Summary Appraisals of the Nation's Ground-Water Resources—Missouri Basin Region

GEOLOGICAL SURVEY PROFESSIONAL PAPER 813-Q

Summary Appraisals of the Nation's Ground-Water Resources—Missouri Basin Region

By O. JAMES TAYLOR

GEOLOGICAL SURVEY PROFESSIONAL PAPER 813-Q

Appraisal of ground-water resources in a vast region, with suggestions for improved management of ground water by planned depletion, storage, salvage, and reuse of available supplies

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 1978

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, *Secretary*

GEOLOGICAL SURVEY

H. William Menard, *Director*

Library of Congress Cataloging in Publication Data

Taylor, Omer James
Summary appraisals of the Nation's ground-water resources, Missouri Basin region

Geological Survey Professional Paper 813-Q
Bibliography: p. 38-39
Supt. of Docs.: I 19.16:813-Q
1. Water, Underground--Missouri River Basin. I. Title. II. Series: United States Geological Survey Professional Paper 813-Q
GB1020.T38 553'.79'0978 78-23743

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402
Stock Number 024-001-03133-7

CONTENTS

ILLUSTRATIONS

TABLES

GLOSSARY OF TERMS

Aquifer. A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Aquifer test. A field procedure used to determine the transmissive and storage characteristics of an aquifer. Commonly consists of measurement of the hydraulic or chemical response of the aquifer to a pumped well, injection well, changes in stream stage, or tracers.

Analog model. Constructed device used to simulate the response of a water-resource system to natural or man-induced conditions. Often an electrical circuit with properties analogous to the hydraulic properties of the water system.

Artificial recharge. Recharge of an aquifer through a man-made structure such as a pit or injection well.

Base flow. Natural discharge from the ground-water reservoir to a stream. The discharge maintains streamflow in the absence of surface runoff.

Confined aquifer. An aquifer containing ground water that is confined under pressure between relatively impermeable or significantly less permeable material and that will rise above the top of the aquifer.

Dissolved-solids concentration. The total dissolved minerals in water, expressed as the weight of minerals per unit volume of water, without regard to the type of minerals.

Ephemeral stream. A stream that flows in direct response to precipitation.

Evapotranspiration. Loss of water by evaporation from wet surfaces and by transpiration through plants.

Gain-and-loss study. A series of surface-water flow measurements in a selected reach of a stream to determine gains or losses in streamflow attributable to interchanges between the stream and associated aquifer.

Gaining stream. A stream or reach of a stream whose flow is being increased by inflow of ground water.

Ground-water discharge. Loss of water from a ground-water reservoir.

Ground-water divide. A zone in an aquifer from which ground water flows in different directions.

Ground-water mining. The process, deliberate or inadvertent, of extracting ground water from a source at a rate so in excess of the replenishment that the ground-water level declines persistently, threatening actual exhaustion of the supply or at least a decline of pumping levels to uneconomical depths.

Ground-water recharge. Addition of water to a ground-water reservoir.

Hydraulic conductivity. The rate at which water may be transmitted through a unit area of an aquifer, under standardized conditions.

Lake evaporation. Evaporation from a large lake or surface reservoir.

Losing stream. A stream or reach of a stream that is losing water to the ground.

Mathematical model. Mathematical technique used to simulate the response of a water-resource system to natural or man-induced conditions. Normally consists of machine-readable data and flow equations that are solved, and results are printed by a high-speed computer.

Phreatophyte. A plant that depends for its water supply upon ground water that lies within reach of its roots. Commonly found along streams or where the water table is close to the land surface.

Potentiometric surface. An imaginary surface connecting points to which water would rise in tightly cased wells from a given point in an aquifer. A map of the potentiometric surface is useful to indicate direction of ground-water movement.

Return flow. That part of irrigation water that is not consumed by evapotranspiration and that returns to its source or another body of water. The term is also applied to the water that is discharged from industrial plants. Also called return water.

Salvage. Capture of water supplies by reducing evapotranspiration or other discharge from the ground-water reservoir or by inducing increase in recharge to the ground-water reservoir.

Specific yield. The volume of water that can be drained by gravity from a saturated rock or soil in relation to the volume of the rock or soil.

Storage coefficient. The volume of water released from storage or taken into storage in an aquifer, per unit surface area of the aquifer per unit change in head.

Stream-aquifer system. A stream and adjacent aquifer that are hydraulically connected. An interchange of water between the stream and aquifer may occur.

Stream depletion. Reduction of streamflow in a stream-aquifer system due to withdrawals from wells that capture streamflow or intercept ground water that would have discharged to the stream.

Transmissivity. The rate at which ground water may be transmitted through a cross section of unit width over the entire thickness of an aquifer, under standardized conditions.

Unconfined aquifer. An aquifer that has a water table and contains ground water that is not confined under pressure by overlying impermeable or significantly less permeable material.

Underflow. Downstream movement of ground water in a valley-fill aquifer.

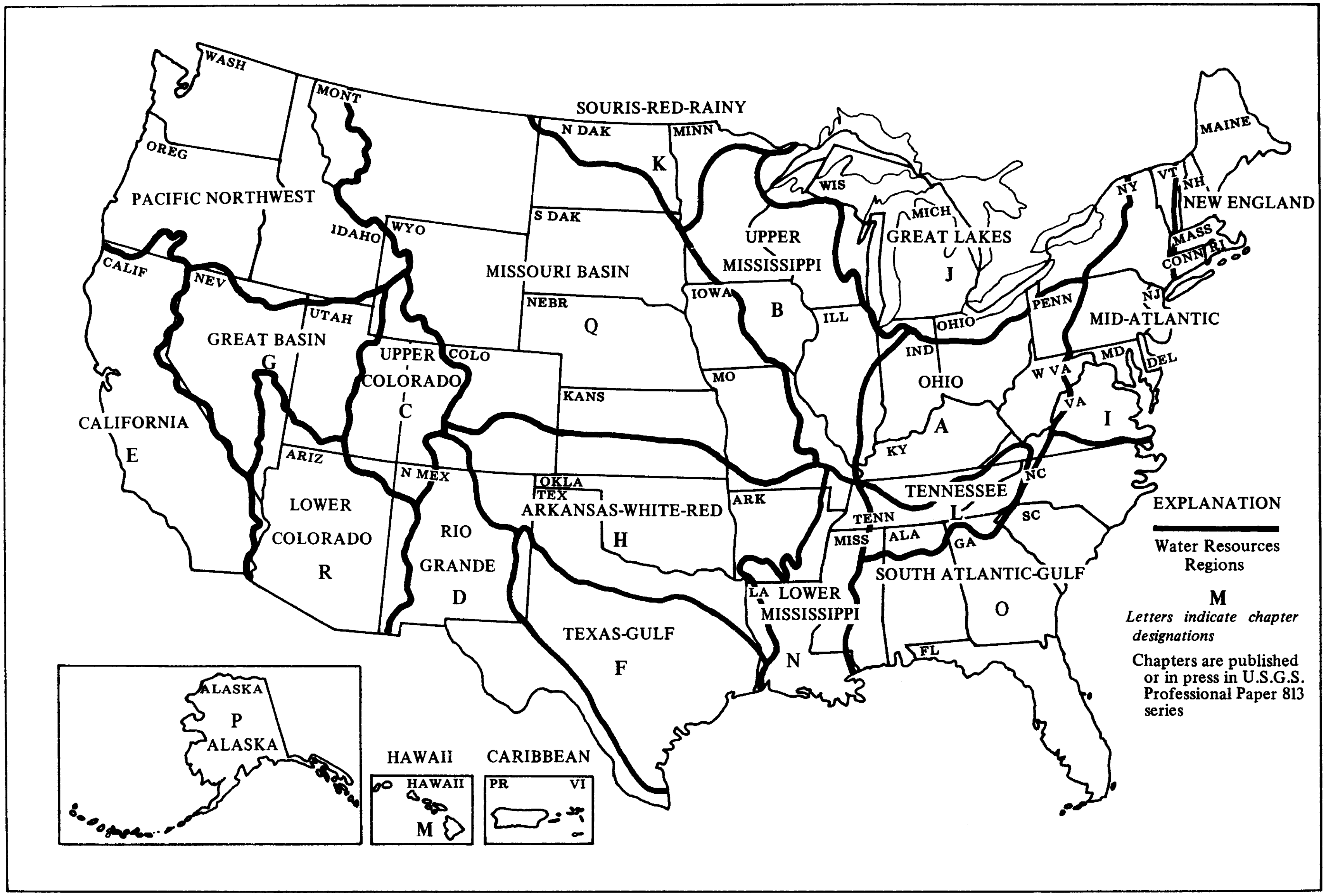
Water management. Design and implementation of plans to utilize, or at least consider, the best combination of available water supplies to meet water-resource objectives, with due regard to water quality.

