Summary Appraisals of the Nation's Ground-Water Resources— Arkansas-White-Red Region

GEOLOGICAL SURVEY PROFESSIONAL PAPER 813-H

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METRIC UNITS

For those readers interested in the metric system, metric equivalents of English units are given in parentheses throughout the text. The English units may be converted to metric units as follows:

English unit	*Conversion factor*	*Metric unit*
To convert	*Multiply by*	*To obtain*
Inches (in.)	25.4	Millimetres (mm).
Feet (ft)	3.048×10^{-1}	Metres (m).
Square miles (mi^2)	2.59×10^{6}	Square metres (m^2).
Gallons per minute (gal/min)	6.31×10^{-5}	Cubic metres per second (m^3/s).
Gallons per day (gal/d)	4.38×10^{-8}	Cubic metres per second (m^3/s).
Feet per day (ft/d)	3.53×10^{-6}	Metres per second (m/s).
Inches (in.)	2.54×10^{-2}	Metres (m).
Acre-feet (acre-ft)	1.23×10^{3}	Cubic metres (m^3).
Acres	4.05×10^{3}	Square metres (m^2).
Miles	1.61×10^{3}	Metres (m).
Tons (short, 2,000 pounds)	9.07×10^{2}	Kilograms (kg).
Cubic feet (ft^3)	2.83×10^{-2}	Cubic metres (m^3).
Gallons	3.79×10^{-3}	Cubic metres (m^3).
Billion gallons per day (Bgal/d).	43.81×10^{3}	Cubic decimetres per second (dm^3/s).
Million gallons per day (Mgal/d).	0.04381	Cubic metres per second (m^3/s).

The conversion from temperature in degrees Fahrenheit (°F) to temperature in degrees Celsius (°C) is expressed by: $°C = (5/9)(°F - 32)$.

SUMMARY APPRAISALS OF THE NATION'S GROUND-WATER RESOURCES—ARKANSAS-WHITE-RED REGION

By M. S. BEDINGER and R. T. SNIEGOCKI

ABSTRACT

The Arkansas-White-Red Region, an area of 265,000 square miles (6.86×10^{11} square metres), is characterized by diversity in geography, climate, and geology and, in turn, by diversity in water resources and water problems. The western semiarid part of the region is water deficient, that is, potential evapotranspiration exceeds precipitation. The eastern, humid part has a surplus. Water use in the region in 1970 averaged 10 billion gallons per day (438 cubic metres per second), of which more than 65 percent was ground water. The largest use of ground water was for irrigation of crops, mostly in the water-deficient areas of Texas, Oklahoma, Kansas, and Colorado. Because of its ready availability and widespread occurrence, ground water is used throughout the region to supply municipal and rural water needs. The most productive aquifers, capable of yielding more than 50 gallons per minute (0.0032 cubic metres per second) to individual wells, are alluvium, carbonate rocks, gypsum, and sandstone. Fresh water in storage in aquifers in the region is estimated to be 2 billion acre-feet (2.5×10^{12} cubic metres). In addition, a large, unmeasured volume of saline water (containing more than 1,000 milligrams per litre of dissolved solids) underlies the fresh water at depths generally less than 500 feet (150 metres).

The flow of water in each aquifer depends upon the physical and hydrologic characteristics of the aquifer, the climate, and the relation to, and the character of, adjacent rocks and streams. These factors also determine the effect of water-supply development or other man-induced stresses on the flow and the quality of water in the aquifers. Analog and digital models of aquifers can be used to evaluate stresses on aquifers and thereby provide water managers and planners with efficient tools for planning the development and continued use of aquifers.

INTRODUCTION

The Arkansas-White-Red Region, as defined by the Water Resources Council, includes about 265,000 square miles (6.86×10^{11} m^2) in the South-Central United States (fig. 1). The three largest rivers—the Arkansas, White, and Red—drain approximately one-tenth of the Nation's conterminous land area, including all of Oklahoma and parts of Colorado, New Mexico, Kansas, Texas, Missouri, Arkansas, and Louisiana.

The Arkansas-White-Red Region is characterized by diversity in geography, climate, and geology, and, in turn, by diversity in water resources and water problems. The principal surface features of the region (Fenneman, 1931) consist of the high Southern Rocky Mountains in the west; the low mountains of the Ozark Plateaus and the Ouachita province, which rise abruptly from the Coastal Plain in the east; and between the two mountain areas, a broad expanse of the Great Plains and the Central Lowland, sloping gradually from west to east, broken in places by escarpments, hills, and a few old, eroded mountains (fig. 2). The climate varies from humid in the east to semiarid in the west. The western half of the region experiences temperature extremes and moisture deficiencies associated with its interior continental location. The eastern part is influenced by the warm moist air from the Gulf of Mexico.

THE WATER RESOURCE

Precipitation (mean annual) is about 50 inches (1,270 mm) in Arkansas and Louisiana, decreases rather uniformly to about 12 inches (300 mm) in the western Great Plains (fig. 3), and increases to 32 inches (810 mm) in the mountains of Colorado and New Mexico. In the Great Plains, annual precipitation is low and highly variable, and serious deficiencies occur during the growing season. The eastern section is subject to climatic extremes—to severe rainstorms and flash flooding and to droughts. Localized floods in the central and western sections result from infrequent but intense rainstorms of short duration. High wind velocities and high evaporation rates, associated with the dry climate of most of the western half of the region, cause annual lake evaporation to exceed precipitation.

The eastern half of the region is characterized by a surplus of water—that is, annual precipitation exceeds potential evapotranspiration. Areas of natural water surplus and of natural water deficiency within the Arkansas-White-Red Region are shown in figure 4. The water deficiency was computed by subtracting values of potential evapotranspiration from the average precipitation. However, even the areas of annual water surplus have seasonal or short-term periods of deficiency.

The occurrence of ground and surface water is entirely different in flow rate, quantity in storage, variability in quality, variability in quantity with time, and

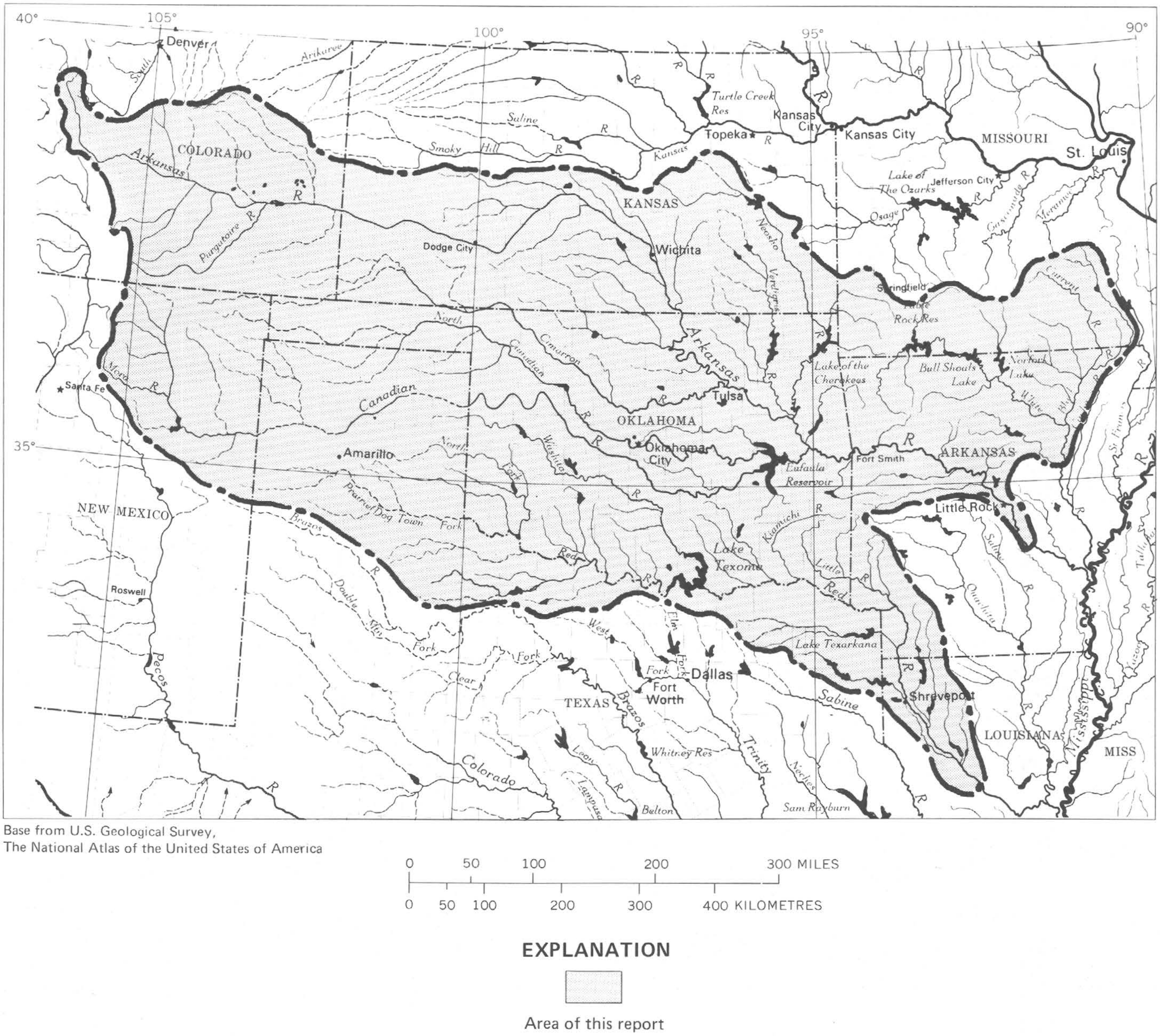


FIGURE 1.—Location of the Arkansas-White-Red Region.

areal distribution. These differences can be used to advantage in managing ground and surface water conjunctively to achieve the most efficient use of the total supply.

The natural streamflow, shown in figure 5, is the average annual flow in streams if there were no upstream development. In areas of direct hydraulic connection between surface water and ground water, the natural runoff may include natural base flow from aquifers.

Water in the Arkansas-White-Red Region is derived from precipitation in the region and interbasin transfers. The water resource fluctuates with variations in precipitation. Fluctuations are moderated by storage in surface-water and ground-water reservoirs. Regionally, the water resource consists of an average annual runoff of about 6 inches (150 mm) from a 265,000-square-mile (6.86×10^{11} m^2) area and an underground storage of about 2 billion acre-feet (2.5×10^{12} m^3). From 1961 through 1973, an average of 82,440 acre-feet ($1{,}016.0 \times 10^8$ m^3) of water was transferred from the Colorado River basin to the Arkansas River basin. Interbasin transfers during this period increased. Plans for diversion call for an eventual average of more than 200,000 acre-feet (2.47×10^8 m^3) to be imported annually from the Colorado River basin to the Arkansas River basin.

