels, natural saltwater from the Arkansas River is migrating inward from the south, and brine waste from old oil-field development is migrating inward from the north (fig. B2.4-1). Preliminary computer modeling indicates that chloride concentrations will increase from a current average of 55 mg/L to a range of 120–300 mg/L by 2050, which could affect ground-water uses for irrigation and municipal water supply.

Proposed operating changes at Cheney Reservoir include greater pumpage from the reservoir's surcharge and flood pools during wet weather. This will allow a corresponding reduction in pumpage from the Equus Beds and will conserve water stored in the aquifer for use during extended dry weather. The city will use more water in the reservoir's conservation pool to meet demand during dry weather and droughts.

Although the Equus Beds have been a major source of water for Wichita for 50 years, little effort was made to optimize facilities in the well field. When the well field was evaluated in 1991, it was discovered that only a few of the 55 wells were operating near original capacity and that old pumps were unable to deliver adequate flow to meet peak water demands. As a result, rehabilitation of the well field was implemented with projects to chemically treat the wells and to replace old pumps and motors with new more efficient ones. Other measures to protect the aquifer from overuse include:

Required metering. Over the years, the aquifer has been over-allocated; ground-water use exceeds recharge from rainfall infiltration. Metering would assure compliance with water rights and provide water-use records for aquifer management.

Perfected ground-water rights for all well users. Water-rights perfection (i.e. developing the water rights by actually using water as authorized by the permits) would establish well users' actual use rate (which is typically less than the water right) and fix the rate for future use.

Purchasing ground-water rights from agricultural landowners. The city has been buying these rights for the approximate price difference between irrigated land and unirrigated land. Because the aquifer is over-allocated, these purchased water rights will be retired by the city to help protect the aquifer from over-pumping.

Because the region's existing and potential water sources are approaching full use, Wichita considered conventional and nonconventional water supplies to meet projected demands. A primary nonconventional plan component includes capturing excess-flow river water and river bank storage water from the Little Arkansas River on an as-available basis. This water will be recharged and stored in the Equus Beds aquifer. Excess water is captured during wet periods, stored, and used during extended dry periods. During droughts, when supplies from the river and reservoir are restricted, additional wells will deliver water to the treatment plant. The plan's ability to meet water demands for 2050 was determined by a computer simulation to model the plan's predicted water-supply capabilities. Model results indicate the Equus Beds aquifer can be filled to near pre-1950's ground-water levels in about 16 years. Computer runs also show the plan will sustain water supply to furnish the projected water demands for 2050.

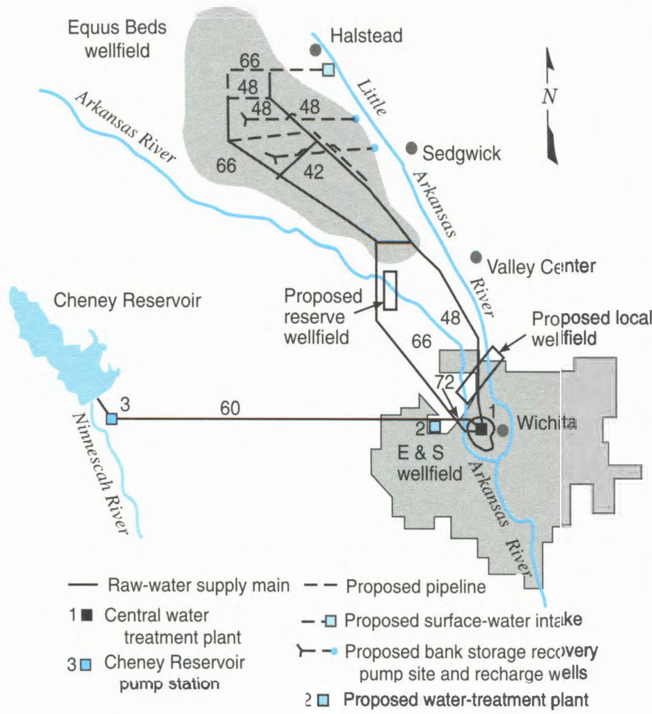


FIGURE B 2.4-1—EXISTING RAW-WATER SUPPLY SCHEMATIC WITH PROPOSED INTEGRATED RESOURCE PLANNING (IRP) FACILITIES. Two-digit numerals are inches. Adapted from Warren et al. (1995).

In contrast to the southern and most of the central High Plains aquifer, certain portions of the central High Plains, such as the Equus Beds and Great Bend Prairie aquifers of Kansas (fig. 2.12), are still considered to be in a state of quasi-equilibrium. The Rattlesnake Creek watershed covers a major portion of the Great Bend Prairie (GBP) aquifer. The hydrologic budgets for both predevelopment and developed conditions of the lower Rattlesnake Creek watershed and associated GBP aquifer (Sophocleous and Perkins, 1993) indicate appreciable differences in the hydrologic components resulting from development (fig. 2.14). For example, the predevelopment natural ground-water recharge across the model area was estimated as 33 mm/yr (1.3 in/yr), whereas the induced recharge under development conditions was estimated as 48 mm/yr (1.9 in/yr). The overall pumpage (assuming an actual pumpage equal to 70% of the appropriated amount) is in approximate equilibrium with the induced recharge. However, because this pumpage is in excess of the sustainable rate of this aquifer (it is appreciably greater than the rate of natural recharge), the aquifer storage is slowly being depleted at a rate approximately equal to that of natural recharge, and streamflows in area streams have been steadily declining since the mid-1970's (Sophocleous and Perkins, 1993; Sophocleous and McAllister, 1987). An example of sustainable development planning for the Equus Beds aquifer of Kansas (fig. 2.12) is presented in Boxed section 2.4 opposite and above (see also Chapter 3).

Conclusions and Recommendations

Considerable dissatisfaction with the term "safe yield" has been expressed. Any change in conditions, such as changes in land use, economics, or importation of new water supplies, would require calculation of a new yield. The safe yield of an aquifer, in some instances, can be substantially augmented by engineering controls. Clearly, *no unique and constant value can be attached to safe yield.* In addition, the definitions of the safe yield of an aquifer often fail to address the impacts of ground-water exploitation on related surface water and on areas outside the area of development. An expanded view of sustainable yield is considered in chapter 3.

There is no valid generic rule, such as pumping the natural recharge, that will lead to a desirable economic or stable (non-depleting) level of ground-water development. Subject to local permeability and storage conditions, such a rule can cause either greatly excessive and increasing drawdown or costly constraints on resource usage regardless of the rate of natural recharge (Balleau, 1988). The level of ground-water development should be calculated using specified withdrawal rates, well-field locations, drawdown limits, and a defined planning horizon. Ground-water models are capable of generating the transition curve for any case by simulating the management or policy alternatives in these terms.

Ground-water management cannot be conceived of separately from management of surface waters. Because of the interdependence of surface water and ground water, operations on any part of the system have consequences for the other parts. The impact of ground-water development on streams is highly variable. The effects on some streams are insignificant, while other stream reaches have changed from perennial to intermittent flow because the regional water table has declined below the stream-bed elevation. *This actually happened in Kansas,* as can be seen in fig. 2.15 (Angelo, 1994). Some ground-water systems, however, are relatively isolated from surface-water bodies and therefore have a low potential for inducing recharge. Nevertheless, as previously shown (tables 2.1 and 2.2), essentially all ground-water withdrawal can deplete surface water to some degree in the long term. The management category of minable water may be a reasonable one to apply to well field areas that would not progress beyond the earliest stages of the transition curve in fig. 2.6A within a reasonable planning horizon. Thus, wise management of water resources needs

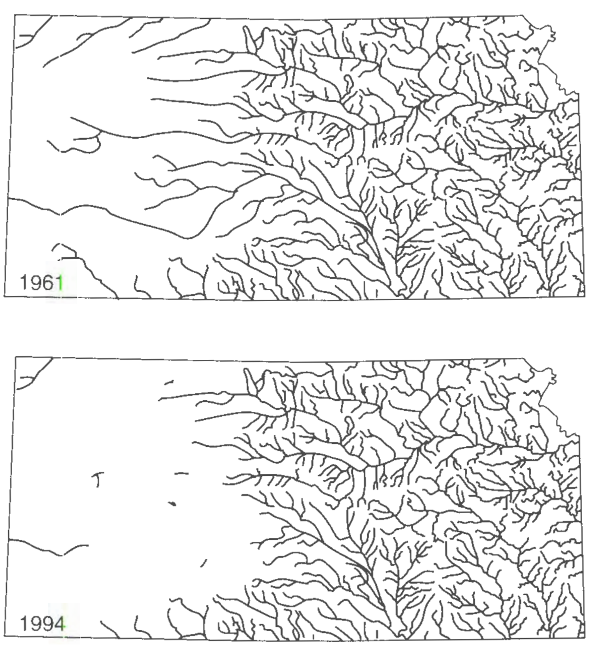


FIGURE 2.15—Major perennial streams in Kansas, 1961 versus 1994. Top illustration is adapted from U.S. Geological Survey 1:500,000-scale base map compiled in 1961. Bottom illustration summarizes streamflow observations made by the Kansas Department of Health and Environment from October 1989 through January 1994. Adapted from Angelo (1994).

to be approached both from the viewpoint of focusing on the volume of water resources available for sustainable use, and from the impact of ground-water exploitation on the natural environment, including ground water, surface water, and riparian ecosystems.

Initially, the effect which wells had on surface water was simply not known, and even now there is not enough information available to allow a complete and efficient administration of conjunctive use. Those who first endeavored to establish a law for ground-water administration were required to do so without the benefit of much scientific knowledge on the subject of hydrology. Accordingly, legal terminology developed that did not really describe the true physical situation (Radosevitch and Sutton, 1972). The result was the establishment of a legal model before the physical model had developed. Eventually, however, the science of hydrology developed to the point of demonstrating the interconnection of surface and associated ground-water. Although the ideas of conjunctive use of surface water and ground water, and the concept of sustainable yield have been around for many years, *a quantitative methodology for the estimation of such yield has not yet been streamlined.* Recently developed sophisticated hydrologic models can project the sources of water from ground-water storage and from surface water throughout the area of response based on specific withdrawal rates, well distribution, and drawdown of water levels to an economic or physical limit. However, integrated methods of regional water resource assessment are still needed. Our understanding of the basic principles of soil and water systems and processes is fairly good, but our ability to apply this knowledge to solve problems in complex local and cultural settings is relatively weak.

The need to manage ground-water resources as an integral part of overall available water resources and in recognition of their place in the equilibrium of the natural environment is better understood today by scientific experts and water-resource managers. *Integrated resource planning* has recently emerged as a tool for total water management "assuring that water resources are managed for the greatest good of people and the environment and that all segments of society have a voice in the process" (AWWA, 1994). The concept of *enlightened management* (Margat, 1994), involving the integrated management of ground water and surface water, which in the past has eluded those directly or indirectly involved in the day-to-day management operations of ground water, is now taking hold in Kansas and other states. Examples in Kansas include the management programs of the City of Wichita and Groundwater Management Districts 2 and 5 (Equus Beds and Great Bend Prairie, respectively) attempting to integrate surface and ground water (outlined in chapter 3), as well as the Division of Water Resources Subbasin Water Resources Management Program, and a number of recently promulgated regulations by the Chief Engineer of Kansas.

The weakest link in the research process is the dissemination of research findings to the farm or regional levels, accounting for the complex physical and human diversity that occurs. Greater effort is needed to develop better ways to communicate results. *A strong public education program is needed* to improve understanding of the nature of ground-water resources and of their complexity and diversity and to emphasize how this understanding must form the basis for operating conditions and constraints. This is the only way to positively influence, for the long term, the attitudes of the different stakeholders involved.

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Appendix A—Estimating the sustained yield of a coastal aquifer based on the unicell lumped- parameter model (based on Mandel and Shiftan, 1981).

The coastal aquifer shown in fig. A2.16 will serve as an example for the six-step procedure of Mandel and Shiftan (1981) outlined in the section on sustainable development.

1) Average annual replenishment may be estimated by any of the available methods.
2) Seawater intrusion into the aquifer may contaminate exploited wells and, therefore, is the most stringent constraint.
3) The laws governing seawater intrusion are well known (Bear, 1979) and are usually based on a sharply defined freshwater-seawater interface and the Ghyben–Herzberg rule, which is based on the hydrostatic equilibrium of two immiscible liquids:

$$z = h(\gamma_f/(\gamma_s - \gamma_f)) = h\alpha, \qquad \text{(eq. A-2.1)}$$

where h is the elevation of the water level above sea level, γ_f and γ_s are the specific weights of freshwater and seawater, respectively, and z is the depth of the interface below sea level. The density contrast, α, between fresh ground water and ocean water equals approximately 40.

The *toe of the interface* is situated at the point where z equals the depth D of the relatively impermeable aquifer base (fig. A2.16). At the landward side of the toe, the aquifer contains only freshwater. The following relations can be deduced for a strip of unit width, say, 1 km, represented by fig. A2.16 (Bear, 1979).

$$L = D\sqrt{K/(\alpha R)}, \qquad \text{(eq. A-2.2)}$$

$$Q_L = (KD^2/(2\alpha L)) - (RL/2), \qquad \text{(eq. A-2.3)}$$

$$Q_0 = (KD^2/(2\alpha L)) + (RL/2), \text{ and} \qquad \text{(eq. A-2.4)}$$

$$L_{opt} = \sqrt{KD^2/(\alpha R)}, \qquad \text{(eq. A-2.5)}$$

where K is the hydraulic conductivity, D the depth of the aquifer base below sea level, L the distance of the toe from the seashore, R replenishment on unit length of the strip, Q_L and Q_O are inflow of ground water from the landward side and outflow into the ocean, respectively, and L_{opt} is the distance that minimizes Q_O.

4) Intensive ground-water abstraction on a sustained basis is possible only at the landward side of the toe of the interface. In order to stabilize the toe at some predetermined position, it is necessary to maintain the water level in this key location at a minimal elevation. This minimal elevation is easily computed by eq. A-2.1 if the depth of the aquifer base is known.
5) Outflow into the ocean is a function of the distance of the toe from the shore (eq. A-2.4). From a hydrological point of view, the optimal distance is the one that minimizes outflow into the ocean (eq. A-2.5). Water-supply engineers and administrators will, however, prefer to keep the extent of seawater intrusion as small as possible. The final position of the toe has to be decided on the basis of hydrologic, administrative, and engineering criteria.
6) The sustained yield is the difference between natural replenishment and the outflow that occurs when the toe is stabilized at the selected final position (eq. A-2.4). Alternatively, one may compute the steady-state flow above the final position of the toe (eq. A-2.3), and subtract it from the estimated steady-state flow in the undisturbed aquifer at this location.

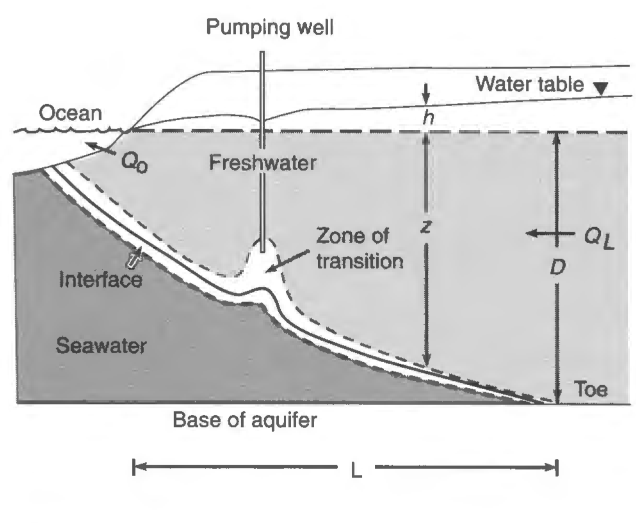

FIGURE A2.16—FRESHWATER LENS IN A COASTAL AQUIFER. Adapted from Mandel and Shiftan (1981).

CHAPTER 3

Evolving Sustainability Concepts: Modern Developments and the Kansas Experience

Marios Sophocleous, R. W. Buddemeier, and R. C. Buchanan

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Introduction

The purpose of this chapter is to put the concept of sustainable water yield, expanded on in chapter 2, into the broader concept of environmental/ecological sustainability, and briefly outline our still-evolving ideas on environmental sustainability. Our view of nature and the role of human intervention in it has changed during the last two decades. The role of water-resource-management institutions is changing from development to management. From the turn of the century through the 1960's, large-scale multipurpose water-resources projects were considered essential to the economic well-being of nations; water management meant planning and operating these projects to maximize four primary uses—irrigation, hydropower generation, municipal and industrial supply, and flood control. Recreation was a late and secondary add-on. This assumption eroded as environmental awareness grew and environmental concerns mounted (Feldman, 1991), in addition to the realization that the old ways of piece-meal management demonstrably failed (see Boxed section 3.1). The most fundamental change is the idea that human uses of water resources and environmental protection and management should be given equal weight. The result is that we now rely less on permanent structural solutions and more on adaptive management of existing physical and semi-natural systems. The ultimate challenge for present and future resource managers is to integrate science, technology, and institutions into the new ethic of sustainability.

The World Commission on Environment and Development, known as the Bruntland Commission, defined sustainable development as a "process of change in which the use of resources, the direction of investments, the orientation of technological developments, and institutional change all enhance the potential to meet human needs both today and tomorrow" (WCED, 1987). Sustainable development is inherently intergenerational because it implies that we must use the environment in ways that are compatible with maintaining it for future generations. This intergenerational perspective constrains our management of the environment and its resources, including water.

Despite progress in defining the goals of sustainable development, the mechanisms to bring about these changes are still a matter of debate. The move from principle to practice is far from easy and poses a series of dilemmas for which there are no clear solutions. Although sustainable development is still an abstract concept, it is as powerful as many other abstract concepts such as liberty, equality, and justice. The concept is a dynamic one and will be continually refined. The ability to adapt to new knowledge (and resulting new ways of thinking about resources) is the hallmark of successful management, and it is a necessary condition for water management as we move from an era of rapid exploitation to one of sustainable use.

Environmental Sustainability: The Broader View

The paramount importance of sustainability arose partly because of the realization that present levels of per capita resource consumption of developed countries may not be possible for all currently living people, much less to future generations, without liquidating the natural capital on which future economic activity depends (Goodland et al., 1993). According to Postel (1996), as of 1995, the world as a whole was consuming directly or indirectly (through animal products) an average of just over 300 kilograms of grain per person a year (based on U.S. Department of Agriculture, Economic Research Service, 1991 figures). At this level of consumption, growing enough grain for the 90 million people now added to the planet each year (based on U.S. Bureau of Census projections, 1993) requires an additional 27 billion cubic meters of water annually—roughly 1.3 times the average annual flow of the Colorado River. Grain consumption per person varies widely by country, but assuming the global average remains the same as today, it will take an additional 780 billion cubic meters of water to meet the grain requirement of the projected world population in 2025—more than nine times the annual flow of the Nile River. Where this water is to come from on a sustainable basis is not obvious. Much of the crop production required to meet future food needs would seem to depend on an expansion of irrigation. However, serious constraints exist here as well. Falling water tables, depleted river flows, the lack of economical and environmentally sound sites for new supply projects,

Boxed section 3.1: Water-resource Sustainability — How Far, How Long?

The failures and unintended consequences of conventional water management and development strategies provide some of the strongest incentives for sustainable-resource management. Examples range from local to regional to global:

- Ground-water pumping has dried up or threatened numerous reaches of baseflow-dependent streams, wetlands, and subirrigated land—with many examples to be found in Kansas along the fringes of the High Plains aquifer (see also chapters 2 and 7).
- Increases in consumptive water use leave behind the salts dissolved in the water—irrigation has contaminated the land in many areas (for example, irrigation drainage water had contaminated the ponds at Kesterson National Wildlife Refuge in California with toxic levels of selenium), and the flow of saline water from irrigation return flow into the Upper Arkansas River basin now threatens the ground-water resources of the alluvial and Ogallala aquifers.
- Part of water's role in the natural cycle is the transport of sediment, which it does best during floods. As streamflows are reduced and controlled, the sediment loads gradually fill reservoirs, seal off stream channels from the alluvial aquifers—and starve the downstream deltas (see also chapter 6).
- Whole regional ecosystems change and disappear with large-scale water development—the Gulf of California has changed from an estuary to a marine lagoon as the Colorado River has been dried up, and nutrient runoff from the central United States has changed the ecology of the area surrounding the mouth of the Mississippi River.

and rapidly growing urban demands are all placing limits on the availability of water for agriculture.

Natural capital is basically our natural environment and is defined as the stock of environmentally provided assets (such as soil, atmosphere, forests, water, wetlands), which provide a flow of useful goods or services. *Environmental sustainability* refers to natural capital. It means maintaining environmental assets, or at least not depleting them. Operationally, this translates into encouraging the growth of natural capital by reducing our level of current exploitation; investing in projects to relieve pressure on natural capital stocks by expanding "cultivated natural capital," such as tree plantations, fish ponds, artificial recharge schemes for aquifers to relieve pressure on natural forests, fish populations, or ground-water resources, respectively; and increasing the end-use efficiency of products (improved light bulbs, appliances, cars, irrigation equipment, manure rather than chemical fertilizer, etc.).

An organism, an economy, or a project, all relate to their environment in basically the same way: they depend on the environment to supply useful inputs of raw materials and energy and to absorb less-useful outputs of waste materials and heat. Either the environmental "source" or the "sink" capacity can be diminished through overuse. Both must be limited for sustainability to succeed. The basic operational principles of sustainability can thus be summarized in the form of practical rules-of-thumb (table 3.1) to guide the design of economic development (Goodland et al., 1993). As a first approximation, the design of new projects should be compared with the input/output rules shown in table 3.1 in order to assess the extent to which a project is sustainable.

The global ecosystem is the source of all material inputs feeding the economic subsystem and is the sink for all its wastes. Population times per-capita resource consumption is the total flow—*throughput*—of resources from the global ecosystem to the economic subsystem, then back to the global ecosystem as waste, as depicted in fig. 3.1.

In general, sustainability can be achieved not through increasing the throughput growth (i.e. materials and energy) but by 'developing' toward that goal. When something "grows" it gets quantitatively bigger; when it "develops," it gets qualitatively better or at least different (Goodland et al., 1993). Quantitative growth and qualitative improvement follow different laws. Our planet changes over time without growing. According to Goodland et al. (1993), to achieve sustainability, the economy, a subsystem of the finite and nongrowing earth, must eventually adapt to a similar pattern of development without throughput growth. Some scholars, notably the ecologists Paul and Anne Ehrlich and the economist Herman Daly, believe that the scale of human pressure on natural systems already is well past a sustainable level. They point out that the world's human population likely will at least double before stabilizing, and that to achieve any semblance of a decent living standard for the majority of people, the current level of world economic activity must grow, perhaps fivefold to tenfold. They cannot conceive of already stressed ecological systems tolerating the intense flows of materials use and waste discharge that presumably would be required to accomplish this growth. However, others perceive that through science and technology, mankind can achieve high-quality living standards with growth.

Ascertaining more clearly where the facts lie in this debate and determining appropriate response strategies are difficult problems—perhaps among the most difficult faced by all who are concerned with human advance and sound natural-resource management (Toman, 1992). Progress on these fronts is hampered by continued disagreements about basic concepts and terms of reference. To narrow the gaps, it may be helpful first to identify salient elements of the sustainability concept about which there are contrasts in view between econo-

TABLE 3.1—RULES-OF-THUMB FOR ENVIRONMENTAL SUSTAINABILITY (modified from Goodland et al., 1993).

1. Output rule
Waste emissions from a project should be within the assimilative capacity of the local environment without unacceptable degradation of its future waste-absorptive capacity or other important services or health problems to communities. For example, sewage-discharge permits should be conditioned on both adequate (properly defined) streamflow for dilution, and on adequate spacing of discharge points for such dilution.

2. Input rule
a. *Renewables*: harvest rates of renewable-resource inputs should be within the regenerative capacity of the natural system that generates them but within a sufficiently short timespan to be of relevance to human beings. The sustainable yield policies of the local Groundwater Management Districts of central Kansas, where the Equus Beds and Great Bend Prairie aquifers are generally adequately replenished, constitute an example of such a rule (see details under the Kansas water-resources-management experience).
b. *Nonrenewables*: depletion rates of nonrenewable-resource inputs should be equal to the rate at which renewable substitutes are developed by human invention and investment. It is suggested (El Serafy, 1991) that part of the proceeds from liquidating nonrenewables should be allocated to research in pursuit of sustainable substitutes. The ground-water mining policies of the western Kansas Groundwater Management Districts, where the Ogallala aquifer replenishment rates are too miniscule to counterbalance the ground-water irrigation-based agricultural economy of the region, coupled with the western Kansas weather modification program and additional proposed water conservation measures, constitute an example of such a rule. The idea here is to extend the life of the aquifer, not sustain it.

mists and resource planners on the one hand, and ecologists and environmental ethicists on the other. Box 3.2 outlines key conceptual issues related to the definitions of sustainability (refer also to the glossary for additional definitions).

Ehrlich and Holdren (1974) encapsulate the sustainability concept as follows: The impact (I) of any population or nation upon environmental sources and sinks is a product of its population (P), its level of affluence (A), and the damage done by the particular technologies (T) that support that affluence,

$$I = P \cdot A \cdot T$$
$$[I = P \cdot Y/P \cdot I/Y]$$

where population (P) refers to human numbers; affluence (Y/P) is output (Y) per capita; and technology (I/Y) refers to environmental impact (or throughput intensity) per unit of output, i.e. a dollar's worth of solar heating stresses the environment less than a dollar's worth of heat from a coal-fired thermal-power plant. Environmental sustainability occurs when impact (I) or throughput, i.e. the maintenance flow of matter-energy, beginning with depletion and ending with pollution, is held below carrying capacity (CC). *Carrying capacity* is a measure of the amount of renewable resources in the environment in units of the number of organisms these resources can support. Carrying capacity is a function of the area and the organism, and it is indeed difficult to estimate, especially for humans, because of major differences in affluence and technology. The only three ways of addressing the need to keep $I<CC$ are: 1) limit population, 2) limit affluence, or 3) improve technology by reducing throughput intensity of production (Goodland et al., 1993). However, the $I = P \cdot A \cdot T$ identity is not sufficiently detailed to explain the feedbacks between population growth and environmental transformations. Moreover, $I = P \cdot A \cdot T$ limits the policy debate to only changing population, consumption levels, and technology, and leaves out the role of economic and political forces that determine who has access to and control over natural resources (Loh, 1995).

Meeting human needs while facing up to water's limits—economic, ecological, and political—entails developing a wholly new relationship to water (Postel, 1993). Historically, we have managed water with a frontier philosophy, manipulating natural systems to whatever degree engineering know-how would permit. Modern society has come to view water only as a resource

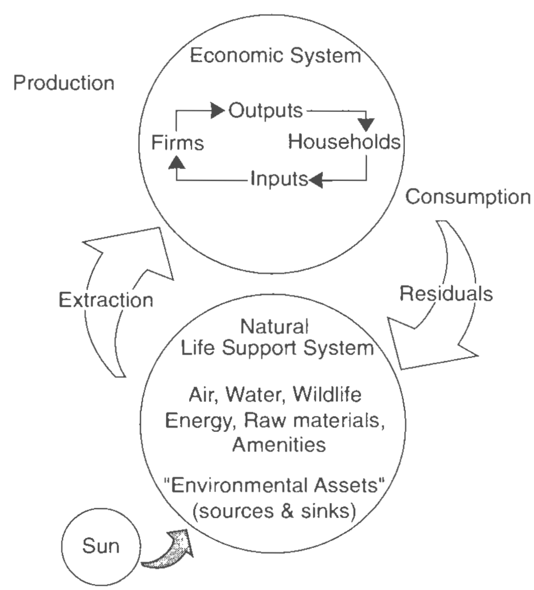

FIGURE 3.1—RELATIONSHIP BETWEEN THE ECONOMIC AND THE ENVIRONMENTAL SYSTEMS. Adapted from Goodland and Daly, 1995.

that is there for the taking, rather than a life-support system that underpins the natural world upon which we depend. The challenge now is to put as much human ingenuity into learning to live in balance with water as we have put into controlling and manipulating it. Conservation, efficiency, recycling, and reuse can generate a new supply large enough to get us through many of the shortages on the horizon, buying time to bring consumption down to sustainable levels.

Environmental Sustainability versus Sustained Yield

Whether environmental sustainability (ES) is 'sustained yield' (S–Y) in the form of water extraction from an aquifer, for example, is debatable. Clearly ES includes, but certainly is far from limited to, sustained yield. ES is more akin to the simultaneous S–Y of many interrelated entities in an ecosystem. ES counts all the natural services of the sustained resource. S–Y counts only the service of the product extracted and ignores all other natural services. Water S–Y counts only the quantity (and quality) of water extracted; ES of water resources counts all services. These include protecting both water quality and quantity, ground and surface waters, biological concerns, the land-water interface ecosystems, and the objectives of the user community. The relation between the two is that if S–Y is actually achieved, then the stock resource (e.g., the water) will be nearer sustainability than if S–Y is not achieved. The optimal solution for a single variable, such as S–Y, usually results in declining utility or declining natural capital sometime in the future, and therefore may not be sustainable. (See also Boxed section 3.2).

Expanding Sustainability Concepts: The Ecosystem Management Approach

Over the past 50 years, the concepts underlying management of water resources have gradually shifted from a deterministic world view based on *the balance of nature* to a recognition that *nature is characterized by chance and randomness*, that natural systems are inher-

Boxed section 3.2: On the Definitions of Sustainability.

Sustain (vt) 1. to give support or relief to 2. to supply with sustenance : NOURISH 3. KEEP UP, PROLONG ..... (Webster's Ninth New Collegiate Dictionary)

Straightforward definitions? Let's see how far they get us as we explore sustainability of resources—and resource uses.

Sustainability has come to be the watchword of those concerned with "intergenerational equity," the idea that succeeding generations should have access to a resource base comparable to our own. Sounds fair—but what is it that we want to be sustainable?

The problem of defining and maintaining sustainability is not just intergenerational, it is interstate and international as well. We may have an obligation to the future, but we know that the present climate and its hydrologic characteristics is not permanent (see chapter 8), so how faithfully and for how long do we try to preserve present conditions? A decade, a human lifetime, a thousand years? It seems utopian to expect sustainable to mean "forever" (Worster, 1993). Then what degree of sustainability should we settle on? And what are the rights and obligations involved in water use that affects people a thousand miles away and in a different country? They are certainly not defined or protected under the doctrines of western water law—and yet as the global interconnectedness of both economies and ecosystems becomes ever more obvious, they cannot be ignored.

"Sustainable yield" is often used as a single-product exploitation goal—the number of trees cut, the number of fish caught, the volume of water pumped from ground or river, year after year without destroying the resource base. But experience has shown, over and over, that a single-product goal is too narrow a definition of the resource, because other resources inevitably depend on or interact with or flow from the exploited product. We can maximize our sustainable yield of water by drying up our streams—but when we do, we find that the streams were much more than just containers of usable water.

The next level of sustainable yield addresses the sustainability of the "system," not just the fish, but the marine food chain; not just the trees, but the whole forest; not just the ground water, but the running streams, wetlands, and all of the plants and animals that depend on them. A worthwhile approach, perhaps even a noble one—but fraught with difficulty. We cannot use a natural system without altering it, and the more intensive and efficient the use, the greater the alteration. How much is too much? What are the central characteristics that must be preserved or sustained? Is there any way to answer these questions before it is too late? Here is the forefront of the definition problem—even if we assume that we care about the next generation, do we permit anything that cannot be proven dangerous or forbid what cannot be proven safe?

At the most abstract level we talk about sustainable development—not the resource, not the ecosystem, but the economic benefit derived from it. Can we have development without growth, or growth without degradation? Many scientists are suspicious of the idea, but it comes naturally to many economists, who have been steeped in the doctrine of substitutability—let a resource become scarce or expensive, and *Homo sapiens* will devise a replacement. It is a comforting concept—if nothing is limiting, then there are no limits!

Substitutability is an attractive theory, but what do we drink when the well runs dry? Sustainability is an attractive goal, but how many people can drink from the stream if they have to leave enough water for the salamanders?

ently variable, patchy, and often require disturbance to persist. (Stream ecosystems in particular depend on natural disturbances such as flooding.) We also recognized the interdependency of system components and the importance of indirect effects (instead of temperature affecting biology, biology is affecting temperature!) The management implication of these realizations is that we must manage for change and for complexity. This approach dictates (Meyer, 1993) 1) management in the context of the *ecosystem* rather than managing parts as though they were in isolation, and 2) use of an *adaptive management* scheme that is responsive to changing environmental conditions.

The term *watershed ecosystem* refers to all of the elements and processes that interact within the catchment basin or watershed. The concept of the watershed includes four-dimensional processes (Doppelt et al., 1993) that connect the longitudinal (upstream—downstream), lateral (floodplain—upland), and vertical (hyporheic or groundwater zone—stream channel) dimensions, each differing temporally. Watersheds are ecosystems composed of a mosaic of different land or terrestrial "patches" that are connected by (drained by) a network of streams. In turn, the flowing water environment is composed of a mosaic of habitats in which organisms, materials, and energy move in complex, yet highly integrated, systems. Physical and chemical processes and complex food webs depend on those movements. Given the dynamic connectedness of a watershed, management activities can fragment and disconnect the habitat patches if they are not planned and implemented from an ecosystem and watershed perspective. In-stream conditions are largely determined by processes occurring within the watershed and underlying aquifers, and they cannot be isolated from or manipulated independently of this context.

Meyer (1993) summarizes the changing concepts of ecological-system management resulting from recent advances in our scientific understanding. Many aquatic ecosystems depend on disturbance. A change in the natural disturbance regime is a major cause of alterations in riverine ecosystems after dam construction. For example, when disturbances caused by variable water discharge, high summer temperatures, and massive sediment transport are removed, the system changes. This has happened below Glen Canyon Dam, and it is one of the issues addressed by the Water Science and Technology Board Glen Canyon Environmental Studies (NRC, 1987) committee. Since dam construction, flood flows and sediment transport have been reduced, resulting in depletion of sand stored in the active channel (Andrews, 1991). Because of stabilized flows, a larger riparian area remains moist, and the riparian zone has expanded and has been invaded by several exotic species, including salt cedar or tamarisk (*Tamarisk chinensis*), camelthorn (*Alhagi camelorum*), and Russian olive (*Elaeagnus angustifolia*) (Johnson, 1991; Bowers et al., 1995). Release of cool, sediment-poor but nutrient-rich water from Lake Powell leads to high biomass of algae (*Cladophora*) and invertebrates in the river (Stanford and Ward, 1991). The continued existence of the native fishes is threatened by the altered thermal environment but more critically by the introduction of nonnative species that are able to thrive in the new environment created by the dam (Minckley, 1991). Native fishes also are failing to reproduce because of the absence of large seasonal changes in water level, which synchronized their breeding cycles (Minckley and Deacon, 1991). Clearly, reservoir operations that have altered the natural-disturbance regime have had an effect on many components of the downstream ecosystem (Carothers and Brown, 1991).

How might one manage for change in this situation? The NRC committee has advocated adaptive management (NRC, 1991). The combination of 1) introducing environmental dimensions into decisions on dam operation at the beginning of the process, 2) using experiments to assess ecological consequences on downstream ecosystems of management activities (i.e. of different release schedules), and 3) continued dialogue between scientists and managers to evaluate policies in the face of a variable environment are at the core of adaptive management (Holling, 1976). The idea of adaptive management grew from a recognition of basic properties of ecological systems, which include *the unexpected can be expected* (see Boxed section 3.3 later on) and *environmental quality is not achieved by eliminating change* (Holling, 1976). Clearly, this is managing for change (Meyer, 1993).

Science will never know all there is to know. Science is a process, not an end point. Rather than allowing the unknown or uncertain to paralyze us, we must apply the best of what we know today—while, at the same time, providing sufficient management flexibility to allow for change and for what we don't yet know. This means we must not plan for riverine systems, for example, to operate near the limits of their capacity.

An additional component of management for change is managing in a probabilistic and risk-assessment framework in which one recognizes the inherent unpredictability of nature (Meyer, 1993). This is particularly appropriate for managing populations of rare species (e.g., desert pupfishes) but also applies to managing a fisheries resource (Meyer, 1993), or a water-resource system. Rather than determining a fixed sustainable yield, managers recognize that yield should vary over time as environmental conditions vary. In the long term this produces a more sustainable yield. This type of management requires greater input of scientific understanding and continued monitoring than is currently practiced (Meyer, 1993).

How do we manage for complexity? The obvious answer, given by numerous Water Science and Technology Board committees (e.g., NRC, 1991), is to manage in an ecosystem context (Meyer, 1993). Rather than managing for a single resource (board feet of lumber or acre-feet of water), managers work to sustain the diversity of services provided by the ecosystem with a recognition of the

Boxed section 3.3: A Failure to Recognize Stream-aquifer Interconnections: Unexpected Things Can Happen!

Sometimes a decision about one aspect of a water system in Kansas has an impact on a variety of systems, impacts not necessarily intended or even recognized when the original decision was made. In 1951, the Bureau of Reclamation constructed Cedar Bluff Dam on the upper reaches of the Smoky Hill River in Trego County in west-central Kansas. Cedar Bluff captures drainage from the Smoky Hill and two of its major tributaries, Ladder Creek and Hackberry Creek. The dam was intended to provide flood control, water for irrigation and municipal use, and water for a fish hatchery below the dam, operated by the U.S. Fish and Wildlife Service. Shortly after the dam was completed, heavy spring and summer rains in 1951 and 1957 filled the reservoir. In about 1965, however, inflow into the reservoir slowed substantially. In other parts of northwestern Kansas, decreased inflow to reservoirs was attributed to a lessening of streamflow caused by lower water tables and the increased use of conservation practices in agriculture, such as terracing and building of farm ponds that dramatically decrease runoff (Bureau of Reclamation, 1984). These causes may apply to the reduced flow into Cedar Bluff. Because of this lack of inflow, the contents of Cedar Bluff Reservoir averaged about 13% of the designed level since 1980 (Ratzlaff, 1987). Releases of water from Cedar Bluff to entities with water rights stopped by 1979.

Hays, Kansas, a city of about 18,000 people, is about 22 miles (35 km) downstream from Cedar Bluff, about 10 miles (16 km) north of the Smoky Hill River. One of the city's primary water sources was a well field in the alluvial aquifer of the Smoky Hill River, which produced about 2,500 acre-feet (3.1×10^6 m^3) of water annually. Lessened streamflows in the Smoky Hill—caused by lower water tables, decreased runoff, and the lack of discharge from the reservoir—meant that considerably less water was available in the Smoky Hill to recharge the alluvial aquifer. Yields in the Hays well field dropped to about 1,000 acre feet (1.2×10^6 m^3) annually (Henson and Zacharias, 1993). In addition, the Smoky Hill River valley below the lake (from Cedar Bluff to the confluence of the Smoky Hill and Big Creek in western Russell County) was declared an Intensive Ground-water Use Control Area (or IGUCA) by the State engineer in 1984 (Macfarlane, 1985). Because of dwindling water supplies, Hays began a number of conservation efforts, resulting in a substantial reduction in per capita water use. The city also began aggressively seeking additional water sources, and eventually purchased land and water rights to a ranch in Edwards County, Kansas, about 85 miles (136 km) away, with plans of transferring water for municipal use in Hays, in spite of considerable opposition to the plan in Edwards County. In short, then, lessened streamflow in the Smoky Hill River in the Kansas River drainage basin, combined with changing agricultural practices and lower water tables, had the domino effect of lessening supplies in Hays, leading to the possible transfer of water from the Arkansas River drainage basin, more than 100 miles (160 km) away from Cedar Bluffs. The reservoir's construction, along with other factors, clearly had a variety of consequences—related to agricultural, municipal, and irrigation water supply, as well as streamflow—that reverberated far beyond the simple building of a dam in Trego County.

complex interactions and numerous indirect effects that characterize ecological systems. Ecosystem management recognizes that if it is the entire system and its continued productivity for a wide array of uses and values that we desire, then production goals for individual resources might not point a path toward sustainability. We need instead objectives that relate to ecological conditions in the basin and that sustain land uses and resource yields compatible with those conditions (Kessler et al., 1992).

The evidence shows that we have altered the hydrologic cycle as well as cycles of most elements, that we seem to be affecting climate, and that biodiversity may be declining rapidly. These events call for a more holistic concept of system management that has the goal of maintaining and restoring the ecological integrity of the resource rather than simply preserving water quantity or quality (Meyer, 1993).

Kansas Water-resources-management Experience

In view of persistent ground-water-level declines especially in western Kansas, the Kansas Legislature in 1972 passed the Kansas Groundwater Act authorizing the formation of local groundwater management districts (GMDs) to help control and direct the development and use of ground-water resources. Since passage of the enabling act, five districts have been formed of which the three western districts overlie all or parts of the Ogallala aquifer. The three western districts (1, 3, and 4) have the greatest number of large-capacity wells and the highest rate of water-level declines in addition to having the least precipitation and least ground-water recharge. Each of these districts has adopted a plan that will allow a portion of the aquifer to be depleted (no more than 40%) over a period of 20–25 years (*planned depletion policy*; this implies that the Ogallala is not a renewable resource at least within a human generation, although the Northwest Kansas GMD4 implemented a *"zero depletion" policy* in 1990 for new wells, as mentioned in Chapter 1.) The districts to the east (2 and 5), which have more precipitation, and thus more ground-water recharge, have initially adopted a *"safe yield" management plan* (during the late 1970's) to balance ground-water pumping with the average annual recharge. According to this policy, the total amount that may be appropriated in a 2-mile (3.2-km) circle around the proposed diversion is limited to the long-term average annual recharge calculated for the circle. Thus, the quantity already appropriated within that 2-mile (3.2-km) circle plus the quantity proposed under the new application must be less than the long-term average annual recharge (implying a renewable ground-water resource). Ground-water pumping between predevelopment (circa 1940's) and 1990's has depleted significant portions of the High Plains aquifer and caused water-level declines of as much as 200 ft (60 m) at places in southwestern Kansas. Figure 3.2 shows the declines in saturated thickness since predevelopment across western and central Kansas. As a result of these declines, the Division of Water Resources has officially closed many areas of western and central Kansas to new ground-water development (fig. 1.37B of Chapter 1).

In addition, as a result of the above mentioned ground-water-level declines, streamflows of western and central streams have been decreasing, especially since the mid-1970's. In response to these streamflow declines, the Kansas Legislature passed the minimum instream flow law in 1982, which requires that minimum desirable streamflows (MDS) be maintained in different streams in Kansas. Although the establishment of MDS is a major step toward conservation of riverine habitat within the state, the trend in reduction of discharge since the mid-seventies appears to be continuing (Ferrington, 1993). Figure 3.3 is a graph of mean daily discharge in the Arkansas River averaged by month for Coolidge, Syracuse, Garden City, and Dodge City for the period of October 1987 to September 1993, where the longitudinal pattern in reduction of surface discharge is clearly visible. Maps comparing the perennial streams in Kansas in the 1960's to those of the 1990's show a marked decrease in miles of streamflow in the western third of the state (fig. 2.15 in Chapter 2).

Kansans have come to realize that ground water and surface water are closely interrelated systems. Ground water feeds springs and surface streams, and surface water recharges aquifers. The decline of ground-water levels around pumping wells located near streams creates gradients that capture some of the ambient ground-water flow that would have, without pumping, discharged as baseflow to the streams. At sufficiently large pumping rates, these declines induce flow out of the body of surface water into the aquifer, a process known as *induced infiltration* or *recharge*. The sum of these two effects leads to *streamflow depletion*. In addition to quantity issues, stream-aquifer interactions are also important in situations of ground-water contamination by polluted surface water, and of degradation of surface water by discharge of low-quality ground water as we saw in Boxed section 2.4 of Chapter 2. Ground-water discharge of saline water (mineral intrusion) or other low-quality ground water to streams results in surface-water quality degradation, as it happens for example in the Rattlesnake Creek east of US–281, and in the Arkansas River from Coolidge to Arkansas City (Whittemore, 1995). In turn, such polluted surface water presents a threat of ground-water contamination to the freshwater Equus Beds aquifer along the Arkansas River valley between Hutchinson and Wichita. In fact, streams and their alluvial aquifers are so closely linked in terms of water supply and water quality that neither can be properly understood or managed by itself, and therefore the combined stream-aquifer system must be considered (see also Boxed section 3.3).

As a result of the above-mentioned declines in ground-water levels and streamflow, both GMDs 2 and 5 have recently (early 1990's) reevaluated their "safe-yield" policies and moved toward conjunctive stream-aquifer management by amending their "safe yield" regulations to

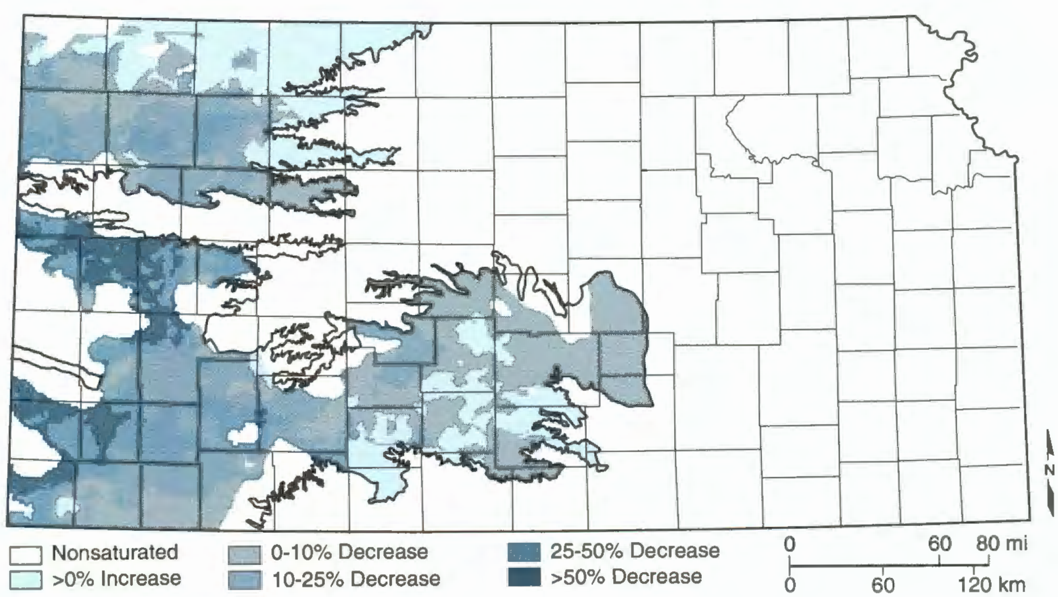

FIGURE 3.2—PERCENT CHANGE IN SATURATED THICKNESS (pre-development through 1996).

include baseflow (the natural ground-water discharge to a stream) as ground-water withdrawals along with regular water-permit appropriations when evaluating a ground-water-permit application. (Baseflow is usually estimated as the streamflow that is exceeded 90% of the time on a monthly basis.) The concept is to prorate the baseflow to a series of phantom wells, known as "baseflow nodes" located on the stream centerline at 1/4-mile (0.4-km) intervals (the GMDs well-spacing requirement), each having an annual quantity of water assigned to it equal to its prorata share of the estimated baseflow, which is considered its appropriation for "2-mile circle" computations. If there are such nodes in a 2-mile (3.2-km) circle, they are each treated as water rights for purposes of determining whether or not a new application should be approved. For regulatory and name-recognition purposes, GMD 2 continues to refer to these regulations as "safe-yield" ones, whereas GMD 5 renamed theirs as "sustainable yield." Hopefully, this new measure together with the establishment of minimum-desirable-streamflow standards will provide additional needed protection to the riverine-riparian ecosystem. (See also the section on statewide water appropriations outside the GMDs in Part IV of Chapter 1.) In addition, the integrated resource planning (IRP) program of the City of Wichita, outlined in Boxed section 2.4 of Chapter 2, will further improve the GMD2 water-related picture.

The Division of Water Resources also is attempting to develop a comprehensive basinwide-management program in areas of Kansas with significant water problems. The purpose of this subbasin water-resources management program is to develop comprehensive, long-term water-management strategies to implement solutions to water problems within the framework of existing State water laws on a proactive basis. This program is intended to be holistic, addressing concerns related to surface-water depletions, ground-water declines, and deterioration of the water quality. The approach taken is that of the *watershed ecosystem*, recognizing that streams are not simply water flowing through a channel, but are the products of their drainage basins or watersheds and their associated aquifers (ground-water basins), and that to understand and model such stream-aquifer interactions, it is necessary to understand the flow paths within the surface- and ground-water watersheds associated with the stream. Close consultation and cooperation with the local district, irrigators' associations, and other interested parties are integral parts of this program.

Thus the concept of integrated management of ground water and surface water on a watershed or basin-scale basis embracing the ecosystem concept is now taking hold in Kansas. Such integrated watershed-management efforts include interrelating the management of water quality and quantity, ground and surface waters, the land-water interface, biologic concerns, and the objectives of the user community. Watersheds are considered generally equivalent to ecosystems. Thus, the ecosystem concept provides a basis for a holistic framework to unite environment and society. The progressive evolution of Kansas water management incorporating local groundwater management

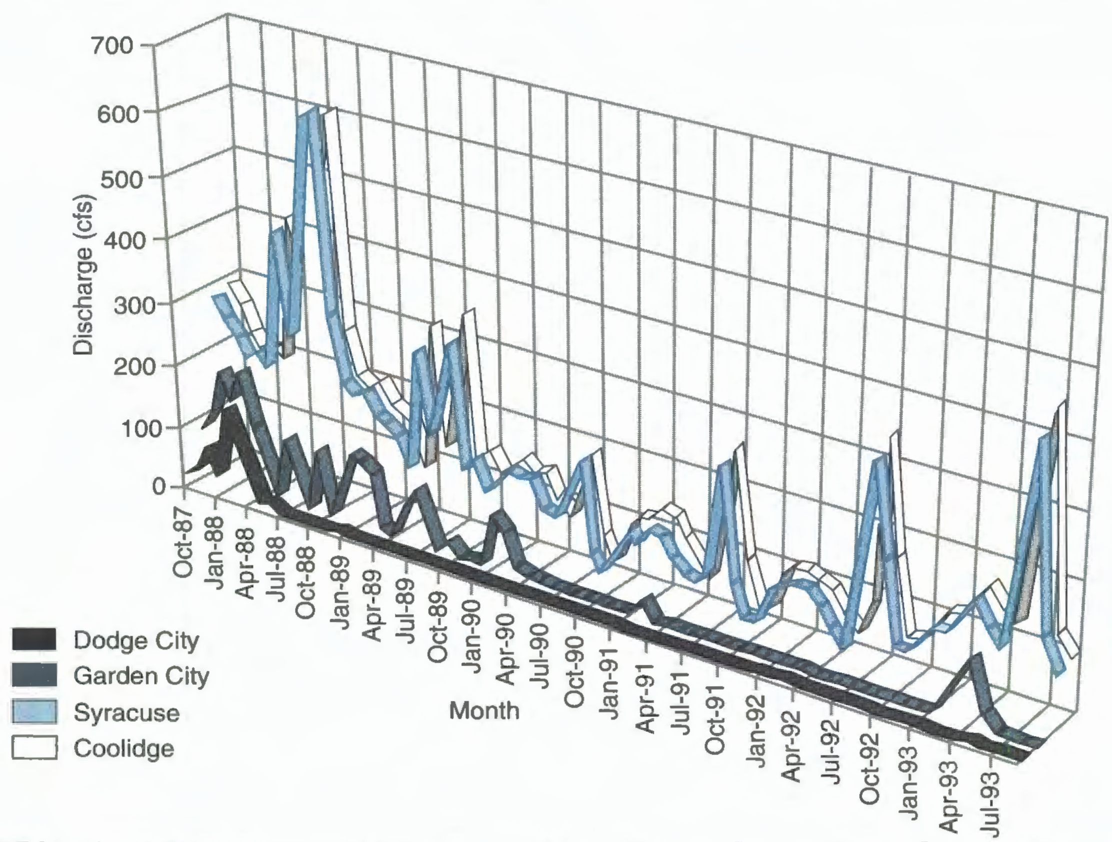

FIGURE 3.3—AVERAGE MONTHLY DISCHARGE OF THE ARKANSAS RIVER AT COOLIDGE, SYRACUSE, GARDEN CITY, AND DODGE CITY STREAM-GAGING STATIONS. Modified from Ferrington (1993).

districts, minimum-streamflow standards, the conjunctive stream-aquifer management embodied in the sustainable-yield policies, integrated resource planning, and the DWR subbasin water-resources-management program are all appropriate steps toward the ethic of sustainable development.

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CHAPTER 4

Is Sustainability a Viable Concept in the Management of Confined Aquifers in Kansas?

P. Allen Macfarlane

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Is Sustainability a Viable Concept in the Management of Confined Aquifers in Kansas?

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Introduction

Unlike shallow unconfined aquifers, which are bounded only by a low-permeability layer below, a confined aquifer is bounded by two low-permeability layers. The confined aquifers that are major sources of water in Kansas are the Dakota and the Ozark Plateau aquifer systems (fig. 4.1). Other confined aquifer systems that are minor sources of ground water are the sandstone aquifers in the Pennsylvanian Douglas Group in northeastern Kansas and the karstified limestones of the Permian Barneston Limestone. Confined to semi-confined conditions also exist locally in the more clayey parts of the High Plains aquifer. Management of these confined systems has not been aggressively pursued because, until recently, they have been poorly understood. However, as the shallower sources of water have become increasingly unable to meet existing demands, interest in these deeper aquifer systems as replacement or supplemental sources has increased. More stringent and informed management policies need to be formulated now to ensure the continued availability of water supplies from these confined systems.

These newer proactive policies will most certainly rely on an assessment of aquifer sustainability. The policies formulated by planners and managers to achieve sustainability will depend on the *planning horizon* (i.e. the length of time into the future covered by a management plan) selected, the goals for managing the water resource, and the hydrogeology of these confined systems. For example, Walton (1964) recognized the limited nature of water supplies in confined aquifer systems. He defined the long-term practical sustained yield for the confined Cambrian–Ordovician aquifer in northeastern Illinois as the total withdrawal rate that could be maintained without completely depleting the aquifer. The goal of this chapter is to evaluate the viability of applying sustainability concepts to the management of confined-aquifer systems in Kansas. In this chapter, the achievement of sustainability is defined using Walton's criteria of nondepletion. This evaluation will be done by reviewing aspects of confined-aquifer hydrology that have a bearing on the concept. Examples from the Dakota and the Ozark plateaus aquifer systems will be used to illustrate the key points in this chapter. It is assumed that the other minor aquifer systems behave in a manner similar to the major confined systems.

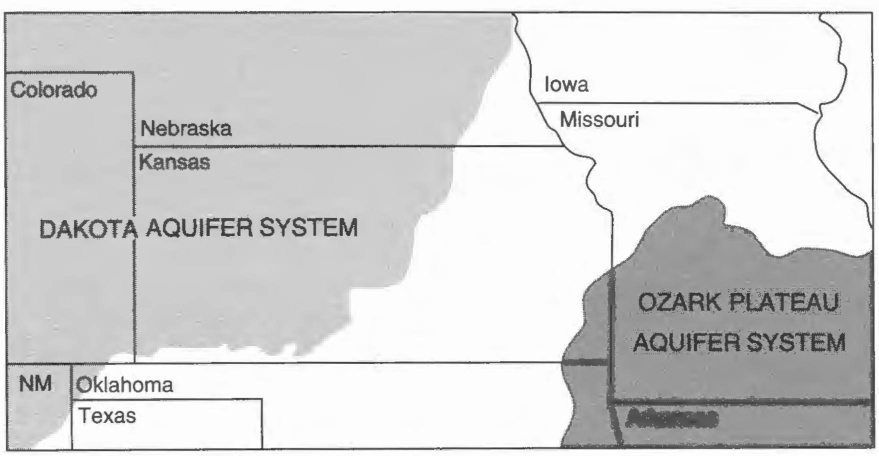

FIGURE 4.1—EXTENT OF THE OZARK PLATEAU AND DAKOTA AQUIFER SYSTEMS IN KANSAS AND ADJACENT STATES.

Ground-water-management Issues

The issues surrounding the sustainability of water resources in confined systems are complex and involve both the quantity and the quality of ground water. These systems will not respond to development in the same manner as unconfined systems because of differences in the sources and amounts of recharge and differences in the mechanisms by which ground water is released to pumping wells. Because of their greater average depth below surface, these confined systems are more likely to contain or be hydraulically connected to other aquifers that contain unusable ground water. As a result, water quality can be a very important consideration in determining the amount of water that can be withdrawn.

In many instances we have a good understanding of the regional flow systems in these confined aquifers; that understanding can not be directly translated to the well-field scale because of uncertainty. The geologic units that constitute the framework of these confined aquifers were deposited in a complex mosaic of depositional environments that range across the marine to nonmarine continuum. The nature of transitions within and between adjacent environments is often reflected in the variability of the deposited sediments. Hence, the composition, distribution, and hydrologic properties of these sediments are initially highly variable. Lithification and chemical reactions with enclosed pore waters over geologic time may further enhance the permeability and porosity contrasts between adjacent rock units. As a result, distribution of porosity and permeability within a sedimentary rock sequence may or may not coincide with formational boundaries. The resulting high degree of heterogeneity in these deposits is a major influence on the hydraulic connection between aquifer systems and the flow of ground water to pumping wells.

Another problem for the development of suitable management policies for confined aquifers is the difficulty of conceptualization. Our understanding of the hydrology of unconfined ground-water systems is more easily pursued on an intuitive level than is the case for confined systems. For example, a saturated thickness can be easily visualized and related to the total amount of water in an unconfined aquifer. Large-scale withdrawals eventually produce water-level declines in the aquifer, and the volume of water removed is not that much different from the change in saturated thickness integrated over the affected area under some circumstances. However, under confined conditions pumping generally does not dewater the aquifer adjacent to the well because the water level remains above the aquifer top. Many planners and managers have a poor grasp of the fundamental differences in the hydrologic mechanisms of water production between unconfined and confined systems.

Hydrogeologic Framework in Kansas

The analysis of regional ground-water flow in large sedimentary basins requires an understanding of the geologic framework through which fluids flow. The total thickness of sedimentary rocks above the Precambrian varies considerably across Kansas and adjacent areas of the plains ranging from less than 2,000 ft (600 m) in southeastern Kansas and southeastern Colorado to almost 7,000 ft (2,100 m) in southwestern Kansas. The sedimentary rock units above the Precambrian range in age from Cambrian through Quaternary and consist of both consolidated and unconsolidated deposits that were deposited in a variety of marine and nonmarine environments (table 4.1, fig. 4.2). Periodic episodes of deposition, uplift, and erosion over geologic time and local variations in the rates of these processes are largely responsible for the observed variation in thickness of sedimentary strata across the state, their hydrologic properties, and chemical quality of their contained porewaters.

Hydrostratigraphic Units

In a heterogeneous sedimentary basin, the spatial variability of hydraulic conductivity can vary over a range of 11 orders of magnitude or more (Macfarlane, 1993). To better understand ground-water flow through such a highly variable geologic framework, it is convenient to delineate hydrostratigraphic units. A hydrostratigraphic unit can be defined as a part of a body of rock that forms a distinct hydrologic unit with respect to the flow of ground water (Maxey, 1964). In a review of the concept, Seaber (1988) redefined the term as "a body of rock distinguished and characterized by its porosity and permeability." Delineation of these units subdivides the geologic framework into *aquifer* and *aquitard* units and thus aids in definition of the flow system across all spatial scales. Fetter (1994) regards a hydrostratigraphic unit with a hydraulic conductivity (K) of greater than about 0.2 ft/day (0.06 m/day) as an aquifer. Table 4.1 shows the generalized subsurface stratigraphy of Kansas subdivided into regional aquifer and aquitard units. In the midcontinent, including Kansas, the regional aquitard units are at least three orders of magnitude less permeable than the regional aquifers (Macfarlane et al., 1992). Figure 4.1 shows the extent of the Dakota and the Ozark Plateaus aquifer systems in Kansas and adjacent areas.

In general, the criteria for delineating aquifer and aquitard units depend on the spatial and temporal scales under consideration. Hydrostratigraphic units defined at one scale may have little bearing on ground-water flow at another scale if the units are spatially highly heterogeneous. For example, some units might be considered aquifers at the regional scale and at the scale of geologic time; however, the same units may be considered aquitards or aquicludes at the more local and shorter time scales associated with a pumping test on a production well. Likewise, local aquifer units contained within a thick regional aquitard may have very little bearing on the regional flow of ground water across the aquitard. Furthermore, units that are considered hydraulically continuous regionally may, at smaller spatial and time scales, become discontinuous. For example, to analyze a basinwide problem, it may be sufficient to identify the upper and lower Dakota aquifers. However at the well-field scale, it may be necessary to identify the extent of individual sandstone bodies that form the local aquifer units and the enclosing mudstones within these geologic units that form the local aquitard units. For the local problem, the geometry and hydraulic continuity of the sandstones as well as their hydrologic properties determine the nature of the aquifer units (Macfarlane et al., 1994).

TABLE 4.1—STRATIGRAPHY AND HYDROSTRATIGRAPHY OF THE KANSAS SUBSURFACE ABOVE THE PRECAMBRIAN, SHOWING THE MAJOR AQUIFER AND AQUITARD (confining units). Modified from Macfarlane (1993) and Jorgensen et al. (1993).

ERA	SYSTEM	ROCK STRATIGRAPHIC UNITS	HYDROSTRATIGRAPHIC UNITS			
			Western and Central Kansas		Southeastern Kansas	
Cenozoic	Quaternary	unconsolidated sediments	alluvial valley aquifers		alluvial valley aquifers	
	Tertiary	Ogallala Formation	High Plains aquifer system			
Mesozoic	Cretaceous	Colorado Group	Upper Cretaceous aquitard			
		Dakota Formation	Upper Dakota aquifer	Dakota aquifer system		
		Kiowa Formation Cheyenne Sandstone	Kiowa shale aquitard			
	Jurassic/ Triassic	Morrison Formation Dockum Group	Lower Dakota aquitard			
Paleozoic	Permian		Upper Permian-Pennsylvanian aquitard			
		Cedar Hills Sandstone	Cedar Hills Sandstone aquifer			
			Lower Permian-Pennsylvanian aquitard			
	Pennsylvanian				Lower Permian-Pennsylvanian aquitard	
	Mississippian		Upper Western Interior Plains aquifer	Western Interior Plains aquifer system	Springfield Plateau aquifer	Ozark Plateaus aquifer system
		Northview Shale Compton Limestone			Ozark confining unit	
	Devonian	Chattanooga Shale	confining unit			
	Silurian/ Ordovician		Lower Western Interior Plains aquifer system		Ozark aquifer	
		Derby-Doe Run Dolomite Davis Formation			St. Francois confining unit	
	Cambrian	Reagan Sandstone			St. Francois aquifer	
Precambrian			basement confining unit			

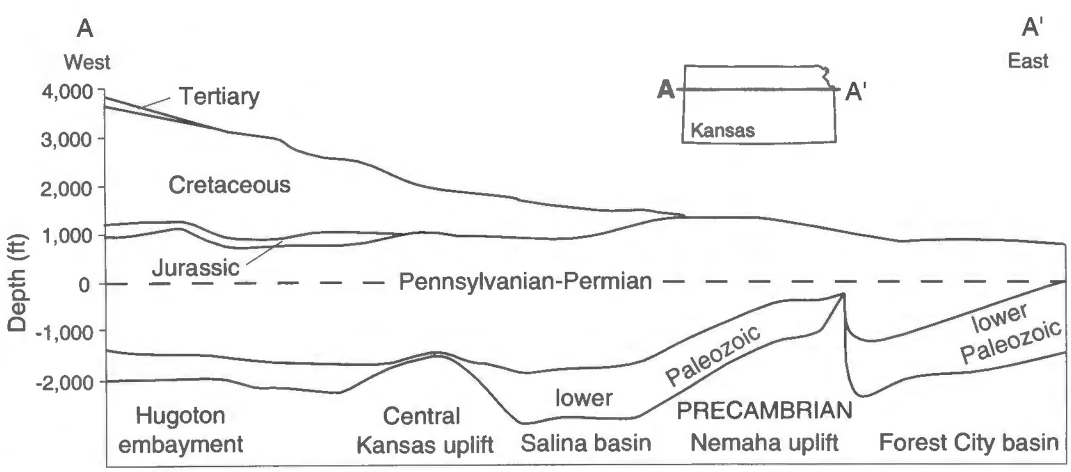

FIGURE 4.2—GENERALIZED WEST TO EAST CROSS SECTION FROM THE KANSAS–COLORADO BORDER TO THE KANSAS–MISSOURI BORDER APPROXIMATELY ALONG I–70 SHOWING THE MAJOR SUBSURFACE GEOLOGY FEATURES OF KANSAS. Modified from Merriam (1963).

Dakota Aquifer System

The geologic units that form the Dakota aquifer in Kansas are the Cretaceous Dakota Formation, the Kiowa Formation, and the Cheyenne Sandstone (table 4.1). The combined thickness of these units can range up to more than 700 ft (214 m) in west-central parts of the state. However, not all of the units that constitute the Dakota contain aquifer-grade material that can yield water to wells. The amount of sandstone, considered to be the aquifer material, varies from less than 10% to more than 50% of the total thickness, even over very short lateral distances. Statewide, the average proportion of sandstone is approximately 30% of the entire thickness. The sandstones occur as irregular, discontinuous bodies within relatively impervious shaly strata and generally occur in several, more or less distinct zones within these geologic units. These ribbonlike, irregular bodies of sandstone were deposited during the early part of the Cretaceous Period (approximately 90–100 million years ago) in river valleys crossing a coastal plain and in coastal environments along the eastern shoreline of the Western Interior sea. Figure 4.3 is a schematic cross section of the Dakota aquifer framework from geophysical logs. Typically, these sandstone bodies range in length up to 20 miles (32 km), in width up to 1.5 miles (2.4 km), and in thickness up to more than 100 ft (30 m). With some exceptions, they tend to be oriented primarily in an east-west direction, parallel to the direction of the ancient drainage. The most permeable part of the aquifer is generally in the river-deposited sandstones in the Dakota Formation and the Cheyenne Sandstone.

The Dakota aquifer system is the most geographically extensive of all the aquifer systems in the upper 2,000 ft (610 m) of the subsurface of western and central Kansas (table 4.1, figs. 4.1 and 4.2). The upper Dakota aquifer consists of sandstones in the Dakota Formation and the upper part of the Kiowa Formation. The lower Dakota aquifer consists of the Cheyenne Sandstone and the sandy lower part of the Kiowa Formation. Over most of western Kansas these two aquifers are separated by a marine shale unit of the Kiowa Formation. Elsewhere, both the regional upper and lower Dakota aquifers are hydraulically connected.

Over most of its extent, the Dakota aquifer is confined by younger Cretaceous chalks and shales that form the Upper Cretaceous aquitard (table 4.1, fig. 4.4). The total thickness of the aquitard generally increases to the west and north of the outcrop/subcrop belt up to more than 2,000 ft (610 m) in northwestern Kansas. In most of southwest and most of south-central Kansas, the Upper Cretaceous aquitard has been eroded and the upper and lower Dakota aquifers subcrop beneath and are in hydraulic connection with the High Plains aquifer. In the river valleys of the central part of the state, the Dakota aquifer is hydraulically connected to the alluvial deposits, which form the alluvial-valley aquifers. Westward-dipping Jurassic and Permian rocks directly underlie the Dakota aquifer in Kansas (Hamilton, 1994). In extreme southwestern Kansas, sandstone aquifers in the Morrison Formation and Dockum Group are considered aquifers that are hydraulically connected to the overlying lower Dakota (Kume and Spinazola, 1985). Consequently, the Morrison–Dockum aquifer is here considered to be part of the lower Dakota aquifer (table 4.1). Elsewhere, the Morrison Formation is not known to be sandy or yield water to wells. Therefore, it is considered to be a part of the Permian–Pennsylvanian aquitard. Permian rocks beneath the Dakota aquifer consist of shale, siltstone, sandstone, and bedded salt with minor amounts of limestone and dolomite. In Kansas, they generally form the upper part of thick regional aquitard composed of Pennsylvanian and Permian units. Within this aquitard is the Cedar Hills Sandstone aquifer. In central Kansas, the Permian Cedar Hills Sandstone directly underlies and is hydraulically connected to the lower Dakota aquifer (fig.4.3).

Ozark Plateau Aquifer System

In Kansas and Missouri this aquifer system consists of karstified and fractured carbonate rock units of Upper Cambrian, Lower Ordovician, and Mississippian age (Jorgensen et al., 1993; Macfarlane and Hathaway, 1987). This regional aquifer system is confined above by a sequence of shales and limestones that forms the Permian–Pennsylvanian aquitard (table 4.1). Below, the aquifer is confined by rocks of Precambrian age. In southeastern Kansas and adjacent parts of Missouri, the Ozark confining unit has been thinned or completely removed by erosion. In most cases, the Ozark aquifer is the only ground-water source used for water supply in southeast Kansas.

The Western Interior Plains aquifer system in table 4.1 consists of karstified and fractured carbonate rock units of Upper Cambrian, Lower Ordovician, Silurian, and Mississippian age to the west of the Ozark Plateau aquifer system in Missouri, Kansas, and Oklahoma (Jorgensen et al., 1993). The Ozark Plateau aquifer system contains fresh and usable ground water and the Western Interior Plains aquifer system contains brackish to unusable brines. The boundary between these two aquifer systems is the 2,500 mg/L isochlor line that cuts across southeast Kansas from Missouri into Oklahoma (fig. 4.1). This isochlor coincides approximately with the hydrologic boundary separating the shallow, freshwater flow system in the Ozark region of Missouri, Arkansas, and northeastern Oklahoma from the deep, regional saltwater-flow system in Kansas and Oklahoma.

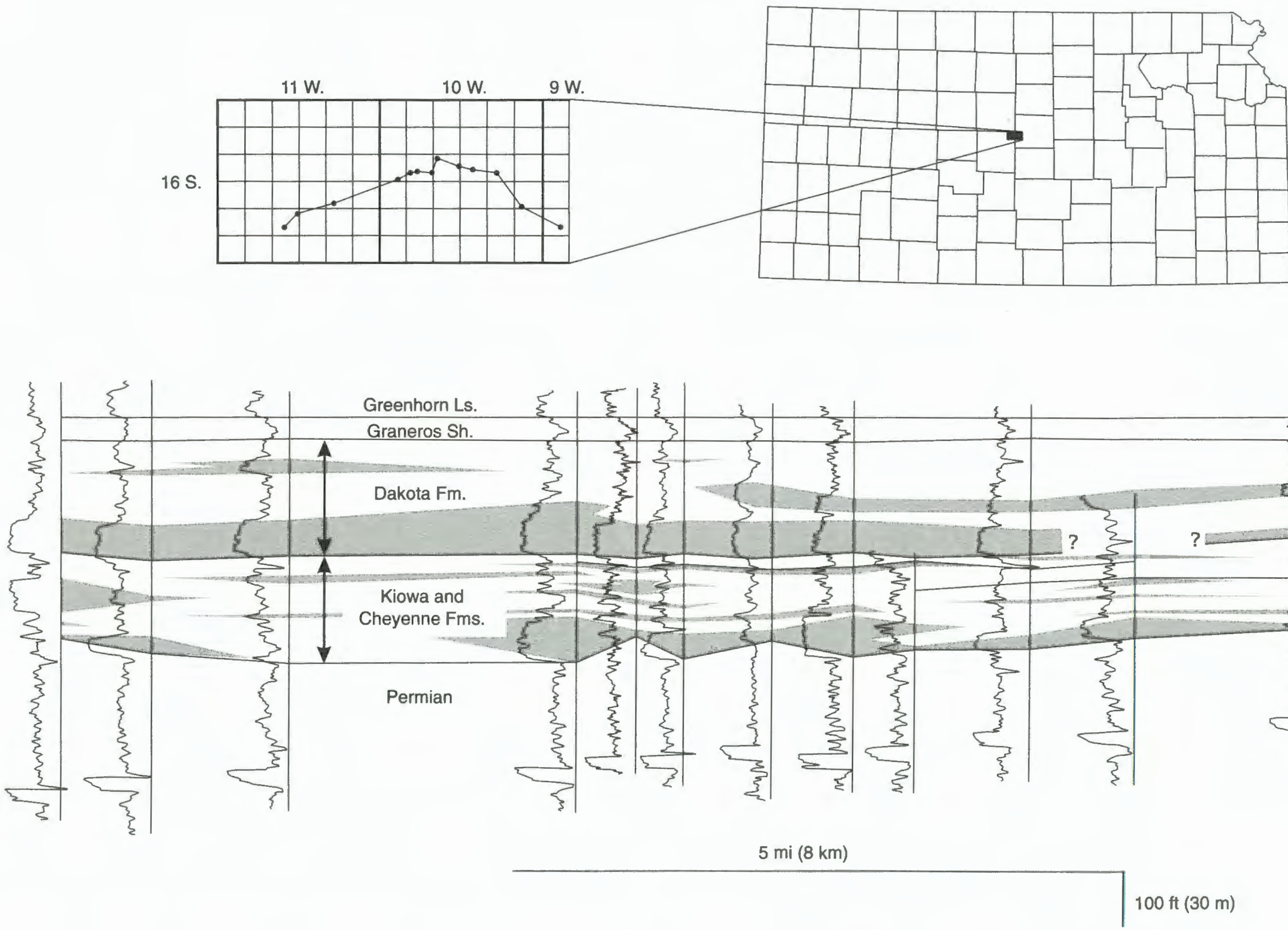

FIGURE 4.3—CROSS SECTION CONSTRUCTED FROM GAMMA-RAY LOGS OF OIL WELLS IN A SMALL AREA OF CENTRAL KANSAS. Deflections of the gamma-ray curves to the right indicate shaly strata. Deflections to the left indicate sandstone, limestone, or dolomite. The shading shows the interpreted distribution of sandstone beds as in the Dakota, Kiowa, and Cheyenne formations.