Water table. The imaginary surface within an unconfined aquifer at which the pressure is atmospheric.

METRIC CONVERSION

(U.S. customary units in this report may be expressed as metric units by use of the following conversion factors)

Multiply	*By*	*To obtain*
inches (in.)	2.54×10^{-2}	meters (m)
inches (in.)	25.4	millimeters (mm)
feet (ft)	.3048	meters (m)
miles (mi)	1.6093	kilometers (km)
square miles (mi^2)	2.590	square kilometers (km^2)
cubic feet (ft^3)	2.83×10^{-2}	cubic meters (m^3)
acres	4.047×10^{3}	square meters (m^2)
gallons (gal)	3.785×10^{-3}	cubic meters (m^3)
acre-feet (acre-ft)	1.233×10^{3}	cubic meters (m^3)
gallons per minute (gal/min)	6.309×10^{-2}	liters per second (L/s)
cubic feet per second (ft^3/s)	2.832×10^{-2}	cubic meters per second (m^3/s)
million gallons per day (mgd)	4.38×10^{-2}	cubic meters per second (m^3/s)



Geographic Index to the Series, U.S. Geological Survey Professional Paper 813, *Summary Appraisals of the Nations Ground-Water Resources.*

Boundaries shown are those established by the United States Water-Resources Council for Water-Resources Regions in the United States.

SUMMARY APPRAISALS OF THE NATION'S GROUND-WATER RESOURCES—MISSOURI BASIN REGION

By O. JAMES TAYLOR

ABSTRACT

The Missouri Basin Region lies in the north-central part of the United States and southern Canada. It includes parts of Alberta and Saskatchewan in Canada; parts of Montana, Wyoming, North Dakota, South Dakota, Minnesota, Iowa, Colorado, Kansas, and Missouri, and all of Nebraska in the United States. The region includes about one-sixth of the contiguous United States and requires large water supplies for irrigation, industrial, public, and rural uses. Climate ranges from semiarid to subhumid. Normal annual precipitation increases generally eastward in the downstream direction, but precipitation is not a dependable source of supply. The Missouri River and its tributaries furnish water to many users, but surface water is often inadequate to meet large demands. Numerous surface reservoirs help to regulate streamflow and provide storage, but they also allow an increase in evapotranspiration, which in some areas exceeds normal precipitation. Ground water occurs in aquifers classified as alluvial deposits of sand and gravel, glacial deposits, dune-sand deposits, basin-fill deposits of sand and gravel, sandstone, siltstone, fractured sandy clay, limestone, and dolomite. Ground water can be developed and managed in an orderly manner provided adequate geologic and hydrologic data are available to determine aquifer characteristics and response to pumping and other hydraulic stresses. These data and determinations are essential to design, testing, and implementation of water-management plans.

Unconsolidated and semiconsolidated aquifers include valley-fill alluvium, areally extensive alluvium, glacial deposits, and basin-fill deposits. The aquifers normally consist of alluvial sand and gravel that contain unconfined ground water that lies near the land surface. Many wells completed in the alluvial aquifers have high yields of good-quality water because most alluvial aquifers are highly transmissive and hydraulically connected to streams. Aquifers in glacial deposits may be difficult to locate and in some areas contain saline water; nevertheless, these aquifers are sources of water supply for many users. Basin-fill aquifers are as much as several thousand feet thick, and many contain large ground-water supplies. Ground-water mining has occurred in semiconsolidated aquifers because of withdrawals from wells. Unconsolidated and semiconsolidated aquifers have potential for conjunctive use with surface water, recycling to reuse available supplies, artificial recharge, and salvage of evapotranspired water.

Sandstone aquifers lie near the land surface and in structural basins. Interbasin movement of ground water occurs in the Virgelle (Milk River aquifer), Fox Hills-basal Hell Creek, and Dakota aquifers. Sandstone aquifers are less transmissive than unconsolidated and semiconsolidated aquifers in general. Confined sandstone aquifers are common, and flowing wells are obtained in many areas. However, flowing wells may cause large declines in water levels if uncontrolled. Water quality is variable in sandstone aquifers but is adequate for most needs. Sandstone aquifers have potential for artificial recharge, induced interaquifer leakage, conjunctive use with surface water, and mining of ground water.

Limestone and dolomite aquifers are extensive in the region, but in some areas they lie deep below the land surface. The occurrence of ground water in small pores, fractures, or large caverns causes yields from wells to range widely. Large flows through cavern systems in the aquifers are indicated by large springs in some areas. Water quality is extremely variable and must be considered in any water-development plan. Limestone and dolomite aquifers have potential for development of large water supplies in some areas. The development may be aided by induced recharge and interaquifer leakage.