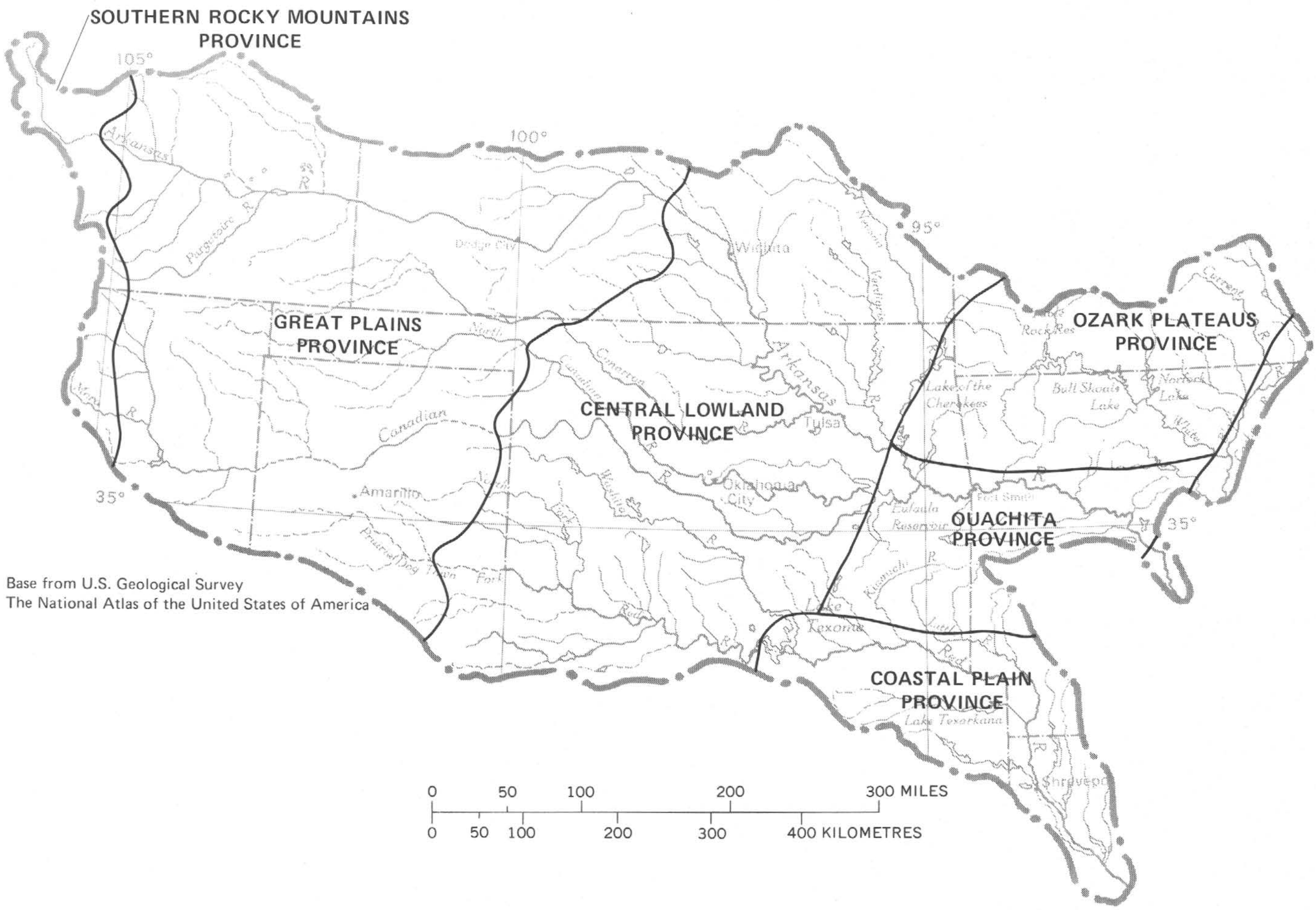


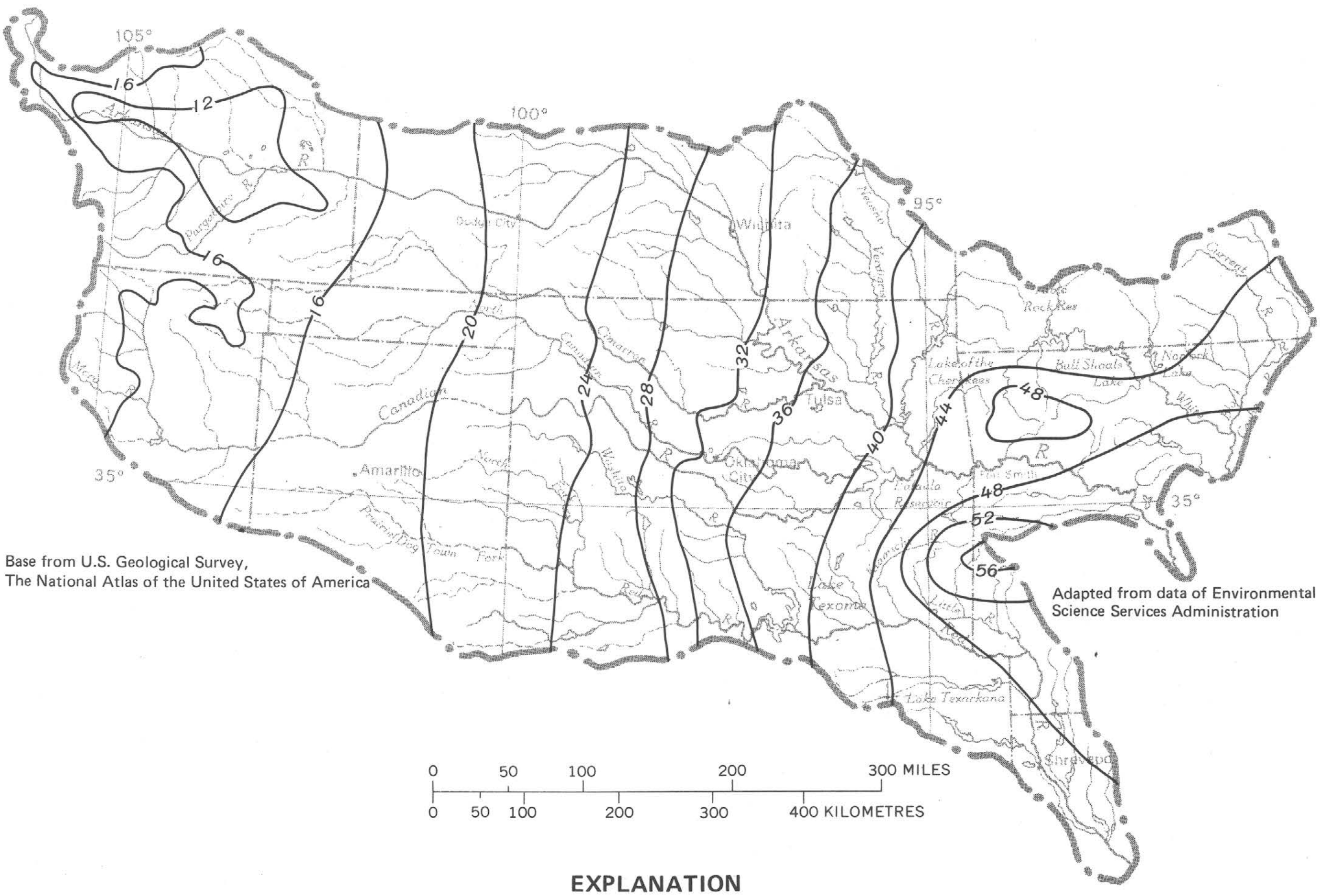
FIGURE 2.—Physiographic subdivisions of the Arkansas-White-Red Region.

The year-to-year difference between extremes of runoff is called the variability, which greatly affects the amount of water that can be developed for use. The natural runoff in the Arkansas-White-Red Region is 73 Bgal/d (3.2×10^3 m³/s). The natural runoff varies widely—in 90 years out of 100 years, the flow exceeds 36 Bgal/d (1.6×10^3 m³/s; Murray and Reeves, 1972), and in 95 of 100 years, the flow exceeds 33.4 Bgal/d (1.5×10^3 m³/s). In addition, great variations in natural streamflow occur seasonally. Annual runoff is more variable in the west-central water-deficient part of the Arkansas-White-Red Region (fig. 6). Storage is required to meet the water demand in dry years. Even at such levels of development as those indicated possible by the available runoff in 90 percent and 95 percent of the years, storage would be required to make the indicated runoff available for use. Thus, the percentage of the mean runoff that is available for development depends on the variability of the annual runoff, the storage in the reservoirs, and evapotranspiration from the reservoirs. Woodward (1957) estimated that in 1955 the dependable water supply was 10 Bgal/d (4.4×10^2 m³/s) and projected that in 1980 the dependable supply will be 20 Bgal/d (8.8×10^2 m³/s), principally because of increased surface-water storage.

ACCENT ON GROUND WATER

Approximately two-thirds of the 10 Bgal/d (4.4×10^2 m³/s) of water withdrawn in the region for public, rural, industrial, and irrigational use in 1970 was from ground water (table 1). Of the 6.6 Bgal/d (2.89×10^2 m³/s) withdrawn from ground-water sources, about 90 percent was for irrigation. The general distribution of ground-water withdrawal and the major areas irrigated by ground water are shown in figure 7. Irrigation is practiced primarily in the major stream valleys and terraces of the Great Plains and Central Lowland, where aquifers provide large well yields. Of the remaining 10 percent of ground water withdrawn, about 4 percent is for industrial supplies, 4 percent is for public supplies, and 2 percent is for rural supplies.

An estimated 2 billion acre-feet (2.5×10^{12} m³) of fresh water is in storage in aquifers in the region, about 60,000 times more than the 1970 water use from both ground- and surface-water sources. Further, the



Base from U.S. Geological Survey, The National Atlas of the United States of America

Adapted from data of Environmental Science Services Administration

EXPLANATION

——— *20* ———
Isohyet of mean annual precipitation, in inches

FIGURE 3.—Mean annual precipitation.

amount of fresh water stored in aquifers is more than 30,000 times that estimated to be perennially available from both ground- and surface-water sources in the region.

TABLE 1.—*Summary of ground water withdrawn in the Arkansas-White-Red Region in 1970, except for hydroelectric-power and thermoelectric-power generation*

[After Murray and Reeves (1972), and Murray, written commun. (1947)]

State	*Withdrawal (Bgal/d)*
Arkansas	0.150
Colorado	.220
Kansas	2.500
Louisiana	.027
Missouri	.058
New Mexico	.074
Oklahoma	.880
Texas	2.700
Total (rounded)	6.600

HYDROLOGIC ASPECTS OF WATER-RESOURCE PLANNING

The quantity of water entering and leaving a hydrologic system, such as that of the Arkansas-White-Red Region, within a given time can be related by the following continuity equation:

Inflow = outflow ± change in storage.

If inflow is greater than outflow, the change in storage is positive; if inflow is less than outflow, the change in storage is negative.

Prior to development by wells, aquifers are in a state of dynamic equilibrium in which inflow and outflow are equal. Ground-water withdrawal upsets this balance by producing a loss from storage. A new state of equilibrium can be reached only by an increase in inflow and a decrease in outflow. Inflow can be increased by a lowering of water level, resulting in:

1. Storage space in the aquifer for recharge that would otherwise be rejected.
2. Induced leakage to the aquifer from confining beds.
3. Induced inflow from surface water.

Outflow can be decreased by a lowering of water level, resulting in:

1. Decrease in evapotranspiration from the aquifer.
2. Decrease in discharge from the aquifer by springs and flow to surface water.

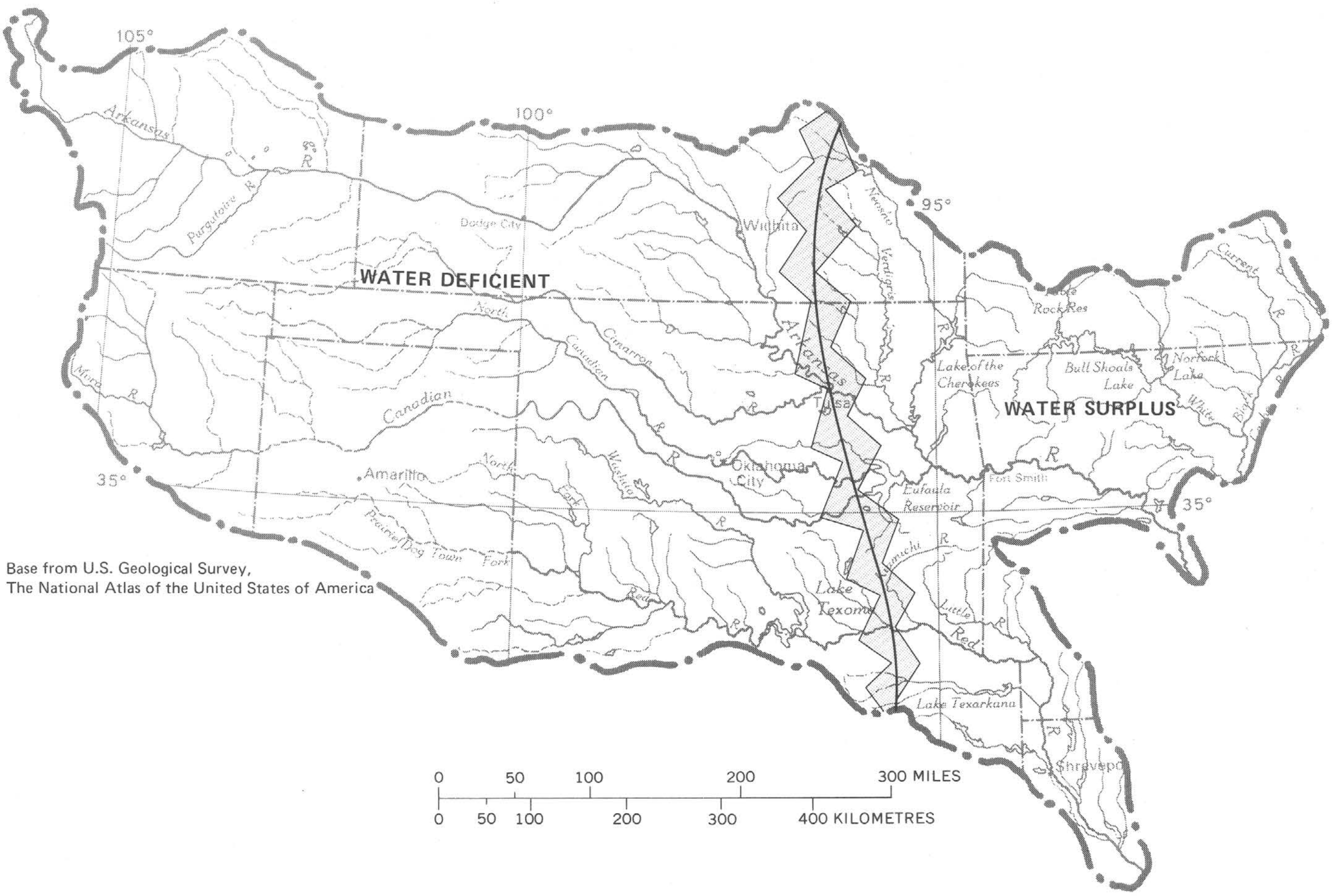


FIGURE 4.—Areas of natural water deficiency and natural water surplus (U.S. Water Resources Council, 1968).

3. Decrease in leakage from the aquifer through confining beds.

Use of ground water (as opposed to the exclusive use of surface water) increases the potential amount of water available for development. The increase includes the amount of water permanently withdrawn from storage in excess of recharge, and the water salvaged by reduction in evapotranspiration. Reduction in exapotranspiration from the aquifer represents an increase in the water available for use in the basin. The water in storage in an aquifer can be managed as a reserve to be withdrawn during seasons of peak demand or periods of drought. The depletion from storage can be replenished during seasons or periods when water is available for recharge.

To express the hydraulic response of an aquifer system to development, the equation of continuity may be written:

$$I + \Delta I = O + \Delta O + Q + \Delta S,$$

in which

I = inflow rate,
ΔI = change in inflow rate,
O = natural outflow rate,
ΔO = change in outflow rate,
Q = rate of withdrawal from wells,

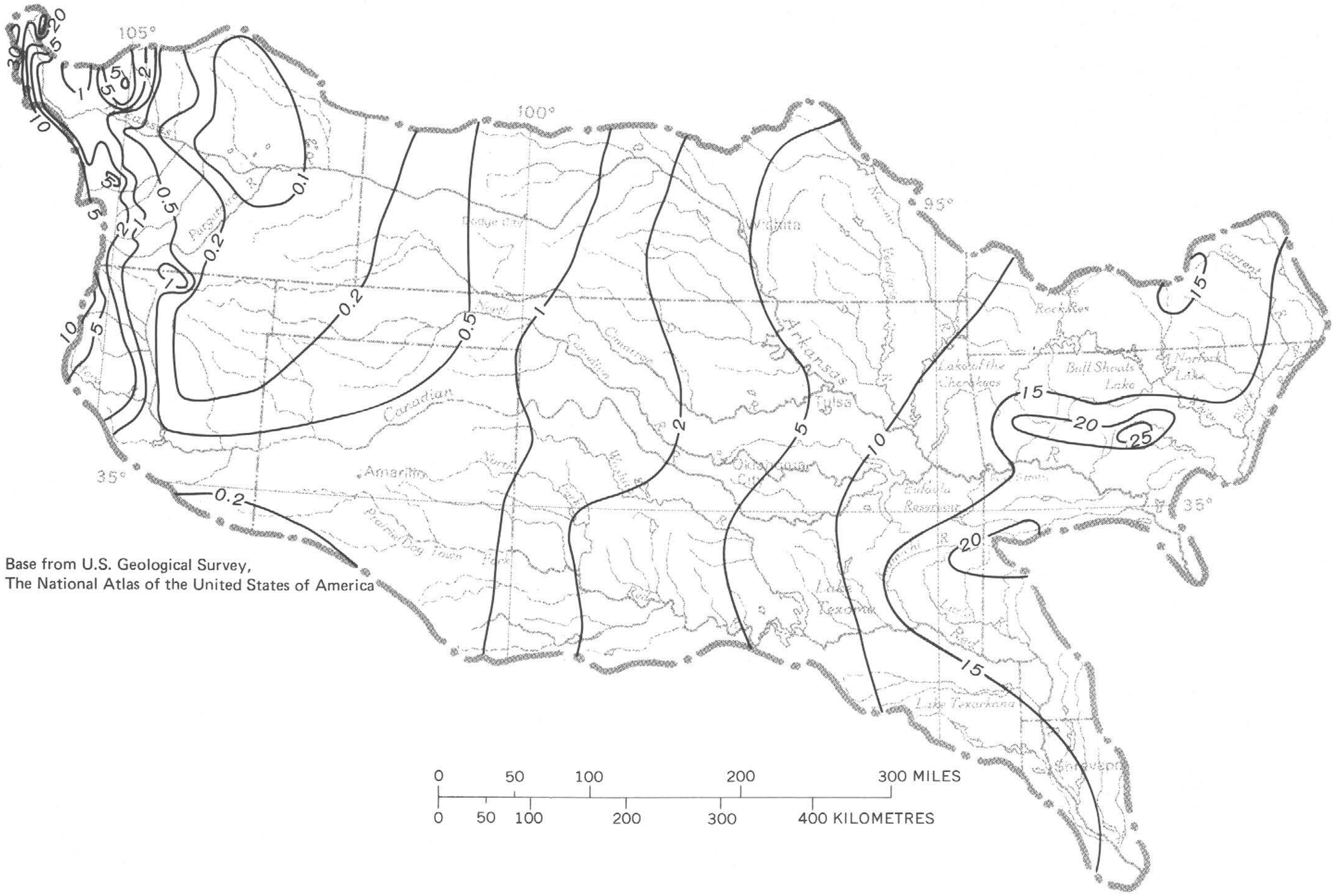
and

ΔS = rate of change in storage.

It is implicit from this equation that an aquifer flow system is a complete functional unit. Application of the equation requires an understanding of the nature of the flow between the aquifer and contiguous streams and confining beds.

A desirable management objective in a groundwater development is to use the aquifer such that a continued decrease in subsurface storage is minimized. To do this, the withdrawal from storage must be balanced by an increase in inflow to the aquifer or a decrease in outflow.

Another management objective is to prevent or retard deterioration of the physical or chemical quality of the water or the environment. Under natural conditions, a state of balance is reached between hydraulic, thermal, and geochemical stresses in the flow system. An imposed hydraulic stress upsets not only the natural hydraulic balance but also the thermal and geochemical balances.



EXPLANATION

—— 20 ——
Line of equal average annual runoff, in inches

FIGURE 5.—Average annual runoff (after Busby, 1966).