Confined and Semi-confined Aquifer Hydrology in Kansas under Predevelopment Conditions

Without exception, ground water is constantly moving from points of recharge where it enters the subsurface hydrologic system to points of discharge where it exits back to the surface. Some of the water only travels a short distance through the shallow subsurface from local recharge to local discharge areas. However, some of the water travels a much longer distance from regional recharge to discharge areas through the deeper subsurface. To define the pattern of moving ground water in a flow system, hydrogeologists use measurements of water-level elevation taken in wells scattered throughout the aquifer system. In most cases, the water-level elevation above mean sea level in a well is equal to the *hydraulic head* in the region of the aquifer adjacent to the well screen. The movement of ground water through the aquifer pores involves a loss of energy and the effect is comparable to the flow of water in river systems. Water naturally flows downhill from elevated regions of the continent (higher hydraulic head) to the sea (lower hydraulic head). In much the same way ground water moves from points of higher hydraulic head to points of lower hydraulic head in a flow system. In a confined aquifer, the hydraulic head is above the top of the aquifer whereas in an unconfined or water-table aquifer, the water table defines the top of the aquifer.

Dakota Aquifer System Hydrology

In the central Great Plains region of eastern Colorado and Kansas, the ground-water flow system in the confined Dakota aquifer is influenced primarily by regional and local topography and the Upper Cretaceous aquitard (Macfarlane, 1995). Hydrogeologists have long observed that the water table or the top of the saturated zone mimics the topography of the land surface. The land surface of this region slopes generally to the east and decreases in elevation from 5,000 ft (1,524 m) or more in eastern Colorado to 1,400 ft (427 m) or less in central Kansas (figs. 4.5 and 4.6). This results in an easterly flow of ground water across the region in all of the aquifer systems.

Due to its great thickness and extremely low permeability in the Denver basin of eastern Colorado, the Upper Cretaceous aquitard hydrologically isolates the flow system in the Dakota from the overlying water table. The Upper Cretaceous aquitard is more than 2,000 ft (610 m) thick in northwest Kansas and thins toward its eastern and southern extent in central and southwestern Kansas. As a result, its control on the flow system in the Dakota aquifer

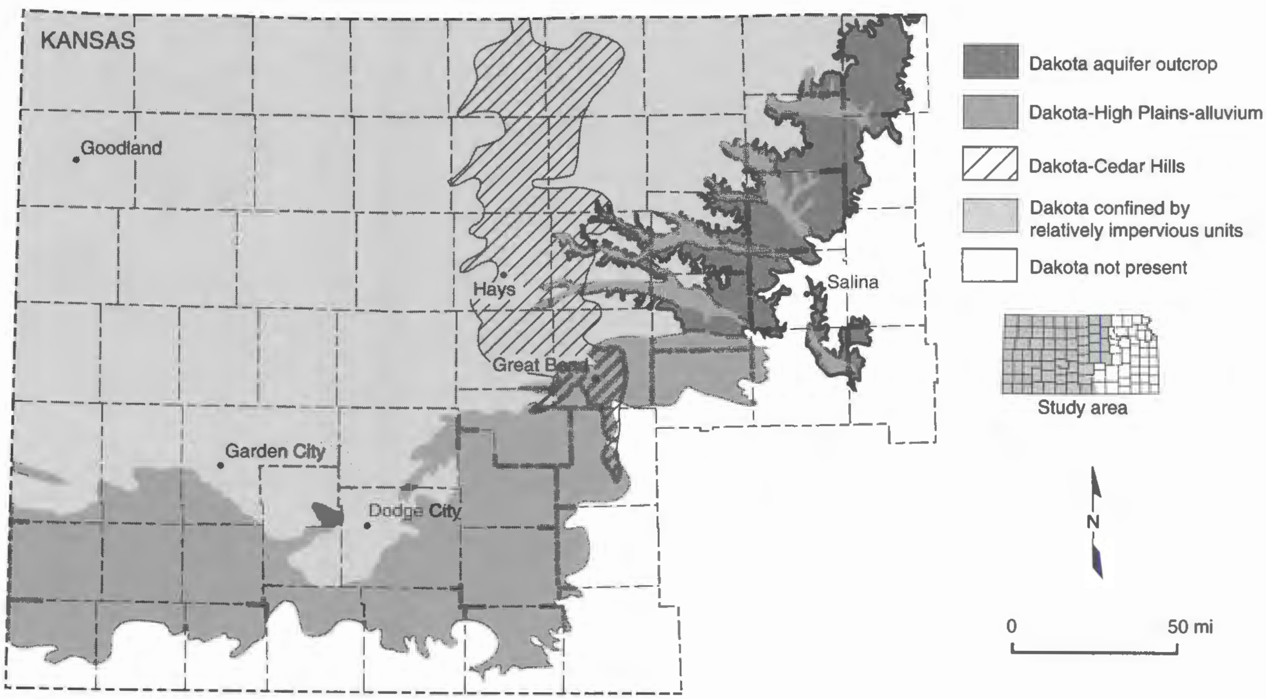

FIGURE 4.4—EXTENT OF THE CONFINED AND UNCONFINED DAKOTA AQUIFER IN KANSAS SHOWING AREAS OF HYDRAULIC CONNECTION WITH OTHER AQUIFER SYSTEMS.

diminishes toward the outcrop/subcrop belt. Within the last 10 million years, differential uplift and intense local dissection of the High Plains surface have created considerable local and regional topographic relief. Incisement is a common feature of the drainage in the Arkansas River basin in southeastern Colorado, and southern Kansas and the Smoky Hill, Saline, and Solomon river systems in north-central Kansas. Many of these river systems have cut down through the aquitard and into the geologic units that constitute the Dakota aquifer system. Consequently, the hydraulic-head difference between the Dakota and the overlying water table is less than 1,000 ft (305 m) in most of western and central Kansas and southeastern Colorado where the confined aquifer is relatively shallow. Here, local topographic relief is an important influence on ground-water flow in the Dakota aquifer.

The regional recharge area for the confined Dakota aquifer system is in the topographically elevated region of southeastern Colorado, south of the Arkansas River (figs. 4.5 and 4.6). Within this part of Colorado, Cenozoic uplift of the High Plains region and erosion by the Arkansas River and its tributaries removed most the Upper Cretaceous aquitard leaving the Dakota aquifer at the surface. The total recharge from precipitation depends on the downward movement of water below the root zone to the water table or seepage into exposed bedrock outcrops. Within this recharge area a part of the Dakota aquifer underlies and is hydraulically connected to the High Plains aquifer. The total amount of seepage downward into the Dakota from the High Plains depends on the hydraulic connection between the two aquifers and the hydraulic-head gradient. In fig. 4.5, most of the recharge is intercepted by *local flow systems* that discharge back to the surface drainage in the recharge area (Macfarlane, 1995). These local flow systems are shallow and have short flow-path lengths. Consequently, the age of ground water in this part of the system is generally less than 10,000 years (Macfarlane et al., 1995).

North of the Arkansas River and within the confined aquifer, ground water moves slowly northeastward towards the regional discharge area in central Kansas due to low aquifer transmissivity (Macfarlane, 1993). Over most of western Kansas, the vertical hydraulic conductivity of the overlying Upper Cretaceous aquitard is very low, on the order of 1 x 10^{-7} ft/day (3 x 10^{-8}m/day) or less (Macfarlane, 1993; Belitz and Bredehoeft, 1988). Freshwater recharge to the confined Dakota is negligible, less than 0.1% of the lateral flow within the aquifer. Most of the freshwater recharge to the confined Dakota enters where

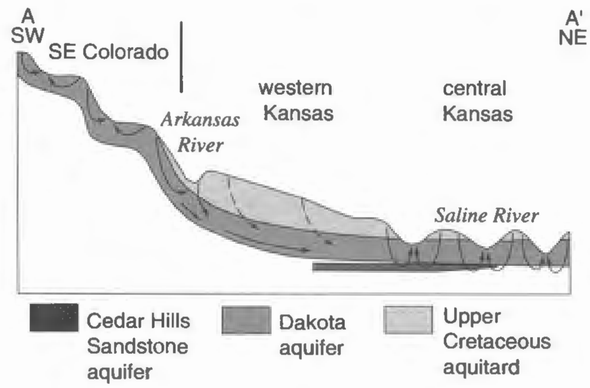

FIGURE 4.6—A CONCEPTUAL MODEL OF GROUND-WATER FLOW THROUGH THE CONFINED DAKOTA AQUIFER FROM THE REGIONAL RECHARGE AREA IN SOUTHEASTERN COLORADO TO THE REGIONAL DISCHARGE AREA OF CENTRAL KANSAS. Most of the recharge to the Dakota aquifer is routed back to the surface by local flow systems in central Kansas and southeastern Colorado.

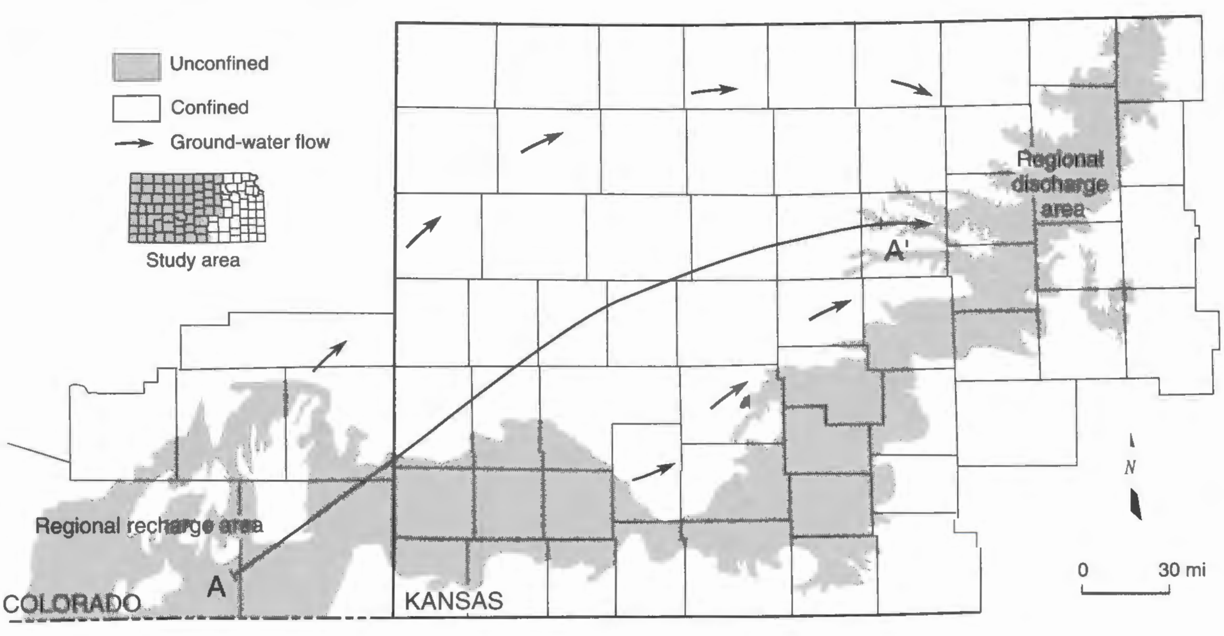

FIGURE 4.5—FLOW DIRECTIONS IN THE REGIONAL FLOW SYSTEM IN THE CONFINED DAKOTA AQUIFER FROM THE REGIONAL RECHARGE TO THE REGIONAL DISCHARGE AREA. The trace of the vertical cross section A-A´ shown in fig. 4.6 is indicated on this figure.

the aquitard is relatively thin and dissected near the outcrop/subcrop areas. Here, the vertical hydraulic conductivity is two to three orders of magnitude higher and recharge from overlying sources may amount to as much as 10% of the lateral flow within the aquifer (Smith and Macfarlane, 1994; Smith, 1995). In central Kansas, an additional source of recharge to the Dakota comes from the underlying Permian Cedar Hills Sandstone aquifer where both aquifers are hydraulically connected (fig. 4.6). The total recharge from this source amounts to less than 1% of the lateral flow in the upper Dakota aquifer.

Because of the low flow rates in the confined Dakota, variable rates of recharge from overlying sources, and the range in flow-path lengths, the age of ground water ranges from 10's to 100's of thousands of years nearer the outcrop/subcrop belt and may exceed a million years in far northwest Kansas (Macfarlane et al., 1995). Acting over time spans of millions of years, the cumulative flow moving downdip from the recharge area in southeastern Colorado has flushed the salinity from a large part of the confined aquifer in Kansas and in southeastern Colorado (Whittemore and Fabryka–Martin, 1992; Smith, 1995; Macfarlane et al., 1995). In northwest Kansas, the lateral flow of ground water has probably not been sufficient to remove the remnant salinity within the confined aquifer (fig. 4.7). The fresh-saltwater transition is a narrow band that cuts across the northwest corner of the state. To the northwest of the transition, total dissolved solids concentrations exceed 10,000 mg/L. In central Kansas, the total dissolved solids concentrations of the brines moving upward from the Cedar Hills Sandstone exceed 20,000 mg/L (figs. 4.6 and 4.7). Freshwater recharge from overlying sources has been insufficient to depress the fresh-saltwater interface much below the top of the upper Dakota aquifer (Smith, 1995). In this part of the state all of the Dakota aquifer is unusable, except perhaps for the uppermost part (fig. 4.7).

The main discharge area for flow from the confined Dakota aquifer is in the river valley systems in central Kansas where they cross the outcrop region (Macfarlane, 1993). In this part of the state, the flow from the regional and local systems mix and exit through fresh and saline water springs and seeps. Salt marshes associated with discharge to surface water are common features in the Saline, Solomon, and Republican river valleys of central Kansas (fig. 4.8). During low-flow periods when baseflow constitutes the bulk of stream discharge, the chloride concentration escalates rapidly causing deterioration of surface-water chemical quality (fig. 4.9). Elsewhere, the freshwater is discharged from the upper Dakota to the Arkansas, Pawnee, and Wet Walnut drainages (Macfarlane and Smith, 1994).

Ozark Plateau Aquifer System Hydrology

The regional recharge area for the Ozark Plateau aquifer system is in the topographically elevated Ozark region of southern Missouri (Macfarlane and Hathaway, 1987; Jorgensen et al., 1993; fig. 4.1). In this region, the outcrop area roughly coincides with the central part of the Ozark uplift. The recharge area for the Ozark Plateau aquifer system (see table 4.1) in Kansas is located nearer the crest of the uplift south of Springfield, Missouri. Where the Ozark aquifer crops out, recharge is from precipitation that has infiltrated below the root zone, seepage into outcrops, solution channels, and fractures. Elsewhere in the recharge area, seepage across the Ozark confining unit (see table 4.1) provides additional recharge to Ozark aquifer. As in the case of the Dakota, not all of the recharge that enters the aquifer system in its recharge area becomes regional flow in the confined aquifer. Jorgensen et al. (1996) estimate that slightly more than half of the infiltrated precipitation in the recharge area is discharged from local flow systems to streams.

Ground-water flow within the Ozark aquifer is gravity driven and is northwestward into the deeper confined part of the aquifer system in southeastern Kansas (fig. 4.10; Jorgensen et al., 1993). In southeastern Kansas, the flow from regional recharge area in the Ozarks of southern Missouri encounters basinal flow in the Western Interior Plains aquifer system (see table 4.1) moving eastward (Macfarlane and Hathaway, 1987; Jorgensen et al., 1993). Ground water in the Western Interior Plains aquifer system is a sodium-chloride brine with dissolved solids concentrations that exceed 20,000 mg/L (Macfarlane and Hathaway, 1987). Where these two water masses meet, a 20–30-mi-wide(32–48-km-wide), fresh-to-saline water transition zone stretches northeast to southwest across the region (fig. 4.11). Figure 4.12 illustrates the likely pattern of ground-water flow in the Ozark Plateau and Western Interior Plains aquifer systems in vertical cross section. Within the transition, the flow direction turns south toward Oklahoma. Well data from within the transition suggest that the freshwater forms a lens below which formation water has not been flushed from the aquifer systems (Macfarlane and Hathaway, 1987). Computer simulation of this part of the Western Interior Plains and Ozark Plateau aquifer systems in the vicinity of the transition zone suggests that ground water is discharged upward across the Permian–Pennsylvanian aquitard to the Neosho River and its tributaries (Jorgensen et al., 1996). Near the Neosho River in Kansas, upward discharge from both aquifer systems to the river causes upwelling of saltwater in both aquifers, resulting in a shallower base of the freshwater-flow system.

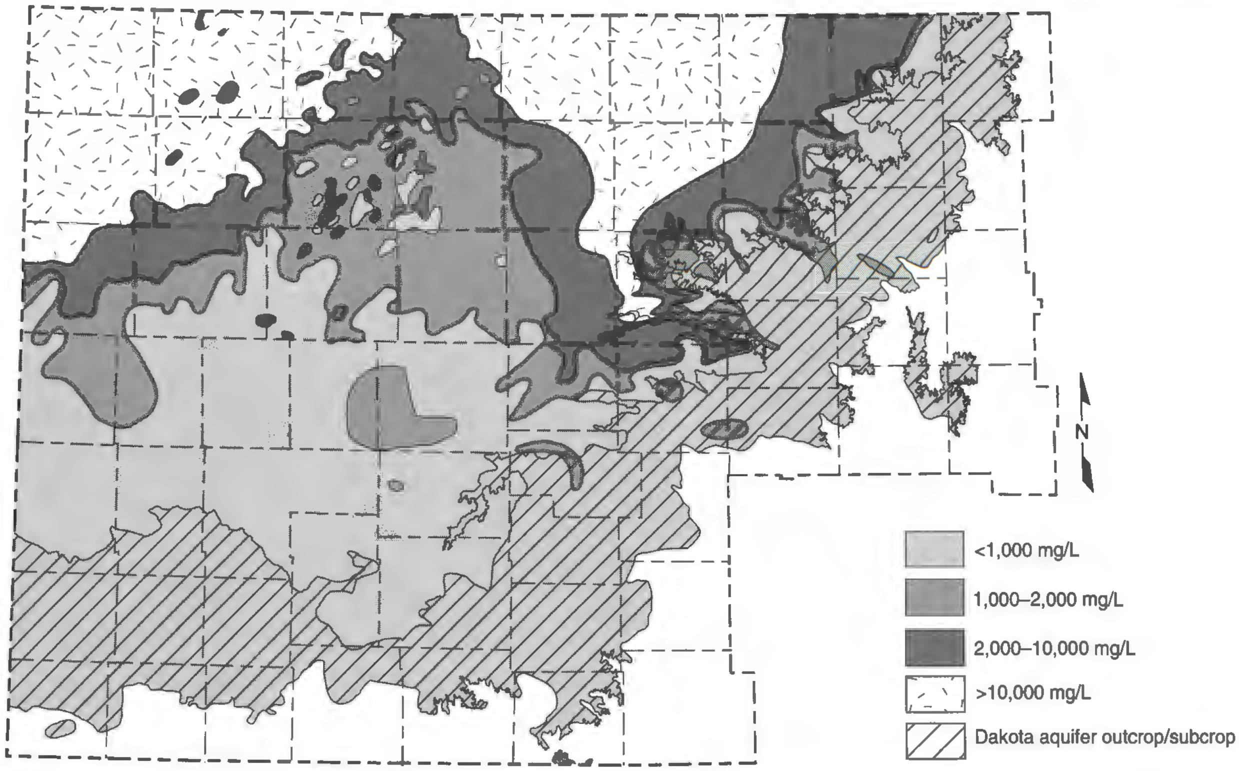

FIGURE 4.7—DISTRIBUTION OF TOTAL DISSOLVED SOLIDS (TDS) CONCENTRATIONS IN GROUND WATERS IN THE UPPER DAKOTA AQUIFER IN WESTERN AND CENTRAL KANSAS. Waters less than 1,000 mg/L TDS are defined as fresh. Water with 1,000-2,000 mg/L TDS is usable for many purposes but is less desirable than freshwater. A concentration of 10,000 mg/L TDS is defined in the State regulations of the Kansas Corporation Commission as the upper limit of usable water; above 10,000 mg/L, a water is classified as unusable or mineralized.

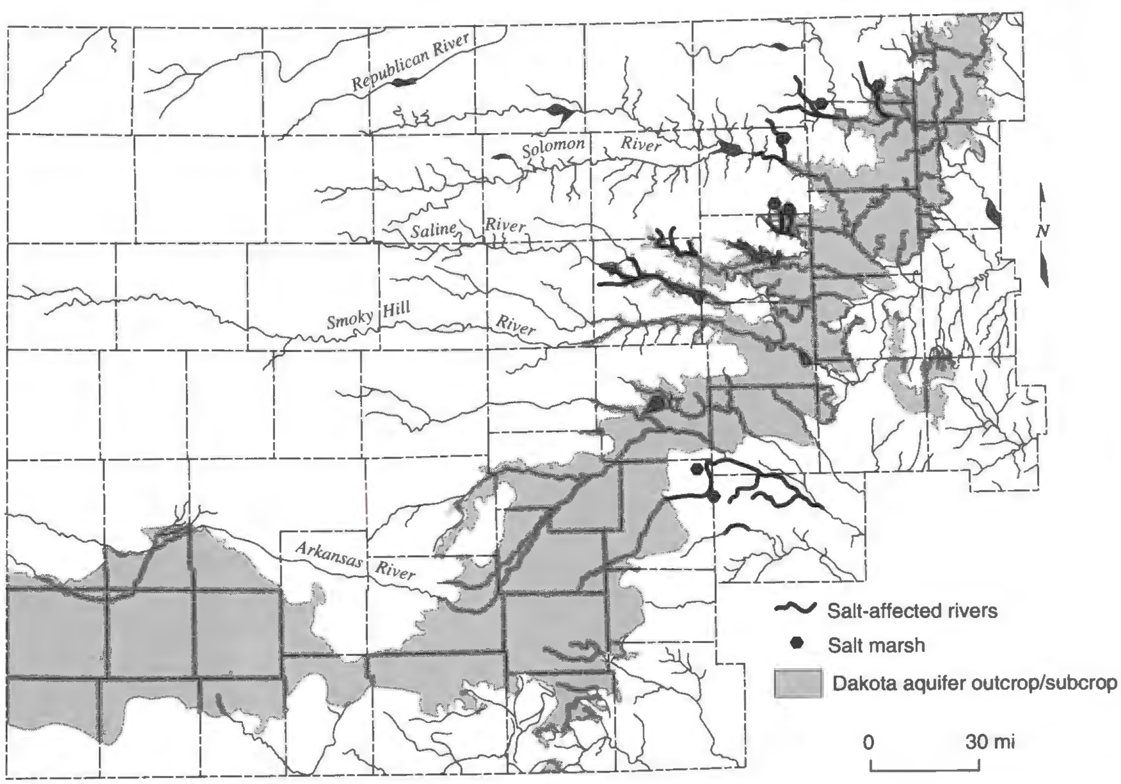

FIGURE 4.8—DISTRIBUTION OF SALT MARSHES, SALT SEEPS, AND SALT-AFFECTED REACHES OF STREAMS IN CENTRAL KANSAS.

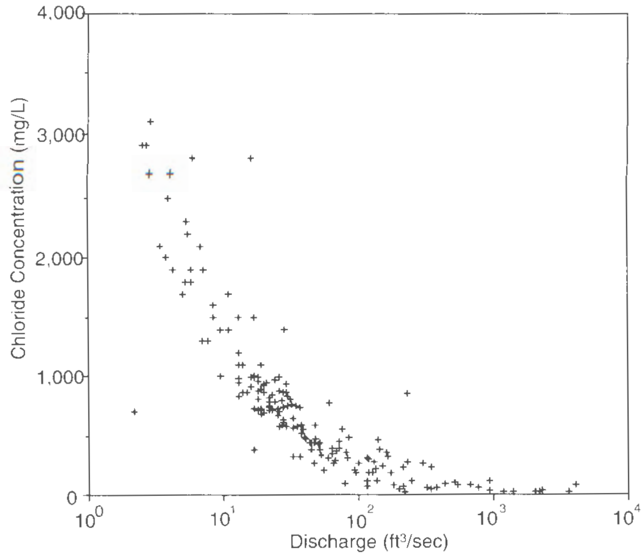

FIGURE 4.9—STREAM DISCHARGE VS. CHLORIDE CONCENTRATION AT THE SALINE RIVER GAGING STATION NORTH OF RUSSELL, KANSAS, FOR THE PERIOD 1966–1975.

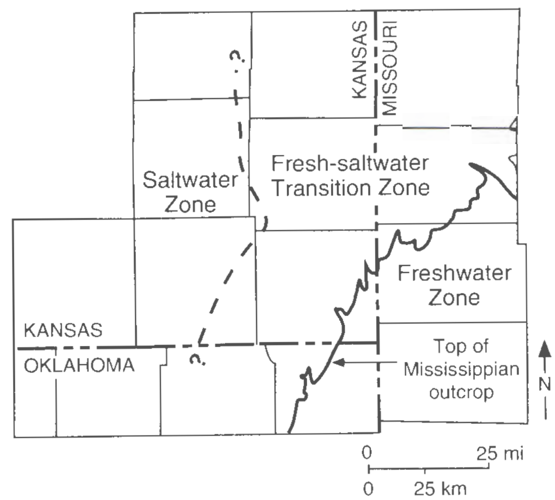

FIGURE 4.11—EXTENT OF THE FRESH-SALTWATER TRANSITION ZONE IN THE OZARK PLATEAU AQUIFER SYSTEM IN SOUTHEASTERN KANSAS AND ADJACENT AREAS OF MISSOURI AND OKLAHOMA. The dashed line is the 2,500-mg/L isochlor line. Modified from Macfarlane and Hathaway (1987).

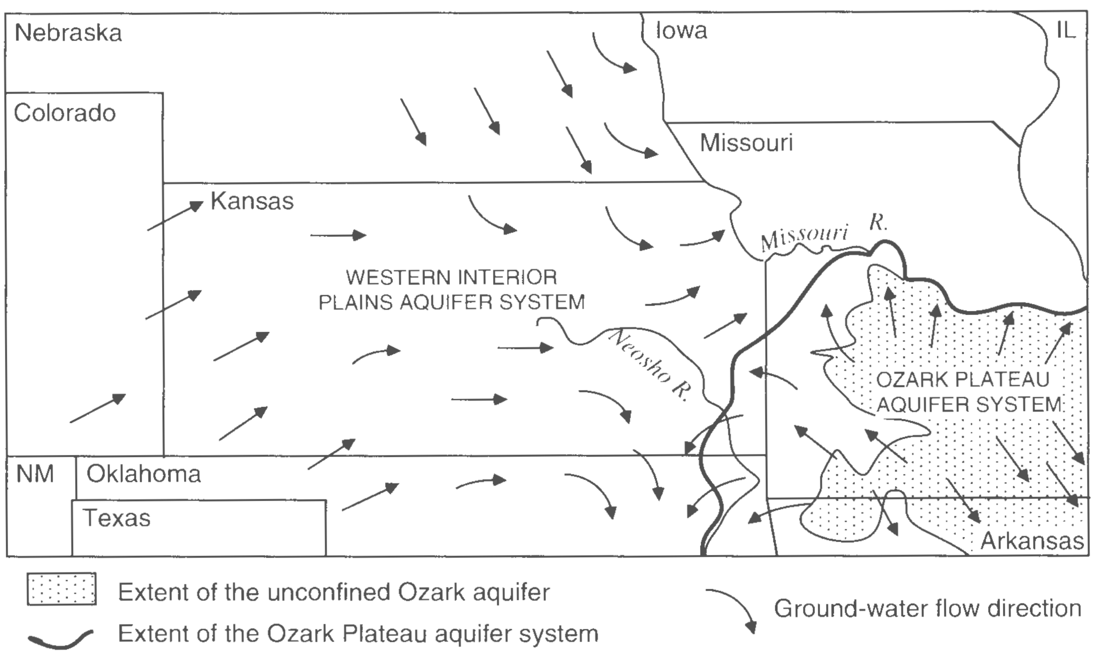

FIGURE 4.10—GROUND-WATER-FLOW DIRECTIONS IN THE OZARK PLATEAU AND WESTERN INTERIOR PLAINS AQUIFERS. In southern Kansas most of the withdrawals of usable ground water come from the upper part of the Ozark aquifer (the lower aquifer unit of the Ozark Plateau aquifer system). The extent of the unconfined Ozark aquifer coincides with the main regional recharge area for the Ozark system.

Impact of Ground-water Withdrawals from Confined and Semi-confined Aquifer Systems

Well Hydraulics under Ideal Conditions

Ground water must be released from storage within the aquifer and move toward a pumping well in order for the well to produce. As water is removed from the well by pumping, the hydraulic head in the well and in the aquifer adjacent to the well screen is decreased. This causes ground water in the aquifer to move laterally toward the well. The drawdown is the decline of water level observed in wells screened in the aquifer being pumped. The amount of drawdown is a maximum at the pumping well and diminishes to zero some distance away. The region affected by drawdown from pumping is referred to as the cone of depression (fig. 4.13).

The flow of ground water to a pumping well and the potential well yield are determined by the transmissivity and the storativity properties of the confined aquifer framework (Freeze and Cherry, 1979). The transmissivity of a confined (or an unconfined) aquifer is the product of the hydraulic conductivity of the aquifer and its thickness:

$$T = Kb, \qquad \text{(eq. 4.1)}$$

where T is the transmissivity (L^2/T), K is the hydraulic conductivity (L/T), and b is the aquifer thickness (L). The hydraulic conductivity is a measure of the overall resistance of the aquifer framework to the flow of water and the properties of the moving fluid (Domenico and Schwartz, 1990). Hence, transmissivity is a measure of the ability of the aquifer to transmit water through its entire thickness.

For the upper Dakota aquifer, transmissivities vary widely and generally increase from west to east because of the eastward increase in hydraulic conductivities and net thickness of sandstone. The occurrence of thicker and more permeable units in central Kansas may result from the dominance of alluvially deposited sandstones in the upper Dakota (Macfarlane et al., 1994). In southwestern Kansas, the reported transmissivities are less than 2,100 ft^2/day (195 m^2/day) (Watts, 1989). In central Kansas, transmissivities of the thicker river-deposited sandstones range from 2,000 to more than 7,000 ft^2/day (186 to more than 650 m^2/day) (Lobmeyer and Weakly, 1979; Wade, 1991). Only a few pumping tests have been conducted in the Ozark aquifer in southeastern Kansas and adjoining areas of Missouri and Oklahoma (Macfarlane and Hathaway, 1987). The reported values range from 34,000 ft^2/day (3,159 m^2/day) at Pittsburg, Kansas, to 540 ft^2/day (50 m^2/day) at Webb City, Missouri. In comparison, the transmissivities reported for pumping tests in High Plains and alluvial valley aquifers are generally higher, reflecting the more permeable nature of the aquifer. Reported values range from 1,400 to 62,000 ft^2/day (130 to 5,760 m^2/day) for the High Plains aquifer (Stullken et al., 1985). Reported transmissivities for the coarser alluvial deposits in Kansas are within the range of values reported for the High Plains aquifer.

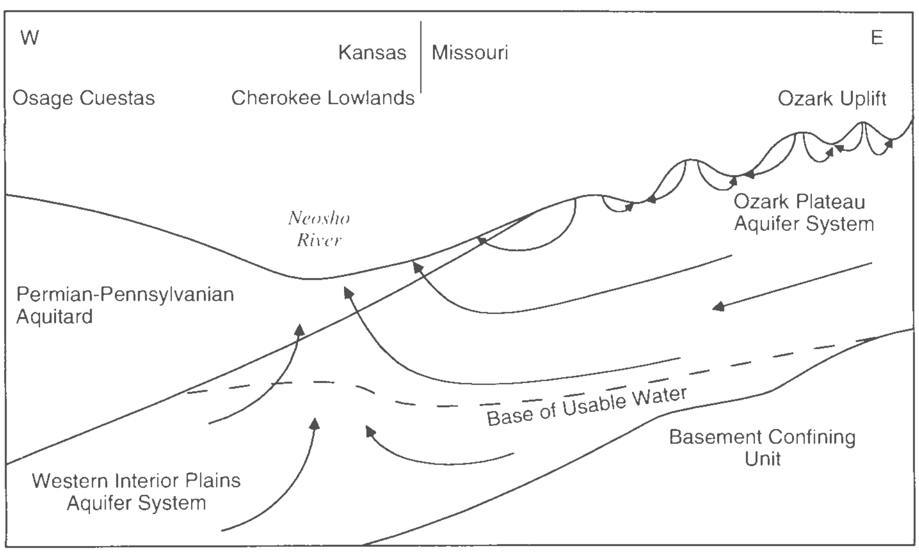

FIGURE 4.12—VERTICAL CROSS SECTION SHOWING GROUND-WATER-FLOW PATTERNS IN THE VICINITY OF THE FRESH TO SALINE WATER TRANSITION ZONE SEPARATING THE WESTERN INTERIOR PLAINS AND OZARK PLATEAU AQUIFER SYSTEMS.

The *storativity* of a confined aquifer is the product of the specific storage and the aquifer thickness:

$$S = S_s b, \qquad \text{(eq. 4.2)}$$

where S is the storativity (dimensionless), and S_s is specific storage ($1/L$). The release of water from storage in confined aquifers is analogous to the process of consolidation in soil mechanics. Water is released from storage by (1) the expansion of water under confinement due to the decrease in fluid pressure due to pumping, and (2) the consolidation (compaction) of the confined aquifer framework due to increase in overburden stress on the aquifer framework. These two phenomena are expressed jointly in the *specific storage* term:

$$S_s = \rho g\,(\alpha + n\,\beta), \qquad \text{(eq. 4.3)}$$

where ρ is the water density (M/L^3), g is the acceleration of gravity (L/T^2), n is the porosity (dimensionless), and α and β are the compressibilities of the aquifer framework and the water, respectively (LT^2/M). In eq. 4.3 the loss of porosity due to changes in grain packing of the framework is reflected in α and the expansion of the water is reflected in the $n\,\beta$ term. In most cases expansion of the water is the most important influence on the specific storage.

When water is released from storage in the aquifer under confined conditions, no loss of saturated thickness occurs, only a decrease in the fluid pressure. The cone of depression around the pumping well describes the decrease in the fluid pressure within the aquifer. In contrast, ground water is released from an unconfined aquifer by the combined effects of partial dewatering of the void space in the fully saturated part of the aquifer and gravity drainage to the water table from the unsaturated zone. The specific yield describes the storage property for an unconfined aquifer and is the volume of water that is released by a unit bulk volume of the aquifer per unit surface area of aquifer per unit decline in the water table (Freeze and Cherry, 1979). Because only drainable water in the pores is released, the specific yield is always less than the porosity. In contrast to the confined condition, the release of water from an unconfined aquifer during pumping causes a decrease in saturated thickness because of the partial dewatering of the aquifer adjacent to the well.

Because the mechanisms that allow water to be released from confined and unconfined aquifers are fundamentally different, the potential recoverable volume of water from each type is drastically different. For example, the storativities of confined aquifers typically range from 5×10^{-3} to 5×10^{-5} (Freeze and Cherry, 1979). In Kansas, the storativities of the Dakota and the Ozark aquifers generally fall at the lower end of this range. In contrast the reported specific yield values for most Kansas aquifers are in the range of 0.05–0.20. The amount of water that can be released to a pumping well withdrawing water from either a confined or unconfined aquifer is (Fetter, 1994)

$$V = S\,A\,(\Delta h), \qquad \text{(eq. 4.4)}$$

where S is either the specific yield or the storativity, A is the surface area overlying the aquifer affected by a decline in the hydraulic head (L^2), and Δh is the hydraulic-head decline experienced due to the withdrawal (L).

In ideal confined and unconfined aquifer systems of infinite areal extent with no regional hydraulic-head gradient, the cone of depression that develops during pumping is circular in plan view. As a result, ground water moves toward the center of the cone of depression from all directions uniformly. The drawdown within, and the size of the cone of depression depend in part on the transmissivity and storage properties of the aquifer (Freeze and Cherry, 1979). Because the storage is less, the hydraulic-head drawdown due to pumping in eq. 4.4 is greater at the well and the cone of depression is more areally extensive in a confined than in an unconfined system.

Where a regional hydraulic-head gradient occurs, the shape of the cone of depression is parabolic in plan view (fig. 4.14). The open end of the parabola is directed upgradient and defines a capture zone. The extent of the capture zone delineates the portion of the flow system that

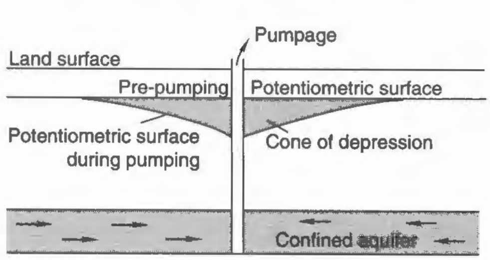

FIGURE 4.13—THE CONE OF DEPRESSION THAT RESULTS FROM PUMPING WATER FROM A CONFINED AQUIFER. Pumping decreases the fluid pressure and, consequently, the hydraulic head (potentiometric surface) in the aquifer.

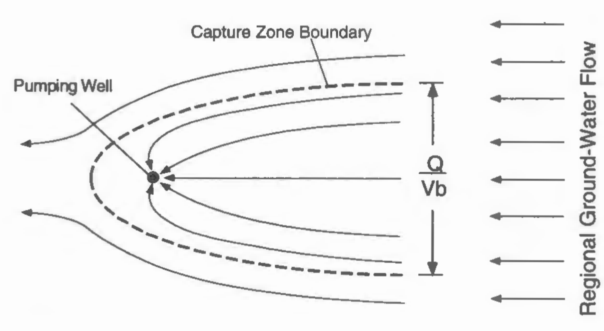

FIGURE 4.14—THE CAPTURE ZONE CREATED BY A PUMPING WELL WITHDRAWING WATER AT A RATE Q IN A REGIONAL FLOW SYSTEM OF THICKNESS b. The aquifer is assumed to be homogenous and isotropic. The Darcian velocity of flow is V. The width of the capture is a function of the pumping rate, the Darcian velocity, and the aquifer thickness. Modified from Walton (1985).

supplies ground water to the pumping well. At steady-state, the rate of withdrawal from the well balances the flow rate moving toward the well in the capture zone. All else being equal, the lower the hydraulic conductivity of the confined aquifer the greater width of the capture zone in plan view (Walton, 1985).

In general, confined aquifer systems are much more sensitive than unconfined systems to well pumping. The *hydraulic diffusivity*, D (L^2/T), is a measure of the sensitivity of an aquifer to hydrologic perturbations and is calculated as

$$D = T/S = K/S_s, \qquad \text{(eq. 4.5)}$$

where S is either the storativity or the specific yield. Higher values of hydraulic diffusivity indicate that local perturbations of the flow system will be transmitted across a larger part of the aquifer than lower values. Figure 4.15 clearly shows that on the whole, the confined aquifer systems in Kansas are more sensitive to the perturbations associated with pumping than are the unconfined aquifers. Locally, the relatively higher values of diffusivity indicate that the cone of depression associated with a pumping well will have a larger areal extent and will develop faster in confined than in unconfined aquifers. If pumping wells are spaced too closely together, their capture zones will overlap, causing mutual interference between the wells. Mutual interference decreases the lateral flow toward each of the pumping wells producing additional drawdown in the aquifer. If both wells continue pumping for longer periods of time, local depletion may occur as less and less of the produced water in both wells comes from areas outside of the coalescing cones of depression. Hence, the spacing between pumping wells needs to be greater in the confined than in the unconfined aquifers to minimize the effect of mutual interference.

In the Dakota aquifer of Kansas, hydraulic-diffusivity values range over more than three orders of magnitude and the sample of 22 values appears to be log-normally distributed (fig. 4.16). Hydraulic diffusivities in western Kansas are generally less than the geometric mean (the average of the log-normal distribution) of the available data. In contrast, diffusivities have a larger range of values in central Kansas. These data suggest that for the same rates of withdrawal, the well spacing may need to be larger in central Kansas than in western Kansas to minimize the impact of mutual interference effects.

Effects of Aquifer Heterogeneity on Well Hydraulics

Aquifer heterogeneity further modifies the impact of well pumping on real flow systems. Aquifer heterogeneity is caused by extreme and systematic spatial variations in the hydraulic conductivity of the aquifer framework. For example, the Dakota aquifer consists of lenticular, permeable sandstone bodies that may be hydraulically connected or isolated. These sandstone bodies are encased in relatively impervious mudstone. Because the mudstones are much less permeable than the sandstones by at least several orders of magnitude, the boundaries of the sandstone bodies form local hydrologic barriers to flow as pumping continues. Analysis of available pumping-test results in Kansas suggests that even for long periods of continuous pumping over several days, the contribution of water from the mudstones to the adjacent aquifer is negligible (Macfarlane et al., 1994). These barriers channelize the flow within these ribbonlike bodies during the pumping period. As a result, the region of the aquifer that experiences drawdown may extend out from the well along the length of these bodies for several miles or more in both the upgradient and downgradient directions. Other hydraulically connected sandstone bodies may also experience some drawdown during pumping. However, in the direction perpendicular to the long axis of these bodies, the drawdown may only extend to its edge. In some cases this may be less than a mile away from the pumping well (fig. 4.17). In the figure,

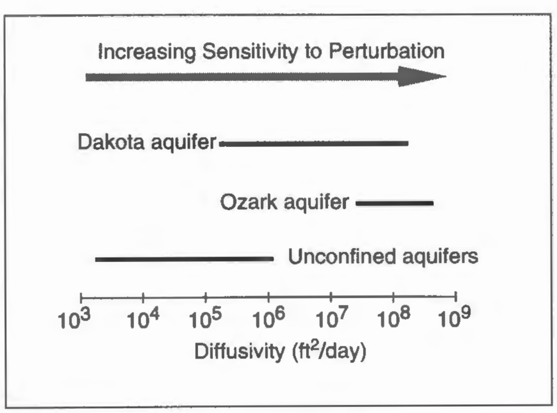

FIGURE 4.15—THE RANGE OF DIFFUSIVITIES OF THE MAJOR CONFINED AND UNCONFINED AQUIFER SYSTEMS.

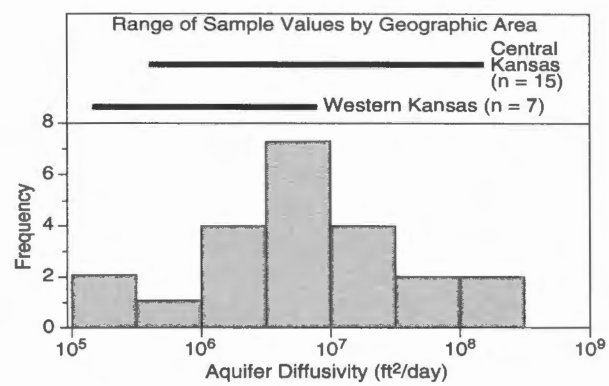

FIGURE 4.16—DISTRIBUTION OF DAKOTA AQUIFER DIFFUSIVITIES IN KANSAS. The available data suggest a log-normal distribution with a geometric mean value of 6.0 x 10^6 ft²/day. The central Kansas diffusivities show a wider range than the data from western Kansas with a higher geometric mean.

the relatively close proximity of a pumping well to these hydrologic barriers accelerates the water-level drawdown with time in nearby observation wells. If two pumping wells are spaced even a few miles apart and are withdrawing water from the same sandstone body, they will likely experience mutual interference (fig. 4.18).

Sources of Water to Pumping Wells in Confined-aquifer Systems

All the water withdrawn by a pumping well in a confined aquifer comes either from storage or capture. (See Chapter 2 in this volume for a more detailed discussion of capture.) Initially, water produced by the well comes entirely from storage in the aquifer adjacent to the well. As the well continues to pump, more and more of the aquifer experiences water-level declines. Eventually, these declines propagate to either the recharge or the discharge area, or both, producing "capture," given sufficient time. When this happens, additional recharge enters or the discharge is decreased from the aquifer system, resulting in an additional source of water added to the aquifer to balance the withdrawal. For confined aquifers, recharge and discharge *include* flows to and from other hydraulically connected aquifers. Capture is the sum of the increase in recharge and the decrease in discharge that results from the pumping. As the well continues to pump, more and more of the water produced by the well is replaced by induced recharge to the aquifer from surface water or other sources (see fig. 2.6 in Chapter 2, this volume).

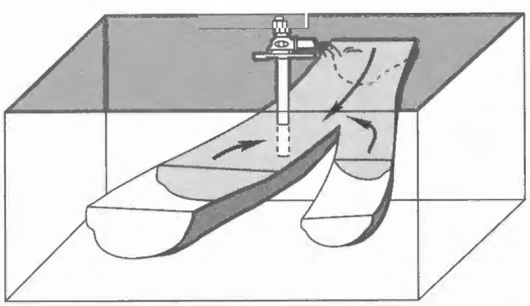

FIGURE 4.17—GROUND-WATER FLOW TO A PUMPING WELL IN A RIVER-DEPOSITED SANDSTONE AQUIFER. Ground-water flow follows the axis of the channel. The effects of ground-water withdrawals may be felt a long distance away from the pumping well depending on the geometry of the sandstone body and its hydraulic diffusivity.

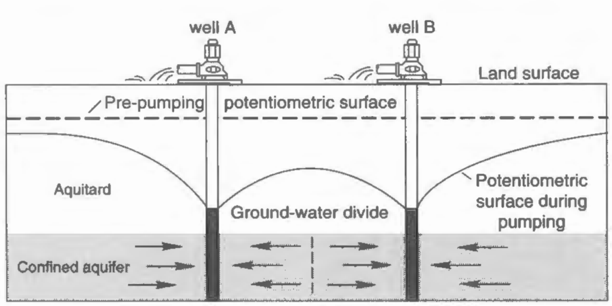

FIGURE 4.18—THE MUTUAL INTERFERENCE THAT DEVELOPS WHEN PUMPING WELLS ARE SPACED TOO CLOSELY TOGETHER IN A CONFINED AQUIFER. Note how the drawdown is greater at the ground-water divide between the wells than at the same point outboard from each well.

The additional recharge coming from the recharge area results from reduced local discharge to streams in the discharge area or from another hydraulically connnected aquifer. The generation of capture by pumping does not create any "new" water, but is merely a re-allocation of the amounts in the total hydrologic budget for a region. All else being equal, the proportion of recharge added to or decreased discharge from the confined aquifer will depend on whether the well is located closer to the source of the recharge or the discharge area. Thus, in the case of the confined upper Dakota aquifer, if the well is located near the fresh/saltwater transition or near the regional discharge area, withdrawals may induce significant saltwater intrusion by increased upward leakage from the lower Dakota or the Cedar Hills Sandstone aquifer. Likewise, withdrawals from the confined aquifer just downgradient of the Arkansas River in southeastern Colorado and adjacent southwestern Kansas or near the area of hydraulic connection with the overlying High Plains aquifer will likely induce additional recharge into the confined Dakota.

The time it takes to generate capture depends on the distance to the source of recharge or the discharge area and the hydraulic diffusivity of the aquifer (Theis, 1940; Glover, 1974). For example, from fig. 2.6 in Chapter 2 of this volume, the dimensionless time, $4Tt/x^2S$, required for capture to be added to a uniform confined aquifer from a source of recharge equal to 50% of the total withdrawal by pumping is approximately 4.4. In this expression, t is the length of the pumping period, and x is the distance from the source of recharge or discharge area. Because the hydraulic diffusivity, D, is equal to T/S, we can solve for the length of the pumping period required in terms of x and D by rearranging terms:

$$t = 1.1\ x^2/D. \qquad \text{(eq. 4.6)}$$

This relationship is plotted in fig. 4.19 for a number of distances from the recharge or discharge areas of the uniform confined aquifer. Using the geometric mean values of diffusivity for the confined Dakota aquifer in western and central Kansas, the plot shows that wells in western Kansas have to pump longer by almost an order of magnitude to achieve the same effect as the wells in central Kansas. For example, the time required to induce recharge equal to 50% of the withdrawal rate 5 mi (8 km) away from the recharge or discharge area in the confined aquifer is approximately one year in western Kansas. However, the same effect can be achieved in central Kansas in approximately one month.

If the heterogeneity of the Dakota is considered in this example, the perturbation of the flow field due to pumping is constrained by the boundaries of the sandstone bodies and is not omnidirectional as it would be in a uniform aquifer. Propagation of the effects of pumping also depends on the hydraulic conductivity of the framework near the boundary between adjacent sandstone bodies where they are physically in contact. For example, if there is a significantly less-permeable layer at the bounding surface between adjacent sandstones, the hydraulic connection between them may be poor even though the sandstones are permeable. Thus, the actual time required to generate significant capture may be considerably less or considerably more depending on the connectivity of the sandstone bodies in the aquifer framework.

Hydrographs of several wells located within the confined Dakota aquifer and near the area of hydraulic connection with the overlying High Plains aquifer demonstrate that capture is occurring due to withdrawals. Figure 4.20 shows the location of a production and an observation well located approximately 6 mi (10 km) apart. Both wells are in Ford County and are screened in the upper Dakota aquifer. The production well (B in fig. 4.20) is 5 mi (8 km) away from where the Dakota is hydraulically connected to the High Plains aquifer to the south. The observation well (A in fig. 4.20) is about 4 mi (6 km) away from where the Dakota discharges to Saw Log Creek to the north. The production well is an irrigation well that has been in intermittent operation since 1967. The hydraulic heads in both the production and the observation wells show a decline within the confined aquifer for the first seven years of record until 1976 (fig. 4.21). After this date, the hydraulic heads are fairly stable except for seasonal fluctuations. The downward trend in water levels indicates that up to about 1976, withdrawals were removing water from storage in the confined Dakota. This resulted in hydraulic-head declines in the aquifer that had not reached the area of hydraulic connection with the High Plains aquifer and the local discharge area in Saw Log Creek. After this time, continued withdrawals appear to have generated sufficient capture to stabilize water levels in the Dakota at a new equilibrium level.

Another similar example comes from the upper Dakota aquifer in western Hodgeman County, Kansas (fig. 4.20). The well (C in fig. 4.20) is 17 miles (27 km) from the area of hydraulic connection with the High Plains aquifer in Gray County to the south and 22 miles (35 km) away from the local discharge point beneath the alluvium in the Pawnee River valley to the east. The hydrograph shows a steady decline of water levels in the confined Dakota from 1968 to 1983 (fig. 4.22). The period following is one of fluctuating water levels associated with seasonal pumping. As in the previous example, the data suggest that ground water was being removed mostly from storage until about 1983. After 1983, a sufficient amount of induced recharge was added to the aquifer to stabilize the water levels in the well during nonpumping periods and, as in the previous example, to establish a new dynamic equilibrium between recharge to and discharge from the aquifer.

The results in fig. 4.19 also show that to a first approximation, withdrawals from the confined Dakota greater than 25–50 miles (40–80 km) away from a recharge or discharge area will probably not generate significant capture to the aquifer for a planning horizon of about 30 years. Thus, withdrawals must come almost

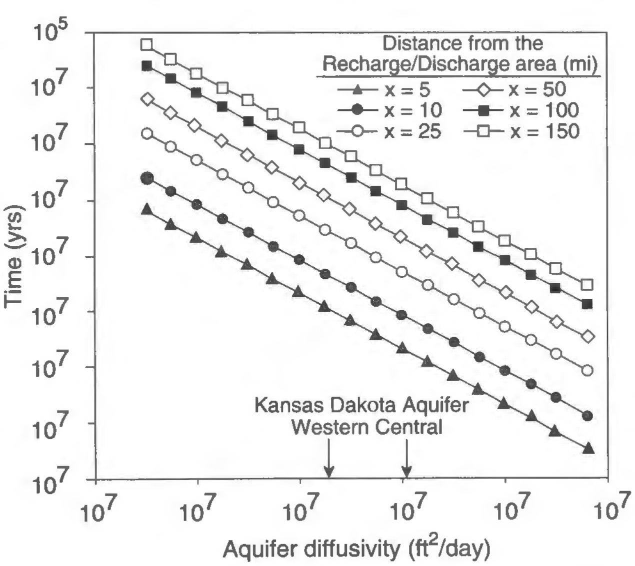

FIGURE 4.19—AQUIFER DIFFUSIVITY VS. THE TIME REQUIRED FOR THE WELL TO GENERATE INDUCED RECHARGE EQUAL TO 50% OF ITS DISCHARGE for a number of distances from either the recharge or the discharge area of a confined aquifer.

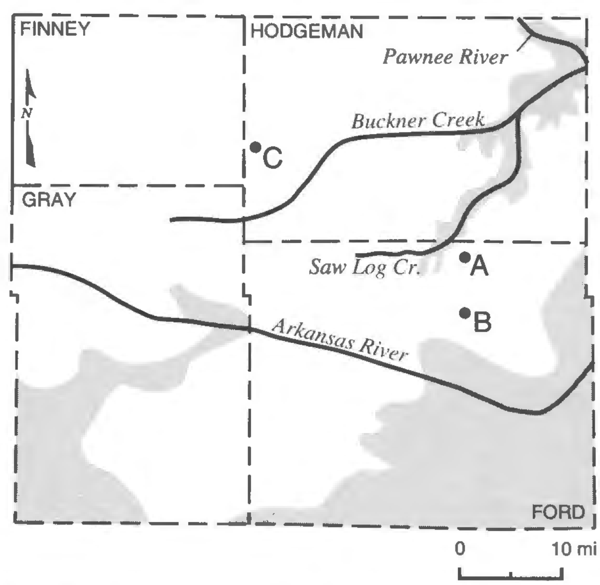

FIGURE 4.20—LOCATION OF THE HODGEMAN AND FORD COUNTY WELLS DISCUSSED IN THIS PAPER. Observation well A is located in the NW NW NW, sec. 12, T. 25 S., R. 23 W., production well B in SE NE SE sec. 10, T. 26 S., R. 23 W., and Well C in SW SW SW, sec. 7, T. 23 S., R. 26 W. The shaded areas on the map indicate areas of hydraulic connection with the High Plains or alluvial aquifers in the Pawnee River drainage.

entirely from aquifer storage in these areas and will eventually cause localized areas of depletion. A computer simulation of ground-water withdrawals from the Dakota aquifer in Ellis County was conducted to assess the effects of pumping on the 12-township (432-mi^2 or 1,106-km^2) model region (Smith, 1995). The Dakota was treated as a heterogeneous aquifer with regions of relatively high and low transmissivity determined from geostatistical analysis of borehole logs. The modeling results showed that after 10 years of continuous pumping at 150 gpm (9.5 L/s) by one well in a high transmissivity zone, all the water was produced from aquifer storage with no additional recharge coming from the overlying or underlying unit. At the end of the simulation period, the resulting cone of depression covered a large part of the modeled area and extended out from the pumping well in an east-west direction up to 12 miles (19 km) and in a north-south direction to 3 miles (5 km). More than 100 ft (30 m) of drawdown was produced at the pumping well.

Semi-confined Conditions in the High Plains Aquifer

Unconsolidated deposits of gravel, sand, silt, and clay occur as discontinuous lenses and layers throughout the High Plains aquifer in Kansas (Stullken et al., 1985). Semi-confined conditions may exist locally in the High Plains aquifer where more permeable sections of the aquifer are interbedded with multiple less-permeable clay and silt layers. The unconsolidated clay and silt layers generally have a higher vertical hydraulic conductivity than their lithified equivalents. Hence, the vertical flows across these layers can be a significant contributor of water to semi-confined aquifers. Hydrographs of a significant number of widely distributed wells in the High Plains aquifer suggest that local semi-confined aquifer conditions are widespread.

In parts of the aquifer that are largely semi-confined, ground-water withdrawals produce much larger declines in hydraulic head during the pumping season than in the unconfined part of the aquifer (Gutentag et al., 1972). The annual hydraulic-head fluctuations in semi-confined aquifers may approximate the fluctuations experienced in confined aquifer systems that are affected by seasonal withdrawals. Figure 4.23 shows the hydrographs of a shallow and a nearby deep well in the High Plains aquifer near Garden City, Kansas, taken from Gutentag et al. (1972). The annual fluctuation of water level in the shallow well is less than 10 ft (3 m), but is more than 20 ft (6 m) in the deep semi-confined aquifer. Due to limited extent of the confining layers, the large drop in hydraulic head from seasonal withdrawals induces significant

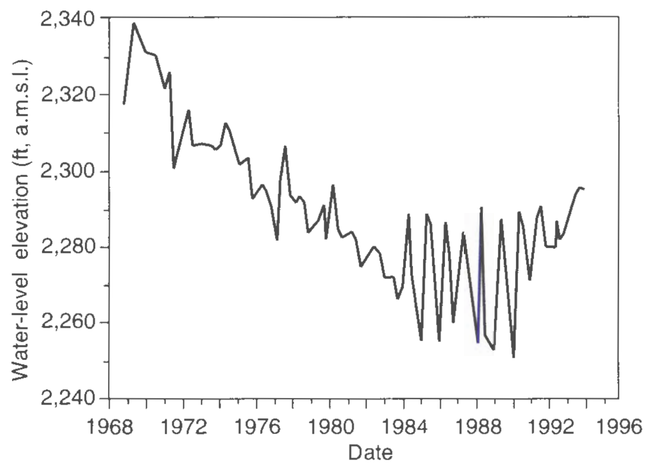

FIGURE 4.22—CHANGES IN HYDRAULIC HEAD IN AN OBSERVATION WELL FROM 1968 TO 1994. The well (C in fig. 4.20) is screened in the upper Dakota aquifer in Hodgeman County, Kansas, and is in use seasonally as a high-capacity well.

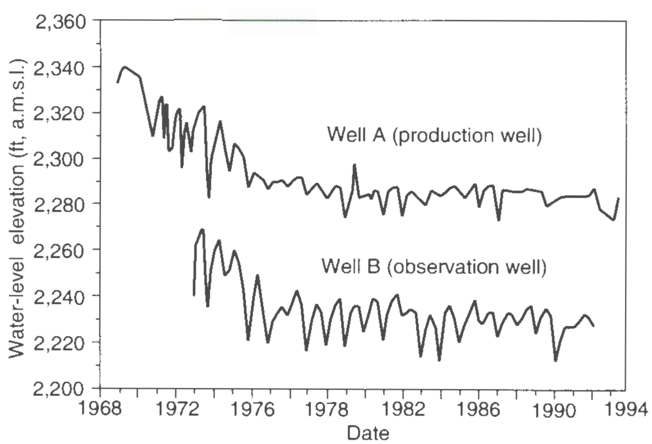

FIGURE 4.21—HYDROGRAPHS OF WELL A (SE NE SE SEC. 10, T. 26 S., R. 23 W.) AND WELL B (NW NW NW SEC. 12, T. 25 S., R. 23 W.) IN THE UPPER DAKOTA AQUIFER OF FORD COUNTY, KANSAS. In fig. 4.20 the wells are approximately 6 mi (10 km) apart.

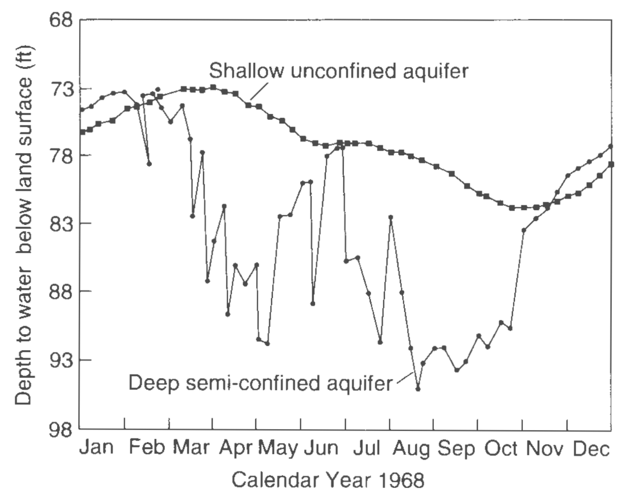

FIGURE 4.23—HYDROGRAPHS OF A SHALLOW AND NEARBY DEEP WELL IN THE HIGH PLAINS AQUIFER AT THE IRRIGATION FARM, GARDEN CITY EXPERIMENT STATION, GARDEN CITY, KANSAS. From Gutentag et al. (1972).

recharge from the unconfined to the semi-confined part of the aquifer. Leakage into the semi-confined aquifer also is induced due to the increased hydraulic-head difference across the confining layers. This results in a partial or complete rebounding of the hydraulic head within the semi-confined aquifer during the nonpumping season. If withdrawals are greater than the capture, the hydraulic head will not totally rebound each year and the pattern of water-level fluctuations may not reflect regional changes in the unconfined aquifer over longer periods of time.

Sustainability Issues in the Management of Confined-aquifer Systems

Sustainability implies the attainment of a new dynamic equilibrium under conditions of widespread development. Under sustainability, an approximate balance exists between recharge, discharge, and withdrawals from the aquifer system. The most direct evidence of this new balance is long-term stability of hydraulic heads in the aquifer that are lower than they were under predevelopment conditions. At that point, recharge into the aquifer increases and discharge from the aquifer decreases, producing capture that is equivalent to the amount of water being withdrawn.

If the production wells are distant from sources of recharge or discharge, the generation of capture is unlikely within a time frame that is practical. Where the High Plains aquifer is present, additional significant freshwater recharge to the confined Dakota is unlikely because of the low vertical-hydraulic conductivity of the overlying aquitard. Hence, all of the water withdrawn from the aquifer will come from storage. Meaningful management plans in this part of the system should be premised on an acceptable rate of water-level decline within the planning period. The primary management tools to control declines are well spacing, restrictions on the rates of withdrawal from the aquifer, and artificial recharge. Depletion of the aquifer will occur if production wells are too close together and if the rates of withdrawal from the aquifer are unregulated. Smith (1995) demonstrated that in the confined upper Dakota aquifer, coalescing cones of depression form quickly when wells pumping continuously at 100 gpm (6.3 L/s) are spaced from 1 to 4 miles (1.6–6 km) apart. After 10 years, larger drawdowns than would be expected from a single pumping well are produced and a much larger area of the aquifer is affected by the withdrawals. Taking into account the heterogeneity of the upper Dakota in Ellis County, Smith recommended well spacings 20 miles (32 km) in an east-west direction and 5 miles (8 km) in a north-south direction to avoid significant mutual interference problems.

Is sustainability a viable concept that can be used to manage the Kansas confined aquifer systems? As we have seen, the attainment of a dynamic equilibrium may be possible only in regions of the aquifer that are close to either the regional recharge/discharge areas or to areas of hydraulic connection with other aquifer systems. Several examples have been presented that demonstrate a new dynamic equilibrium has been established locally in the confined aquifer. The time to attain this new equilibrium depends on the distance away from the source of recharge or discharge and the properties of the aquifer. Management on the basis of sustained yield may be more realistic in this part of the confined system for planning horizons on the order of a few decades.

Ultimately, however, sustainability is not a viable management concept for these regions of the confined aquifer. The reallocation of water within a region's total hydrologic budget may have undesirable consequences for other parts of the hydrologic cycle. The generation of capture may result in saltwater-intrusion problems if the points of withdrawal from the aquifer are located too closely to water-quality transitions, as in the case of the Ozark aquifer, or sources of saltwater recharge, as in the case of the Dakota and the Cedar Hills Sandstone aquifers. The generation of capture may not be beneficial if the additional recharge moving into the confined aquifer is coming from an already overappropriated, hydraulically connected aquifer system.

The steps taken to prevent depletion in other parts of the Kansas confined aquifer systems clearly depend on the total intensity of development. For example, at low intensities of development in the Dakota aquifer, a well spacing greater than about 20 miles (32 km) and control of pumping rates should be adequate to prevent overdevelopment. At higher intensities, prevention of depletion is only possible by maintaining the points of withdrawal in proximity to sources of recharge or the discharge areas from the aquifer, if capture from these sources is deemed desirable in the overall management plan for the aquifer. Walton (1964) correctly noted that the practical sustained yield of the heavily pumped Cambrian–Ordovician aquifer in northeastern Illinois depended not on the natural recharge rate, but on the rate at which water could move toward the pumping centers from the recharge area.

All the major confined aquifer systems in Kansas are multistate in extent. Unfortunately, the recharge areas for the confined Ozark and the Dakota aquifer systems in Kansas are located in Missouri and Colorado, respectively, and their flow paths cross state lines (figs. 4.5 and 4.10). The sensitivity of these aquifer systems to development suggests that their management should be coordinated across state lines, possibly through interstate compacts to minimize the potential for depletion or saltwater encroachment. This could be particularly crucial for Kansas because of its "downgradient" location with respect to the recharge areas for these systems.

Summary

Confined aquifer systems are different from unconfined systems because of fundamental differences in their response to withdrawals. The transmissivities are generally lower in confined aquifers than in unconfined aquifers because they are less permeable. The storage is also smaller in the confined aquifer. As a result, well yields are generally lower and the drawdown due to pumping is much greater. Water is released to a pumping well in a confined aquifer by consolidation of the aquifer framework and volume expansion of the water, whereas in the unconfined aquifer, the water produced comes from the drainable porosity of the aquifer. Consequently, rates of withdrawal from the confined system are generally much less because of the larger drawdowns experienced in these aquifer systems. The larger drawdowns result from higher hydraulic diffusivities in confined than in unconfined aquifer systems.

Confined aquifer systems are more sensitive to development than unconfined systems because of their hydrologic properties. Hydraulic diffusivity, a measure of the ability of the aquifer to transmit perturbations through the aquifer, is much higher in confined than in unconfined aquifers. The ability to increase recharge, decrease discharge, or both (capture) is directly related to the aquifer diffusivity and inversely related to the distance from the point of withdrawal and the source of the capture.

The creation of a new dynamic equilibrium after development is achievable in a practical sense in areas of confined aquifer systems that are close to sources of recharge or discharge areas and for planning horizons on the order of a few decades. These shallower parts of the confined aquifer systems should be managed as part of a unit including the aquifers to which they are in hydraulic connection. Elsewhere, in the deeper and more isolated parts of confined aquifer systems, management based on the sustainable yield concept is not practical within a reasonable planning horizon. Management policies could be based on an acceptable rate of hydraulic-head decline within the aquifer during the planning period and implemented using controls on well spacing and rates of withdrawal.

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CHAPTER 5

Water Chemistry and Sustainable Yield

G. L. Macpherson and **M. A. Townsend**

CHAPTER 5

Water Chemistry and Sustainable Yield

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Introduction

The chemistry of water determines its aesthetic character and imposes limitations for some uses. Damage to the health of animals (e.g., humans or livestock) or plants, damage to infrastructure (e.g., pipes, boilers), damage to soils, or impairment of manufacturing processes are among the potential consequences of using water of poor quality. Availability of ground water, that is, water quantity, is discussed in other chapters in this volume. In this chapter, the processes affecting the chemical quality of ground water are discussed because the quality of water is a critical part of the sustainable yield assessment of an aquifer. Although quantity of water is important and limiting in many cases, unacceptable water chemistry can render even very large available volumes of water useless.

A review of the most important chemical reactions and processes affecting water chemistry in the first section of this chapter provides a foundation for understanding variations in water chemistry, both natural and induced. Ground water is nearly always moving through an aquifer, although rates vary greatly. This movement of ground water flushes out resident fluids. The fluids being flushed can be residual from original deposition of the aquifer, such as sea water, or can be some other type of saline or freshwater from a time when ground-water flow was different from the present. During the flushing process, chemical reactions occur as the new water is chemically altered by the rock: dissolution or precipitation of minerals, attachment (sorption) or detachment (desorption) of ions onto surfaces, or ion exchange may occur. These reactions apply principally to dissolved species that do not change their electrochemical state (redox state) or are not volatile. Those groups of species that do make such changes, and so, in a sense, change form, include nitrogen compounds such as nitrate, organic compounds, and some metals. Part of the section on chemical reactions reviews the conditions that control the reactions involved in this change of form. Furthermore, some dissolved species may act as convenient indicators of different water sources, as they do not tend to participate in chemical reactions. All of this information (the tendency to participate in reactions and knowledge about what types of chemical reactions are likely to occur) becomes helpful in understanding the origins of the chemistry of a ground water (hindsight) and in predicting the consequences of aquifer development on water chemistry (prediction).

The second section of this chapter reviews the pathways by which water with unacceptable quality can enter aquifers. A review of the importance of the unsaturated zone to altering the chemistry of ground-water recharge is followed by discussion of different sources of recharge and how they can be affected by the pumping of ground water. Both intra-aquifer flow (mixing of fluids from down- and updip, for example) and inter-aquifer flow (in which pumping induces cross formational flow of fluids) have the potential to mix waters of different chemistry that are not in equilibrium with the conditions at the pumping well(s). Pertinent examples from Kansas and elsewhere illustrate the potential impact of mismanagement of ground-water resources.

These two aspects, chemical processes and ground-water pathways, constitute the entire basis for understanding the limits that chemistry imposes on sustainable yield of aquifers. This chapter considers only aquifers in sedimentary rocks because these are the only significant type in Kansas. Aquifers in crystalline rocks in other parts of the world provide water of different chemical quality, but these are not discussed here. Figure 5.1 shows the general locations of the different aquifers and sites mentioned in this chapter.

Background

The chemistry of potable ground water differs from the chemistry of sea water, not only in the amount of total dissolved solids (TDS) but also in the relative amounts of the dissolved chemical species. Similarly, most abundant dissolved species in ground water and sea water are different from the major components of common rocks in the earth's crust. These facts indicate that chemical reactions other than simple dissolution affect the interaction between water and rocks.

Components Dissolved in Water

Table 5.1 shows the most abundant components of potable ground water, sea water, an average composition for the earth's crust, several important rock types, and the earth's atmosphere. These are grouped as major components and minor or trace components, with an approximate order of magnitude decrease in concentration between categories. The differences among these groups are quite apparent: major chemical elements in the earth's crust are oxygen and silicon, with lesser amounts of aluminum, iron, calcium, sodium, potassium, and magnesium; major dissolved species in sea water are chloride (the ionic form of the element, chlorine), sodium, sulfate, and magnesium. Major components of the earth's atmosphere are nitrogen and oxygen gas. The major-ion chemistry of sea water and the average composition of the earth's crust and atmosphere are stable, for all practical purposes.

Ground-water chemistry, in contrast to earth and sea-water chemistry, is strongly influenced by two factors. First, the original depositional water in an aquifer may be flushed out by a chemically different water, and so the degree of flushing determines the chemistry of ground water available to react with the aquifer matrix. The extent of flushing is determined by both the hydraulic properties of the aquifer matrix and climatic conditions during the history of the aquifer. Second, the solid material with which the water has been in contact, and especially the solubilities and reactivities of minerals in the matrix, determine how much the depositional water is modified.

Flushing of Aquifers

Sedimentary rocks in Kansas were deposited mostly in rivers or areas adjacent to rivers, in deltas which were at the boundary between land and sea, and in shallow-ocean to deep-ocean environments. Thus, the original depositional water for aquifers in Kansas sedimentary rocks ranges from river-like water to sea water. The degree of flushing of an aquifer during a period of relatively unchanging climate depends upon a) the climate (volume of potential recharge water due to the climate), b) the size of the recharge area allowing freshwater to displace depositional water, c) the permeability of the aquifer materials to water flow, and d) to a certain extent, the length of time allowed for flushing. Domenico and Robbins (1985) demonstrated that, after a period of time, a steady-state distribution of water chemistry is reached in a homogeneous aquifer when transport of dissolved ions is accomplished only by fluid flow (advective transport). After a steady state is attained, the redistribution of water chemistry continues but is limited to processes such as diffusion, which is the very slow movement of ions driven by chemical gradients.

For an aquifer with a relatively large recharge area such as the Equus Beds aquifer (fig. 5.1), steady-state ground-water flow is characterized by aquifer fluids similar in composition to the recharge water (as modified by chemical reactions with the aquifer matrix). For an aquifer with a small recharge area (smaller than the breadth of the aquifer), the original depositional water can remain in the aquifer and is distributed so as to envelop the recharging water (fig. 5.2).