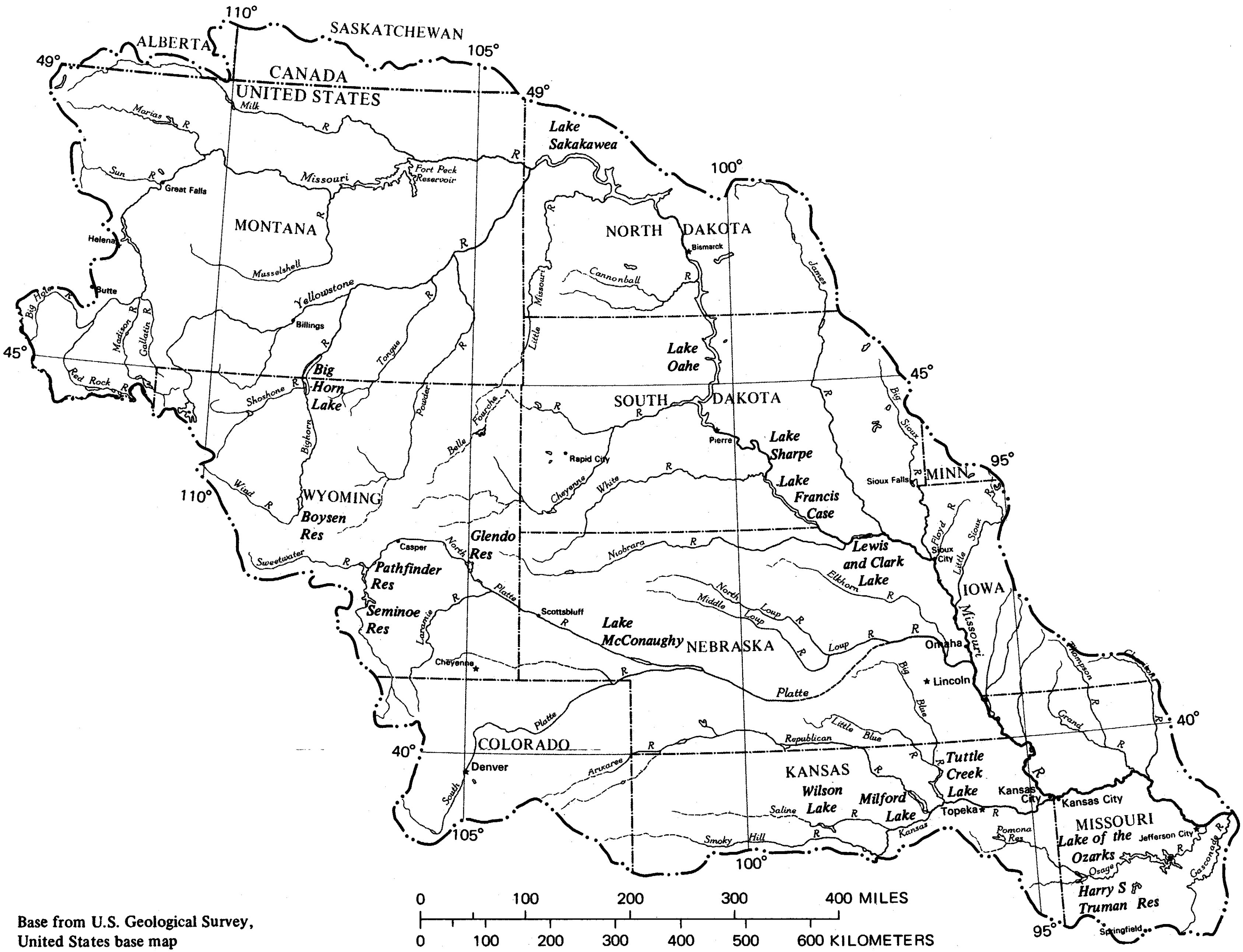
Saline ground water occurs throughout the Missouri Basin Region. Dissolved-solids concentration as much as 30,000 milligrams per liter has been measured in aquifers in glacial deposits in Montana. Saline water is common in sandstone aquifers in Wyoming, North Dakota, and South Dakota; maximum reported concentration is 280,000 milligrams per liter in water from the Tensleep Sandstone in Wyoming. Limestone contains saline water in many areas; maximum dissolved-solids concentration is about 350,000 milligrams per liter for the Madison Group in the Williston Basin in North Dakota.

Comprehensive water-management planning in the Missouri Basin Region will require periodic or continuing inventory of precipitation, streamflow, surface-water storage, and ground water. Water demands for irrigation, industrial, public supply, and rural use are increasing rapidly. Reliance on ground-water supplies is increasing even though in many areas the ground water is still mostly undeveloped. Optimal use of water supplies will require the establishment of realistic goals and carefully conceived water-management plans, each of which will necessarily be based on an adequate baseline of hydrologic data and knowledge of the highly variable hydrologic systems in the region.

INTRODUCTION

LOCATION AND EXTENT OF BASIN

The Missouri Basin Region lies in the north-central part of the contiguous United States and southern Canada; it includes small parts of Alberta and Saskatchewan Provinces; parts of Montana, Wyoming, North Dakota, South Dakota, Minnesota, Iowa, Colorado, Kansas, Missouri, and all of Nebrska (fig. 1). The area includes about 519,000 mi^2, (about one-sixth) of the United States and about 9,700 mi^2 of Canada. Resources vary widely over the region and include corps, timber, livestock, fossil fuels, economic minerals, and water. The Missouri Basin Inter-agency Committee (1969a) prepared an extensive description of the resources of the Missouri Basin Region.



Base from U.S. Geological Survey, United States base map

FIGURE 1.—The Missouri Basin Region, showing surface drainage.

Physiography of the Missouri Basin Region is extremely variable. The western part of the region includes mountainous and foothill areas of Montana, Wyoming, and Colorado where igneous, metamorphic, and sedimentary rocks are severely folded and faulted. Headwaters of the Missouri River and many of its tributaries lie in the western part of the region where surface relief is large. East of the mountains lie glaciated areas in the northern part of the region and the plains of Montana, Wyoming, western Dakotas, and Colorado. The plains are underlain by extensive structural basins and interrupted by domes and uplifts, including the Black Hills Uplift. Sedimentary rocks crop out over the basins, and most rock types are exposed in uplifted areas. Surface relief is moderate in the plains, and streams drain toward the east and northeast.

Topographic and structural features of the lower part of the region are subdued. The plains become more gentle in south-central North Dakota, eastern South Dakota, Nebraska, southwestern Iowa, and northern Kansas. Sedimentary rocks are exposed and streams drain to the south and east. In the plains of northwestern Missouri, limestone is exposed. Hilly uplands and rolling plateaus are interrupted by the broad gentle uplift of the Ozark Region, where karst topography is developed. Streams drain generally toward the east into the Mississippi River.

PURPOSE AND SCOPE

Ground-water resources in the Missouri Basin Region constitute a large part of the total water resources. In parts of the region, ground-water resources are barely used; in other parts of the region the use of ground water contributes greatly to overall water supply. Full utilization of ground water in water management certainly has not been reached. The purpose of this report is to encourage further consideration of the use of ground water in regional water planning and management by:

1. Describing the known occurrence, characteristics, and behavior of ground-water resources in the Missouri Basin Region.
2. Indicating areas of the region in which hydrologic data and interpretive investigations of ground water are needed.
3. Suggesting preliminary ways to broaden water management to include fuller use of ground water.
4. Explaining proven methods for investigating and utilizing ground-water supplies.

Various State and Province officials supplied valuable hydrologic information and made helpful review comments. Their assistance is greatly appreciated.