The rationale for response of the system to changes in stress may be stated as follows:

1. The system reacts to each stress in accordance with the laws of conservation of energy and mass.
2. Any given stress or combination of stresses on the flow system will result in a trifold response, that is, hydraulic, thermal, and chemical responses in the system.
3. The response of the system to the stress is uniquely dependent upon the geometry and the physical and chemical characteristics of the system. In addition, a stress or response may involve a change in the physical or chemical character of the system framework.

The breadth of impact of a given stress on the aquifer may be illustrated by the use of table 2. The object of this table is to point out that a wide range of actions can affect an aquifer system. Actions that can affect the ground water include not only actions directed toward management of ground water and surface water but also to those related to agriculture, urbanization, manufacturing, and many others that are not directed toward water management.

Neither the list of actions nor the responses to stress shown in table 2 are intended to be complete. The table is intended as a checklist and an aid to the planner or water manager in considering systematically the full ranges of stresses and responses that an action will produce. The table may be considered to be an expansion of a part of an environmental-impact matrix, as presented by Leopold, Clarke, Hanshaw, and Balsley (1971). Also, it may be expanded and redesigned to aid in evaluation of the impact of a particular action on ground water.

The principal nature of stress on the aquifer for each action can be indicated in the table. Framework stresses include physical changes in the system framework, such as dredging, resulting in greater connection between the aquifer and streams, or channelization, resulting in new boundary conditions on part of the aquifer. A hydraulic stress is one that produces a

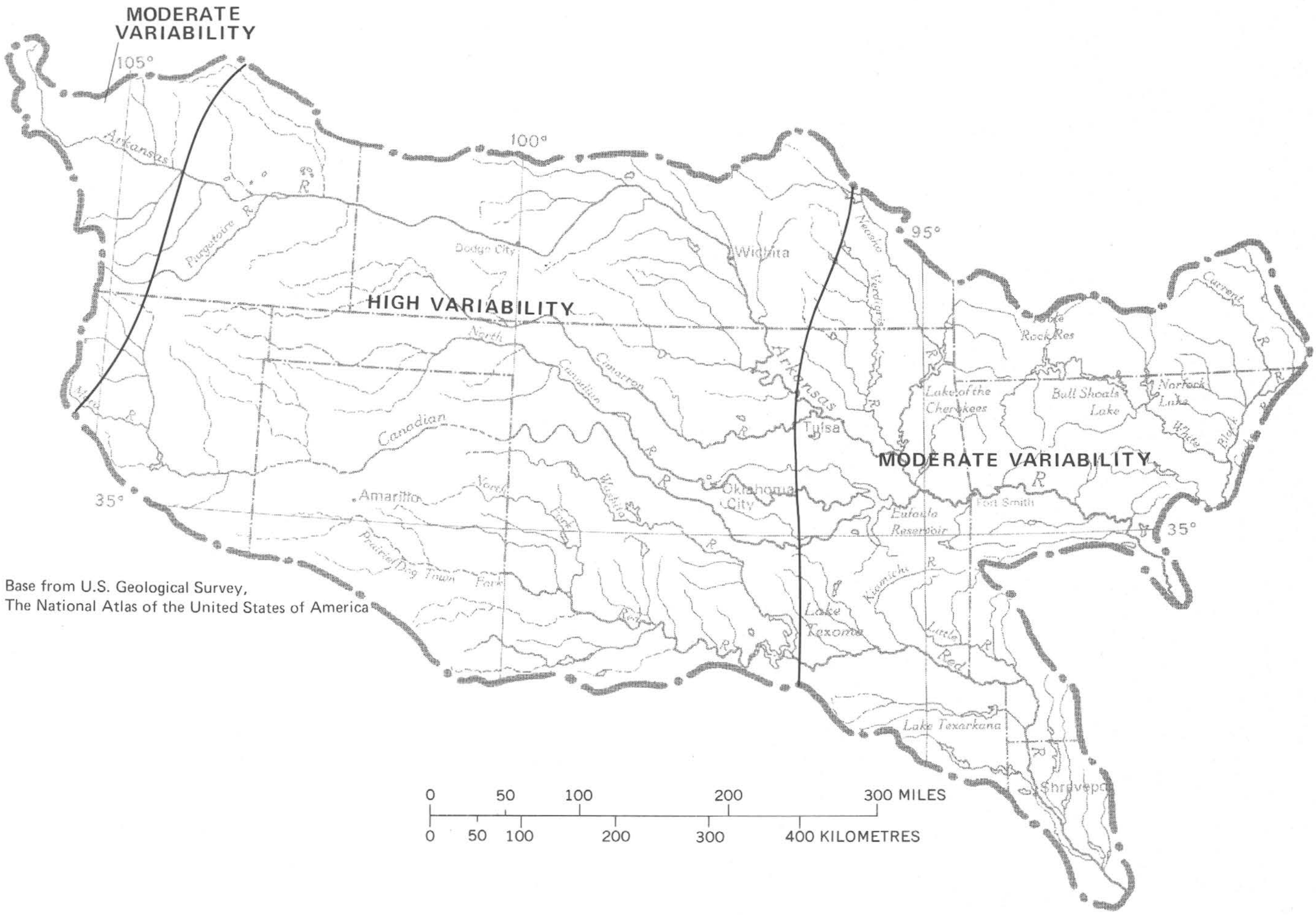


FIGURE 6.—Variations of the annual runoff (after Busby, 1966).

change in head or flow on a hydrologic boundary. Likewide, a thermal stress is one that produces a change in heat flow or heat gradient across a hydrologic boundary. A chemical stress is one that results in a direct change in chemical character of the water flowing into the aquifer or a chemical change in the system framework itself.

Responses of the aquifer are classified by the same groupings as those used for stress; however, the nature of the response of the aquifer is not limited to the same nature as the stress. Large changes in the aquifer framework in response to stress are not common but can be very significant, such as the extensive subsidence caused by large withdrawals in certain areas of California, at Mexico City, Mexico, and in the Houston, Tex., area. Earth movements in Denver, Colo., and vicinity have been attributed to injection of waste liquids. Subsidence has not been documented in the Arkansas-White-Red Region. The areas susceptible to subsidence are thick unconsolidated deposits, such as occur in the Gulf Coastal Plain and in deep basins in Colorado.

Hydraulic response in the aquifer is the most common response, particularly to water-management stresses. Hydraulic response has been divided into several changes in head and flow conditions in the aquifer and directly related effects, such as changes in well yield and specific capacity. The divisions of hydraulic response, as well as the other major response categories, are not intended to be comprehensive nor exclusive. Overlap between some of the divisions occurs and is sometimes desirable. Change in saturated thickness of the aquifer has been included in this table as a hydraulic response rather than a change in the aquifer framework.

Thermal response may be significant, particularly in applications where cooling water is required. The spectrum of chemical response is vast and complex. Only a few broad subdivisions of chemical response are given in table 2.

Table 2 can be used in the manner similar to that described by Leopold and others (1971) as follows: First, identify all actions that are a part of the proposed project. Second, in the rows of the proposed ac-

TABLE 2.—*Impact matrix relating*

Actions of potential impact on ground water	Principal nature of stress				Response of aquifer				
						Hydraulic			
	Framework	Hydraulic	Thermal	Chemical	Framework	Change in seepage to or from streams	Increase in leakage from confining beds and interbedded clays	Rise in water level	Decline in water level
Direct modification of hydrologic regime:									
Weather modification									
Desalinization									
Surface-water management:									
Reservoirs									
Flow regulation									
Water-retarding structures									
Locks and dams									
Revetments									
Levees									
Dredging									
Ditches and canals									
Channelization									
Interbasin diversions									
Pumping plants									
Surface-waste disposal									
Storm drains									
Irrigation									
Ground-water management:									
Relief wells									
Supply wells									
Dewatering wells									
Artificial-recharge									
Underground-waste disposal									
Subsurface drains									
Indirect modification of hydrologic regime:									
Agriculture:									
Fish farming									
Cultivation									
Land clearing									
Land leveling									
Terracing									
Fertilizer application									
Pesticide application									
Feedlots									
Pastures and grazing									
Timber management									
Urbanization:									
Homes and buildings									
Streets, parking lots, and airports									
Sewage lines									
Sanitary landfill									
Sewage spreading									
Septic tanks									
Mining and mineral production:									
Production									
Surface excavation									
Subsurface excavation									
Well drilling and fluid removal									
Manufacturing and processing									
Tourism and recreation									

stress and response in aquifer systems

Response of aquifer—Continued											
Hydraulic—Continued							Chemical				
Change in rate or direction of ground-water movement	Change from nonartesian to artesian, or vice versa	Change in saturated thickness of aquifer	Change in well yield	Change in specific capacity	Change in evapotranspiration or rejected recharge	Thermal	Change in dissolved-solids content	Dispersion and diffusion of introduced fluid of exogenous quality	Salinization of soils	Chemical reaction between introduced fluid and natural ground water	Chemical reaction between introduced fluid and system framework

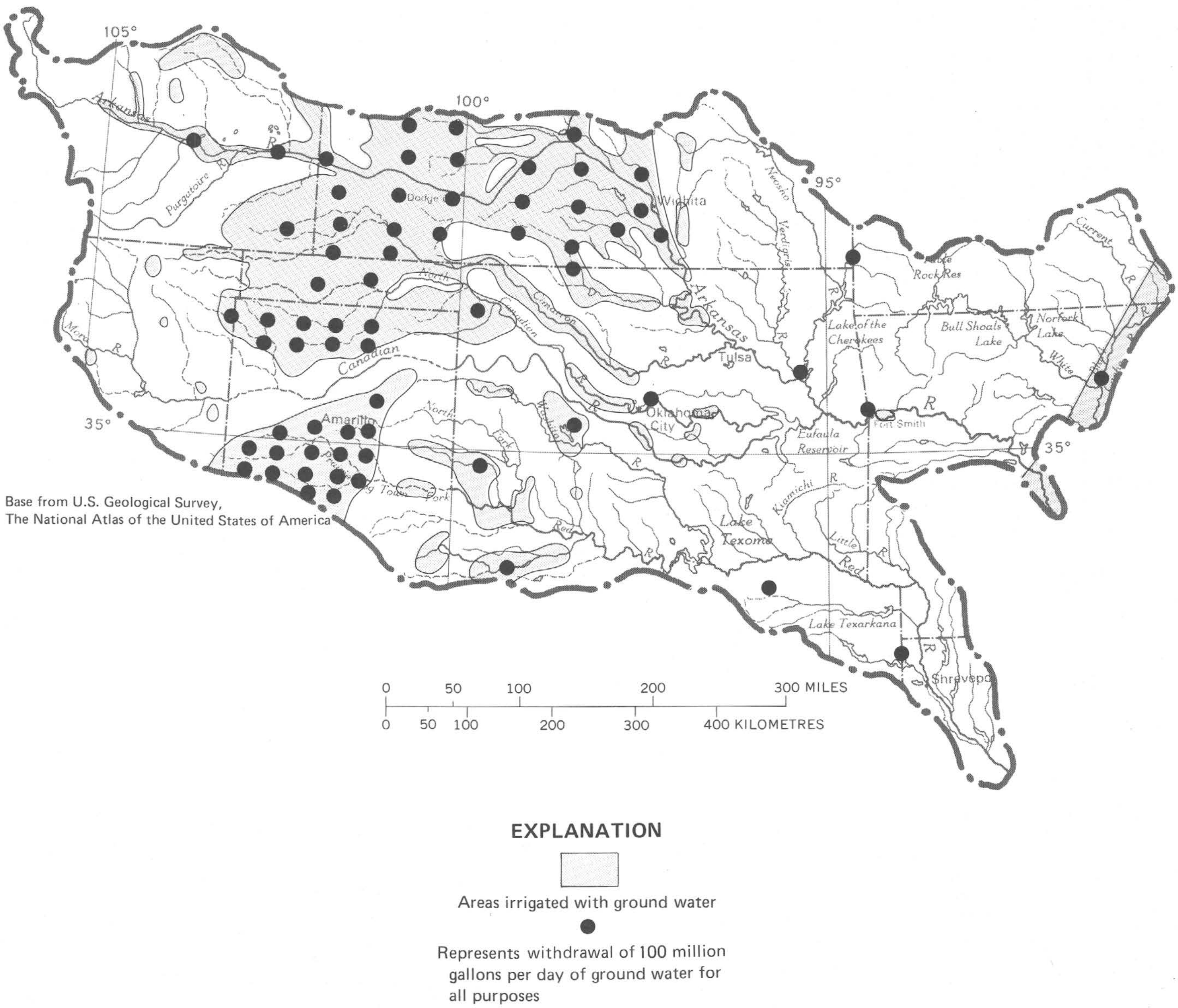


FIGURE 7.—Ground-water withdrawal and principal irrigated areas.

tions, place an "X" at the intersection with each applicable stress category. Third, consider the response to the combined stresses. Place a slash at the intersection of the action row with the response column. At this stage, an expansion of the response categories may be desired, depending upon the nature of the stress and the characteristics of the system being evaluated. Fourth, in the upper left corner of each box containing a slash, place a number from 0 to 3, which indicates the magnitude of the response; 3 represents the greatest magnitude of the response and 0, the least. In the lower right corner of the box, place a number from 0 to 3, which also indicates the significance of the possible response.

As examples, the matrix is used to illustrate the responses of aquifers to three projects (table 3). First, consider a navigation project involving construction of locks and dams, dredging of the channel, ditching to redirect interior drainage, and building revetments to stabilize the channel. These actions will produce changes in the framework and hydraulic, thermal, and chemical stresses. The greatest and most significant change will be a rise in water level in the aquifer. Small water-level declines will occur immediately downstream from the navigation dams. The resulting change in saturated thickness will be large but not significant in affecting transmissivity or the specific capacity of wells. In areas where water levels are raised, there will be significant increases in evapotranspiration from the aquifer. Increased evapotranspiration and seepage around dams will produce small thermal and chemical responses in water in the aquifer, and possibly salinization of the soils. The revetments and dredging will produce changes in the degree of connection between the aquifer and the stream and consequential changes in seepage. Ditching will cause water-level changes and attendant changes in the rate and direction of flow.

An irrigation project, in a semiarid climate, that derives water by ground-water withdrawals and surface-water diversion, will cause hydraulic and chemical stresses and small thermal changes. Declines in water levels near pumping wells, rises in water levels near leaky canals, and changes in seepage to the river will be the most significant hydraulic responses. Dissolved-solids concentration of the water in the aquifer will increase because of reuse and evaporation of the applied irrigation water. Salinization of soils will occur where applied water is insufficient to flush salts from the soil.

A water supply developed in a large artesian sand aquifer imposes a hydraulic stress. The response is largely hydraulic—lowering of water levels and related changes and the changes in the flow regime in the outcrop area. Responses may include a framework response, such as subsidence, and small thermal and chemical responses.

GROUND WATER IN WATER-RESOURCE PLANNING

CONJUNCTIVE USE WITH SURFACE WATER

Few projects have been deliberately planned to use ground water and surface water conjunctively. However, as discussed, many aquifer systems include hydrologically connected streams. This natural aquifer-stream connection results in an unplanned form of conjunctive use. The consequence may be deleterious or beneficial. But, even if beneficial, the benefits can be increased by sound hydrologically based planning. Planned conjunctive use of ground water and surface water unfolds a new dimension of water planning in which practices such as interbasin transfers of water, artificial recharge, and streamflow augmentation are employed.

The most readily amenable types of hydrologic systems for conjunctive management are the alluvial aquifer-stream systems along most of the length of the Arkansas and Red Rivers and along the lower White River. Pumping from the aquifer induces flow from the river to the aquifer or intercepts water that is moving toward the river; thus, drawdown in the aquifer is less than if there were no connected river. Poor-quality water in the middle reaches of the Arkansas River (Kansas and Oklahoma) is mixed with good-quality ground water, resulting in a quality that is satisfactory for irrigation and suitable for municipal supply after minimal treatment. The upper Arkansas River valley is intensively irrigated by ground and surface water. Conjunctive use of ground water and surface water, as practiced in the Arkansas River valley in Colorado, increases the usable water supply by 30 percent over the supply that could be developed by using surface water alone. The dependable supply could be further increased 23 percent by water-management practices that more fully utilize conjunctive-use techniques (Taylor and Luckey, 1974).