Original depositional water and recharge water (water displacing or mixing with water present in an aquifer, either naturally or as induced) may have had a distinctive chemistry before contact with the aquifer matrix. Rain-

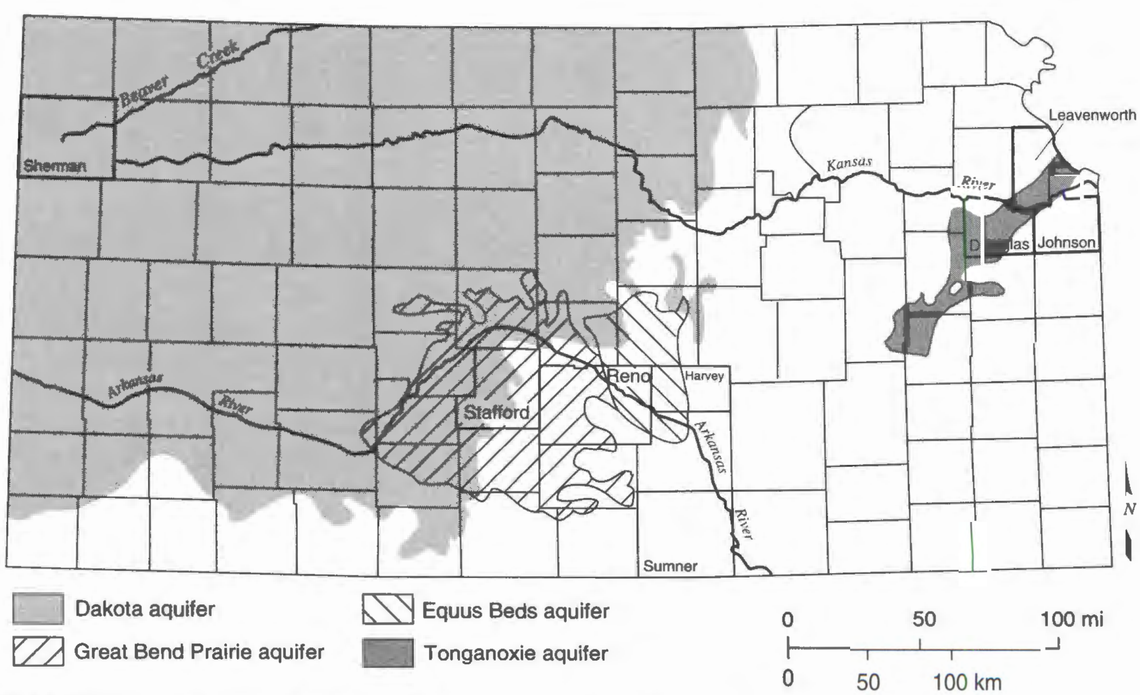


FIGURE 5.1—LOCATION OF AQUIFERS AND SITES IN KANSAS MENTIONED IN THIS CHAPTER.

TABLE 5.1—MAJOR AND MINOR COMPONENTS OF CHEMICAL RESERVOIRS THAT INFLUENCE GROUND-WATER CHEMISTRY.

a) Atmosphere, Water, Earth's Crust*

Atmosphere† ppm by volume		Freshwater mg/L		Sea Water†† mg/L		Earth's Crust††† elemental, % or ppm	
				Major Components			
N_2	780,000	HCO_3	x00	Cl	19,350	O	46.6%
O_2	209,460	Ca	x - x00	Na	10,760	Si	27.72%
Ar	9340	Na	x - x00	SO_4	2710	Al	8.13%
CO_2	320	Mg	x - x0	Mg	1290	Fe	5.00%
H_2O	40-40,000	SO_4	x - x00	Ca	411	Ca	3.63%
		Cl	x - x00	K	399	Na	2.83%
		K	x - x0			K	2.59%
		Si	x - x0			Mg	2.09%
						Ti	0.44%
						Mn	0.09%
						P	0.10%
				Selected Minor Components			
Ne	18.18	CO_3	0.x - x	Br	67	Ba	0.04%
He	5.24	F	0.x - x	Sr	8	F	625 ppm
CH_4	1.4	NO_3	0.x - x	B	4.5	Sr	375 ppm
Kr	1.14	Sr	0.x - x	F	1.3	S	260 ppm
H_2	0.55	Fe	0.0x - x	Si	0.5 - 10	C	200 ppm
N_2O	0.33	B	0.x - x	NO_3	0.005 - 2	Zr	165 ppm
Ozone	0.01-0.03	Ba	0.x	Li	0.18	V	135 ppm
SO_2	0.001-0.004	Br	0.0x - 0.x	Rb	0.12	Cl	130 ppm
				I	0.06	Cr	100 ppm
				Ba	0.010	Rb	90 ppm
				Mo	0.010	Ni	75 ppm
				U	0.0033	Zn	70 ppm
						Cu	55 ppm

† Brownlow, 1996.
†† Modified from Drever, 1988.
††† From Klein and Hurlbut, 1993.
* "x" indicates order of magnitude; x is 1 to 9 mg/L; 0.x - x means 0.1 to 9 mg/L; x0 means 10 to 90 mg/L; x00 means 100 to 900.

b) Major Rock Types (% or ppm)*, **

	Basalt	Granite (low Ca type)	Clays and shales	Sandstones	Carbonate rocks
			Major Components		
O	n.g.	n.g.	52.8%	n.g.	n.g.
Si	23%	34.70%	23.8%	36.80%	2.40%
Al	7.80%	7.20%	10.45%	2.50%	0.42%
Fe	8.65%	1.42%	3.33%	0.98%	0.38%
Ca	7.6%	0.51%	2.53%	3.91%	30.23%
Na	1.80%	2.58%	0.66%	0.33%	0.04%
K	0.83%	4.20%	2.28%	1.07%	0.27%
Mg	4.60%	0.16%	1.34%	0.70%	4.70%
P	0.11%	0.06%	0.077%	0.017%	0.04%
Ti	1.38 %	0.12%	0.45%	0.15%	0.04%
Mn	0.15%	0.039%	0.067%	0.00x%**	0.11%
			Selected Minor Components		
Ba	330	840	800	x0	10
F	400	850	500	270	330
Sr	465	100	450	20	610
S	300	300	3000	240	1200
C	n.g.	n.g.	10,000	n.g.	n.g.
Zr	140	175	200	220	19
V	250	44	130	20	20
Cl	60	200	160	10	150
Cr	170	4.1	100	35	11
Rb	30	170	200	60	3
Ni	130	4.5	95	2	20
Zn	105	39	80	16	20
Cu	87	10	57	x **	4

n.g. not given
* modified from Parker, 1967
** "x" indicates order of magnitude. For example, 0.00x% is 0.001 to 0.009%; x is 1 to 9

water, as an example of a recharge water, is typically very dilute (low TDS). During storage in the soil zone, however, evapotranspiration (evaporation and water use by plants) usually results in an overall increase in dissolved solids concentration (see *Dissolution/Precipitation*, below, for more on changes in carbon dioxide content in soil). The increase is not the same for all dissolved components, however: those dissolved components that do not interact with the mineral matrix or biota concentrate in the soil water proportional to the amount of water that evaporates, while those that do interact may increase in concentration but the increase is less than expected from the amount of evaporation. In general, concentration factors of two to ten times are probably typical (Gerritse and Adeney, 1992). Because of differential concentration of dissolved components, ratios of components are frequently used to identify rainwater that has been concentrated in the soil zone. Sea water, an example of a depositional water rather than a recharge water, is saline (high TDS). It contains some components that are stable through time and others that participate in several kinds of geochemical and biochemical reactions. Determination of reliable indicators of remnant sea water continues, as investigators discover previously unsuspected sources or sinks for various elements (Fabryka–Martin et al., 1991; Land, 1995a).

A precursor saline water may be suspected if TDS and especially chloride are present in areas thought to be poorly flushed. The section of the Dakota aquifer (figs. 5.1, 5.24B) in northwestern Kansas, for example, contains saline, chloride-rich ground water. Portions of the Dakota to the south and southeast of the saline area, especially those in the subcrop and outcrop of the Dakota, today contain much fresher water. Present flow directions in the Dakota are from recharge areas in central and southern Colorado to the east and east-northeast (Macfarlane et al., 1989; see also Chapter 4, this volume). In addition, local recharge in the outcrop area in central Kansas (also the regional discharge area) creates local flow cells with much fresher water. The precurser fluid in the freshwater portion of the Dakota cannot be determined directly, but the structural history of the region and the saline region in northwestern Kansas provide clues. Tectonic tilting in Kansas related to the most recent major uplift of the Rocky Mountains has made western and northwestern Kansas topographically higher than it was before that uplift (Merriam, 1963). This elevation change may have been great enough to radically change the ground-water-flow directions in the Dakota, originally from southeast to northwest, to the present direction of west to east. The Dakota saline water in northwestern Kansas may thus be the remnant of the unflushed, downgradient portion of an ancient flow system. That flow system would have exhibited a salinity gradient of freshwater in the southeast and progressively more saline water toward the northwest. Even though this hypothesis is difficult to prove, it suggests that the precursor fluid in the freshwater portion of the Dakota was chemically related to the saline water in northwestern Kansas, and that, because of present-day flow directions, the saline fluid in northwestern Kansas occupies a stagnant portion of the aquifer.

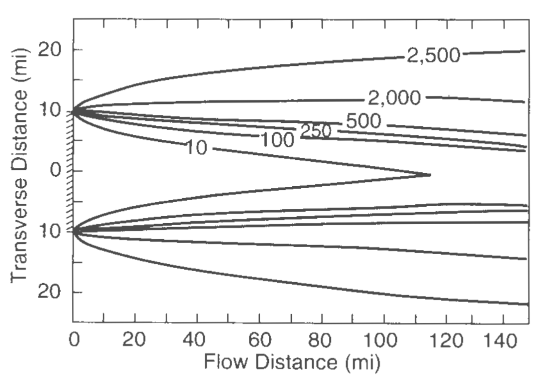


FIGURE 5.2—DISTRIBUTION OF A CONSERVATIVE CHEMICAL SPECIES IN A HOMOGENEOUS AQUIFER AFTER STEADY-STATE FLOW IS REACHED. The width of the recharge area is shown by the hachured area on the y-axis of the plot. Concentration of the dissolved species in the resident fluid was 2,500 mg/L. Contours of concentration of the species show that there is mixing between the resident fluid and recharging fluid (concentration of 10 mg/L); from Domenico and Robbins, 1985.

Types of Water-rock Chemical Reactions

A typical aquifer matrix consists of minerals that are chemically stable to unstable and may also contain varying amounts of organic matter that may be highly reactive to fairly inert. Chemical reactions between water and aquifer matrix change the proportions of dissolved species in the water when relatively long time periods are involved (days to years, depending upon the reaction). Some reactions are facilitated by bacteria and may involve the aquifer matrix or just the water. These reactions generally follow the rules of kinetics, in which there is a reaction rate that is limited by such things as temperature, nutrients, or other conditions in the aquifer.

In chemical reactions, the products of the reactions may contain elements in the same form, even as the same molecule. Alternately, the products of the reactions may contain the elements in a different phase (such as transformation from liquid to solid or liquid to gas) so that the chemical reactions cause removal (or addition) of the element from ground water. In addition, transformations can result from change in redox state (see Boxed section 5.1, Redox) of an element. In these cases, the element is transformed to a different oxidation state (see Boxed section 5.1) which may, in turn, cause transfer of the element to a different molecule. Changes in redox can alter the toxicity of the element or otherwise reduce the usefulness of the water by, for example, causing the water to become corrosive or to deposit scale.

The following brief discussion summarizes the terminology used in the rest of this chapter in order to clarify references to these types of transformations. It is important to stress that strict categorization using this terminology is not always possible, as dissolved species that behave one way in one hydrogeologic setting may behave differently in another setting. Therefore, the descriptions used in this chapter for the most part apply to *potable* ground water.

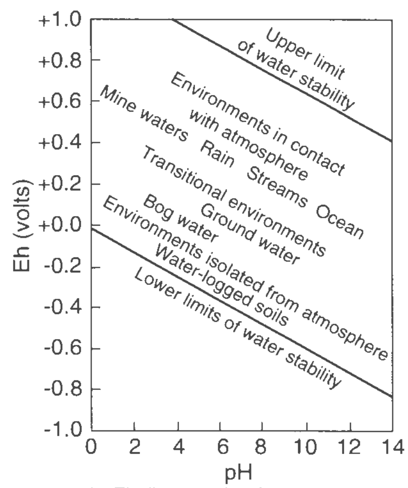
First, the term *conservative* is used here to describe a dissolved species with the tendency to remain in the water phase and to not participate in chemical reactions that tend to remove that species from ground water. Conservative elements can be useful as indicators of how the water component of ground water is changing (evaporating, being diluted or mixed with another water). These elements also move at the same speed as ground water, acting as a useful tag of ground-water-flow rate. *Nonconservative* describes those species that are readily removed from or added to ground water during reaction with a solid phase such as minerals or organic matter. A change in a nonconservative species concentration along a ground-water-flow path implies that a chemical or biochemical reaction between water and the aquifer matrix has occurred.

Labile species are those that change form, either by changing oxidation state or by changing the type of com-

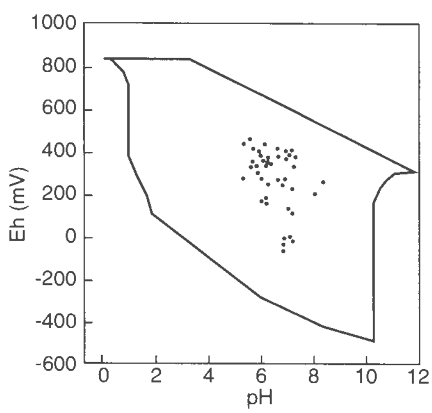
Boxed section 5.1: Redox: *Red*uction and *Ox*idation

The term "redox" is a contraction of the words *reduction* and *oxidation*. The redox state of a fluid represents, in a complex way, whether elements that have multiple oxidation states (and so are redox elements) will tend to be in their higher (more oxidizing) or lower (more reducing) states. The oxidation state of an element is the number of electrons it contains in excess of or as a deficit of the number of protons in its nucleus. Because electrons carry a negative electrical charge and protons a positive electrical charge, the elemental state (protons = electrons) is uncharged. If an element can lose electrons relative to the elemental state, it becomes posi-tively charged (protons>electrons), and if it can gain electrons then it becomes negatively charged (electrons>protons). The oxidation state, then, corresponds to the excess or deficit of electrons. In theory there are steplike changes in the oxidation state of ground water that reflect which species pair is controlling the redox state of the water. The solubility of redox elements often is strongly controlled by pH as well as the redox state, so that the oxidation state of ground water is usually portrayed on a bivariate plot showing pH and a system parameter "pe" or "Eh" that represents the redox state (right). The parameter "pe" is a calculated measure of the number of electrons and the para-meter "Eh" is a measure of the voltage potential that develops between an electrode with a known potential and the solution. As shown below on the figure on the right, uncontaminated ground waters in the world fall within a fairly restricted portion of the total pH-Eh (or pe) region that is theoretically available. Some typical as well as unusual aquatic environments are shown on the figure on the left.

Elements with multiple oxidation states that are most important in hydrogeology include oxygen, carbon, nitrogen, manganese, iron, and sulfur.



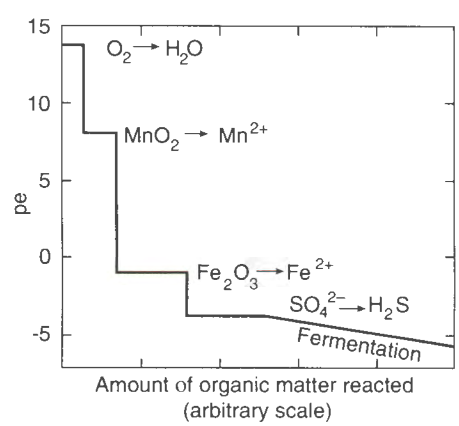
pH–Eh diagram showing generalized positions of some aquatic environments (from Johnson et al., 1989).



Outlined area shows the region delineated by Bass Becking et al. (1960) for a large number of measurements of natural waters. Small circles are ground-water samples (from Fish, 1993).

The Natural Progression: Oxidizing Ground Water Becomes Reducing Ground Water As It Flows

The redox state of an aquifer is thought to change in a step-wise fashion with depth or with increasing distance along a flow path. Dissolved oxygen in water yields the highest amounts of usable energy to bacterial mediators as it is reduced to O^{-2}, and so is consumed first by oxidation-reduction reactions. Other dissolved substances yield less energy so are used by bacteria next, with consequent change in oxidation state, and so on. Thus, a recharging water, most likely containing dissolved oxygen, is initially highly oxidizing, then makes a step decrease to a lower overall oxidation state as the oxygen is reduced and dissolved oxygen is consumed. Subsequent step-like changes are linked to changes in other metal and nonmetal redox "indicators": the nitrogen system, the iron and manganese systems, the sulfur system, and the carbon-dioxide system (right). Changes in redox state of a fluid can cause precipitation or dissolution of solids and may result from a) mixing caused by aquifer mismanagement, b) contamination, as well as from c) the normal flushing that occurs when "native" fluids are displaced by different fluids.



(from Drever, 1998; reprinted with permission of Prentice–Hall, Inc.)

pound in which they are found; this includes transformation from dissolved or liquid state to gaseous state. *Refractory* species (sometimes known as recalcitrant when only microbially mediated reactions are considered; Johnson et al., 1989) do not undergo these types of transformations. (In this chapter, labile and refractory apply to both inorganic and organic species.) Thus, labile transformations are of two basic types, one involving change in redox state and the second in change from liquid to gaseous state. In summary, a labile species changes forms readily; a refractory species does not. For the most part labile species are nonconservative, although refractory species are not necessarily conservative. Table 5.2 lists the major dissolved

TABLE 5.2—PERSISTENCE OF DISSOLVED SPECIES IN WATER; organics section modified from Domenico and Schwartz, 1990, p. 428; reprinted by permission from John Wiley & Sons, Inc.

Major Components

	Labile	Refractory	Conservative	Nonconservative	MCL**, mg/L
Cations					
calcium		Ca			
magnesium		Mg			
sodium		Na		Na	tbc*
potassium		K		K	
Anions					
bicarbonate		HCO_3		HCO_3	
sulfate	(SO_4)	(SO_4)	(SO_4)	(SO_4)	500
chloride		Cl	Cl		250†
Others					
dissolved silica		H_4SiO_4		H_4SiO_4	

Selected Minor Components

	Labile	Refractory	Conservative	Nonconservative	MCL**, mg/L
Inorganic and Nutrients					
aluminum		Al		Al	0.05 -0.2 †
arsenic	As			As	0.05
antimony	Sb			Sb	0.006
barium		Ba		Ba	2
beryllium		Be	Be		0.004
bromide		Br	Br		
cadmium	Cd			Cd	0.005
chromium	Cr			Cr	0.1
copper	Cu			Cu	1.3††
cyanide	CN			CN	0.2
fluoride		F		F	4
iron	Fe			Fe	0.3 †
lead		Pb		Pb	0.015††
manganese	Mn			Mn	0.05 †
mercury	Hg			Hg	0.002
nickel	Ni			Ni	0.14
ammonium as N	NH_4-N			NH_4-N	
nitrate as N	NO_3-N			NO_3-N	10
nitrite as N	NO_2-N			NO_2-N	1
phosphate as P		HPO_4-P		HPO_4-P	
selenium	Se			Se	0.05
silver		Ag		Ag	0.1 †
thallium		Tl		Tl	0.002
vanadium		V		V	
zinc		Zn		Zn	5 †

Organics

	Labile	Refractory	Conservative	Nonconservative	MCL** mg/L
Volatile Organics					
trichloroethylene	TCE			TCE	0.005
benzene	C_6H_6			C_6H_6	0.005
toluene	$C_6H_5CH_3$			$C_6H_5CH_3$	1
xylenes (total)	e.g., 1,2-$(CH_3)_2C_6H_4$			xylenes	10
vinyl chloride	CH_2=CHCl			CH_2=CHCl	0.002
carbon tetrachloride	CCl_4			CCl_4	0.005
Pesticides & Herbicides					
Atrazine	Atrazine			Atrazine	0.003
Chlordane	Chlordane			Chlordane	0.002
Dioxin	Dioxin			Dioxin	3×10^{-8}
2,4-D	2,4-D			2,4-D	0.070
Heptachlor	Heptachlor			Heptachlor	0.0004

**EPA Maximum Contaminant Level, in mg/L. Complete listing of regulated chemicals with maximum contaminant levels, maximum contaminant-level goals, secondary maximum-contaminant level, and toxicity doses can be found on the EPA Web page: http://www.epa.gov/OST/Tools/dwstds.html

†: secondary maximum contaminant level ††: action level; standard is "zero" *tbc: to be considered

species in ground water and some of the minor dissolved species, along with their classifications according to the labile-refractory and conservative-nonconservative terminology. Also included in this table are the Environmental Protection Agency drinking-water standards for the species listed.

Overview—Sources of Dissolved Species in Ground Water

Naturally occurring dissolved species in ground water are present because of: a) rainwater recharging an aquifer, b) degree of concentration of rainwater in the soil zone before moving into an aquifer, c) presence of depositional water, though probably altered by biogeochemical reactions, d) chemical reactions between water and soil, including organic matter, e) chemical reactions between water and rock, and f) biological action.

Ground-water chemistry in carbonate (limestone, dolomite) aquifers is relatively simple because of the relatively simple mineralogy in the aquifer. Ground water in these aquifers is typically a calcium bicarbonate type water, with varying amounts of magnesium and sulfate, depending on the amounts of dolomite and gypsum or anhydrite, respectively, present (e.g., White, 1988).

Progressive, normal changes in ground-water chemistry because of water-rock interaction in siliciclastic aquifers (sandstone, sand and gravel, or similar aquifers; fig. 5.3) result in a continuum from calcium bicarbonate dominated water through sodium bicarbonate, sodium sulfate, and sodium chloride dominated water when freshwater progressively displaces a sodium chloride type water such as sea water. These changes reflect the importance of dissolution of calcite (calcium bicarbonate water), cation exchange on clay minerals (sodium bicarbonate water), and finally an interface with the less-flushed part of the aquifer (sodium sulfate and sodium chloride type waters). Two examples of deviations from this normal progression in water chemistry are found in the Dakota aquifer of Kansas.

The Dakota aquifer (fig. 5.1) crops out at high elevations in Colorado, where it is recharged. Ground water travels generally eastward through the subsurface in eastern Colorado and western Kansas, and then discharges in the vicinity of the outcrop and subcrop of the Dakota in central Kansas (see Chapter 4, this volume). Chemistry of the Dakota ground water in the Kansas outcrop area resembles recharge-area ground water, because the outcrop is being recharged by local meteoric water as well as by ground water that has travelled through the Dakota from Colorado and western Kansas (Macfarlane et al., 1989). Besides the situation just described in the Dakota aquifer in Kansas, the case in which there is a very long flushing time or the case in which there is no precursor saline fluid in an aquifer also results in the absence of the sodium chloride and possibly sodium sulfate type waters at the end of the flow path.

A second example showing a variance from normal ground-water chemistry changes occurs when there is cross formational leakage of a fluid into the central part of an aquifer. Leakage of, for example, a saline, sodium chloride type water into an aquifer at the midpoint of the flow system results in a sodium chloride facies present at the aquifer midpoint. The other water types develop on either side of the point of leakage. The Dakota aquifer in Kansas shows such a pattern of water-chemistry types (fig. 5.4 and fig. 5.24 later in this chapter; Macfarlane et al., 1989). In general, the rate of leakage, water quality, and volume of leakage collectively determine the seriousness of this phenomenon. In the case of the Dakota aquifer, the change from a chloride content of less than 100 mg/L to more than 500 mg/L occurs in the vicinity of cross formational leakage of sodium chloride (Na-Cl) brines from Permian aquifers underlying the Dakota. The increase in TDS limits the usefulness of Dakota ground water in west-central Kansas.

Contaminants introduced into ground water are affected by many of the same processes as natural recharge: a) mixing with in situ water, b) evaporative concentration (usually restricted to the soil zone), c) reaction with the aquifer matrix, and d) biological alteration. The discussion below elaborates on these processes in terms of conservative versus nonconservative species and labile versus refractory

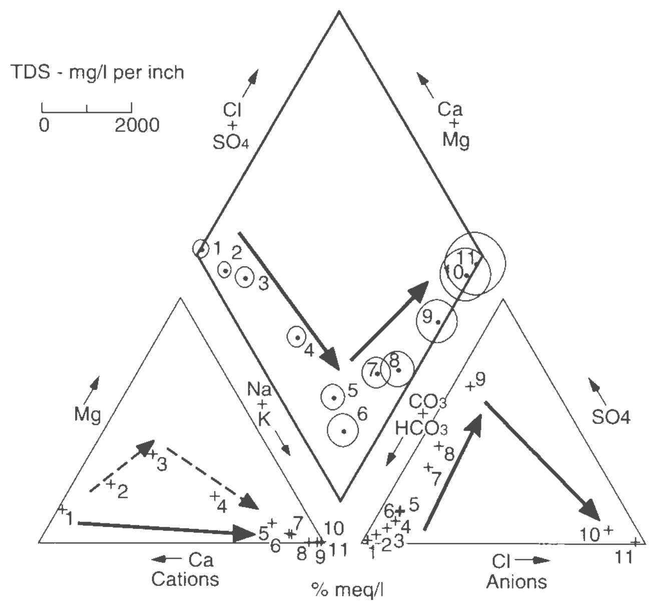


FIGURE 5.3—TYPICAL CHANGES IN GROUND-WATER CHEMISTRY WITH TIME AND DISTANCE ALONG A FLOW PATH RESULT IN CHANGES IN MAJOR DISSOLVED IONS. The above are artificial data simulating the typical evolution; arrows show direction of movement. This type of presentation is known as a Piper diagram (Piper, 1944), in which triangles show proportions of cations and anions, and data from the triangles are projected onto the central diamond along lines parallel to one side of the triangles. Circles indicate TDS, and in the typical progression, ground water increases in TDS as it changes from a calcium-bicarbonate water (Ca-HCO3) near a recharge area to a sodium-chloride water (Na-Cl) near the farthest extent of flushing of the aquifer.

species. Chemical and biochemical reactions are discussed in terms of their reactivity instead of according to the distinction between chemical and biological, to focus on how water chemistry can change and thus be a factor in determination of safe yield.

Chemical Reactions in Ground Water

Ground water may gain or lose dissolved species as it moves through the soil zone and aquifer, when it mixes with chemically different water, or merely as a matter of time when chemical reactions are slow. The following sections describe the most abundant dissolved chemical species in ground water and how likely they are to be involved in chemical reactions. Although not comprehensive, the sections focus on the most abundant dissolved species or the most important chemical reactions. Also included is a brief discussion of the implications to the mixing of chemically different ground water, and contrasts of "fast-path" ground-water flow (found in fractured rocks) and "slow-path" ground-water flow (found in most other circumstances).

Conservative Dissolved Species

Conservative dissolved species in ground water, those not easily removed from solution, may fingerprint a single source of that particular dissolved species. In practice, there are often several potential sources for these species, so that identification of the contributing source(s) becomes difficult to impossible. For some elements the use of isotopic ratios (see Boxed section 5.2, Isotopes and Ground Water; Glossary, isotope) provides a better fingerprinting tool than the element itself. In addition, some isotopes decay spontaneously to other elements at a steady rate, making them useful for dating the water and, of course, making them nonconservative. The use of isotopes in studying ground-water chemistry is explained in many textbooks (e.g., Ferronsky et al., 1982; Bowen, 1988; Drever, 1988; Faure, 1986; Pearson et al., 1991) and will not be discussed further here.

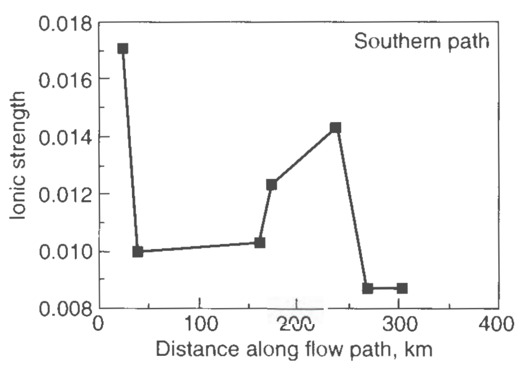


FIGURE 5.4—CHANGE IN IONIC STRENGTH ALONG A GROUND-WATER FLOW PATH (A–A´ SHOWN IN FIG 4.5) IN THE DAKOTA AQUIFER, KANSAS. Ionic strength is a representation of the concentration of dissolved ions in a solution and is directly proportional to total dissolved solids. Notice the abrupt increase in ionic strength in the middle part of the flow path. This is the locus of cross formational flow of deeper, saline water into the Dakota.

The single dissolved species in potable ground water that is considered a major component and that is conservative is chloride (Cl^-). The two sources for naturally occurring chloride in ground water (excluding chloride resident in the depositional water) are chloride found in rainwater that recharges ground water and chloride added to ground water when it dissolves halite (NaCl). Halite may originate from dry fallout (dust carried by wind and deposited on vegetation and the land surface) or from large salt deposits such as those found in salt domes or bedded halite. In the latter case, chloride concentrations in ground water can be very high near the halite source and decrease away from it, making it easily identified as a point source. In temperate to humid climates where large salt deposits are absent, halite should be extremely rare in aquifers because it is highly soluble and thus should be quickly dissolved from an aquifer. Nevertheless, halite is often declared the source of chloride in water when chloride content cannot be attributed to rainfall recharge. In these cases, dry fallout, precursor saline fluid resident in low-permeability areas of an aquifer, or cross formational flow of saline water may be the source.

Sulfate (SO_4^{-2}) is typically conservative but labile (can change form) under highly reducing conditions (see Labile and Refractory Species section following). When sulfate concentration in ground water is higher than in soil water, minerals are the source of the sulfate. (Soil-water sulfate may be higher than rainwater sulfate because of evapotranspiration.) Under oxidizing conditions, sulfate can be added to ground water through transformation from the sulfide form of sulfur (such as pyrite or other mineral sulfides). Mineral sulfides may supply a significant amount of sulfate to ground water, especially in water that is in contact with coal or lignite (Hem, 1985). Ground water with moderate to high concentrations of sulfate, however, probably acquired the sulfate from other minerals or from evapoconcentration processes. Gypsum ($CaSO_4 \cdot 2H_2O$) and anhydrite ($CaSO_4$) are naturally occurring minerals with solubilities that are high, but not as high as halite. In Kansas, gypsum can form in the soil zone when evapotranspiration rates greatly exceed precipitation, so that water is evaporated from the soil leaving the salts behind (Moran et al., 1978). Gypsum is one of the salts commonly observed in dry soils in temperate climate regions (Sposito, 1989) and in arid regions, white efflorescence at the surface is often a sodium-sulfate precipitate (Hem, 1985). Wetting and drying cycles through the seasons can lead to pulses of sulfate recharging an aquifer: evapoconcentrated soil solutions are flushed into the aquifer during a heavy rain after a dry spell, or gypsum precipitated in the soil can be redissolved in the rainwater moving down through a soil. The high solubility of gypsum guarantees that persistence is unlikely during wet periods. Because very dry conditions are necessary for precipitation of gypsum, dissolved

Boxed section 5.2: Isotopes and Ground Water

Isotopes of the same element contain the same number of protons but different numbers of neutrons. Isotopes are radioactive (parent) if they decay spontaneously to another (daughter) element. Isotopes are stable if they do not decay. Most elements in the periodic table have one or more naturally occurring stable isotopes and some have a radioactive isotope.

Radioactive isotopes can be useful in dating some aspect of ground water, because radioactive elements decay spontaneously and constantly, the constancy permitting the time calculation. The decay time is often expressed in terms of the half-life, the amount of time needed for one-half of the starting material to spontaneously decay to the daughter product. To calculate the age, one solves for "t" in the following equation:

$$P_t = P_0\, e^{-kt}$$

where P denotes parent isotope,
t denotes condition at some time,
0 denotes condition at the initial time,
k is the decay constant; the half-life, $T_{0.5}$, is related to k according to: $T_{0.5} = ln(2)/k$.

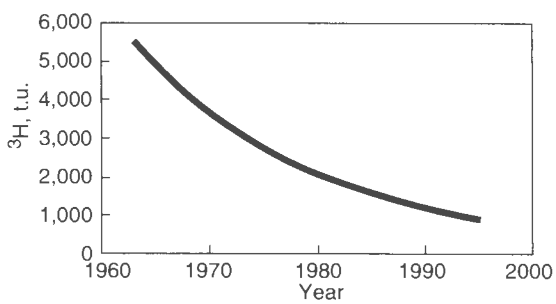
The half-lives of several radioactive isotopes are listed below, to demonstrate the possibility of dating the time of ground-water recharge (time of removal from the atmosphere) over quite a long time. These are not the only radioactive isotopes used for dating in hydrogeology.

Radioactive Isotope	Half Life	Useful Dating Range	Source†
Tritium $^3H_1$	12.3 yrs	~100 yrs from 1954	2
Argon $^{39}Ar_{18}$	270 yrs	50–1,000 yrs	1
Silicon $^{32}Si_{14}$	276 yrs	50–1,500 yrs	1
Carbon $^{14}C_6$	5,730 yrs	1,000 –75,000 yrs	1, 2
Chlorine $^{36}Cl_{17}$	301,000 yrs	80,000–1,500,000	1, 2

† Principal source for radioactive isotopes:
1 cosmic bombardment of the earth's atmosphere, incorporated in rain, snow, etc.
2 atmospheric testing of weapons, 1952 to 1969; incorporated in rain, snow, etc.

Although most sources of radioactive isotopes are natural, a few were been artificially increased during restricted periods in the recent past. Tritium and carbon-14 were both byproducts of atmospheric testing of bombs during the 1950's and 1960's. Therefore, ground water that was recharged during that time contained an unusually high amount of tritium. The graph below illustrates the theoretical amount of tritium ($^3H_1$) in such a ground water that was recharged from atomospheric precipitation in 1963. Radioactive decay causes a decrease in concentration through time, but if that ground water were sampled in 1997, it would contain much more tritium than today's rain contains (10 to 20 tritium units, t.u.), thus identifying it as water recharged during the era of atmospheric testing of weapons. This is an example of a dating technique that is useful in a general way in that it identifies a period of time during which the ground water might have been recharged. Other radioactive isotopes can allow more precise dating of the time of recharge.

As shown below, water recharged in 1963 might have contained about 5,500 tritium units (t.u.). By 1997 (the end of the trend line), the amount of tritium left in such a water is about 800 t.u., much higher than modern rainwater. Because the amount of tritium in rainwater during the 1950's and 1960's was not constant, the exact age of a ground water with high tritium levels cannot be uniquely determined, but high tritium levels (in the absence of contamination from nuclear reactor cooling water, for example) indicate recharge during the era of atmospheric bomb testing.



Stable isotopes provide the opportunity for a different kind of interpretation of chemical processes. Stable isotopes do not transform, but because there is a small difference in mass of the element because of the different number of neutrons in the nucleus, chemical or physical processes that discriminate for or against higher mass can alter an isotope ratio: the ratio of two isotopes of the same element. The larger the *relative* change in mass between the two isotopes, the greater the discrimination, or fractionation. Listed following are isotope ratios commonly used to look for fractionation processes in ground water.

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Boxed section 5.2 continued

Element	Isotopes		Relative mass difference	Processes that fractionate
Hydrogen	$^2H_1$	$^1H_1$	2/1 : 100%	evaporation of water, formation of clay minerals, temperature of recharge water
Oxygen	$^{18}O_8$	$^{16}O_8$	18/16 : 12.5%	evaporation of water, formation of clay minerals, temperature of recharge water
Carbon	$^{13}C_6$	$^{12}C_6$	13/12 : 8.33%	biological processes, CO_2 solution/exsolution, oxidation/reduction of C (organic matter; CO_2 based species)
Nitrogen	$^{15}N_7$	$^{14}N_7$	15/14 : 7.1%	oxidation/reduction of N (in organic matter; in gases or of nitrate)
Sulfur	$^{34}S_{16}$	$^{32}S_{16}$	34/32 : 6.25%	ocean evaporation (ratio preserved in gypsum), oxidation/reduction of S (pyrite; gypsum)

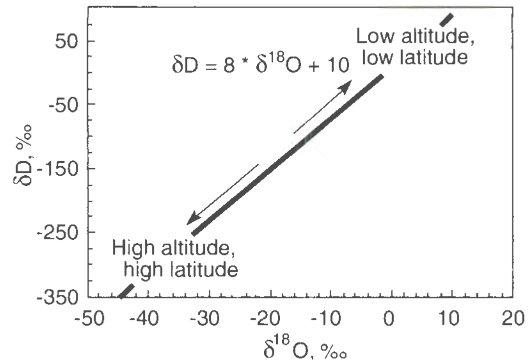
Stable isotope ratios are compared to a standard and expressed according to the following notation.

$$\delta^n R \text{ in units of ‰ (per mil)} = \frac{R_{smpl} - R_{std}}{R_{std}} * 1000$$

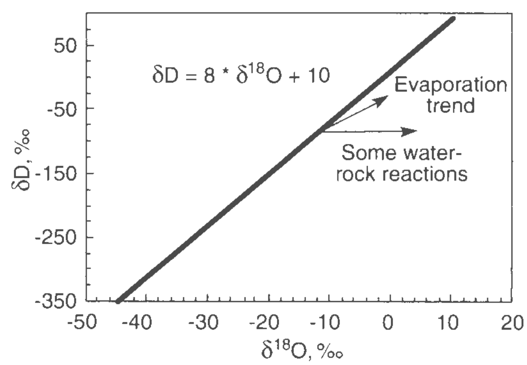
where

- R is the ratio of the low-abundance to the high-abundance isotope,
- n is the mass number of the low-abundance isotope,
- $_{smpl}$ is the unknown sample, and
- $_{std}$ is the international standard.

The graph below shows the meteoric water line, a relationship between δD (or δ^2H) and δ^{18}O that is nearly contant in rainwater around the globe.



Ground water with δD and δ^{18}O values that do not fall on the meteoric water line has undergone alteration from rainwater. Alteration processes include evaporation before recharge of the rainwater to ground water and water-rock interaction. The trends from the meteoric water line that these processes take are shown on the plot below. The starting point for any alteration process is the δD-δ^{18}O composition of rainwater that recharges ground water.



More information about stable and radioactive isotopes can be found in Ferronsky and Polyakov (1982), Bowen (1988), Drever (1988), Faure (1986), and Pearson et al. (1991), as well as in other similar books.

sulfate in ground water is very nearly a conservative species.

Most other major dissolved species in ground water, calcium (Ca^{+2}), magnesium (Mg^{+2}), sodium (Na^{+1}), potassium (K^{+1}), and bicarbonate and carbonate (HCO_3^{-1} and CO_3^{-2}) are nonconservative. They participate in one or more common chemical reactions that either remove them from or add them to ground water, as discussed in the next section.

Nonconservative Dissolved Species

Three categories of chemical reactions involving nonconservative species are presented below. Dissolution and precipitation of solids affects concentrations of major dissolved species and some minor species in ground water. Sorption of dissolved ions onto surfaces of solids exerts a strong control on the concentration of minor dissolved species in ground water. Ion exchange, in which ions move in and out of selected locations within a mineral structure, strongly affects the major-ion content of a ground water and may also affect the minor-ion content.

DISSOLUTION/PRECIPITATION

Water dissolves all solids to some extent. The most soluble minerals (those which result in the most mass in a unit volume of water) are generally the least available for dissolution because they are so soluble (Domenico and Schwartz, 1990). The most soluble minerals, the most common being halite and gypsum, generally only provide dissolved ions to water and do not precipitate from ground water (an exception being gypsum in the soil zone, as discussed above). Excluding the most soluble common minerals, then, it can be said generally that small adjustments in ground-water chemistry occur constantly as the water both dissolves and precipitates solids in order to be in a state of equilibrium with them all at the temperature and pressure in the aquifer.

Commonly occurring minerals that dissolve congruently (completely, with no reaction products being solids) and that have an important influence on ground-water chemistry are calcite, dolomite, and quartz. In restricted regions, evaporite minerals such as halite and gypsum can completely control the chemistry of ground water, but these cases will not be included here because of the focus on potable ground water.

Quartz is the principal mineral in most sandstones and so is quite abundant. Dissolution of quartz (SiO_2) results in the addition of dissolved silica, known as silicic acid (H_4SiO_4), to water, although it is not the sole source. (Note that silicic acid does not behave as an acid in typical ground waters, that is, it does not yield its hydrogen ions to attack other minerals.) This reaction (simplified, as are all others in the chapter) may be represented by

$$SiO_2 + H_2O \longleftrightarrow H_4SiO_4 \qquad \text{(eq. 5.1)}$$

quartz + water <—> silicic acid

The chemical reaction is written with a double arrow because it can proceed either left to right (dissolving quartz) or right to left (precipitating quartz or, more realistically, amorphous silica). For this reaction and others shown here, the reverse reaction may be inhibited partially or completely, and thus rarely occur. Nevertheless, calculations involving solubility are based on reversible equilibrium thermodynamics, and so all reactions are shown as being completely reversible.

The dissolution of quartz provides a component of dissolved solids to ground water that is useful to interpreting origins of water chemistry. For example, silicic-acid content can be used to differentiate end-member waters in a mixture (D. O. Whittemore, personal communication, 1994) and can be used to calculate the in situ temperature of the ground water as a geothermometer, making use of the well-characterized dependence of solubility of quartz on temperature (Siever, 1962; Fournier and Potter, 1982).

The amount of calcite and dolomite that will dissolve in water depends upon the partial pressure of carbon dioxide ($P\text{-}CO_2$) in the water. The acid created by dissolving CO_2 in water attacks these two minerals. The dissolution of CO_2 is expressed as:

$$CO_2 + H_2O \longleftrightarrow H_2CO_3 \qquad \text{(eq. 5.2)}$$

carbon dioxide + water <—> carbonic acid

The acid, H_2CO_3, is called carbonic acid, and again the chemical reaction is written with a double arrow to make it clear that the reaction can go in either direction: if there is more CO_2 in the "atmosphere" in contact with the water than can be dissolved in the water, then H_2CO_3 is created as the reaction proceeds to the right and the "atmosphere" is robbed of CO_2 and water. If conditions change (e.g., water exits the ground to form a spring, or something acts to consume the CO_2 in the "atmosphere," or the temperature of the water increases as the water moves deeper into the ground), then the reaction proceeds to the left, consuming H_2CO_3 and producing CO_2 and water. Carbon dioxide is present in fairly low concentrations and thus the $P\text{-}CO_2$ is low in the atmosphere (table 5.1), resulting in fairly low concentrations in rainwater. In soils, however, the activity of bacteria increases the amount of CO_2 by a factor of 10 to 100 or more, providing most of the CO_2 for water-rock reactions.

Calcite and dolomite are important contributors to the chemistry of potable ground water in that they are relatively easily dissolved and are fairly abundant in rocks. Calcite releases calcium ions and bicarbonate ions to water during dissolution:

$$CaCO_3 + H_2CO_3 \longleftrightarrow Ca^{+2} + 2\,HCO_3^{-1} \qquad \text{(eq. 5.3)}$$

calcite + carbonic acid <—> calcium + bicarbonate

Dolomite dissolves in a similar fashion:

$$CaMg(CO_3)_2 + 2H_2CO_3 <\!\!-\!\!-\!\!>$$
dolomite + carbonic acid <—>

$$Ca^{+2} + Mg^{+2} + 4\ HCO_3^{-1} \qquad \text{(eq. 5.4)}$$
calcium + magnesium + bicarbonate

Calcite is found almost everywhere. Dolomite also is very common and is frequently cited as the principal source for Mg^{+2}. Almost all calcite contains small amounts of Mg^{+2} in the mineral lattice, as well, and almost certainly provides a significant amount of Mg^{+2} to ground water. In addition, recent work suggests ion exchange to be a very important contributor of Mg^{+2} (Appleo, 1994; Chu, 1995; see Ion Exchange, following).

A precipitate from ground water is known as an authigenic mineral (one formed in place, not transported) if it was precipitated some time after the aquifer was deposited and as cement if it acts to bind loose sediment together. Thus, both the grains (sediment) and cements or authigenic minerals can dissolve to change water chemistry. Furthermore, there may be several generations of cement, recording a history of the fluids and the temperature-pressure conditions to which the sediment has been exposed. The most common cements in sandstones are calcite and quartz; the most common cement in limestones is calcite. Dissolution/precipitation reactions of these minerals were covered above.

Major dissolved species that are nonconservative in ground water, then, include calcium, magnesium, and bicarbonate, because they are part of the reactions dissolving and precipitating calcite and dolomite. Bicarbonate can also be added to water during the weathering of other rock-forming minerals, especially the feldspars but also other alumino-silicates. Quartz, a major component of sandstones, is slightly soluble and its dissolved counterpart, silicic acid, also is nonconservative.

SORPTION

Sorption is an equilibrium reaction just as dissolution/precipitation reactions are. Sorption describes the affinity of a dissolved species for the surface of a solid. The solid phase involved in sorption can be mineral, which strongly attracts many dissolved metals, or organic, which strongly attracts many hydrophobic organic compounds as well as metals.

Three groups of mineral-like substances, aluminum, iron, and manganese oxyhydroxides, are inorganic substances that are strong sorbers (Drever, 1988). These substances are present in most sandstone aquifers and may also be present in limestone aquifers. They include many different forms of oxides and hydroxides, many of which are hydrous (contain water as part of their structure). In addition, they are highly reactive and often exist as coatings on other grains. Because the grain size is very small, the surface area of these substances is large (often on the order of 200 m^2/gm: Drever, 1988), and thus their absorptive capacity is large. Most mineral surfaces sorb numerous kinds of dissolved ions due to the electrostatic attraction between the ion and the surface and because of complexation reactions that occur at the surface (Johnson et al., 1989), but the aluminum, iron, and manganese oxyhydroxides are the strongest sorbers among minerals or mineral-like substances (or, more generally, inorganically formed solids).

Solid organic material in aquifers sometimes has a large sorptive capacity (van Riemsdijk and Hiemstra, 1993), although the complexity of organic compounds and their sorption behavior makes it difficult to quantify organic sorption (Drever, 1988). Organic material varies in reactivity according to its type and maturity: it may come from terrestrial matter (plant debris, mostly) or marine organisms (in ancient rocks) and changes as it ages, both in texture and in composition (e.g., Dow, 1978; Waples, 1980; Magoon and Dow, 1994). Humus is the dark-colored solid matter in soil that includes all organic components except for those identifiable as unaltered or partially altered biomass; humus comprises humic substances and biomolecules (Sposito, 1989). The humic substances that persist in the soil profile are the most studied fraction of organic matter in soils. These substances are depleted in nitrogen and enriched in sulfur relative to soil organic matter as a whole. The much higher carbon-to-nitrogen (C/N) ratio of humic substances is an indication of the change from material highly susceptible to microbial attack to material resistant to attack (Sposito, 1989).

Sorption of metals from water onto inorganic surfaces is often pH-controlled. The pH of the water (see Glossary, pH) controls the attachment of H^+ or OH^- ions to surfaces, which in turn causes them to have a positive or negative charge (Stumm and Morgan, 1981). Sorption of ferric iron (Fe^{III}) onto a hydrous oxide surface removes from about 20% to almost 100% of the iron in solution as the pH varies from 1 to 3. For the same surface, lead and copper sorption from solution ranges from less than 5% to about 90% over the pH range of 4.5 to 6.5, and cadmium sorption ranges from about 20% to about 95% over the pH range of about 6.5 to 8.5 (fig. 5.5). In these cases, there is always less sorption at lower pH than at high pH, because of the charge on the metal ion. Negatively charged ions behave in the opposite way, being more strongly sorbed at lower pH than higher. It may also be true that chemical forces in addition to electrical forces, are involved in sorption processes. Murray (1975) demonstrated that significant sorption occurred at the zero point of charge on manganese oxide (δ-MnO_2), the point at which the surface is neither negatively nor positively charged.

Organic matter also has a pH-dependent, negative surface charge (Riemskijk and Hiemstra, 1993). Metals that commonly sorb onto organic matter include aluminum (Al), vanadium (V), chromium (Cr), manganese (Mn), iron

(Fe), nickel (Ni), copper (Cu), zinc (Zn), cadmium (Cd), and lead (Pb) (Sposito, 1989). Organic matter provides an important limit to concentrations of potentially toxic metals in ground water.

Sorption affects the concentration of dissolved organic compounds as well as dissolved metals in ground water. Two different phenomenon create the potential for sorption. First, organic molecules in aqueous solution are attracted by the net negative surface charge on humus (solid organic matter). Second, sorption occurs when electrostatic forces binding dissolved organic molecules to organic solids are stronger than the forces holding organic molecules in water (Sposito, 1989). The distribution of organic molecules between water and organic matter is an equilibrium process and the amount sorbed becomes strongly a function of the amount of organic matter present. Organic compounds that react with soil organics in rural areas come mostly from agricultural chemicals and their degradation products. In urban areas, organic compounds that can react with soil organics include lawn-care products, oil and grease, and household chemicals. Soil humus may effectively arrest movement of these compounds into the subsurface. However, some compounds may become complexed with dissolved organic compounds, facilitating their movement into and through aquifers. A general rule is that the more soluble in water an organic compound is, the smaller is its tendency to sorb onto organic (or other) substances (Sposito, 1989).

In summary, sorption is a reversible process that describes the affinity of dissolved species for the surfaces of solid materials, either organic or inorganic. Because the process is reversible, metals or organics sorbed to surfaces can be desorbed if aqueous solution composition changes. This creates the possibility for addition of species to water through desorption that were not a component of the displacing aqueous solution (fig. 5.6). The mixing of fluids that can result from poor aquifer management could conceivably create such a situation.

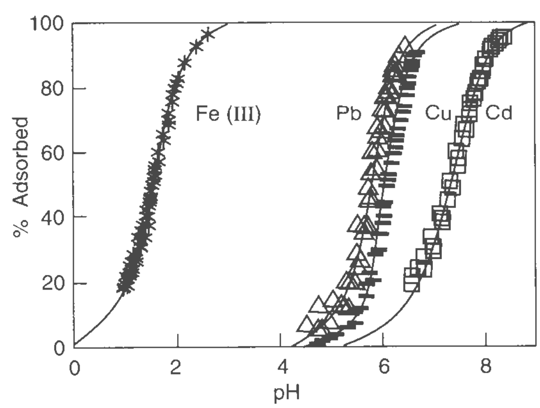


FIGURE 5.5—METAL-ION ADSORPTION ON AMORPHOUS SILICA AS A FUNCTION OF pH (Johnson et al., 1989). For each metal shown, adsorbed amount decreases with decreasing pH. Furthurmore, Fe(III) is completely sorbed at pH of about 3, while lead, copper, and cadmium are still dissolved.

ION EXCHANGE

An important mechanism of nonconservative behavior of ions in solution is ion exchange. The process of ion exchange requires a solid phase that has a charge deficiency (is negatively charged) for exchange of cations, or a charge excess (is positively charged) for exchange of anions. Most solids that are important ion exchangers affect cations in solution, although anion exchange can occur in some circumstances (Drever, 1988, p. 218–219).

Clay minerals are important ion exchangers that acquire their charge imbalance because of imperfect chemical composition, most often because of substitution of an aluminum ion (+3 charge) for a silicon ion (+4 charge). The clay-mineral lattice then acquires a permanent negative charge that is not affected by the pH of the surrounding solution. The negative charge attracts cations into specific sites within the layered structure of the clay mineral. The layers containing the exchangeable ions also contain water molecules, thus providing relatively easy ingress and egress for the exchanging ions.

Capacity for exchange is determined empirically, by measuring the uptake and release of ammonium ions from a sediment sample. This Cation Exchange Capacity (CEC) is frequently reported in units of milliequivalents per 100 grams (meq/100 gms), and is the amount of electrical equivalents of ions divided by 1,000 per 100 gms of sediment. Different clay minerals have different ion

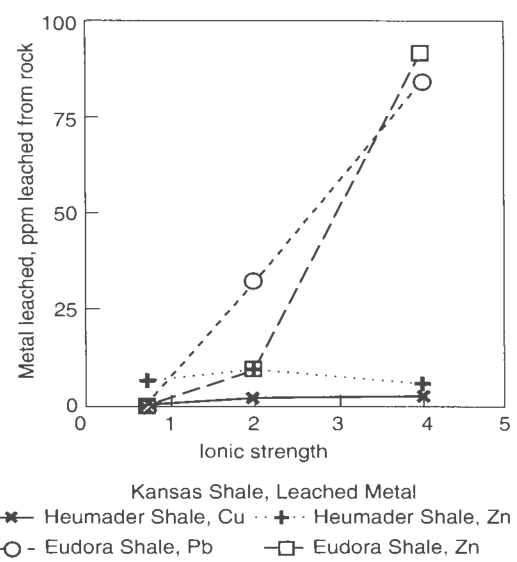


FIGURE 5.6—LEACHING SHALES WITH VARIOUS SALINITIES OF NA-CL TYPE WATER causes metals such as copper (Cu), zinc (Zn), and lead (Pb) to leave sorption or ion-exchange sites and reside in the leaching water. This effect depends upon salinity (here reported as ionic strength) and also temperature and type of salt. Note that movement of saline fluids from deeper aquifers (see section III) could cause metals to leach from sediments; data from Long and Angino (1982). Both shales are from Kansas.

exchange capacities. The highest CEC of the common clay minerals is on the order of 80 to 150 meq/100 gms (smectite or montmorillonite clays). Another group of clay minerals has intermediate to low CEC at 10 to 40 meq/100 gms (illite clay minerals), and other clay minerals have very low CEC at less than 10 meq/100 gms (kaolinite and chlorite clays; Drever, 1988).

Ion exchange is an equilibrium process, in which the exchange of one ion for another onto a solid material is described by a constant. As with other equilibrium processes, the constant represents the ratio of the products of the chemical reaction to the reactants. A typical ion exchange reaction is:

Na-solid + K^{+1} <—> K-solid + Na^{+1} (eq. 5.5)

Na-solid	K^{+1}	K-solid	Na^{+1}
sodium on exchange sites of a solid	dissolved potassium	potassium on the exchange sites of a solid	dissolved sodium

This exchange is one atom of sodium for one atom of potassium and is driven by equilibrium processes. A more complicated situation exists for exchange of ions that have difference valences:

Na_2-solid + Ca^{+2} <—> Ca-solid + $2Na^{+1}$ (eq. 5.6)

Na_2-solid	Ca^{+2}	Ca-solid	$2Na^{+1}$
sodium on the exchange sites of a solid	dissolved calcium	calcium on exchange sites of a solid	dissolved sodium

This exchange is two-for-one in order to satisfy the electrical charges in the solution. Constants derived from experiments producing ion exchange are highly sediment and ion specific and are difficult to generalize. It is well established, however, that solids exhibit a preference for ions that is charge- and size-dependent. The order of cation affinity for exchange is known as the Hofmeister series (Stumm and Morgan, 1981), and is written from left to right in order of decreasing preference of the solid for the ion (and so increasing likelihood of the ion residing in the solution):

$Cs^{+1} > K^{+1} > Na^{+1} > Li^{+1}$
for the common monovalent ions
$Ba^{+2} > Sr^{+2} > Ca^{+2} > Mg^{+2}$
for the common divalent ions
<— preferred on the solid...........preferred in the liquid —>

Describing preference order for a combined monovalent and divalent list is more difficult because the exchange is strongly controlled by the total concentrations involved (e.g., Drever, 1988). In essence, when estimating exchange between Ca^{+2} and Na^{+1}, Ca^{+2} is the preferred ion on the solid phase when TDS content is low, and Na^{+1} is the preferred ion on the solid phase when TDS content is high, even if the ratio of Na^{+1} to Ca^{+2} content stays the same. A generalized list of ion exchange affinities (at approximately the same total concentrations) could be as follows (Domenico and Schwartz, 1990), again in order of most strongly preferred on the left to least preferred on the right:

$Al^{+3} > Ca^{+2} > Mg^{+2} > NH_4^{+1} > K^{+1} > H^{+1} > Na^{+1} > Li^{+1}$
<— preferred on the solid.............preferred in the liquid —>

This list demonstrates that, in general, higher-charged, smaller ions are more strongly attracted to ion exchange sites than lower-charged, large ions or ions with large hydrated-ion radii such as lithium.

The process of ion exchange is completely reversible and occurs relatively rapidly as long as water (and dissolved ions) can pass freely through the sediment. An important caveat is that clay minerals, the best ion exchangers, make up the largest portion of low-permeability materials (mud layers and shales). The equilibration of low-permeability material with water recharging adjacent high-permeability materials is slow simply because of the time it takes the recharging water to penetrate the low-permeability material. Thus, mud or shale provides a reservoir of exchangeable ions that can influence the chemistry of water within an aquifer over a long period of time.

Recent work from two independent studies demonstrates the long time required for equilibration of marine shales with recharging (fresher-than-seawater) water (Appelo, 1994; Chu, 1995). In Kansas, the Dakota aquifer (fig. 5.1) is a series of sandstones and mudstones deposited in fluvial (river) and deltaic settings. Chu (1995) used a computer model to simulate the patterns observed in the water chemistry of the Dakota aquifer. Cation-exchange processes, thought to be the most important type of reaction affecting the water chemistry in the Dakota, are apparently ongoing. The computer model showed that, using reasonable numerical values to represent the Dakota's chemical properties, equilibration of clay minerals with the freshwater recharging it is not yet complete, even though the marine or marginal-marine clays were deposited more than 65 million years ago (fig. 5.7). In the Dakota sandstones, the chemical patterns seen on maps of the Dakota water chemistry evolve through time as incoming freshwater displaces resident water and ion exchange of different ions occurs (Chu, 1995). The best approximation of the evolution of ion exchange is that calcium and magnesium first replace sodium on ion-exchange sites and later calcium replaces magnesium on ion-exchange sites. The lateral (map-view) sequence created (fig. 5.8), from the downgradient saline fluid to the upgradient, fresher-water part, is a) a saline (Na-Cl) fluid—Zone I, b) a Na-HCO_3 type fluid created as ion exchange processes are more or less complete—Zone II, c) a Na-Mg type fluid and a Mg type fluid that is usually transient and not observed—Zone II–Zone III transition, and d) a Ca-HCO_3 or Ca-Mg-HCO_3 fluid that represents recharge water in steady-state equilibrium with the aquifer matrix—Zone III. This sequence indicates that the clays are still yielding ions from ion-exchange sites that were saturated with sodium when the clays were in contact with sea water (see table 5.1 for the composition of sea water).

In summary, the conservative and nonconservative dissolved species discussed above usually make up the largest proportion of dissolved solids in potable ground water. The chemical behavior of labile and refractory species, discussed in the next section, is important. This is because the transformation that they may undergo can cause them to be removed from ground water, either through precipitation as a solid or through volatilization, and/or the transformation can render them either less or more harmful than before the transformation.

Labile and Refractory Species in Ground Water

INTRODUCTION

Labile species typically found in ground water include those that undergo changes in redox potential and those that are volatile. Refractory species are those that may or may not have the capacity to undergo transformations but do not undergo transformation under ordinary ground-water conditions at significant rates. The following discussion focuses on labile species but is limited to those most commonly studied in potable ground water.

Two fundamental kinds of transformations are discussed in the following sections, those in which organic compounds are transformed into other compounds and those in which there is a change in redox state of an element. Transformation processes often facilitate removal of a compound from water through precipitation in a solid phase or through change into a gas phase. Of course, the redox change can work in the opposite direction, to add components to water. Both types of transformations are typically mediated by bacteria, meaning that conditions in the aquifer must be favorable for activity of the appropriate bacteria. Pumping a well can alter conditions in the aquifer, potentially either inducing or inhibiting these transformations. The change occurs principally because of introduction and mixing of different kinds of water from above, below, or laterally within the aquifer (see below, The Consequences of Mixing).

Transformations of organic compounds occur because of hydrolysis (reaction with water to attach OH^{-1} or H^{+1} to the compound, usually making it more water soluble), ionization (stripping off a H^{+1}, making the compound more water soluble), and biodegradation (a general term describing all reactions in which bacteria transform compounds; Johnson et al., 1989). In addition, organic compounds vary tremendously in their solubility (how much dissolves in water) and volatility (tendency to form a gas).

Redox reactions are those that involve the transfer of electrons and thus are involved in oxidation (loss of electrons) or reduction (gain of electrons), resulting in a change in valence for the species. Some elements can lose or gain as many as eight electrons and can exist in multiple oxidation states with different valences. Elements behave differently depending upon oxidation state, in that they exist in different kinds of solids (with different solubilities) and molecules and affect animals differently upon ingestion. The redox state of a fluid (see Boxed section 5.1, Redox) is a complex representation of the oxidation states of all the redox elements present in a fluid.

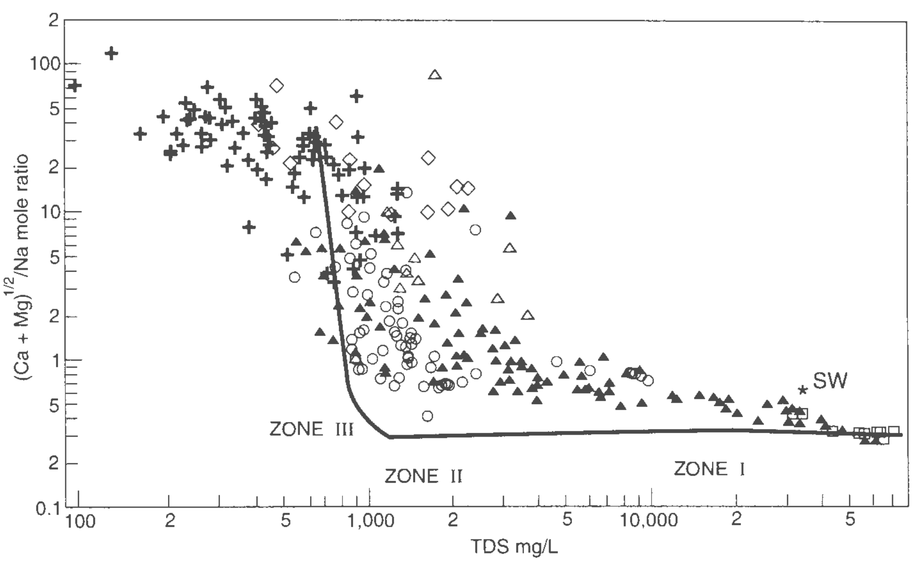


FIGURE 5.7—THE RATIO OF $(Ca+Mg)^{0.5}$ / (NA) IN UNITS OF MOLS, *versus* TDS for field data (points) and a computer simulation (line). Sea-water composition is shown for comparison (*). The identified zones represent different stages of completion of ion exchange in the Dakota aquifer; from Chu, 1995.

For this discussion of labile species in ground water, the focus is on a nutrient (nitrate), organic compounds, and metals with multiple redox states. Although there are others, these are discussed because they are the most common contaminants in ground water and most often limit its use. Introduction of one or more of these species because of poor management of an aquifer could render the ground water unacceptable for its intended use, and thus these species have the most impact on issues of safe yield.

NITRATE

Nitrate is one of the most common contaminants of ground water. It is harmful in very high concentrations to livestock and in only moderately low concentrations to human infants (EPA maximum contaminant level is 10 mg/L nitrate-nitrogen. Nitrate concentration can be reported as nitrate ion [NO_3^-], with a drinking-water limit of 45 mg/L, or as nitrate-nitrogen, with a drinking-water limit of 10 mg/L). Nitrate almost always enters aquifers from the land surface, and thus factors that accelerate downward movement of water can in turn accelerate entrance of nitrate to an aquifer. Nitrate may or may not persist in water, as discussed below.

Dissolved nitrogen in ground water occurs in many forms, from the most oxidized form, nitrate (NO_3^{-1}), to the most reduced form, ammonium (NH_4^{+1}). Transformations among nitrogen species are typically mediated by specific genera of bacteria and are often studied within the context of the nitrogen cycle (see Boxed section 5.3, The Nitrogen Cycle).

The ultimate source of nitrate is the atmosphere, which is mostly nitrogen gas (N_2). Although bacteria transform small amounts of N_2 to NO_3^{-1} in root nodules on legumes, most naturally occurring nitrate comes from decay of organic material that contains small amounts of nitrogen relative to carbon, hydrogen, and oxygen (Drever, 1988):

$$\underset{\text{organic matter}}{C_{106}H_{263}O_{110}N_{16}P} + 138\ O_2 \longrightarrow \underset{\text{carbon dioxide}}{106\ CO_2} +$$

$$\underset{\text{nitrate}}{16\ NO_3^{-1}} + \underset{\text{phosphate}}{HPO_4^{-2}} + 122\ H_2O + 18\ H^{+1} \quad \text{(eq. 5.7)}$$

Large quantities of nitrate are introduced to ground water through human activities. Oxidation of animal waste to nitrate (barnyards, feedlots, septic systems) and nitrogen-based fertilizers in agricultural regions are the two most important sources of introduced nitrate in ground water.

The two principal pathways by which nitrate is reduced are 1) through nitrous oxide species to nitrogen gas (N_2; called denitrification) and through nitrite (NO_2^-) to NH_4^{-1} (called DNRA, dissimilatory nitrate reduction to ammonium; Korom, 1992; Smith et al; 1991; Postma et al., 1991). Denitrification can be accomplished by bacteria using organic carbon as a source for electrons to reduce the nitrate (heterotrophic bacteria) or by using another source of electrons (autotrophic bacteria), as shown by the following two equations:

$$4NO_3^{-1} + \underset{\substack{\text{organic matter,}\\ \text{simplified representation}}}{5C} + 2H_2O \longrightarrow 2N_2 + 4HCO_3^{-1} + CO_2 \quad \text{(eq. 5.8)}$$

$$6NO_3^{-1} + \underset{\text{pyrite}}{2FeS_2} + 2H_2O \longrightarrow 3N_2 + \underset{\text{goethite}}{2FeOOH} +$$

$$4SO_4^{-2} + 2H^{+1} \quad \text{(eq. 5.9)}$$

DNRA proceeds generally from nitrate to ammonium, and may occur where nitrate amounts are limited:

$$NO_3^{-1} \longrightarrow NO_2^{-1} \longrightarrow NH_4^{+1} \quad \text{(eq. 5.10)}$$

Requirements for these reactions are the presence of nitrate-reducing bacteria (e.g., *Thiobacillus denitrificans* is one bacteria that denitrifies), oxygen-limited conditions in the aquifer (dissolved oxygen content less than about 2 mg/L; Hendry et al., 1983), and the other nutrients necessary for the bacteria. Absolute controls on rates of denitrification are not well established (Korom, 1992), but an excess amount of easily oxidized material in an aquifer (such as plant debris) can reduce even high supply rates of nitrate to nitrogen gases and prevent contamination of an aquifer (Simpkins and Parkin, 1993).

Poor aquifer management can create a nitrate problem in ground water. Much of fertilizer nitrate is used by plants or denitrified in the soil zone. Rapid passage of recharge water through the soil zone and bypass of the soil zone through flow in fractures can reduce the effectiveness of plant use, denitrification, and DNRA in minimizing nitrate content of recharge water. For those systems in

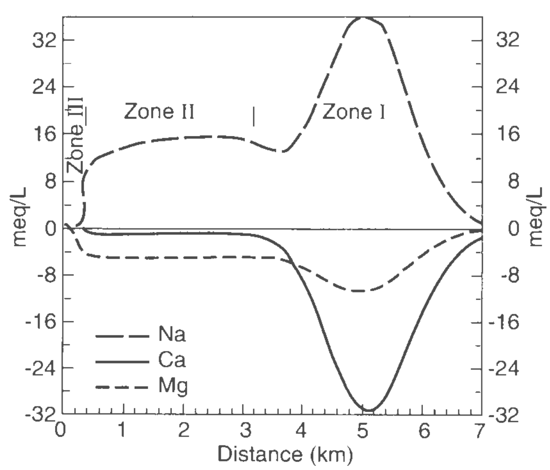


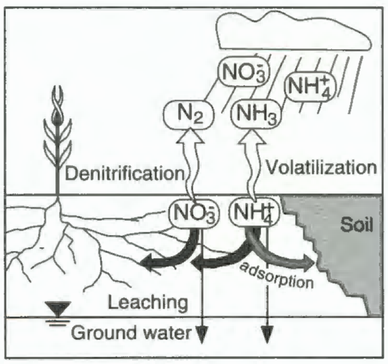
FIGURE 5.8—MODELLED CONCENTRATIONS OF SODIUM, CALCIUM, AND MAGNESIUM IN THE DAKOTA AQUIFER ALONG A GROUND-WATER-FLOW PATH. The plot shows concentrations in excess of (positive values) or as a deficit from (negative values) concentrations expected from mixing with no chemical reaction of resident fluid and recharging fluid. The pattern shows expected changes in water chemistry because of cation exchange; from Chu (1995).

Box 5.3: The Nitrogen Cycle

Nutrients such as nitrogen are cycled through biological materials, the atmosphere, soils, and water in a continuous loop. The cycle, in a natural world, completely accounts for all available nitrogen, and none of the various parts of the cycle gain or lose nitrogen except as changes in climate affect the transformation processes. In the natural cycle, rain and snow (precipitation) containing nitrate and ammonium fall on the earth.

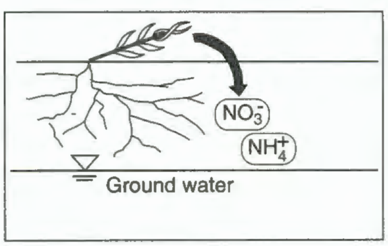
If the rain soaks into the soil to become part of the **soil water**, the nitrate and ammonium. . .

- might be used by **plants**.
- might be **adsorbed** onto the surfaces of organic matter or clays.
- might be converted to nitrogen gases or ammonia gas which are volatile and return to the **atmosphere**.
- might move downward into the **ground water**.



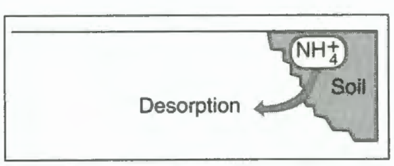
The nitrate and ammonium in the **plants**. . .

- nourishes the plants, then is shed from the plant where it decomposes in the soil zone, returning nitrogen to the **soil water**.



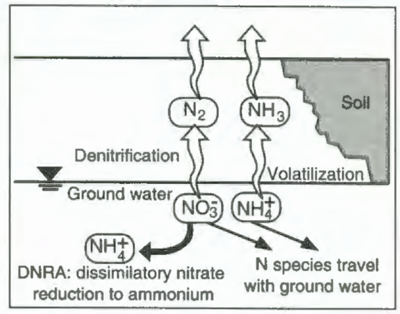
Ammonium that is **adsorbed**. . .

- can be desorbed and returned to the **soil water** if conditions are right.



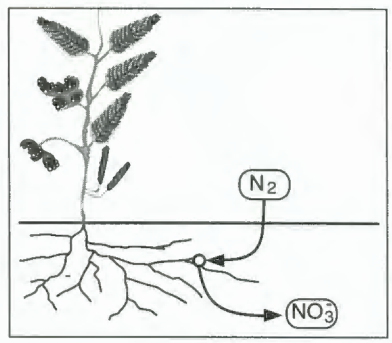
Nitrate and/or ammonium in the **ground water**. . .

- might be converted by bacteria to nitrogen or ammonia gases, and so eventually return to the **atmosphere**.
- nitrate might be reduced by bacteria to ammonium.
- might travel with the ground water to its surface discharge point, to then be used by **plants** or be transformed to gases and return to the **atmosphere**.



Nitrogen in the **atmosphere**. . .

- can be converted to nitrate in **soil water** by nitrogen-fixing plants.



Other sources of nitrogen, from human activities, are fertilizer and animal waste such as sewage, barnyard waste, and feedlot waste. Nitrogen from these sources is subject to the natural processes described above, but overloading of nitrogen in an area can result in natural processes unable to transform the nitrogen species as quickly as they are supplied, with the result that ground water typically becomes enriched in nitrate.

which DNRA dominates, introduction of oxygen-rich water into a reducing environment can reverse the DNRA reaction, effecting transformation of NH_4^{+1} to NO_3^{-1} and thus creating a nitrate problem. Issues associated with vertical movement of ground water and lateral movement as induced by pumping are discussed later in this chapter (see Inter-aquifer Ground-Water Flow).

Example: Equus beds, South-central Kansas—The Equus beds aquifer in south-central Kansas (fig. 5.1) is the principal source of irrigation, domestic, and municipal water in that region. Unconsolidated Pliocene and Pleistocene sand, gravel, and silt deposits comprise the high-permeability but heterogeneous aquifer. Ground water in the Equus beds in Harvey County has been studied in some detail. Harvey County has little topographic relief except for sand dunes in restricted areas. The thickness of the unsaturated zone and the saturated thickness of the aquifer thins from west to east across the county. Total dissolved solids in the ground water vary between about 250 and 1,000 mg/L, with major dissolved components being calcium, sodium, bicarbonate, and sulfate.