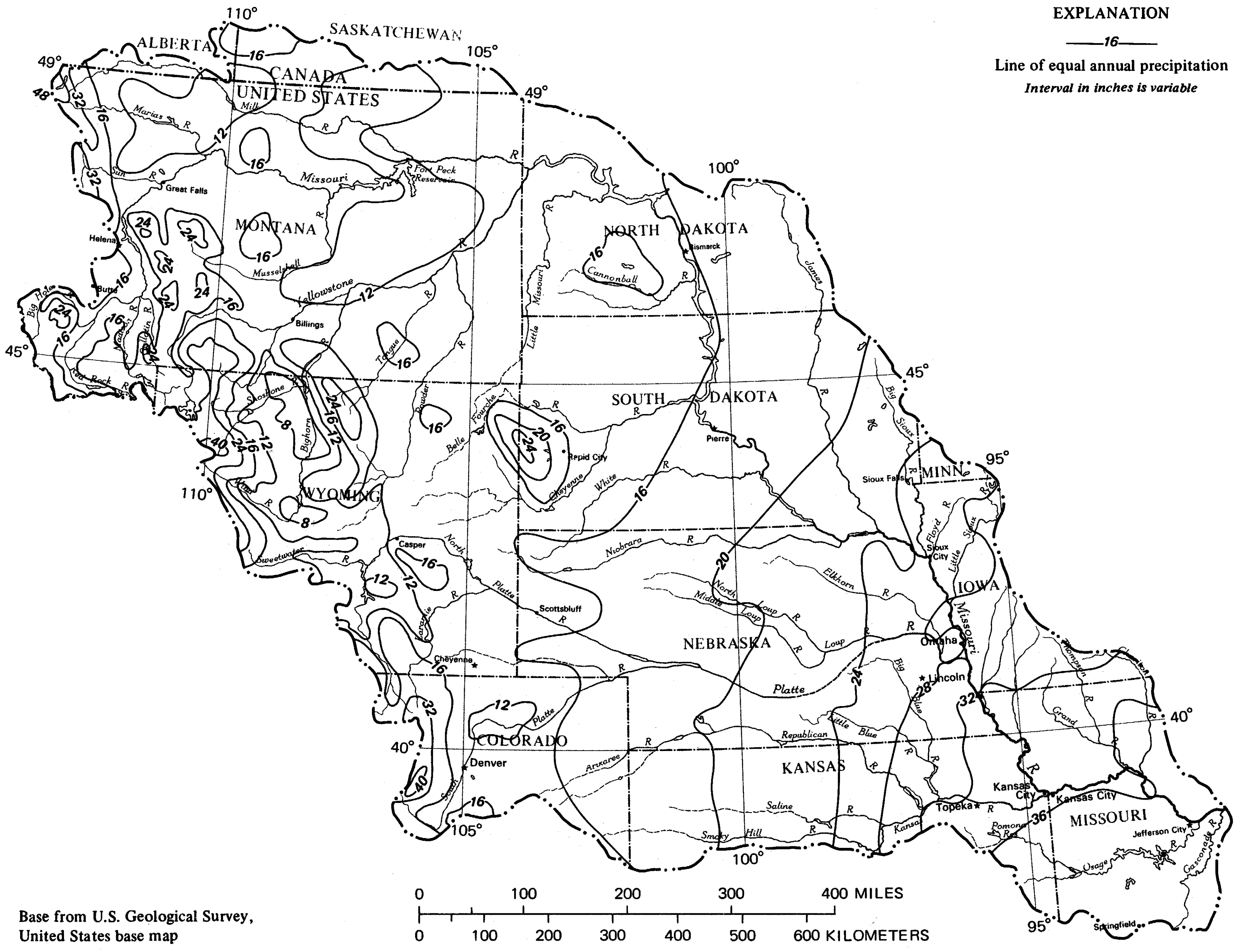
WATER SUPPLY OF THE BASIN

HYDROLOGIC SETTING

CLIMATE

Normal annual precipitation (Environmental Science Services Administration, 1968, p. 43–44) varies greatly in the region as shown on figure 2. Range is from about 48 in. in northwestern Montana to as little as 8 in. in central Wyoming. A broad area of relatively high precipitation lies in eastern Nebraska, western Iowa, eastern Kansas, and Missouri. Normal annual precipitation does not indicate the wide variation in annual or seasonal precipitation observed in the region, which is noted for wide climatic variations. Annual precipitation commonly ranges from less than half to more than double the normal annual precipitation. Seasonal precipitation is more variable than annual precipitation. Below- and above-normal precipitation may occur concurrently in different parts of the region. Therefore precipitation as a source of surface-water replenishment and ground-water recharge is not as dependable as the figures for normal annual precipitation would seem to indicate.

Consumption of surface and ground water by evaporation and transpiration is termed evapotranspiration. Evaporation is large during periods of intense solar radiation, low relative humidity, and rapid wind movement. Distribution of lake evaporation (Environmental Science Services Administration, 1968, p. 63) is shown in figure 3. Annual evaporation ranges from about 28 in. in western Montana and northern Wyoming to about 62 in. in western Kansas. Over most of the region annual lake evaporation greatly exceeds annual precipitation. Therefore, little precipitation remains to replenish surface-water and ground-water supplies. Transpiration consumes ground water in areas in which dense growths of phreatophytes are maintained by a high water table. Transpiration consumes surface water in areas of phreatophytes near streams or lakes. Transpiration losses depend on local hydrologic conditions and cannot be generalized accurately over the region.



Base from U.S. Geological Survey, United States base map

FIGURE 2.—Normal annual precipitation 1931–60 in the Missouri Basin Region.