ARTIFICIAL RECHARGE

Conjunctive-use potential, involving utilization of the vast underground space in the western part of the Arkansas-White-Red River basins, calls for the technique of artificial recharge for storage of seasonal excess water or imported water. Artificial recharge has been the topic of much discussion and study. Although artificial recharge is frequently cited as a panacea for water-shortage problems, in reality its feasibility for application depends upon several factors.

Artificial recharge through wells is costly because of technical problems, maintenance costs, and large capital expenditure requirements. One of the inherent advantages of use of ground water over the use of surface water is the wide distribution and availability of ground water throughout large areas. In artificial recharge through wells, the reverse of withdrawal, the wide areal distribution is a disadvantage, requiring a surface-distribution system to many artificial-recharge wells. Generally, water recharged through wells and later withdrawn will cost at least twice as much as withdrawing native ground water. Studies by Sniegocki (1963) showed the cost of recharging through wells to be prohibitive for supplying water for irrigation in the Grand Prairie Region of Arkansas.

Artificial recharge through water spreading may be feasible on parts of the Arkansas-White-Red Region, including the High Plains. The feasibility of recharge by spreading is dependent upon the local conditions, requiring a large surface area of highly pervious earth materials above the aquifer.

REDUCTION OF CONSUMPTIVE WASTE

The salvage of evapotranspiration losses is the only practical means at present by which the amount of water available for use could be increased. A large part of the evapotranspiration loss is by transpiration by nonbeneficial plants such as phreatophytes.

TABLE 3.—*Impact matrices of water-resource*

Actions of potential impact on ground water	Principal nature of stress: Framework	Principal nature of stress: Hydraulic	Principal nature of stress: Thermal	Principal nature of stress: Chemical	Response of aquifer: Framework	Response of aquifer: Hydraulic: Change in seepage to or from streams	Response of aquifer: Hydraulic: Increase in leakage from confining beds and interbedded clays	Response of aquifer: Hydraulic: Rise in water level	Response of aquifer: Hydraulic: Decline in water level
Navigation project in alluvial-stream aquifers:									
Locks and dams		×	×	×	1/1	3/1		3/3	2/1
Revetments	×					1/0		0/0	
Dredging	×	×	×			2/1			2/1
Ditching	×	×	×			3/3			3/3
Irrigation project in alluvial-stream aquifers:									
Reservoirs		×	×	×		2/1		2/1	
Diversion canals	×	×	×	×	3/2	3/3		3/2	
Irrigation		×	×	×	3/2	2/1		2/2	
Supply wells		×				3/3	1/0		3/3
Industrial supply from artesian-sand aquifers:									
Supply wells		×			2/1	2/1	3/3		3/3

Phreatophytes send their roots down to the water table or capillary fringe. They consume large quantities of water in arid and semiarid regions, where they infest large acreages, particularly along those streams where the water table is shallow. They may cause serious siltation problems by clogging stream channels, thereby retarding streamflow.

In the eastern part of the Arkansas-White-Red Region, where water is more plentiful, as well as in the western part, many species of plants either of low economic value or of no value consume large quantities of water that would otherwise be available for beneficial use. Transpiration by noneconomic plants in the Arkansas River valley, downstream from Pueblo, Colo., averages 140,000 acre-feet (1.7×10^8 m^3) per year (J. E. Moore, oral commun., 1974).

Reduction of evapotranspiration losses may require removing noneconomic plants or depriving them of their source of water. The efficacy of a given procedure depends upon proper planning, based on an understanding of the conditions. Perhaps the most direct method of removing the water supply from the phreatophyte would be the lowering of the water level below the root depth of the plant. This procedure may also reduce loss of water by evaporation from the aquifer through the capillary fringe. Phreatophyte control by pumping from wells may not be feasible near perennial streams.

Control of plants of no economic value by removal could be augmented by replacement with economically valuable plants. Such practices have been successful in restoring rangeland in the western part of the Arkansas-White-Red Region. There, deep-rooted nonbeneficial plants and shrubs intercept water before it reaches the water table. Lowering of the water level would be of minimal value. In rangelands it has been shown (Rechenthin and Smith, 1967, p. 11), that many of the nonbeneficial plants consume up to four times as much water per pound of dry matter produced than the beneficial grasses consume.

LEGAL AND ORGANIZATIONAL CONSIDERATIONS

Water-resource management includes a comprehension of legal theories and procedures involving water. The laws are relatively few and simple in the eastern water-surplus part of the Arkansas-White-Red Region but are more complex in the western water-deficient *development actions on aquifer system*

Response of aquifer—Continued											
Hydraulic—Continued							Chemical				
Change in rate or direction of ground-water movement	Change from water table to artesian or vice versa	Change in saturated thickness of aquifer	Change in well yield	Change in specific capacity	Change in evapotranspiration or rejected recharge	Thermal	Change in dissolved-solids content	Dispersion and diffusion of introduced fluid of exogenous quality	Salinization of soils	Chemical reaction between introduced fluid and natural ground water	Chemical reaction between introduced fluid and system framework
3/2		3/0	1/0	0/0	3/3	2/1	2/2	2/2	1/1	1/0	1/0
2/1		0/0				1/0					
3/2		1/0	1/0	0/0	2/2	2/1					
1/1		2/1	1/0	1/0	1/1	0/0	1/0				
2/2		2/1	1/1	1/0	2/1	1/0	2/1			1/1	1/1
2/1		2/1	2/1	1/0	2/2	1/0				1/1	1 1
3/1		3/2	3/3	2/2	2/2	0/0					
3/2		0/0	3/2	0/0	2/1	1/0	1/0	1/0		1/0	1/0

part (fig. 4.). Obviously, a resource in surplus supply has little need of legal tools for its local allocation. Regional management by methods such as water transport to water-deficient areas from water-surplus areas may necessitate allocation procedures.

In most of the eight States in the Arkansas-White-Red Region, the laws are now in the process of modification or development. Consequently, only the principal terms presently used in water law in the Arkansas-White-Red Region are considered.

These terms are riparian, overlying, and appropriative rights. Under riparian rights, the land adjacent to a stream or lake is riparian to that body of water. Under common law, the waters of the stream are available on a correlative basis for the use of all riparian owners. In overlying rights, the overlying landowner either possesses rights that are analogous to riparian rights on a stream or asserts absolute title to water under his land. Under appropriative rights, the right to water use is based upon priority of diversion and application of the water to beneficial use.

The riparian doctrine of reasonable use has been accepted by the Arkansas Supreme Court. This general rule applies to surface water, as well as to ground water. In addition to the riparian doctrine, the Arkansas Legislature has adopted some aspects of the appropriative doctrine, whereby a State agency may allocate a fair share of water to persons where there is a shortage.

Colorado's basic principle of water law is that of appropriation and includes ground water that is tributary to a watercourse. The State recognizes the need for clarification of the question regarding ground water not adjacent to a watercourse and is in the process (1974) of modification of the water laws.

The water law in Kansas is based on the principle of prior appropriation and applies to surface and ground water.

In a general way, Louisiana follows the riparian rule. In 1910 the State declared that all surface water then not in private ownership was the property of the State, subject only to the jurisdiction of the United States on navigable waters. Almost no attention has been given to water laws concerning ground water.

Missouri adheres to the riparian doctrine in the administration of water rights and includes ground water and surface water in this category. Modifications in the State's water laws are being considered.

In New Mexico, both surface water and ground water are managed under the doctrine of prior appropriation. The State engineer recognizes the relation between surface water and ground water and requires that new pumping of ground water be offset by retirement of existing surface-water rights equivalent to the anticipated depletion of streamflow.

Oklahoma is operating under the appropriative theory of water rights. Riparian rights are recognized only to the extent of domestic, household, and stock water. The State's ground-water law provides for adjudication of ground-water rights in designated critical areas. Ground water and surface water are treated as separate entities.

Texas enacted a ground-water law in 1949 that authorized the formation of local districts having the power to make and enforce regulations governing the withdrawal of percolating ground water. By virtue of this law, Texas has given the power of regulation to local groups, thus placing the responsibility for regulation at the lowest possible governmental level capable of performing the desired functions. The districts in Texas are unique in that their boundaries are required to be coterminous with the underground reservoir or subdivision thereof.

A compact, in the general sense, is a type of water law that deals with streamflow across State boundaries. Noteworthy examples are compacts between Colorado and Kansas, Kansas and Oklahoma, and Oklahoma and Arkansas, on the flow of the Arkansas River and the proposed compact on the flow of the Red River. For the most part, these compacts do not deal with ground-water flow across State boundaries. Considerable quantities of ground water are exchanged between Colorado and Kansas, and Kansas and Oklahoma, in the vicinity of the Arkansas River. Only negligible amounts of ground water move across the boundary between Oklahoma and Arkansas.

This brief review of the water laws in the Arkansas-White-Red River basins shows that variations exist in the application of the three principal doctrines. As indicated, most of the States are in the process of modifying these laws.

MODELS FOR WATER-RESOURCE PLANNING

The development of sophisticated and accurate digital and analog models for representation of ground-water-flow systems has provided efficient tools for water-resource planning and for water-management decisions. The scope of modern-modeling techniques provides a basis for environmental evaluations of quantity and quality of water and for considering the effects of economic and legal constraints on water use. This section discusses modern techniques of ground-water modeling, with special reference to model applications in the Arkansas-White-Red Region.

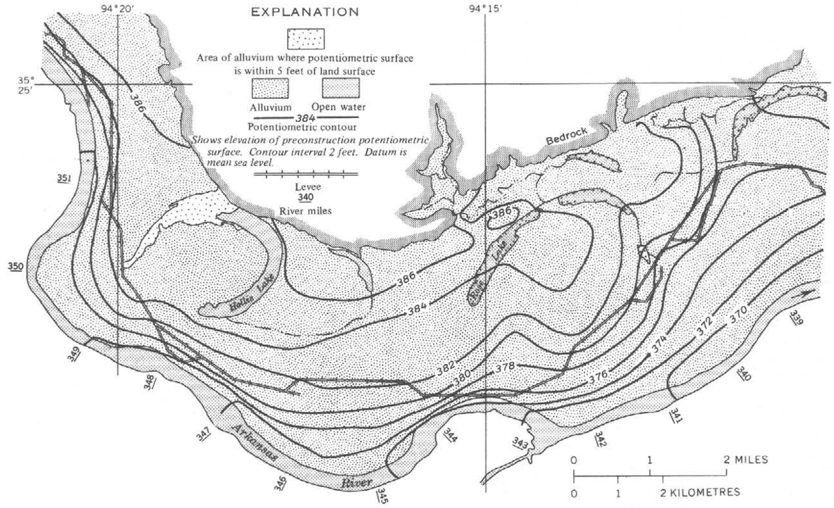
Analog and digital models simulate the hydrologic properties and boundaries of the hydrologic system. The scientific basis for both models is the finite-difference approximations of the equations that define the flow system. The main difference between the two types of models is that in the digital model flow equations are solved mathematically and in an electric analog model the equations are simulated with a resistor-capacitor network. Each type has certain advantages, depending on the system to be modeled.

The analog model can simulate very large, complex hydrologic problems, such as one that involves two or more aquifers with fine-grained interbeds and confining beds. It provides a visual display of the aquifer characteristics (transmissivity and storage) and boundaries (impermeable and stream contacts). The analog is also programed and read by the use of visual-display units. The visual nature of the analog and its operation, and the readiness with which stress acting on the aquifer, such as pumping or river stage, can be changed and the effects observed, make the analog useful in visibly modeling the operation of the hydrologic system.

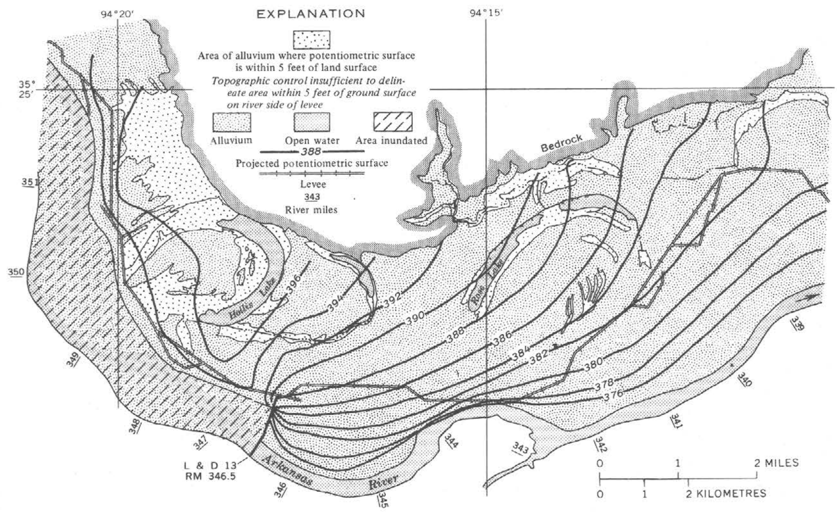
The digital model can solve the more complex problems, such as heat flow, movement of contaminants, chemical quality changes, and transient changes in transmissivity with saturated thickness. Digital models can also incorporate legal, economic, and environmental constraints on the system and can be programed to seek the best water-use conditions. Data input, data output, and program changes can be managed more efficiently by using digital models.

Analog models of the lower Arkansas and Verdigris River alluvial aquifers were used to analyze the effects of rocks and dams on the potentiometric surface (fig. 8). The Arkansas and Verdigris Rivers are made navigable by a series of 17 locks and dams for a distance of 450 miles (7.2×10^5 m) from the Mississippi River through Arkansas to near Tulsa, Okla. The analog models represent 2,350 square miles (6.1×10^9 m^2) of alluvial aquifer adjacent to the river (Bedinger and others, 1970). They were made up of resistors and capacitors in a rectangular network to represent the transmissivity and storage characteristics of the aquifer. Resistor-capacitor nodes in the model were spaced to represent distances of ⅛ – ½ mile (201 to 805 m). Resistors connected at each node of the aquifer network were used to model evapotranspiration as a function of the depth to water level.

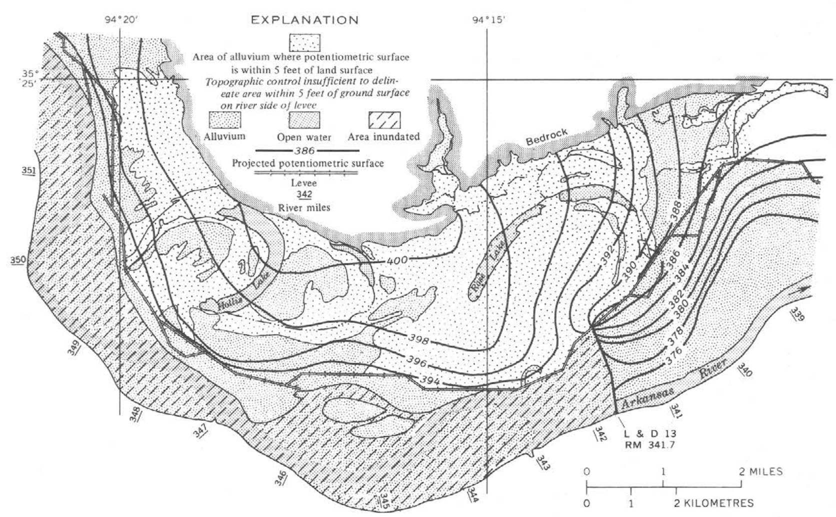
A combination of an electric analog and a digital model was used in the Arkansas River valley of Colorado to define the operation of an aquifer-stream sys-



A. Area studied in selection of a site for lock and dam 13, near Fort Smith, Ark.



B. Projected potentiometric surface for damsite (lock and dam 13) at river-mile



C. Projected potentiometric surface for damsite (lock and dam 13) at river-mile 341.7.

FIGURE 8.—Preconstruction ground-water conditions and projected ground-water conditions in a part of the Arkansas River valley, Arkansas (from Bedinger and others, 1970, p. 63–65).

tem and to predict effects of changes in water management. The area modeled, extending about 150 miles (2.4×10^5 m) from Pueblo, Colo., to the Kansas boundary (Moore and Wood, 1967), is underlain by an alluvial aquifer that is hydraulically connected to the river. The ground water and surface water constitute one supply. The development of ground water for irrigation has caused legal disputes between ground-water and surface-water users because withdrawals by wells have reduced the flow of the Arkansas River. An electric analog model was developed to simulate the stream and the aquifer. Applied irrigation water, precipitation, evapotranspiration, and well withdrawal were the hydrologic stresses incorporated in the model.