Crops are irrigated and fertilized in Harvey County, making conditions favorable for nitrate contamination of ground water, but measured NO_3-N concentrations are low to undetectable in part of the county (area 1, fig. 5.9; Townsend and Sleezer, 1994 and 1995). Nearby (area 2, fig. 5.9), even though dryland farming techniques are used, NO_3-N concentrations are up to three times the EPA Maximum Contaminant Level (MCL). This suggests that conditions are favorable for denitrification in area 1 but not in area 2. A reducing environment in area 1 is indicated by detectable dissolved iron (Fe^{+2}) and ammonium, and a slight hydrogen sulfide (H_2S) odor. Nitrogen isotope ratios of dissolved nitrate show enrichment of the ^{15}N isotope: the pairing of low-nitrate concentrations with enriched ^{15}N is a conventional indicator of nitrate reduction. In addition, sulfate concentrations are higher than in nearby areas, which, in conjunction with dissolved iron, suggests that iron sulfides may be the electron donor to nitrate reduction. Townsend and Sleezer (1995) showed that an average of 9–20 mg/kg of NO_3-N was stored in the upper 3 m (10 ft) of the vadose zone within the selected field-site region. Thus, nitrate is available for leaching between the land surface and 3-m (10-ft) depth. High concentrations of nitrate in this upper soil zone contrast with decreased concentrations in ground water beneath, suggesting that the conditions for denitrification are met somewhere between 3- and 10-m (10–33-ft) depth.

Therefore, in Harvey County, conditions in the Equus beds aquifer and the overlying unsaturated zone are optimum for the reduction of nitrate in some places, and in other places not, even in the same general area. Understanding what controls denitrification is an ongoing area of research, and teasing out the sensitivity of an aquifer to contamination remains an important goal.

ORGANICS

Organic molecules contain reduced carbon (-IV to 0 valence) in combination with other elements, dominantly hydrogen and oxygen. The structure of organic molecules can be quite complex, but generally the more complex an organic molecule the less likely it will dissolve in water and the more likely it will remain as a separate phase (table 5.3). Organics as a separate phase can be more dense than water (dense nonaqueous phase liquids, DNAPL's) or less dense than water (light, nonaqueous phase liquids, LNAPL's) and consequently move downward in an aquifer by gravitational forces or float on water, respectively.

In addition to size of the molecule, a few other general rules control how well organic molecules dissolve in water. First, organic compounds may be classified as polar or nonpolar, depending upon whether the electrical charge of the compound is distributed unevenly (in two poles) or evenly around the molecule. Because water is a polar molecule, it dissolves polar organic molecules much more readily than nonpolar ones. Second, in general, organic matter is the primary material for sorption of organic molecules, so the more organic material in the host rock of an aquifer the more organic sorptive capacity of the aquifer. Finally, chemical reactions involving organic molecules are usually kinetic reactions: the rate of chemical reaction often depends upon the concentration of one or more participants in the reaction, and the rate of reaction is slow enough that it can be measured.

The EPA list of priority pollutants, with established maximum contaminant levels, is about 75% organic compounds. Research has focused on the breakdown pathways of these components. Most of the early data on the various degradation processes of the organic priority pollutants are summarized in Mabey et al. (1982). Principal degradation processes and controls on solubility of organic molecules include molecule size and charge, volatility, hydrolysis, ionization, and biodegradation (e.g., Johnson et al., 1989).

In general, whether aquifer management accelerates movement of organic compounds depends on the properties of the organics. The tendency to be removed from solution increases if the organic compound has low solubility and is volatile, is easily sorbed, or can be easily hydrolyzed or ionized and thus made more susceptible to biodegradation. Biodegradation, if complete, reduces organic compounds to harmless CO_2 and water; if incomplete, it can, in some cases, create compounds more harmful than their precursors.

METALS

Some metals lose or gain electrons as a way of improving stability in solutions (Stumm and Morgan, 1981, p. 323). The transition from one redox state to another for an individual element is often pH as well as *pe*

TABLE 5.3—SOLUBILITY OF SELECTED ORGANIC COMPOUNDS.†

Compound	Molecular Mass (g/mol)	Solubility (g/m^3)
C_6H_6 (Benzene)	78.0	1780
C_7H_8 (Toluene)	92.0	515
C_8H_{10} (o-Xylene)	106.0	175
C_9H_{12} (Cumene)	120.0	50
$C_{10}H_8$ (Naphthalene)	128.0	33
$C_{12}H_{10}$ (Biphenyl)	154.0	7.48

† More complex molecules generally have a higher molecular mass, and are thus less soluble; modified from Domenico and Schwartz, 1990; reprinted by permission from John Wiley & Sons, Inc.

dependent (see Boxed section 5.1, Redox; fig. 5.10). Changes in redox state often cause dissolution or precipitation of metal oxides, hydroxides, and sulfides, and indirectly cause precipitation or dissolution of carbonates or other minerals. The redox state of an aquifer system (see Boxed section 5.1, Redox), as indicated by the *pe*, is buffered by the rocks or sediments that contain the water. Thus, the redox state is not expected to change significantly unless there is a radical change in water moving through the aquifer (see *Consequences of Mixing*, p. 149) or the aquifer is composed of unreactive minerals (such as very pure quartz sand), making it poorly buffered.

Several metals are affected by the redox state of water (table 5.4). Some general statements can be made about the effect of a change in redox state on the mobilization of metals. Because elements with multiple redox states are usually also affected by pH, both factors are considered in the groupings found in table 5.4. The table is not compre-

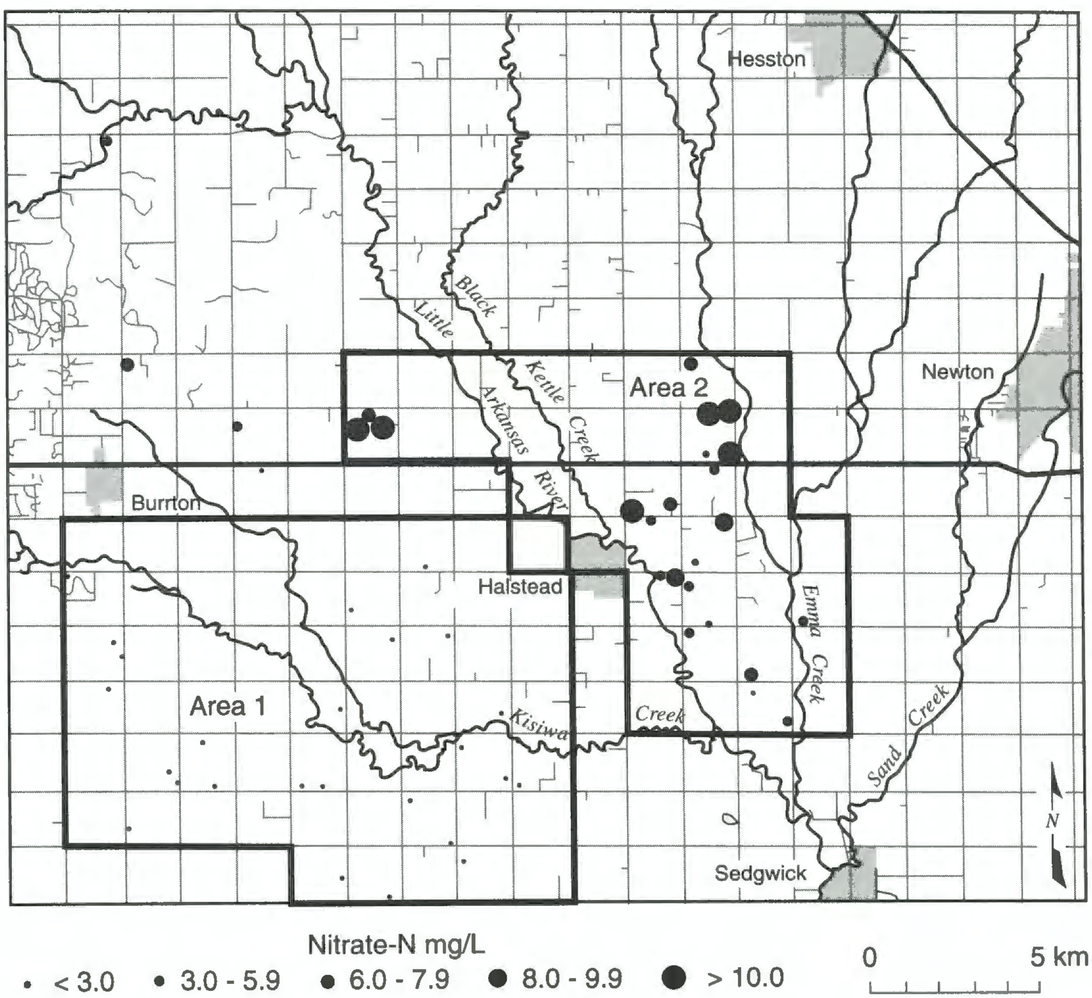


FIGURE 5.9—NITRATE-N CONCENTRATIONS IN DOMESTIC WELLS, HARVEY COUNTY, KANSAS (Townsend and Sleezer, 1995).

TABLE 5.4—pH-REDOX STABILITY† REGIONS FOR SELECTED IONS.

Element(s)	pH Conditions	Redox Conditions
As (arsenic)	1) moderate to low 2) high	1) reducing 2) all
Hg (mercury)	1) all	1) oxidixing
Cu (copper)	1) low 2) high	1) oxidizing 2) intermediate
Fe (iron), Mn (manganese), Pb (lead)	1) low	1) all
Ni (nickel), Co (cobalt), U (uranium)	1) low 2) high	1) all 2) intermediate to oxidizing
Cr (chromium)	1) all but intermediate	1) intermediate to reducing

† pH and redox conditions given show the general ranges for stability of the species in solution (in the dissolved form).

hensive, but lists a few elements of interest in ground water and the conditions under which they are mobile. Some elements or groups of elements are mobile under more than one set of pH-redox conditions. The different sets are numbered.

Under other pH and redox conditions, the above metals are immobile. By effecting a change from a condition under which a metal is immobile to one in which it is mobile, dramatic changes in water quality can occur.

Redox zonation exists naturally in ground water but also can be created by introduction of foreign materials such as landfill leachate. Baedecker and Back (1979) demonstrated that the compressed chemical zonation of an aquifer in the vicinity of a leaking landfill is similar to the broader zonation that occurs in marine sediments (fig. 5.11). Near the landfill where leachate is "fresh," the reduced forms of carbon, nitrogen, and sulfur (methane, ammonia, and hydrogen sulfide) exist in preference to the oxidized forms. Iron and manganese are found in solution in abundance. Farther from the landfill, the oxidized forms of carbon, nitrogen, and sulfur (dissolved CO_2 species, nitrate, and sulfate) become dominant in the leachate plume and the presence of oxygen in the water makes dissolved iron and manganese precipitate as oxyhydroxides (more on this topic in a later section, under Contamination, Landfills).

In summary, many metals (and some nonmetals) are stable in different oxidation states under normal ground-water conditions, and transformation among oxidation states can affect the metals' mobilities. Many transition metals are mobile under acidic, reducing conditions, but some may also be mobile under very alkaline conditions as well. Some metals are immobile under reducing conditions and mobile under oxidizing conditions. In many cases the situation is complicated by the fact that mobility is affected not only by pH and redox conditions, but also by the presence or absence of other phases or dissolved species, such as minerals that can sorb the metals under certain redox conditions (Matisoff et al., 1982) or dissolved species such as sulfides that precipitate fairly insoluble solids with the transition metals.

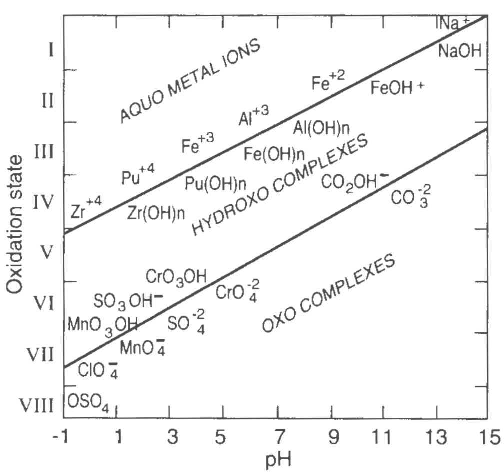


FIGURE 5.10—GENERALIZED DEPICTION OF THE STABILITY AREAS FOR SOME REDOX-SENSITIVE ELEMENTS (from Stumm and Morgan, 1981; reprinted by permission of John Wiley & Sons, Inc.).

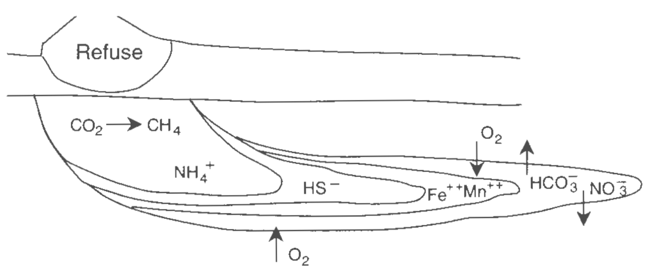


FIGURE 5.11—CHEMICAL ZONATION CAUSED BY LANDFILL LEACHATE LEAKING INTO AN AQUIFER (from Baedecker and Back, 1979). Ground water is reducing near the landfill (contains methane, CH_4, hydrogen sulfide species, HS^-, and ammonium, NH_4^+) and is progressively more oxidizing (contains carbon dioxide species like bicarbonate, HCO_3^-, sulfate, SO_4^{+2}, and nitrate, NO_3^-) as it mixes and reacts with resident, oxidizing ground water.

Entry of Poor-quality Ground Water to an Aquifer

Unsaturated Flow Processes

INTRODUCTION

Ground water generally moves vertically downward through the unsaturated zone to the water table. Unsaturated flow occurs where pore spaces in the soil profile are not completely filled with water. In the unsaturated zone, physical and chemical interactions occur among air, water, and sediment. Much of aquifer recharge occurs from the land surface through the unsaturated zone. Flow through the unsaturated zone is complicated by the presence of rapid flow paths called macropores (such as large pores, burrows and channels, roots, fractures) and by restrictions to flow, exemplified by discontinuous silt or clay layers. The source of the recharge water, the rapidity with which the recharge reaches the aquifer, and the chemical reactions that occur in the unsaturated zone all determine the quality of the water recharging an aquifer.

Examples of the types of water that can enter the unsaturated zone include rainfall, surface water during overland flow or flooding, and playas and other temporary holding ponds for surface water. Sources of recharge water that may contain undesirable chemicals or undesirable concentrations of salts include point sources of liquids such as landfills that produce leachate, spills at agrichemical preparation locations on farmsteads, and irrigation water. The unsaturated zone is composed of the root zone (upper 1.2 m [4 ft]); the intermediate vadose zone, which is the zone between the root zone and the capillary fringe above the water table; and the capillary fringe (fig. 5.12). The capillary fringe is the zone where air in the soil zone meets a fluctuating water table. The thickness of the capillary fringe depends upon the soil-grain size, finer-grained sediments allowing thicker capillary fringes to form. The elevation of the top of the capillary fringe fluctuates with the amount of recharge, just as the water table fluctuates.

Movement of water through the soil profile is complex because of the variety of forces that affect the flow process. The major impact on flow in the unsaturated zone is the effect of the surface area of soil particles and small soil pores that adsorb water (fig. 5.13). Particles with large surface area can adsorb water more tightly than particles with small surface area. Small soil pores hold water more tightly than large soil pores because of capillary attractive forces. Therefore, water drains through large pores more easily than through small pores and, by extension, sandy soils with large pore spaces will drain more easily than soils composed of clays or mixtures of clay, silt, and sand.

In general, water flows from areas of high-water potential to those of low-water potential. The gradient created by an area of high-water potential forces flows from wetter to drier soils or from areas of high pressure to those of low pressure. In most situations the direction of flow is from the land surface downward, although situations occur where capillarity and evapotranspiration cause water to migrate upward through the soil profile toward land surface.

The two end-member types of unsaturated flow are diffuse flow and macropore flow. Diffuse flow is the slow movement of a wetting front through a porous media (e.g., soil and unconsolidated sediments) to the ground-water table. In diffuse flow, water moves slowly from pore to pore displacing air and/or water in its path. Diffuse flow represents a relatively smooth migration of water through interconnected pores.

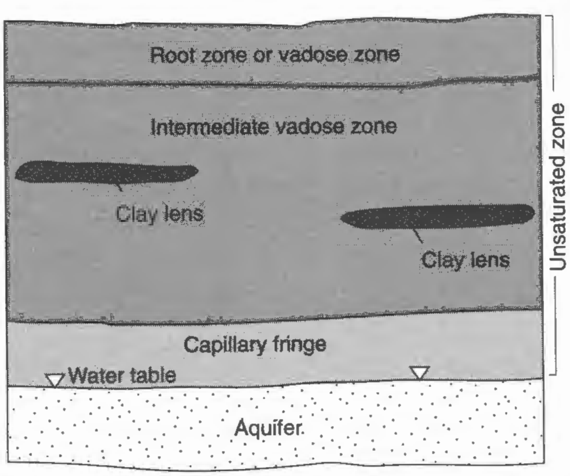


FIGURE 5.12—SCHEMATIC DIAGRAM SHOWING A CROSS SECTIONAL VIEW OF THE UNSATURATED ZONE AND UPPER PART OF AN AQUIFER.

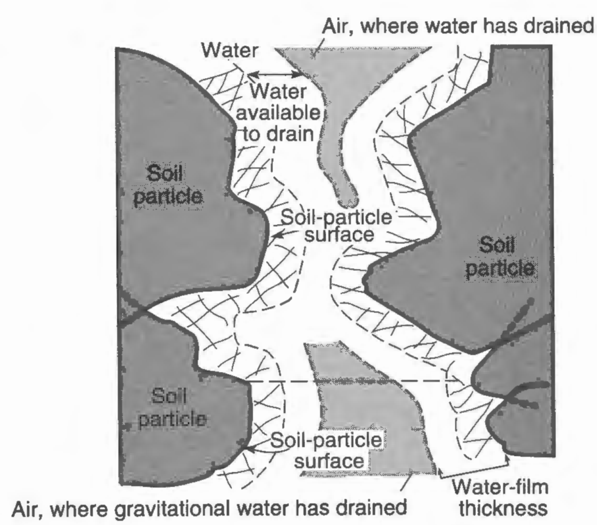


FIGURE 5.13—CROSS SECTION OF A SOIL PORE. Water is held more tightly near soil particle surfaces (hatchured areas). At some distance away water is weakly held and available for drainage by gravity (from Miller and Donahue, 1990).

Macropore or preferential flow involves the rapid movement of water down a vertically interconnected pore network or fracture. Macropores commonly are caused by cracks in the soil due to drying, physical structure of the soil, decayed root channels, abandoned worm tubes, or chemical changes within the soil itself. Macropores can permit rapid and massive movement of water (with contaminants, if present) to the ground-water table without the benefit of retardation or filtration by the soil. Macropore flow can result in contaminants arriving at the water table faster than expected. Tracer tests, designed to determine flow rates in the unsaturated or saturated zones, can be used to identify macropore flow by comparing expected and observed arrival times of a tracer chemical: a tracer that arrives more quickly than expected from the permeability of the soil indicates macropore flow.

FRACTURED VERSUS POROUS AQUIFERS AND UNSATURATED ZONES

The rapidity of transport into aquifers through the unsaturated zone strongly influences some chemical processes. Thus, scenarios predicted for ground water in porous media, where water moves relatively slowly, are different from scenarios predicted for ground water in fractured rocks, where water can move rapidly through open or nearly open fractures. In addition, an aquifer that is composed of porous media, whether consolidated or unconsolidated, will have a moderate to thick unsaturated zone overlying it and aquifers composed of fractured media often have very thin unsaturated zones overlying the aquifer proper. Fractures are nearly always present in limestones and other carbonate rocks, may be present in consolidated sandstones and shales, and may also be present in thick deposits of very fine grained material such as glacial till. Fractures are unlikely in unconsolidated material composed primarily of sand or gravel.

Aquifers present in Kansas are of both types: porous media such as unconsolidated sediment (examples being river alluvium, the Ogallala/High Plains aquifer, and the Great Bend Prairie aquifer) or sandstone (such as the Dakota aquifer), and fractured media (principally limestone, such as the Cottonwood Limestone of east-central Kansas and the Cambrian–Ordovician or Ozark aquifer system of southeastern Kansas).

EFFECTS OF SOIL STRATIGRAPHY

Soil stratigraphy, describing nonuniform, heterogeneous soil, is one factor that affects flow in the unsaturated zone. Soil is typically composed of multiple layers of sands, silts, clays, caliche, and possibly mineralized zones in a heterogeneous mix. Water movement is strongly affected by the stratigraphy of and structure within the soil and, in particular, relatively large effects are caused by discrete, impermeable layers. The presence of impermeable clay or clay/silt layers in the unsaturated zone can result in a perched water table above the layers (fig 5.14a), retarded flow around or through the clay layer (fig. 5.14b), or flow downgradient with the clay zone acting as a major diversion point (fig. 5.14c; Miller and Donahue, 1990; Kung, 1990). Finer-scale effects occur where there are gradations in soil-grain size and texture. These gradations enhance entrapment of air that in turn affects permeability to water. As stated above, flow is generally from areas of wetter soil to dryer soil (high-water potential to low-water potential), and variable soil stratigraphy increases the magnitude of wet-to-dry gradients. The latter phenomenon results from the relation between permeability and moisture content in unsaturated sediments: maximum permeability occurs in fully saturated sediments, and permeability decreases nonlinearly with decrease in moisture content (Domenico and Schwartz, 1990).

Unsaturated flow is generally vertical in coarse-textured soils such as loamy sands, more lateral in fine-textured soils such as clay loam, and inhibited when a sand occurs below a fine-textured soil because of a "shadow" effect (fig. 5.15; Miller and Donahue, 1990). Fine-textured soil lenses can create a perched water table if the water supply is large enough (fig. 5.14a). With or without a perched water table, flow will not occur through a sand underlying the fine-textured layer, even though the sand is inherently more permeable when wet, until the fine-textured unit is saturated.

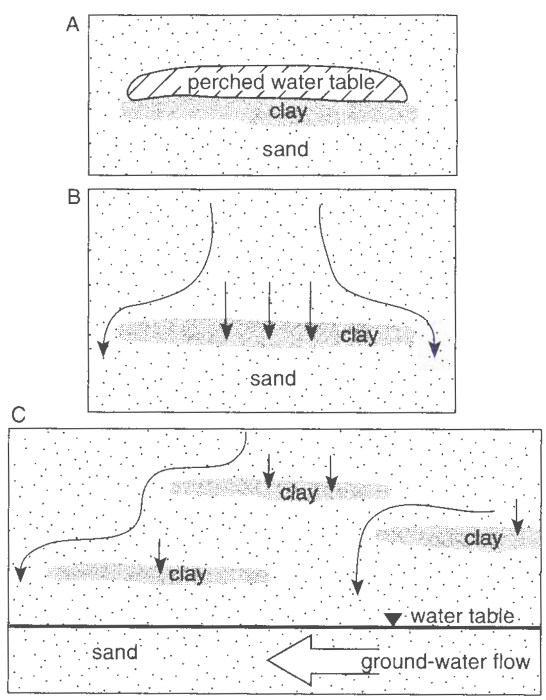


FIGURE 5.14—PERCHED AQUIFERS. a) Occurrence of perched water-table aquifer because of permeability differences between fine-textured zones and surrounding sediment. b) Flow is retarded because of permeability differences. In addition to perching, water can flow around fine-textured zones and also eventually saturate the zone (small arrows). c) Slight changes in dip of strata can permit downgradient movement of water as it is deflected by less-permeable zones.

The slow movement of water through the unsaturated zone has implications for safe-yield policies. In areas where extensive pumping occurs, depletion of aquifers surrounded by semi-confining layers that limit recharge can result in the total loss of a usable aquifer. In addition, continuous withdrawal of water can cause the collapse of fine-textured layers. This subsurface collapse can propagate to the land surface, creating large areas of subsidence that may be accompanied by small faults. Land subsidence because of ground-water pumpage exceeding recharge rates has been observed in numerous places, including Houston, Texas (up to 2.7-m [8.9-ft] land-surface subsidence); Mexico City, Mexico (up to 8 m [26.4 ft]); Venice, Italy (up to 3 m [9.9 ft]); and Long Beach, California (up to 9 m [29.7 ft]; Pipkin, 1994). The geology of these regions where subsidence occurred is characterized by relatively thick, fine-grained, unconsolidated, water-saturated sediment (clay and silt) confining an aquifer. The reduction in pore pressure that occurs as water is removed from the underlying aquifer causes compaction of the overlying, fine-grained material. The collapse is not reversible, so areas that have subsided will not "rise" again when pumping stops. This might occur in only a few locations in Kansas. Potential areas of subsidence in Kansas include floodplains of large rivers where muds are deposited over sands and gravels or parts of the glacial-drift aquifer.

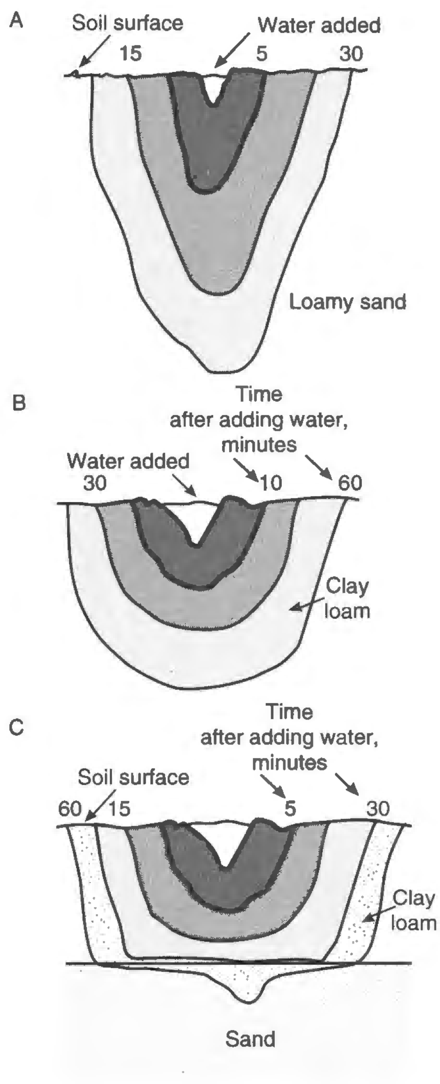


FIGURE 5.15—TYPICAL WETTING PATTERNS EXPECTED FOR SATURATED AND UNSATURATED FLOW AS INFLUENCED BY TEXTURE AND LOCATION OF THE WATER SOURCE. *Saturated* soil-water flow, which always has unsaturated flow occurring at the same time, is mostly vertical in coarse-textured soils (loamy sand), more lateral in fine-textured soils (clay loam). A temporary inhibition to flow occurs when sand is below a finer-textured soil (clay loam over sand; from Miller and Donahue, 1990).

The presence of clay/silt layers also causes interactions with the dissolved ions carried by water. Three aspects of this interaction are briefly discussed here. First, clays act as adsorption points for anions and cations, the magnitude of which depends upon the type of clay and the pH of the water. The attraction of anions or cations to a clay surface causes a decrease of ion concentration in the water or change the pH of the water, which in turn may permit further dissolution of other minerals in the soil as the water moves downward. Adsorption of ions to clays can also disperse the clays, thereby decreasing the permeability of the soil. Decreases in the quantity of recharge that reaches the ground-water table have a direct impact on the safe-yield development of an aquifer.

Second, clays can act as agents of cation exchange, where cations of different sizes and valences occupy interlayer sites within the clay-mineral structure. The most common type of cation exchange occurs when water moving through a soil is a calcium-bicarbonate type water and the clays are sodium-rich. Equilibrium between the water and the clay is approached as calcium exchanges for (trades places with) sodium in the clay mineral. Calcium is preferred on the cation-exchange sites in clays in dilute water because calcium is smaller and has a larger charge (+2 *versus* +1 for sodium) than sodium. Conversely, when sodium-rich water is used for irrigation, the increase of sodium in the soil zone can increase the dispersive properties of the soil zone, decrease the permeability, and increase the sodium concentration in water that moves downward through the soil zone. These effects are detrimental to the soil both from a chemical and tilth point of view.

A third way in which clay layers can affect the movement of water is by acting as a barrier to flow, thereby creating a local perched aquifer. The water in the perched aquifer may allow chemical reactions that are not possible in the rest of the unsaturated zone. For example, if the temperature and organic carbon content are suitable and anaerobic bacteria are present, denitrification (see previous section, *Nitrate*) can occur in the perched aquifer, resulting in a decreased nitrate content and increased bicarbonate content. In addition, ponding can permit more rapid evaporation of water in the surface layers of the soil resulting in a zone of increased salinity. Such zones can cause a soil to become sodic. The increased salinization over time will degrade both the soil and the water moving through the soil zone to the ground water. This will be discussed further in the next section.

EFFECTS OF ARID CLIMATE ON SOIL

Caliche zones in the unsaturated zone result from the effects of an arid climate on the movement of water through the soil profile. Rainwater has low total dissolved solids and a low pH, meaning that it is aggressive in terms of dissolving minerals in the soil. Furthermore, there is more carbon dioxide in the soil zone than in the earth's atmosphere because of the breakdown of organic matter and root respiration. The partial pressure of carbon dioxide is a measure of the amount of carbon dioxide in the air: for example, the total soil-atmosphere pressure is the sum of the partial pressures of the individual gases in the soil atmosphere, such as N_2, O_2, CO_2, and much smaller amounts of other gases. The higher partial pressure of CO_2 in the soil atmosphere affects the recharging water by lowering the pH of the water. Calcite (calcium carbonate) dissolution results from this more acidic water, causing the pH to rise. In arid and semi-arid regions, the deeper part of the soil profile has less biological activity and the resulting partial pressure of carbon dioxide is lower. Recharge water carried downward through the high carbon dioxide zone to the lower carbon dioxide zone becomes oversaturated with respect to calcite and so it precipitates. Furthermore, evaporation in the upper part of the soil zone concentrates the dissolved solids and draws water back toward the land surface. Both the evaporation of the water and the upward movement cause more precipitation of calcite through a number of complicated steps (Buol et al., 1989).

Caliche zones are commonly found throughout soil profiles in semi-arid areas such as western Kansas but are also routinely found at the base of finer-textured horizons in areas with fluctuating water tables, such as in south-central Kansas. Like clay/silt horizons, caliche zones can act as perching zones or as points of diversion as water migrates through the soil profile to the ground water. In addition, because calcite dissolution causes pH to become more basic, the change may affect other pH-sensitive chemical reactions in the soil, such as volatilization of ammonia gas ($NH_{3(g)}$; see Boxed section 5.3, The Nitrogen Cycle, and related text above). The volatilization of ammonia reduces the concentration of the pool of nitrogen available for nitrification, thus causing a reduction in nitrate in the system. The change in pH may also affect precipitation, transformation, or mobility of other contaminants.

Sources of Recharge to Aquifers

INTRODUCTION

Sources of ground-water recharge include precipitation (both rainfall and snowmelt), irrigation, and leakage from other sources such as playas, landfills, storage tanks, ponds, farmsteads where agrichemicals are handled, and factories. Recharge can also occur vertically upward from underlying aquifers.

Precipitation provides some of the most chemically active recharge in the hydrologic system. Precipitation, unaffected by industrial sources of atmospheric pollution, has a pH of about 5.6 (Hem, 1985) and is very poorly buffered (pH is easily changed). The average pH of precipitation from 1983 to 1991 at one site in east-central Kansas was 5.1 ± 0.6; in southeastern Kansas, pH of rainfall averaged 4.88 and in western Kansas, pH of rainfall averaged 5.83 for water year 1992–93 (Geiger et al., 1994). Variations in pH are due to the sources of ions in the water, the effects of dust moving through the atmosphere and interacting with precipitation, and the effects of surface-soil conditions when rainfall occurs (Randtke, 1996, personal communication). The presence of high P-CO_2 in the soil atmosphere (see equation 5.2, above, and related discussion) greatly increases the acidity of the recharging rain water. This water is usually neutralized by reactions with minerals in the soil zone, but has the potential to affect transport of many species.

Acidic water acts to mobilize chemical constituents in a soil. Common chemical reactions involve carbonate and sulfate minerals. Dissolution or precipitation of carbonates changes the water pH and to some extent the TDS content of the soil water, and dissolution of sulfates causes an increase in the TDS. In addition, low pH water is more likely to mobilize metals or other compounds such as ammonium that might be attached to clays or colloids.

Irrigation water is a potential source of recharge. This water may come from surface water, such as rivers, or ground water, the more common source in Kansas. The irrigation water is pumped from the source to the area to be sprayed or flood-irrigated. Depending upon the region's climate, evapotranspiration may change the chemistry of the water prior to its movement into the vadose zone. Evapotranspiration concentrates the dissolved species in water because of simple evaporation and/or because of water use by plants (transpiration). Whereas evaporation concentrates all dissolved species in water, transpiration is selective, concentrating only those constituents not used by the plants. In either case, many chemical constituents in the soil water become more concentrated than in the source water used for irrigation. This concentrated water migrates through the vadose zone and interacts with the soil, thereby recharging an aquifer with water containing more dissolved solids than expected. The end result can be a degradation of water quality over time (Deverel and Fujii, 1990; Parker and Suarez, 1990; Tanji, 1990).

EXAMPLES—EVAPOTRANSPIRATION AFFECTING RECHARGE WATER

Evaporation of the water during irrigation of cropland may increase the TDS content in the underlying ground water over time. In addition, use of agrichemicals can contaminate ground water by transporting chemicals from the surface to the ground water. Irrigation thus influences assessment of safe yield from the water-quality perspective, as well as having a direct influence on withdrawal of water from an aquifer. The following sections describe two examples in Kansas where irrigation has probably caused deterioration of water quality in an aquifer.

SOUTH FORK, BEAVER CREEK—In Sherman County, Kansas, the Ogallala aquifer in the vicinity of the South Fork of Beaver Creek (fig. 5.1) is contaminated by nitrate, with concentrations above the U.S. Environmental Protection Agency drinking-water limit of 10 mg N/L (fig. 5.16; Townsend, 1995). This area was farmed in sugar beets from the 1950's to early 1980's. Sugar beets are a high fertilizer-use crop (276–360 kg N/ha; 200–300 lb N/acre). Flood irrigation was used during this time, and the South Fork of Beaver Creek was used as the tailwater runoff route for irrigation water. The market for sugar beets collapsed in the early 1980's, and at that time much of the flood irrigation was replaced by more efficient center-pivot irrigation and different crops were grown.

Ogallala aquifer water in this area now has a significantly higher total dissolved solids content than ground water in other parts of Sherman County. A working hypothesis is that the higher dissolved solids content is due to concentration of the salts in flood-irrigation water because of evaporation and transpiration. Comparison of water samples collected in 1978 with samples collected during a period from 1987 to 1994 shows that both total dissolved solids and nitrate-N have increased (fig. 5.17). This increase, well after the cessation of activity that may have created the problem, suggests a slow transport of water with higher total dissolved solids and nitrate from pre-1980's farming practices, and that water is now arriving at the irrigation wells.

The mechanism for introduction of the concentrated irrigation water into the Ogallala aquifer in this part of Sherman County may not be simple transport through the

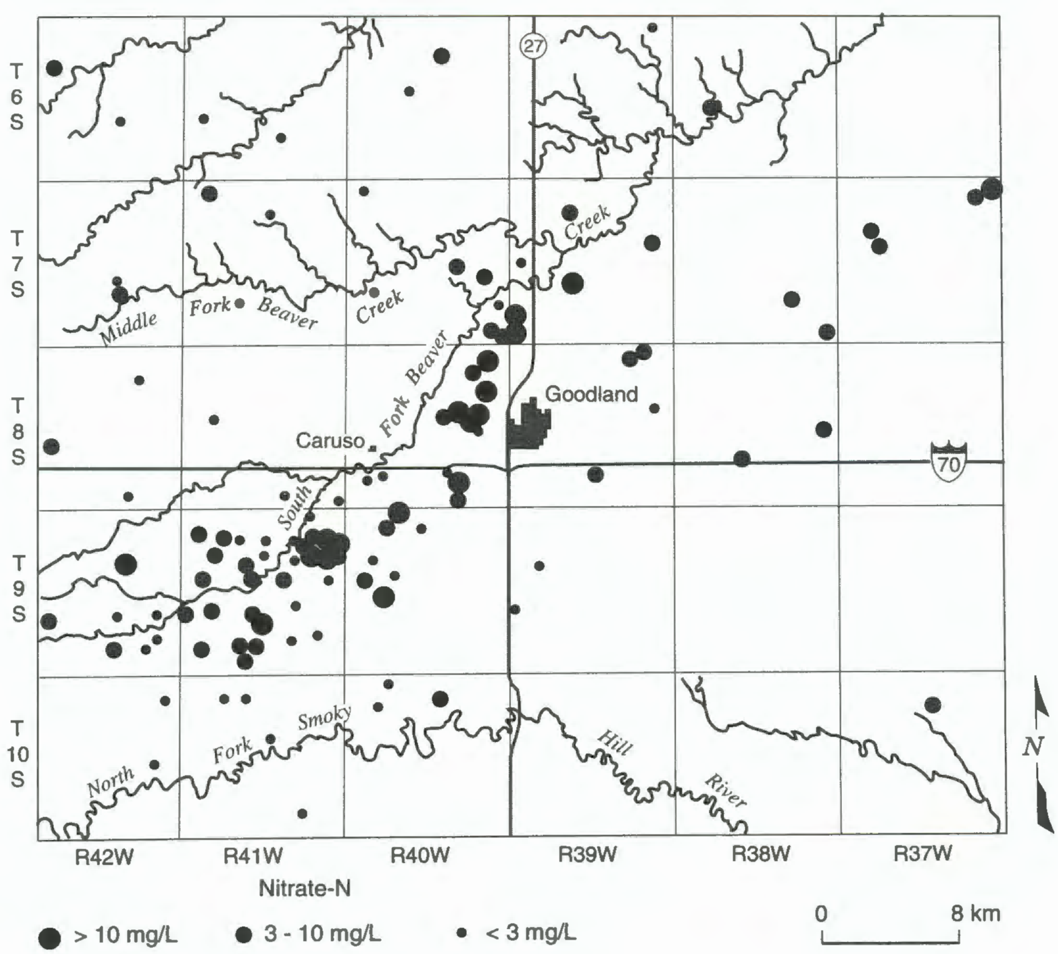


FIGURE 5.16—LOCATION MAP OF WELLS SAMPLED FROM 1989 TO 1994 IN SHERMAN COUNTY, KANSAS. Graduated dots indicate level of nitrate-N concentration measured at each site (from Townsend, 1995).

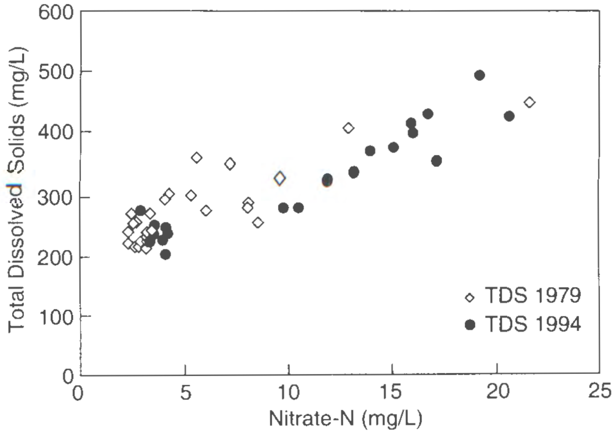


FIGURE 5.17—Relationship of increased nitrate and TDS concentration is shown. Samples collected in 1978 have lower values than in more recently collected samples, suggesting continued concentration processes over time. Points shown on this plot are from the same well for the two collection periods or from wells in close proximity to each other for the two collection periods.

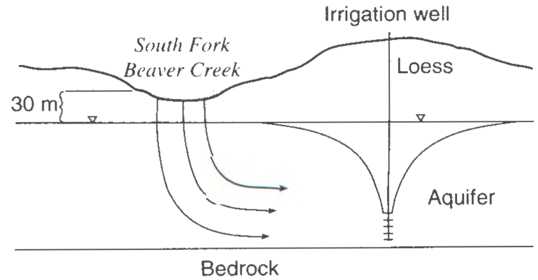


FIGURE 5.18—Proposed recharge mechanism for nitrate-rich tailwater runoff to South Fork of Beaver Creek to reach the deeper Ogallala aquifer (Townsend, 1995).

unsaturated zone. The South Fork of Beaver Creek received the excess (tailwater) irrigation water from the sugar-beet fields, so that until the early 1980's it received high total-dissolved solids, nitrate-laden water some of the time. Farmers in the area recall the stream running bank-full during the irrigation season; water in the stream must have been composed almost entirely of the irrigation-return water. The streambed of the South Fork of Beaver Creek is approximately 30 m (100 ft) above the ground-water table. Depth to water in nearby irrigation wells is considerably deeper (60 m [200 ft] or more) despite the only modest increase in ground elevation away from the creek (fig. 5.18). The increased head from the water in the stream and the gradient between the stream and the wells suggests that the South Fork of Beaver Creek is a losing stream for at least some times of the year, causing ground-water recharge through the stream bed. In this way, higher dissolved solids, nitrate-laden water from the irrigation tailwater could have entered the Ogallala aquifer and travelled toward the irrigation wells in the vicinity of the creek.

Arkansas River Basin—The Arkansas River corridor from the Colorado state line to Great Bend, Kansas (fig. 5.1), shows evidence of the effect of evaporation on ground-water quality. In this area, the concentration of total dissolved solids has increased significantly because of evapotranspiration of irrigation return flows to the river in both Colorado and Kansas (Whittemore, 1995b). Figures 5.19–5.21 show the elevated sulfate, nitrate, and chloride concentrations that occur in this area. In all three graphs the dashed line represents no change in concentration through time. The data points in each figure respresent ground waters sampled in 1994 by the Department of Agriculture, which are the same irrigation wells or wells very close to irrigation wells sampled in 1975 by the Kansas Geological Survey.

Increases in sulfate and chloride concentration from 1975 to 1995 (points above the dashed line) may reflect mixing of the relatively high-salinity Arkansas River water with ground water (fig. 5.19, 5.20). The data-point distribution for chloride and sulfate suggests two sources of chloride and sulfate (see *The Consequences of Mixing*, below). The spread of points supports the hypothesis of mixing between the river and the ground water, and suggests that the high-salinity river water is recharging the ground water. Increased ground-water-flow gradients caused by pumping of the many irrigation wells in the area is a likely reason for the river water moving into the alluvial aquifer adjacent to the river.

Decreases in sulfate and chloride concentration (points below the dashed line) generally occur in an area of southwestern Kansas that has a substantial percentage of land in the Conservation Reserve Program. Decreases may be related to land- and water-use changes (decreased irrigation perhaps resulting in decreased induced stream-aquifer interaction).

The nitrate-N graph (fig. 5.21) shows that many wells in the area have produced water with higher nitrate concentration in 1994 than in 1975. Because the area has been farmed for many years, it is unlikely that the source of nitrate is related to nitrification of organic nitrogen. The area is heavily irrigated, and the use of fertilizer with irrigation on an alluvial soil is likely to result in increased nitrate concentration in the ground water.

The overall decline in water quality in this area has occurred because of the shallow water table, irrigation return flows concentrated by evapotranspiration, and the low precipitation rate (35–40 cm/yr [14–16 inches/yr]) and recharge rate that might otherwise dilute the ground water.

EXAMPLES—RECHARGE AFFECTED BY POINT AND NONPOINT CONTAMINATION

Recharge can be affected by other fluids in a variety of situations. Point sources of contamination result from vertical flow originating from a specific, restricted location of contamination on the ground surface. Examples of point sources of contamination include landfills, storage tanks, ponds or lagoons, and areas at both commercial sites

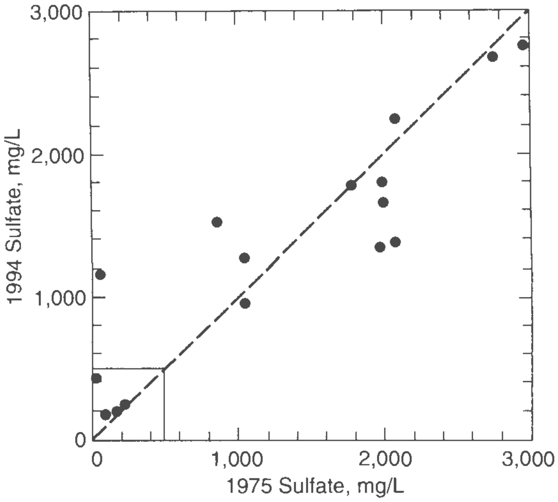


FIGURE 5.19—CHANGES IN SULFATE CONCENTRATION IN WATERS FROM IRRIGATION WELLS SAMPLED IN 1975 AND 1994 IN THE ARKANSAS RIVER VALLEY (Whittemore, 1995b). Dashed line represents the condition in which concentrations were the same for both 1994 and 1975. Points above the dashed line indicate an increase in sulfate during the period; points below the line a decrease for the same period. Solid line represents U.S. EPA drinking-water limit of 250 mg/L.

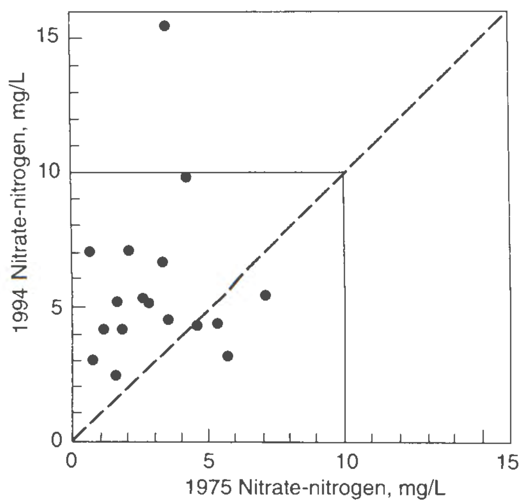


FIGURE 5.21—CHANGES IN NITRATE-NITROGEN CONCENTRATION IN WATERS FROM IRRIGATION WELLS SAMPLED IN 1975 AND 1994 IN THE ARKANSAS RIVER VALLEY (Whittemore, 1995b). Dashed line represents the condition in which concentrations were the same for both 1994 and 1975. Points above the dashed line indicate an increase in nitrate during the period; points below the line a decrease for the same period. Solid line represents U.S. EPA drinking-water limit of 10 mg/L.

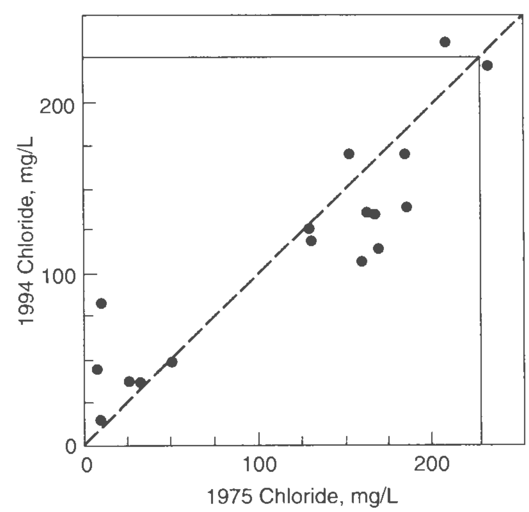


FIGURE 5.20—CHANGES IN CHLORIDE CONCENTRATION IN WATERS FROM IRRIGATION WELLS SAMPLED IN 1975 AND 1994 IN THE ARKANSAS RIVER VALLEY (Whittemore, 1995b). Dashed line represents the condition in which concentrations were the same for both 1994 and 1975. Points above the dashed line indicate an increase in chloride during the period; points below the line a decrease for the same period. Solid line represents U.S. EPA drinking-water limit of 250 mg/L.

and farmsteads where chemicals are prepared by dissolving or diluting more concentrated stock. Contamination can also occur from more diffuse sources. This type, called nonpoint-source contamination, is one in which the source of contamination is so widespread that no single location can be identified as a sole source for the observed contamination. Examples of nonpoint-source contamination include widespread use of chemicals on cropland, road salt that dissolves in snowmelt and recharges shallow ground water, or nitrate contamination from lawn and golf-course fertilization.

Many different inorganic and organic chemicals are supplied from point and nonpoint sources. The two categories discussed below, landfills and agricultural chemicals, are representative of point and nonpoint sources of contamination that may enter an aquifer. Planning for safe and sustainable production of an aquifer must take into account the possibility of such contamination affecting water quality of the ground water.

LANDFILLS—Municipal landfills may be a source of inorganic contaminants such as nitrate, chloride, sulfate, iron, and manganese, and also a source of organic contaminants such as acetic acid and various volatile organic carbons (VOC's). These constituents are concentrated in the landfill environment and exit the landfill as leachate. Some components of the leachate react and some do not react with the surrounding aquifer, both cases resulting in degradation of ground-water quality. If a large volume of the aquifer is affected and/or pumped wells are nearby, then safe-yield determination of that aquifer is affected as calculations of capture zones of the pumped wells are made. A complication to interpreting the landfill-leachate effect on ground water is that the composition of some components of the leachate change with time (fig. 5.22). For example, many organic compounds are susceptible to degradation by bacteria, but the rate of degradation varies widely, making predictive models of the effects of landfills on ground water difficult. In addition, transport of metals such as iron and manganese depends upon the redox state of the water, so that transport of some metals is restricted to the area in which the leach-ate has created strongly reducing conditions (fig. 5.11).

The following examples of contamination from landfills in Kansas represent different geologic and hydrologic settings common in Kansas. Ground-water contamination from landfills either is not common or at least is not well documented in Kansas at this time. The following examples show that although leachate contamination of ground water in Kansas does occur, positioning of landfills downgradient from water-supply wells has prevented serious contamination problems.

A study of the Reno County, Kansas, landfill (fig. 5.1; Heck et al., 1992) showed that dissolved organic compounds, some carcinogenic, have moved out of the landfill. This landfill is located on relatively impermeable silt and clay, and the contamination has been found in the underlying and more permeable sand and gravel aquifer. The landfill, however, is strategically located in that the contaminated water is moving toward Salt Creek, under which the ground water is naturally too salty to drink. For this reason it is unlikely that humans will inadvertently consume the ground water affected by landfill leachate. Furthermore, the Arkansas River lies between Salt Creek and the the city of Hutchinson. The sand-and-gravel aquifer affected by the leachate most likely discharges to the river. However, the distance to the river is enough that natural degradation of organic compounds and sorption of toxic metals is likely before discharge to the river.

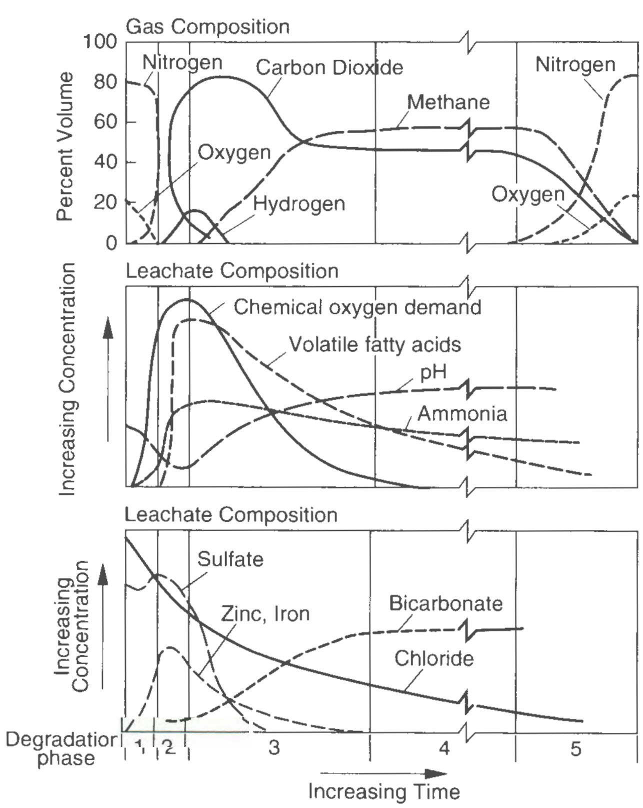


FIGURE 5.22—Expected changes in selected components of landfill leachate with time (from Heck et al., 1992).

The Sumner County, Kansas, landfill (fig. 5.1) is representative of the old and now illegal use of sand-and-gravel pits for waste disposal (Myers et al., 1993). The pit used for the Sumner County landfill was originally almost as deep as the water table, with the result that the landfill material placed in the pit is very close to the water table of the underlying aquifer. Investigation of the water quality in the area shows measureable concentrations of some organic and inorganic chemicals downgradient from the landfill, but the concentrations are probably relatively low because of mixing with the relatively fast-moving, clean ground water in the sand-and-gravel aquifer.

Landfills placed on rock that has fracture porosity also can affect ground-water quality because of the relatively rapid transport through fractures. The rapid transport reduces the amount of natural degradation and sorption that occurs before leachate enters ground water. The City of Olathe, Kansas, landfill, in Johnson County, eastern Kansas (fig. 5.1; Rasmussen et al., 1994) was excavated to fractured limestone and shale bedrock before being filled. At this site, much of the produced leachate found downgradient of the landfill will likely discharge to nearby creeks because of the geology and topography at the site. Flow paths are difficult to determine in such a setting, and degradation of surface-water quality is more of an issue than ground-water quality.

From these cases, it is clear that landfills have the potential to affect ground-water quality. Landfill design, age, geologic and topographic setting, and proximity to usable ground water all determine the impact of the inevitable escape of leachate from a landfill. Landfills may represent a threat to ground-water quality, and thus must be considered in determination of safe yield of an aquifer.

Agrichemicals–Atrazine—Fertilizers, pesticides, and herbicides are agricultural chemicals that can lower ground-water quality. In many Midwestern states, herbicides are more commonly used than pesticides, and atrazine is the dominant chemical used in areas growing corn, soybeans, and grain sorghum (Burkart and Kolpin, 1993). The escape of herbidicides from cultivated land is apparently even more regional: in the western part of the Midwest (fig. 5.23), more herbicides, particularly atrazine and its metabolites (degradation products), are found in the surface and ground water than in the eastern part. In Kansas much of the work evaluating the occurrence of herbicides has focused on surface water, particularly in eastern Kansas where corn, sorghum, and soybeans are grown (e.g., Pope et al., 1996). The annual precipitation rate and patterns, topography, geology, and soils in this area create a region in which more precipitation ends up as overland flow than infiltration to the ground water. As a result, atrazine concentrations are generally higher but seasonally dependent in the streams and more constant in lakes and reservoirs (Pope, 1995; Stamer et al., 1995). Well production that results in stream-to-aquifer flow paths could therefore cause movement of atrazine-contaminated surface water into an adjacent aquifer.

Investigations of atrazine concentrations in ground water in Kansas are so recent that most studies are surveys of wells in order to assess the extent of the problem. One of the earliest surveys, by Steichen et al. (1988), found that four wells sampled in a random sampling design across the state (100 wells total) had atrazine concentrations above the 3-ppb drinking-water limit. In addition, eight wells in the study had pesticide(s) detected in the well water. The herbicide and pesticide results contrast with indicators of fertilizer-affected ground water: 28 wells had nitrate-N above the drinking-water limit of 10 mg/L.

A recent statewide study of atrazine concentration in various aquifers in Kansas showed that approximately 72% of 84 wells sampled (including repeated sampling of the same wells) had atrazine concentrations below the detection limit of 0.10 ppb, 24% of the wells had concentrations between 0.10 and 1.5 ppb, and 4% of the wells were greater than the 3-ppb EPA drinking-water limit (Townsend et al., 1997). Of the wells with atrazine above the drinking-water limit, all were found to be affected by point-source contamination.

In another survey done by Perry and Anderson (1991), 111 irrigation wells were sampled. Only 5% of these wells had detectable atrazine, and all concentrations were below the drinking-water limit. The areas with detectable atrazine in ground water have shallow water tables and coarse-textured soils that may have facilitated the movement of atrazine to the ground water. Of the wells sampled, nine had nitrate-N above the drinking-water limit. The nitrate, from agricultural fertilizer, proves that water affected by agricultural practices is reaching the ground water. Therefore, the small number of wells affected by atrazine suggests that all agrichemicals cannot be expected to behave the same way during transport from the land surface to the water table.

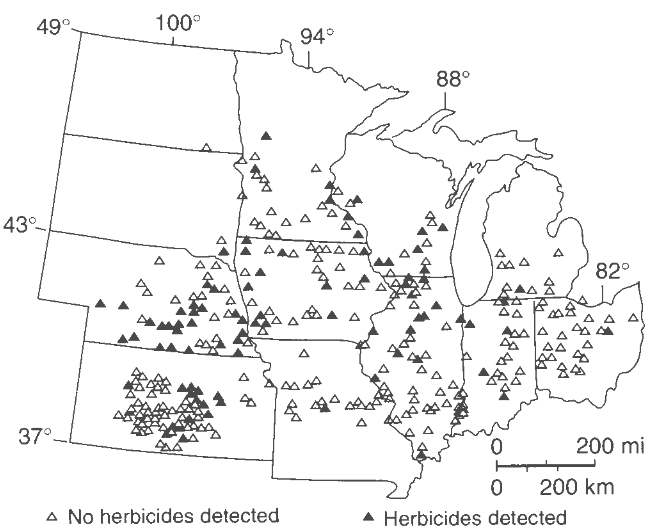


FIGURE 5.23—SAMPLING SITES (ALL TRIANGLES) IN THE MIDWEST DURING A SURVEY FOR HERBIDICES IN SURFACE AND GROUND WATER. Filled symbols show locations of samples with detectable herbicide, mostly atrazine and its metabolites (from Burkart and Kolpin, 1993). Note the higher number of positive detections in the western part of the region.

The persistence of atrazine is apparently affected by a number of factors, some or all of which may affect the persistence of other agrichemicals, such as nitrate, differently. Application rates determine the loading of herbicide to the land surface, irrigation influences the amount of movement below the root zone, vadose-zone stratigraphy determines rate of transport through the unsaturated zone, and bacterial degradation of the atrazine determines whether or not atrazine "survives" during water transport through the unsaturated zone (Sophocleous et al., 1990). The ratio of one degradation-product concentration to the atrazine concentration may be a useful indicator of residence time in the soil zone. Short residence time indicates efficient "bypasses" for water through the soil zone (such as macropores) or proximity to source, such as in point-source instead of nonpoint-source contamination (Thurman et al., 1992; Squillace et al., 1993).

Investigation of the fate of herbicides in the unsaturated zone and in ground water, therefore, is really just beginning. Safe and sustainable pumping rates for aquifers must take into account arrival time of recharge that may be tainted with herbicides or other agrichemicals. Guidelines for areas susceptible to such contamination should certainly include consideration of agricultural practices, soil type (including description of transport paths, especially macropores), and climate and irrigation practices, as well as more specific information about degradation products of agrichemicals and their production rates.

INTER-AQUIFER GROUND-WATER FLOW

Recharge may occur from an underlying aquifer (possibly containing more saline water) to an overlying aquifer (usually containing fresher water). A hydraulic gradient between units favors upward flow when, for example, natural pressure gradients are higher in a deeper aquifer or when drops in the water table or potentiometric surface in the shallower aquifer are induced by extensive pumping. Several areas in Kansas demonstrate inter-aquifer flow that results in poor-quality water entering a freshwater aquifer.

EFFECTS OF NATURAL GRADIENTS ON UPWARD RECHARGE—Natural hydraulic gradients cause movement of poor-quality water from a deeper aquifer (Permian) into an overlying freshwater Dakota aquifer system (fig. 5.1). Areas in the Dakota where this occurs correspond to areas where intervening confining units have pinched out (see Chapter 4 of this volume). The distribution of dissolved chloride in Dakota aquifer water shows that very high chloride is found in a beltlike region trending approximately northeast-southwest and paralleling the Dakota outcrop. The western part of this region coincides with areas where the Dakota is in hydraulic connection with a deeper aquifer containing saline water, the Cedar Hills aquifer (fig. 5.24; Macfarlane et al., 1989). The higher hydraulic head in the deeper aquifer causes saline-water discharge into the Dakota aquifer, rendering the water unpotable. The eastern part of the area containing saline water demonstrates that a considerable part of the Dakota aquifer downgradient from the zone of leakage has been affected by the saline fluid discharging into the Dakota along a fairly narrow corridor.

Effects of Pumping on Upward Recharge—In south-central Kansas, numerous areas of saltwater intrude from the underlying Permian aquifer into an overlying unconsolidated freshwater alluvial aquifer, especially in the Great Bend Prairie region (fig. 5.1). Current work in salt-affected areas indicates that the fluctuation of water chemistry (chloride, nitrate-N, and total dissolved solids) may be strongly affected by pumping patterns in the

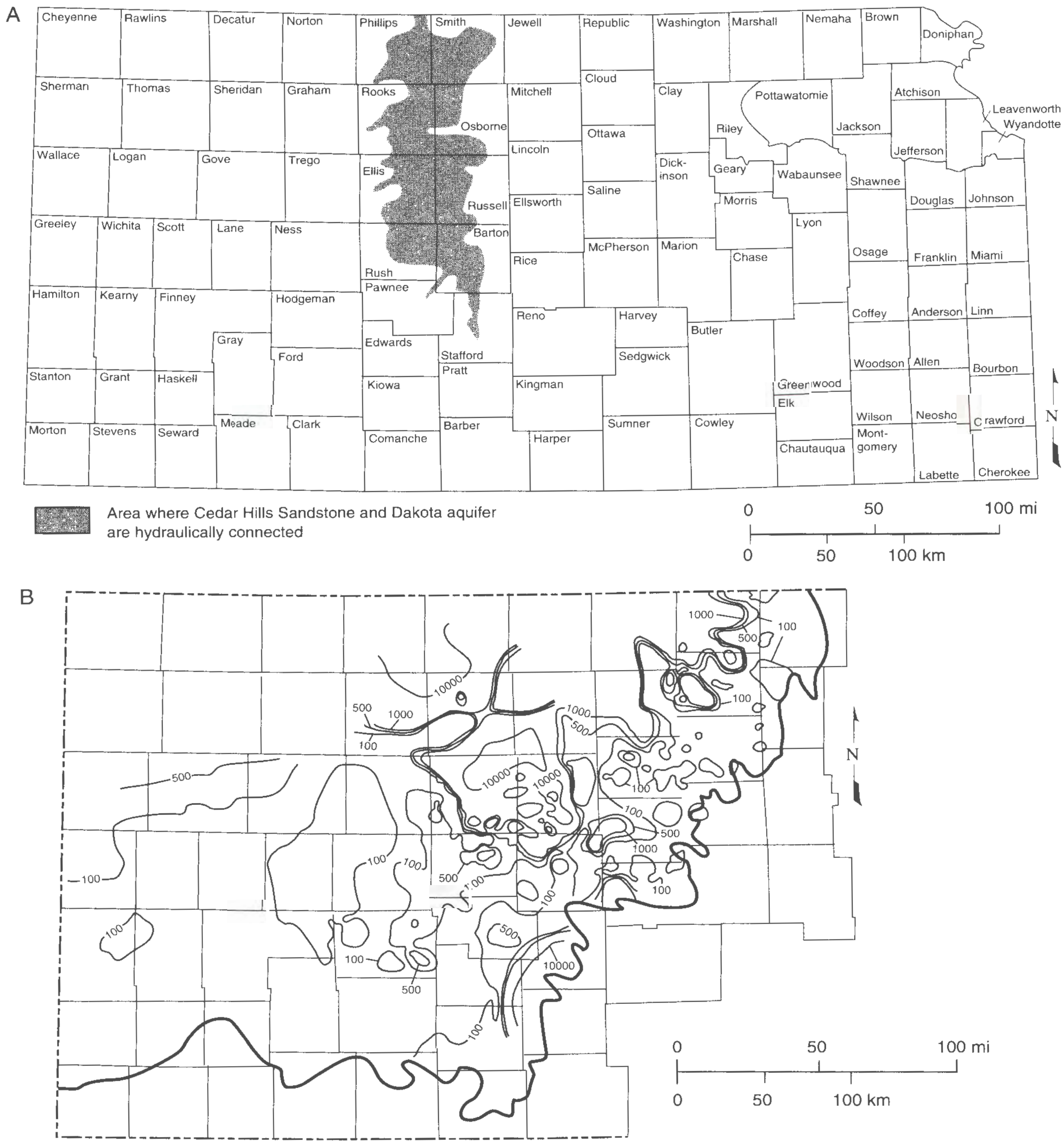


FIGURE 5.24—Dakota aquifer, Kansas. A) Patterned area shows where the Dakota and underlying Cedar Hills aquifers are hydaulically connected (modified from Macfarlane et al., 1989). B) Contours of chloride (mg/L) in the Dakota aquifer, Kansas. Heavy line is the trace of the outcrop or subcrop of the Dakota aquifer. Where the Dakota is hydraulically connected to the Cedar Hills, higher chloride concentrations are present.

alluvial aquifer above unconfined Permian bedrock. When pumping begins, nitrate-N concentrations (the source for which is presumed to be fertilizer from the land surface) are high but decrease with increased pumping time. Chloride concentrations (the source for which is the saline Permian aquifer) are low at the beginning of pumping and increase during the irrigation season (fig. 5.25; Young, 1995). Nonsteady changes in concentration of these components occur with time, suggesting that there is mixing of stratified sources of water, the degree of which depends upon the size of the cone of depression that develops around the pumping well.

In addition to fluctuations in water chemistry, fluctuations in the water levels of the freshwater aquifer and the Permian aquifer are observed throughout the irrigation season (fig. 5.26; Young, 1995). At times during the irrigation season, the water level in the deeper portions of the freshwater aquifer falls below the water level of the Permian aquifer, indicating that the underlying aquifer is under higher pressure than the overlying alluvial aquifer. There is most likely slow, upward, natural discharge from the Permian aquifer at all times, but upward discharge rates are probably increased because of pumping of irrigation water from the shallow aquifer and the consequent drop in hydraulic head.

In some areas, the total dissolved nitrogen in Permian aquifer water is higher than in the overlying alluvial aquifers. Dissolved nitrogen in the Permian aquifer ground water is in the reduced form, ammonium (see Boxed section 5.3, The Nitrogen Cycle), and does not result from agricultural-fertilizer contamination. Upward movement of saline Permian-aquifer fluid, especially as accelerated by pumping of the overlying aquifer, results in addition of nitrogen species to the shallower alluvial aquifer. The nitrogen species are then mostly oxidized to nitrate in the more oxidizing environment of the alluvial aquifer (Whittemore, 1993). Therefore, distinctions must be made between two situations causing increased salinity accompanied by elevated nitrate concentrations, the first resulting from evapotranspiration and the second from dissolution of Permian salt accompanied by naturally occurring elevated nitrate concentrations. These distinctions are important to planning for sustainable production rates of an aquifer in order to minimize the intrusion of saline fluids into a freshwater aquifer.

INTRA-AQUIFER GROUND-WATER FLOW

The pumping of wells causes a reduction in pressure within an aquifer that reverses normal ground-water flow. Because gradations in the chemistry of ground water typically occur within an aquifer, mixing of chemically different water can cause chemical reactions in the mixed fluids (see *Chemical Reactions in Ground Water,* p. 124). Furthermore, the movement of fluid implies that the fluid must readjust to a different part of the aquifer. The moving fluid may have been in equilibrium with a different type of rock, under different redox conditions and temperatures, or may have been naturally of a different chemistry because of other factors. This fluid reacts with the new environment by dissolving or precipitating solid phases and being involved in sorption or desorption reactions. Besides reacting directly with the solid matrix, the introduced fluid also mixes with the resident fluid, the proportion of which can determine the extent of mineral reactions that occur.

Vertical stratification of fluids in aquifers has been observed in many aquifers, introducing the expectation

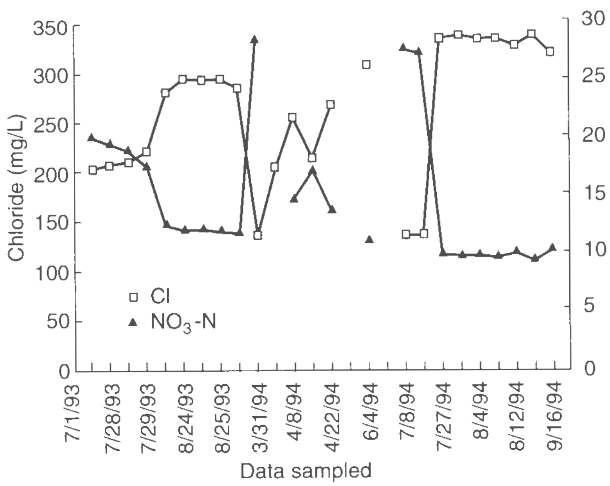


FIGURE 5.25—CHLORIDE AND NITRATE-N CONCENTRATIONS FOR WELLS AT SIEFKES SITE IN STAFFORD COUNTY, KANSAS. Note the effect of pumping on increasing chloride concentration over time and decreasing nitrate-N concentration over time (after Young, 1995).

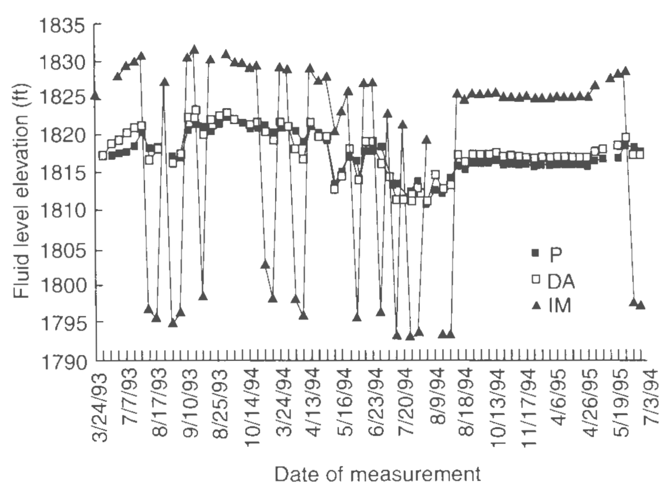


FIGURE 5.26—HYDROGRAPHS OF PERMIAN (P), DEEP-AQUIFER (DA), AND WATER-TABLE (IM) MONITORING WELLS AT SIEFKES SITE. Note that Permian water levels rise above water-table (IM) levels after extended periods of pumping (after Young, 1995).

that pumping a well should mix chemically different fluids. The amount of chemical stratification is a response to the heterogeneity of the aquifer (see Glossary, *heterogeneity*) as well as the hydrodynamics of recharge and throughflow. A theoretical, completely homogeneous aquifer with a large hydraulic conductivity is expected to have relatively homogeneous water chemistry in all climatic settings except arid because residence time of the water in the aquifer is relatively short. All other types of aquifers should be chemically stratified. One example of vertical chemical gradients is found in the alluvium of the Kansas River near Lawrence, Douglas County, Kansas (figs. 5.1 and 5.27; Macpherson et al., 1996), where the gradient is not smooth but contains peaks and valleys throughout the profile. Another example, from the Great Bend Prairie alluvial aquifer (fig. 5.1), shows an extreme case of vertical chemical stratification in which saline fluids from salt dissolution are "puddled" at the base of the alluvial aquifer (fig. 5.28; Garneau, 1995; Buddemeier et al., 1992).

Patterns and extent of lateral variations in water chemistry within an aquifer are much better documented

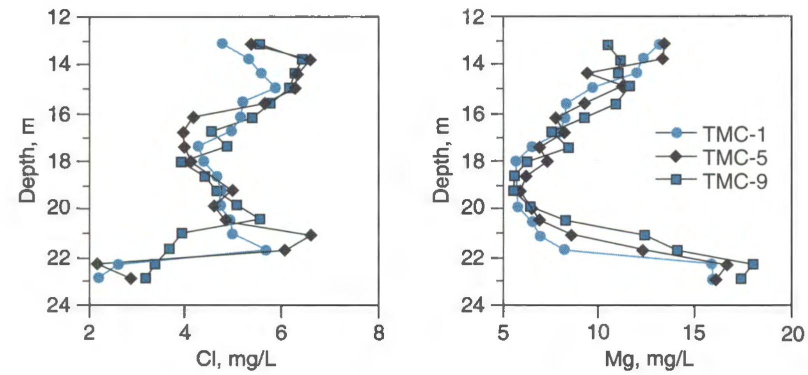


FIGURE 5.27—VARIATIONS IN CHLORIDE (LEFT) AND MAGNESIUM (RIGHT) WITH DEPTH IN KANSAS RIVER ALLUVIUM NEAR LAWRENCE, DOUGLAS COUNTY, KANSAS. The profiles demonstrate chemical stratification in an alluvial aquifer, probably controlled by permeability differences in the sediments.