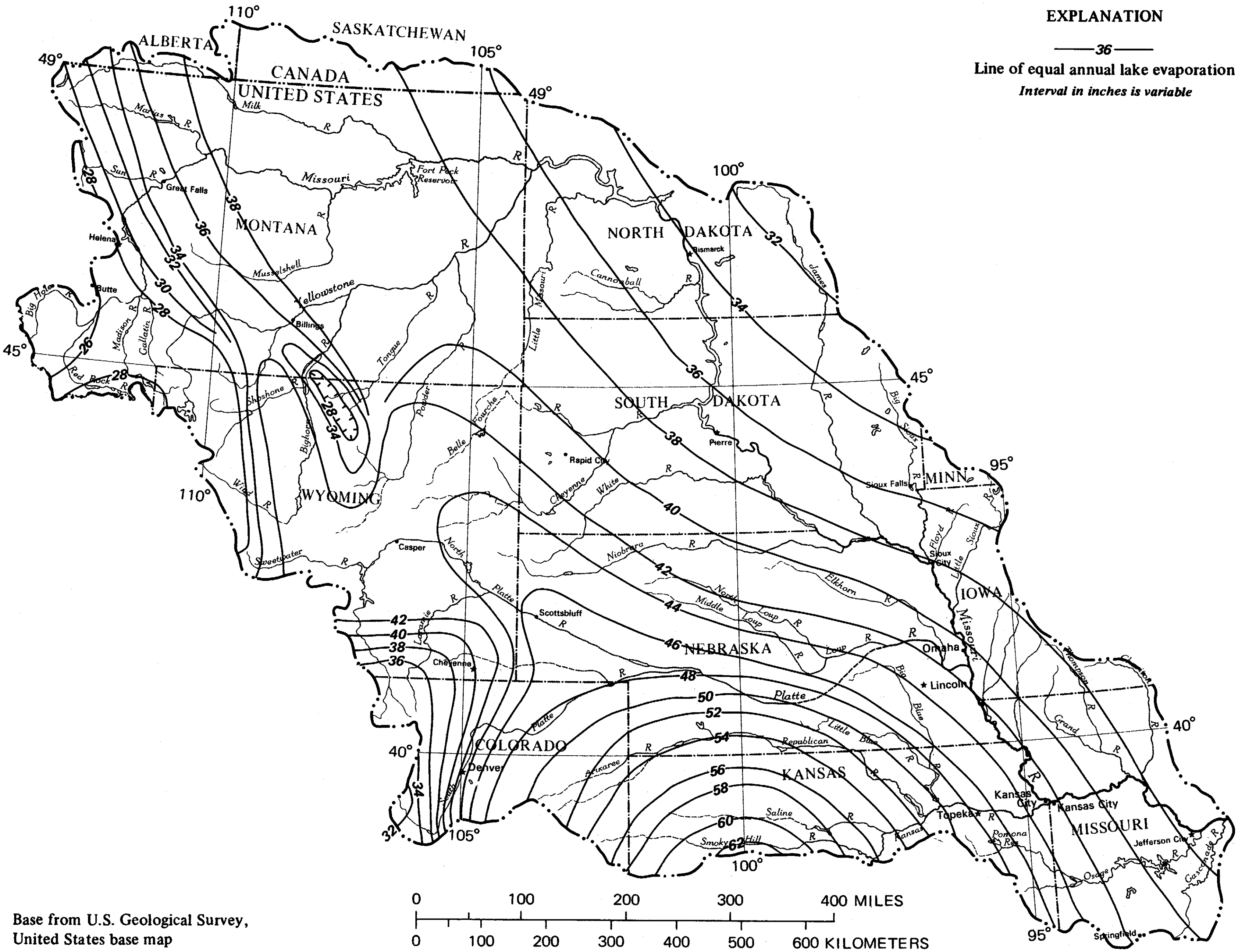


FIGURE 3.—Average annual lake evaporation 1946–55 in the Missouri Basin Region. (Environmental Sciences Administration, 1968, p. 63.)

SURFACE WATER

The Missouri is the longest river in the United States. Headwaters of the Missouri River are in southwestern Montana, 2,315 mi from its confluence with the Mississippi River at St. Louis, Missouri. Surface drainage in the Missouri Basin Region is shown on figure 1. Major tributaries to the Missouri River in downstream order include the Milk, Yellowstone, Little Missouri, Cheyenne, Niobrara, James, Big Sioux, Little Sioux, Platte, Kansas, Grand, Chariton, Osage, and Gasconade Rivers. Surface runoff within the region is approximately proportional to the precipitation and drainage area. Tributaries in Missouri and small parts of Kansas and Iowa drain about 8 percent of the area of the region but contribute 30 percent of the average annual flow of the region (Missouri Basin Inter-agency Committee, 1969b, p. 58).

Surface reservoirs constructed for varied and multiple purposes are numerous in the region. Major reservoirs along the Missouri River include Fort Peck Reservoir in northeastern Montana; Lake Sakakawea in western North Dakota; Lake Oahe in north-central South Dakota; Lake Sharpe, Lake Francis Case, and Lewis and Clark Lake in southern South Dakota. Numerous reservoirs along the tributaries contribute to the estimated total surface storage capacity of 112 million acre-ft in the region (Missouri Basin Inter-agency Committee, 1969b, p. 68).

Water quality of streams is suitable for most purposes. Over most of the region the average dissolved-solids concentration is less than 1,000 mg/L. Concentrations range from 1,000 to 4,000 mg/L in most streams of western North Dakota and western South Dakota, the lower South Platte River Valley in Colorado and Nebraska, and the upper Powder River Valley in central Wyoming (Missouri Basin Inter-agency Committee, 1969c, p. 108).

GROUND WATER

Ground water of the Missouri Basin Region occurs in a variety of aquifers that have been classified as alluvial deposits of sand and gravel, glacial deposits, dune-sand deposits, basin-fill deposits of sand and gravel; and as formations of sandstone, siltstone, fractured sandy clay, limestone, and dolomite. The alluvium of Pleistocene and Holocene age is generally located along stream valleys, except in central Nebraska, where the alluvium of Pleistocene age is areally extensive. Glacial deposits of Pleistocene age in the region are mostly in a broad band along the Missouri River. A major dune-sand aquifer of Pleistocene and Holocene age occurs in north-central Nebraska. Unconsolidated basin-fill deposits of Tertiary age that are thousands of feet thick occur in intermontane valleys of Montana. The Brule aquifer, siltstone and fractured sandy clay of Oligocene age, underlies parts of Wyoming, South Dakota, Colorado, and Nebraska. Sandstone aquifers ranging in age from Cambrian to Cretaceous lie near the land surface and in basins of various depths. The Madison Limestone aquifer of Early Mississippian age lies at depth in much of the western part of the Missouri Basin Region but remains mostly untested. Limestone and dolomite aquifers of Permian and Pennsylvanian age are present also in Nebraska, Iowa, Kansas, and Missouri. In addition the region may contain undiscovered aquifers capable of yielding large water supplies. Recharge to the aquifers is derived from precipitation, irrigation water, leaky reservoirs, losing streams, and leakage from other aquifers. Natural ground-water movement is generally in the direction of surface drainage; however, movement in deep aquifers may be unrelated to surface drainage because ground-water movement between surface drainage basins has been identified. The aquifers discharge to streams, springs, phreatophytes, wells, and to other aquifers. General yields to wells and depth to water for the region are summarized by LaRocque (1966).

DEVELOPMENT OF WATER SUPPLIES

AVAILABLE SOURCES OF WATER SUPPLY

Sources of water supply in the Missouri Basin Region are listed below with a brief description of each. All supplies are not available at all places and times, but normally the water user can choose from several alternative sources.

Precipitation.—Snowfall and rainfall replenish all sources of supply in the Missouri Basin Region. Precipitation provides for agricultural needs and contributes to surface runoff, surface storage, and ground-water recharge throughout the Missouri Basin Region. Precipitation is not predictable over extended periods of time, and water-management plans must take into account departures from normal precipitation patterns. However, data are available on the normal monthly precipitation and, for some areas, on the probability of specified rates of precipitation. Snowmelt in mountainous areas and resulting surface runoff are predictable to a degree of accuracy proportional to the frequency of field measurements of the snowpack.

Streamflow.—Precipitation, snowmelt, surface runoff, releases from surface reservoirs, base flow, and underflow contribute to streamflow. Resulting surface-water supplies are available in the extensive stream network of the Missouri Basin Region. Numerous long-term streamflow records are available that describe the average streamflow and observed or calculated variations at stream-gaging sites. However, most streamflow is derived from unpredictable and undependable precipitation. Streamflow is most abundant in the lower part of the region, where it serves a large part of the population but only a small part of the area of the Missouri Basin Region.