The analog model was stressed at 266 points to obtain reponse curves showing the effect of aquifer stress on streamflow. The response curves, summarizing differences in aquifer transmissivity, specific yield, and boundaries, were then prepared as a stream-depletion factor map (Moulder and Jenkins, 1969). The lines of equal-stream-depletion factors connect points where the hydrologic stresses on the aquifer have the same effects on the streamflow (fig. 9). The stream-depletion-factor map was the basis for constructing a digital model of the aquifer-stream system, to analyze and optimize water-management plans for any given set of management objectives. The model was designed to predict the availability of surface water at successive diversion points downstream, on a month-to-month schedule, and to show change in ground-water storage. Output data from the model of the Arkansas River valley have been used for planning maximum water use within legal, economic, environmental, and hydrogeologic constraints. The results have been used for modifying water law, for developing ground-water supplies, and for distributing water.

Digital models have been developed to couple the computer solutions of ground-water-flow equations with mass-transport and dispersion equations of a dissolved-chemical constituent in an aquifer (Bredehoeft and Pinder, 1973). This coupling permits the modeling of the spread of saline water or other contaminants in an aquifer. The model has been used to simulate changes in salinity related to irrigational practices in the Arkansas River valley of southeast Colorado (fig. 10) (Konikow and Bredehoeft, 1973), where the ground water and surface water are interrelated in an aquifer-stream system. Crops are irrigated by both diverted surface water and pumped ground water from the alluvial aquifer. Much of the irrigation water is lost by evapotranspiration, but some of it infiltrates the alluvial aquifer and provides return flow to the stream. Dissolved solids in the return flow become concentrated because of the evapotranspiration. The downvalley reuse of water causes a buildup of salts

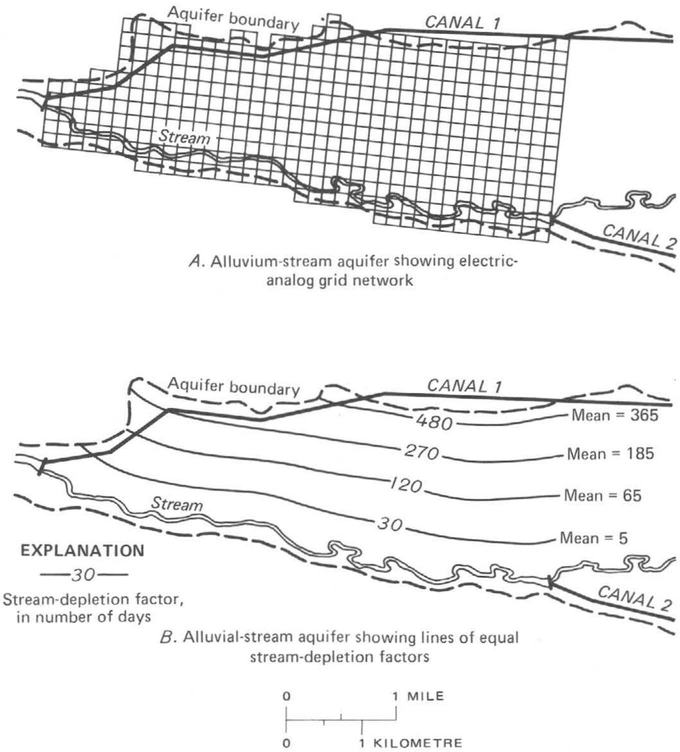
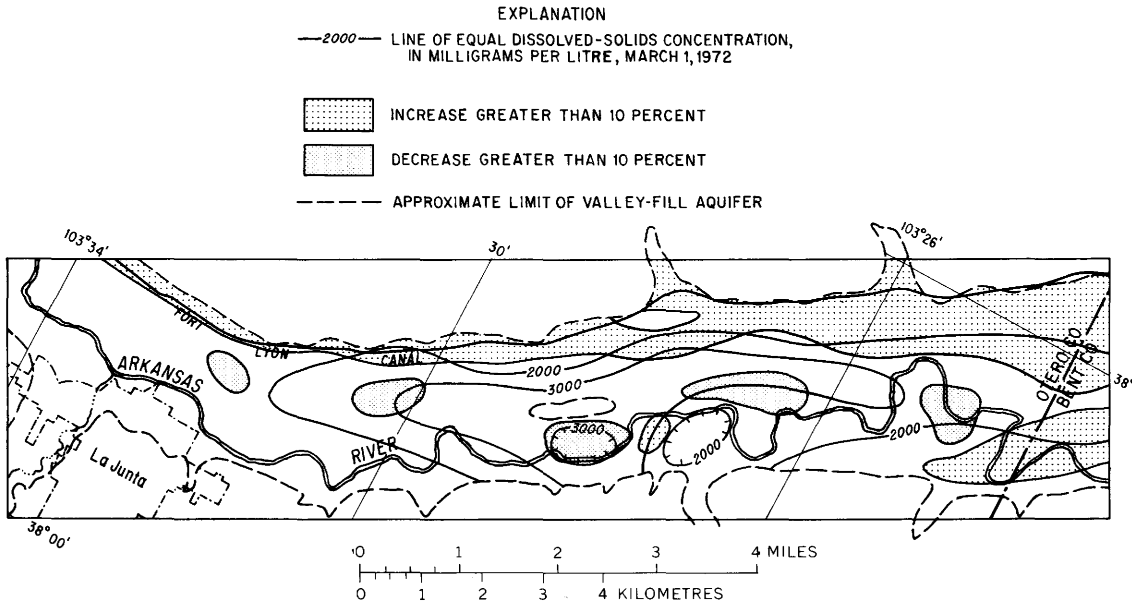


FIGURE 9.—An alluvial-stream aquifer in part of the Arkansas River valley, Colorado, showing (A) the electric analog grid network and (B) lines of equal-stream-depletion factors (from Moulder and Jenkins, 1969).

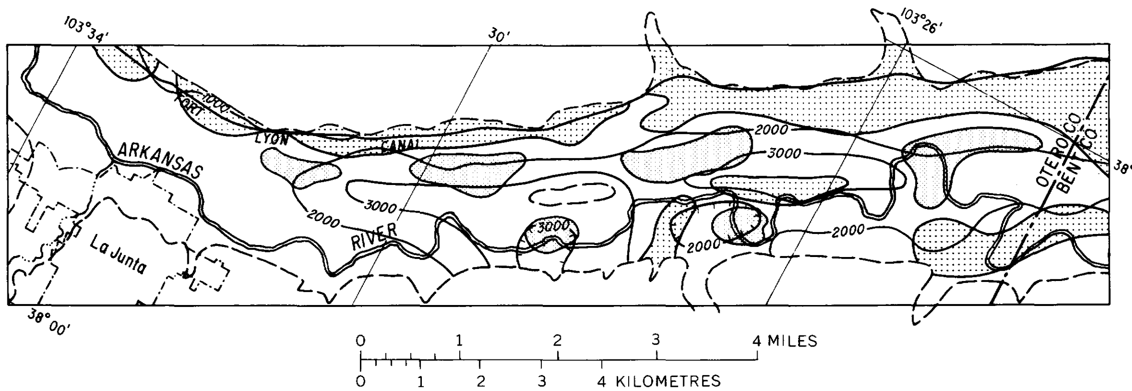
approaching levels that could restrict the use of the water.

The model can be used to predict the effects of changes in management or irrigational practices on the quality and quantity of ground and surface water. For example, the model could be used to evaluate the impact of increased pumping from irrigation wells, increased surface-water diversions, increased irrigated acreage, floods, droughts, and increased salinity in the river due to upstream activities. The model can aid in determining the feasibility of plans to improve the quality of ground water or to limit salinity increases in the river during critical low-flow periods.

One application that illustrates the versatility of digital models for use by the planner is the development of models that simulate the physical and chemical responses of a flow system to changes in environmental and managerial stresses. The digital models may also incorporate features to perfect management of the system under environmental, social, legal, and economic constraints. A model of the aquifer-stream system in southeastern Colorado was used to simulate the dependable supply under various water-distribution schemes. Included in analysis are flow components, such as salvage of water from phreatophytes, evapotranspiration, different



A. Observed dissolved-solids concentration on March 1, 1972, and observed changes since March 1, 1971



B. Calculated dissolved-solids concentration on March 1, 1972, and calculated changes since March 1, 1971

FIGURE 10.—Observed and calculated dissolved-solids concentrations in ground water in a part of the Arkansas River valley, Colorado (from Konikow and Bredehoeft, 1973).

reservoir-operation regulations, use of imported ground water and surface water, additional reservoirs, additional ground-water use, and application of excess streamflow (Taylor and Luckey, 1974).

GROUND WATER IN THE ARKANSAS-WHITE-RED REGION

The Arkansas-White-Red Region comprises the following six aquifer types: (1) Stream-valley alluvium, (2) terrace alluvium, (3) alluvium of intermontane valleys and buried alluvial valleys, (4) carbonate and gypsum, (5) sand and sandstone, and (6) undifferentiated sandstone, carbonate rock, shale, and (or) basalt. Their distribution is shown in figure 11.

Information is available about the aquifers from offices of the U.S. Geological Survey and from State agencies in the respective States in which the aquifers occur; references to published information and unpublished data can be obtained from the agencies listed later in this report. Included are data on thickness, permeability, transmissivity, storage coefficient, recharge rates, water in storage, depth to water, direction and rate of ground-water movement, water use, well yields, water quality, and other information, such as grain size of aquifer materials. A summary of data is given in table 4. Geologic and geographic distribution of formations that are principal aquifers are given in table 5.

The quality of ground water throughout the Arkansas-White-Red River basin varies considerably, depending upon the original character of water entering the aquifer, the nature of the rocks through which

TABLE 4.—*Principal aquifers in the Arkansas-White-Red Region*

Aquifer type	Nature of rock	Thickness (ft)	Areal extent	Depth to water (ft)	Hydraulic conductivity (ft/d)	Well yields (gal/min)	Development and use	Ground water in storage (acre-ft x 10^8)
Stream valley alluvium	Sand and gravel	50-200	Along large streams in flood plains. Extensive in Coastal Plain of Arkansas and Louisiana.	0-30	100-1,500	300-5,000	Extensive; principal source of ground water; frequently overdeveloped. Not used in some areas.	2.8
Terrace alluvium		50-600	Plains of Texas, New Mexico, Colorado, Kansas, and Oklahoma.	50-300	10-700	50-1,000	Extensive; subject to overdevelopment and water mining, particularly in High Plains of Texas.	4.1
Alluvium of intermontane valleys and buried alluvial valleys		100-5,000	Arkansas River basin in Colorado.	0-50				0.2
Carbonate and gypsum	Limestone and dolomite, and gypsum beds. Generally a dense rock, but subject to solution along fracture and bedding planes.	50-1,500	Limestone and dolomite in southern Missouri, northern Arkansas, southeastern Kansas, and Oklahoma. Gypsum in Oklahoma and Texas.	30-450	50-1,500	50-1,000	Moderately to heavily developed; overlooked as a source of water in some areas. More subject to pollution than other aquifers because of cavernous nature.	3.2
Sand and sandstone	Sand grains ranging from very fine to coarse. Generally cemented with siliceous material or carbonate. Unconsolidated in the Coastal Plain.	100-500	Sandstone principally in Kansas, New Mexico, and Oklahoma. Sand in Coastal Plain of Arkansas, Texas, and Louisiana.	20-300	(1)	10-1,000	Extensive; subject to overdevelopment and water mining. Loss of artesian head in many areas ranging from 2 to 300 feet.	7.9
Undifferentiated sandstone, carbonate, shale, or basalt	Consolidated rocks, including sandstone, interbedded shale, carbonate, and crystalline igneous rocks.	100-5,000	Sandstone, carbonate, and shale locally throughout region; basalt in parts of New Mexico, Colorado, and northwestern Oklahoma.	1,200	(2)	5-50	Mainly domestic use, not heavy, concentrated use, because of low permeability and low well yields. Difficult to predict well yields.	2.2

[1] Generally less than 100 ft/d.
[2] Generally less than 10 ft/d.

the water has moved, the contaminants that may have been introduced, and (or) the concentration of mineralization by evaporation or transpiration. The quality ranges from fresh to saline. Fresh water (containing less than 1,000 mg/l of dissolved solids) is generally present at shallow depths, and saline water, at greater depths.

The prevalent dissolved-solids concentrations and chemical types in streams at low flow are shown in figures 12 and 13. At low flow the streamflow is largely ground-water discharge. The quality characteristics of water in streams at low flow are therefore indicative of the quality of the water in the aquifers in contact with the streams. The dissolved-solids concentration (fig. 12) is generally low in the eastern part of the region and at the higher elevations along the west margin of the region. The areas having high dissolved-solids concentrations coincide with the distribution of shale beds

TABLE 5.—*Names and geographic distribution of major geologic units that form aquifers*

Aquifer type	Major geologic unit names	Distribution
Stream valley alluvium		Valleys of major streams.
Terrace alluvium	Seymour Formation	Texas.
	Equus zone of McPherson Formation	Kansas.
	Ogallala Formation	Texas, New Mexico, Colorado, Kansas, and Oklahoma.
Alluvium of intermontane valleys and buried alluvial valleys		Upper Arkansas River valley and Wet Mountain valley, Colorado.
Carbonate	Reeds Spring Limestone	Oklahoma.
	Boone Formation	Arkansas.
	Roubidoux and Gasconade Formations and the Eminence and Potosi Dolomites of the Arbuckle Group	Arkansas, Missouri, Kansas, and Oklahoma.
	Arbuckle Group undivided	Oklahoma and Kansas.
Gypsum	Dog Creek Shale and Blaine Gypsum	Oklahoma and Texas.
Sand and sandstone	Sparta Sand	Arkansas and Louisiana.
	Wilcox Group, Carrizo Sand, and Trinity Group	Oklahoma, Texas, and Arkansas.
	Purgatoire Formation, Cheyenne Sandstone, and Dakota Sandstone	Colorado, Kansas, New Mexico, and Oklahoma.
	Vamoosa Formation, Rush Springs Sandstone, Garber Sandstone, Wellington Formation, Member of Gasconade Formation, Simpson Group, and Gunter Sandstone	Oklahoma.

in southern Colorado and northern New Mexico, with salt springs and the pollution by oil-field brine in northern and central Oklahoma; and with the occurrence of gypsum beds in Texas through central Oklahoma to southern Kansas. The chemical types (fig. 13) reflect the nature of water in the shallow aquifers.

Saline ground water (containing more than 1,000 mg/l dissolved solids) is at depth beneath fresh water in most of the Arkansas-White-Red Region (Feth and others, 1965). Saline water is at depths less than 500 feet (150 m) throughout most of the area. The rate of use of saline ground water in the region in 1970 was estimated to be 38 Mgal/d (1.66 m^3/s; Murray and Reeves, 1972)—a very low rate compared with the rate of use of fresh water and compared with the amount of saline ground water that is available. When considered as a resource, the potential of saline water falls mainly into two categories—(1) direct use in industrial processes, such as cooling, or for irrigation where a moderate mineral concentration may not be a disadvantage, and (2) use after dilution or demineralization to whatever degree may be required by the intended user. Aquifers containing saline water may be considered as a resource potential for temporary storage of fresh water (Moulder, 1970) and disposal of wastes.