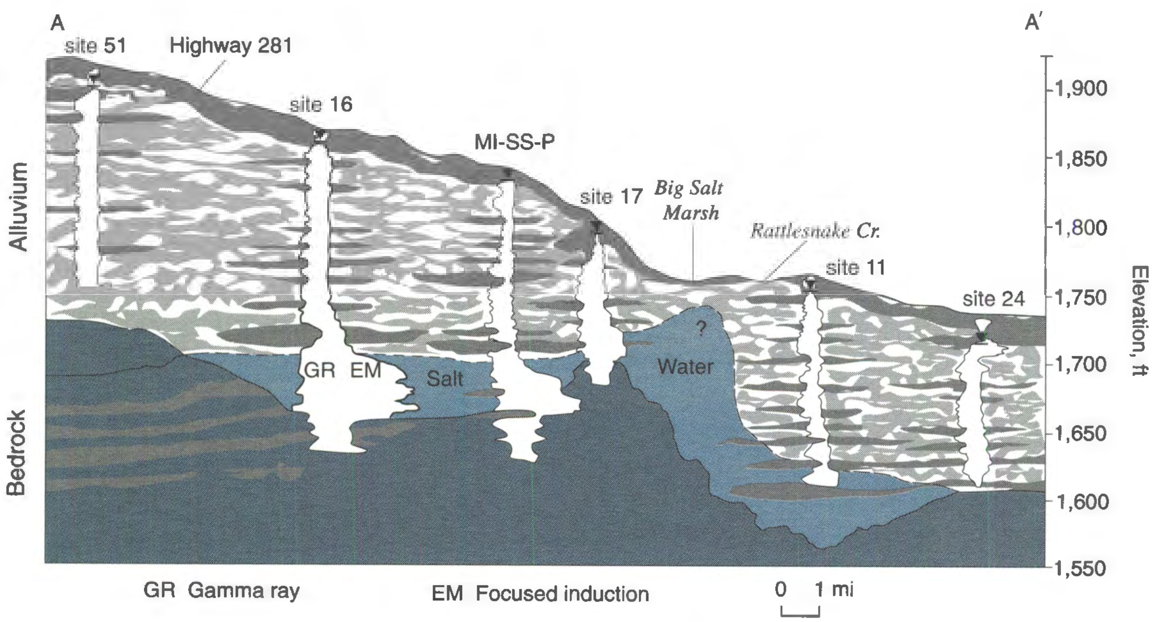


FIGURE 5.28—CLAY LENSES (GRAY) AND SALTWATER (MEDIUM BLUE) IN THE GREAT BEND PRAIRIE ALLUVIAL AQUIFER, STAFFORD COUNTY. This west-east cross-section shows estimated locations of discontinuous clay lenses (from gamma ray and focused induction well logs) and shows upconing of saltwater (especially site 17) from bedrock (blue-gray) attributed to pumping of a well. Deeper water, in this case saline, is drawn upward into pumping wells (modified from Garneau, 1995).

than vertical variations, being first linked to specific chemical processes by Foster (1950). Progressive change during recharge of dilute rainwater into an aquifer and subsequent movement along ground-water-flow paths is caused by mineral dissolution/precipitation, ion exchange, sorption, and adjustments due to changes in redox state in the aquifer. It is important to note that ground-water movement is typically very slow. In addition, the pore space that contains the water in an aquifer normally accounts for up to a maximum of 30% of the total volume in a lithified aquifer and perhaps 40% in an unconsolidated one. For these reasons, the chemistry of ground water is usually determined by the composition of the aquifer matrix, i.e. the minerals in the rock that hosts the aquifer. Furthermore, differential ground-water velocities in a typical heterogeneous aquifer result in water in the pores of the coarser-grained parts of the matrix having a chemistry different from water in the pores of the finer-grained parts. This spatial variation in water chemistry becomes more complex as the amount of aquifer heterogeneity increases.

CONSEQUENCES OF MIXING

Both vertical and lateral water-chemistry variability provide the opportunity for waters of different chemistry to mix when an aquifer is pumped. The lowering of hydraulic head that causes water to be produced from a well creates hydraulic gradients in the vicinity of the well that affect the aquifer according to the hydraulic conductivity of the rock or sediment. In the normal case of aquifer heterogeneity, although most of the water produced from a well comes from the zones of highest hydraulic conductivity, some will be drawn from the lower-conductivity zones, causing mixing of fluids from the different zones. Identifying mixing of different fluids can be straightforward if no chemical reactions result from the mixing, or more complicated if reactions remove or add dissolved species and mask the compositions of the pure end members. Although some scientists use statistical techniques to identify mixing (Christophersen and Hooper, 1992), there are simple cases in which mixing is relatively easy to identify.

When chemical reactions do not occur as the result of mixing, the end-member fluids often can be identified by plotting two components of the solution on bivariate plots and observing the relationships. Two end members with no mixing plot as separate clusters of points (fig. 5.29), two end members mixing with no chemical reaction plot as linear arrays (fig. 5.30), three end members mixing with or without chemical reaction are evident when a triangular region encompasses the spread of the data points (fig. 5.31), or the data fall on a linear trend but are clustered instead of continuous (fig. 5.32). Mixing can also be deduced from a plot of the concentrations of all of the determined ions in solution when plotted on a Schoeller diagram (fig. 5.33). This simulation demonstrates dilution of a saline water, evident by the parallel lines of the same pattern. A bivariate plot on which one variable is a ratio of two or more variables and the other is a single variable

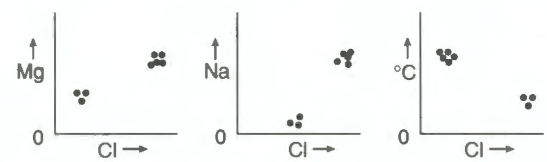


FIGURE 5.29—EIGHT SPRINGS PLOT IN TWO DISTINCT CLUSTERS, SUGGESTING COEXISTENCE OF TWO CHEMICALLY DIFFERENT WATERS THAT HAVE NOT MIXED. Concentrations are in meq/L (from Mazor, 1991; figs. 5.29–5.34 reprinted by permission of John Wiley & Sons, Inc.).

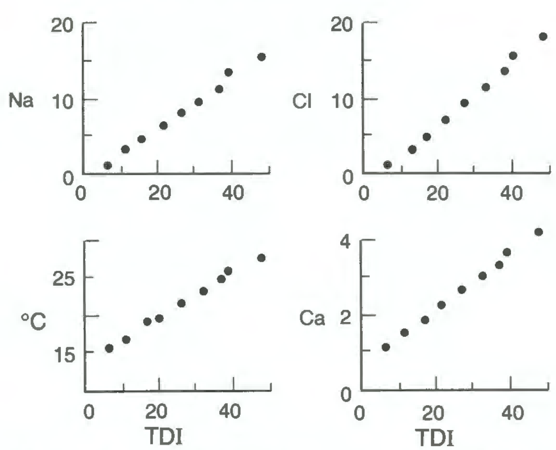


FIGURE 5.30—SPRING WATER (DIFFERENT FROM FIG. 5.29) SHOWS MIXING WITHOUT CHEMICAL REACTIONS, SUGGESTING A SALINE, HOT END MEMBER AND A FRESH, COOL END MEMBER. Concentrations are in meq/L (from Mazor, 1991).

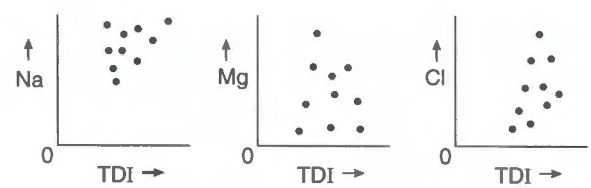


FIGURE 5.31—TRIANGULAR AREAS ON COMPOSITIONAL DIAGRAMS FORM WHERE THREE DISTINCT WATER TYPES INTERMIX IN VARYING PROPORTIONS (from Mazor, 1991).

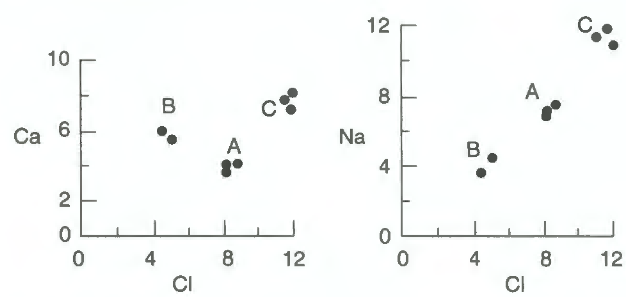


FIGURE 5.32—WHERE THREE DISTINCT WATERS EXIST IN A REGION BUT DO NOT MIX, ISOLATED CLUSTERS OF DATA APPEAR ON SCATTER PLOTS SUCH AS THESE (from Mazor, 1991).

will show a curvilinear array of data points when two-member mixing occurs (fig. 5.34).

Mixing of fluids frequently causes chemical reactions to occur. The reactions result from several chemical phenomena. First, nonlinear mineral-solubility relation results in a mixed fluid that is over- or undersaturated with respect to a mineral even when the fluid end members were saturated. Second, when a mixed fluid has a TDS higher or lower than the fluid end members, the mixture will become undersaturated (corrosive) or oversaturated (encrusting) with respect to mineral phases (e.g., Freeze and Cherry, 1979). This phenomenon results from ions being chemically less "reactive" (having a lower "activity") in a high-TDS fluid than in a low-TDS fluid. Third, the common-ion effect results in precipitation of a mineral when the fluids have an ion in common but at different concentrations because of equilibration with different minerals. For example, a fluid (fluid "A") in equilibrium with the soluble mineral gypsum contains high concentrations of calcium. Fluid "A" can also be in equilibrium with calcite, which also contains calcium, as long as the carbonate concentration of the fluid is very low (the product of the calcium content and the carbonate content, or $[Ca^{+2}]*[CO_3^{-2}]$, is a constant at any temperature). A fluid "B," in equilibrium with calcite but never having been in contact with gypsum, will contain only small amounts of calcium and equivalent amounts of carbonate. A mixture of fluids "A" and "B" will be oversaturated with respect to calcite, because the product, $[Ca^{+2}]*[CO_3^{-2}]$, will be larger than the equilibrium value as a result of the high calcium content of fluid "A." Finally, mixing may also cause sorption or desorption of trace elements or organics from surfaces, or changes in ion-exchange equilibrium as well as changes in redox potential.

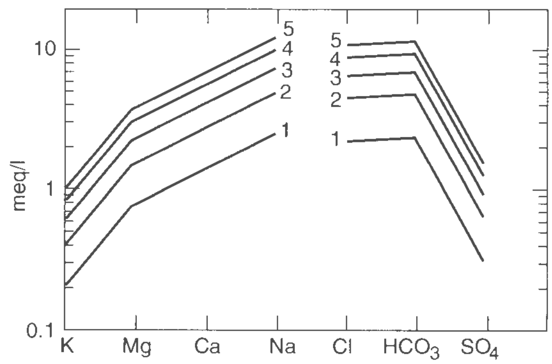


FIGURE 5.33—Dilution of a saline water (#5) with a dilute water (#1) is easily visualized on a Scoeller diagram such as this (from Mazor, 1991).

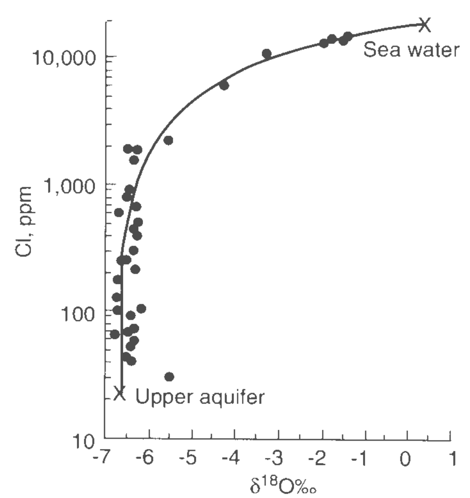


FIGURE 5.34—A plot of a single variable, such as chloride, *versus* a ratio variable, such as the oxygen isotope ratio $\delta^{18}O$ (units of per mil, ‰), suggests mixing of waters when data from the same region or even the same aquifer fall along a curve. In this case, coastal wells near the Gulf of California show an effect from sea-water intrusion (from Mazor, 1991).

Besides chemical reactions that cause a mixed-fluid chemistry to be different from the simple proportion of the end-member fluids, the unexpected coexistence of water "tags" can provide insight into the introduction of water to a new part of the aquifer. For example, the simultaneous presence of tritium (^3H), indicating water recharged within the past 40 years or so, and very small amounts of carbon-14 (^{14}C; see Glossary, *isotope*, and Boxed section 5.2, Isotopes and Ground Water), indicating very old water, suggests the addition of very dilute, recently recharged water to older water. Other indicators of mixing may not be present, but the presence of indicators of water recharged in the distant past in the same fluid with indicators of water recharged in the recent past is a fairly robust argument for the mixing of old water with new. Similarly, compounds added to the atmosphere from manufactured products, such as chlorofluorocarbons formerly used as a propellant for spray cans, also are useful indicators of recently recharged water (Dunkle et al., 1993).

Selected examples of mixing of fluids and the consequences of mixing are given below. These were chosen on the basis of their known or anticipated relevancy to Kansas aquifers, but the examples given do not cover all the possible types and consequences of mixing fluids, either in Kansas or elsewhere.

Example–Bromide/chloride ratio, a Tracer of Water Sources—An example of the usefulness of a bivariate plot for identifying sources of water in Kansas is given by Whittemore (1995a). In this method, the ratios of a minor halogen element, bromide (Br^-), to a major halogen element, chloride (Cl^-), when plotted against chloride fall in distinct, restricted areas of the graph for different waters. These water end members attain a distinctive Br/Cl ratio and chloride concentration through inheritance (such as a sea-water signature or a rainwater signature) or water-rock interaction (such as dissolution or reprecipitation of halite, Holser, 1979; or breakdown of organic matter and consequent release of Br, Macpherson, 1994). Whittemore gives an example of freshwater in the Great

Bend Prairie aquifer (fig. 5.1) mixing with saline water from the underlying Permian units, the signature of which is a fairly narrow, curved, mixing corridor between low chloride, high Br/Cl and high chloride low Br/Cl end members (fig. 5.35). The saline water results from dissolution of the mineral halite (rock salt) and is distinctive from oil-field brines produced in the area: the oil-field brines have higher Br/Cl ratios as well as high chloride content. Mixtures of the three end-member fluids in this area, the oil-field brines, freshwater, and saltwater from halite dissolution, plot along distinct curves or in limited envelopes. Analysis of samples that are intermediate to the end members allows a semi-quantitative assessment of the proportions of each of the end members in the mixture (fig. 5.35).

EXAMPLE–MIXING AND CORROSION—One of the best known consequences of the mixing of different waters is that of two waters, both of which are saturated with respect to calcite but are at equilibrium with different partial pressures of carbon dioxide. The relationship between the amount of Ca^{+2} and partial pressure of CO_2 in solution at equilibrium with calcite is not linear (fig. 5.36). Mixing of fluids labeled A and B on the plot results in a fluid composition found on the line connecting these two points. Because of the curvature of the equilibrium line, the mixed fluid, no matter the proportion of A and B, is undersaturated with respect to calcite and will dissolve calcite. This phenomenon is thought to be one of the reasons for the formation of karst features in limestones (e.g., Thrailkill, 1968) and may account for much of the widening of fractures in limestone aquifers that makes them productive aquifers. This effect is not exclusive to limestones: modeling of the Dakota aquifer in Kansas (which has carbonate cements) has suggested that mixing of saline fluids from the underlying Cedar Hills Sandstone aquifer with Dakota aquifer water causes undersaturation with respect to the carbonate minerals (fig. 5.37; Macfarlane et al., 1989). The implications of this phenomenon are very interesting: mixing of a small amount of saline water with a more dilute aquifer water through intrusion, either natural or induced, causes the mixed fluid to become corrosive with respect to the carbonate minerals. Because carbonates are very common, the corrosive fluid will dissolve part of the aquifer matrix, causing it to become more porous and permeable, allowing more saline water to intrude. In this way, the zone of intrusion can propagate and through time affect a large part of an aquifer.

Mixed ground water may become corrosive or encrusting with respect to other minerals, as well. A theoretical example is given next, demonstrating the effect of the mixing of waters with different iron content and different Eh conditions (see Boxed section 5.1).

EXAMPLE–DISSOLVED IRON AND MIXING—Iron is a redox-sensitive metal that is fairly commonly found in ground water. Iron exists in two oxidation states in water, ferrous iron, Fe^{II}, having a valence of +2 and ferric iron, Fe^{III}, having a valence of +3. Fe^{III} is the dominant form of dissolved iron under the unusual conditions of very acid

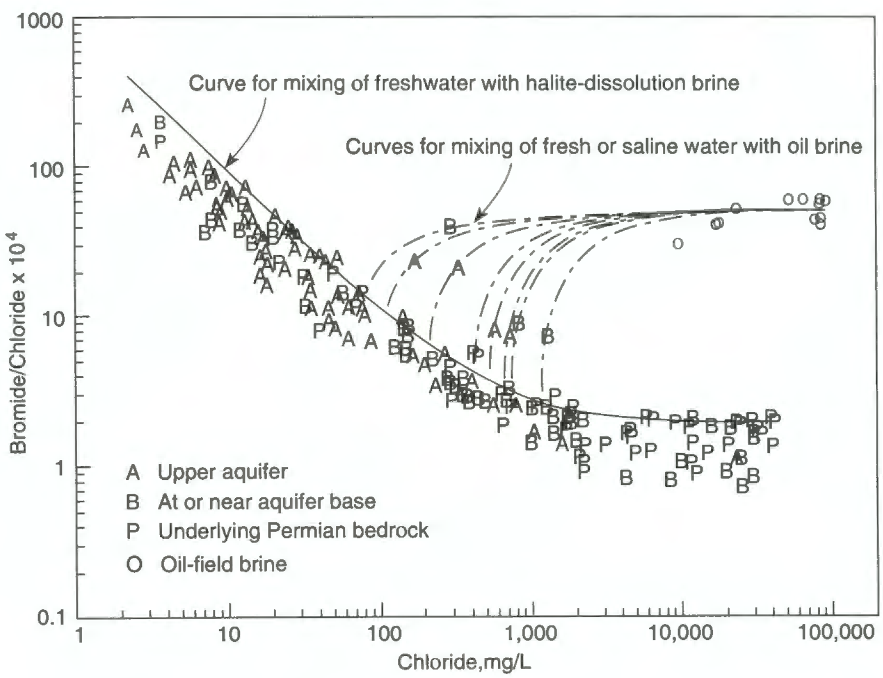


FIGURE 5.35—Br/Cl MASS RATIO-CHLORIDE CONCENTRATIONS ARE DISTINCTIVE FOR DIFFERENT TYPES OF WATER IN KANSAS. Halite-dissolution water contains high Cl and low Br/Cl (P's on the plot). Freshwater (derived from rainwater) has low Cl and high Br/Cl (A's in the upper left on the plot). Oil-field brines shown here have high Cl and intermediate Br/Cl (O's on the plot). Mixing of freshwater and salt-derived water plots below the solid curved line; a mixture of the three water sources plots on any of a whole family of curves, some of which are shown here as dashed. The proportion of the three end members can be approximated from the position on the mixing lines (from Whittemore, 1995a).

pH and very high *pe*. Fe^{II} dominates in more typical conditions of less acid to very alkaline pH and moderately high to very low *pe* (fig. 5.38). The common and mature oxide-mineral phases that contain iron are hematite (Fe_2O_3) with ferric iron and magnetite (Fe_3O_4) with both ferric and ferrous iron. These minerals, along with pyrite (FeS_2), are often the primary sources of iron in solution. (In some aquifers, iron-rich alumino-silicate minerals such as pyroxenes and amphiboles also are a source of iron.) Iron typically precipitates from solution into solids that are not true minerals but types of amorphous oxyhydroxides such as $Fe(OH)_3$ and $Fe(OH)_2$ or FeOOH. Because these precipitates are very fine grained, total iron in a solution, without filtering, is often dominated by colloids of iron oxyhydroxides that are suspended in the solutions (Whittemore and Langmuir, 1975).

For ground water in a steady state, one can fairly safely assume little change in the water chemistry through time. Development of an aquifer can result in the mixing of waters from different aquifers or from different parts of an aquifer, with the result that chemical reactions are accelerated and water chemistry different from what is expected from simple mixing can result. Mixing of ground water from the Tonganoxie aquifer (Douglas Group) and the Kansas River alluvium in Douglas County could occur where Kansas River alluvium overlies the Pennsylvanian sandstone, in Douglas and Leavenworth counties (fig. 5.1). Computer mixing of published water

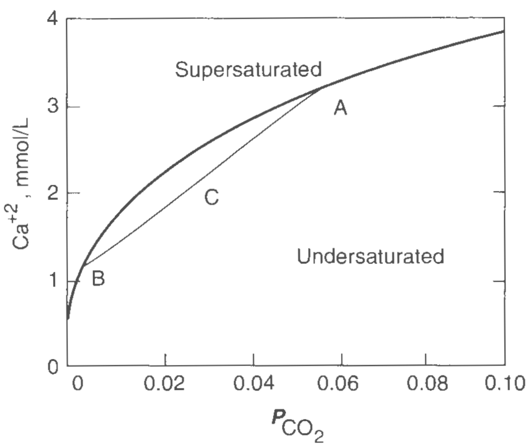


FIGURE 5.36—If two waters (A and B) that are in equilibrium with calcite (fall on the heavy line) mix, the resulting mixture (anywhere on the light line) is undersaturated with respect to calcite and will dissolve calcite (from Drever, 1988; reprinted by permission of Prentice–Hall, Inc.).

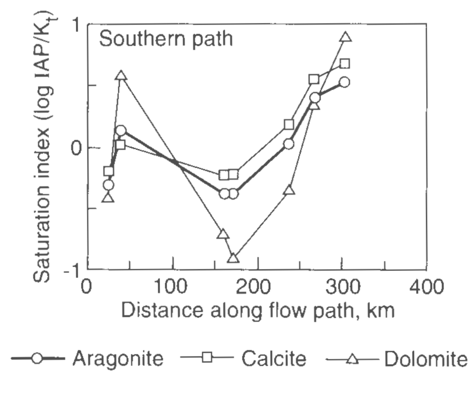


FIGURE 5.37—The saturation state of three carbonate minerals along one ground-water flow path in the Dakota aquifer, Kansas. A saturation index of zero (0) is perfect saturation; negative saturation indices indicate undersaturation and positive saturation indices indicate oversaturation. The Dakota aquifer ground water becomes undersaturated (saturation index <0) with respect to the carbonates downgradient of the Cedar Hills Sandstone subcrop. Leakage of water from the Cedar Hills Sandstone and the subsequent mixing causes the undersaturation (Macfarlane et al., 1989).

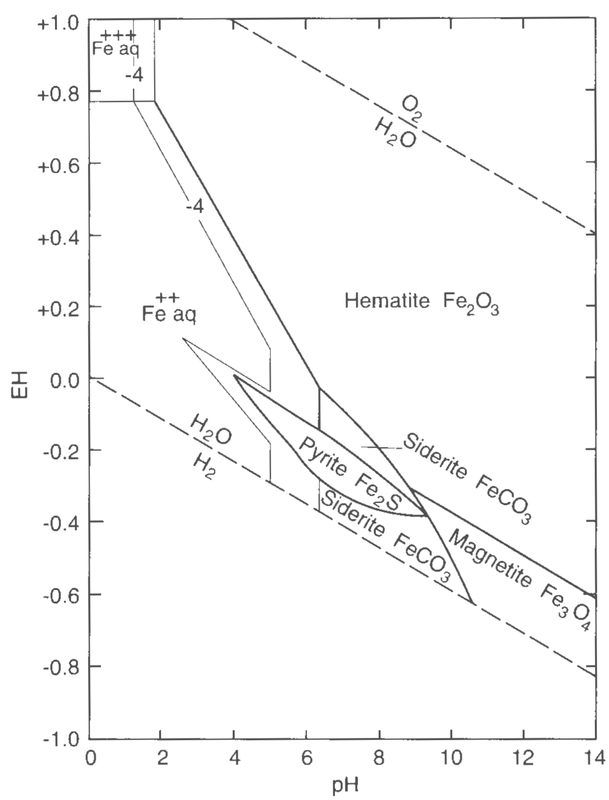


FIGURE 5.38—Stability fields of iron oxides, iron carbonates, and iron sulfides. Conditions chosen to create this diagram are: temperature of 25°C, 1 atmosphere total pressure, total dissolved sulfur of 10^{-6} mol/L (if all sulfur was sulfate, concentration would be about 0.1 mg/L), total dissolved carbonate of 1 mol/L, total dissolved iron of 10^{-6} (heavy lines) or 10^{-4} (light lines; equilivalent to about 0.06 or 6 mg/L, respectively). (From Garrels and Christ, 1965.)

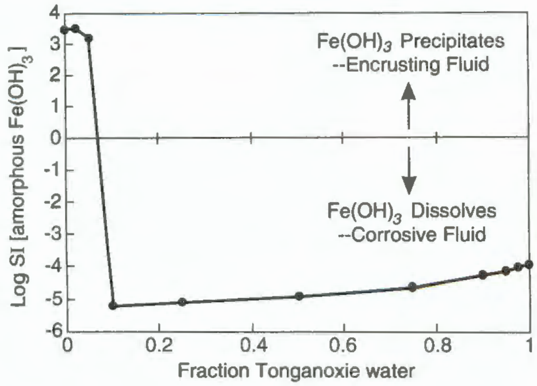


FIGURE 5.39—THEORETICAL MIXING OF TONGANOXIE AQUIFER WATER AND KANSAS RIVER ALLUVIUM GROUND WATER. In this case, mixing in the proportion of about 9 parts to 1 part results in a dramatic change in the mixture's tendency to dissolve (log SI <0) or precipitate (log SI>0) ion compounds.

analyses (from Miller et al., 1991) using the geochemical speciation program PHREEQE (Parkhurst et al., 1990) shows that a mixing of Kansas River alluvium ground water with Tonganoxie aquifer water causes a dramatic change in the saturation state with respect to the amorphous iron hydroxides (fig. 5.39). A mixture of about 10% Tonganoxie ground water with 90% alluvium ground water is the crossover point for strong oversaturation with respect to iron oxyhydroxides (the case for pure alluvium ground water) to strong undersaturation (the case for pure Tonganoxie ground water). The crossover point is not always at a 9:1 proportion, but is determined by how well buffered each of the mixing end members are relative to each other. In this case, the Tonganoxie ground water is more strongly buffered against redox changes (that in turn control saturation with respect to iron-bearing minerals) than the alluvium ground water.

Recharge to Aquifers, Water Chemistry, and Safe Yield—Conclusions

Recharge of an aquifer affects the quality as well as the quantity of ground water in an aquifer. Land-use practices and point- and nonpoint-source contamination may affect water quality of surface-derived recharge directly. Natural variations in soil permeability can change the quality of ground-water recharge through the unsaturated zone. Finally, enhancement of cross formational flow or flow from low-permeability zones within aquifers can affect water quality. In all cases, physical and chemical processes influence the final water chemistry.

Impedance and enhancement of flow are physical processes in the unsaturated zone that affect the chemistry of the water. Impedance of flow increases the residence time of water, allowing evapotranspiration and/or chemical reactions to change water chemistry. Enhancement of flow occurs through fractures or macropores, providing a way for water to bypass the unsaturated zone and therefore not be affected by normal chemical and biochemical reactions that strip water of potentially harmful components. Vadose-zone stratigraphy describes the heterogeneity of sediments that affects flow rates through the soil zone.

Two kinds of chemical reactions common in the unsaturated zone are ion exchange and precipitation. These can affect clay minerals and result in decreased permeability. The lowered permeability not only lowers the quantity of water that recharges the aquifer, but also increases the water residence time in the soil, permitting changes in the chemistry of the recharge water.

Recharge from a saline aquifer beneath or adjacent to a water-supply aquifer can result in deterioration of water quality if pumping practices result in a mixing of the two waters. In addition, the mixing of fresh and lesser quality waters can occur from movement upward because of artesian pressures in a lower aquifer or natural discharge points because thinning of an aquifer abuts an adjacent freshwater aquifer.

Degradation of water quality can also occur because of pumping when there is lateral variation of water chemistry. In fact, lateral changes are to be expected, as are various types of chemical stratification that are dependent upon heterogeneity in the aquifer hydraulic conductivity.

Some generalities can be made about expected changes in water quality because of mixing induced by pumping. The upconing of water from deeper parts of an aquifer or from cross formational flow from deeper aquifers will usually result in the introduction of saline fluids with a composition dominated by sodium (Na) and possibly calcium (Ca) and chloride (Cl). Introduction of rainwater concentrated by evaporation or evapotranspiration may also be saline and in some cases may be sulfate-rich. Irrigation water concentrated by evaporation or evapotranspiration may contain high levels of nutrients such as nitrate and other agrichemicals, as well as being more saline versions of the ground water or surface water used for irrigation. Movement of fluids from point sources such as landfills, storage tanks, and ponds into an aquifer can be identified by studying the fluids at the point source, but in general may be rich in dissolved organic carbon (DOC) and possibly metals.

Mixing of fluids may be simple, in that the mixed fluid composition is in simple proportion to the end members. More commonly, a mixed fluid becomes corrosive or encrusting with respect to selected minerals, the best documented being calcite and the iron minerals. Furthermore, a mixed fluid may undergo ion exchange with nearby clay minerals because the proportions of ions in the mixture are no longer in equilibrium with the clays. The resulting fluid may not necessarily be recognizable because of loss or gain of dissolved species as the fluid comes into equilibrium with its surroundings. The use of conservative and refractory species, those that tend to not react with the matrix, allows identification of end members in many cases. Examples of identifiers used successfully include Br/Cl ratios and isotopes.

The management of an aquifer or a system of aquifers must include consideration not only of yield (the volume of water) but also the quality of water to be produced. It is the rule, not the exception, that stratification of chemistry occurs within as well as between aquifers. Only very homogeneous aquifers that are well flushed (because they have high hydraulic conductivity and are found in climates that are temperate to humid) are likely to have homogeneous chemistry: these are exceedingly rare. The variation in water chemistry can occur on all scales. On a small scale, zones of lower and higher hydraulic conductivity contain slightly to very different chemistries of water over distances of centimeters. On a large scale, long-term flushing of an aquifer results in mostly lateral gradation in water quality over distances of 10's to 100's of kilometers.

The entry of poor-quality fluids into an aquifer can occur through the unsaturated zone or from within or beneath the aquifer. Irrigation water can be concentrated through evaporation and add salinity, nutrients, or agrichemicals to ground water. Downgradient saline fluids within an aquifer can be drawn upgradient toward wells, or saline fluids at the base of an aquifer can be drawn upward to a well during pumping. Saline fluids from salt dissolution can leak upward into aquifers where confining beds are absent and hydraulic gradients favor such movement. This natural discharge can be accelerated through removal of fluids from the freshwater portion of the aquifer.

Water tends toward equilibrium with the solids with which it is in contact. Causing a fluid to move to a new position, therefore, may induce a chemical change. The change can occur because of mixing with another fluid, or because the fluid has come into contact with different mineral or organic phases. The changes occur because of several types of chemical reactions. A solid may dissolve and add dissolved components to the water or a solid may precipitate out of the water, removing solids. Ion exchange can occur when the ratio of cations in the fluid is not in equilibrium with the ratio on the clay minerals. Sorption or desorption can occur when the dissolved metals or organics are out of equilibrium with their respective components sorbed on the aquifer matrix. Species that are volatile may be removed from solution with a change in pressure or temperature, and species that are redox sensitive may change redox state, causing precipitation or dissolution of related mineral phases.

In Kansas, agriculture depends upon good-quality ground water and yet it indirectly or directly causes degradation of water quality through evaporation and the addition of agrichemicals. Recharge of this water through the unsaturated zone can eventually degrade the very source of water used for irrigation. The impact may be lessened somewhat by natural degradation processes in the unsaturated zone (for agrichemicals), but will not be totally eliminated.

In the Great Bend Prairie region and other regions of central Kansas, natural discharge of saline water from dissolution of buried Permian salt causes salinization of shallow alluvial aquifers. Population growth in these regions will result in the development of aquifers as a water supply. The movement of saline water into an alluvial aquifer is accelerated by pumping. In theory, the impact of saline-water movement could be managed so as to cause only a small portion of saline fluid to be mixed with the fresher water.

In the Dakota aquifer of Kansas, regional changes in water quality have been identified from the Colorado state line to the discharge areas in central Kansas. Ion exchange of calcium and magnesium for sodium causes a gradation in the ratios of these ions down the regional hydraulic gradient, as long-term flushing of the aquifer continues. The absence of a hydraulic barrier causes discharge of deeper, saline fluids from the Cedar Hills aquifer into the Dakota in selected regions, and a prominent zone of higher salinity fluids identifies those areas. Furthermore, in the Dakota in northwestern Kansas, saline fluids may represent the downgradient portion of an ancient flow system. These fluids have the potential to move into the freshwater portions of the Dakota if there is uncontrolled development of the Dakota as a ground-water supply. For each of these situations, aquifer development may induce movement of fluids into different parts of the aquifer and/or mixing, allowing chemical reactions to proceed as the fluids approach equilibrium with the solids.

Aquifer management should include assessment of the chemistry of fluids likely to move during the pumping of wells. The effects of mixing of the fluids and equilibration of the moving fluids with the aquifer can be predicted using simple to complex computer programs, depending upon the complexity of the problem and the amount of information available about aquifer parameters and chemical parameters. The outcome will necessarily be poor- to well-constrained predictions of the effects of aquifer development. Computer modeling of hydraulic-head changes in combination with modeling of the chemical changes that might occur is essential to the most efficient management of our water resources.

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CHAPTER 6

Yield Estimates for Surface-water Sources

David I. Leib and **Thomas C. Stiles**

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Introduction

Yield is used to characterize the capacity of a water resource to serve as a long-term water supply. It is a fundamental water-supply planning concept, and an understanding of its attributes is critical for those who participate in water-supply issues. In the context of surface-water resources, yield is often synonymous with safe yield or firm yield. Safe yield or firm yield in the context of water reservoirs is defined as the maximum quantity of water which can be guaranteed during a critical dry period (Linsley and Franzini, 1979). The simplicity of this definition, however, belies two "complicating" factors. First, yield changes as watershed conditions, such as land use and ground-water–surface-water interactions, evolve. Second, yield is uncertain because of our inability to know the severity and duration of future drought periods. This chapter discusses the dynamic nature of yield. In particular, using Kansas surface-water resources as the example, this chapter describes the concept of yield, the determination of yield, the sensitivity of yield to underlying assumptions, and the interaction of yield and water-supply policy.

Some Yield Concepts

Surface-water yield depends primarily on inflows and storage. In the case of an unregulated stream, the firm yield is often conceptualized as the minimum historical flow during a specified time period. With this working definition, the firm yields at several locations along Kansas streams are given in table 6.1. In most cases, these minimum daily historical flows occurred prior to significant regulation by large reservoirs.

Two major assumptions are implicit to determining yield in this fashion. The first assumption is that the available streamflow record adequately captures the long-term streamflow characteristics of the basin. This is often not valid, even in the rare instances where good-quality long-term streamflow records are available. For example, the Great Plains droughts circa 1757 and 1860 were probably harsher than those seen so far in the twentieth century (Stockton and Meko, 1983). The second assumption is that streamflow regimes are stationary. However, watersheds evolve in response to stresses such as altered land-use practices and changing ground-water–surface-water interactions. Over a time scale of decades, these transformations can have a significant impact (Koelliker et al., 1995). The typical result in semi-arid nonurban regions is less runoff per unit of rainfall. Thus, it is highly unlikely that a sequence of streamflows (and firm yield) from the 1930's would repeat in the 1990's, even in response to identical climatic factors.

In addition, a major change in firm yield at a site can occur when reservoir storage is placed upstream. When water-supply reservoir storage is added on a stream, additional water is lost from the river system due to increased evaporation from the exposed reservoir surface area. Paradoxically, the firm yield of the river-reservoir system increases. This increase in firm yield and the corresponding decrease in average yield are fundamental impacts of a water-supply reservoir. The gain in firm yield often has vital importance and value. The loss of average yield is usually unimportant.

Referring back to table 6.1, the firm yield of the Neosho River at Iola would be on the order of 50 cubic feet per second (cfs [1.4m^3/s]), if the full conservation storage capacity of John Redmond Reservoir were dedicated to maximizing downstream firm yield. This is in spite of the fact that John Redmond Reservoir has a

TABLE 6.1—SIMPLE DAILY FIRM YIELD AT SELECT LOCATIONS.

Location	Stream	Firm Yield, cfs	Period of Record
Topeka	Kansas River	170	1917 - 1994
Enterprise	Smoky Hill River	38	1935 - 1994
Wichita	Arkansas River	5	1935 - 1994
Ottawa	Marais Des Cygnes	0	1902 - 1994
Iola	Neosho River	0	1899 - 1994

surface area of approximately 10,000 acres (4,047 ha) and can have a net evaporative loss of 25,000 acre-feet (30.8×10^6 m^3) in a dry year. Similarly, the firm yield of the Kansas River at Topeka would be on the order of 700 cfs (19.8 m^3/s) if the full conservation-storage capacities of Milford Reservoir and Tuttle Creek Reservoir were dedicated to maximizing downstream firm yield.

A concept that is closely related to firm yield is that of reliability. Reliability, as applied to a reservoir, is defined as the probability that a reservoir will deliver the expected demand throughout its lifetime without incurring a deficiency (Linsley and Franzini, 1979). The reliability approach avoids the difficulties associated with depending directly on the historical record by using a stochastic methodology. The reliability approach has much merit, but also entails the use of probabilistic descriptions and stochastic data-generation techniques. These methods, as well as many others for determining yield, are discussed in McMahon and Mein (1978). Still other approaches to reservoir yield can be found in Sheer (1980) and Smith (1993).

Lastly, although yield might appear to be wholly a water-supply concept, it is closely related to water quality. In fact, there is often a direct trade-off between yield and water quality. This is evident in California, where 5 million acre-feet (6.17 km^3) per year, on average, is expended to San Francisco Bay in order to control ocean-derived salinity in the Sacramento–San Joaquin Delta (California Department of Water Resources, 1987). This outflow protects the quality of water that is exported south of the delta and also provides significant environmental and public-trust benefits. From a purely water-supply perspective, however, these benefits are realized by foregoing some yield.

In Kansas, portions of several major rivers are subject to high-salinity levels that can inhibit the use of water for supply purposes. The release of lower-salinity water stored in reservoirs for blending purposes is one option for managing these salinity episodes (U.S. Army Corps of Engineers, 1982). However, stored water that is dedicated to managing salinity is not available to augment low flows, thus potentially diminishing the firm yield of the system. A quantitative description of a relationship between yield and salinity is described in Wurbs et al. (1995).

Statutory Reservoir Yield in Kansas

Kansas statutes refer to yield in several instances. Two important references are found in the State Water Plan Storage Act. The first describes the quantity of water that the State may reserve to store in a reservoir (known as a water-reservation right) as:

> "...an amount sufficient to insure a yield of water from the reservoir for beneficial use through a drought with a 2% chance of occurrence in any one year with the reservoir in operation" (K.S.A. 82a-1303).

The same Act also specifies the yield that may be contracted by the State:

> "...the director shall not contract for withdrawals of water from a particular reservoir which in the director's opinion are in excess of the yield capability from the conservation storage water supply capacity in such reservoir committed to the state computed to provide water through a drought having a 2% chance of occurrence in any one year with the reservoir in operation" (K.S.A. 82a-1305).

Definitions for some yield terminology can be found in the Kansas Administrative Regulations:

> "Drought having a 2% chance of occurrence in any one year" means a drought having a statistical chance of occurring once every 50 years, on average (K.A.R. 98-5-1f).
>
> "Reservoir Yield" means the quantity of water which can be withdrawn from storage in the reservoir. Reservoir yield is determined by the rate of flow of the stream into the reservoir, losses due to evapotranspiration from the reservoir surface, and the volume of water impounded in the reservoir (K.A.R. 98-5-1k).
>
> "Yield" means the quantity of water which can be withdrawn from storage in a reservoir for a given period of time (K.A.R. 98-6-1q).

Based on these citations, the yield in the statutes and regulations is clearly a firm yield, with the critical dry period being defined probabilistically as the 2% chance drought. Although the term drought can refer to a shortage of precipitation, soil moisture, or streamflow (Dracup et al., 1980), it can be inferred that the statutes are concerned with a streamflow deficiency. Furthermore, although a duration is not explicitly stated, it also can be inferred that the statutes are referring to an annual drought. Thus, statutory yield is succinctly and adequately defined.

Vagaries arise, however, in going from a well-defined, useful concept to a quantitative implementation of that concept. This is true in many instances, whether in economics (e.g., determining the money supply), demographics (e.g., taking the census), or college football (e.g., determining the national rankings). All depend on assumptions and limited data. In all cases, including yield, no definitive methodology will result in assigning perfectly accurate numbers to the concept. Nonetheless, the necessity of quantifying the concept requires that a workable methodology is implemented.

Two approaches have been used to determine yield from Kansas reservoirs. The Kansas Water Resources Board used a statistical method (Peck, 1984). This methodology was based primarily on statistics of historical data and extrapolations from that data. As such, it was subject to all the benefits and drawbacks of relying on recorded data, statistical techniques, and extrapolation.

The Kansas Water Office has implemented a mass-balance, reservoir-operations methodology. The administrative-policy statement that describes this methodology has several important aspects. First, the policy states that its goal is to pragmatically and consistently administer the State Water Plan Storage Act. Second, it asserts that the statutorily defined drought with a 2% chance of occurrence in any one year occurred within the 1952–57 drought period. Third, the policy describes the mass-balance, operations-study methodology that will be used to compute yield. Lastly, the policy recognizes that yield determinations are subject to revision as additional data become available. The key assumption is the assertion that the 2% drought can be represented by the 1952–57 period. This is particularly useful for planning purposes because people either remember the 1952–57 drought or can get a sense of it based on recorded hydrologic, climatic, and other records. For many regions of the state, it was the worst extended drought in the past 50 years. In a simplistic sense, this gives some credence to idea that is was a 2% drought. The main drawback of this assumption is that the 1952–57 drought, like any sequence of historical flows, will not repeat in the future. Therefore, a yield during the "next" 2% drought will differ from a yield based on the 1952–57 drought. There is no absolutely correct method for implementing the Kansas statutory definition of yield. The Kansas Water Office methodology is thought to define a pragmatic, consistent, and reasonable approach.

Determination of Yield: Mass-balance Approach

Reservoir yields are often determined by operations studies. Operations studies are simulations of the physical systems based on the principle of conservation of mass. A generalized mass balance equation for a single-purpose water-supply reservoir is:

$$BSTOR + IN + PREC - EVAP - SEEP - REL = ESTOR \quad \text{(eq. 6.1)}$$

where:

BSTOR = storage at beginning of period
IN = storable inflow during time period
PREC = precipitation on reservoir surface during time period
EVAP = evaporation from reservoir surface during time period
SEEP = seepage loss during time period
REL = release during time period
ESTOR = storage at end of time period

The key variables in an operations study are hydrologic (inflows, seepage losses), climatic (precipitation, evaporation), physical (elevation-area-capacity relationship), and operational (release rules). The key parameters in an operations study are the simulation period, the simulation time step, and the level of development. Taken together, these variables and parameters define an operations study.

Inflows are often developed from historical measured data, with the historical record adjusted to account for spatial and temporal factors. Spatial adjustments are necessary if the drainage area that contributes to the recording gage(s) differs significantly from the drainage area that contributes to the reservoir. Temporal adjustments are necessary if the watershed conditions, in particular the rainfall-runoff relationship or ground-water–surface-water interaction, have changed since the historical flows were recorded. This temporal adjustment attempts to determine the inflow series that would have resulted from a repeat of the historical climatic conditions on the watershed of a given year specified by the level of development. In most cases, it entails a reduction of the historical flows and is referred to as a depletions analysis. Boxed section 6.1 summarizes this type of analysis for the inflows to a north-central Kansas reservoir.

Inflows must also be adjusted for institutional factors such as water rights. For example, in an appropriation doctrine state such as Kansas, reservoir inflows are subject to bypass requirements for downstream senior water-right holders. The reservoir storage space itself may require a water right in order to store water. The terms, conditions, and limitations of relevant water rights must be considered in the yield analysis.

Reservoir seepage losses can be determined as a function of the beginning storage or considered a constant loss per time period. A percentage of the seepage losses may enter the river and be considered to comprise a portion of a minimum reservoir release requirement.

Climatic inputs are taken from weather-station data. The overall adequacy of the climatic data, in particular the density of the weather data, can have a marked impact on results (Linsley et al., 1975). In addition, spatial averaging of the available climatic data is required. The choice of which of the available data to use and the method of averaging the data can also have a large impact on results (Curtis et al., 1994).

Key operational data include the reservoir capacity at the level of development. Reservoir capacity decreases with time due to sediments carried by the inflows that are deposited and trapped by the impoundment. The prediction of the sediment load to a reservoir is subject to large errors (Singh, 1992). Furthermore, the deposition and transport of sediments within a reservoir is also problematic. Sediment surveys, which are measurements of the reservoir capacity at a given instant in time, are conducted periodically. The reservoir capacity at the level of development of interest is determined by interpolating, or extrapolating, from the measured sediment survey data.

Release is the dependent variable. The firm yield of the river-reservoir system would be the maximum constant release that could be sustained in each and every time period. It can be determined by either optimizing or iteratively simulating the operations of the system.

Because yield is a function of time, the level of development specifies the point in time for which a yield is desired. The level of development is governed by the planning or contracting horizon, which can be 40 years or longer for a water-resources project. Inputs that must be adjusted to correspond with the level of development are the inflows, which are affected by altered rainfall-runoff or ground-water–surface-water interactions, and reservoir capacity, which is affected by sedimentation. Typically, climatic factors are assumed stationary. Accounting for trends in climatic factors may become more common as climate analysis improves, especially if a very extended planning horizon is used.

The simulation period is usually one or more critical historical drought periods. Operations studies with other goals, such as determination of an average yield, may use the entire available historical record. If critical periods are used, the status of reservoir storage at the beginning of the simulation is important. The firm yield will be highly correlated to the initial reservoir storage in systems where the ratio of reservoir storage to inflow is large.

The time step specifies the temporal scale for which results are of interest. Time steps range typically from annual to hourly. Annual, monthly, and weekly time steps are common for water-supply studies. Weekly, daily, and hourly studies are common for flood control and hydropower studies. Firm yield results depend on the time step. With everything else being equal, longer time steps result in larger firm yields due to averaging over critical periods.

The mass balance approach toward firm yield can provide very precise results, but accuracy is limited by input data and assumptions. The largest sources of inaccuracies are the lack of knowledge of critical period inflows and reservoir capacity, as adjusted for the level of development, and the scarcity of climatic data. Thus, even for the case of an overly simplified reservoir, the firm yield determination depends on some key assumptions and data limitations.

Determination of Yield for Kansas Reservoirs

Most large reservoirs are jointly operated facilities that serve multiple purposes. A simple multiple-purpose reservoir may have a conservation (water-supply) capacity and a flood-control capacity sharing the same facility. These capacities are segmented by elevation; that is, the conservation capacity is composed of storage below a specified boundary elevation whereas the flood-control capacity is composed of storage above the boundary elevation. For some facilities, the boundary elevation changes on a regular annual cycle.

In many cases, the conservation storage is further partitioned in order to serve multiple purposes. This can be done via a boundary elevation, as in the flood-control storage-conservation storage designation, or via percentage allocations. In Kansas, the conservation storage in Federal reservoirs in which the State owns an interest are subdivided based on percentage allocations. Figure 6.1 is a schematic of a facility with this configuration. In effect, the facility can be thought of as two or more separate reservoirs that are related by virtue of the physical resources that they share. It is often the yield of one of these distinct reservoirs (such as pool i in fig. 6.1) that needs to be determined.

Equation 6.2 is an extension of Equation 6.1 and describes the mass balance for a conservation pool in a multiple-conservation-pool facility. Note that for the purposes of yield analyses, which address the drought portion of the hydrologic spectrum, flood-control operations can be effectively ignored by assuming that any flood waters are immediately released.

$$BSTOR_i + IN_i + PREC_i - EVAP_i - SEEP_i - REL_i - H_{ij} + H_{ji} = ESTOR_i \quad \text{(eq. 6. 2)}$$

where:

$BSTOR_i$ = storage at beginning of period in pool i
IN_i = storable inflow during time period available to pool i
$PREC_i$ = precipitation during time period available to pool i
$EVAP_i$ = evaporation during time period from pool i
$SEEP_i$ = seepage loss during time period from pool i
REL_i = release during time period from pool i
H_{ij} = handover to other conservation pools from pool i
H_{ji} = handover from other conservation pools to pool i
$ESTOR_i$ = storage at end of time period in pool i
i = conservation pool of interest
j = other conservation pools

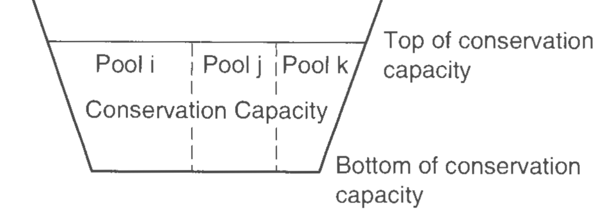

FIGURE 6.1—RESERVOIR POOL SEGMENTATION SCHEMATIC.

Boxed section 6.1: Historical Inflow Modifications: The Milford Reservoir Example

In order to give a sense of the modifications to the historical record that must be contemplated, we present an example pertaining to Milford Reservoir and the Republican River basin. Milford Reservoir is located in north-central Kansas on the Republican River upstream of Junction City (fig. B6.1.1). It has a design conservation capacity of 300,000 acre-feet (0.37 km^3) and a design flood-control capacity of 700,000 acre-feet (0.86 km^3). It was placed in service in 1967.

The U.S. Geological Survey (USGS) has maintained a streamflow gage on the Republican River at Clay Center, which is approximately 30 mi (48 km) upstream of Milford Dam, since 1917. Thus, daily flow records of the 1952–57 drought are available. The Clay Center gage has a drainage area of approximately 24,542 mi^2 (6.36×10^6 ha). Milford Dam has a drainage area of approximately 24,880 mi^2 (6.44×10^6 ha). The USGS has determined that approximately 7,500 mi^2 (1.94×10^6 ha) of this region is noncontributing.

The following checklist presents some of the adjustments that might be made to the observed 1950's Clay Center flows in order to account for spatial (i.e. because the gage does not measure all inflows to Milford Reservoir) and temporal (i.e. because the changing conditions have altered the rainfall-runoff relationship in the watershed since the measured 1950's flows) factors.

Spatial

1. Account for drainage area contributing to reservoir that is downstream of Clay Center gage.
2. Account for greater precipitation and runoff-generating capacity at downstream end of watershed relative to the rest of the watershed.

Temporal

1. Account for decreased flows across the Nebraska–Kansas stateline due to increased land treatment and consumptive use in the Republican River valley in Nebraska.
2. Account for decreased gains from the Nebraska–Kansas stateline to Clay Center due to:
   a. Irrigation development
   b. Land-treatment conservation practices
3. Account for Milford Reservoir water-right provisions; that is, some of the inflow to the reservoir must be bypassed downstream according to terms and limitations of the Milford water right.

The spatial factors suggest that Milford inflows are 1.01 to 1.10 times the measured Clay Center flows. The temporal factors suggest that, under current watershed conditions, the Clay Center flows would be approximately 0.4 to 0.5 of the observed historic 1952–57 flows (KWO, 1996). Because yields depend significantly on inflow, the decisions regarding these factors will have a major impact on the yield determination.

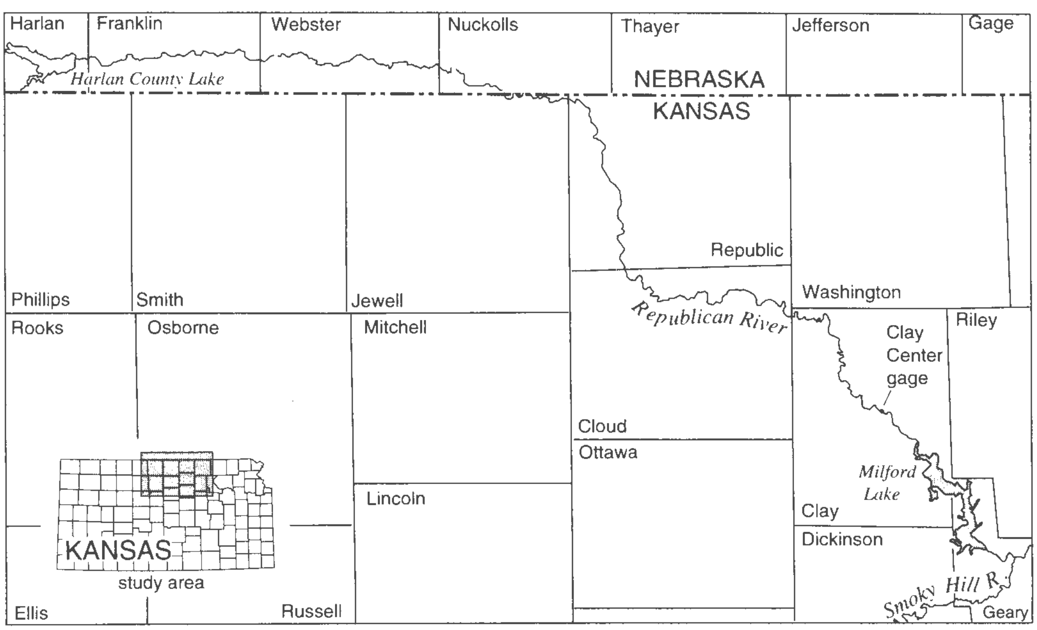

FIGURE B6.1.1—MILFORD LAKE (modified from map by Kansas Water Office).

Boxed section 6.2 illustrates the water balance for an eastern Kansas reservoir.

The variables are analogous to those in equation 6.1, but are modified to reflect sharing among pools. In principle, storable inflows are allocated based on the pool-capacity percentages. If the capacity of a pool is 30% of the total storage of the conservation capacity, that pool is generally entitled to 30% of the storable inflows. This guiding principle, however, can be modified by contractual agreements or water-rights provisions that give preference under specific inflow or storage conditions to one pool at the expense of the others.

Sedimentation is apportioned based on capacities also. Unused sediment storage within the conservation capacity is prorated among the conservation pools. If the sediment within the conservation capacity exceeds the allocated sediment storage, then the pools share the lost conservation capacity by proration.

Evaporation and precipitation are allocated based on storage. A pool would be assessed (or credited) for 45% of the net evaporation (gross evaporation - precipitation) during a given time step if the storage in that pool were 45% of the total conservation storage at the beginning of the time step. The allocation of net evaporation is independent of pool capacities.

Releases are taken in full from the appropriate pool. Because the pools are operating as independent reservoirs that share the same facility, one pool might be empty while another might have ample stored water. A release to support the designated purpose of an empty pool could not be expected even though other pools, and thus the conservation capacity as a whole, might have ample water.

The handover terms allocate water when a pool does not have unused capacity available to store all the inflows to which it is entitled, but at least one other pool does. The first term, H_{ij}, delineates spillage from the pool of interest to the others. The second term, H_{ji}, delineates spillage from other pools to the pool of interest. Like inflows, handovers are apportioned based on storage capacities. Handovers are not possible when all the individual conservation pools, and therefore the entire conservation capacity, are filled. In this case, remaining handovers become flood water stored and released from the flood-control capacity.

Handovers are another way in which the operations of one pool can affect the yield of another. Consider a reservoir with a conservation storage capacity composed of three pools: i, j, and k. If the yields from pools j and k are uncommitted and remain in the reservoir, then, relative to the case where these pools are making significant releases, pools j and k are less likely to be able to store all the inflows to which they are entitled. This will result in greater handovers to pool i, thereby increasing the yield of pool i.

The parameters for this more detailed form of the operations study are identical to those for the simpler form. For Kansas yield studies, monthly time steps are most common. As yields are expressed typically on a daily time scale (in million gallons per day) or even on a time scale of seconds (in cubic feet per second), some averaging is implicit in the results.

The application of the mass-balance approach for yield analyses in Kansas reservoirs has the same advantages and disadvantages that the simplified mass-balance approach has. In addition, having several distinct pools share one physical facility adds a significant complication: namely, the ability for operations in one pool to affect the yield of another. To determine the yield of one pool, the operating policies of the other pools must be known or assumed. This can be problematic if, as in the State's water-marketing program, releases from a pool are made on demand of one or more contracting entities and do not follow any established operating rule.

Policy Implications of Yield

Reservoir-yield estimates are fraught with policy implications. In addition to affecting water-supply policies at the reservoir, a yield determination can affect policies pertaining to regional water supply, reservoir recreation, and downstream riverine resources. Often, the highly inter-related nature of water-resources systems and objectives leads to a chaotic effect (Gleick, 1987); namely, a small change in a yield estimate can have significant repercussions in numerous water-policy arenas.

In Kansas, water supplies are marketed based on the aforementioned 2% yield criterion. Even allowing for computational uncertainties, the odds of drought-level inflows and high evaporative losses are low for any given year. Defining water-supply yield at this probability leaves a large quantity of water available in most years. As a consequence, much of the average reservoir yield remains uncommitted.

Water-supply users place great value on supply reliability and generally tend to view the 2% yield criterion as prudent and beneficial. However, a water-supply entity in search of additional water supplies might feel that the 2% criterion, or a yield calculation based on that criterion, unnecessarily restricts the water supply available from a resource. From the perspective of this entity, the 2% yield criterion could be viewed as a policy that institutionalizes the under-utilization of an important resource.

The recreation sector is a primary beneficiary of the 2% yield policy. Because firm yield demands are far less than average yield, reservoirs typically remain in a robust condition during moderate- or short-duration droughts. As a consequence, significant drawdowns for water-supply purposes are limited to more extreme droughts. Recreation facilities at reservoirs operate within a relatively narrow zone of lake elevation. Therefore, a 2% yield policy enhances the utility of the lake for recreational activities such as boating, swimming, and water skiing.

Resources downstream of the reservoir also benefit from a 2% yield policy. Streamflows are enhanced by reservoir releases during dry conditions. Often, the river is used as the conveyance mechanism for water-supply releases. The Kansas Department of Agriculture, Division of Water Resources, is obligated statutorily to protect water released from Federal reservoirs under contract provisions from diversion by unauthorized downstream users. In this case, natural riparian demands first-use water-supply releases. While transit losses are viewed as a cost from the perspective of a water-supply user, they constitute a benefit to a drought-starved river reach. As a rule, severe droughts will shift significant benefits from those of retaining water behind the dam to those realized by moving water from the reservoir to the downstream river system.

Water-supply policy that depends on a quantified yield is vulnerable to the underlying assumptions used to calculate the yield. The establishment of a yield value implies a deterministic capability to predict future drought conditions. Runoff from watersheds is a nonlinear response to rainfall and antecedent conditions. Alterations in land use, soil moisture, rainfall-intensity variations, water-use patterns, and vegetative conditions create time-variant states in the watershed that result in infinite potential outcomes. As a result of these complexities, the assumptions behind a yield determination are as important as the yield value itself. In order to properly assess policy

Boxed section 6.2: Water Balance at John Redmond Reservoir

In order to give a sense of the magnitude of the individual terms in equation 6.2, we will use the example of John Redmond Reservoir on the Neosho River in southeast Kansas (fig. B6.2.1). John Redmond Reservoir has a current estimated design-life conservation capacity of 49,160 acre-ft (60.64×10^6 m^3). The conservation capacity is divided into a water-quality pool (11,710 acre-ft [14.44×10^6 m^3] or 23.82% of conservation capacity) and a water-supply pool (37,450 acre-ft [46.19×10^6 m^3] or 76.18% of conservation capacity). The water-quality pool makes releases on a schedule that varies by month and is designed to operate with approximately a 10% chance of shortage. The design water-supply pool has a computed 2% yield of 27.2 million gallons per day (42.1 cfs [1.19 m^3/s]). The following table summarizes the 2% yield calculation water balance for the June 1952–September 1955 critical drought period. The reservoir began and ended the period with the conservation capacity full, so the net change in storage components is zero. All units are thousand acre-feet.

	Conservation Capacity	Quality Pool	Supply Pool
Inflow	256.2	61.0	195.2
Evaporation	86.8	17.2	69.6
Releases (incl.seepage)	142.7	45.0	97.7
Spills to flood control	26.8	0.7	26.2
Handover: quality to supply	—	0.0	
Handover: supply to quality	—		1.8

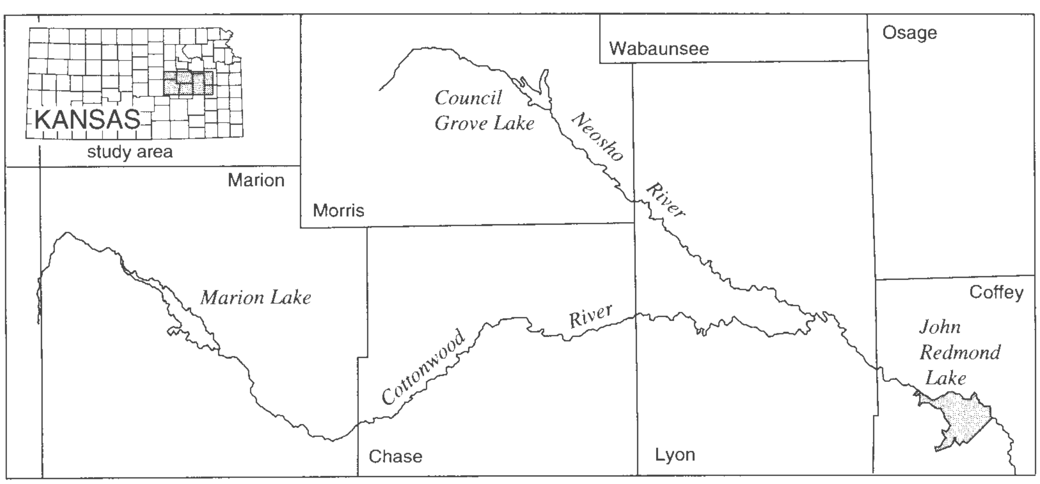

FIGURE B6.2.1—JOHN REDMOND LAKE (modified from map by Kansas Water Office).

implications and options, contingency plans must be developed should actual conditions deviate from those that were assumed in the development of the yield estimate. Contingencies could include the reduction of demands as water-supply storage decreases, the recalculation of yield using observed antecedent conditions, or the reapportionment of available yield among competing users in order to minimize hardships.

The apportionment of shortages among stakeholders is one key provision that must be addressed. While available-yield determinations are saddled with uncertainty, allocation of yield shortages among users is a deterministic procedure. Equity is expressed through allocation of remaining storage in proportion to each user's relative allocation of the original yield. In cases where certain individual withdrawals were less than contractual allowances, allocations of storage should be weighed inversely to the amount previously withdrawn. Withdrawals must be monitored in order to maintain equity among users.

Experiences from past droughts have shown that users tend to adjust their own demand rates as storage declines (Sheer, 1980). Because the assumed yield policy is based on a constant demand in the face of deterministic inflow conditions, the occurrence of drier-than-assumed conditions requires one of two responses: suffer a shortage under current demand rates or reduce demands in response to the actual conditions. One expedient method for setting mid-drought corrections is hedging, which accepts small release reductions in the early stages of a drought in order to offset a large deficit in the later stage of a drought (Maass et al., 1962).

The sustainability of reservoir yield through a multiple-year drought has repercussions for other facets of reservoir operations. As demand for water approaches the expected yield, the reservoir's ability to accommodate other purposes can be reduced. For example, drawdowns of the normal conservation pool to enhance fisheries and shoreline wildlife habitat can require storage evacuations of approximately 30% of capacity in order to have the desired effects. This action temporarily reduces reservoir storage, and therefore the yield. Such a drawdown plan can be operated in situations where the expected demand over the course of the drought remains well below the yield of the effectively smaller reservoir. Once the demand curve and yield curve begin to converge, drawdown policy must become more conservative, shifting from a routine action to an opportunistic tactic. Under heavy subscription of water supply, drawdowns for fisheries or recreation are coordinated to take advantage of the anticipated drawdowns seen under the drought cycle. The benefits of drought-induced drawdowns to a reservoir fishery are a function of the timing and duration of the lower water levels.

Although the primary means of maintaining the water-supply capability of a reservoir during drought is demand reduction, conjunctive use policies also extend the utility of reservoir storage. Conjunctive use entails the utilization of multiple sources of water to meet a common demand. A general hierarchy of use among water sources would be: streamflow, reservoir storage, ground-water storage. The conjunctive use of streamflow and reservoir storage is the heart of the water-assurance concept. Users rely on the available streamflow to first meet their demands, thereby resting their reservoir supplies. Once streamflows have receded below a specified threshold level, reservoir releases can be called upon to meet demands. In the course of a drought cycle, this strategy reduces the length of time that a reservoir is called upon to meet demands. Because yield is a function of time, a rested reservoir can provide water above its design yield over the compressed time period.

The same concept holds for surface and ground water. Surface water can be used in an opportunistic manner that reduces aquifer demand because surface water is typically more transient than water stored in aquifers. Reservoir drafts may be larger than yield early in a drought. Once the reservoir reaches a depleted state, it can be rested for recovery while demand shifts to the aquifer. With system operations, the flexibility of diverse water sources leads to enhanced reliability; the yield of the system can be greater than the sum of yields of the individual components.

Reservoir yield has to be viewed as an function of nonlinear inputs. The anticipated inflows which occur under drought are located at the extreme end (i.e. those flows having a greater than 95% chance of being exceeded) of the historic flow-duration curve, which is a graph of the cumulative frequency of historic flows. The extreme low-flow region of a typical flow-duration curve is defined by few data points due to the rarity of these events. Furthermore, the data that are available are often widely scattered. Therefore, extreme drought is difficult to analyze and forecast. Reservoir policies established to maintain yield under these conditions must recognize two tenets: 1) the historic drought of record will not repeat itself exactly; and 2) the historic drought of record will be altered for the worse by subsequent anthropogenic perturbations in the watershed.

While extreme drought may be defined as having a 2% chance of occurrence or being a once-in-fifty year event, probability calculations enable this risk to be quantified over any extended time period. Using the basic risk equation (Linsley et al., 1975) that describes the probability of an event happening at least once in a specified time period, the chances of an extreme (2%) drought occurring at least once in the next 20 years is one out of three. Similarly, there is a one out of two chance that an extreme drought will occur at least once in the next 35 years. Water-supply planning horizons are often in the range of 20 to 40 years. Thus, the probability of an extreme drought occurring at least once during the typical planning horizon ranges from 1/3 to greater than 1/2.

Compounding the complacency induced by the definition of extreme drought is the loss of institutional memory at utilities and reservoir-operation centers. In

Kansas, the last major multiple year drought was 40 years ago (1952–57). Professional points of reference are rarely available to provide guidance for operational policies and decisions. Furthermore, most of the reservoir facilities have never been subjected to severe drought stress, so their functionality under extreme conditions is somewhat uncertain. Further complications can be expected to arise as the recreation sector, which has enjoyed the utility of predominantly near-full reservoirs, is confronted with a diminished facility. This typically heightens public interest and focuses attention on reservoir-operation rules and decisions.

Vigilance is the key to managing the yield policy. With regard to policy implications, it is important to remember that a yield estimate and the assumptions and uncertainties that form the foundation of the yield estimate can not be separated. During droughts, the consistency of actual conditions to previously assumed conditions must also be monitored and assessed. Contingency plans must be developed and implemented when the assumptions are violated, which is inevitable.

Are Reservoir Yields Sustainable?

Fundamentally, reservoir yield is a function of inflow, net evaporation, and storage. In the absence of stresses such as changing watershed or climatic conditions, inflow and net evaporation may be considered stationary. Storage, however, is continually decreasing due to sedimentation. The rate of storage decrease depends primarily on the soils, land uses, hydrology, and hydraulics in the watershed upstream of the reservoir. Nonetheless, unless compensatory actions are undertaken, storage decreases monotonically with time. Because reservoir yield can not be sustained if reservoir storage is not, the ultimate yield of a river-reservoir system will tend to the yield of the river alone. An interesting discussion of reservoir sedimentation and by extension, the sustainability of reservoir yield, can be found in Reisner (1986).

Large reservoirs are designed with a sediment storage capacity sufficient to store the estimated sediment load expected to occur over the design life of the project. A 50- or 100-year design life is used for most projects. With all else equal, the storage (and therefore the yield) will be greater than design as long as there is unused sediment storage capacity. The converse also is true. The prediction of future sedimentation loads and deposition is difficult and prone to large errors (Singh, 1992). Consequently, the actual useful life of a project can differ significantly from the design life. Table 6.2 illustrates the design and estimated actual conservation storage capacities for two major Federal reservoirs in Kansas.

The sediment storage in the conservation capacity at John Redmond filled approximately 25 years before design. Conversely, as of 1993, Tuttle Creek could provide additional yield from 173,000 acre-feet (0.213 km^3) of unused conservation-capacity sediment storage. Both reservoirs are losing capacity to sedimentation and have the same ultimate fate. In the absence of any mitigation efforts at Redmond, however, their prospects over the intermediate term of their design lives are very different. Additional sediment information for three major reservoirs along the Kansas River is provided in Boxed section 6.3.

Reservoir yield can be prolonged significantly in several ways. In a multi-purpose facility, the capacity of one storage capacity can be augmented by reducing another capacity. Raising the boundary elevation that separates the flood control capacity from the conservation capacity will augment the conservation-storage capacity at the expense of the flood-control capacity. Flood-control capacities can be many times larger than conservation capacities, so a large percentage gain in conservation storage (and therefore yield) can be garnered with a small percentage loss of flood-control capacity. Note that this is primarily an institutional and operational change, but may require some structural modification to outlet works as well.

At John Redmond, this type of adjustment could be completed while maintaining the design storage of the flood-control capacity. The overall sediment in the facility is less than expected. The problem is that the sediments have been deposited in the conservation capacity to a much greater degree than expected. Relative to design, the conservation capacity has less storage than expected while the flood-control capacity has more storage than expected. The reservoir could be re-balanced by raising the top-of-conservation level. The flood-control capacity would lose storage but still have more capacity than design.

TABLE 6.2—DESIGN AND ESTIMATED CONSERVATION STORAGE CAPACITIES.

Reservoir	Design Capacity (acre-ft)	in Year	Est. Actual Capacity (acre-ft)	in Year
John Redmond	62,500	2013	57,800	1993
Tuttle Creek	122,000	2012	295,000	1993

Boxed section 6.3: The Kansas River System: Sedimentation Data and Water-supply Management

The Kansas River in northeast Kansas (fig. B6.3.1) is formed by the confluence of the Smoky Hill River and the Republican River at Junction City, Kansas. It flows generally eastward until it joins the Missouri River at Kansas City. The Kansas River corridor is home to approximately 1/3 of the state's population. The Kansas River, and its alluvium, is a major source of water supply for this fast-growing region.

There are four multi-purpose Corps of Engineers reservoirs on major tributaries of the Kansas. Three of them, Milford Reservoir, Tuttle Creek Reservoir, and Perry Reservoir, are on northside tributaries and were put into service in the 1960's. The following table summarizes the conservation capacity lost to sedimentation in these facilities. All storage units are thousand-acre-feet.

	Milford	Tuttle Creek	Perry
in-service year	1967	1962	1969
original conservation capacity	415	425	240
estimated 1996 conservation cap	370	295	205
conservation capacity lost	45	130	35
percentage loss	11%	30%	15%
project design life, years	100	50	100
design storage at end of project life	300	122	150

The total conservation capacity lost to-date is approximately 210,000 acre-ft (0.26 km^3), or an amount greater than the current conservation capacity of Perry Reservoir. By the time that the conservation capacities reach their design storage levels, over 500,000 acre-ft (0.62 km^3), or almost half of the total original conservation capacity, will have been lost.

In the face of monotonically decreasing capacities and increasing demands, the utilization and management of the water-supply resources become critical. On the demand side, conservation programs and practices can slow the rate of water-demand growth. On the supply side, continually improving water-management practices can improve the efficiency of water-supply operations.

The entities that depend on the Kansas River for water supplies have responded to these challenges by forming the Kansas River Water Assurance District. This District has contracted for water-supply storage in each of the three reservoirs listed above. The District uses this storage to assure the supply of water to District members during drought periods. District storage is operated as a unified system and the efficiency benefits attributable to the sytem operations accrue to District members. In order to help ensure that District water is being used wisely, each District member must adopt a conservation plan that adheres to guidelines developed by the Kansas Water Office.