Stored surface water.—Water supplies are stored throughout the Missouri Basin Region in on-channel reservoirs, off-channel reservoirs, and lakes. The surface storage facilities help to regulate streamflow and provide carryover storage. Average lake evaporation is so high in the Missouri Basin Region that surface storage for extended periods of time will result in large losses of water that are accompanied by increases in the dissolved-solids concentration. Evaporation occurs throughout the year. For example, surface storage from November through April will result in evaporation of 16 to 38 percent of the average annual lake evaporation shown on figure 3 (Environmental Science Services Administration, 1968, p. 63).

Ground water.—As described in this report, aquifers of many different types that contain large supplies of water are numerous and widespread in the Missouri Basin Region. Ground water is a dependable and predictable resource if the hydrologic characteristics of the aquifers are well known. Ground water in storage may be increased by salvage of rejected recharge to, or reduction of discharge from, the ground-water reservoir. Sound water-management practices may require depletion of ground-water reserves or use of the ground-water reservoirs to store surplus amounts of surface water. Changes in ground-water storage may be determined by means of periodic measurements of water levels in an observation well network. Ground water in storage is not normally subject to the high evaporative losses associated with stored surface water. Estimated volumes of ground water stored in the Missouri Basin Region are listed in table 1. Volumes in each area include ground water in all aquifers, provided that dissolved-solids concentration is less than 3,000 mg/L. Estimated total ground-water storage of 150,000 billion ft^3 is about 64 times the average annual flow of the Missouri River in the lower part of the region near Hermann, Mo., and about 30 times larger than the total capacity of all surface-water reservoirs.

TABLE 1.—*Estimated ground-water in storage in the Missouri Basin Region*
[Adapted from written communication, C. F. Keech, 1976]

Area	Ground water in storage (billion ft^3)
Northeastern Montana	17
Western Montana	4
Central Montana	8
Southeastern Montana and northeastern Wyoming	22,000
Western North Dakota and western South Dakota	20,000
Eastern North Dakota and eastern South Dakota	13,000
Southeastern Wyoming and northeastern Colorado	2,000
Northern and central Nebraska	54,000
Western Iowa, eastern Nebraska and northeastern Kansas	3,300
Northern Kansas and southern Nebraska	20,000
Northwestern Missouri	15,000
Total	150,000

DEMANDS FOR WATER—PAST, PRESENT, AND FUTURE

Recent trends in water use in the United States have been summarized by Murray (1968) and Murray and Reeves (1972). Ground- and surface-water use in the Missouri Basin Region increased 20 percent from 1965 to 1970. Total ground-water use in the region increased by more than 67 percent from 1965 to 1970, as shown in table 2. Ground-water use also increased for each use category. Irrigation use was increased by more acreage brought under cultivation and efforts to increase crop yield by applying more water. The use of sprinklers for irrigation purposes is a major cause of the increased irrigated acreage and increased use of ground water for irrigation. In Nebraska, the number of registered irrigation wells increased from about 7,000 in 1950 to 55,078 in 1976 (Ellis and Pederson, 1977). Water withdrawn for irrigation probably will continue to increase throughout the region because under present economic conditions, irrigated-land farming is more profitable than dry-land farming. In the 1960's the region produced one-third of the Nation's wheat, 21–31 percent of the feed grains, and a large part of the rye, sugar beets, and flaxseed.

Industrial use of ground water in the region increased by 153 percent from 1965 to 1970. Water requirements for energy development are likely to cause

TABLE 2.—*Water use, in million gallons per day, Missouri Basin Region, 1965 and 1970*

Use	Water withdrawn, 1965			Water withdrawn, 1970		
	Ground water	Surface water	Ground and surface water	Ground water	Surface water	Ground and surface water
Irrigation	2,700	13,000	16,000	4,500	14,000	19,000
Industrial	340	2,400	2,700	860	3,200	4,100
Public supply	340	630	970	430	590	1,000
Rural	300	170	470	380	180	560
Total (rounded)	3,700	16,000	20,000	6,200	18,000	24,000

a further increase in the use of ground water by industry. Surface-minable coal deposits occur in Alberta, Saskatchewan, Montana, Wyoming, North Dakota, South Dakota, Colorado, Nebraska, Iowa, Kansas, and Missouri in the Missouri Basin Region. The coal may occur within aquifers, and in some areas the coal itself is an aquifer. In other areas the coal is part of the confining beds that may overlie or underlie other aquifers. Coal mining, coal transportation, and coal utilization affect ground water in various ways. Mining may disrupt natural recharge, movement, storage, and discharge of ground water. Water-quality changes are common due to leaching associated with changes in the flow system. The Surface Mining Control and Reclamation Act, Public Law 9587, was passed in 1977, partly to insure that future mining practices preserve ground- and surface-water resources and to restore previously mined areas to more natural hydrologic conditions.

Expected high demand for coal in the future will affect ground-water supplies and quality in the region. A coal slurry pipeline has been proposed to transport coal from Wyoming to steam generating plants in Arkansas, and water from the Madison aquifer is proposed as the transport medium for the coal. The estimated maximum withdrawal is 15,000 acre-ft/yr for 20 yr. Water withdrawn would never be returned to the aquifer. The use of ground water for steam generating plants near coal fields is also common. Water is either consumed or returned to the aquifer or streams at high temperatures that cause thermal pollution.

Ground water is pumped in the region by the petroleum industry for waterflooding, a process in which water is used to flush petroleum out of reservoir rocks. Waterflooding using ground water is currently practiced in Saskatchewan, Montana, Wyoming, North Dakota, Colorado, Nebraska, and Kansas. Production wells are completed in aquifers that range from shallow alluvial aquifers that contain freshwater to deeply buried bedrock aquifers that contain saline water.

Increases in public supply and rural use of ground water are also given in table 2. The rates of increase indicate an increasing reliance on ground water.

Demand for water, including ground water, is influenced by economic factors, especially the price for water that users are willing to pay. Normally, users of water for irrigation or rural purposes require low-cost supplies; users of water for industrial or public-supply purposes can afford to pay higher prices for supplies. Competition for water supplies may cause a shift in water demand and use toward those users that are willing to pay higher prices, provided that a change in use is permitted by regulations. The market price of water also varies with current quantity available. The quantity of water available for use may be increased by effective water management. Increased quantities will lower prices if accompanied by favorable production conditions. The quantity available for use may be decreased by overdrafts or by seasonal or extended droughts. Decreased quantities will raise prices if accompanied by unfavorable production conditions such as increased withdrawal costs due to declining water levels or increased treatment costs due to impaired water quality.

LEGAL AND REGULATORY CONSTRAINTS

Legal and administrative regulations are used to apportion available water supplies. Regulations are imposed by special purpose districts, Provinces, States, treaties, compacts, and decrees. Local special purpose districts may impose regulations that apply within the district boundaries. The Provinces of Alberta and Saskatchewan require licensing to use ground water for most purposes. States commonly select riparian or appropriation regulations that apply within their boundaries, although special rules may be designated for certain basins, areas, streams, or aquifers. Riparian rights allow a landowner to divert water from streams or lakes adjacent to his property or from ground water beneath his property, provided that he does not appreciably reduce the flow or impair the quality for downstream uses. Appropriation rights allow the owner of a right to divert or store water at a given rate based on a priority system. The amount of the right is based on need, and the priority is based on the beneficial use in time. The senior right is assigned to the user who first benefically used the water, and more junior rights are assigned to those who beneficially used the water later in time. Both the riparian and appropriation systems may be constrained to encourage conservation. In the Missouri Basin Region the riparian rights doctrine is used in Minnesota, Iowa, and Missouri. The appropriation rights doctrine is used in Montana, Wyoming, North Dakota, South Dakota, Colorado, Nebraska, and Kansas.