The areas of potential or existing ground-water pollution (fig. 14) are chiefly associated with areas of naturally high dissolved solids in streams and aquifers and the limestone terrane of the Ozark region. Water of naturally high dissolved solids may be further concentrated by evaporation and reuse for irrigation. Infiltration of irrigation water to the aquifer increases the salinity of the aquifer. The highly permeable limestones of the Ozark region are subject to pollution by entry of polluted wastes. Saline water may be induced to enter freshwater aquifers from adjacent saline-water aquifers and streams.

AQUIFER SYSTEMS IN THE REGION

The flow operation of each aquifer system depends on the characteristics of the aquifer, the climate, and the character of adjacent rocks and streams. These are the principal factors that also determine the response of aquifer flow systems to development or other man-induced stresses.

STREAM-VALLEY ALLUVIAL AQUIFERS

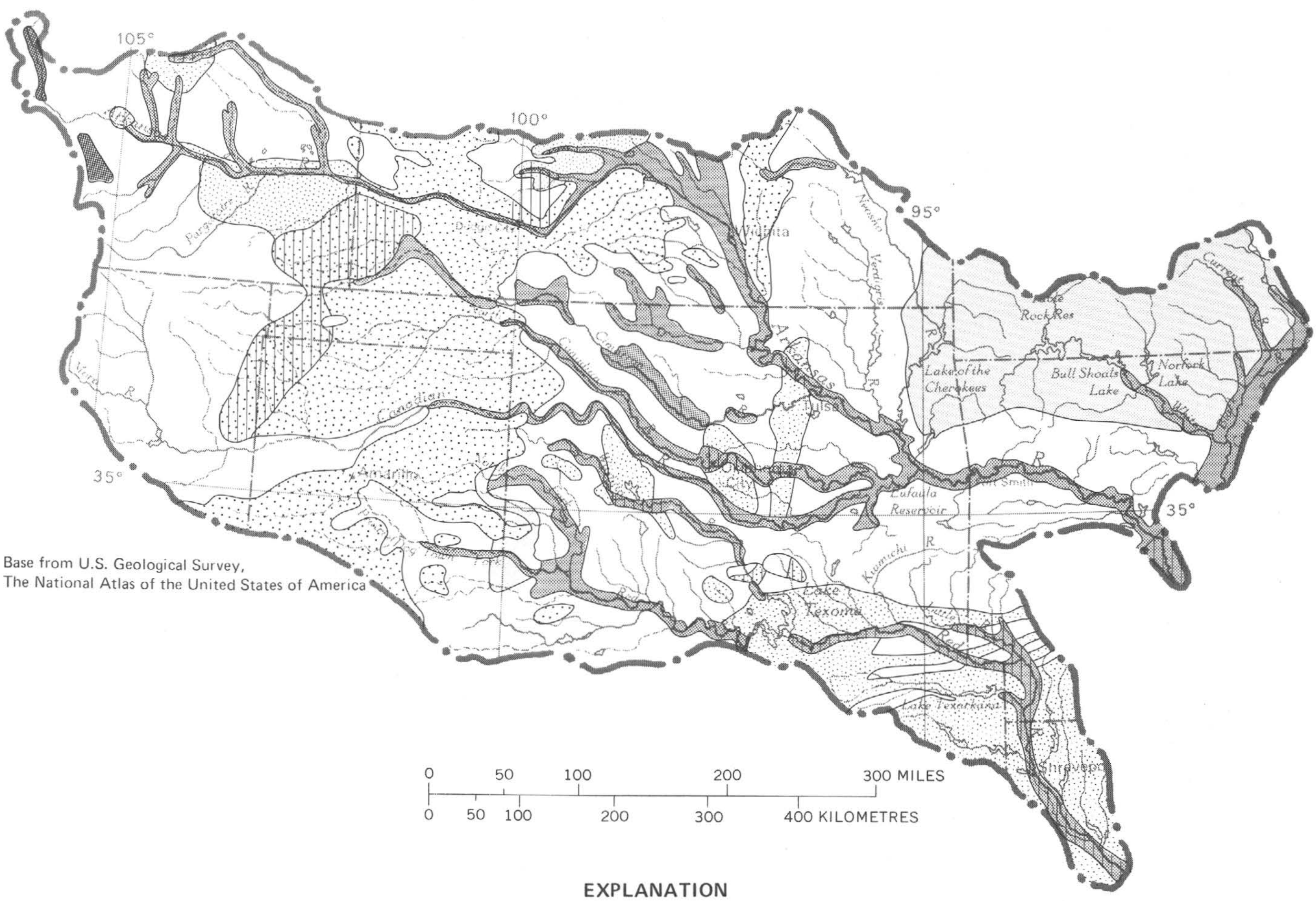
Alluvial deposits in stream valleys cover more than 28,000 square miles (7.25×10^{10} m^2) of surface area and constitute some of the most productive aquifers. The alluvium generally ranges in thickness from 50 to 200 feet (15.2 to 61.0 m) and ranges in width from 1 to 10 miles (1.6×10^3 to 16.0×10^3 m), except in the Coastal Plain, where the width is several tens of miles. The aquifers are generally composed of sand and gravel in the lower part of the alluvium.

The alluvial aquifers are in connection with the predominantly perennial streams. Ground water in the alluvium generally is at shallow depths, within reach of roots of plants. The alluvial material above the sand and gravel varies from fine sand to silt and clay; consequently, the water in the aquifer may be under water-table or semiconfined conditions.

The alluvium commonly lies in a valley cut in less permeable rock. Locally, the alluvium is in contact with rocks of equal or greater permeability.

OPERATION OF THE FLOW SYSTEM IN THE WATER-DEFICIENT AREA

Recharge by rainfall is low, ¼–½ inch (6.4×10^{-3} to 1.3×10^{-2} m) per year. Streams may be perennial or intermittent. Discharge is by evapotranspiration and by flow to streams. In response to withdrawal of ground water, water levels are lowered, reducing the amount of both evapotranspiration and rejected recharge. The amount of water salvaged from rejected recharge is relatively small because of low precipitation and high loss of precipitation by evaporation. Water-level declines also reduce streamflow, either by decreasing flow to the stream or by inducing flow from the stream into the aquifer. Operation of a stream-valley alluvial aquifer in a water-deficient area is illustrated in figure 15.



EXPLANATION

Stream valley alluvium
Sand and gravel, less than 200 feet (60 m) thick, traversed by streams

Alluvium of intermontane valleys and buried alluvial valleys
Sand and gravel as much as 5,000 feet (1,500 m) thick

Terrace alluvium
Extensive deposits of sand and gravel bordering major streams or capping interstream divides

Carbonate and gypsum
Limestone and dolomite of the Central Lowland and Ozark Plateaus; gypsum beds of the Central Lowland of Texas and Oklahoma

Sand and sandstone
Fine to coarse sand, unconsolidated in the Coastal Plain, elsewhere cemented with silica or carbonate material. Ruled pattern indicates presence of sand or sandstone aquifers in addition to aquifer indicated

Sandstone, carbonate, shale or basalt undifferentiated
Consolidated rocks, principally sandstone, carbonate and crystalline igneous rocks of low water yield

FIGURE 11.—Principal aquifers in the Arkansas-White-Red Region (modified from Lohman and others, 1953).

The amount of water in storage in the aquifer is small, about 10 times the annual withdrawal. Perennial overdrafts in excess of recharge cannot occur. Large developments, such as those in which a large part of the valley is irrigated by ground water, temporarily draw water from storage, but most of the water withdrawn must be restored by induced infiltration from rivers. Thus, the water supply is limited by available streamflow. Excess salts will build up in soil unless water in excess of evapotranspiration is applied.

CASE HISTORY—ARKANSAS RIVER VALLEY, COLORADO

The 150-mile (2.41×10^5-m) reach of the Arkansas River valley from Pueblo to the Colorado-Kansas State boundary is intensively irrigated by ground and surface waters. The annual delivery by wells and canals is 725,000 acre-ft (8.95×10^8 m^3) of water, of which about 150,000 acre-ft (1.85×10^8 m^3) is from wells. Storage in the aquifer is small, about 10 times the annual with-

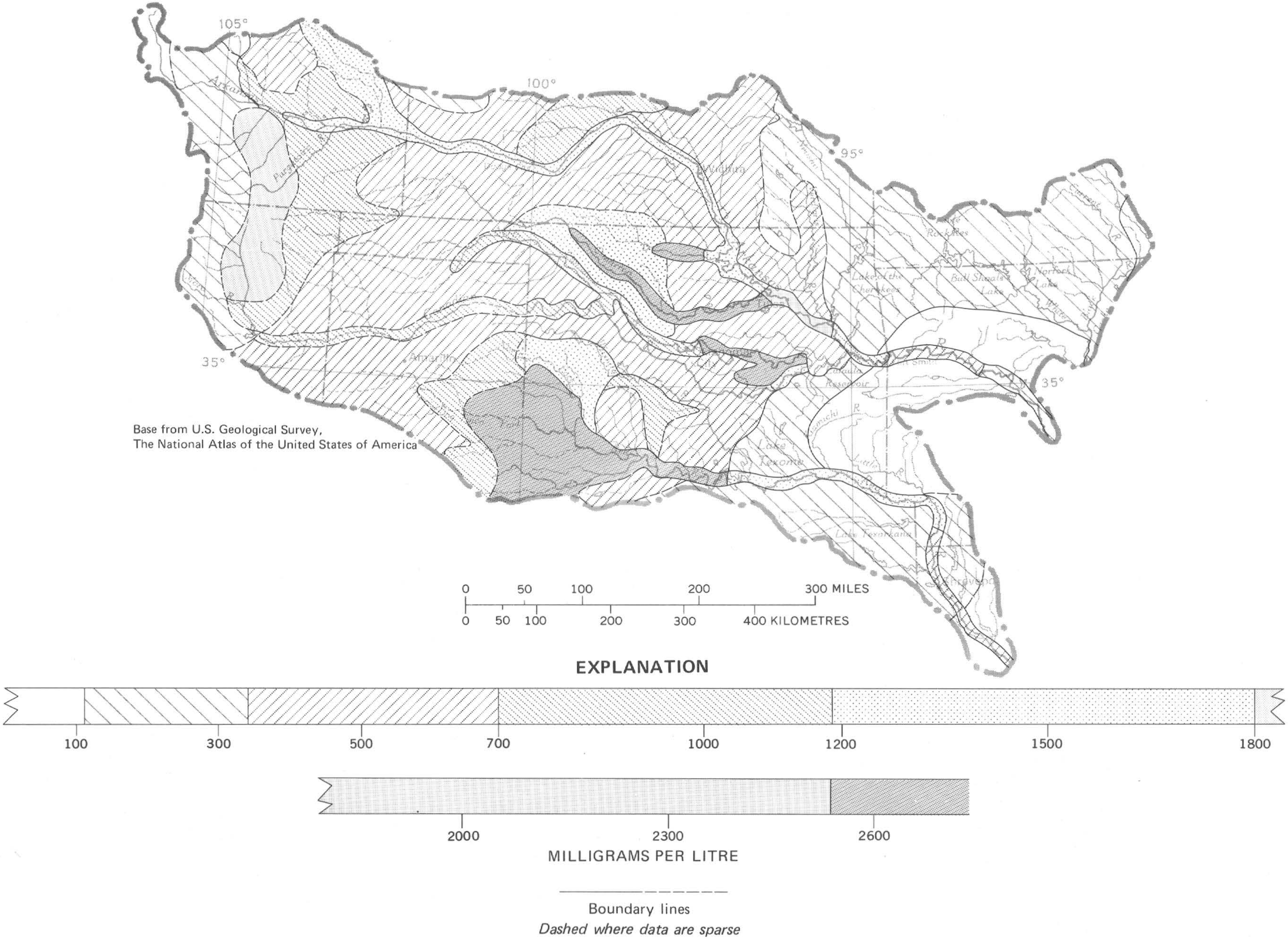


FIGURE 12.—Prevalent dissolved-solids concentration of water in the rivers at low flow (modified after Rainwater, 1962).

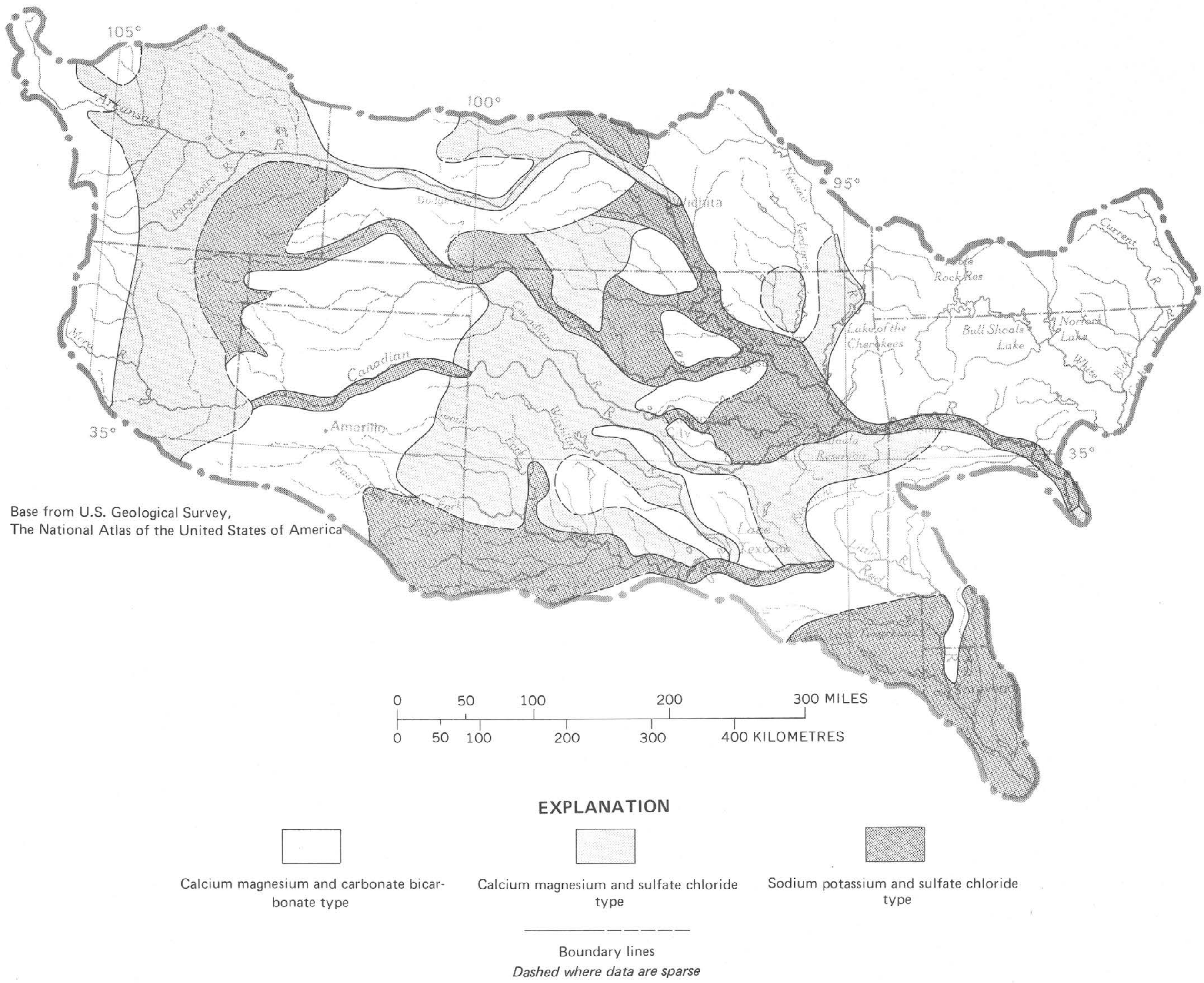


FIGURE 13.—Prevalent chemical types of water in the rivers at low flow (after Rainwater, 1962).

drawal. Water is withdrawn from storage during the irrigation season and is then replenished by rainfall, by infiltration of surface applications for irrigation, and influent seepage from the rivers and canals during and after the irrigation season. Because little water is salvaged from evapotranspiration by lowering the water level, the water supply in the aquifer is limited by the streamflow. Because of the heavy demand and reuse of water, the water quality in the aquifer progressively deteriorates downstream in the valley. Studies by Taylor and Luckey (1974) show that under present conditions use of ground water from storage during the irrigation season increases the water available during the irrigation season by as much as 113,000 acre-ft (1.39×10^8 m^3).