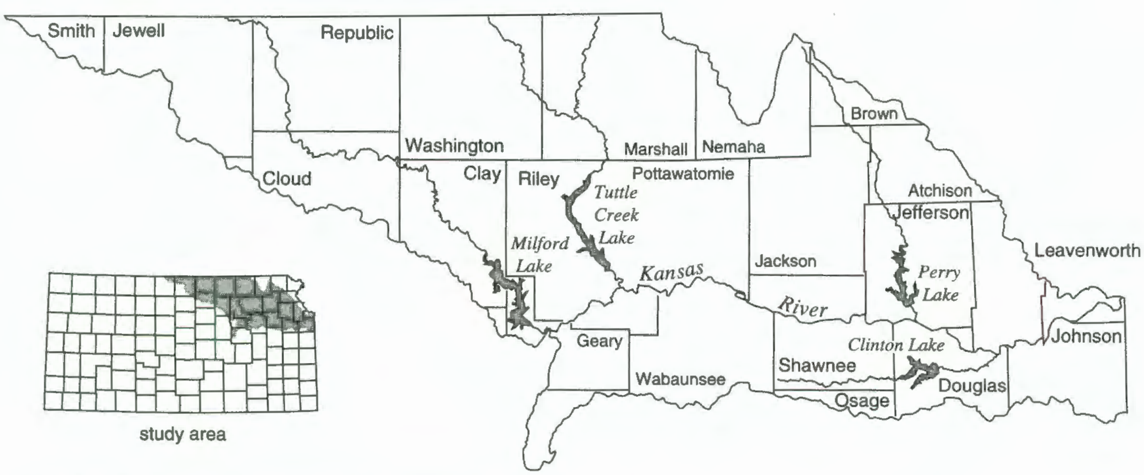

FIGURE B6.3.1—KANSAS–LOWER REPUBLICAN RIVER BASIN.

Other means of increasing storage, such as physically raising the height of the dam or removing accumulated sediment deposits, are possible. These projects, however, are usually unjustifiable from economic and environmental perspectives. To date, neither of these approaches has been used for any major reservoir in Kansas.

Lastly, yield lost to diminished storage capacity could be offset by augmenting reservoir inflow. Augmentation usually implies the acquisition of water from other basins. Proposals of this type raise numerous political concerns that, in addition to environmental and economic factors, must be considered. Although many ambitious proposals have been advanced, few projects of this type have been started in the western United States in the last several decades.

Conclusion

Yield is a fundamental aspect of water-supply planning and management. At face value, yield is easy to define and conceptualize. Many complicating issues arise, however, in going from the concept or definition to the actual quantification of yield for a water-supply source. Yield determinations are highly dependent on methodology and assumptions, as well as data sources that can be sparse and nonstationary. Furthermore, yields are often prospective in the sense that the item of interest is a yield at the end of a contracting or planning horizon. The necessity of determining yields for projected future conditions exacerbates many of the uncertainties incumbent in the analyses.

The mass-balance (operations study) methodology has many advantages with regard to quantifying yields. It is being used in Kansas to determine yields from reservoirs in which the State of Kansas owns an interest. The mass-balance approach provides a pragmatic and consistent methodology for determining yield. Still, the level of precision associated with this approach exceeds the level of accuracy.

Yield determinations affect many facets of water policy. In Kansas, a yield estimate places an upper limit on the amount of water supply that can be marketed from a reservoir. This de facto rationing of a water resource can have significant implications for entities in search of water supplies. Therefore, it can affect the larger regional water-supply situation. Yield determinations also have corollary implications for policies pertaining to reservoir recreation, reservoir fisheries, and downstream streamflows and riverine habitat.

Reservoir yields depend primarily on inflows and reservoir storage. As such, reservoir yields decrease with time due to reservoir sedimentation. The loss of storage results in a loss of reservoir yield unless compensatory actions are taken. These measures can include augmentation of inflow, increasing the conservation storage capacity via structural or institutional means, or physically removing the accumulated sediments. Except for increasing the conservation storage via institutional means, these approaches are generally not feasible due to economic, environmental, and political concerns.

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CHAPTER 7

Effects of Agriculture on Water Yield in Kansas

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CHAPTER 7
Effects of Agriculture on Water Yield in Kansas

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Introduction

Most of the land area of Kansas (over 90%) is used for agricultural purposes. Nearly all of the potential water supply for Kansas (98%) comes from precipitation onto the land surface. The amount of precipitation averages about 28 inches (70 cm) per year over the state. The primary source of water resources available over the long term for other users in the state is runoff and percolation from the precipitation that falls on agricultural land within the state. Therefore, the activities of agriculture to use and manage the land play a role in affecting the amount and quality of water available for water-resource purposes. Effects of agriculture on water yield are of particular interest because the prior appropriation doctrine is used to allocate water rights. Therefore, understanding how agricultural activities influence the quantity of water lost from agricultural lands is crucial to account for the effects of more efficient use of water from precipitation as well as to decide how much water is potentially available for appropriation by other users.

Effects of agriculture on water yield have been of interest for many years. In much of the state, natural ecosystems, particularly prairies, have been converted to agricultural production of cultivated crops. Two important changes occur. First, surface runoff is increased because the potential for loss by runoff is increased from soil that is bare or partially bare during the cropping cycle. Bare soil has a lower rate of infiltration than the same soil covered with growing plants or crop residue. Second, actual evapotranspiration is decreased because annual crops are actively growing for a shorter period of the year than perennial plants. This increases the potential for percolation and subsequent recharge. The exact effects of these changes depend upon the interactions of the climate, soil, and agricultural-management practices including those of soil and water conservation at a particular location.

In most of the state, water supply is limited because precipitation usually is less than potential evapotranspiration for much of the growing season. The success of dryland agricultural technology hinges on its ability to use precipitation as effectively as possible by a combination reducing runoff and increasing the amount of water used as evapotranspiration through useful crops. Additionally, where ground water is available, making use of it is usually very desirable.

The necessity to control wind and water erosion and improve water management was soon recognized in Kansas agriculture. Conservation techniques began to emerge in the 1930's following the disastrous drought. National programs to reduce erosion soon were developed. Kansas has been a leader in the adoption of soil- and water-conserving techniques including terracing, conservation tillage, farm ponds, and watershed dams. A terrace is a broad channel, bench, or embankment constructed across the slope to intercept runoff and to detain the water or to channel the excess water to protected outlets for disposal from the field. Conservation tillage is a practice that uses mechanical or chemical means to control weeds and/or plant crops such that plant residues cover at least 30% of the soil surface to promote wind- and water-erosion control and moisture conservation.

To quantify the effects of agriculture, several factors that interact must be considered—climate, soil, and agricultural-management practices which include type of land use, production practices, and conservation practices. Ideally, there would have been field experiments conducted to determine these effects. However, few have been done, and the length of time the experiments were operated were often insufficient to understand the interactions of all of the factors. Thus, simulation-modeling techniques have been required to obtain estimates of effects and to explain the effects on the availability of water resources in the state. The remainder of this chapter focuses on the development of a model, the results from a specific study, and a broader interpretation of those results for the entire state.

Background for Computer-simulation Modeling

In the 1960's, the U.S. Department of Agriculture Soil Conservation Service (SCS), now known as the Natural Resources Conservation Service (NRCS), and Agricultural Research Service (ARS) used a joint task force to develop procedures to assess the effects of land and watershed treatment on streamflow. Land and watershed treatment include change in land use from cropland to permanent cover crops such as native or tame grasses, structural measures such as terraces, tillage and surface-residue management, irrigation, farm ponds and watershed dams. The result was a rational approach based upon annual amounts of precipitation, a climatic variable, extent of land-use changes and conservation practices and other factors. At the time this work was done, however, the effectiveness of residue management was uncertain and the extent of future use of land treatment and other conservation practices was not well known. The procedure, however, has been used by the NRCS, and it did serve as a good basis for future work on the effects of land treatment on water yield. One major limitation of the procedure, however, was that the effects of land treatment and conservation practices on a continuous basis on water yield could not be determined easily. In particular, the variability from year to year in climate could not be accounted for very well with the rational technique.

Continuous computer-simulation modeling allows questions about effects of changes in land use, crops, and management practices to be assessed at various locations over a simulation period of many years. While direct comparison with measured results from field experiments are not possible because such measurements have not been made on whole watersheds, results can be compared with measured streamflow if conditions in a drainage area are simulated for a period of time. In the late 1960's, water yield into several flood-control and irrigation-supply western Kansas reservoirs that had been built in the 1950's was much less than expected. When well-above-average amounts of precipitation that occurred in the early 1970's did not result in expected inflows to these reservoirs, the Bureau of Reclamation began a study of the Solomon River basin in Kansas to identify what was happening to the water supply. Speculation implicated changes in land use and soil- and water-conservation practices, changes in the precipitation regime, and increased use of ground water from alluvial aquifers were involved. Work began at Kansas State University to develop a method to assess the effects of land use and soil- and water-conservation practices on water yield on a watershed basis.

Potential Yield Model

When a method was needed to assess the effects of land use and conservation practices on large watersheds for the Bureau of Reclamation, a continuous computer simulation model, called the Potential Yield (POTYLD) (Koelliker et al., 1981, Koelliker et al., 1982), was developed for this purpose. POTYLD simulates the daily change in the water budget for different climatic and land-use conditions to estimate the dispensation of precipitation as interception, runoff, actual evapotranspiration, percolation, and change in water content in the soil. The model utilizes values of runoff curve numbers (RCN) to predict the split between runoff and infiltration for land uses from daily amounts of rainfall and snowmelt (See chapter 1 for more information on RCN values). Individual land uses and conservation-practice conditions can be described by a RCN, and the RCN technique is used widely to predict runoff from design storms. It follows that the RCN method can predict runoff over a period of time provided the antecedent moisture condition (AMC), how wet the soil was at the time of each storm, can be determined. This technique to assess runoff through a computer-simulation model is now used widely in watershed-simulation models. Recently, POTYLD has been modified to include additional refinements and to include irrigation; consequently, the name was changed to Potential Yield Revised (POTYLDR) (Koelliker, 1994a, 1994b). This model simulates the water budget on a daily basis for different land uses and estimates the water yield on a monthly or annual basis for a drainage area. A more comprehensive description of POTYLDR can be found in Appendix 7.A of this chapter.

The POTYLDR model is useful to estimate effects of land-use changes and agricultural soil-water conservation practices on surface-water yield and on percolation. Exact comparisons with data from the field are difficult because such data are very limited. The following section does provide the results of a comprehensive study to combine all impacts on water yield into Webster Reservoir along with estimates of the effects across the state. Extended use of the POTYLDR model for other studies, too, provides evidence that it reasonably documents real effects that have been and are being experienced in Kansas.

Results of Modeling Water-yield Changes

Several studies have been done with POTYLD. The most extensive was for the South Fork of the Solomon River basin above Webster Reservoir in northwest Kansas (Koelliker et al., 1981). Webster Reservoir, located on the South Fork of the Solomon River in Rooks County, has a watershed of 1,150 mi^2 (2,980 km^2; fig. 7.1). It was completed in 1956, primarily to serve as a water supply for an 8,400-acre (3,400-ha) irrigation district and to control flooding and to provide recreation. After about 1975, however, the irrigation district seldom received a full delivery of water, and in several years no water was delivered. At streamflow-gaging stations in the region with 30 or more years of records, average streamflow during the 1970's was less than 25% of the long-term average. A report by the Bureau of Reclamation (1984) concluded that phreatophytes, water-loving plants, and changes in the nature of precipitation events were not important contributors to the declining streamflow. That same report did, however, conclude that withdrawal of ground water from the alluvial aquifer was an important contributor. The largest effect by far upon declining streamflow was that of soil- and water-conservation practices, a finding substantiated by POTYLD.

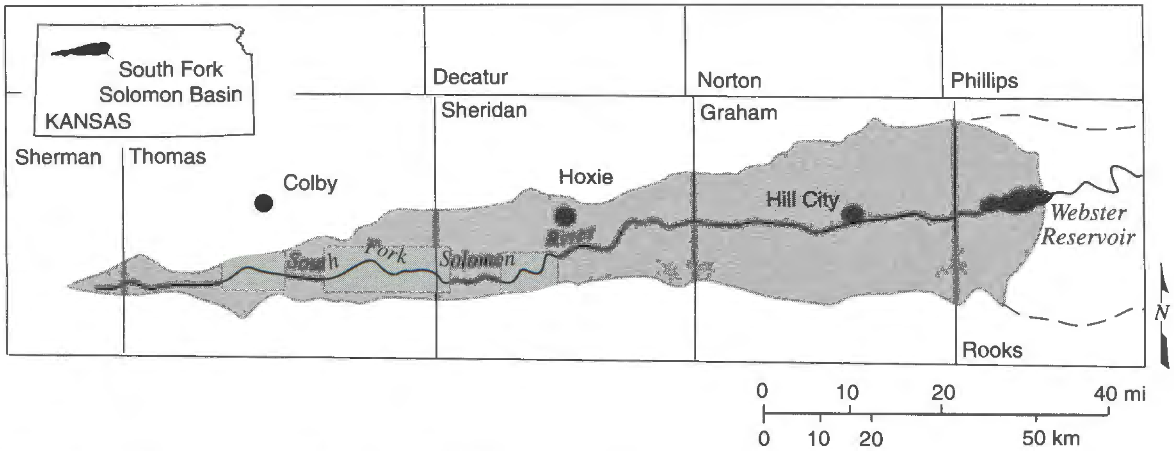

FIGURE 7.1—MAP OF THE SOUTH FORK SOLOMON RIVER BASIN (Koelliker et al., 1981).

Figure 7.2 shows streamflow for two conditions along with measured streamflow into Webster Reservoir for a period when both daily precipitation and streamflow were available for the study. The curve labeled "1950" represents the expected streamflow into Webster Reservoir if conditions above the reservoir had remained unchanged after 1950 until the end of the simulation period in 1978. The curve labeled "changing" accounted for changes in land use, conservation practices, and ground-water withdrawals during the period simulated. A 3-year moving average is used because of limited availability of continuous weather records to represent the area. Rainfall is spatially quite variable because of the continental-type climate in the area. Because long-term changes were of interest, averaging shows the trend more clearly.

The results of the study showed that by 1980, the expected water yield into Webster Reservoir was predicted to be less than half the historic inflow (1920–1955) of 50,900 acre-feet/year (62.8×10^6 m^3/yr). The Bureau of Reclamation reported the inflow to Webster Reservoir for the period, 1979–1988, averaged 13,300 acre-feet/year (16.4×10^6 m^3/yr; Kutz, 1990), which further substantiated the results obtained by the use of POTYLD.

Fluctuations in all three curves in fig. 7.2 are caused by temporal changes in amounts of precipitation and the ability of that precipitation to produce runoff. Amounts of individual rainfall events and their timing and aerial distribution are critical to the production of runoff. Continuous simulation is very helpful to evaluate fluctuations in streamflow because it can account for conditions in the watershed when precipitation occurs. By aggregating results from several sub-basins for a stream, the aerial distribution also can be accounted for partially. This is very helpful to describe the impact of precipitation on yield. A study of the Upper Republican River basin of northeastern Colorado, southern Nebraska, and northwestern Kansas was done using POTYLD as a major component of the work (Koelliker et al., 1983). While changes in precipitation regime appear to be occurring in the Great Plains, the length of record (1920–1978) available for that study did not show it. When POTYLD was used with 1950 basin conditions held constant, essentially no decrease in water yield with time was expected. A more recent study to estimate the future water supply for the Cheyenne Bottoms Wildlife Refuge, which comes from streamflow originating in west-central Kansas, showed a difference attributable to precipitation. For the period 1973–1988, the ability of precipitation to produce streamflow from this drainage basin was about 27% below that for the earlier period 1948–1972 (Koelliker, 1991).

An historical view of land use and development of agricultural technology on streamflow can be done by simulating for many years with conditions in the watershed fixed at given points in time. Then, the average of the results can be graphed against time to see if there are trends and effects. Such an analysis was done for the South Fork of the Solomon River above Webster Reservoir. In addition, the effects of changes in land use, conservation practices, and ground-water withdrawals during the period show the estimated impact of agriculture on water yield (fig. 7.3) (Koelliker, 1984). Initially, the watershed was all rangeland before 1850. Figure 7.4 shows the important changes with time that have occurred in the watershed. Agriculture was started around 1860 and by about 1930, 70% of the watershed was cropland. Drought and erosion has caused some cropland to be put

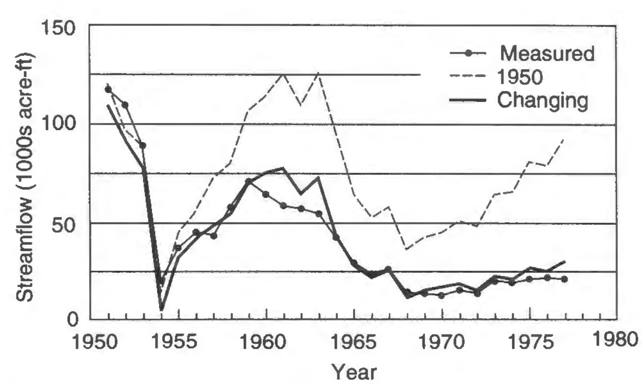

FIGURE 7.2—COMPARISON OF THE THREE-YEAR MOVING AVERAGE ACTUAL STREAMFLOW ABOVE WEBSTER RESERVOIR with streamflow predicted with changing conditions, and when 1950 conditions were held constant (adapted from Koelliker et al., 1981).

back to grass since 1930. Development and adoption of conservation practices have progressed since the 1930's. From the early 1950's, development of ground-water resources has reduced baseflow in the stream. In the future, amounts of surface-water yield will be less than the amount estimated for conditions before agricultural development began.

In fig. 7.3, the line labeled POTENTIAL YIELD represents an estimate of the total streamflow from the watershed if agricultural land use and practices in the 1930's had remained in place. That period is chosen only because it was the set of conditions in the last 150 years that produced the greatest streamflow. Records from that period also probably influenced the design conditions that were used for the development of Webster Reservoir and its original operations plan. The line labeled ACTUAL YIELD represents the expected amount of streamflow into the reservoir as affected by the changing conditions in the watershed. This line does not imply that water yield does not fluctuate from year to year. It shows an expected average for a given date that would have resulted if the precipitation from 1920 to 1978 had occurred on the watershed when it was in a particular set of conditions that were in place on that date. The split of the actual yield into surface runoff and ground water is an estimate based upon the types of land use with time and the effects of withdrawals of ground water for irrigation.

The contributions of the various soil- and water-conservation practices are estimated with time on the graph. Dams are stockwatering and erosion control structures that create features commonly known as farm ponds. These farm ponds in aggregate collect runoff from over one-third of the watershed. Terraces have been installed on nearly one-half of the cropland in the watershed to reduce water erosion and to improve moisture conservation. Here, residue refers to a variety of agricultural-management practices to keep the soil surface partially or totally covered with plant residue to reduce potential for water and wind erosion. Conservation tillage of various kinds is the most widely used practice. Irrigation is used to describe the effects of withdrawals of ground water from the alluvial aquifer. Nearly all the water withdrawn is subsequently lost as evapotranspiration from the irrigated areas.

The latest conditions in the watershed above Webster Reservoir have not been studied with POTYLDR. Further evidence of the effects of agriculture on water yield appeared from the flood of 1993. This flood and the precipitation that caused it were remarkably similar to the flood year of 1951 (see chapter 1 comparison of 1951 and 1993 floods). Although the reservoir was not completed in 1951, the streamflow-gaging station just upstream was operational and estimates of the inflows to the reservoir had the lake existed have been made for that period by the Bureau of Reclamation. Figure 7.5 shows the precipitation and inflow to Webster Reservoir on a monthly basis for both floods. The amount of inflow in 1993 was essentially half the amount in 1951. This points out that even in years with high precipitation, the effects of agriculture on watersheds in the western half of Kansas can be and are substantial.

At the same time that runoff is reduced, more water is added to the soil to aid subsequent crop production and to add to percolation. At Webster Reservoir, the amount of baseflow into the reservoir appears to be higher than in 1951. Some of the water that did not leave as runoff is slowly seeping from the watershed and reaching the reservoir. Much more of the seepage water may be being used to satisfy ground-water withdrawals in the alluvial aquifers that are above the reservoir.

The impact of agriculture on available water resources for other uses above Webster Reservoir has been substantial. At the same time, however, the water that was lost previously has been converted into more production on the land where it fell. This fact is based upon yield of wheat on dryland in the Northwest Crop Reporting District, which

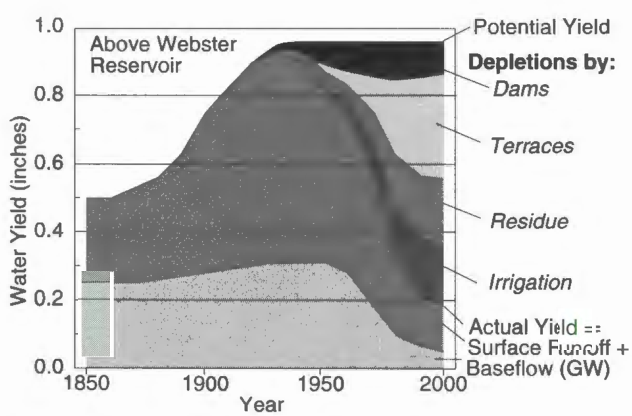

FIGURE 7.3—Historical perspective of the effect of agricultural technology on water yield above Webster Reservoir showing increases caused by conversion to cropland and depletions caused by various soil- and water-conservation practices and changes in agricultural technology (adapted from Koelliker, 1984).

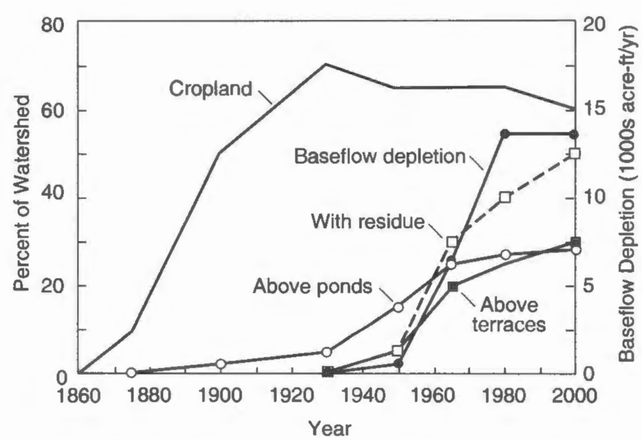

FIGURE 7.4—Historical amounts of cropland, conservation practices, and baseflow depletions in the South Fork Solomon Basin above Webster Reservoir (adapted from Koelliker, 1984).

includes the watershed above Webster Reservoir (fig. 7.6) (State Board of Agriculture, 1989, and previous). Wheat yields have increased steadily since the 1930's. This is the result of better agricultural technology, which includes better varieties, fertilizer and herbicides, and management practices. All of these factors, however, are benefitted by more available water. In this area, the USDA ARS estimates that about 40% of the total increase in agricultural production can be attributed to better water conservation.

There is a tradeoff here between more agricultural production on dryland and water resources available for users downstream. This work points out that the availability of water resources may not be constant over time. It will be necessary to make adjustments in water use so that the demand is more in line with the supply. As Robert Ingersoll, a 19th century orator from Kansas, stated, "In nature there are no rewards or punishments—there are consequences."

General Procedure to Estimate the Magnitude of Land-use Changes on Water Yield

Agriculture and agricultural land-use changes are affected by location in the state. The POTYLDR model has been used for several studies in Kansas, and from those general results, inferences can be drawn about the effects of agriculture on water resources in the state. One of the most important aspects that influences the magnitude of land-use changes is that the climate at a particular location can be described by the moisture deficit (MD). The MD is defined as the difference between the average annual lake evaporation and the average annual precipitation at a location. Figure 7.7 shows a map of the average in each county (DWR, 1994). There is a substantial difference in MD across the state (see also fig. 1.12 of Chapter 1). MD is greatest in the southwest corner of the state where lake evaporation is greatest and precipitation is near the lowest in the state. The MD is smallest along the eastern border of the state where lake evaporation is lowest and precipitation is more abundant. This variable is one that correlates well with many of the important effects that climate plays on agriculture. The greater the MD the more arid the climate while the lower the MD the more humid is the climate.

The greater the MD the greater the potential to reduce total runoff if the soil can hold the extra water that infiltrates it so that it will be lost later by evapotranspiration. As MD decreases, the potential of percolation increases because the soil cannot hold all of the water that infiltrates during extended wet periods. Soil type is important, particularly the soil's ability to store water that is available for later use by plants. Deep, silt-loam-type soils are best, whereas shallow, sandy-type soils are poorest for storing water. Crops, too, have an effect. Perennial crops and grass use the most water because they are actively growing during a longer portion of the year. Annual or summer crops use less because they are growing for a shorter period of the year. Fallowed soils do not use water, although water is lost from fallowed soil by evaporation. The least water loss is from fallow land with good crop-residue cover, provided no plants are allowed to grow. Protecting the soil surface on fallowed land with residue decreases runoff, decreases evaporation, and may increase the potential for percolation during wetter years.

Further, experience with the results from the POTYLD model for many locations in Kansas shows that its results are in general agreement with what is observed. The depth of the amount of reduction in surface runoff increases with decreasing MD where conservation practices are added. The effect, however, as a percentage

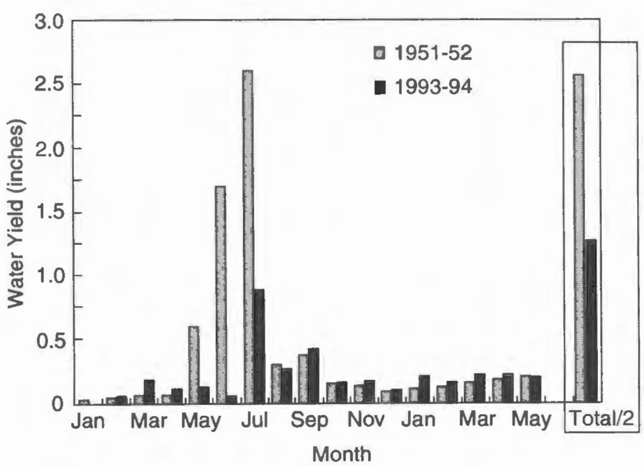

FIGURE 7.5—COMPARISON OF MONTHLY INFLOW TO WEBSTER RESERVOIR FOR THE FLOODS OF 1951 AND 1993.

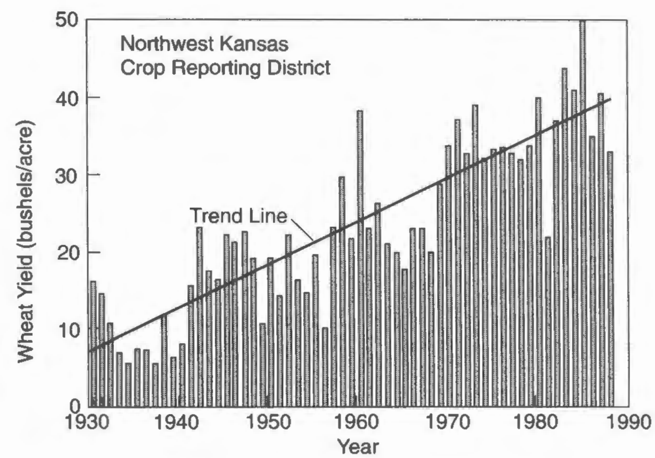

FIGURE 7.6—DRYLAND WHEAT YIELDS IN THE NORTHWEST KANSAS CROP REPORTING DISTRICT (data from Kansas State Board of Agriculture).

of total yield decreases as the MD decreases. With decreasing MD, more percolation results from conservation practices. Finally, the effect of conservation practices on total water yield is greatest in areas where the MD is moderate. To illustrate the effect of MD on water yield across Kansas, results of simulating a change in continuous wheat production caused by changing from a condition of little conservation practices to good conservation practices are discussed in Appendix 7.A. The change is expressed primarily in a decrease in the RCN by five and a slight increase in the residue factor that reduces the rate of surface evaporation. Figure 7.8 shows how the general amount of total water yield (surface runoff + percolation), decrease in surface-runoff, increase in percolation, and the total decrease in water yield are affected by the MD. The reader is cautioned to notice that the "average annual" is a log scale in fig. 7.8. In areas where the MD is high, most of the surface runoff prevented by better conservation practices because of more infiltration is stored as soil moisture which is subsequently lost as evapotranspiration because the climatic demand for water is large. With moderate amounts of MD, a larger amount of water yield occurs because there is more potential surface runoff to affect. Some increase in percolation results because not all of the extra water can be stored in the soil during wetter periods. In areas where the MD is low, runoff is still reduced, but nearly all of the extra water that enters the soil becomes percolation. Here, the ability of the atmosphere to increase evapotranspiration during wet periods is insufficient to cause much of the additional water that does not become surface runoff to become evaporation. Also, practices that are effective at reducing runoff require residue cover on the surface. The residue cover also decreases evaporation from the soil. Thus, the total amount of water yield is affected very little in areas where the MD is low. In some cases, water yield may actually be increased in eastern Kansas, particularly during wet periods because evaporation is decreased. In eastern Kansas, if water is not lost by evapotranspiration, it will eventually become streamflow. There is just not enough storage in the soil to hold all of it for later use.

When the maximum potential for agricultural soil- and water-conservation practices to reduce surface runoff are added together they can have a substantial effect. Figure 7.9 shows a generalized map of these aggregate effects to reduce runoff from the amounts of streamflow that were reported for conditions around 1930. By the late 1990's, a substantial amount of these effects of agriculture are occurring. The numbers on fig. 7.9 show the percent reductions that were experienced during the 1980's for various locations in western Kansas.

The above information is for one set of conditions described previously. Results for a wide variety of land uses and conservation practices found across Kansas have been produced with POTYLDR by making simulations at five locations (Koelliker, 1994a). Predicted average annual depth of runoff and percolation are included in table 7.1 from the representative RCN value for a Soil Conservation Service Group B/C soil (silt loam soil). For all locations, the same planting and harvest date for row crops (grain sorghum, May 10 and October 15) and small grain (winter wheat, October 10 and June 25) were used. The fallow shown is for a combination of wheat-fallow rotation with the wheat having an RCN equivalent to the small grain practice shown earlier in the table. Pasture/range growing season was March 15 through October 31. These results can be generalized to other locations by relating the values to the MD at a particular location. The MD for three of the locations (Horton, Great Bend, and Garden City) were adjusted somewhat because the stations have more or less annual precipitation than is typical for the MD each one was most representative of across the state. Figure 7.10 shows there is a general relationship

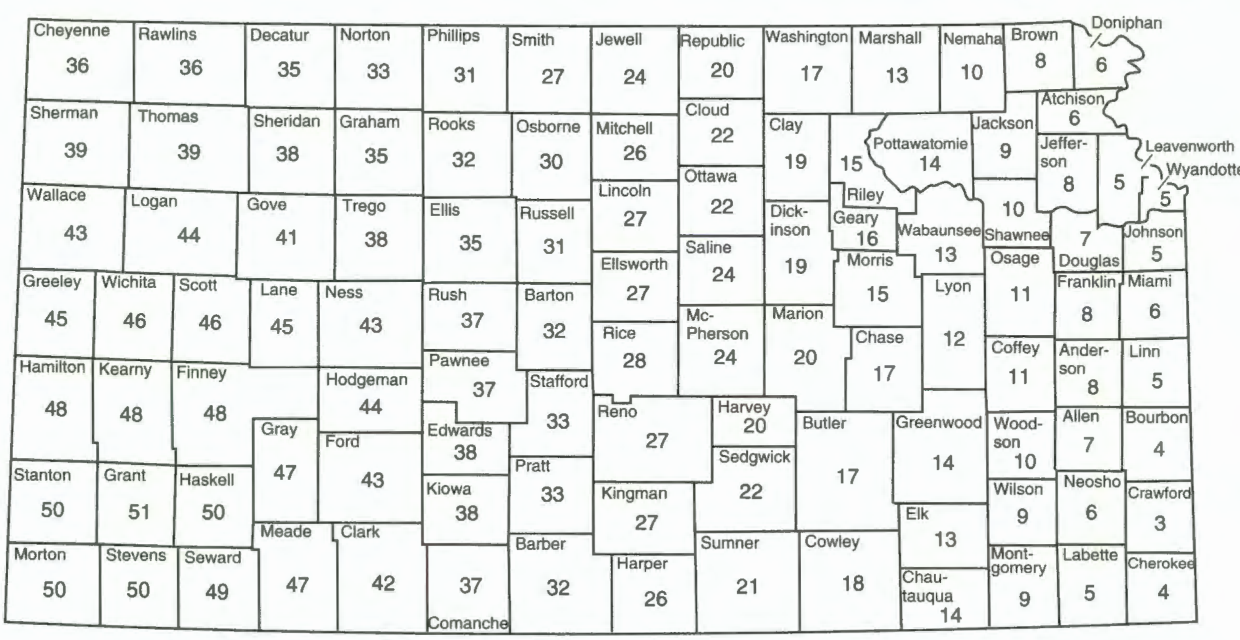

FIGURE 7.7—POTENTIAL NET EVAPORATION FOR KANSAS COUNTIES (Division of Water Resources, 1994).

between runoff and percolation and the adjusted MD across the range of conditions simulated. The transmission loss factor (*TLF*) is the ratio of runoff estimated upstream to the amount of runoff actually measured at a gaging station downstream. If the value of the *TLF* at each location as shown for each station in table 7.1 is used along with the amount of runoff shown in table 7.1, then the estimated effect of an agricultural practice change on surface streamflow can be calculated by dividing the runoff by the *TLF*.

With the values in table 7.1, it is possible to compare the effect of a change in land use and/or conservation practice from one condition to another condition and to estimate the effect on long-term average amount of runoff and percolation. Consider the effects of changing from an initial land use of annual cropping with row crops with straight row conservation practice (line 1 in table 7.1) to a second condition of pasture/range (line 29) that might result if highly erodible cropland were placed into the Conservation Reserve Program at Great Bend. Predicted average annual runoff for initial conditions, *I*, is 3.19 inches (81 mm) and for final conditions, *F*, is 1.52 inches (39 mm). Essentially no change in percolation is expected. The *TLF* is 1.15 for Great Bend. Further, consider if 4.0% (*P*) of the watershed were to be changed. To estimate the decrease in average annual water yield (*Y*) use,

$$Y = (I - F) \cdot P / (TLF \cdot 100) \qquad \text{(eq. 7.1)}$$

The result is, $Y = 0.06$ inches (1.5 mm). At Great Bend, water yield averages about 1.5 inches/year (38 mm/year). So, total water yield would be reduced by about 4%.

As agriculture developed, much pasture/range was converted to cropland and later conservation practices were added to cropland to reduce erosion and/or to improve moisture conservation. The impact of these changes depends upon the amount of the watershed affected and the magnitude of the change in runoff. Figure 7.11 shows a comparison of surface-water yield from small grain production with various conservation practices to the surface-water yield from pasture/range across the amounts of MD found in Kansas. Straight row was the earliest agricultural practice. Later, contouring and conservation tillage or residue management were added along with terraces as conservation practices. The line "Best Management Practice" includes the applicable type of terrace, conservation tillage, and contouring at each of the five locations simulated. The graph shows that the amount of surface runoff from small grain production can be reduced to that expected from pasture/range across Kansas with good management.

The effect of conservation practices on reducing runoff as a percent of the total water yield increases with increasing MD. When MD = 15 inches (38 cm) as found in eastern Kansas, the reduction from straight row to best management practice is about 30%. With MD = 40 inches (100 cm) as is the case in most of the western half of Kansas, the reduction in water yield is about 60%, similar to the results shown in fig. 7.9.

In summary, this section shows that effects of conservation practices and land-use changes in Kansas on water yield can be substantial, particularly in areas where the MD is large. Conservation practices have the ability to hold much of the potential runoff, which is then lost as evapotranspiration. These practices are most effective during drier years when streamflow is limited, which further aggravates the problem of allocating limited water resources to other users. The simulation method described in this chapter provides a way to determine the magnitude of these effects on a continuous basis so that effects with time on water yield and water availability can be evaluated. Other measures such as watershed projects and irrigation withdrawals from alluvial aquifers along streams add further to potential depletions of streamflow. The impact on ground-water recharge is positive in the central portion of the state where several good aquifers store and transmit the additional water to potential ground-water users. In eastern Kansas where the potential to increase percolation is even better, there is limited opportunity to

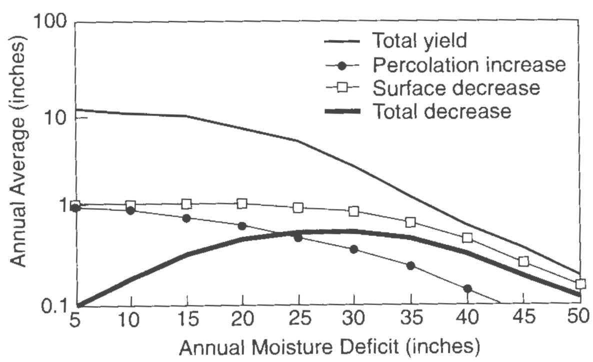

FIGURE 7.8—SIMULATED EFFECTS ON ASPECTS OF THE WATER BUDGET WHEN THE RCN VALUE FOR CONTINUOUS WHEAT IS REDUCED FROM 75 TO 70 ON A SILT LOAM SOIL AS RELATED TO THE MD ACROSS KANSAS.

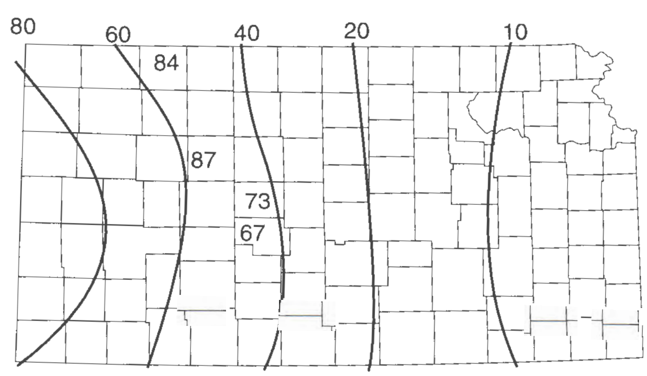

FIGURE 7.9—GENERALIZED POTENTIAL OF SOIL AND WATER CONSERVATION PRACTICES AND AGRICULTURAL TECHNOLOGY TO REDUCE STREAMFLOW BELOW THE AMOUNT MEASURED IN THE 1930–1950 PERIOD, BY PERCENT.

TABLE 7.1—Simulated results from POTYLDR for average annual runoff and percolation, in inches, for various land uses and conservation practices (Koelliker, 1994b).

LOCATION	HORTON	MANHATTAN	GREAT BEND	COLBY	GARDEN CITY
Period of record simulated	1935–1975	1958–1986	1948–1988	1940–1980	1948–1988
Lake evaporation inches	48.90	51.13	61.47	55.65	64.03
Precipitation, inches	35.60	32.89	25.54	19.31	17.97
Moisture deficit, inches	13.30	18.24	35.93	36.34	46.06
Adjusted moisture deficit, inches	15.30	18.24	28.93	36.84	42.86
Transmission-loss factor	1.02	1.03	1.15	1.25	1.43

No. Land use	Conservation practice	RCN AMC II	Runoff	Perc.	Runoff	Perc.	Runoff	Perc.	Runoff	Perc.	Runoff	Perc.
1. row crops	straight row	81	7.61	2.39	6.37	1.17	3.19	0.07	1.92	0.02	1.27	0.00
2. row crops	contoured	78	6.24	3.73	5.19	2.20	2.54	0.28	1.55	0.07	0.99	0.03
3. row crops	level terrace	74	n/a	n/a	n/a	n/a	1.97	0.55	1.20	0.14	0.74	0.05
4. row crops	lev. terr., cl.-end	64	n/a	n/a	n/a	n/a	n/a	n/a	0.57	0.42	0.30	0.14
5. row crops	conserv. tillage	77	5.81	4.63	4.86	2.90	2.39	0.52	1.45	0.11	0.95	0.04
6. 2	graded terrace	75	5.19	4.97	4.30	3.19	2.04	0.58	1.27	0.14	0.79	0.05
7. 2 + 3		72	n/a	n/a	n/a	3.88	1.61	0.82	1.01	0.23	0.60	0.07
8. 2 + 4		62	n/a	n/a	n/a	n/a	n/a	n/a	0.46	0.50	0.23	0.18
9. 2 + 5		75	5.24	5.19	4.38	3.36	2.11	0.67	1.28	0.15	0.82	0.05
10. 2 + 3 + 5		70	n/a	n/a	n/a	n/a	1.46	1.05	0.90	0.29	0.54	0.09
11. 2 + 4 + 5		61	n/a	n/a	n/a	n/a	n/a	n/a	0.43	0.55	0.21	0.22
12. 6 + 5		74	5.16	5.28	4.29	3.43	2.04	0.71	1.24	0.16	0.80	0.05
13. 1 +	irrigated	81	9/05	4.58	8.09	3.26	4.78	0.86	3.15	0.41	2.50	0.09
14. 1 + 5 +	irrigated	77	6.78	6.93	6.14	5.23	3.56	1.65	2.31	0.80	1.81	0.35
15. small grain	straight row	78	6.08	3.80	4.87	2.34	2.33	0.18	1.36	0.03	0.90	0.02
16. small grain	contoured	75	5.03	5.01	4.00	3.31	1.88	0.44	1.10	0.14	0.71	0.04
17. small grain	level terrace	71	n/a	n/a	n/a	n/a	1.44	0.74	0.85	0.29	0.51	0.06
18. small grain	lev. terr., cl. end	63	n/a	n/a	n/a	n/a	n/a	n/a	0.45	0.56	0.23	0.17
19. small grain	conserv. tillage	74	5.03	5.55	3.99	3.74	1.90	0.60	1.15	0.24	0.72	0.04
20. 16	graded terrace	74	4.98	5.39	3.92	3.61	1.84	0.56	1.09	0.22	0.68	0.04
21. 16 + 17		70	n/a	n/a	n/a	n/a	1.32	0.90	0.78	0.39	0.46	0.08
22. 16 + 18		60	n/a	n/a	n/a	n/a	n/a	n/a	0.39	0.65	0.19	0.18
23. 16 + 19		74	5.04	5.60	4.08	3.78	1.91	0.62	1.15	0.25	0.72	0.04
24. 16 + 17 + 19		68	n/a	n/a	n/a	n/a	1.19	1.08	0.73	0.50	0.42	0.12
25. 16 + 18 + 19		59	n/a	n/a	n/a	n/a	n/a	n/a	0.36	0.78	0.17	0.23
26. 20 + 19		71	4.16	6.46	3.26	4.47	1.52	0.86	0.92	0.39	0.55	0.08
27. 15 +	irrigated	78	6.84	6.02	5.77	4.49	3.25	1.79	2.06	1.17	1.57	0.54
28. 15 + 19 +	irrigated	74	5.54	7.43	4.69	5.70	2.56	2.33	1.65	1.54	1.21	0.83
29. pasture/range		75	4.53	2.57	3.51	1.07	1.52	0.06	0.81	0.00	0.46	0.00
30. 29	improved	70	3.38	3.78	2.54	1.93	1.07	0.18	0.56	0.01	0.30	0.00
31. hay (alfalfa)		76	4.61	1.74	3.54	0.56	1.53	0.02	0.80	0.00	0.48	0.00
32. 31 + irrigated		76	6.58	4.76	5.52	3.31	3.42	0.98	1.94	0.73	1.76	0.21
33. fallow-wheat	straight row	86	n/a	n/a	n/a	n/a	3.69	0.72	2.37	0.25	1.70	0.04
34. fallow-wheat	contoured	83	n/a	n/a	n/a	n/a	3.01	1.26	1.92	0.52	1.35	0.13
35. fallow-wheat	level terrace	79	n/a	n/a	n/a	n/a	2.28	1.92	1.46	0.90	0.96	0.29
36. fall.-wheat	lev. terr., cl. end	68	n/a	n/a	n/a	n/a	n/a	n/a	0.71	1.54	0.38	0.72
37. fall.-wheat	conserv. tillage	81	n/a	n/a	n/a	n/a	2.94	1.74	1.87	0.81	1.29	0.24
38. 34	graded terrace	80	n/a	n/a	n/a	n/a	2.59	1.71	1.65	0.79	1.10	0.22
39. 34 + 35		77	n/a	n/a	n/a	n/a	1.94	2.25	1.27	1.10	0.81	0.42
40. 34 + 36		67	n/a	n/a	n/a	n/a	n/a	n/a	0.63	1.64	0.33	0.78
41. 34 + 37		79	n/a	n/a	n/a	n/a	2.72	1.94	1.73	0.93	1.18	0.31
42. 34 + 35 + 37		75	n/a	n/a	n/a	n/a	1.85	2.76	1.19	1.37	0.75	0.61
43. 34 + 36 + 37		66	n/a	n/a	n/a	n/a	n/a	n/a	0.61	1.89	0.31	0.96
44. 38 + 37		79	n/a	n/a	n/a	n/a	2.47	2.17	1.59	1.06	1.06	0.40

Notes: Soil is silt loam which fits SCS hydrologic group B/C and SCS Irrigation Class 3; unless noted otherwise, good hydrologic condition assumed.

make the additional percolation become usable ground water. It may seep out gradually to enhance the dry weather flow for a few weeks following wet periods.

The procedure described to estimate change in the surface runoff portion of water yield has been studied more intensely than that for percolation and the potential for ground-water recharge from such percolation. The operation of POTYLD, however, also estimates the amount of percolation as shown in fig. 7.7. An aspect of recharge that is important to understand when considering sustainable yield is that for many locations, particularly in drier areas, recharge occurs infrequently. The section following in the inset Boxed section 7.1 illustrates this phenomenon.

Conclusion

Agriculture has made substantial changes to the land use in Kansas for more than 150 years. Sustainable crop production by agriculture without irrigation, in large part, has been a matter of developing management practices that increase the effectiveness of use of the limited water supply and that protect the soil resource from excessive erosion. Adoption of conservation practices that decrease runoff and reduce evaporation losses have been important. In much of the state, the effectiveness of these practices has resulted in more efficient use of water for grain and forage production. Since water use by agriculture is a consumptive use that results in evaporation of water from the land surface, more effective use means that less water is left to become runoff or potential ground-water recharge. In the western half of the state, in particular, streamflow has been reduced from the amounts measured before about 1950 by a combination of agricultural practices including withdrawal of ground water for irrigation along streams. Reductions of streamflow by as much as 50% or more have been experienced. In the eastern half of the state, the effect has been limited because of the difference in climatic conditions. As ways to use water more efficiently are developed and adopted for Kansas conditions, this means less for nonagricultural uses, particularly in the drier regions of the state. In the future these effects will probably result in a further decrease in the amount of water available for appropriation by other users.

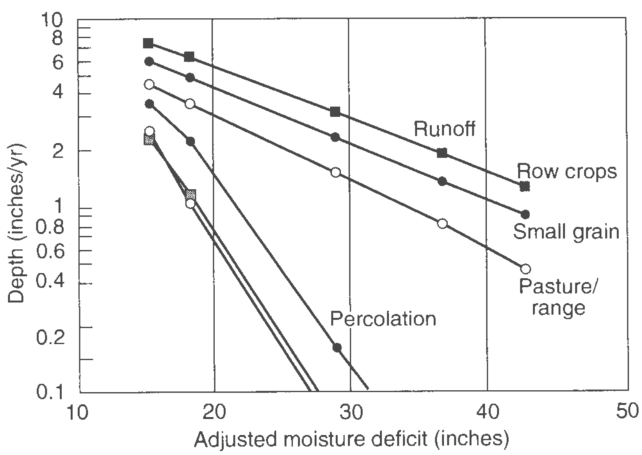

FIGURE 7.10—Simulated average annual depth of runoff and percolation from row crops and small-grain production with straight-row conservation practice compared with pasture/range as affected by moisture deficit (Koelliker, 1994b).

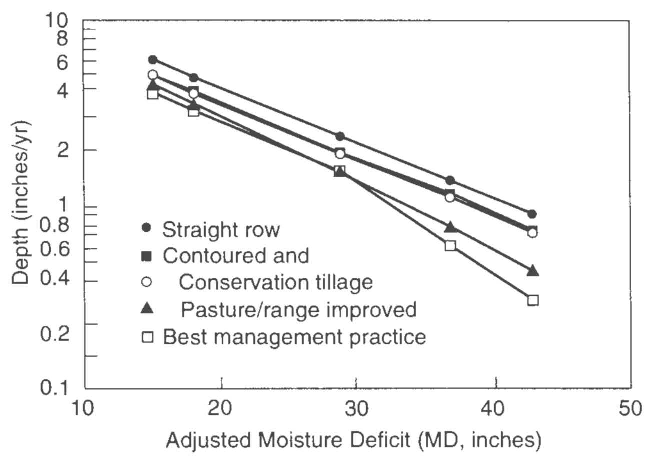

FIGURE 7.11—Comparison of simulated average annual runoff from small-grain production with various conservation practices to pasture/range as affected by moisture deficit (Koelliker, 1994b).

Boxed section 7.1: Event Nature of Percolation or Potential Recharge

Under average conditions, evapotranspiration demand for water exceeds that supplied by precipitation. So, on average the soil should not become so saturated with water that percolation occurs. Average conditions, however, seldom occur in the continental climate that prevails in Kansas (see also Chapter 1). There are periodic episodes when drought and wet periods occur. Much of the percolation that results in ground-water recharge occurs in extended wet periods.

To illustrate this point, a 44-year simulation for Great Bend was made with POTYLDR. Great Bend (MD = 35 inches [89 cm]) is representative of that part of the state where agricultural practices have important effects on water yield, and aquifers benefit from increase in percolation. Representative RCN values for a Soil Conservation Service Group B/C soil (silt loam soil) for Great Bend are shown in table B7.1.1. The planting and harvest date for grain sorghum were May 10 and October 15, respectively, and for winter wheat they were October 10 and June 25, respectively. The results of the conditions simulated for Great Bend produced average amounts of runoff and percolation as shown in table B7.1.1. Percolation or recharge is least from pasture/range which has a long growing season and is greatest from irrigated crops.

TABLE B7.1.1—SIMULATED RESULTS FROM POTYLDR FOR AVERAGE ANNUAL RUNOFF AND PERCOLATION, IN INCHES, FOR VARIOUS LAND USES AT GREAT BEND ON A SILT LOAM SOIL.

Land use	Predicted annual average, inches Runoff	Percolation
pasture/range, good condition	1.1	0.2
pasture/range, fair condition	1.5	0.1
continuous wheat	1.8	1.2
wheat-fallow	2.5	2.6
irrigated wheat	2.5	3.6
grain sorghum, conventional	2.3	0.4
grain sorghum, conservation tillage	2.1	0.7
irrigated grain sorghum	3.2	2.2

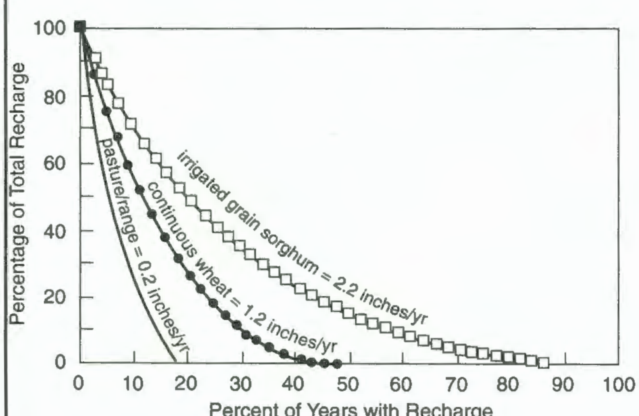

FIGURE B7.1.1—SUMMARY OF SIMULATED PERCENT OF ACCUMULATED PERCOLATION FROM THREE LAND USES AT GREAT BEND ON A SILT LOAM SOIL VERSUS THE PERCENT OF YEARS WITH PERCOLATION.

Here, the average amount of net irrigation water applied to the soil in 2.0-inch (5-cm) increments when the available soil moisture decreased to 50% was 9.0 inches (23 cm) and 13.0 inches (33 cm) for wheat and grain sorghum, respectively.

Figure B7.1.1 was prepared from the annual results from three of the simulations to show the distribution of percent of years with percolation within the simulation period for three of the land uses. For pasture/range in good condition, recharge was estimated to occur in less than 20% of the years and half of the recharge occurred in less than 5% of the years. For continuous wheat, recharge was predicted to occur in less than half of the years and half of the total occurred in about one year in eight on average. Irrigated grain sorghum showed some recharge in about seven out of eight years; however, half of the total recharge occurred in about one year out of five. The example above is for one location only. Where recharge is most needed in western Kansas, the climate has a greater moisture deficit. There, recharge is even less than for the example above, and more of the recharge occurs in a lower percentage of the years. While runoff events are rather widely spaced in time, recharge events are even more widely spaced in time. Providing a sustainable yield from an aquifer that must be periodically replenished, the event nature of recharge must be taken into account. The time between years with recharge for the Great Bend example for pasture/range is illustrated in fig. B7.1.2. Here, three periods with lengths of eight years or longer between recharge events were predicted in the 44-year simulation for the range/pasture land use.

Sustainable yield from ground water must include estimates of total recharge as an upper limit as well as the distribution of recharge in time and space over the aquifer. Using average annual values is risky, especially if the storage capacity of the aquifer is limited.

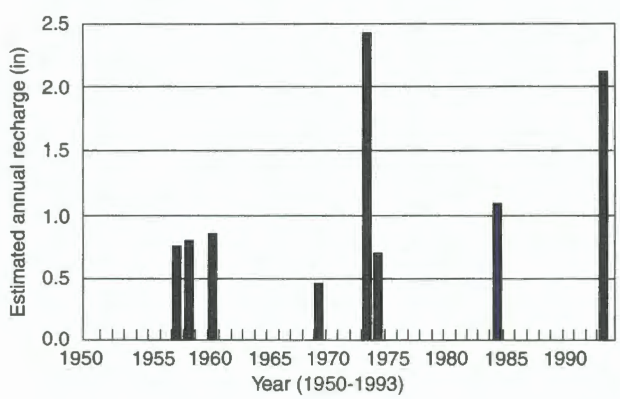

FIGURE B7.1.2—SUMMARY OF PREDICTED ANNUAL AMOUNT OF RECHARGE (PERCOLATION) FROM RANGE/PASTURE AT GREAT BEND ON A SILT LOAM SOIL.

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Appendix 7.A

POTYLD MODEL DESCRIPTION

Continuous watershed-simulation modeling was common by the mid-1970's. Zovne et al. (1977) developed a continuous water-budget simulation model that worked on daily time steps for use in assessing the performance of open feedlots to control runoff from feedlots. The model predicted runoff from the feedlot drainage area, operation of a storage pond, and water budgets for various land areas where the runoff was applied according to some management scheme. The model utilized runoff curve numbers (RCN) values to predict the split between runoff and infiltration for the feedlot and areas where runoff was applied to daily amounts of rainfall and snowmelt (See Chapter 1 for more information on RCN values). The model named

FROMKSU was designed to be physically based, to use readily available information to describe conditions in an area of interest, and to be capable of being applied anywhere in the continental U.S. Its detailed description is contained in Zovne and Koelliker (1979).

The Potential Yield (POTYLD) model simulates a continuous water budget for land uses with different conditions in a watershed on a daily basis (see fig. 7.A1). Up to 18 different land-use combinations can be simulated in one run of the model. Estimates of the upstream runoff and percolation that would result from various land uses and conservation practices are provided. A RCN value for antecedent moisture condition (AMC) II is needed for each land use and conservation practice based upon soil characteristics, land cover, conservation practice, and management practice. Soil characteristics are assumed to fall into one of 12 irrigation group classifications for Kansas (USDA–SCS, 1975), which define the water-holding characteristics of the soil layers and soil-water evaporation characteristics. A continuous water-budget simulation produces estimates of water content in the soil. AMC values are adjusted based upon available soil moisture (ASM) in the upper 1.0 ft (30 cm). AMC I holds below 50% ASM, AMC III holds above 90% ASM, and AMC II holds in the intermediate range of ASM.

The water budget is driven by daily precipitation and minimum and maximum temperature for a single station representative of the area under study. Large areas are divided into sub-areas which are modeled separately, then combined for better representation of the entire watershed. Long-term monthly average values of percent sunshine, relative humidity, solar radiation, windrun, and average temperature are used to estimate potential evapotranspiration (PET) by the Penman combination equation after Gray (1973). Long-term monthly values are obtained by triangulation from published values for first-order weather stations (Water Information Center, 1974). Geographical coefficients, Brunt a and b (Brunt, 1944) are used to calibrate Penman's PET such that predicted average annual lake evaporation at a location agrees with published values (Zovne and Koelliker, 1979). Actual water use by crops is simulated by multiplying daily PET by a monthly Blaney–Criddle crop coefficient (Blaney and Criddle, 1962) and a coefficient based upon ASM.

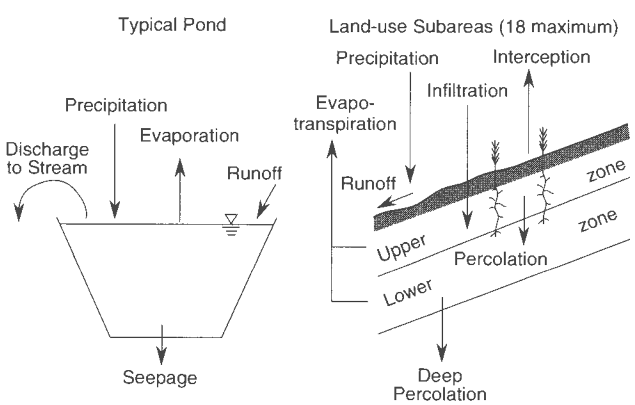

FIGURE 7.A1—SCHEMATIC OF POTYLD WATER-BUDGET MODEL (adapted from Zovne and Koelliker, 1979).

The crop coefficients are calculated by pre-programmed equations in the program which require the user to provide planting and harvest dates. The soil-moisture coefficient is 1.0 for ASM greater than 30%; below 30% it decreases linearly to zero when ASM is zero. When crops are not growing, bare soil and fallow water loss is simulated by a decay-rate equation (Ritchie, 1972) and adjusted for assumed amount of surface residue. Water loss by percolation from the rooting zone is assumed to cascade from the lower layer whenever the ASM in the lower zone exceeds 90%. POTYLD simulates the complete daily water budget for a "typical" pond. The pond is defined by assigning a stage-storage and stage-surface area relationship along with a seepage loss rate. The model treats the pond as an inverted frustum of a pyramid which can match most actual relationships fairly well. Runoff into the typical pond is determined by routing runoff from specified areas of the various land-use subareas which would be typical of the drainage area for a pond in the particular study area. Modeled results of predicted depletions of surface water caused by ponds have compared closely with depletion effects described by Sauer and Masch (1969) for watershed flood-control dams in Texas. Figure 7.A2 shows the general relationship from Sauer and Masch and the average results found for typical ponds above Webster Reservoir (Koelliker et al., 1981).

Substantial revisions have been made to the model and the name changed to POTYLD (Revised) (Koelliker, 1994a, 1994b). Enhancements to the PET routine to reflect greater daily and annual variation based upon daily minimum and maximum temperature and a function to simulate annual variation in heat storage and dissipation at the surface have been made. Also, RCN between AMC I and AMC III is varied linearly with ASM between 50 and 90%. AMC II holds when ASM is 70%.

COMPARING MODEL RESULTS WITH ACTUAL STREAMFLOW

Results from POTYLD must be adjusted by estimates of transmission losses and the effects of depletion from or additions to streamflow in order to compare with actual streamflow records. In addition, because agricultural effects on upstream yield are changing with time, changes must be accounted for in output from POTYLD by making successive runs with the inputs that represent conditions applicable over the period of the streamflow record. Once all of these changes are accounted for, then modeled results can be compared directly with reported streamflow records.

Transmission loss refers to the ratio of annual volume of upstream runoff to downstream streamflow. It accounts for natural losses caused by infiltration, evaporation, and detention storage. The value of the transmission loss factor (*TLF*) was originally predicted by a technique developed by Sharp et al. (1966). This loss is related to the ratio of PET (Thornthwaite's values) to annual amount of precipitation. Our work shows that annual moisture deficit (MD), defined as lake evaporation minus precipitation, is an effective characteristic of the climate that can be used estimate the *TLF* (Koelliker et al., 1995). In dry years when runoff is low and MD is higher, the *TLF* is larger and in wet years when MD is lower *TLF* approaches 1.0 as shown in Figure 7.A3.

Finally, estimates of depletions or additions to streamflow from ground-water use, importation, exportation, return flows, etc. must be accounted for to compare POTYLD modified results with reported streamflow records.

Average MD for each county (DWR, 1994) is shown in fig. 7.7. There is a substantial difference in MD across the state. MD is greatest in the southwest corner of the state where lake evaporation is greatest and precipitation is near the lowest in the state. MD is lowest in the far eastern part of the state where lake evaporation is lowest and precipitation is more abundant. This variable is one that correlates well with many of the important effects that climate plays on agriculture. The greater the MD the more arid the climate while the lower the MD the more humid is the climate. In Kansas this helps explain why northeast Kansas is in the western end of the Corn Belt even though it receives less precipitation than southeastern Kansas which has a larger MD than the northeast. Predicted effects of land use and conservation practices on water yield based upon MD are shown in table 7.1.

Results from POTYLD for an entire watershed provide evidence that various practices and land use effects when aggregated together are useful to assess or estimate combined effects of individual practices. When the model, FROMKSU, was used to study feedlots in different parts of the United States, it was noted that the water yield from the runoff disposal areas using published RCN values (USDA, SCS, 1972) generally agreed reasonably well with values reported for streamflow. In more arid areas, however, water yield was overestimated as expected because transmission losses and effects of ground-water withdrawals have important effects on streamflow. This provided reasonable confidence it the applicability of RCN values to larger watersheds. When POTYLD was developed, however, RCN values were not available to account for levels of residue management, particularly on wheat-fallow. Work reported by Rawls et al. (1980) on effects of residue and tillage on RCN values was influential for predicting how much RCN values for important practices in the area could be reduced when residue management was used. Field simulations in the area were run by Steichen (1983) and those results substantially agreed with predicted amounts that RCN values could be reduced as predicted by Rawls et al. (1980). Finally, field data for runoff from bare fallow and stubble mulch were available for Alliance, Nebraska (Fenster et al., 1977). Those results were simulated with POTYLD and showed the RCN value for stubble mulch with good residue management was six less (73 vs. 79) than for bare fallow on the same soil (Koelliker et al. 1981).

The reference list at the end of Chapter 7 contains several references to work where POTYLD has been used. Also, a copy of the user's manual, computer code, and diskettes are available from the author.

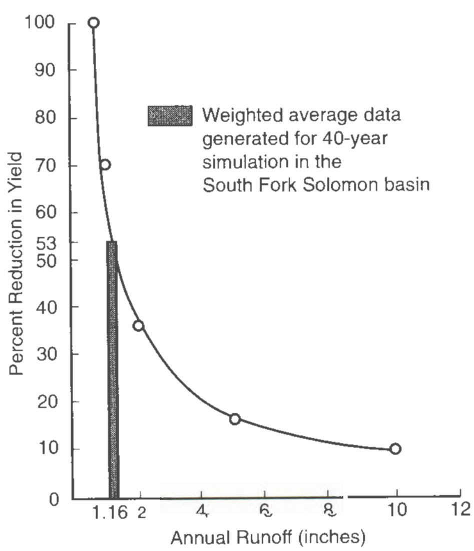

FIGURE 7.A2—FUNCTION OF PERCENT REDUCTION IN WATERSHED YIELD DUE TO PONDS AS A FUNCTION OF ANNUAL RUNOFF IN THE WATERSHED.

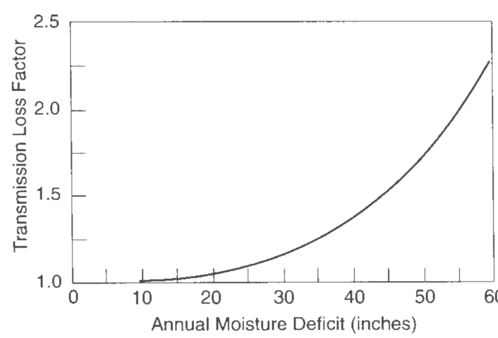

FIGURE 7.A3—TRANSMISSION LOSS FACTOR FOR REDUCING UPSTREAM RUNOFF TO COMPARE WITH MEASURED RUNOFF AT A DOWNSTREAM STREAMFLOW GAGING STATION [adapted by Koelliker et al. (1995) from Sharp et al. (1966)].

CHAPTER 8

Climate Change and Sustainable Water Yield

Robert W. Buddemeier

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Climate Change and Sustainable Water Yield

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Introduction

Other chapters of this book describe some of the complexities that underlie the apparently simple terms "safe yield" and "sustainable yield." Although these can be defined with the seemingly authoritative rigor of equations based on hydrologic balance, the definition and interpretation of the terms of the equation quickly become dependent on less precise and more problematic human values—risk assessment and acceptance, relative valuation of diverse shared resources, and cultural expectations concerning decision-making and conflict resolution.

Even if some agreement on values and goals can be reached, the technical basis for determination of "safe yield" is not simple. At the most fundamental level, it depends on the assumption of basic stability in the larger features of the hydrologic cycle: long-term consistency of water input in the form of precipitation and the flow of surface water and ground water, and of the factors such as temperature, wind, and sunlight that control evaporation and transpiration. We may not know the natural patterns and quantities well enough, they may be uncomfortably variable, and human activities (such as land use and water development) may alter local or regional aspects of the hydrologic system. Nevertheless, if the basic natural patterns are stable we can hope to learn what they are, to compensate for their variability, and to enhance beneficial human effects and control or reverse the undesirable ones.

The purposes of this chapter are to examine and to challenge the comfortable assumption of underlying stability in the hydrologic cycle. Water flux—the rates, patterns, and distribution of evaporation, precipitation, runoff, and recharge—is a key component of what we call climate. We know that climate is subject to both natural and human-induced changes on various scales. Past climate changes can complicate modern water-budget calculations if present ground-water reserves are the result of past periods of much higher net recharge; much of the water in the Ogallala aquifer probably represents such an accumulation during periods of cooler, wetter climate (see chapter 1 on Kansas water resources).

Although past climate changes can combine with modern withdrawal practices to produce present concerns about "mining ground water," the major focus of this chapter is on the probable consequences of future and presently occurring climate change. The local and regional hydrologic effects of global changes cannot be reversed or stabilized at a local level: adaptation is the only near-term management option. Such adaptation will almost certainly require reconsideration of the concepts, as well as the present water quantities, associated with "safe yield" and ideas of sustainability.

Climate, History, and Hydrology

Many definitions of "climate" are possible, but from a practical, quantitative standpoint, climate is 30 years worth of weather. The U.S. National Weather Service (NWS) uses the data from its network of climatological stations to prepare "30-year norms" at 10-year intervals, and these compiled statistics on weather/climate parameters are commonly used as representative of long-term average behavior. Such data—on rain, snow, temperature, and streamflow—are available for most of the developed world for a period of many decades to over a century. These form the engineering basis for such practical applications as reservoir design and water-rights appropriations.

Figure 8.1 shows examples of some of the key climate variables for Kansas. Average annual precipitation tells us something about the total water availability, summer mean temperature suggests patterns of drying and evaporation, and the difference between precipitation and potential evaporation addresses directly the major controls on the average aridity of regions within the state.

Yet farmers, highway crews, and hydrologists all know that there is more to climate than average weather. Observations taken on the scale of counties and averaged over days, months, or years do not adequately capture the hydrologic effects of intense local thunderstorms, or the complex time-sequence of weather conditions that causes greatly enhanced runoff over saturated or frozen ground. Over longer time scales our data base is inadequate to do more than hint at the frequency with which we might expect a recurrence of the Dust Bowl of the 1930's, the great El Niño of 1982–83, or the Mississippi Valley floods of 1993. This critical information is calculated, almost always on the basis of assumptions that the observed climate means and variabilities are stable and a reliable guide to the future (see Chapter 1 on Kansas water resources, and Chapter 9 on statistics and variability).

Over these longer time scales and over regions where human instrumental records do not exist, we rely on other human observations and historical records, and on inferences about the present and past controls on biology and other natural processes that leave records behind—in sediment or soil formation, in tree rings or pollen deposits, or in the isotopes and trace element ratios of natural products. To test our assumptions and understanding of the past and present, and to make predictions of the future, we rely upon models—ranging from simple conceptual analogies to computer simulations of complex physical and chemical processes.

A broad classification scheme for climate has emerged from biogeography and ecology. Ecologically based climate zones, based on large-scale ecosystem classifications (biomes), represent an operational approach to defining the climate of a region by the characteristics of its plant communities. Although somewhat less precise and quantitative than numbers derived from instrumental data, biotic climate zones of the past can be inferred from paleoenvironmental records. Their present distribution has the advantage of focusing attention on an issue of prime concern to humans: the amount and nature of the real or potential productivity of the land, and its climatic controls.

Humans have an understandable tendency to think of natural climate change as something slow and distant—woolly mammoths and cave men are unimaginably far removed from the video store and the coffee shop. In part this is due to the historical accident of our position on top of an unusually long and stable climatic plateau (see Boxed section 8.2). Yet even within this period of relative stability there have been major variations. The prairies have been dominated by grasslands for thousands of years, yet in historical times the Norsemen colonized Greenland (ca. 985 AD) during a period of mild climate known as the Medieval Warm Period, and were frozen out in the mid-15th century by the onset of a protracted cold period called the Little Ice Age. In the late 19th century, settlement of the Plains experienced "booms" in wet periods and "busts" (economic depressions) caused by multi-year droughts (Shortridge, 1995); droughts, floods, and temperature extremes persist in the news in the present decade. It is a stock inter-generational joke that winters were always colder when the older people were young—but sometimes it is true. As concerns about human alteration of climate have caused us to look more closely at both past and present environments, we are finding ever more evidence for changes more rapid and more extreme than we have assumed.

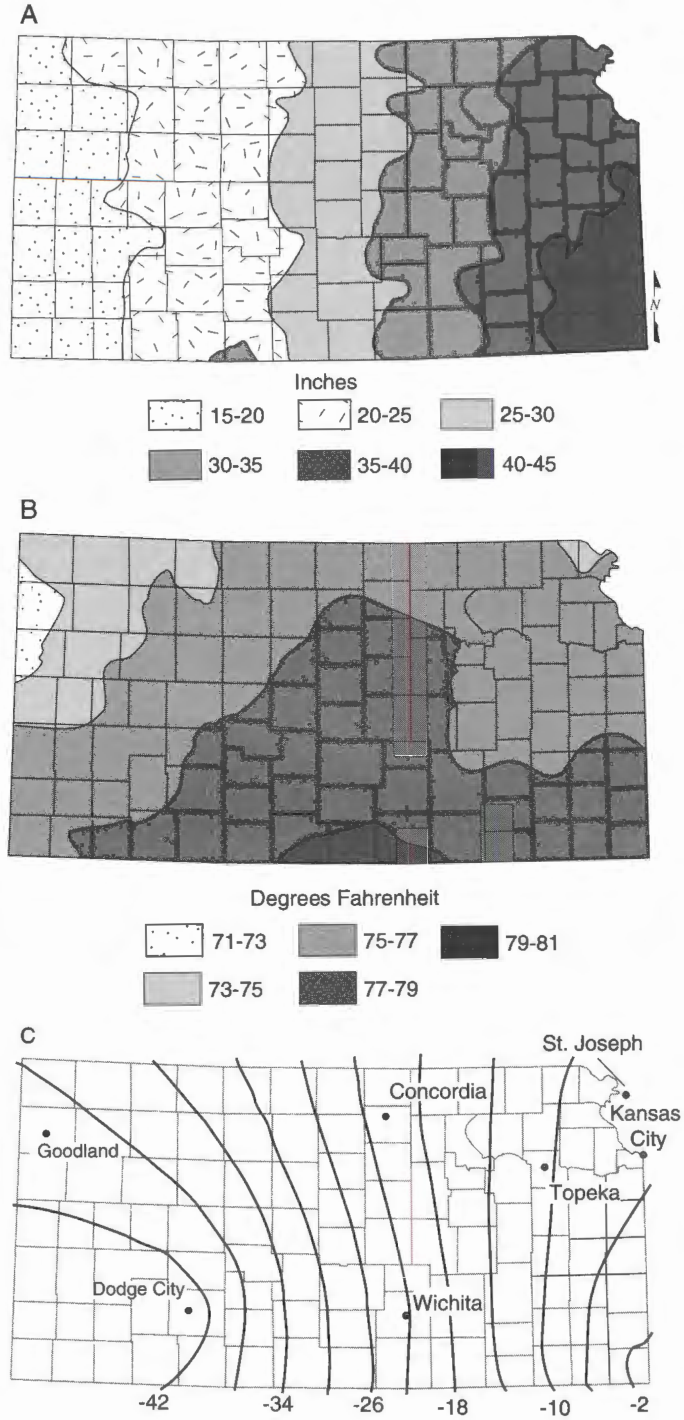


FIGURE 8.1—(A) Normal annual precipitation for Kansas (Goodin et al., 1995); (B) Distribution of summer mean temperatures in Kansas (Goodin et al., 1995); (C) Distribution of potential water balance (precipitation minus free water surface evaporation) for the state (from fig. 1.12B, chapter 1; see also remainder of chapter 1 discussion of Kansas hydroclimatology).