An international treaty, interstate compacts, and court decrees regulate streams that cross political boundaries in the region. The treaty apportions streamflow of the Milk and St. Mary Rivers and their tributaries between the United States and Canada. Interstate compact agreements have been ratified for division of streamflow among States drained by the Yellowstone River and tributaries, Belle Fourche River, Upper Niobrara River, South Platte River and certain tributaries, Republican River, Big Blue River, and Little Blue River. The court decrees affect the apportionment of streamflow among States drained by the Laramie River and the North Platte River. Some of the regulations limit storage, diversion, and irrigated acreage in affected areas. Only the Upper Niobrara Compact and the Big Blue River Compact (Big and Little Blue Rivers) regulate ground-water use in the drainage basins. Most international and interstate agreements do not consider ground water because of the lack of a data base for determining, and the means of controlling, ground-water flow across political boundaries. However, apportioned streamflow and regional water supplies are affected by ground water because:

1. Streamflow may be augmented by natural drainage of aquifers.
2. Streamflow may be augmented by return flow from irrigated areas.
3. Streamflow may be depleted by natural recharge of aquifers.
4. Streamflow may be depleted by discharging wells near streams.
5. Ground-water underflow and regional flow commonly cross political boundaries.

Constraints to basinwide management of water resources will be numerous and varied. Lack of ground-water information in the Missouri Basin Region is a constraint that limits development. Proper planning will improve the level of information and permit more utilization of ground water. Water apportionment rules should lead to efficient use of supplies through modern water-management techniques. Apportionment rules should be based on knowledge of all sources of water supply and on knowledge of the behavior of water-resource systems in order to facilitate efficient use. Costly projects such as water transfer, reservoir construction, deep drilling, or water treatment may not be necessary if all alternatives in water management are considered.

GROUND-WATER RESOURCES

For discussion purposes the ground-water resources of the Missouri Basin Region are grouped into three general types: unconsolidated and semiconsolidated aquifers, sandstone aquifers, and limestone and dolomite aquifers. All principal aquifers of the region in each State and Province are given in table 7 at the end of the report.

UNCONSOLIDATED AND SEMICONSOLIDATED AQUIFERS

Unconsolidated aquifers include valley-fill alluvium, alluvium, dune sand, glacial deposits, and basin-fill alluvium. Semiconsolidated aquifers include deposits of gravel, sand, sandstone, and fractured sandy clay. Exposures of unconsolidated and semiconsolidated aquifers are shown on plate 1. In many areas the unconsolidated and semiconsolidated aquifers overlie each other or other aquifers that are discussed later.

VALLEY-FILL ALLUVIAL AQUIFERS

The valley-fill alluvial aquifers consist of unconsolidated gravel, sand, silt, and clay, and are located along, and hydraulically connected to, the principal streams and their tributaries. Therefore the aquifers tend to be elongate. The maximum thickness of valley-fill aquifers is about 240 ft in Colorado along the South Platte River valley but probably averages about 50 ft over the Missouri Basin Region. In general, aquifers in main stream valleys are more extensive and thicker than aquifers in tributary valleys. Valley-fill aquifers are absent in some reaches of the main streams and in the upper reaches of most tributaries. In parts of North Dakota and South Dakota the aquifers are not distinguishable from glacial aquifers and are inundated in some areas by surface-water reservoirs. Data describing the areal extent and saturated thickness of the valley-fill aquifers are poorly known in many parts of the region, and information is needed to design plans for improved use of the aquifers.

Valley-fill aquifers are recharged by precipitation, irrigation water, leakage from other aquifers, and losing streams. Ground-water movement normally is in the downstream direction, so underflow in tributary valleys contributes to the ground water in the main valleys. In general the ground water in the valley-fill aquifers is in transit toward the lower part of the basin. Discharge from the aquifers is by drainage to streams, evapotranspiration, wells, and leakage to other aquifers. Evapotranspiration occurs where phreatophytes grow along stream valleys or anywhere the water table lies close to the land surface, as in many valleys in the Missouri Basin Region. Large-capacity wells completed in valley-fill alluvium yield as much as 4,000 gal/min along the North Platte River in Wyoming. Generally the maximum yields from wells in tributary valleys are smaller because aquifer materials are finer grained and aquifers are less extensive than those in the main stream valleys. More water-table maps and gain-and-loss studies in streams are needed to define the flow systems of the valley-fill aquifers.

Aquifer testing of valley-fill aquifers indicates that the transmissivity and specific yield are normally large. In many areas additional aquifer testing is needed in order to prepare maps showing the areal distribution of transmissivity and specific yield for use in models and planning. Aquifer testing can be conducted either by pumping large-capacity wells and observing the effect on the water table or by measuring fluctuations of the water table that are caused by changes in the stage of the stream. For example, the annual stage change, normally about 12 ft for the Missouri River in Missouri, is propagated through the alluvial aquifer and could be analyzed to determine the areal distribution of transmissivity and specific yield of the aquifer (Ferris, 1950).

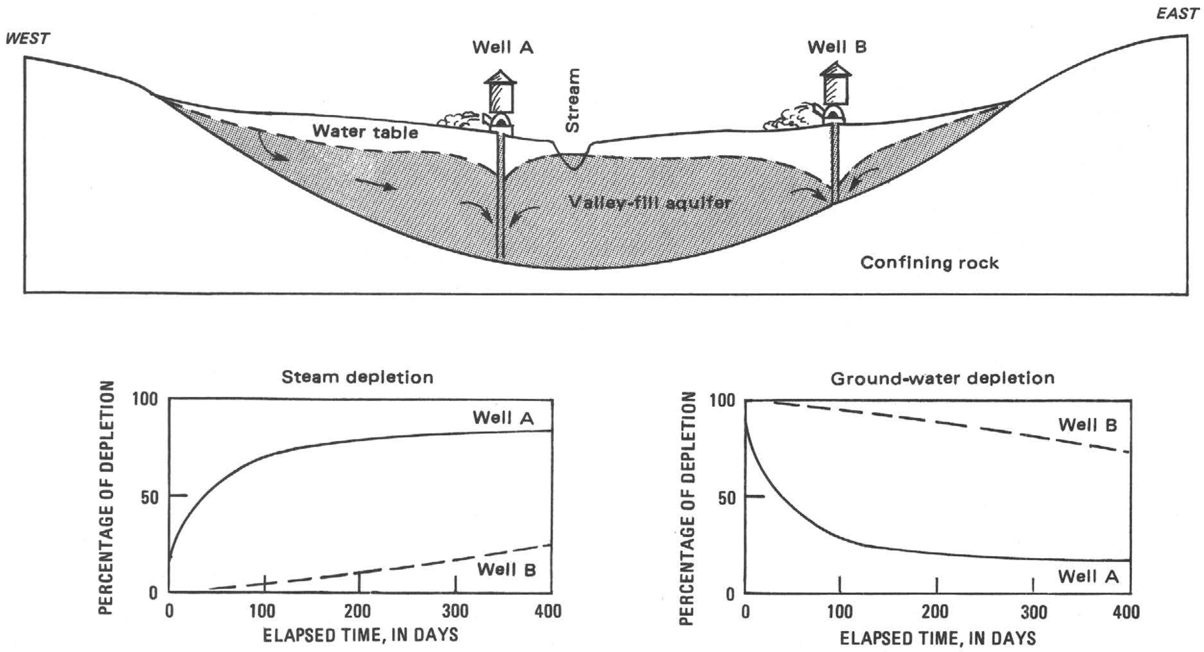
Water quality in the valley-fill aquifers is suitable for most intended purposes. The dissolved-solids concentration ranges from about 100 mg/L to about 4,000 mg/L; however, the concentration is normally less than 1,000 mg/L.