OPERATION OF THE FLOW SYSTEM IN THE WATER-EXCESS AREA

Recharge by infiltration of rainfall is about 3–10 inches (0.076–0.25 m) per year. Discharge is by evapotranspiration and seepage to the stream (fig. 16). In response to withdrawal, water levels are lowered, thereby reducing losses by evapotranspiration, reducing rejected recharge, and reducing base flow to the stream. Drawdown near the stream will induce flow from the stream to the aquifer. Large ground-water developments can be supported by water salvaged from evapotranspiration and by increased net infiltration of rainfall and reduced ground-water flow to streams. Streamflow is large and does not limit development. The quality of water in the aquifer is generally good.

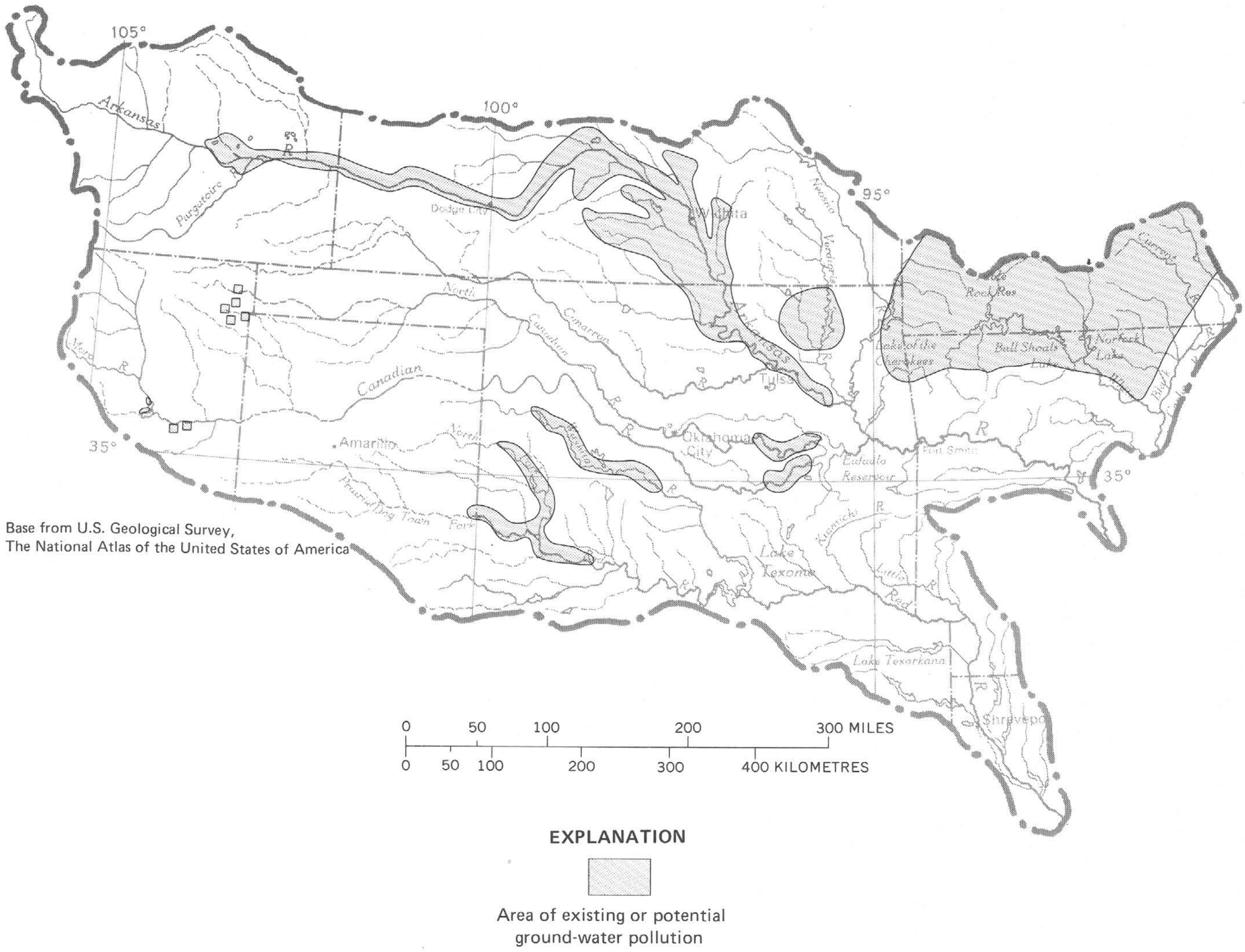


FIGURE 14.—Areas of potential or existing ground-water pollution in the Arkansas-White-Red Region.

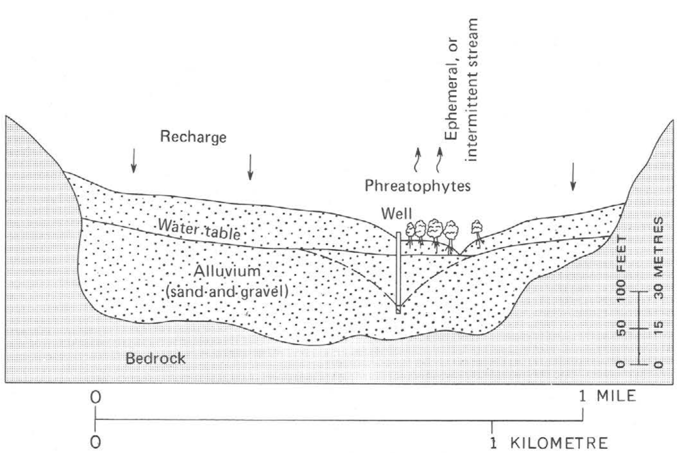


FIGURE 15.—Stream-valley alluvial aquifer with an ephemeral, or intermittent, stream in the water-deficient area.

TERRACE-ALLUVIAL AQUIFERS

Terrace alluvium is extensive in the plains of Texas, Colorado, Oklahoma, Kansas, and New Mexico. The sand-and-gravel section of the terrace alluvium is as much as 600 feet (1.8×10^2 m) thick and averages 300 feet (91 m) thick. Perennial streams generally are incised below the base of the terrace deposits. Terrace-alluvial aquifers contain large amounts of water in storage—as much as 75,000 acre-feet (9.2×10^7 m^3) per square mile (2.59×10^6 m^2) of surface area. Water levels are 50 feet (15 m) or more below the land surface.

OPERATION OF THE FLOW SYSTEM

Recharge to the aquifer, derived solely from sparse precipitation, is estimated to be $^1/_{20}$–½ inch (1.3×10^{-3} to

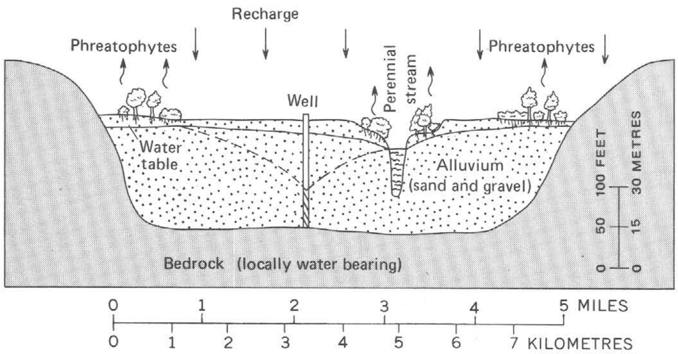


FIGURE 16.—Stream-valley alluvial aquifer with a perennial stream in the water-excess area.

1.3×10^{-2} m) per year. The natural discharge is to the adjacent valley alluvium or by seeps and springs along the terrace escarpment (fig. 17).

In response to withdrawal, there is little or no salvage of evapotranspiration from the water table because of generally low initial water levels. Also because streamflow is generally intermittent, there is little water induced from the stream to the aquifer. Withdrawals in excess of the meager recharge must come from storage.

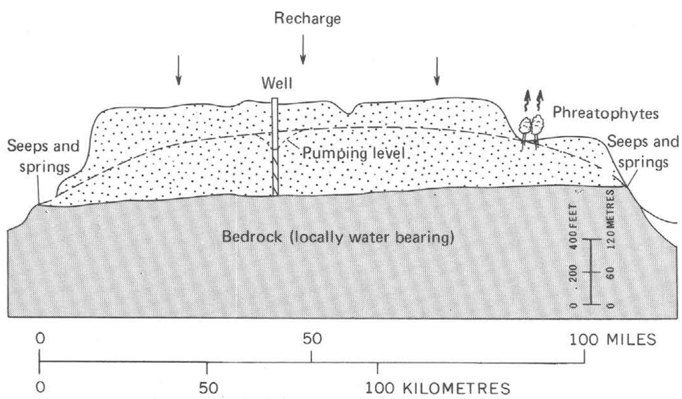


FIGURE 17.—Terrace alluvial aquifer.

CASE HISTORY—OGALLALA FORMATION IN THE SOUTHERN HIGH PLAINS OF TEXAS AND NEW MEXICO

Ground-water withdrawals increased from about 92,000 acre-feet (1.1×10^{8} m^3) per year, in 1934, to more than 4,600,000 acre-feet (5.7×10^{9} m^3) per year and are used mainly for irrigation. The storage of ground water prior to pumping was very large, approximately 460,000,000 acre-feet (5.7×10^{11} m^3).

Recharge from precipitation is approximately 69,000 acre-feet (8.5×10^{7} m^3) per year. Rechenthin and Smith (1967) estimated that a program in the High Plains to remove wasteful nonbeneficial plants and restore grass vegetation would save approximately 290,000 acre-feet (3.59×10^{8} m^3) of water annually. Much of the area of nonbeneficial plants does not overlie the aquifer, but, even if a large part of this salvaged water infiltrated to the water table, the increased annual accretion to the aquifer would amount to only about 5 percent of the annual withdrawal.

Salvaged rejected recharge and natural discharge are very low. The withdrawal is depleting water in storage, and the ground water is being mined.

A form of conjunctive use has been suggested for the High Plains in which surface water would be transported to the area from the Mississippi River valley. The large volume of unsaturated sand and gravel in the terrace deposits is a potential reservoir for the imported water. Increasing population and demand for food and fiber production may shift the plan into economic reality.

SAND AND SANDSTONE AQUIFERS

Unconsolidated sand in the Coastal Plain and sandstone partly cemented with calcium carbonate or silica in the High Plains and Central Lowland constitute the sand and sandstone aquifers. The sand and sandstone range in thickness from 100 to 500 feet (30 to 150 m). The aquifer is nonartesian (under water-table conditions) in the outcrop area. Where the sand or sandstone in the subsurface is confined by shale, clay, or siltstone of low permeability, the aquifer is artesian (under confined conditions).

OPERATION OF THE AQUIFERS

Recharge is by infiltration of rainfall in the outcrop area (fig. 18). The recharge rate is highly dependent upon climatic conditions; it ranges from less than 1 inch (2.5×10^{-2} m) per year in the western, water-deficient part of the region to 4–6 inches (0.1 to 0.15 m) per year in the eastern part of the region. Recharge to the sand also occurs where it is overlain by extensive, saturated sand and gravel in the Coastal Plain. Natural discharge is by seepage to streams incised into the aquifer in the outcrop area and by seepage to confining beds in the subsurface.

Pumping in the area where the aquifer is artesian produces large, widespread declines in head. Water is initially pumped from storage; as pumping continues, water is induced from interbedded fine-grained beds and confining beds. As the cone of depression reaches outcrop areas, water is induced from the streams and from the overlying alluvium into the sand aquifer.

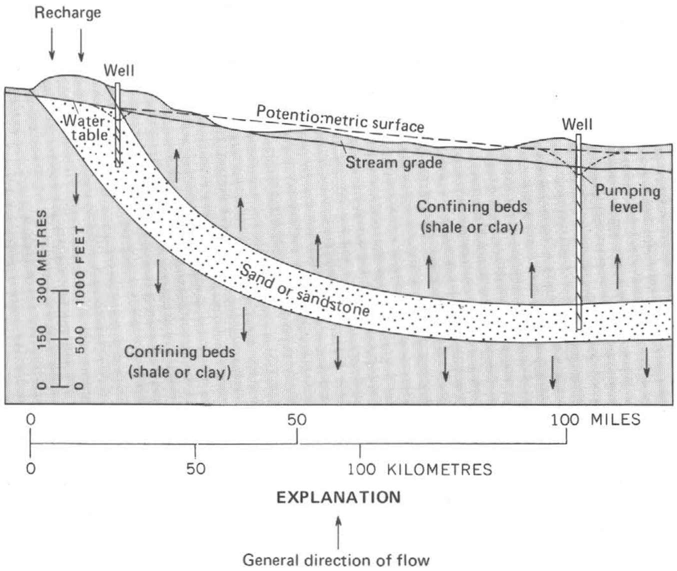


FIGURE 18.—Sand or sandstone aquifer.

CASE HISTORY—THE SPARTA SAND OF THE COASTAL PLAIN

The Sparta Sand and the contiguous sand beds above and below it form an aquifer that extends over thousands of square miles in Arkansas, Louisiana, Missouri, Tennessee, Kentucky, and Mississippi. Only a small part of the Sparta's extent is in the Arkansas-White-Red Region. But the aquifer cannot be dissected along arbitrary lines for analysis, such as those bounding States or Water Resources Council regions. Significant water withdrawal from the Sparta Sand began in 1886 at Memphis, Tenn. Since then, more than 3½ trillion gallons (10,740,000 acre-ft) (1.32×10^{10} m^3) of water has been pumped from the aquifer. Analog-model analysis of flow in the Sparta Sand by Reed (1972) showed that in 1965 only about 20 percent of the 350 million gallons (1,074 acre-ft) (1.32×10^{6} m^3) of water pumped was from storage in the aquifer. Sixty percent of the water was derived from leakage from confining beds and 20 percent of the water was induced recharge or captured discharge in the outcrop area.

Pumping from the aquifer is not evenly distributed areally. Consequently, large drawdowns in artesian head have occurred near centers of large withdrawals. Analog-model studies have shown that the Sparta Sand can provide large sustained yields. Projections to the year 1990 of the drawdown in artesian head, in response to a pumping rate of 630 Mgal/d (27.6 m^3/s), show that at some pumping centers water levels will decline below the top of the aquifer. Local excessive drawdowns can be alleviated by more even distribution of pumping.

CARBONATE-ROCK AND GYPSUM AQUIFERS

Carbonate rocks crop out extensively over the Ozark Plateaus region, principally in Missouri and Arkansas. Gypsum beds form productive aquifers in southwest Oklahoma and north Texas. Limestone, dolomite, or gypsum aquifers range in thickness from 50 to 1,500 feet (15 to 460 m). Porosity and permeability are due to solution of the rock. Water in storage ranges in amount from moderate to very large.

OPERATION OF THE FLOW SYSTEM

Recharge is by infiltration of rainfall in the outcrop area (fig. 19). Natural discharge is to streams in the outcrop area and by seepage to confining beds where the formation is in the subsurface. The rates of water movement and well yields are variable but are highest in the outcrop area. Recharge may be as much as 20 inches (0.51 m) a year. The depth to water is 30–450 feet (9–137 m). Water pumped from the aquifer in the outcrop area is derived from storage and results in a decrease in natural discharge. Where these aquifers are confined in the subsurface, they operate similarly to the confined sandstone aquifers.