Boxed section 8.1: The Kansas Prairie—A Natural Adaptation to High Variability

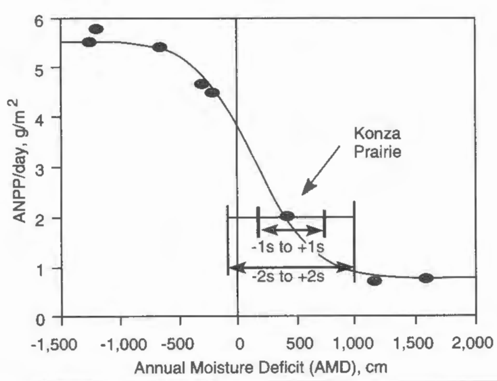
The Konza Prairie Reserve in north-central Kansas is an area of grassland preserved essentially as it was before European settlement. It also is the site of a Long-term Ecological Research (LTER) site operated by Kansas State University with National Science Foundation support. The LTER program studies and compares ecosystem dynamics at a range of locales nationwide. The results of the first phases of investigation are striking: the prairie is intermediate between desert and forest in terms of its average production of biomass (growth of vegetation)—but its relative range of variation is far greater than the other ecosystems. In unusually good (wet) years, the prairie may be nearly as productive as the forests, while in bad (dry) years productivity may be nearly as low as some desert environments. Figure B8.1.1 shows these results in graphic and tabular form. Compare the annual moisture-deficit values (shallow-lake evaporation minus precipitation) plotted here with fig. 8.1 and chapter 1 on Kansas water resources.

Dominance by a plant community able to respond over this wide range of conditions implies that high variability has been a major long-term climate feature of the Great Plains. The potential for high productivity under conditions of adequate water supply exemplify the recognized agricultural potential of the area—water, land management, and irrigation to provide enough moisture are human adaptations to a variable but potentially productive environment. The high natural variability, in turn, also implies that the productivity of introduced agricultural crop species would be at risk if the available water supply were to diminish, or its variability to increase.

TABLE B8.1.1 and FIGURE B8.1.1—GRAPHED AND TABULATED VALUES OF PLANT PRODUCTIVITY AND WATER BALANCE (positive values of AMD indicate available water) at the various Long-term Ecological Research (LTER) sites. These data, supplied by J. K. Koelliker of Kansas State University, illustrate the extremely wide range of net primary production corresponding to the moisture variations seen at the prairie site. By contrast, the wetter (forest) and drier (desert or high plains) sites exhibit much lower variability for comparable ranges of moisture deficits. This suggests that Kansas is poised at a climatic balance point in terms of supportable ecosystems. Relationship between annual net primary production (ANPP) per day of the growing season and average annual moisture deficit (AMD) at selected LTER sites in the continental United States was prepared by J. K. Koelliker (Kansas State University, January 1996).

	Average annual values				Growing season*	ANPP/day of growing season, g/m2
LTER Site	ANPP g/m2	Lake evap, mm	Precip, mm	Moist. def, mm		
H. J. Andrews, Oreg	1,650	508	1,778	-1,270	300	5.50
Coweeta, N Car	1,450	965	2,159	-1,194	252	5.75
Hubbard Brook, N Ham	950	457	1,118	-660	175	5.43
Harvard Forest, Mass	800	813	1,092	-279	172	4.65
Niwot Ridge, Colo	225	508	711	-203	50	4.50
Konza Prairie, Kans	450	1,295	851	444	221	2.04
Central Plains, Colo	110	1,473	330	1,143	160	0.69
Jornada, N Mex	180	1,829	229	1,600	250	0.72

*Average number of days between dates when low temperature is above -5 C.



Prospects for Future Climate

Essentially all the energy that drives the earth's climate system comes from the sun—other sources of energy, such as heat flow from the center of the earth and tidal energy, are a tiny fraction of a percent of the total supplied by the sun. Natural climate variations are believed to be linked to changes in the energy transfer between sun and earth. Such changes may occur in three ways: variation in solar output, change in the earth-sun geometry, or changes in the proportions of solar energy reflected and absorbed by the earth.

Variations in solar output are the most uncertain and controversial of the possible contributors to climate change. We are confident that the sun's output has declined over the lifetime of the solar system—but the rate of change is imperceptible on the scale of even long-term climate change. We know that the sun has activity cycles of 11 and 22 years—but while these may contribute to climate variability, the cycles are too short to drive long-term trends. There is some evidence for solar variations with time scales of thousands of years (Bond and Lotti, 1995; O'Brien et al., 1996), but the best current quantitative estimate of their magnitude is several tenths of a degree C (Stuiver et al., 1995)—which is climatically significant, but still smaller than the effects attributed to orbital variations and the "greenhouse effect."

The long-term glacial-interglacial cycles appear to be strongly correlated with the so-called "Milankovich cycles"—systematic variations in the tilt and wobble of the earth's axis relative to the sun, and in the eccentricity of earth's orbit (Imbrie and Imbrie, 1980). These cycles have periods of different lengths, but all are measured in tens of thousands of years. When the effects of orbital cycles on the seasonality of high-latitude radiation are calculated and used as input for a climate model, the resulting output closely matches oceanic isotope tracers of climate variation, as shown in fig. 8.2. Most (but as usual, not all) scientists believe that orbital variations are the dominant factor controlling the occurrence and timing of the glacial cycles of the past few million years, and that their effects on climate can be seen in older times as well.

It is important to understand that these orbital variations make little (in the case of eccentricity) or no (in the case of tilt and wobble) change in the absolute annual amount of total solar energy falling on the earth's projected area. They do, however, make major differences in the seasonal and latitudinal distribution of solar energy. The major temperature and climate changes are the result not of primary energy input, but of how the distribution of this input affects feedback processes within the atmosphere-ocean system. The strength and importance of this internal climate feedback is illustrated by the role of greenhouse gases.

One very important class of components of the climate feedback system is the "greenhouse gases"—so-called because their action is similar to that of the glass in a greenhouse. Incoming solar radiation is primarily in the visible wavelengths, whereas the energy absorbed and re-emitted to space by the earth is in the longer, infrared wavelengths. A number of atmospheric gases, both natural and human-made, are transparent to visible light but relatively opaque to infrared radiation. The higher their concentration in the atmosphere, the more energy is trapped near the earth's surface—and it is this trapped energy that drives the climate system. Water, in the form of clouds and atmospheric moisture, is one of the most powerful greenhouse gases, but because its concentration is so variable in time and space, the roles of the other atmospheric greenhouse components are better understood.

Energy budgets clearly show that the natural "greenhouse effect" is critical for maintaining the earth's surface temperature above freezing, and the potential for human-induced climate change by alteration of greenhouse-gas concentrations has been recognized for nearly a century (MacCracken et al., 1990). The issue has received serious scientific attention since careful measurements of atmo-

Boxed section 8.2: *Homo sapiens*: Taking Advantage of Climatic Stability

For the past several million years, the Earth's climate has oscillated between glacial and interglacial conditions, with global temperature changes of more than 5° Celsius (9° F) and sea-level variations of over 100 m (approximately 400 ft). The most recent cycle is the best characterized, and its general characteristics are illustrated in fig. B8.2.1 (Delacourt and Delacourt, 1991).

As the glaciers of the last great Ice Age melted and broke up, the earth's environment changed dramatically, and sometimes with great rapidity—for example, at times sea level rose many meters in the period of less than a century (Blanchon and Shaw, 1995). These changes culminated in a warm period (known as the Hypsithermal Interval) between about 9,000 and 4,000 years ago. By 6,000–7,000 years ago, sea level had come very close to its present elevation, and the world settled into a period of benign stability of temperature and sea level unusual in recent geologic history. Although modern humans had been in existence and expanding their range for tens of thousands of years before this, what we know as civilization and culture exploded during the climatic stability of the Late Holocene. Agriculture, permanent cities, written languages—all of their origins are coincident with the onset of climate stability and have developed over its course. Modern human societies are the end products of a rather anomalous period of earth history, and our ideas of "normal" arguably result from a combination of climatic accident and collective amnesia.

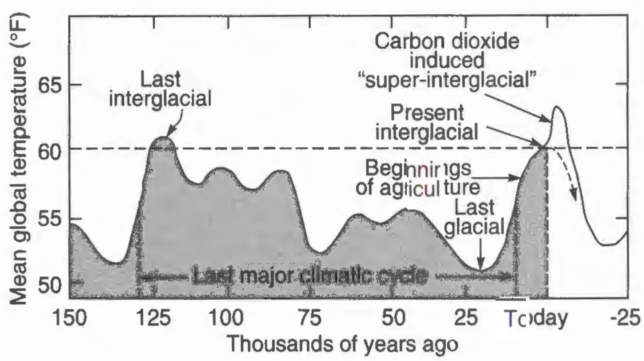


FIGURE B8.2.1—RECONSTRUCTION OF ESTIMATED GLOBAL CLIMATE (expressed as mean global temperature—curves of sea level, the inverse of ice volume, atmospheric CO_2, etc. have very similar forms) over the last glacial-interglacial cycle, with a possible projection 25,000 years into the future. A future cooling trend is predicted by the Milankovich astronomical theory of the Ice Ages. However, this cooling trend is expected to be delayed over the next 2,000 years because of a human-induced "super-interglacial" interval resulting from the combustion of fossil fuels and other modifications of atmospheric composition and the earth's surface (Delacourt and Delacourt, 1991).

spheric CO_2 (a major greenhouse gas) concentration showed systematic increases, resulting from fossil fuel combustion, cement production, and biomass burning. A recent update of these observations is shown in fig. 8.3 (Keeling et al., 1995). Measurements of gas bubbles trapped in glacial ice have made it possible to recreate the recent history of atmospheric concentrations of a number of greenhouse gases; their systematic increase, which is closely correlated with industrial development, points unequivocally to human alteration of a critical component of the climate-control system. These records are summarized in fig. 8.4.

The Intergovernmental Panel on Climate Change (IPCC) is an international body established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) to review and assess available scientific information on climate change, to assess environmental and socio-economic impacts of climate change, and to formulate response strategies. The IPCC published its initial reports in 1990, and prepared a second series of reports in 1995 (Bruce et al., 1996; Houghton et al., 1996; Watson et al., 1996). Over the course of its existence, the IPCC has moved from an initial position that anthropogenic climate change is highly probable to its more recent position that "The balance of evidence suggests a discernible human influence on global climate" (Santer et al., 1996). As the data base and scientific consensus supporting the reality of anthropogenic climate change has strengthened, the subject has become more controversial in some political and economic circles, and there is heightened attention to a range of topics that fall under the general classification of global change (see Boxed section 8.3).

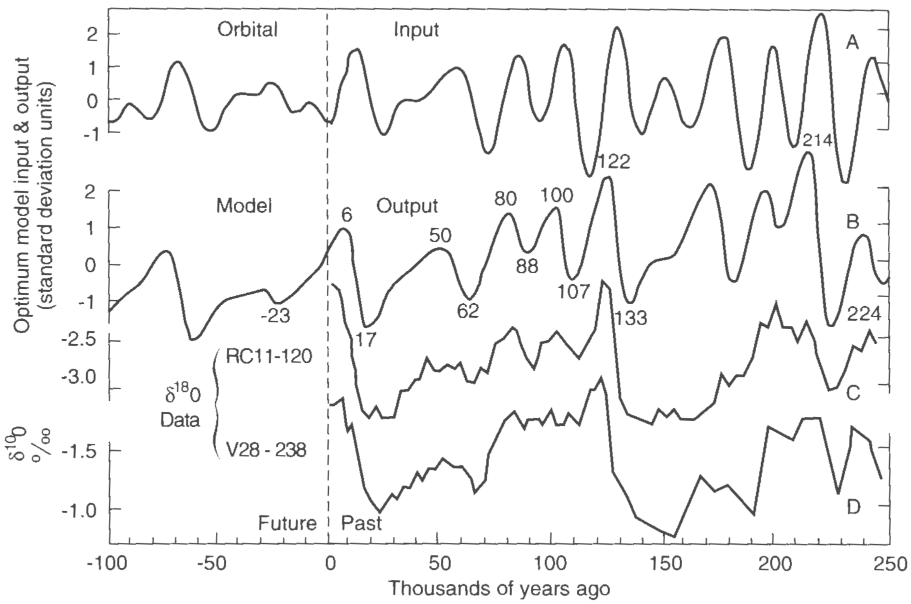


FIGURE 8.2—HINDCASTS AND FORECASTS OF GLOBAL ICE VOLUME BASED ON A MODEL OF THE INSOLATION VARIATIONS DUE TO 'MILANKOVICH VARIATIONS IN THE EARTH'S ORBIT' (Imbrie and Imbrie, 1980). The orbital variations produce an input (curve A) that yields the calculated curve of ice volume (curve B— numbers indicate ages in thousands of years). These results can be compared to the ^{18}O data from sediments in the southern Indian Ocean (curve C) and the Pacific Ocean (curve D), which should be related to the actual ice volume at the time. Note that the projection considers orbital factors only and does not take into account any human intervention in the climate cycle.

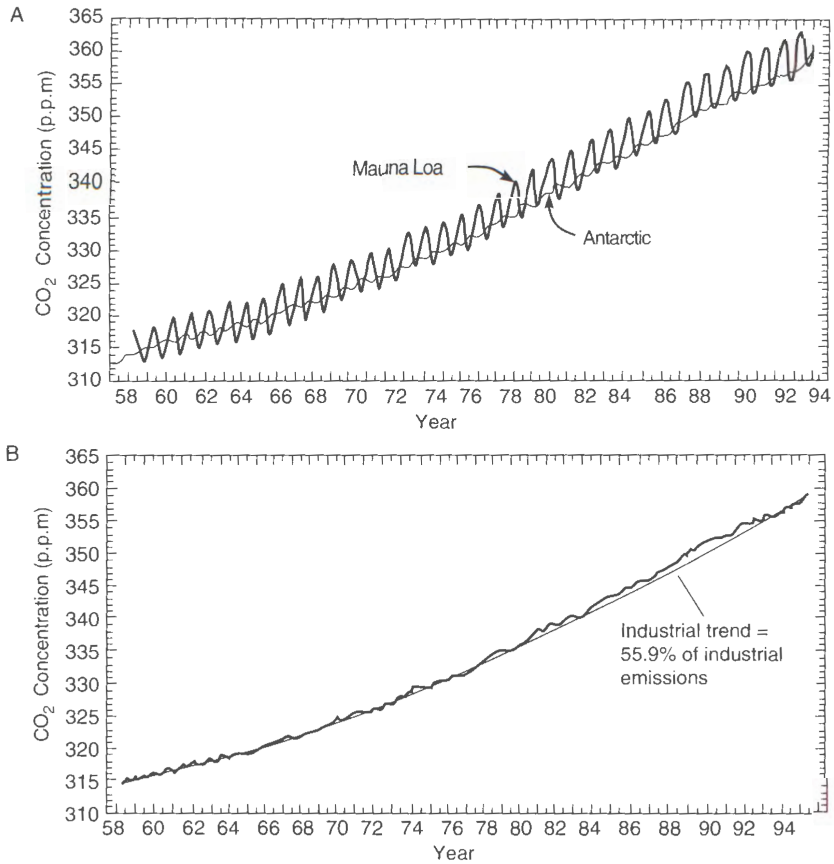


FIGURE 8.3—(A) THE CO_2 CONCENTRATION OF THE ATMOSPHERE, MEASURED IN HAWAII (LOW LATITUDE, NORTHERN HEMISPHERE) AND ANTARCTICA (HIGH LATITUDE, SOUTHERN HEMISPHERE). The trends are identical and the seasonal variations (due to vegetative uptake and release) exhibit the patterns and relative magnitudes predictable from the sampling locations. (B) Comparison of the smoothed trend line of atmospheric CO_2 concentration with the best-fit trend line of industrial emissions (calculated from data on global fossil-fuel combustion, cement production, and miscellaneous CO_2 sources). It appears that between 50 and 60% of the anthropogenic CO_2 emissions remain in the atmosphere. Adapted from Keeling et al. (1995).

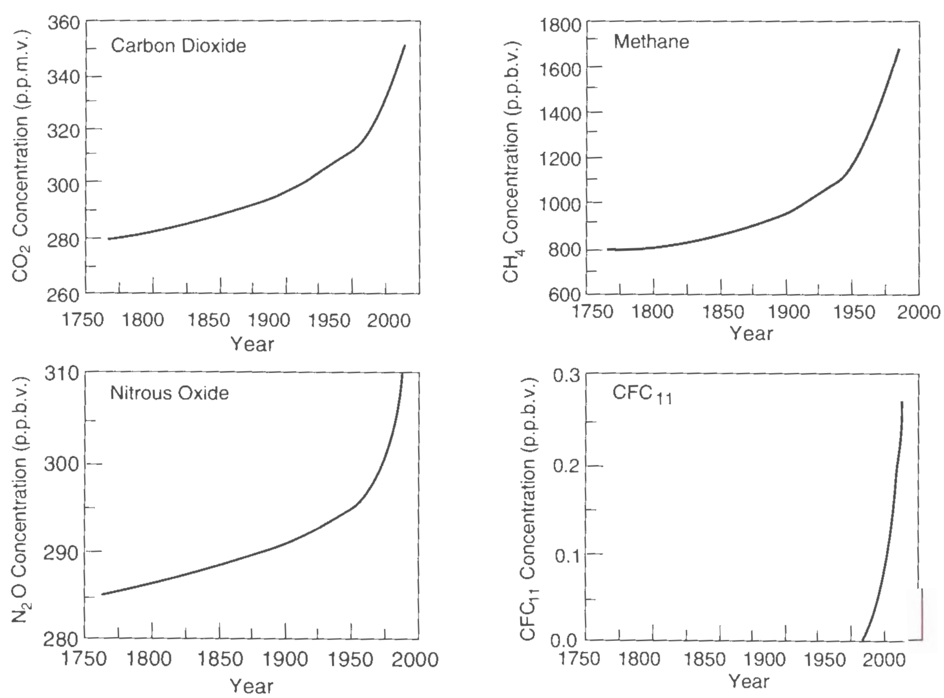


FIGURE 8.4—INCREASES IN CONCENTRATIONS OF SELECTED GREENHOUSE GASES SINCE 1750. Concentrations of CO_2 and methane, which were relatively constant up until the 1700's, have increased steeply since then due to human activities. Nitrous oxide concentrations have risen since about 1750, with the steepest increases after 1950. CFCs, which are entirely anthropogenic in origin, appeared initially in the 1930's and have increased steeply since 1950; from Houghton et al. (1990).

Boxed section 8.3: Certainty and Confusion—The Physics and Terminology of Global Change

Global Change, Global Warming, Climate Change, The Greenhouse Effect—all of these terms and more, with or without adjectives such as "natural," "anthropogenic," "enhanced," etc., are used in news stories and debates. The variety of definitions used and the legitimate scientific uncertainties create confusion that is systematically compounded by those whose political or economic interests would not be served by serious attention to the problems of changing climate (Gelbspan, 1995).

Fortunately, the physical basis for climate concerns is straightforward, and the arguments over temperature effects only serve to highlight the importance of changes in the hydrologic cycle, with which we are primarily concerned.

It is known with a high degree of accuracy that the earth receives an annual average of 343 Watts per square meter (W/m^2) from the sun (MacCracken et al., 1990). In round numbers, 100 W/m^2 are reflected, and 240 W/m^2 are absorbed by the atmosphere and land and ocean surface. These 240 W/m^2 do the work of driving atmospheric and oceanic circulation, the hydrologic cycle, photosynthesis, etc., and in the process are degraded and re-emitted as infrared radiation (to be in equilibrium, net energy loss must equal net energy gain). These processes are illustrated in fig. B8.3.1. We also know that the surface temperature of the earth is roughly 15° C., or about 288° K on the absolute (Kelvin) temperature scale. Basic physics and our knowledge that essentially all of the earth's energy comes from the sun tells us that, without feedbacks, there should be about a 1.2° change in surface temperature for a change of one W/m^2 absorbed (Houghton et al., 1990).

Just as the energy balance is well understood, so are the atmospheric concentrations of most greenhouse gases (figs. 8.3 and 8.4) and the details of their light- transmission and energy-absorption characteristics. It is possible to calculate with a high degree of accuracy the additional energy absorption due to changing gas concentrations. Table B8.3.1 presents a summary of these calculations for conditions as of 1990 (Berner and Berner, 1996). We can see from this table that the additional "energy forcing" of the climate since the beginning of the Industrial Revolution is substantial—in the simple calculation, equivalent to as much as several degrees of temperature change.

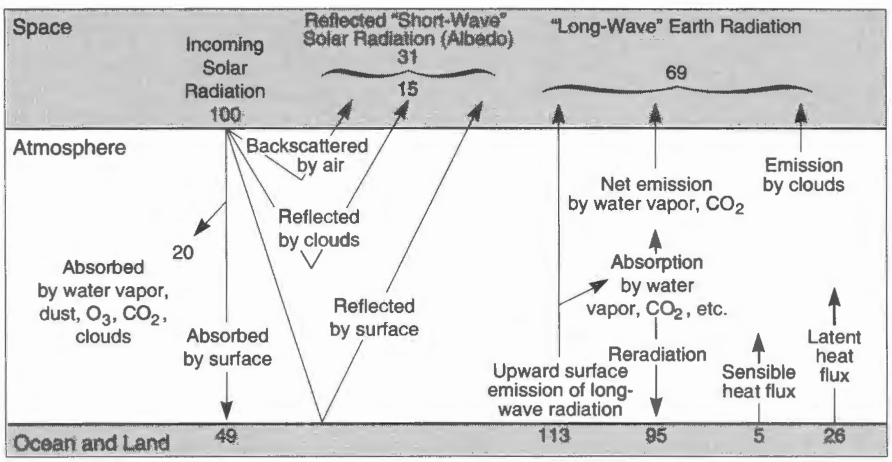


FIGURE B8.3.1—MEAN ANNUAL RADIATION AND HEAT BALANCE OF THE ATMOSPHERE AND EARTH. Units are assigned so that the incoming solar radiation (343 watts/m^2) is set equal to 100 units. "Short-wave" solar radiation has wavelength less than 4 micrometers; "long-wave" earth radiation has wavelength greater than 4 micrometers; from Berner and Berner (1996); see also MacCracken et al. (1990).

TABLE B8.3.1—EXTRA TRAPPING OF INFRARED RADIATION ΔQ (POSITIVE RADIATIVE FORCING) BY EXCESSES OF TRACE ATMOSPHERIC GASES ABOVE THEIR PREINDUSTRIAL CONCENTRATION.

Gas	Preindustrial Concentration 1765 (ppm)	Concentration 1990 (ppm)	Concentration Change per year (%)	ΔQ (W/m^2)	ΔQ (percent)	Lifetime (yr)
CO_2	279	354	0.5	1.5	61	50-200
CH_4	0.8	1.72	0.9	0.42	17	10
Stratospheric H_2O	—	—	—	0.14	6	
N_2O	0.285	0.310	0.25	0.1	4	150
CFC-11	0	0.00028	4.0	0.062	2.5	65
CFC-12	0	0.000484	4.0	0.14	6.	130
Other CFCs	0			0.085	3.5	
				—	—	
Total				2.45	100	
Stratospheric O_3 loss				-0.08	-3.3	

Boxed section 8.3 continued next page

Boxed section 8.3 continued from previous page

The fact that this amount of change in air temperature has not yet occurred is one of the sources of debate and confusion about "Global Warming," even though we know that there are major lags in the climate system because of the high heat capacity and slow responses of the oceans and melting ice, and we now realize that some of the predicted warming is being masked by anthropogenic aerosol emissions (Schwartz and Andreae, 1996). Yet when this energy forcing is considered as "Climate Change" rather than simply as "warming," we understand better the implications for water resources. Much of the energy not appearing directly as increased temperature is doing work that changes the hydrologic cycle and the atmospheric and oceanic patterns that redistribute water on the earth's surface.

The energy budget shows that the climate system must be changing, and the modest responses of temperature are very cold comfort indeed for those concerned about water-related issues.

Climate Change and Water

Projections and Models

In the late 1980's, as scientific and societal concern about global change was increasing rapidly, atmospheric General Circulation Models (GCMs) were becoming more powerful and more credible. These GCMs are complex numerical computer solutions of the equations that describe the physical interactions within the climate system (see fig. B8.3.1), and are used to calculate the effects of energy budget changes (for example, as a result of doubling atmospheric CO_2 concentrations) on the global patterns of temperature and precipitation. As the results of several different approaches to global climate simulation became available, a number of assessments of the effects of climate change on water resources were made. These culminated in major syntheses prepared by organizations such as the U.S. Enviromental Protection Agency (USEPA), American Associaton for the Advancement of Science (AAAS), and the Intergovernmental Panel on Climate Change (IPCC) (Smith and Tirpak, 1989; Tegart et al., 1990; Waggoner, 1990).

Many of the "warmer-world" climate and hydrologic simulations highlight the sensitivity of runoff to relatively minor changes in temperature and precipitation (p. 4–5 to 4–6 in Tegart et al., 1990). An example of this is shown in Boxed section 8.4. Because of Kansas' position at the "balance point" for aridity (see fig. 8.1 and Chapter 1 on Kansas water resources) and water-controlled productivity (fig. B8.1.1), high sensitivity like this points to a particularly high probability of water-supply changes within the state. The authors of numerous chapters in the IPCC 1995 update all point to the special vulnerability to climate change of water resources, agriculture, and freshwater ecosystems in arid or semi-arid environments (Arnell et al., 1996; Kaczmarek, 1996; Reilly, 1996).

Another study prepared a vulnerability assessment of United States water systems based on storage volume relative to renewable supply, consumptive use relative to available renewable supply, the ratio of hydroelectricity to total electricity, ground-water overdraft relative to total ground-water withdrawal, and variability of streamflow (Gleick, 1990). For each of the five factors considered vulnerable to a change in hydrologic conditions, a basin was awarded a "warning lamp"—the Arkansas–White-Red basin (including southern Kansas) had three lamps "lit," and the Missouri basin (northern Kansas) had four, indicating a relatively high level of potential vulnerability for the state. Figure 8.5 shows the national pattern of vulnerabilities—with the drier western regions having the greatest vulnerability to hydrologic change.

Some of the General Circulation Models (GCMs) indicate increased drying and soil-mosture deficits in the interiors of continents, specifically including North America (Tegart et al., 1990, p. 4–5 to 4–6). Analysis based on historical records has generally focused on the 1930's—the Dust Bowl—as the most likely analogy for future climate (Glantz, 1988). These comparisons, and recognition that runoff and recharge may be extremely sensitive to relatively small changes in the hydrologic cycle, should be disquieting news for Kansas water planners. However, to date the projections have had relatively little impact on water policy and planning, in part because the regional hydrologic estimates from the various GCMs were neither precise nor considered particularly reliable. This is largely due to the coarse-grid scales of the GCM; because they are so computationally intensive, the global models are run with grid cells hundreds of miles on a side and with very simplified surface characteristics. For this reason they cannot resolve convective or cyclonic systems, or topographic features important to local precipitation. Thus vulnerability is estimated on a subcontinent scale, but management is done at the basin scale (Kaczmarek, 1996).

One of the responses to lack of resolution and precision in GCM treatment of such factors as soil moisture and its variability has been to couple the more robust outputs of GCMs (such as temperature and precipitation) to more detailed regional hydrologic models. Gleick (1986, 1987) first applied this method to the Sacramento–San Joaquin basin in California, and Nash and Gleick (1993) subsequently used a similar approach in the Colorado River basin.

Both these river basins are highly managed and have a significant component of mountain snowmelt, and the water is fully or largely allocated. Boxed section 8.4, and Table B8.4.1 contained therein, summarize the findings on climate sensitivity of the Colorado River basin.

A striking outcome of these studies that is relevant to discussions of variability (see below) is the effect of shifts in the intra-annual pattern of precipitation and runoff. Climate change scenarios may produce a net increase in annual precipitation and runoff, but if there is a shift to higher peak flows earlier in the year, the result may be less water available because under the new flow regimes, existing reservoirs cannot be operated to preserve both the same storage and the same flood protection for which they were originally designed.

An Emphasis on Variability

Whether we forecast by physical model or by historic or paleoclimatic analogies, some kinds of forecasts are easier than others. It is likely (Boxed section 8.3) that the predictable increase in atmospheric energy retention will result in warming, and very likely that warming will speed up the hydrologic cycle on a global basis. An accelerated hydrologic cycle will result in increases in both precipitation and evaporation, but not necessarily in the same places or at the same time—predictions of midcontinent drying reflect the probability that increased precipitation may be concentrated along the trajectories of marine air masses, while evaporation will be more generally distributed.

Since the original IPCC assessments in 1990, our understanding of climate change issues and symptoms has grown faster than anticipated. At that time, it was estimated that it would take a decade or more to confidently identify evidence of anthropogenic climate change (Wigley and Barnett, 1990). Rapid improvements in atmospheric and oceanic modeling, measurement techniques, and methods of data analysis have both shortened the predicted time and increased confidence in predictions (Santer et al., 1996).

However, the details of regional water distribution in time and space are still not yet reliably predictable, and while the fact that oceanic and atmospheric circulation patterns shifted in the 1970's and have not gone back to "normal" (Kerr, 1992; Karl et al., 1995) may argue for the

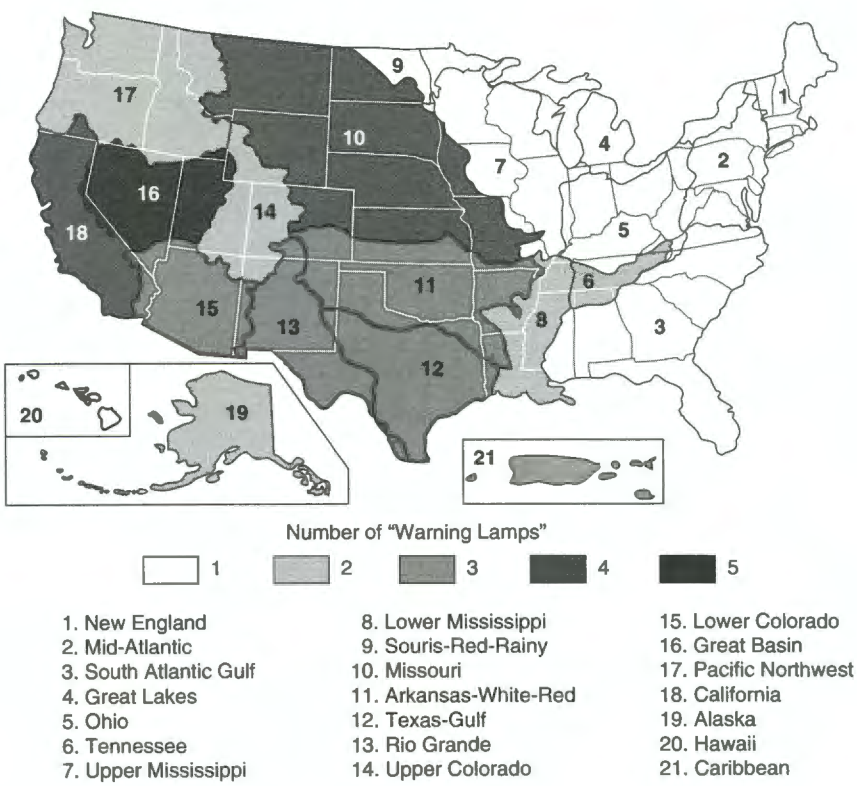


FIGURE 8.5—VULNERABILITY TO CLIMATE CHANGE OF HYDROLOGIC REGIONS (Gleick, 1990). Numbers next to boxes in legend correspond to the number of "warning lamps" judged to be turned on as a result of specific vulnerabilities assessed on the basis of storage volume relative to renewable supply, consumptive use relative to available renewable supply, the ratio of hydroelectricity to total electricity, ground-water overdraft relative to total ground-water withdrawal, and variability of streamflow. In all basins, at least one measure of vulnerability exceeds the warning level. For Kansas, the Missouri basin has four lamps lit, and the Arkansas basin has three— a significant level of estimated vulnerability.

Boxed section 8.4: Climatic Sensitivity of the Colorado River Basin

The following excerpts from Nash and Gleick (1993) illustrate the profound effects that seemingly modest changes in temperature or precipitation can have on a highly managed water resource—and the resulting uncertainties in the water-resource outcomes of climate change.

Changes in Colorado River Basin Hydrology

The principal impacts of changes in temperature and precipitation on runoff in the Colorado Basin are summarized below.

- Increases in temperature of 2°C alone, with no change in precipitation, cause mean annual runoff in the Colorado River basin to decline by 4–12%.
- A temperature increase of 4°C causes mean annual runoff to decrease by 9–21%.
- Increases or decreases in annual precipitation of 10–20% result in corresponding changes in mean annual runoff of approximately 10–20%.
- A temperature increase of 4°C would require an increase in precipitation of 15–20% merely to maintain annual runoff at historical levels.
- Temperature increases shift the seasonality of runoff in the Colorado basin, causing a distinct increase in winter runoff and a decrease in spring runoff. This is the result of a decrease in winter snowfall and snowpack, an increase in winter rain, and a faster and earlier spring snowmelt. These temperature-driven changes could increase the potential for winter and spring flooding in some regions.
- General Circulation Model (GCM) temperature and precipitation scenarios modeled as part of this study suggest that precipitation increases would be offset by increased evapotranspiration, with the net effect being a reduction in runoff ranging from 8 to 20%.
- Of the three GCMs used to develop climate scenarios in this study, the Geophysical Fluid Dynamics Laboratory (GFDL) model results in the most extreme decreases in runoff for all the sub-basins studied (-10 to -24%) because it predicts a relatively large regional temperature increase and no change in precipitation. The least extreme effects are generated by using either the United Kingdom Meteorological Office (UKMO) or the Goddard Institute of Space Studies (GISS) grid points, which incorporate respective increases in precipitation of 30 and 20% and lead to increases in runoff of 0 to 10%.
- High-elevation basins appear to be more sensitive to changes in temperature and precipitation than low-elevation basins. Of the three sub-basins studied, the East River near Almont, Colorado, is the most sensitive to changes in temperature and precipitation because of its higher elevation.
- In general, runoff in the Upper Colorado River basin is slightly more sensitive to a 10% change in precipitation than to a 2°C change in temperature. Thus, while increased temperature will cause significant decreases in runoff, the overall response of the basin will ultimately depend upon the direction and magnitude of changes in precipitation.

In summary, the results of hydrologic modeling suggest that large changes in streamflow may occur in the Colorado River basin as a result of plausible climatic changes. GCM scenarios indicate that runoff in the basin is likely to decrease. The impacts of these potential changes in streamflow would be felt throughout the basin as changes in water deliveries, reservoir storage, and hydroelectricity production.

TABLE B8.4.1—SENSITIVITY OF WATER-SUPPLY VARIABLES TO CHANGES IN NATURAL FLOW IN THE COLORADO RIVER BASIN (Nash and Gleick, 1993), shown in percentages. Values in parentheses represent decreases.

Change in Natural Flow	Change in Actual Flow	Change in Storage	Change in Power Generation	Change in Depletions	Change in Salinity
-20	(10-30)	(61)	(57)	(11)	15-20
-10	(7-15)	(30)	(31)	(6)	6-7
-5	(4-7)	(14)	(15)	(3)	3
5	5-7	14	11	3	(3)
10	11-16	28	21	5	(6-7)
20	30	38	39	8	(13-15)

reality of climate change, it also interferes with our ability to use past conditions as an exact model for the future.

In spite of uncertainty about detailed predictions of specific changes in water availability, uncertainty has been drastically reduced in some topical areas. Early in this decade, Karl et al. (1991) estimated that it might be at least another decade before the greenhouse temperature signal could be reliably detected in central North America, and as much as 40 years before the precipitation signal could be discerned. Yet in 1995, two of these same authors (Karl et al., 1995) published an analysis of United States climate trends and stated there is only a 5–10% chance that observed patterns are not the result of climate change. The basis for the turnabout was improved methods of analysis of complex patterns of climate variability.

Karl et al. (1995) present the following adaptation of the IPCC conclusions concerning probable climatic changes for which a credible physical mechanism is understood:

These changes, in rough order of our confidence in the projections, include:

- An increase of mean surface temperature, more pronounced during the cold season;
- An increase in precipitation, especially during the cold season;
- More severe and longer lasting droughts, particularly during the warm season;
- A small, but significantly greater increase of night-time temperature compared with daytime temperature, primarily during the warm seasons;
- A greater portion of warm-season precipitation derived from heavy convective rainfall (showers or thundershowers) compared with gentler, longer-lasting rainfalls; and
- A decrease in the day-to-day variability of temperature.

Although no single factor alone would be likely to produce absolutely conclusive evidence of climate change (see Boxed section 8.3), some appropriate combination of the factors should provide much more reliable evidence. Accordingly, the researchers (Karl et al., 1995) created two composite indices—a Climate Extremes Index (CEI), and a Greenhouse Climate Response Index (GCRI). Both are based on data on tem-perature and precipitation extremes archived at the National Climate Data Center, and both were applied to the records of the conterminous United States over the past century. The results indicate that both the CEI (fig. 8.6) and the GCRI (fig. 8.7) have been above the "expected" (stable climate) value since the 1970's—behavior exhibited only for much briefer periods in the 1930's and 1950's.

Not only do these analyses lend support to the popular view that weather has been more extreme in recent years, but they approach statistical validation of the reality of greenhouse climate-change trends—as evidenced by the authors' conclusion that there is only a 5–10% chance that the observed United States pattern could be due entirely to natural variation. Indeed, data from even more sensitive regions outside the United States now suggest that there has been a decade-scale shift in high-latitude plant productivity (Myneni et al., 1997).

Water Quantity—Not the Only Issue

Water quality is an issue that looms ever larger in societal plans for water use and development. As supplies of good-quality freshwater become more limited or more fully used, we are becoming more painfully aware of the limitiations imposed by water-quality problems—some of natural origin, some caused by human waste disposal or contamination, and some the logical consequence of ever more efficient use of available water.

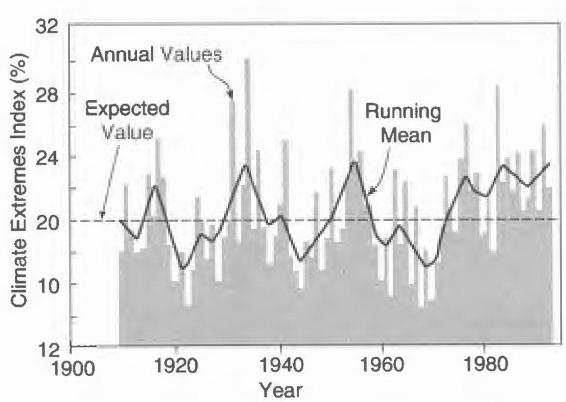


FIGURE 8.6—THE HISTORICAL COURSE OF THE CLIMATE EXTREMES INDEX (CEI) (Karl et al., 1995). This index, based on the proportion of the United States experiencing extreme conditions of temperature or precipitation in a given year, has recently remained above the "stable climate" value for a period roughly three times as long as other positive excursions in the earlier record.

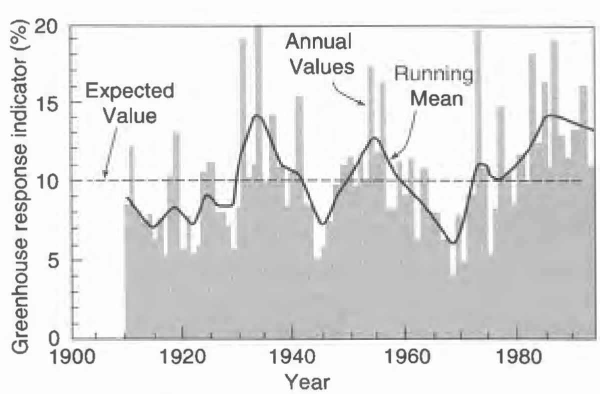


FIGURE 8.7—THE GREENHOUSE RESPONSE INDEX (GRI), like the CEI (fig. 8.6) shows unusually sustained positive values in recent decades, lending support to the view that anthropogenic climate change is occurring (Karl et al., 1995).

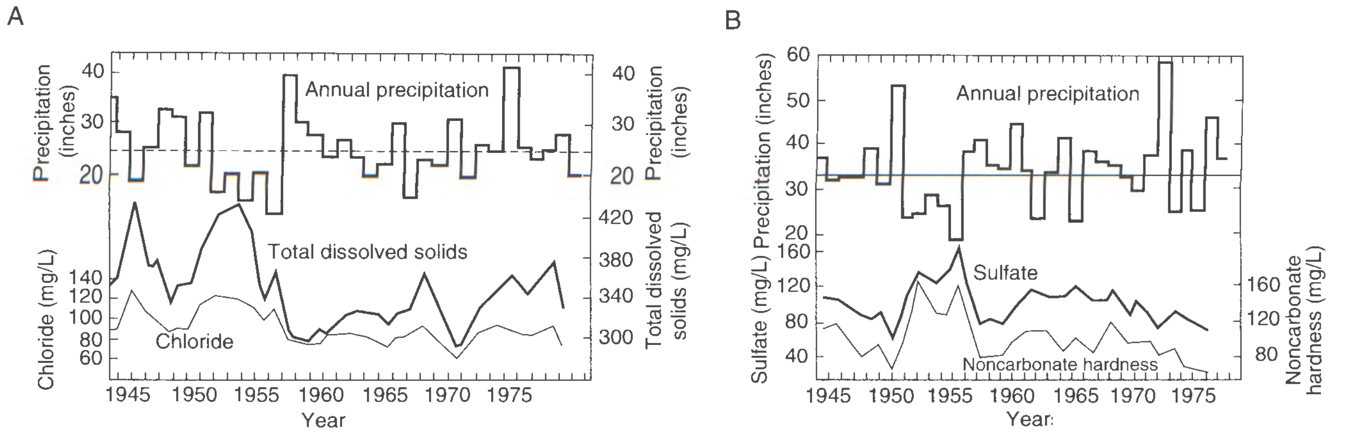


FIGURE 8.8—VARIATION IN WATER-QUALITY PARAMETERS FOR PUBLIC WATER SUPPLIES DRAWN FROM TWO AQUIFER SYSTEMS IN KANSAS. (A) Havensville in northeastern Kansas; precipitation values are shifted six months to the right to demonstrate the match with sulfate and noncarbonate hardness. (B) Arlington in south-central Kansas; precipitation data are shifted three years to the right in this case. The curve matches show the effect of dry periods on water quality of ground water; the time lag (curve shift) in the two cases reflects the differences in recharge pathways and residence times in the two areas; from Whittemore et al. (1988).

Consumptive use of water results in evaporation of the water, but not of the dissolved salts—so salinity rises with evaporation, and the proportion of water evaporated rises with increased re-use and storage. The problem of soil and water salinization as a result of intensive irrigation is acute in some parts of the country, and is a significant problem in Kansas along parts of the Arkansas River valley. This type of problem can be expected to intensify if climate change increases both irrigation demand and the evaporation rate of the water applied.

Climate change, particularly if it involves longer or more intense dry spells or a shift in the net balance between precipitation and evaporation (fig. 8.1C), may adversely affect the quality of both surface and ground water. The overall topic has been reviewed (Jacoby, 1990), and Boxed section 8.4 contains examples of salinity effects calculated for the Colorado basin.

In Kansas, the effects of precipitation and recharge on ground-water quality have been studied (McGregor et al., 1988; Whittemore et al., 1989). Figure 8.8 shows the relationship between precipitation and water-quality variations in two municipal supplies obtained from shallow alluvial aquifers. The prospect of climate-induced water quality and water quantity variations in both surface- and ground-water resources poses major challenges for water managers and planners.

Climate and Water—The Present is the Future

An emphasis on variability and a recognition that climate change is very probably already a fact of life brings some perspectives into focus. Regardless of what long-term averages do, we can expect greater seasonality of precipitation, more frequent and intense extreme events (storms), more floods, and possibly more droughts (Arnell et al., 1996; Kaczmarek, 1996; Karl et al., 1997).

The reliability of reservoir yields and surface-water rights will almost certainly decrease because of shifts in the seasonality and patterns of runoff. Soil-moisture deficits in summer and fall are likely to increase—if not on average, then at least in terms of the number of dry years (Arnell et al., 1996). Demand for ground water is likely to increase, especially for the critical irrigated component of world agriculture (Reilly, 1996); whether recharge increases or decreases will depend on complex local combinations of land use and climatic factors. Long-term sustainable yield of the integrated hydrologic system is likely to decrease, and with it the reliability of regional water-resource systems (Kaczmarek, 1996); an increase in the frequency of periods in which yields once considered "safe" can not be assured or delivered seems highly probable.

The analyses of Karl et al. (1997) provide a statistical basis for estimating the new climate norms, and from that, event probabilities. Using these revised norms and probabilities, hydrologic principles and the earlier analyses of hydrologic-system responses can be applied to develop new comparisons of probable demand and probable supply. Because the mismatch is likely to be greater than at present and because water is critical to the state's well-being, this revision and comparison should be a high priority for both government and the private sector.

Beyond Water

This chapter has focused primarily on climate and hydrology. Climate change has collateral impacts on many aspects of life through nonaqueous mechanisms as well. An area of particular concern to Kansas is agriculture, which uses by far the largest fraction of water consumed within the state (see table 1.3, chapter 1 on Kansas water resources).

The effects of climate change on agriculture also have been intensively studied on a variety of levels (Adams et al., 1990; Kaiser and Drenne, 1993; Peterson and Keller, 1990; Rosenzweig and Parry, 1994). Although water is an important component of these analyses, there are many others, ranging from government policies to climatic effects on the distribution of pests and diseases. Even the climate-change expectations listed above have other detrimental effects; drier summers and more intense rains will increase the losses associated with soil erosion (O'Hara et al., 1993; Pimentel et al., 1995). Perhaps more intriguing than the model-based studies cited are actual global data indicating that world grain yields may have increased in variability as they have increased in average amount (Naylor et al., 1997).

The complexity of responses to change in a natural system—even a highly altered and managed "natural" system like agriculture—is great. Boxed section 8.5 presents a still-oversimplified chain of relationships that starts with water on the farm and ends with the carbon cycle responses of the global ocean. The optimists will see each new interaction as an opportunity for correction of problems; the author of this chapter is a pessimist who finds it difficult to see how changing the natural environment won't be disruptive to a society and an economy that have been optimized for conditions as they were.

Summary and Recommendations

The evidence summarized in this chapter strongly suggests that we are entering a somewhat warmer and definitely more variable global climate. Sustainable water yields may or may not be reduced in the long-term average, but they will almost certainly be less reliable in the short term. Extreme events—floods, droughts, storms—will be more frequent occurrences. Climate warming may increase demand for water at a rate even greater than that predicted on the basis of economic development.

Kansans, whether animal, vegetable, or mineral, have a long history of adapting to climate variability. Human Kansans have chosen to adapt by managing both surface-water and ground-water supplies to reduce and mitigate natural variability. In doing so, they have worked with the climate and resources that they found, building reservoirs or well fields and awarding water rights that are consistent with the climate-as-it-was. These rights and structures—or at least their present mode of operation—can not be expected to yield the same results in the now-and-future-climate.

Change is generally uncomfortable, but it need not be disastrous. Action taken now can prepare the state and its

Boxed section 8.5: Supply and Demand and Feedback

At first glance it seems straightforward to assess the effects of climate change on the sustainable yield of water resources—just figure out how it affects recharge and runoff. We have already seen some of the problems that lie just below the surface of that approach—the amount of usable water is not determined just by annual totals, but also by when, where, and how it arrives.

For a further glimpse of some of the complications, let us run through a series of arguments that arise when we look at climate-change effects on agriculture, which is by far the largest user of water in Kansas.

If we take some of the more worrisome predictions of climate models—a shift in seasonal patterns of precipitation away from the growing season, and increased soil moisture deficits in the midcontinent region—we might conclude that demand will rise faster than supply, and that we are facing the prospect of decreased production and/or increased resource depletion.

However, tests have shown that higher CO_2 levels increase growth and productivity of some plants, and even more importantly, may increase water-use efficiency. An optimistic view of these observations would assert that it will all balance out and we need not worry.

Unfortunately, the chain of counter-arguments does not stop here. There are multiple further complications. One is that the increase in water-use efficiency is per unit leaf area—the water use per unit ground area may increase rather than decrease if canopy cover increases (also a potential effect of CO_2 fertilization). Another is that it is not just food crops that benefit from CO_2; weeds do too, and both insect pests and crop diseases are likely to thrive in warmer climates (Reilly, 1996). This may point to a need for increased biocide use in a high-CO_2 environment. A third complication is that CO_2 fertilization may boost carbohydrate production, but the plants will not have a matching increase in other nutrients such as nitrogen and phosphorous—so even if gross production goes up, nutritional value and palatability of the product could decline unless fertilization is increased (Allen–Diaz, 1996).

Agricultural chemicals are a major source of water-quality concern in Kansas (see chapters on water-quality and water-resource issues), and efforts are being made to decrease their use rather than increase it, as might be required to compensate for the effects of CO_2 and warming. On a larger scale, changes in the nitrogen cycle caused by land use and agriculture are an important feature of "global change" that feeds back into climate issues because the health and nutrient supply of the world's oceans are likely to have a major long-term effect on their exchange of carbon dioxide with the atmosphere (Turner and Rabalais, 1991).

The moral of the story: we cannot stop examining the problem just because we get to an answer that we like, or think we understand.

citizens to mitigate the worst effects of climate change and take advantage of possible benefits. The following list, although necessarily limited and incomplete, indicates some of the possible approaches.

- Recognize the nature of the problem and acknowledge that it is worth preparing. Flood and drought responses are like immunization against epidemic disease—if you wait until the problem is at hand, it is too late.
- Consciously follow a "no regrets" (or few regrets) policy in preparation. Great pain and sacrifice is not yet necessary; we can substantially improve our position for the future by doing things that have little present cost and are desirable in any case. Most soil- and water-conservation measures fall in this category.
- Recognize that surface water and ground water are not separate components, but all part of the same hydrologic cycle and that conjunctive use and management will be needed to improve the reliability and value of both resources.
- Reassess recent trends and projections related to water use and management, using the climate statistics of the past 20 years (for which there is evidence for systematic change—see figs. 8.6 and 8.7) to examine and predict the effects of variability. A realistic assessment of reservoir-storage capacity relative to demand and flood-control potential will be particularly important—not only to the utility of the surface-water system, but also to ground-water demands and recharge dynamics.
- Establish and encourage better integration of flood control and water-supply enhancement (especially ground-water recharge and off-line storage) programs. There may be creative ways to turn the problems of excess moisture and more frequent drought into mutual solutions rather than paired disasters.
- Expand and enhance water-conservation programs; increased uncertainty about future supplies and demands suggests that a higher value be placed upon water reserves now in the ground but being depleted, as is the case with much of the Ogallala aquifer.
- Establish at the State level a mechanism for ongoing technical review of the rapidly changing field of climate-change research and data, and for assessing its implications for state programs and economic prospects. Coordinate these efforts with well-developed programs already in existence in other states such as Nebraska and Texas (Norwine et al., 1995).
- Enhance public-information and education programs focused on issues of sustainable development, planning for change, and effective decision-making under conditions of uncertainty. Policy makers, planners, and managers should be a priority target.

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CHAPTER 9

Managing Uncertainty in Yield Estimates

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CHAPTER 9

Managing Uncertainty in Yield Estimates

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"Doubt is not a pleasant state
but certainty is a ridiculous one."

—*Voltaire*

Introduction

There are few things in life that we are certain about (notably death and taxes), and water is not one of them. Of course, there will always be water: some of it, somewhere, for some time. However, for planning purposes we need to know how much water will be available, where, and when. Furthermore, we need to know it with a high degree of confidence in order to have reliable water supplies. There are two ways to know these things: either we measure or we estimate. But we do not always get to choose; some variables we can measure (e.g., water levels) and some we can only estimate (e.g., rock permeability). In both cases there can be significant uncertainty as to the actual values at a given time and location.

Uncertainty can be of two types: natural variability or lack of knowledge. Most people are familiar with uncertainty due to natural variability, as they evaluate weather forecasts on a daily basis. River stages are another example: we have years of daily records, but still cannot predict future water levels much in advance. However, rainfall, temperatures, and river stages are accessible to measurement; when we measure them, we register their natural variability. On the other hand, uncertainty due to lack of knowledge relates to things that we cannot measure but still affect the prediction to be made. This latter category is very pervasive in subsurface hydrologic systems, because we can seldom measure the variable that we need to predict. Examples include water yield and aquifer permeability.

Regardless of their origin, we deal with all uncertainties in a similar way. We only have two choices: ignore it or recognize it. The price of ignoring it can be too high in water-resources planning: we will fail to get the needed quantity of water. A better choice is to explicitly recognize all sources of uncertainty and evaluate their impact on the variables that we need to estimate (e.g., water yield). Because uncertainty and risk are companions, evaluating uncertainty allows the assessment of risks and management of its consequences.

Water-resources planners face an irreducible dilemma. They realize that our knowledge of the hydrologic system is fraught with uncertainties, but decisions still need to be made. The key question is: Will those uncertainties affect the decisions to be made? The only way to know is to incorporate uncertainty into the analysis in a quantitative fashion, by means of probabilities. This alternative is always superior to neglecting uncertainty to avoid dealing with it. By doing this, decision-makers can set policies that meet acceptable levels of risk. In this chapter, I advocate such an approach and show how this can be done using available information.

Example: Uncertainty in Hydrologic Systems

A simple example will serve to illustrate some basic ideas about uncertainty. Consider the daily discharges in the Kansas River near Lecompton. Sixty years of daily records, from 1937 to 1996, are summarized in fig. 9.1. Figure 9.1A shows the histogram of relative frequency; fig. 9.1B shows the cumulative relative frequencies (the maximum value of 1 corresponds to certainty). The relative frequency is the number of times a given value occurs, divided by the total number of observations. Both plots in fig. 9.1 provide a wealth of information: we observe not only the range of possible values (from 185 cfs to 398,000 cfs [5–11,270 m^3/s]), but also the likelihood of observing values in a given interval. We can use the sample data to make inferences about particular events. However, to do that we first need to assign a likelihood to each event: this measure is called probability. In view of the sample data it seems reasonable to make the relative frequencies equal to the corresponding probabilities (this is true in the limit of large sample size). In what follows, we will use the term probability instead of frequency.

We wish to estimate the probability of a flood on any given day. To do this we need to group the information in fig. 9.1A into two exclusive events: smaller or larger than a given threshold value. This is done automatically in fig.

9.1B, which measures the probability of having discharges less than a given value. For example, we can read in fig. 9.1B a probability of 80% of having discharges smaller than 10,000 cfs. Because probabilities of complementary events add up to one, we calculate a probability of 20% of having a flood with discharges larger than 10,000 cfs.

This example shows all the basics of dealing with uncertainty. Information can be grouped to display the relative likelihood of events of interest, including mutually exclusive events (e.g., discharges larger or smaller than a given value). Probabilities can be read directly from the cumulative distribution function (CDF) depicted in fig. 9.1B. The CDF is obtained by adding up the values of the probability density function (pdf) depicted in fig. 9.1A. Risk is the probability of an undesirable event. We can either select the event and calculate the risk, as done above, or set the maximum acceptable risk level and determine the corresponding event. For example, in fig. 9.1B we read that a flood risk of 50% corresponds to a discharge of 3,300 cfs.

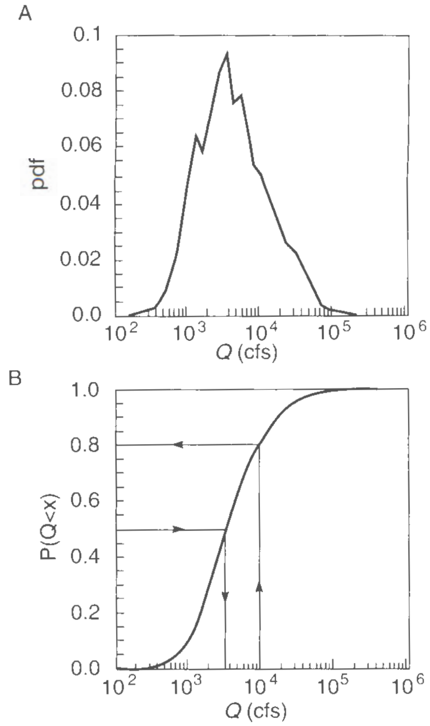

FIGURE 9.1—VARIABILITY OF DAILY DISCHARGES IN THE KANSAS RIVER AT LECOMPTON. (A) Probability-density function (pdf). (B) Cumulative-distribution function (CDF).

Example: Uncertainty in Ground-water Yield Estimates

Water-yield estimates are the result of a hydrologic-balance calculation, based on the initial stock of water, the additions (e.g., precipitation), and subtractions (e.g., evaporation). Since these quantities vary over time, so does the water-yield estimate. This presents a potential problem for defining unique yield values to guide policy making. One possibility is to perform the balance calculations under long-term average conditions (which might materialize or not). This might be appropriate for ground-water systems with long response times, but not for systems that are relatively fast to respond to changes in major fluxes. For those systems, a better choice might be to evaluate yield under conditions of relative drought, when additions are much less than those during average conditions; this is perhaps the simplest way to hedge against the risk of running out of water.

Estimates of ground-water yield are always uncertain because—unlike river stages—they are not directly measurable. They are estimated using a model of the hydrologic system, in terms of other variables that are estimates themselves (by contrast, the yield from a surface-water reservoir has significantly less uncertainty). Here we use the term yield estimates to emphasize the fact that they are inherently uncertain.

We will illustrate yield uncertainty by way of an example. Consider an unconfined aquifer subject to recharge from precipitation and otherwise not connected to surface-water bodies; an underlying aquitard prevents recharge from below. We wish to evaluate the feasibility of pumping water from this aquifer for irrigation, on a long-term equilibrium basis. This system can be described at different levels of detail; here we choose the simplest conceptualization using the lumped parameters shown in fig. 9.2. The corresponding steady-state mass-balance equation is

$$I + R - P = O \qquad \text{(eq. 9.1)}$$

where R is the recharge, P is pumping, I is the regional-flow input, and O the regional-flow output. Pumping is a decision variable that can take one of three possible values, $P = \{1; 2; 3\}$. Other available information allows us to estimate values of I and R as follows (all numerical figures in this example have the same arbitrary units):

$I = \{9; 10; 11\}$ mean $[I] = 10$
$R = \{1; 2; 3\}$ mean $[R] = 2$

These values portray uncertainty in a very simple fashion: each variable can take on three possible values, all equally likely (each one has a probability of occurrence equal to 1/3). Because in reality both I and R are continuous variables, the three-point discrete representation can only approximate their true variability. However, the mathematics are much simpler, and we can still illustrate the same points. Figure 9.3 shows the relative frequency plots for I and R. There is a direct equivalence with the plots in fig. 9.1, but by custom the discrete functions have different names: the relative frequency plot is the probability mass function (pmf), and the cumulative one is the cumulative mass function (CMF). Otherwise we use them in much the same way as their continuous counterparts. The only difference is that the CMF has sudden jumps at points where the pmf is nonzero (fig. 9.3 shows vertical bars of height equal to 1/3 that describe the pmf of both I and R).

We assume a realistic constraint on the regional flow output O: due to an agreement with the authorities of the downgradient groundwater management district, O cannot be arbitrarily lowered to satisfy pumping needs. The agreement recognizes that uncertainty is a fact of life, and establishes a risk-based constraint: O has to equal or exceed nine units with a probability of 80% or better (if we assume that uncertainty is due to interannual variability, this constraint is equivalent to accepting that O can be less than nine units in one out of every five years, on average). Here risk is the probability of failing to meet the standard that O equals or exceeds nine units. Alternative standards could be expressed in terms of other variables, such as maximum water-level declines, maximum concentration of dissolved solids at the pump, etc. The novelty of this approach is that a (small) risk of noncompliance is accepted to build some flexibility into management policies. Knowing that the complement of risk is reliability, and that both quantities add up to unity, we can see that the above policy has a reliability of 80% and a risk of 20%.

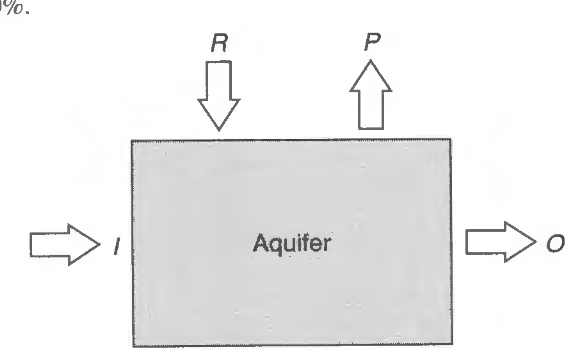

FIGURE 9.2—BOX DIAGRAM DEPICTING FLUXES IN AND OUT OF AN AQUIFER: freshwater recharge (R), pumping (P), regional ground-water flow input (I), and regional ground-water flow output (O).

Armed with this information, we can evaluate the behavior of the system with and without pumping. That is, using the above balance equation we calculate values of the output O, corresponding to each value of pumping P. Under predevelopment conditions ($P = 0$), $I + R = O$. Because I and R can each take on three different values, O can take on the following nine values: {10; 11; 12; 11; 12; 13; 12; 13; 14}. Each of the nine values is equally likely (each has a probability equal to 1/9), but some of them occur more than once. This can be easily accounted for by counting repeated occurrences and adding their original probabilities as shown in table 9.1; the resulting values of O and their probabilities are summarized in the following table and displayed in fig. 9.4B.

The corresponding cumulative probabilities, Prob[$O < x$], are obtained by adding up the individual values smaller than a given threshold, as shown in the last column of table 9.1 and plotted in fig. 9.4A. We can use this figure to

TABLE 9.1—REPEATED OCCURRENCES OF VALUES OF CALCULATED OUTPUT AND THEIR ORIGINAL PROBABILITIES.

x	Prob[$O = x$]	Prob[$O < x$]
10	1/9	0
11	2/9	1/9
12	3/9	3/9
13	2/9	6/9
14	1/9	8/9

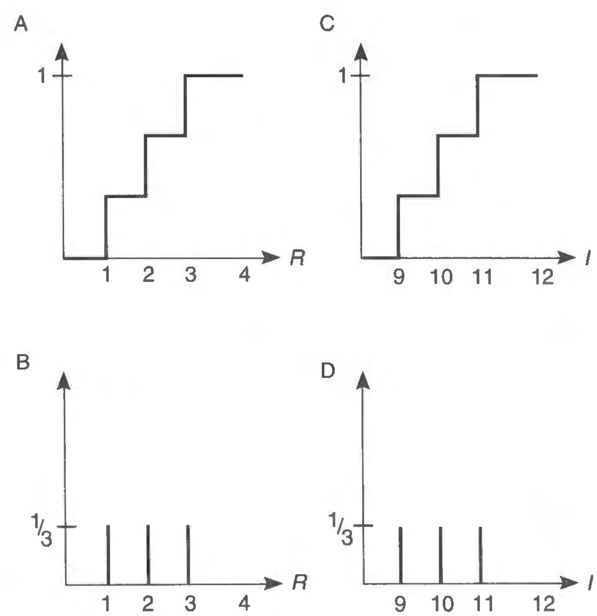

FIGURE 9.3—UNCERTAINTY IN THE ESTIMATES OF FRESHWATER RECHARGE R AND REGIONAL GROUND-WATER FLOW INPUT I, as measured with three-point probability mass functions (pmf) and cumulative mass functions (CMF). (A) CMF of recharge R. (B) pmf of recharge R. (C) CMF of ground-water-flow input I. (D) pmf of ground-water-flow input I.

evaluate the probability of compliance with the minimum-flow requirement: the risk of having O less than nine units has to be smaller than 20%. Examination of fig. 9.4A reveals that the probability Prob[$O < 9$] is zero, because all values are larger than nine units. Then, in the absence of pumping, this constraint is easily met.

To analyze the impact of pumping, we simply repeat the calculation of O for different values of P. The results are displayed in fig. 9.5 and shown in table 9.2. From table 9.2 we can read the probability of compliance with the minimum flow requirement, for each value of P. We observe that when $P = 3$ the requirement is not met, since Prob[$O < 9$] = 3/9 = 33%. However, $P = 2$ is acceptable, because Prob[$O < 9$] = 1/9 = 11%.

Now examine the alternative of neglecting uncertainty. We change the risk-based constraint to an equivalent deterministic one: the output O can have a minimum value of 10 units. We adopt the mean values for I and R ($I = 10$; $R = 2$), and find out that a pumping level of $P = 2$ units is acceptable. By coincidence this value is the same as the one determined with full knowledge of uncertainty. However, there is a large chance (1/3) that O will be less than 10 units, as shown in table 9.2 and in fig. 9.5. In other words, we are taking a risk of 33% of not meeting the minimum-flow requirement, but we do not know it. In general we can expect such apparently risk-neutral policies to carry an even larger risk (called risk-neutral because uncertainty and risk are neglected altogether). We can easily see that this is true even in the above example.

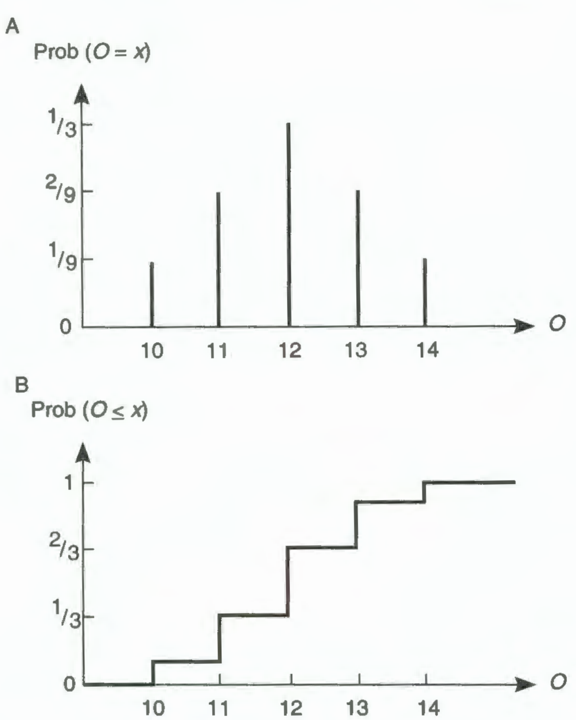

FIGURE 9.4—UNCERTAINTY IN THE ESTIMATES OF REGIONAL GROUND-WATER FLOW OUTPUT O IN THE ABSENCE OF PUMPING, as predicted with a steady-state mass balance model. (A) Probability-mass function (pmf). (B) Cumulative-mass function (CMF).

TABLE 9.2—PROBABILITY OF COMPLIANCE WITH MINIMUM FLOW REQUIREMENT FOR EACH VALUE OF PUMPING (P).

$P = 1$ case:	x	Prob[O = x]	Prob[O < x]
	9	1/9	0
	10	2/9	1/9
	11	3/9	3/9
	12	2/9	6/9
	13	1/9	8/9
$P = 2$ case:	x	Prob[O = x]	Prob[O < x]
	8	1/9	0
	9	2/9	1/9
	10	3/9	3/9
	11	2/9	6/9
	12	1/9	8/9
$P = 3$ case:	x	Prob[O = x]	Prob[O < x]
	7	1/9	0
	8	2/9	1/9
	9	3/9	3/9
	10	2/9	6/9
	11	1/9	8/9

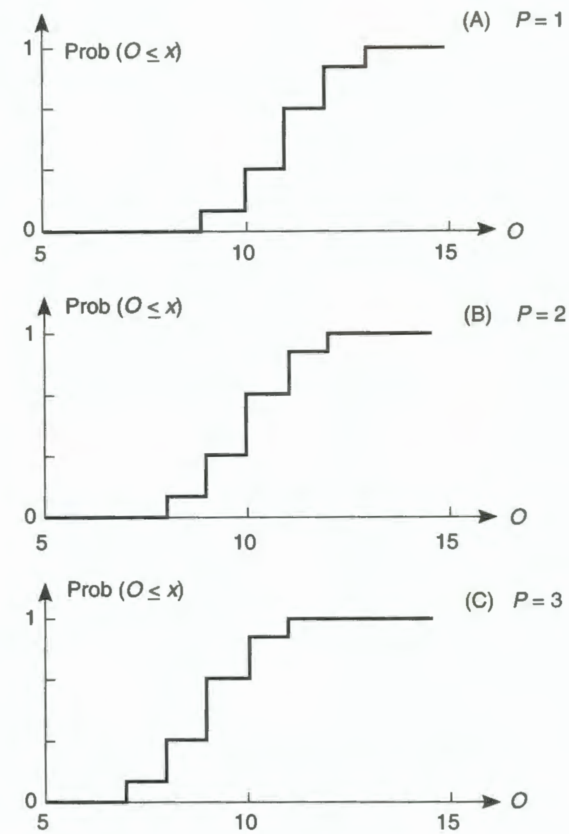

FIGURE 9.5—UNCERTAINTY IN THE ESTIMATES OF REGIONAL GROUND-WATER-FLOW OUTPUT O FOR THREE DIFFERENT LEVELS OF PUMPING P, as predicted with a steady-state mass-balance model. Cumulative-mass functions are shown for (A) $P = 1$, (B) $P = 2$, (C) $P = 3$.

Imagine that we improve the resolution of our estimates by using more than three points to represent both I and R; the result will be a CMF with more steps than those in fig. 9.5. As we increase the number of points, the CMF approaches a smooth curve, while the mean value of O approaches 10 units; this process is schematically depicted in fig. 9.6. In a symmetric distribution, this means that there is a risk of about 50% of having actual values smaller than 10 units!

Managing Uncertainty and Making Decisions

Review the essence of the previous two examples. We recognized that each problem had a significant component of uncertainty and chose to incorporate it into the analysis. We tested a simple way to quantify uncertainty by means of three-point discrete distributions for each uncertain quantity. We learned how to graphically display information about uncertain quantities in terms of appropriate probability distributions (pdf and CDF for continuous, and pmf and CMF for discrete quantities). We also evaluated a risk-based constraint and made a decision based on it. In a nutshell, we learned a proactive approach to uncertainty management and decision-making under uncertainty.

The two examples illustrate that dealing with uncertain quantities is not a complicated process. However, it requires a sustained interest in exploring all possibilities, and a determination not to discard information too early in the process. By seeking and preserving the most information, we can present more alternatives to the decision makers, who can then make choices in terms of the risk level that they deem acceptable. This approach is superior to the alternative, where one makes a decision disregarding uncertainty and then hopes that the actual risk will turn out to be small.

On the other hand, there is a small price to pay to incorporate uncertainty in analyses and quantify the risk of alternative decisions. First, we may need to entertain more complex models of the hydrologic system in order to incorporate all possible sources of uncertainty. Second, we need to seek more information to define a range of values for each quantity (instead of a single estimate). However, this is not hard to do: all we need are realistic upper and lower bounds. With these bounds and a best estimate for each quantity, we can easily conduct a three-point uncertainty analysis, as demonstrated in the ground-water-yield example.

There is more to decision-making under uncertainty than the regulatory framework used in this example, where we assumed that an acceptable risk level had already been fixed. In most cases, decision-makers will evaluate the tradeoff between risks and consequences, often considering a suite of decision variables. There are many ways to combine disparate quantities in a single criterion, which can then be optimized to reduce the risk of an adverse event (cost-benefit analysis is a well-known example). An important advantage of using such a unified framework is that the impact of procuring additional information can be measured in terms of whether it can change the optimal decision (these are known as value-of-information analyses).

This points to the fact that uncertainties are not important per se, but only to the extent that they change the decisions to be made. This is especially important in water-resources management; we could be rather uncertain about some aspect of the hydrologic system, but if this uncertainty does not change the decision, it becomes irrelevant for management purposes. For this reason it is crucial to propagate uncertainties in the analysis all the way to the decision-making step. This also makes life easier because we do not need to decide a priori which uncertainties are of scientific interest and which of management relevance; this is decided automatically in the framework of decision-making under uncertainty.

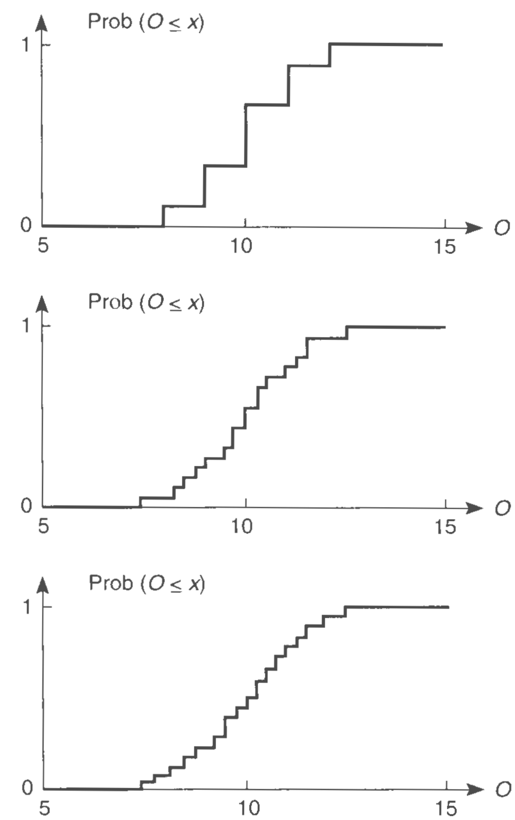

FIGURE 9.6—DISTRIBUTION OF REGIONAL GROUND-WATER-FLOW OUTPUT O FOR PUMPING $P = 2$. Schematic illustration of the effect of refining the calculation by using more points to represent the variability of both recharge R and regional ground-water-flow input I.

Uncertainties Affecting Ground-water-yield Estimates

In the ground-water-yield example, we used the simplest possible balance model to determine an acceptable water yield (pumping rate). This was useful to illustrate the main concepts, but hardly realistic as to the type and amount of information that would be needed in practice. Dealing with more information requires hydrologic models that incorporate more details of the natural system, and this means more sources of uncertainty. In this section we review some of those sources and their impact on ground-water-yield estimation.

A hydrologic model is always a simplified representation of the real system. Regardless of the scale of phenomena included in the model, details at smaller scale are not explicitly represented. If necessary they can be accounted for as additional uncertain variables. For example, spatial variability in aquifer properties can be represented in reasonable detail at the scale of a well field, but disregarded at the basin scale. Although average property values can be used at the basin scale, we can still preserve some information on its variability by treating it as an uncertain variable.

Consider a ground-water model. Once the scale and the spatial boundaries of the model are selected, we deal with four types of quantities: inputs, outputs, parameters, and decision variables. Decision variables , such as pumping rates, are controlled by the decision-makers and therefore carry no uncertainty. Outputs, such as water-table elevation, are the measures of system response predicted by the model; as we have seen, the model can predict uncertainty in outputs if desired. Then, it is only inputs and parameters that we need to assess as uncertain quantities. In the rest of this section we discuss model inputs and parameters as sources of uncertainty, and their impact on the uncertainty of model outputs, such as water yield.

Parameters of a ground-water model are related to the geology: thickness and spatial extent of aquifers and aquitards, lithology, porosity, permeability, etc. These quantities are spatially variable and only accessible to measurement at selected locations; at other locations we may obtain estimates by interpolation. Such estimates can then be treated either as perfectly known or as uncertain quantities in the model. Depending on the scale of the model, more than one spatially variable quantity may have to be considered. For example, uncertainty in hydraulic conductivity is relevant at the local scale (e.g., a well field); at the regional and basin scale other variables, such as formation thickness and horizontal continuity, compound their uncertainty to make the aquifer transmissivity an uncertain variable.

Figure 9.7 illustrates the natural variability in hydraulic conductivity in an aquifer, obtained from core samples (this distribution can also be interpreted as a measure of the uncertainty at unmeasured points in the same aquifer). The figure shows two distributions with the same mean value but different spread about the mean. Depending on whether the real distribution follows curve A or B, the ground-water system will behave very differently, and calculations that rely only on the mean value will miss significant information. Curve B has a larger spread than curve A, and therefore more extreme values on both ends of the spectrum displayed in fig. 9.7; the left tail of curve B corresponds to K values of smaller magnitude than the smallest values in curve A, while the right tail represents the reverse situation. The larger hydraulic-conductivity values at the right tail in curve B will correspond to larger velocity and shorter travel times than in curve A. This will affect yield estimates when subject to water-quality constraints. For example, if salinity transport from underlying aquifers is of concern, the critical travel time will be measured from a salt source to the point of interest, such as a well or a gaining stream.

Inputs of a ground-water model are a diverse group of variables. They include water fluxes in and out of the model area, and water levels at reference locations such as lakes and streams. Water levels are regularly measured and carry little uncertainty, while fluxes are usually estimated and may carry significant uncertainty. Inflows to a ground-water model include incoming regional flow, recharge from underlying aquifers, and freshwater recharge from precipitation. Outflows include outgoing regional flow, discharge to streams, and pumping wells. These model inputs reflect the influence of external processes on the ground-water system, among them human activities and climate.

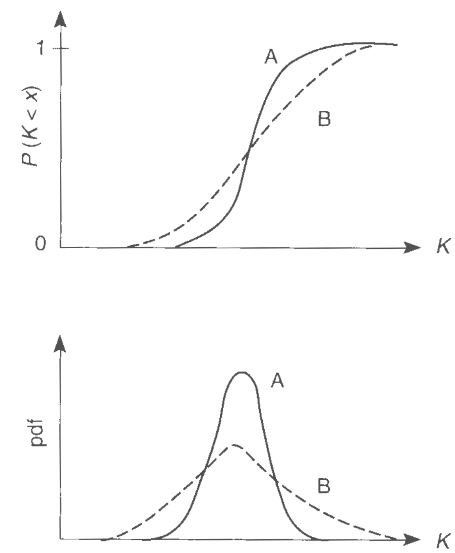

FIGURE 9.7—HETEROGENEITY IN HYDRAULIC CONDUCTIVITY K IN A SINGLE AQUIFER. Two distributions with the same mean but different standard deviation.

As discussed in Chapters 2 and 4, estimating ground-water yield is highly dependent on estimates of ground-water recharge and discharge change, which are subject to considerable uncertainty even under stable climatic conditions. Recharge estimates should reflect the natural variability in precipitation and temperature, with seasonal and multi-year cycles. Climate change would greatly increase the uncertainty in recharge estimates; this effect can be so dramatic as to overwhelm the uncertainty due to natural variability under a stable climate (see Chapter 8).

Estimating uncertainty in climate-related variables such as precipitation, temperature, and evapotranspiration presents unique difficulties. The primary reason is that we have to make inferences based on relatively short records (a hundred-year-long record is short in terms of climate processes). These records can capture at best some of the natural variability, but they provide no information about periods of qualitatively different climate. However, a number of such scenarios can be obtained from climate models and appropriately translated into ground-water models in terms of freshwater recharge. For example, we might want to examine the impact of an increase in precipitation. Figure 9.8 displays one possible scenario, where the whole distribution of mean annual precipitation is assumed to have shifted by a constant amount (curve A is the original distribution; curve B is the shifted one with a larger mean value). Under the scenario represented by curve B, wet years will have larger precipitation, while dry years will not be as dry as earlier (both in comparison to curve A). By conducting quantitative analyses like these, we can incorporate a realistic source of uncertainty that is not based on past data, but on analysis of possible futures.

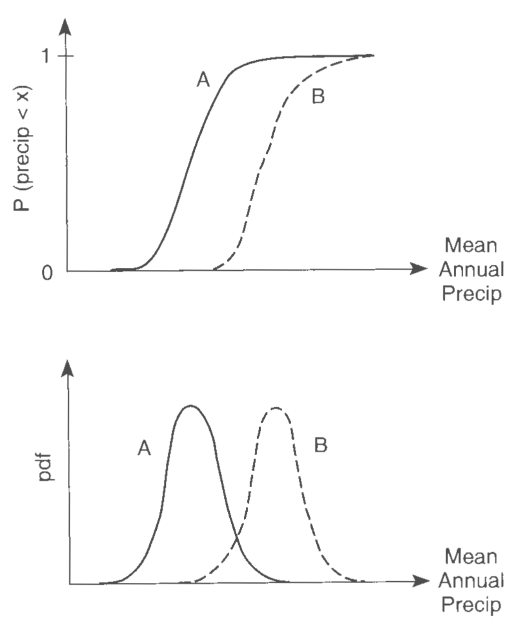

FIGURE 9.8—EFFECT OF CLIMATE CHANGE ON THE DISTRIBUTION OF MEAN ANNUAL PRECIPITATION, assuming that all values are increased by the same constant amount.

This is a type of knowledge uncertainty that we can only uncover through what-if analyses. The same applies to changes in land-use and agricultural practices.

Uncertainties in model inputs and parameters translate into uncertainty in those variables chosen as model outputs. Examples include water-level decline, ground-water discharge to streams, and salt content. Existing records for such variables provide a summary of system response, which can be useful to calibrate or constrain model parameters. However, the response is not immediate and there is always a lag between changes in inputs and the corresponding changes in outputs. Ground-water flow and transport processes reflect changes in inputs, according to their own characteristic time scales. Ground-water flow adjusts to changes in pumping and/or regional recharge within a time period that depends on the average aquifer properties at the appropriate scale. For example, a pumping well in the Dakota aquifer may take months or years to generate a steady-state-capture zone (see fig. 4.18). An example at the basin scale is the depletion time, which can be calculated with the linear-reservoir model (see fig. 2.8).

Water managers need to assess typical time scales such as these to characterize the transient response of the system before evaluating management options. The next step is to assess how much information we really have in the corresponding records. In simple terms, even assuming that the system is in steady-state, long records are needed to reliably define statistics such as the mean and standard deviation. However, the length of a time series is not measured by the raw number of data points; instead, what matters is the number of times that the time scale of interest fits into the record length.

Let us consider an example under typical conditions of central Kansas. If we are interested in the time scale of freshwater recharge, we have to consider only the years that had rather large precipitation events. This is because there is no recharge in those years with small or average precipitation events (Chapter 7 justifies this statement, using detailed modeling of water percolation through soils typical of central Kansas). As depicted in fig. B7.1.2, only eight such events occurred in the 40-year period from 1953 to 1993. Thus, in terms of the variable of interest, the records are five times shorter than originally thought! The importance of this issue cannot be overstated, because the flip side of extracting less information from the data is an increase in uncertainty. This applies equally to model inputs and outputs.

Ground-water Management Under Yield Uncertainty

Being aware of the uncertainties discussed in the previous section, we can now address some of the implications for ground-water-yield management policies in Kansas.

First we should note that current ground-water-management policies do not incorporate uncertainty considerations, in contrast to regulations pertaining to surface-water reservoirs (see Chapter 6). At the most basic level this means that the risks associated with current policies are unknown. We suggest that a first step in the right direction would be to start working towards defining risk-based policies. This will require a preliminary assessment of the uncertainties involved in yield estimates.

A practical advantage of recognizing uncertainty in yield estimates is that the concepts of safe yield or guaranteed yield lose much of their meaning. This should make easier the shift to a new management paradigm, based on achieving an equilibrium yield sometime in the future. Such a long-term equilibrium value will be highly dependent on the level of risk that can be tolerated. By openly dealing with risk, ground-water managers have to periodically define the meaning of safe yield (by changing either the risk level and/or the total ground-water appropriation). We can view this process as essentially deciding how much protection is necessary or affordable, much the same as individual decisions about insurance.

Assuming that the long-term objective would be some sort of sustainable yield policy (defined as a new achievable equilibrium), the preliminary appraisal will measure the imbalance between the current level of appropriations and the level required in the long term. In most of western Kansas, it is obvious that the long-term appropriation level will be significantly smaller than the current one. That much can be said in general, and beyond this point there will be many policy options to consider. Basically we will have to decide how to go from point A to point B (the two appropriation levels), and how much time we will allow for the transition. However, as long as there is going to be a transition, it will require a dynamic appropriation policy, even if that means making changes every 10 or 20 years. The financial impacts on current water-rights holders could be minimized by placing a cap in the reduction of rights that can be mandated (e.g., 10% every 10 years). Such a policy would keep water rights relatively stable in the scale of one or two generations (25 to 50 years), while allowing the necessary corrections over a century or two.

Because of the many uncertainties involved, the process of adjustment should be viewed as a learning experiment in itself. Therefore, decisions will have to be revised and updated periodically. Analyses will have to be refined and more information procured to reduce the overall uncertainty. One possibility would be to rank the individual components of uncertainty in the analysis, and then focus on reducing those that contribute the most to the overall uncertainty. Such a ranking will have to be case-specific and scale-specific to be both accurate and useful to guide decisions. Repeating this process as new information becomes available will lead to better estimates of ground-water yield, reducing the associated uncertainty.

The above discussion cannot be construed to imply that the uncertainties are so important as to preclude any action until we obtain more information. On the contrary, incorporating uncertainty is just a way to make the most of the available information and evaluate actions in terms of the risks involved. Parallel analyses, with and without consideration of uncertainty, would often lead to the same course of action. Take the example of the Ogalalla aquifer in western Kansas, where continuous water-level declines in the last few decades clearly indicate an overexploitation of the resource. Yield estimates that neglect uncertainty will predict diminishing yields of a given magnitude in the future. Yield estimates that incorporate uncertainty will predict a high risk of having yields of smaller magnitude than the present ones. However, in both cases, the recommended action would be similar, recognizing that the system is rapidly moving towards depletion under the current level of appropriations. Hence, this region is a prime candidate for implementing a policy of gradually decreasing total appropriations, starting now. The level of reduction in appropriations can be adjusted periodically, as explained above, as we learn more about the system by monitoring its response to reduced pumping.

In other words, there are cases where a clean signal can be extracted from the available information in spite of the uncertainties. In those cases (e.g., the Ogalalla in western Kansas), we can clearly define where the system is today and the trend in the near future if we do nothing about it. The anthropogenic impact on the Ogallala system has been of such magnitude that the first-order picture is clear, and uncertainties only add a confidence band to it. We need to consider uncertainties in order to make detailed hydrologic and economic calculations to support specific decisions, but not to put together a one-page white paper on the availability of ground water in western Kansas.

Concluding Remarks on Risk and Uncertainty

"If a man will begin with certainties, he shall end in doubts,
but if he will be content to begin with doubts, he shall end in certainties."
—*Francis Bacon*

The most basic idea presented in this chapter is that by recognizing uncertainty we can make the most of the available information, thus leading to better decisions. Fortunately, dealing with uncertain quantities is not a complicated process. It only requires a determination not to discard information too early in the process, and a sustained interest in exploring all possibilities.

Uncertainties enter the analysis when we evaluate not only what we know, but also what we do not know about the hydrologic system. The uncertainties inherent in hydrologic characterization bring an element of risk to water management and decision making, because there is always a finite risk that the action taken will not produce the desired result. Thus, risk and uncertainty are inseparable companions.

Although natural systems can never be perfectly known, decisions still need to be made. Uncertainty must not paralyze decision making. On the contrary, if properly handled, it can only enrich and facilitate decision making. At the most basic level, explicitly evaluating uncertainty provides a wider range of possible scenarios or outcomes from which to choose management actions. Ideally, full consideration of uncertainty will result in the implementation of risk-based water-management policies.

The practical lesson of this chapter is that any value of water yield has a risk of not being realized 100% of the time. It is the job of water managers to reach a balance between the desire for larger yields and the reality of larger risks associated with them. The need to balance risks and water yields is independent of the degree of uncertainty. More studies can reduce some uncertainty but not all, because part of the uncertainty depends on controlling factors outside the systems studied, such as climate change. Ultimately, the right answer to any yield-estimation question is . . . We do not know for sure: it depends on the risk that we want to accept.

Further Reading

Much has been written about the issues discussed in this chapter. The following references provide good starting points for further study.

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CHAPTER 10

Concluding Comments on Managing Water-resources Systems: Why "Safe Yield" is Not Sustainable

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"For in the end we will conserve only what we love;
we will love only what we understand;
and we will understand only what we are taught."

—*Baba Dioum*,
African Conservationist

Water resources are essential to both economic development and the maintenance of natural systems. Few areas of public policy are as contentious as the issues surrounding management of our environment and natural resources, such as water.

Among the greatest challenges facing society today is the need to understand more fully the complex ecological processes that maintain our human life-support system and to integrate knowledge about these processes into management and policy decisions (Reichman and Pulliam, 1996). As Pulliam and O'Malley (1996) emphasized, knowing what we have, understanding how natural ecosystems work, and effectively communicating to decision-makers about environmentally sustainable practices are crucial if we are to ensure that the natural goods and services that we have enjoyed will continue to be available for both present and future generations.

Arrow et al. (1995) argue that the current economic system fails to account for the depletion of resource stocks and ecosystem services, and that the environmental resource base, of which water is part, is finite. When inventories are depleted and the physical plant is allowed to deteriorate, it is possible to make a profit in the short term while watching net worth waste away. Such is the road to bankruptcy. Businesses routinely make decisions that may have short-term costs but obvious benefits to their long-term sustainability. This comparison to the business world captures the sense of intergenerational equity and stewardship that are central to an ecosystem management philosophy (Christensen et al., 1996). Ecosystem management is the ecological analog to the economic stewardship of a trust or endowment dedicated to benefitting all generations.

During the past few decades we have gained a better understanding of soil and water ecosystems and related processes, but too little of this knowledge has been applied successfully to fundamental management programs. Although major gaps remain in our understanding of such systems and processes, of more importance are the gaps between what is known and what is applied (NRC, 1991). Therefore, we need to develop better ways to communicate results and facilitate their implementation.

One such gap between what is known and what is applied is the use of the sustainability concept of "safe yield" of ground water, which persists today despite being repeatedly discredited in the literature. Unfortunately, misconceptions and narrowmindedness about safe yield and ground-water management persist, leading to continued ground-water depletion, stream dewatering, and loss of wetland and riparian ecosystems. Hopefully this volume has contributed in elucidating some of the issues involved.

To protect ground-water supplies from overexploitation, some state and local agencies have enacted regulations and laws based on the sustainability concept of "safe yield." Safe yield is traditionally defined as the attainment and maintenance of a long-term balance between the amount of ground water withdrawn annually and the annual amount of recharge. Therefore, safe yield allows water users to pump only the amount of ground water that is replenished naturally through precipitation and surface-water seepage. Although this traditional safe-yield concept sounds reasonable, it ignores discharge from the system. Under natural or equilibrium conditions, recharge to an aquifer results, in the long term, in an equal amount of water that is discharged from the aquifer into a stream, spring, or seep. Consequently, if pumping equals recharge, the streams, marshes, and springs eventually dry up. Continued pumping in excess of recharge also eventually depletes the aquifer. This has happened in various locations across the Great Plains and elsewhere, as we have shown in Chapters 2 and 3. Probably the best known example is the Ogallala or High Plains aquifer, in which water-table declines of more than 100 ft (30 m) have occurred in parts of Texas, New Mexico, and Kansas. Maps comparing the perennial streams in Kansas in the 1960's to those of the 1990's show a marked decrease in miles of streamflow in the western third of the state. Policy-makers are primarily concerned about aquifer drawdown and surface-water depletion, both unrelated to the natural-recharge rate (Balleau, 1988). Despite its irrelevance, natural recharge is often used in ground-water policy to balance ground-water use under the banner of safe yield. Adopting an attractive fallacy that the natural-recharge rate represents a safe rate of yield does not provide scientific credibility.

To better understand why this is happening, a knowledge of hydrologic principles (concisely stated by C. V. Theis in 1940) is required (see also Chapter 2). Under natural conditions, prior to development by wells, aquifers are in a state of approximate dynamic equilibrium: over hundreds of years, wet years in which recharge exceeds discharge offset dry years when discharge exceeds recharge. Discharge from wells upsets this equilibrium by producing a loss from aquifer storage; a new state of dynamic equilibrium is reached when there is no further loss from storage. This can be accomplished only by an increase in recharge, a decrease in natural discharge, or a combination of the two. Ground water pumped from the aquifer comes from two sources: aquifer storage and induced recharge of surface water (because natural recharge is balanced by natural discharge under equilibrium conditions). Initially, ground water comes from storage, but this source ultimately ceases. The timing of the change from storage depletion to induced recharge is a key factor in developing water-use policies. This transition takes a long time by human standards. Distinguishing between natural recharge and induced recharge to ascertain possible sustained yield is exceedingly difficult and is an area that needs further research. Calibrated stream-aquifer models could provide some answers in this regard.

Although the ideas of sustainable yield have been around for many years, a quantitative methodology for the estimation of such yield has not yet been perfected. A suitable hydrologic basis for determining the magnitude of possible development would be a quantification of the transition curve (from ground-water-storage depletion to full reliance on induced recharge), coupled with a projected pattern of drawdown for the system under consideration (Chapter 2). The level of ground-water development would be calculated using specified withdrawal rates, well-field locations, drawdown limits, and a defined planning horizon (Balleau, 1988). Since the 1980's, three-dimensional numerical models of the complete stream-aquifer hydrogeologic system have been employed to provide a predictive tool explaining the connection between well-field withdrawal and surface-water depletion, and are capable of generating the transition curve for most situations.

Ground-water management cannot be conceived of separately from management of surface waters. Because of the interdependence of surface and ground water, operations on any part of the system have consequences for the other parts. The impact of ground-water development on streams is highly variable. The management category of minable water may be a reasonable one to apply to well-field areas that would not progress beyond the earliest stages of the transition from storage depletion to induced recharge within a reasonable planning horizon, as shown in Chapter 4 on confined aquifers. Thus, wise management of water resources needs to be approached both from the viewpoint of focusing on the volume and quality (Chapter 5) of water resources available for sustainable use, and from the impact of ground-water exploitation on the natural environment, including ground water, surface water, and riparian ecosystems.

Initially, the effect of wells on surface water was simply not known, and even now there is too little information to allow a complete and efficient administration of conjunctive use in most areas. Those who first endeavored to establish laws for ground-water administration were required to do so without much knowledge about hydrology. The result was the establishment of a legal model before the physical model had developed. Eventually, however, the science of hydrology developed to the point of demonstrating the interconnection of surface and associated ground water. The failures and unintended consequences of conventional and safe-yield-based water-management and development strategies provide some of the strongest incentives to replace such strategies with the broader sustainable-resource-system management. A few examples of such failures are given in Chapter 3 and range from local to global.

Safe yield is often used as a single-product exploitation goal—the number of trees that can be cut, the number of fish that can be caught, the volume of water that can be pumped from the ground or river, year after year, without destroying the resource base. However, experience has repeatedly shown that a single-product goal is too narrow a definition of the resource, because other resources inevitably depend on, or interact with, or flow from the exploited product. We can maximize our sustainable yield of water by drying up our streams, but when we do, we learn that the streams were more than just containers of usable water.

The conventional safe-yield approach is ambiguous, limited, and restrictive. Any change in conditions such as vegetation or land use, urbanization, location of pumping wells, or incorporation of new water supplies, requires calculation of a new yield. Thus, the conventional safe-yield approach lacks an unambiguous quantitative definition. Also it fails to recognize the impact of ground-water exploitation on the natural environment (Chapter 2). Thus, it is not satisfactory.

A better definition of safe yield would address the sustainability of the "system" and its water yield—not just the trees, but the whole forest; not just the fish, but the marine food chain; not just the ground water, but the running streams, wetlands, and all the plants and animals that depend on them. Given the dynamic connectedness of a watershed, management activities can fragment and disconnect the habitat "patches" if they are not planned and implemented from an ecosystem and watershed perspective (Chapter 3). In-stream conditions are mainly determined by processes occurring within the watershed and underlying aquifers, and they cannot be isolated from or manipulated independently of this context. Such a holistic approach, however, is fraught with difficulty. We cannot use a natural system without altering it, and the more intensive and efficient the use, the greater the alteration.

Science will never know all there is to know. This calls for applying the best of what we know today—while, at the same time, providing sufficient management flexibility to allow for change and for what we do not yet know. Evidence shows that we have altered the hydrologic cycle as well as cycles of many chemical elements, that we seem to be affecting climate (Chapter 8), and that biodiversity may be declining rapidly (Meyer, 1993). As shown in several chapters of this volume, we must manage for change and for complexity because natural systems are inherently "patchy" and complex. This also implies managing in a probabilistic and risk-assessment framework (see Chapter 9) in which one recognizes the inherent unpredictability of nature. Instead of determining a fixed sustainable yield, managers should recognize that yield varies over time as environmental conditions vary (Meyer, 1993).

Our understanding of the basic principles of soil and water systems and processes is fairly good, but our ability to apply this knowledge to solve problems in complex local and cultural settings is relatively weak (NRC, 1991). Communication is vital. We need people who can transfer research findings to the field and who can also communicate water users' needs to the researchers. As Christensen et al. (1996) pointed out, delivering a refereed journal publication to a manager's desk is not sufficient if we wish our best science to move quickly into management application. This breakdown in communication most probably accounts for the persistence of simplistic but misguided concepts such as conventional ground-water safe-yield management today. Our education system has mostly failed to stress the importance of sustainability in water-resources management. As Balleau (1988) commended, "Hydrology as a science has not been markedly successful in communicating its basic principles, such as mass-balance," especially in stream-aquifer systems. A water-policy study team (DuMars et al., 1986) advising the New Mexico Legislature concluded that "[t]his concept and its ultimate impact on the environment . . . is little understood by hydrologists and lay people alike." A strong public-education program is needed to improve understanding of the nature, complexity, and diversity of ground-water resources, and to emphasize how this understanding must form the basis for operating conditions and constraints. This is the only way to positively influence, for the long term, the attitudes of the various stakeholders involved.

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CHAPTER 11

Selective Glossary of Hydrology and Environmental Sustainability-related Terms

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(Note: Cross-referenced terms are shown in *italics*)

A

ablation (glacial): all processes, which include melting, evaporation (sublimation), wind erosion, and **calving** (breaking off of ice masses), that remove snow or ice from a glacier or snowfield. The term also refers to the amount of snow or ice removed by these processes.

acre-foot (AF): AF, a-f, ac-ft, aft. 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.

adaptive management: sustainable-management practices for *ecosystems* and species that are responsive to uncertainties and ecological fluctuations, as well as being reversible and flexible.

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*.

albedo: portion of incoming *solar radiation* that is reflected by a surface.

alluvial aquifer: aquifer formed by material laid down by physical processes in a river channel or on a *floodplain*.

alpha radiation: radiation consisting of positively charged helium nuclei. Alpha-emitting substances in natural water are mainly radium and radon which are members of the uranium and thorium series. See also *radioactivity*.

altithermal period: period of high temperature, particularly the one from 8000 to 4000 B.P. (before the present era), which was apparently warmer in summers, as compared with the present, and with the precipitation zones shifted poleward. Also called the *hypsithermal period*.

analytical model: model that uses closed-form mathematical solutions to the governing equations applicable, for example, to ground-water flow and transport processes.

anisotropy: condition of having different properties in different directions.

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.

appurtenant: existing as part of a broader property right. A surface *water right* may exist as part of the rights associated with ownership of land bordering a body of water or a ground water right may exist as part of the rights associated with ownership of the overlying land.

aquiclude: body of earth material of low *hydraulic conductivity* that can absorb water, but cannot transmit it at a rate sufficient for economic extraction by wells.

aquifer: one or more geologic formations containing sufficient saturated porous and permeable material to transmit water at a rate sufficient to feed a spring or for economic extraction by a well.

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: see *yield*.

aquifuge: body of earth material which is impervious to water and unabsorbtive.

aquitard: hydrogeological unit of much lower permeability than an aquifer (two or more orders of magnitude less) that will not sustain a water supply.

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 ground water: see *confined ground water.*

artesian well or **artesian spring**: 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 (An): 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.

atmosphere (The): envelope of air surrounding the earth and bound to it by the earth's gravitational attraction. Studies of the chemical properties, dynamic motions, and physical processes of this system consitute the field of *meteorology*.

atomic number: see *isotope*.

available water (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.

basin: see *drainage basin*.

basin yield: see *yield*.

beneficial use: use of water, such as domestic, municipal, agricultural, mining, industrial, stock watering, 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.

beta radiation: radiation consisting of electrons or positrons. See also *radioactivity*.

biochemical cycle: chemical interactions among the *atmosphere*, *biosphere*, hydrosphere, and lithosphere. Examples are the *carbon*, oxygen, nitrogen, phosphorus, sulfur, and *hydrologic cycles*.

biological diversity (**biodiversity**): variety of living organisms at all levels, from genes to species, populations and communities, including the variety and hierarchy of habitats and *ecosystems* that contain different biological communities.

biomass: total dry organic matter or stored energy content of living organisms that is present at a specific time in a defined unit (community, *ecosystem*, crop, etc.) of the earth's surface.

biome: large, easily recognized community unit formed by the interaction of regional climates with regional biota and *substrates*. Examples include the tundra biome, the grassland biome, the desert biome, etc.

biosphere: portion of earth and its *atmosphere* that can support life. The part (reservoir) of the global *carbon cycle* that includes living organisms (plants and animals) and life-derived organic matter (*litter*, *detritus*). The **terrestrial biosphere** includes the living biota (plants and animals) and the litter and soil organic matter on land, and the **marine biosphere** includes the biota and detritus in the oceans.

biota: see *carbon cycle*.

BOD: Biochemical Oxygen Demand. A measure of the amount of oxygen required to neutralize organic wastes.

brackish water: see *saline water*.

boundary condition: mathematical expression of a state of the physical system that constrains the equations of the *mathematical model*.

Brundland Commission: see *WCED*.

C

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.

caliche: zone or accumulation near the surface, more or less cemented by secondary carbonates of calcium (Ca) or magnesium (Mg) precipitated from the soil solution. It may occur as a soft thin soil horizon, as a hard thick bed beneath the *solum*, or as a surface layer exposed by erosion. It also is called **hardpan**, **calcareous duricurst**, or **calcrete**.

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.

carbon cycle: all parts (reservoirs) and fluxes of carbon; usually thought of as a series of the four main reservoirs of carbon interconnected by pathways of exchange. The four reservoirs, regions of the earth in which carbon behaves in a systematic manner, are the *atmosphere*, *terrestrial biosphere* (usually includes freshwater systems), oceans, and sediments (includes fossil fuels). Each of these global reservoirs may be subdivided into smaller pools ranging in size form individual communities or *ecosystems* to the total of all living organisms (**biota**). Also defined as carbon exchanges from reservoir to reservoir by various chemical, physical, geological, and biological processes.

carrying capacity: (1) the maximum number of organisms that an area or habitat can support without reducing its ability to support the same number of organisms in the future; (2) the amount of biological matter the system can yield, for consumption by animals or humans, over a given period of time without impairing its ability to continue producing, or the number of animals it can support without being degraded; (3) the maximum population of a given species that can be supported indefinitely, in a particular region, allowing for seasonal and random changes, without any degradation of the natural resource base that would diminish the maximum population in the future; (4) the maximum intensity of use an area will continuously support under a management program without inducing a permanent change in the biotic environment.

catena: sequence of soils of about the same age, derived from similar parent material and occuring under similar climatic conditions, but having different characteristics due to variation in relief and in drainage.

CERCLA: Comprehensive Environment Response, Compensation, and Liability Act. Also known as **Superfund**. The Act gave EPA the authority to clean up abandoned, leaky hazardous waste sites.

chlorofluorocarbons (CFCs): family of inert gases, including CFC-11, CFC-12, and CFC-13. These chemicals are used in refrigeration, air conditioning, packaging, and insulation or as solvents or aerosol propellants. These gases are of concern for two reasons. First, in the upper *stratosphere* they result in ozone degradation. Second, they are also potent *greenhouse gases*. CFCs are currently regulated under the Montreal Protocol on Substances that Deplete the Ozone Layer.

climate: generalized weather at a given place on earth over a fairly long period (usually decades); a long term average of weather. Compare *weather*.

climate change: long-term fluctuations in temperature, precipitation, wind, and all other aspects of the earth's climate. External processes, such as *solar-irradiance* variations, variations of the earth's orbital parameters (eccentricity, precession, and inclination), lithosphere motions, and volcanic activity, are factors in climatic variation. Internal variations of the climate system also produce fluctuations of sufficient magnitude and variability to explain observed climate change through the *feedback* processes interrelating the components of the climate system.

climatic year: 12-month period used in the collection of precipitation data. Climatic years begin July 1 and end the following June 30, and are designated by the calendar year in which the climatic year ends.

climax: in ecology, the final stable or equilibrium stage of development that a community, species, flora, or fauna attains in a given environment. The major world climaxes correspond to *biomes*.

conceptual model: interpretation or working description of the characteristics and dynamics of the physical system.

cone of depression: cone-shaped lowering of the *water table* or *potentiometric surface* around a pumped well.

confined aquifer: aquifer that is bounded above and below by formations of significantly lower *hydraulic conductivity*.

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: term which replaces the terms *aquiclude*, *aquitard*, and *aquifuge,* and defined as a body of "impermeable" material stratigraphically adjacent to one or more aquifers. In nature, however, the confining bed's *hydraulic conductivity* may range from nearly zero to some value distinctly lower than that of the aquifer.

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 of matter: see *mass balance*.

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.

contaminant plume: zone of polluted ground water downgradient from a point source of pollution.

continuous cropping: one crop planting following soon after harvest, without seasonal *fallowing*.

contour cropping: use of tillage that follows the contours of a slope, rather than up and down a slope. It helps prevent erosion and *runoff*.

crop residue: organic material that remains in the field following harvest.

crop rotation: successive planting of different crops in the same field over a period of years, usually to reduce the pest population or to prevent soil exhaustion.

cropping patterns: yearly sequence and spatial arrangement of crops or alternating crops and *fallow* within a given area. The fallow crop may be natural or planted.

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.

curie (Ci): unit in reporting radioactivity in water, defined as 3.7×10^{10} radioactive disintegrations per second (the approximate specific activity of 1 gram of radium in equilibrium with its disintegration products). This unit is very large for the purpose of expressing natural radioactivity levels, and for this reason such data are often expressed in *picocuries* (*pCi* or curies $\times 10^{-12}$). See *radioactivity*.

current meter: device for measuring water velocity, consisting of a propeller that turns at a rate dependent on the water velocity.

curve number: Natural Resources Conservation Service-developed technique to estimate storm runoff from watersheds with various kinds of soil and land use.

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*.

Delphi method: method of seeking consensus among a panel of evaluators on questions that involve value judgments of relative worth.

dendrochronology: dating of past events and variations in the environment and the climate by studying the annual growth rings of trees. The approximate age of a temperate forest tree can be determined by counting the annual growth rings in the lower part of the trunk. The width of these annual rings is indicative of the climatic conditions during the period of growth; wide annual rings signify favorable growing conditions, absence of diseases and pests, and favorable climatic conditions, while narrow rings indicate unfavorable growing conditions or climate.

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 are usually 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.

desertification: progressive destruction or degradation of vegetation cover especially in arid and semiarid regions bordering existing deserts. Overgrazing of rangelands, large-scale cutting of forests and woodlands, drought, and burning of extensive areas all serve to destroy or degrade the land cover. The climatic impacts of this destruction include increased *albedo* leading to decreased precipitation, which in turn leads to less vegetation cover; increased atmospheric dust loading could lead to decreased monsoon rainfall and greater wind erosion and/or atmospheric pollution.

detritus: parts of dead organisms and cast-off fragments and wastes of living organisms.

dew point: temperature at which condensation occurs for a given amount of water vapor.

discharge: volume of water (and suspended sediment in surface water) that passes a given location within a given period of time.

discharge area: area in which water is lost naturally from the saturated zone.

dispersivity: scale-dependent aquifer parameter that determines the degree to which a dissolved constituent will spread in flowing ground water.

dissolved oxygen (DO): amount of oxygen gas dissolved in a given quantity of water at a given temperature and atmospheric pressure. It is usually expressed as a concentration in parts per million or as a percentage of saturation.

distributed-parameter models: models that account for spatial variations in parameters throughout the system.

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.

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) interval 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

Earth Summit: see *UNCED*.

ecological or **ecosystem functions**: processes among and within the various biological, chemical, and physical components of an *ecosystem* that consist of specific activities or flows, such as nutrient cycling, biological productivity, hydrology, and sedimentation; dynamic and sequential interactions that characterize the evolution of the *system*, such as exploitation, conservation, release, and reorganization; and the cumulative effect of these processes and interactions, such as the ability of ecosystems to support life. Ecological functions that are currently perceived to support and protect the human activities of production and consumption or affect overall well-being in some way, thus impacting on human welfare and even existence.

ecosystem: biological communities that interact with the physical and chemical environment as a unified *system*, while simultaneously interacting with adjacent ecosystems and with the *atmosphere*.

ecotone: transitional zone in which one type of *ecosystem* tends to merge with another ecosystem.

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*.

El Niño: irregular changes in the ocean currents off the west coast of South America that result in prolonged increases in sea-surface temperatures along the coast of Peru and in the equatorial eastern Pacific Ocean. El Niño has been linked to distant atmospheric features having diverse effects, such as the Indian monsoon, shrimp production in Louisiana, and wildland fires in the United States.

elevation head: see *hydraulic head*.

environment: sum of all external conditions affecting the life, development, and survival of an organism.

environmental sustainability: widely espoused goal that seeks to improve human welfare by protecting the sources of raw materials used for human needs and ensuring that the *sinks* for human wastes are not exceeded, in order to prevent harm to humans. Environmental sustainability means *natural capital* must be maintained, both as a provider of inputs ("sources"), and as a *sink* for wastes. This means holding the scale of the human economic subsystem to within the biophysical limits of the overall ecosystem on which it depends. Environmental sustainability needs sustainable production and sustainable consumption. On the sink side, this translates into holding waste emissions within the assimilative capacity of the environment without impairing it. On the source side, harvest rates of renewables must be kept within regeneration rates. Nonrenewables cannot be made fully sustainable, but quasi-environmental sustainability can be approached for nonrenewables by holding their depletion rates equal to the rate at which renewable substitutes can be created. See also *sustainable development*.

ephemeral flow: when water flows in a channel only after precipitation.

epilimnion: warm, less-dense top layer in a stratified lake. Compare *hypolimnion*.

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: sum of *evaporation* and *transpiration*.

externalities: social benefits and social costs not included in the market price of an economic good.

F

fallow: period during which land is left to recover its productivity (reduced by cropping) mainly through accumulation of water, nutrients, attrition of pathogens, or a combination of all three. During this period, the land may be bare or covered by natural or planted vegetation. The term may be applied to the land itself or to the crop growing on it.

feedback mechanism: sequence of interactions in which the final interaction influences the original one. Also see *positive feedback* and *negative feedback*.

field capacity: quantity of water held back by soil or rock against the pull of gravity. It is sometimes limited to a certain drainage period (2 or 3 days), thereby distinguishing it from *specific retention*, which is not limited by time.

finite-difference method: numerical technique for solving a system of equations using a rectangular mesh representing the aquifer and solving for the dependent variable in a piece-wise manner.

finite-element method: numerical technique for solving a system of equations using an irregular triangular or quadrilateral mesh representing the aquifer and solving for the dependent variable in a continuous manner.

firm yield: see *safe yield*.

firn: material that is transitional between snow and glacier ice. It is formed from snow after passing through one summer melt season and becomes glacier ice after its permeability to liquid water falls to zero.

floodplain or **flood plain**: 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 the 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*.

food chain: sequence of organisms, each of which uses the next lower member of the sequence as a food source.

fractal: object that has variation that is self-similar at all scales, in which the final level of detail is never reached and never can be reached by increasing the scale at which observations are made.

free ground water: *unconfined* ground water whose upper surface is a free *water table*.

G

gaging station: site on a stream, lake, reservoir, or other body of water where direct systematic observations of hydrologic data are obtained.

Gaia hypothesis: proposal that the earth is alive and can be considered a system that operates and changes by *feedback* of information between its living and non-living components. The idea that life on earth helps sustain its own environment.

gaining stream: stream reach in which the *water table* adjacent to the stream is higher than the water surface in the stream, causing ground water to seep into the stream, increasing its flow.

gamma radiation: radiation consisting of electromagnetic wave-type energy similar to X-rays. See also *radioactivity*.

General Circulation Models (GCMs): large-scale computer models used to predict the response of the climate system to a carbon dioxide (CO_2) increase or other stresses. Generally, the atmosphere, land, and oceans are divided into a number of discrete layers, with each layer consisting of a two-dimensional grid of thousands of points. The model then solves equations for the transport of heat, momentum, moisture (in the atmosphere and land), and salinity (in the ocean) on this three-dimensional grid. The typical resolution is 4° latitude by 5° longitude.

Geographic Information Systems (GIS): computer-based systems for storing and manipulating geographic (spatial) information.

Ghyben-Herzberg principle: principle that accounts for the existence of a body of freshwater floating on sea water within an aquifer because of the different densities. Generally speaking, freshwater extends to a depth about forty times the height that the freshwater table is found above sea level. Conversely, a lowering of the freshwater table by 1 ft (0.3 m) will cause sea water to rise 40 ft (12.19 m) within the aquifer.

gravitational potential: see *soil-water potential*.

greenhouse effect: popular term used to describe the roles of water vapor, carbon dioxide, and other *trace gases* in keeping the earth's surface warmer than it would be otherwise. These "*radiatively active*" gases are relatively transparent to incoming *short wave radiation* but are relatively opaque to outgoing *long wave radiation*. The latter radiation, which would otherwise escape to space, is trapped by these gases within the lower levels of the atmosphere. The subsequent reradiation of some of the energy back to the surface maintains surface temperatures higher than they would be if the gases were absent. There is concern that increasing concentrations of greenhouse gases, including carbon dioxide, methane, and manmade *chlorofluorocarbons*, may enhance the greenhouse effect and cause global warming.

greenhouse gases: gases, including water vapor, carbon dioxide, methane, nitrous oxide, *chlorofluorocarbons*, and *ozone*, that insulate the earth, letting sunlight through to the earth's surface while trapping outgoing radiation. Also see *greenhouse effect* and *trace gas*.

gross alpha activity: see *radioactivity*.

gross primary production (or **productivity**): total amount or weight of organic matter created by *photosynthesis* over a defined time period (total product of *photosynthesis*). Abbreviated GPP.

ground water: subsurface-water body in the zone of saturation or (more commonly, available ground water is defined as) that portion of the water beneath the surface of the earth 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: 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.

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*.

Holocene: most recent epoch of the *Quaternary period*, covering approximately the last 10,000 years.

homogeneous: material is homogeneous if its hydrologic properties are identical everywhere.

human capital: see *natural capital*.

human-made or **reproducible capital**: economic assets, such as buildings, equipment, plants and machinery, tools, financial assets, skilled labor, that are produced by the economy and capable of contributing to long run economic potential or welfare, usually measured in terms of the present value of the income, or welfare, it generates.

humus: decomposed organic material.

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. See also *permeability, intrinsic permeability*.

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*.

hydrogeology: see *hydrology*.

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: cyclic transfer of water vapor from the earth's surface via *evapotranspiration* into the atmosphere, from the *atmosphere* via precipitation back to earth, and through *runoff* into bodies of water.

hydrologic equation: equation that balances the *hydrologic budget*.

hydrological drought: see *drought*.

hydrology: study of the characteristics and occurrence of water, and the *hydrologic cycle*. Hydrology concerns the science of surface and ground waters, whereas *hydrogeology* principally focuses on ground water, though the terms are commonly used interchangeably.

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.

(hydro)static pressure: pressure exerted by or existing within a liquid at rest with respect to adjacent bodies.

hypolimnion: bottom layer of cold water in a lake. Compare *epilimnion*.

hyporheic zone: interstitial habitat penetrated by riverine animals and extending to no more than a few meters below the water/substratum interface in streams, in most cases centimeters away from the river channel. This biologically active zone is in direct and frequent contact with both the stream and the ground water. The hyporheic zone may be regarded as an *ecotone* between the surficial streambed (approximately top 15 cm) and the true ground waters that constitute the *phreatic zone*. Being a transition zone, the spatial extent of the hyporheic zone is not precisely delineated.

hypsithermal period: period about 4,000 to 8,000 years ago when the earth was apparently several degrees warmer than it is now. More rainfall occurred in most of the subtropical desert regions and less in the central midwest United States and Scandinavia. It is also called the *altithermal period* and can serve as a past climate analog for predicting the regional pattern of climate change should the mean earth surface temperature increase from an increase in atmospheric carbon dioxide concentration.

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.

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*.

infrared radiation: see *longwave radiation*.

injection well: well used for injecting water or other fluid into a ground-water aquifer. See also *artificial recharge*.

insolation: solar radiation incident on a unit horizontal surface at the top of the *atmosphere*. It is sometimes referred to as *solar irradiance*. The latitudinal variation of insolation supplies the energy for the general circulation of the atmosphere. Insolation depends on the angle of incidence of the solar beam and on the *solar constant*.

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.

instrumental value: value, or "worth," of something in terms of an "instrument" for satisfying individuals' needs and preferences; for example, the instrumental value of *biodiversity* derives from the role that the mix of micro-organisms, plants, and animals plays in providing ecological services and resources vital to human welfare.

integrated watershed management: process of formulating and implementing a course of action involving natural and human resources in a watershed, taking into account the social, political, economic, and institutional factors operating within the watershed and the surrounding river basins and other relevant regions to achieve specific social objectives. Typically this process would include (1) establishing watershed-management objectives, (2) formulating and evaluating alternative resource-management actions involving various implementation tools and institutional arrangements, (3) choosing and implementing a preferred course of action, and (4) thorough monitoring of activities and outcomes, evaluating performance in terms of degrees of achievement of the specified objectives. See also *watershed approach*.

interbasin transfer: physical transfer of water from one *watershed* to another.

interflow: see *underflow*.

inter-generational equity: extent to which the economic opportunities available to the current generation are also available to future generations; for example, whether activities undertaken by the current generation that lead to irreversible loss of *biodiversity* and increasing ecological scarcity today will affect adversely future generations' welfare, and even threaten their existence.

intra-generational equity: extent to which the economic opportunities available to the current (or a future) generation are equally available to all members of that generation; for example, whether the gains from irreversible loss of *biodiversity* and increased ecological scarcity are enjoyed disproportionately by some human populations and societies, and the costs borne disproportionately by others.

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*.

intrinsic value: having value, or "worth," in itself, regardless of whether it serves as an "instrument" for satisfying individuals' needs and preferences; for example, many more arguments for preserving biodiversity are based on the premise that organisms should be "saved" from extinction because all living entities have a fundamental intrinsic worth.

isohyet: line that connects points of equal rainfall.

isopleth: line that connects points of equal amounts of a quantity such as *evapotranspiration*, chloride concentration, etc.

isotherm: line that connects points of equal temperature.

isotope: refers to the fact that a chemical element in the periodic table may have two or more species that behave nearly identically chemically but have different atomic masses and physical properties. One of two or more atoms that have the same *atomic number* (i.e. the same number of protons in their nuclei) but differing in the number of their neutrons. Isotopes are **radioactive** (parent) if they decay spontaneously to another (daughter) element. Isotopes are **stable** if they do not decay. Radioactive isotopes such as tritium (^3H) and carbon-14 (^{14}C) are used to determine how long water containing these isotopes has been out of contact with the earth's atmosphere, and thus underground.

isotropic: said of a medium whose properties are the same in all directions. See *anisotropy*.

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.

kriging: estimation method that assumes that the best estimate is a weighted average of one or more sample points. Kriging is the method of analysis by which optimal values of the weights are determined.

L

lacustrine: pertaining to or formed in a lake or lakes.

laminar flow: type of flow in which the fluid particles (i.e. small "parcels" of fluid, bigger than molecules but small in relation to the passageway through which the fluid is flowing) all move smoothly more or less in the same direction as the bulk of the fluid. Laminar flow typically occurs when fluid is moving very slowly through small openings (like capillary tubes) or in very thin sheets.

lapse rate: rapidity with which temperature decreases with altitude. The normal lapse rate is approximately 3.5 degrees F per 1,000 feet (6.5 degrees C per kilometer) change in altitude. The dry adiabatic lapse rate is about 5.4 degrees F per 1,000 feet (9.8 degrees C per kilometer), and the wet adiabatic lapse rate varies between 2 and 4 degrees F per 1,000 feet (3.6 to 6.9 degrees C per kilometer).

latent heat: energy transferred from the earth's surface to the *atmosphere* through the *evaporation* and condensation processes.

lentic system: nonflowing or standing body of freshwater, such as a lake or pond. Compare *lotic system*.

litter: undecomposed plant residues on the soil surface.

Little Ice Age: cold period that lasted from about A.D. 1550 to about A.D. 1850 in Europe, North America, and Asia. This period was marked by rapid expansion of mountain glaciers, especially in the Alps, Norway, Ireland, and Alaska. There were three maxima, beginning about 1650, about 1770, and 1850, each separated by slight warming intervals.

littoral zone: of the seashore, between the high and low tide marks. Pertaining to the shallower life zone near the shore, out to the usual limit of influence of wave action, tides and daylight.

live storage reserves: see *ground-water storage reserves*.

local flow system: see *ground-water flow system*.

longwave radiation: radiation emitted in the spectral wavelength greater than 4 micrometers corresponding to the radiation emitted from the earth and atmosphere. It is sometimes referred to as *terrestrial radiation* or *infrared radiation*, although somewhat imprecisely.

losing stream: stream reach in which the water table adjacent to the stream is lower than the water surface in the stream, causing infiltration from the stream channel, recharging the ground-water aquifer and decreasing the streamflow.

lotic system: flowing body of freshwater, such as a river or stream. Compare *lentic system*.

lumped-parameter models: models that ignore spatial variations in parameters throughout an entire system.

M

mass balance: application of the principle of the *conservation of matter*. For example, the mass of a glacier is not destroyed or created; the mass of a glacier and all its constitutive components remains the same despite alterations in their physical states. The mass balance of a glacier is calculated with the input/output relationships of ice, *firn,* and snow, usually measured in water equivalent. Output includes all ablative processes of surface melting, basal melting, evaporation, wind deflation, **calving**, and internal melting. Input includes direct precipitation, avalanching, and the growth of superimposed ice.

mass flux: see *flux*.

mass curve or **Ripple diagram:** cumulative plot of reservoir inflow on the ordinate against time on the abscissa which permits simple graphical evaluation of reservoir yield. Widely used in surface water engineering design.

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.

mean sea level: average height of the sea surface, based upon hourly observation of the tide height on the open coast or in adjacent waters that have free access to the sea. In the United States, it is defined as the average height of the sea surface for all stages of the tide over a 19-year period. Mean sea level, commonly abbreviated as MSL and referred to simply as sea level, serves as the reference surface for all altitudes in upper atmospheric studies.

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 (µmhos/cm): see *specific conductance*.

Milankovitch theory: astronomical theory formulated by the Yugoslav mathematician Milutin Milankovitch that associates climate change with fluctuations in the seasonal and geographic distribution of *insolation* resulting from three changes in the geometry of the earth's orbit. One is that the path of the earth around the sun forms an ellipse, the shape of which changes over a period of about 100,000 years. The second is that the rotational axis of the earth is tilted with respect to the plane of its orbit; the tilt is now 23.5°, but it has varied several degrees over a period of 41,000 years. The third phenomenon is a wobble in the axis of rotation, an event that seems to recur every 21,000 years. The Milankovitch theory has gained acceptance primarily because young marine sediments exhibit cycles of 23, 000, 42,000, and 100,000 years—very close to the cycles Milankovitch calculated.

milligrams per liter—mg/L: milligrams per liter of water. This measure is equivalent to *parts per million (ppm).*

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. Minumum 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.

MINK study: study of the likely effects of increasing temperatures on the agricultural economy of the Missouri, Iowa, Nebraska, and Kansas region.

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: non-pumping well used primarily for drawing water-quality samples; also for measuring ground-water levels.

N

natural capital: characterization of environmental resources as assets in the economy that have the potential to contribute to economic productivity and welfare; for example, the value of a natural resource as an economic asset depends on the present value of its income, or welfare, potential. Natural capital is distinguished from other forms of capital, namely *human* or *social capital* (people, their capacity levels, institutions, cultural cohesion, education, information, knowledge), and *human-made capital* (houses, roads, factories, ships).

natural recharge: naturally occurring water added to an aquifer. Natural recharge generally comes from snowmelt and precipitation or storm runoff.

negative feedback: interaction that reduces or dampens the response of the *system* in which it is incorporated.

net primary production (or **productivity**): part of the *gross primary production* that remains stored in the producer organism (primarily green plants) after deducting the amount used during the process of respiration. Abbreviated NPP.

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.

NPDES permit: permit issued under the National Pollutant Discharge Elimination System for companies discharging pollutants directly into the waters of the United States.

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 state 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: non-pumping well used primarily for observing the elevation of the *water table* or the *piezometric pressure*; also to obtain water-quality samples.

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*.

ozone: molecule made up of three atoms of oxygen (O_3). In the *stratosphere*, it occurs naturally and it provides a protective layer shielding the Earth from *ultraviolet radiation* and subsequent harmful health effects on humans and the *environment*. In the *troposphere*, it is a chemical oxidant and major component of *photochemical smog*.

P

palynology: science of reconstructing the past flora and past climate from pollen data obtained from lake and bog sediments. The fossil pollen record is a function of the regional flora and vegetation at a given time and location.

Pampas: see *prairie*.

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.

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.

perihelion: point at which an object, travelling in an elliptical orbit around the sun, is at its closest to the sun.

permanent wilting percentage or **point**: water content of soil when indicator plants growing in that soil wilt and fail to recover when placed in a humid chamber.

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.

phenology: study of periodic biological phenomena with relation to climate, particularly seasonal changes, such as the time that certain plants and trees come into leaf and flower, and the date of the first and last appearance of animals and birds in a particular habitat. These phenomena can be used to interpret local seasons and the climatic zones.

photochemical smog: air pollution caused by chemical reactions among various substances and pollutants in *the atmosphere*.

photosynthesis: manufacture by plants of carbohydrates and oxygen from carbon dioxide and water in the presence of chlorophyll with sunlight as the energy source. Oxygen and water vapor are released in the process. Photosynthesis is dependent on favorable temperature and moisture conditions as well as on the atmospheric carbon dioxide concentration. Increased levels of carbon dioxide can increase net photosynthesis in many plants.

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.

picocuries (pCi): see *curie*.

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.

playa: flat-floored bottom of an undrained desert basin, becoming at times a shallow muddy lake after heavy rainfall; or the flooding of a river which on evaporation may leave a deposit of salt or gypsum. A salt pan. The Great Basin in Nevada and Utah in the western United States has many playas.

Pleistocene: earlier of the two epochs of the *Quaternary Period* starting 2 to 3 million years before the present and ending about 10,000 years ago. It was a time of glacial activity.

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.

positive feedback: interaction that amplifies the response of the *system* in which it is incorporated.

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.

prairie: gentle undulating, almost flat, generally treeless, grassy plains of North America, covering the southern regions of Alberta, Saskatchewan, and Manitoba in Canada and central United States from the foothills of the Rocky Mountains about as far east as Lake Michigan. The light summer rains with local droughts and high summer temperatures encourage a rich growth of grass, but few trees. They form the North American equivalent of the *Pampas* of South America, the *Steppes* of Eurasia, and the *Veldt* of South Africa.

precautionary principle: caution, "margins of error," or "safeguards" should be invoked for those human interventions in the natural environment where (i) our understanding of the likely consequences are limited, and (ii) there are threats of serious or irreversible damage to natural systems and processes.

pressure head: see *hydraulic head*.

primary productivity: see *gross primary productivity* and *net primary productivity*.

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.

Q

Quaternary Period: latest period of geologic time, covering the most-recent 2,000,000 years of the earth's history. It is divided into two epochs: the *Pleistocene*—2 million years ago to approximately 10,000 years ago—and the *Holocene*—the period from approximately 10,000 years ago to the present. The Quaternary Period is the artificial division of time separating prehuman and human periods. It contains five ice ages and four interglacial ages, and temperature indications seem to show sharp and abrupt changes by several degrees.

R

radioactivity: release of energy and energetic particles by changes occurring within atomic or nuclear structures. Radioactive energy is released in various ways such as *alpha radiation*, *beta radiation*, and *gamma radiation*. Radioactivity data are expressed in terms of concentration of specific nuclides. General measurements of *total* or *gross alpha* or beta and gamma activity also are often reported. The radioactivity of water is usually expressed in terms of the rate of radioactive disintegration (*curies*) per liter of water.

radiatively active gases: gases that absorb incoming solar radiation or outgoing *infrared radiation* thus affecting the vertical temperature profile of the atmosphere. Most frequently cited as being radiatively active gases are water vapor, CO_2, methane, nitrous oxide, *chlorofluorocarbons*, and *ozone*.

radiosonde: balloon-borne instrument for the simultaneous measurement and transmission of meteorological data up to a height of approximately 30,000 meters (100,000 feet). The height of each pressure level of the observation is computed from data received via radio signals.

rating curve: plot of discharge as a function of gage height. Data for a rating curve are obtained by *current meter* measurements of discharge.

RCRA: Resource Conservation and Recover Act—Federal legislation requiring that hazardous waste be tracked from "cradle" (generation) to "grave" (disposal).

recharge: to add water to an aquifer, either naturally or by artificial means; also the water added to an aquifer.

recharge area: area that contributes water to an aquifer. Normally considered to be the natural area of recharge, as contrasted with a constructed recharge basin.

recurrence interval: average amount of time between events of a given magnitude. For example, there is a 1% chance that a 100-year flood will occur in any given year; a runoff peak discharge which has a 5-year recurrence interval can be expected to be equaled or exceeded once every 5 years on the average. This is the same as saying that the peak discharge has a 20% chance of being equaled or exceeded once in any given year (100%/5 = 20%).

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.

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.

root zone: subsurface zone extending from the land surface to the maximum depth penetrated by roots.

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: amount of dissolved salts in a given volume of water.

saltwater intrusion: movement of saltwater into freshwater aquifers.

saturated thickness: vertical thickness of an aquifer that is saturated with water.

self-organization: capacity of *ecosystems* to develop and evolve in a dynamic fashion within the constraints set by energy flow and *biogeochemical cycling*; ecosystems are formed in response to these fluxes, are maintained and developed by them, and will respond continuously to them through numerous *feedbacks*.

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.

shortwave radiation: radiation received from the sun and emitted in the spectral wavelengths less than 4 micrometers. It is also called *solar radiation*.

silviculture: management of forest land for timber.

simulation: in ground-water-flow modeling, one complete execution of a ground-water-modeling computer program, including input and output.

sink: as used in resource management, a process whereby, or a feature from which, water or other substances are extracted from the system.

soil horizon: layer of soil or soil material approximately parallel to the land surface and differing from adjacent genetically related layers in physical, chemical, and biological properties or characteristics such as color, structure, *texture*, consistency, kinds and number of organisms present, degree of acidity or alkalinity, etc.

soil moisture: water in the root zone.

soil-water potential: energy with which water is held in a soil at any water content. It is the potential energy per unit quantity (unit mass, unit weight, or unit volume) of water in a system, compared to that of pure (no solutes), free water (no external forces other than gravity) at the same location (which represents the reference state of zero value). Potential energy is the energy of the water that is potentially available to be released when the water moves from one position to another. Because water is held in the soil by forces of adsorption, cohesion, and solution, soil water is not usually capable of doing as much work as pure free water; hence, the soil-water potential is normally negative. The soil-water potential can be considered as the sum of component potentials such as *matric* or *capillary potential* (resulting from the capillary and adsorptive forces due to the soil matrix), *gravitational potential* (resulting from relative elevation differences), *osmotic potential* (resulting from the presence of solutes; it comes into play whenever a membrane or diffusion barrier is present that transmits water more readily than salts or solutes), and others. A soil-water *potential gradient* (which is the change of energy potential with distance) is required to cause fluid to flow. For some applications, certain combinations of component potentials are used so often that for ease of referring to them it is desirable to give the combination a name. For liquid water flow in soils, it is convenient to combine component potentials that serve as driving forces—pressure, matric, and gravitational potentials, and call the combination by the name of *hydraulic potential*. If the unit quantity is measured as weight, then the units of hydraulic potential are energy per unit weight, which are exactly equal to the units of *hydraulic head*.

solar constant: rate at which solar energy is received just outside the earth's *atmosphere* on a surface that is normal to the incident radiation and at the mean distance of the earth from the sun. The current value is 0.140 watt/cm^2.

solar irradiance: see *insolation*.

solar radiation: see *shortwave radiation*.

solum (plural: **sola**): upper and most weathered part of the soil profile; the A and B *soil horizons*.

solute-transport model: application of a model to represent the movement of constituents dissolved in ground water.

specific conductance: measure of the ability of a water to conduct an electrical current, expressed in *micromhos per centimeter* at 25^{0}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: fraction of a saturated bulk volume consisting of water that will drain by gravity when the water table drops; specific yield is less than *porosity* because some water is too strongly absorbed to the earth material to drain. The ability of an *unconfined or water- table aquifer* to store water is measured by its specific yield. Specific yield can be several orders of magnitude larger than the *storage coefficient*, thus producing more water when developed.

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.

Steppes: see *prairie*.

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.

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*.

stratosphere: region of the upper atmosphere extending from the *tropopause* (8 to 15 km altitude) to about 50 km.

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.

strong sustainability: view that, given the limits to substitution between some natural capital and other economic assets (such as *reproducible* or *human-made capital*), as well as the problems of irreversibility, uncertainty of threshold effects and the potential scale of social costs associated with loss of certain environmental assets, *sustainable development* cannot be assured without imposing some conditions on the depletion of natural capital; for example, if some minimum level of *biodiversity* is essential for *ecosystem functioning* and resilience, preserving the economic opportunities available to future generations requires the prevention of biodiversity loss that threatens this minimum threshold level.

sublimation: transition of water directly from the solid state to the gaseous state, without passing through the liquid state; or vice versa.

substrate: (i) that which is laid or spread under; an underlying layer, such as the subsoil; (ii) the substance, base, or nutrient on which an organism grows; (ii) compounds or substances that are acted upon by enzymes or catalysts and changed to other compounds in the chemical reaction.

subsurface water: all water below the land surface, including *soil moisture*, *capillary fringe* water in the *vadose zone*, and *ground water*.

summer fallow: special case of fallowing in which all vegetative growth is prevented by shallow tillage in conjunction with or without herbicides during the summer months, in place of growing a crop, in order to store water for use by the next crop.

Superfund: see *CERCLA*.

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. See *strong sustainability* and *weak sustainability*. Sustainable development by its very nature is a multidimensional concept. This concept involves not only the management and conservation of the natural resource-base, but also the social, institutional, technological, and cultural changes involved. Though it is extremely difficult to conceptualize ideally what sustainable development means, definition of sustainable development has to be sufficiently broad to be able to capture the various dimensions involved. See also *environmental sustainability*.

sustained (sustainable) yield: volume of ground water that can be extracted annually from a ground water basin without causing adverse effects.

systems analysis and **systems**: is the study of systems, groups of interacting, interdependent parts linked together by complex exchanges of energy, matter, and information. There is a key distinction between "classical" science and system science. Classical (or reductionist) science is based on the resolution of phenomena into isolatable causal trains and the search for basic, "atomic" units or parts of the system. Classical science depends on weak or nonexistent interaction between parts and essentially linear relations among the parts, so that the parts can be added together to give the behavior of the whole. These conditions are not met in the entities called systems. A "system" is characterized by strong (usually nonlinear) interactions between the parts, feedbacks (making resolution into isolatable causal trains difficult or impossible), and the inability to simply "add-up" small-scale behavior to arrive at large-scale results. Ecological and economic systems obviously exhibit these characteristics of systems, and are not well understood using the methods of classical, reductionist science. One might define "systems analysis" as the scientific method applied both across and within disciplines, scales, resolutions, and system types.

T

terrestrial radiation: see *longwave radiation*.

texture (soil): relative proportions of sand, silt, and clay particles in a mass of soil.

thalweg: line of maximum depth in a stream. The thalweg is the part that has the maximum velocity and causes cutbanks and channel migration.

thermal pollution: reduction in water quality caused by increasing its temperature, often due to the disposal of waste heat from industrial or power generation processes. Thermally polluted water often undergoes biological changes that render it less valuable for drinking, recreation, habitat, or industrial use.

thermocline: fairly thin zone in a lake that separates an upper warmer zone (*epilimnion*) from a lower colder zone (*hypolimnion*).

thermohaline: refers to the combined effects of temperature and salinity that contribute to density variations in the oceans.

total dissolved solids (TDS): quantity of minerals (salts) in solution in water, usually expressed in milligrams per liter.

trace gas: minor constituent of *the atmosphere*. The most important trace gases contributing to the *greenhouse effect* are water vapor, carbon dioxide, *ozone*, methane, ammonia, nitric acid, nitrous oxide, ethylene, sulfur dioxide, nitric oxide, dichloro-fluoromethane or Freon 12, trichlorofluoromethane or Freon 11, methyl chloride, carbon monoxide, and carbon tetrachloride.

Tragedy of the Commons: idea that no one takes responsibility for things that everybody owns, generally associated with Garrett Hardin.

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.

tropopause: boundary between the troposphere and the stratosphere (about 8 km in polar regions and about 15 km in tropical regions), usually characterized by an abrupt change of *lapse rate*. The regions above the troposphere have more increased atmospheric stability than those below. The tropopause marks the vertical limit of most clouds and storms.

troposphere: inner layer of the atmosphere below about 15 km, within which there is normally a steady decrease of temperature with increasing altitude. Nearly all clouds form and weather conditions manifest themselves within this region, and its thermal structure is caused primarily by the heating of the earth's surface by *solar radiation*, followed by heat transfer by turbulent mixing and convection.

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

ultraviolet (UV) radiation: type of *shortwave radiation* that is damaging to plants and animals, including humans. The amount of UV radiation that reaches the earth depends on the amount of stratospheric *ozone*. An increase in UV radiation due to a decrease in stratospheric ozone will pose a direct threat to human health (increased cataracts, immune suppressions, and skin cancers) and will have a negative impact on plant yields for many species.

UNCED: United Nations Conference on Environment and Development. Held in Rio de Janeiro, June, 1992. Also referred to as the *Earth Summit*.

unconfined (or **water-table) aquifer**: aquifer in which the water table is at the upper boundary of the ground-water-flow system that is at atmospheric pressure.

unconsolidated deposits: sediment that is loosely arranged or unstratified, or whose particles are not cemented together.

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*.

unsaturaze zone: see *vadose zone*.

upconing: process by which saline water underlying freshwater in an aquifer rises upward into the freshwater zone as a result of pumping water from the freshwater zone.

V

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*.

Veldt: see *prairie*.

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*.

volative organic compound (VOC): organic chemical that volatilizes (evaporates) relatively easily when exposed to air.

volume flux: see *flux*.

W

wadi: steep-sided valley, rocky ravine, river bed, or gully that is usually dry in a semi-desert or desert area of the Sahara and the Arab countries of southwest Asia.

waldsterben: German word meaning forest death and used to describe the rapid decline and death of large areas of trees. It is thought to be a result of ozone pollution that damages the leaves of trees, resulting in stunted growth and an inability to regenerate. More than half of Germany's forests are affected, as well as extensive areas in most other European and Scandinavian countries. The main cause is considered to be pollution from vehicle exhausts.

water demand: amount of water used over a period of time at a given price.

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*.

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.

water table: upper boundary of a free ground-water body, at atmospheric pressure.

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 percent 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-vapor feedback: process in which an increase in the amount of water vapor increased the *atmosphere's* absorption of *longwave radiation*, thereby contributing to a warming of the atmosphere. Warming, in turn, may result in increased evaporation and an increase in the initial water vapor anomaly. This feedback, along with carbon dioxide, is responsible for the *greenhouse effect* and operates virtually continuously in the atmosphere.

water year: 12-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.

watershed: that surface area which drains to a specified point on a water course, usually a confluence of streams or rivers.

watershed approach: is the application of *integrated watershed management* in the planning and implemention of resource management and rural development projects or as part of planning for specific resource sectors such as agricultural, forestry, or mining. Imbedded in this approach is the linkage between uplands and lowlands in both biophysical and socioeconomic contexts.

WCED (World Commission on Environment and Development): United Nations commission, also known as the *Brundtland Commission*, which garnered almost worldwide political concensus on the urgent need for sustainability; its findings are published in the widely acclaimed report "Our Common Future" (1987).

weak sustainability: view that sustainable development can be assured through the conservation of aggregate capital alone; that is, although *natural capital* is being depleted, it is being replaced with even more valuable *human-made capital* and thus the value of the aggregate stock—comprising both human-made and the remaining natural capital—is increasing over time in terms of its ability to maintain or enhance human welfare.

weather: day-to-day variation in atmospheric conditions. Compare *climate*.

weather generator (stochastic): program that generates weather values for daily precipitation, temperatures, and solar radiation based on observed historical patterns.

weather modification: deliberate modification of weather so as to increase precipitation and thereby increase water supplies. **Cloud seeding** is the most common method of weather modification.

well yield: 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.

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. *Well yield:* maximum pumping rate that can be supplied by a well without drawing the water level in the well below the pump intake. *Aquifer yield*: maximum rate of withdrawal that can be sustained by an aquifer. *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.

Z

zone of aeration: see *vadose zone*.

Biographical Sketches of Chapter Contributors

Rex C. Buchanan is the associate director for public outreach at the Kansas Geological Survey. He is a native of central Kansas, has an undergraduate degree in biology and history from Kansas Wesleyan University and master's degrees in history of science and in journalism from the University of Wisconsin–Madison. He is the editor or author of several books, including *Kansas Geology: An Introduction to Landscapes, Rocks, Minerals, and Fossils* (University Press of Kansas, 1984), co-author (with James R. McCauley) of *Roadside Kansas: A Traveler's Guide to Its Geology and Landmarks* (University Press of Kansas, 1987); and co-compiler (with Robert Buddemeier) of *Kansas Ground Water* (Kansas Geological Survey, 1993). Buchanan joined the Survey in 1978.

Robert W. Buddemeier received his B.S. from the University of Illinois, and his Ph.D. from the University of Washington, both in chemistry. He has maintained an interest in the carbon cycle, climate, and environmental system dynamics since his dissertation on calibration of the marine radiocarbon time scale. He has been employed as an environmental chemist, oceanographer, and hydrologist, and has worked at the University of Hawaii and Lawrence Livermore National Laboratory before coming to The University of Kansas (KU). He is presently Senior Scientist in the Geohydrology Section of the Kansas Geological Survey, and Courtesy Professor in the KU Geography Department.

James K. Koelliker is a native Kansan from White Cloud in northeastern Kansas. His academic training is in Agricultural Engineering, a B.S. in 1967 from Kansas State University, and a Ph.D. from Iowa State University in 1972. In addition, he holds an M.S. in water resources from Iowa State University. Most of his career has been devoted to teaching and research, particularly on aspects of water-resources systems and the impact of agricultural activities on water supply and water quality in Kansas. He previously served 19 years as a faculty member in Civil Engineering at Kansas State University. He became Professor and Head of the Biological and Agricultural Engineering Department at KSU in 1997. He is a registered professional engineer in Kansas and Colorado.

David I. Leib is a Water Resource Planner at the State of Kansas Water Office and a registered professional engineer in California and Kansas. His main areas of interest include reservoir operations, water-supply planning, and surface-water hydraulics. He is a graduate of Rice University (B.S., CE), Stanford University (M.S., CE), and Northwestern University (M.S., Applied Mathematics).

P. Allen MacFarlane completed his undergraduate degree in geological engineering at the Colorado School of Mines in 1970, his master's degree in geology at The University of Kansas in 1978, and his doctoral degree in environmental health science at The University of Kansas in 1993. He has been a member of the Geohydrology Section at the Kansas Geological Survey since 1978. Macfarlane was the coordinator of the Survey's eight-year research program to evaluate the water-resources potential of the Dakota aquifer in Kansas. His research interests lie in the areas of ground-water-resource evaluation, waste-disposal problems, and the hydrogeology of sedimentary basins.

Gwendolyn L. Macpherson earned a B.S. in geology from Syracuse University, and an M.A. and Ph.D. in geology from the University of Texas at Austin. She is an Associate Professor of Geology at The University of Kansas. Her research focuses on low-temperature aqueous geochemistry, with emphasis on identifying sources and sinks for trace elements and nutrients in fresh and saline ground water, primarily through field sampling and secondarily through computer modeling.

Hernán A. M. Quinodoz was a hydrologist with the Kansas Geological Survey. He holds graduate degrees in Civil Engineering from the University of Minnesota (M.Sc.) and University of Illinois at Urbana–Champaign (Ph.D.). His experience includes development and application of computer models for surface- and ground-water systems, using both deterministic and stochastic methods. He specializes in modeling of hydrologic systems, contaminant transport in the environment, and applications of risk analysis to hydrologic and environmental systems. He is now a senior analyst with Abt Associates, a policy research and consulting firm in Bethesda, Maryland.

Marios Sophocleous received his B.S. in natural sciences and geology from the University of Athens, Greece, in 1971, his M.S. in water resources from the University of Kansas in 1973, and his Ph.D. in hydrogeology from the University of Alberta, Canada, in 1978. He has been employed at the Kansas Geological Survey since 1978, where he became Senior Scientist in 1987. He is an Adjunct Professor of Geology at The University of Kansas, an Associate Editor of the *Journal of Hydrology*, and a member of the editorial boards of *Computers & Geosciences* and *Current Research on Earth Science*. His areas of research are broad and include experimental investigations and numerical modeling of soil-water and ground-water flow and pollutant transport, aquifer-recharge processes, stream-aquifer interactions, regional ground-water flow and watershed hydrology, and water-resources evaluation and management.

Thomas C. Stiles is the Assistant Director at the Kansas Water Office overseeing the development and implementation of the State Water Plan. He has worked at the agency for 15 years, starting as a hydrologist in charge of establishing instream flows in the state. Prior to his current position, he was the Water Resource Manager for hydrology, conducting technical studies and coordinating water research. Stiles received a Bachelor of Science degree in watershed science from Colorado State University and a Master of Science degree from the University of Minnesota in forest hydrology. He has worked for consultants on matters of water data and has helped teach courses in water-resource planning and management.

Margaret A. Townsend has a B.S. (Beloit College, Wisconsin) and an M.A. (University of Texas at Austin) in geology. She has worked as a hydrogeologist for 20 years both at the Kentucky Geological Survey and currently at the Kansas Geological Survey. Her specialty is water-chemical processes, particularly the sources and occurences of nitrate in ground water. She uses ground-water chemistry and isotopes in her work. She has done many field studies using soil-water lysimeters, wells, and surface measurements for evaluation of water-chemistry problems.

Index

E

F

G

H

I

Q

R

S

T

U

V

W

Y

Z