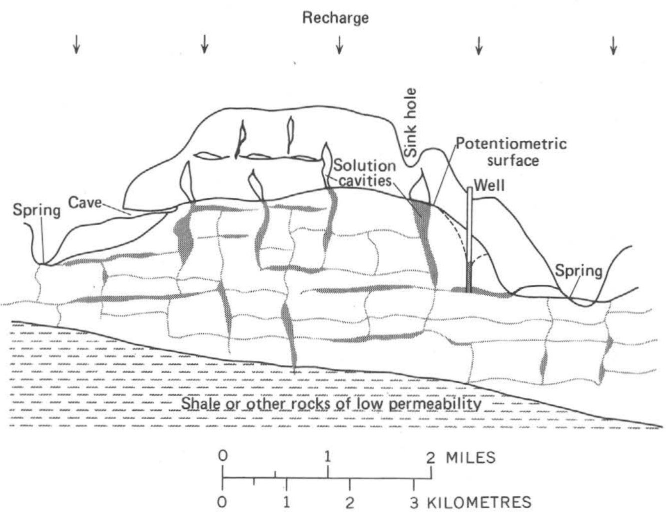


FIGURE 19.—Carbonate-rock and gypsum aquifer.

CASE HISTORY—LIMESTONE AREA OF THE OZARK REGION IN MISSOURI AND ARKANSAS

Thick, dense limestone and dolomite of Paleozoic age underlie a large area. Permeability of the limestone is due to joints, bedding planes and solution openings. Recharge is high in some areas where there is no surface runoff. Recharge and ground-water flow are rapid, soon appearing as increased discharge in springs.

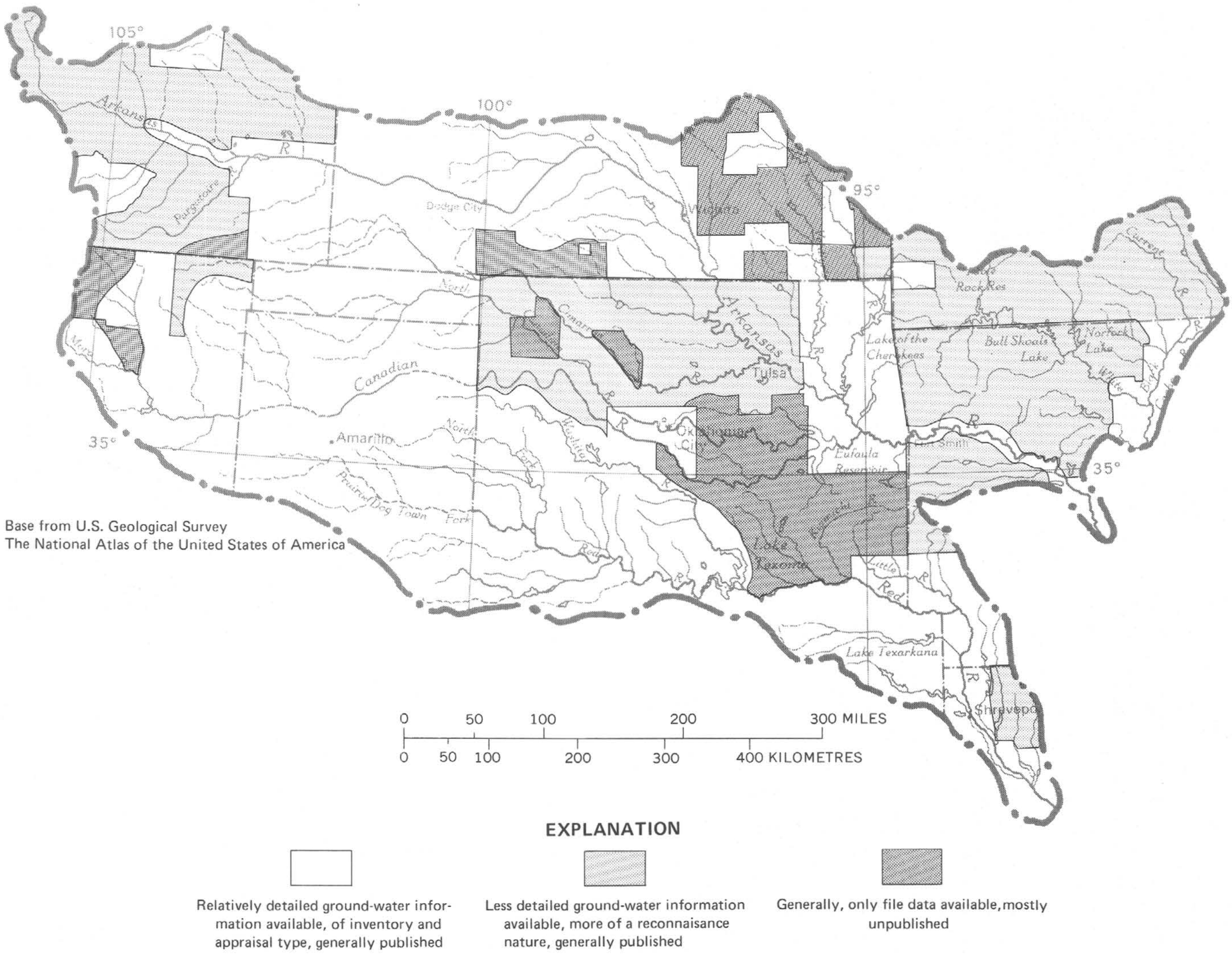


FIGURE 20.—Areas of principal ground-water investigations in the Arkansas-White-Red Region.

There are many large springs and caves, and sinkholes are common. Water travels long distances rapidly underground. Wells yield as much as 500 gal/min (3.2×10^{-2} m^3/s), depending on openings encountered by the well.

Pollution is a problem; pollutants travel rapidly and can enter in large quantities. Pollution by mining wastes and by collapse of sewage ponds has occurred in the carbonate area of Missouri.

PREVIOUS STUDIES AND NEEDS IN THE ARKANSAS-WHITE-RED REGION

Ground-water information is available for nearly all the Arkansas-White-Red Region. In those areas not covered by reports, file data are available from appropriate water-oriented State and Federal agencies. A list of these agencies in each State is given immediately preceding "Selected References" in this report. Areas of principal ground-water investigations for which reports are available are shown in figure 20. Reports on the area are classified as detailed or reconnaissance. Both types of reports generally contain information on the most productive aquifers, including well yields, thickness, extent, potentiometric surface, water-table configuration, top of the aquifer, storage coefficient, transmissivity, water quality, and the nature of overlying and underlying beds. The detailed reports generally contain more data at more points than the reconnaissance reports and also contain information on recharge, discharge, water use, and relation of aquifers to streams.

To date, few areas in the region have been modeled by analog or digital models. The few model studies of ground-water systems reflect a prevailing lack of quantitative consideration of ground water in water-resource planning in the Arkansas-White-Red Region.

Ground water now can be adequately evaluated in terms of quantity, availability, quality, cost of development, and impact on the environment through the use of models. Greater consideration should be given to use of ground water in making planning decisions. The inclusion of ground water in water planning affords many more alternatives for development and control of water supply. If ground-water reservoirs underlying an area can yield water to wells at rates exceeding 50 gallons per minute (3.2×10^{-3} m^3/s), planners can be certain that these sources are significant and that they should not be ignored. If these reservoirs also contain good-quality water in amounts equal to the storage capacity of existing surface-water reservoirs and potential surface-water reservoir sites, planners can be certain that ground water should play a principal role in any water-development plans (Moore, 1971). Future studies in the region should incorporate the use of models in providing planners with quantitative analyses required for incorporating ground water into water-management plans.

General studies provide a valuable basis for conceptual models or even initial analog or digital models useful in designing data-collection and analysis programs. The appraisal and reconnaissance studies (fig. 20) provide some data for all three modeling needs—definition of the system, stress on the system, and response of the system. The reports generally lack definition of aquifer hydrologic characteristics in quantitative terms required for detailed modeling, as well as lack quantitative hydrologic data on confining beds or the degree of connection of the aquifer with streams. Data on stress and response of the system to stress are generally incomplete for adequate model analysis. For example, many studies lack sufficient data on the history and the distribution of withdrawals from the aquifer. In many model studies, withdrawals are historically the major stresses on the aquifer and the pumping history should be duplicated in testing the model.

Other critical information on aquifer stresses that are not commonly collected or analyzed as a part of an appraisal study are recharge to the aquifer and its relation to the depth to water. In addition to the natural recharge from precipitation, information is required on the recharge and return surface flow of applied irrigation water.

Reconnaissance and appraisal studies generally are limited by political boundaries. Areas for model studies are best delineated by the natural boundaries of the hydrologic system (Bedinger and Sniegocki, 1972). Ideally, these are boundaries across which there is no flow, or boundaries at which the hydrologic head or flow conditions can be defined—that is, streams, lakes, or wells. Natural system boundaries should be used in planning future studies in the area. Exceptions may include the very extensive water-table aquifers in which intensive development is limited to a small part of the aquifer. Nevertheless, ultimate needs for systemwide water planning should be considered in continuing data-collection programs and in comprehensive ground-water studies.

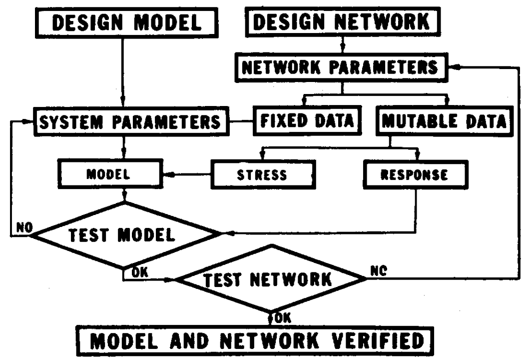


FIGURE 21.—Model and network development (after Bedinger and Sniegocki, 1972).

The relation between data networks and the use of data in modeling is shown by the flow diagram in figure 21. Data on response of the system to stress are used conjunctively with stress data in testing the model. Response data are thus needed for adequate historic and spatial coverage to assess the validity of the model. These data, or the lack thereof, may be more critical than stress data. In some instances much of the stress history, such as pumpage and recharge, can be reconstructed from indirect records of agricultural or industrial production or from population and climatic records. Response data cannot be so reconstructed and therefore must be available before a model study is initiated. It follows that areas of potential model studies should be identified and that continuing records be kept of stress and response. These data-collection programs should be designed to provide adequate sampling in frequency and areal distribution.

Regionally, continuing ground-water data-collection programs (exclusive of studies in designated areas) by the U.S. Geological Survey and by State and private agencies consist principally of observations of water levels in wells. In some areas periodic measurements of spring flow and analyses of ground-water quality are made every 5 years by the Survey. These data do not provide a sufficient history of stress and response for adequate model analysis. The most serious deficiency in data collection in the Arkansas-White-Red Region concerns water-use information. Not only is the coverage inadequate, but the accuracy of some of the information is variable and questionable. Inadequate data collection constitutes a major problem and causes lengthy delays in model analysis.

Outstanding needs for detailed quantitative definition of several ground-water systems exist in the western, water-deficient part of the Arkansas-White-Red Region. The systems needing study include the large, basin-fill aquifers in Colorado and the limestone aquifer of the Arbuckle Group of Oklahoma. These aquifers are virtually unused and could potentially play a significant part in meeting future water needs in the Arkansas-White-Red Region. The large basin-fill ground-water reservoirs in the Arkansas River basin in Colorado are estimated to hold 20 million acre-feet (2.46×10^{10} m^3) of water (P. A. Emery, L. A. Hershey, and J. M. Klein, written commun., 1974). Presently, they are virtually unused. The reservoirs could be utilized in conjunctive-use planning for irrigation requirements in the Arkansas River valley and may be used for storing water from interbasin transfers during times of excess. This water could then be used during times of demand for irrigation or other use, or, as an alternative, the water in these basins could be mined to supply water during water-deficient periods. Water-development plans in Oklahoma include interbasin transport of water from Broken Bow, Hugo, Pine Creek, and several to-be-constructed reservoirs in the vicinity of Oklahoma City. Part of the water would be used for municipal supplies and the rest moved to southwest Oklahoma for other uses. These plans call for transporting surface water across a very productive aquifer in the limestone of the Arbuckle Group. This aquifer is not included in the water-transport plan, but it could potentially supply a significant part of the water required, and it would be relatively near the area of use.

The aquifer systems mentioned could play significant parts in regional and local water-management plans, but further study would be required before ground water can be fully incorporated in these plans. Studies are needed to define the extent and characteristics of the aquifer and to define the flow system quantitatively, so that the response of the system to stress could be predicted. These studies would also provide information needed to determine well spacing, well yields, cost of pumping, and cost of construction of wells and collection systems.

SELECTED STATE AND FEDERAL WATER-ORIENTED AGENCIES IN THE ARKANSAS-WHITE-RED REGION

Arkansas:

U.S. Geological Survey
Water Resources Division
2301 Federal Office Building
Little Rock, Arkansas 72201

Arkansas Geological Commission
State Capitol Building
Little Rock, Arkansas 72201

Arkansas Department of Pollution
Control and Ecology
8801 National Drive
Little Rock, Arkansas 72209

Colorado:

U.S. Geological Survey
Water Resources Division
Denver Federal Center, Building 25
Lakewood, Colorado 80225

Colorado Water Conservation Board
102 Columbine Building
1845 Sherman Street
Denver, Colorado 80203

Colorado Division of Water Resources
Office of the State Engineer
303 Columbine Building
1845 Sherman Street
Denver, Colorado 80203

Southeastern Colorado Water
Conservancy District
905 Highway 50 West
Pueblo, Colorado 81008

Kansas:

U.S. Geological Survey
Water Resources Division
1950 Avenue A, Campus West
University of Kansas
Lawrence, Kansas 66045

Kansas Water Resources Board
4th Floor, Mills Building
109 West 9th Street
Topeka, Kansas 66612

Kansas Geological Survey
1930 Avenue A, Campus West
University of Kansas
Lawrence, Kansas 66045

Kansas State Board of Agriculture
Division of Water Resources
10th Floor, State Office Building
Topeka, Kansas 66612

Louisiana:

U.S. Geological Survey
Water Resources Division
6554 Florida Boulevard
Baton Rouge, Louisiana 70806

Louisiana Geological Survey
Department of Conservation
Post Office Box G, University Station
Baton Rouge, Louisiana 70803

Louisiana Department of Public Works
Post Office Box 4155, Capitol Station
Baton Rouge, Louisiana 70804

Louisiana Department of Highways
Post Office Box 4245, Capitol Station
Baton Rouge, Louisiana 70804

Missouri:

U.S. Geological Survey
Water Resources Division
Post Office Box 340
Rolla, Missouri 65401

Missouri Department of Natural Resources
Division of Research and Technical Information
Post Office Box 250
Rolla, Missouri 65401

New Mexico:

U.S. Geological Survey
Water Resources Division
Post Office Box 4369
Albuquerque, New Mexico 87106

New Mexico State Engineer
State Capitol Building
Santa Fe, New Mexico 87501

New Mexico Interstate Stream Commission
State Capitol Building
Santa Fe, New Mexico 87501

Oklahoma:

U.S. Geological Survey
Water Resources Division
200 Northwest 4th Street, Room 4301
Oklahoma City, Oklahoma 73102

Oklahoma Water Resources Board
2241 Northwest 40th Street
Oklahoma City, Oklahoma 73112

Oklahoma Geological Survey
The University of Oklahoma
Norman, Oklahoma 73069

Texas:

U.S. Geological Survey
Water Resources Division
Federal Building
300 East 8th Street
Austin, Texas 78701

Texas Water Development Board
Post Office Box 13087
Austin, Texas 78711

Texas Water Quality Board
Post Office Box 13246
Austin, Texas 78711

Texas Water Rights Commission
Post Office Box 13207
Austin, Texas 78711

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