Valley-fill alluvial aquifers and the associated streams in the Missouri Basin Region form stream-aquifer systems in which pumping of water wells in various locations may be used to control the timing of depletion of ground water in storage and streams, the two sources that supply the wells. Examples of well and stream relationships are shown in figure 4. Typically, the width of the valley is 10 mi, and the thickness of aquifer is 50 ft. Wells discharging on both sides of the stream are shown in figure 4*A*. Wells discharging on one side of the stream have little or no effect on the aquifer or wells on the other side of the stream, provided that streamflow is maintained and good hydraulic connection exists between the aquifer and the stream. However, all wells compete for water in the stream. The discharging well A, close to the stream, depletes streamflow more rapidly than ground water. The discharging well B, distant from the stream, depletes ground water more rapidly than streamflow. However, eventually all water withdrawn by the wells will deplete the stream. Ground-water levels will stabilize during prolonged withdrawals, and the levels will recover after the cessation of withdrawals. Depletion of streamflow also can be delayed by pumping wells that are completed in an aquifer that has a low transmissivity and (or) a high specific yield. The effects of natural or artificial recharge or discharge on streamflow and ground water are similarly controlled by distance, aquifer transmissivity, and specific yield.

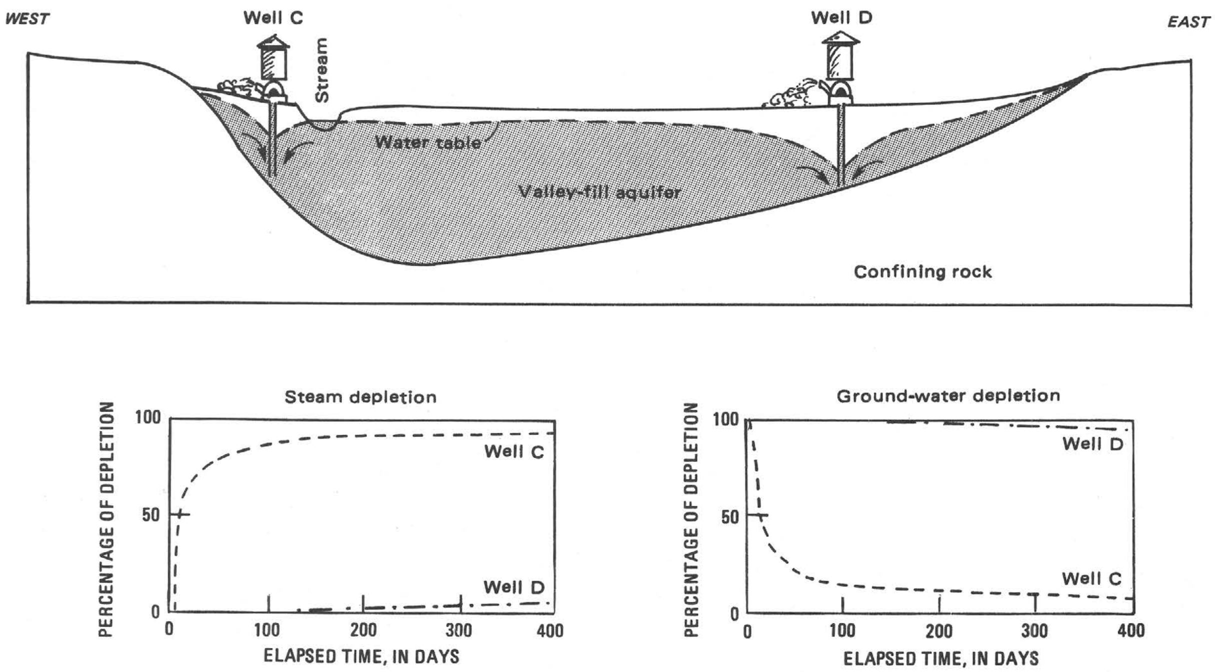
The value of water management for the stream-aquifer system is apparent because the timing of some of the effects on the stream and aquifer can be selected. During periods of surplus or adequate surface runoff, it may be desirable to pump wells near the stream in order to deplete streamflow rapidly. When surface runoff is small or when all streamflow is allocated among the other users, it may be desirable to pump wells distant from the stream and delay depletion of the stream until a later period when streamflow is more abundant. Withdrawals from wells in the valley-fill aquifers of the Missouri Basin Region deplete the streamflow and affect downstream users. However, part of the streamflow probably is derived from ground water, so the surface and ground water in the stream-aquifer system actually constitute a single water supply.

Effects of an aquifer boundary and well location on the timing of depletion are shown in figure 4B. The location of a discharging well C on the west side of the valley in a narrow zone between the stream and the aquifer boundary causes the stream depletion to be extremely rapid because the stream is near and no ground water can cross the aquifer boundary. Well D is very distant from the stream, and the percentage of stream depletion is small, even after a pumping period as long as 400 days. The situation portrayed in figure 4B exists along many streams in the Missouri Basin Region, especially along the Missouri River in Missouri. Because the river lies close to one boundary in many reaches of the alluviated valleys, the water manager has many choices to design beneficial timing of stream depletion due to withdrawals from wells, or beneficial return flow due to recharge operations.

Additional water-management techniques are shown in figure 5. Reuse of the available water supply is shown in a valley irrigated from canals and wells (fig. 5A). Part of the canal water is consumed by evapotranspiration, and part recharges the alluvial aquifer. On the west side of the valley a well field withdraws the recharged water and reapplies it, causing additional recharge which in turn is withdrawn again. The well field allows timely and localized reuse of the water supply. About 50 percent of each application of irrigation water in the South Platte River valley recharges the valley-fill aquifer (Hurr and others, 1975). The recharge resulting from each application indicates that a water supply is only partly consumed with each application and the supply can be partly reused with successive applications. On the east side of the valley, without wells to withdraw water from the aquifer, the return flow can be reused only after the delay of return to the stream. Return flow also migrates downstream and therefore may not be available for use in the reach of the valley where it is needed. The withdrawal and recharge scheme described above is not possible near the stream, because pumped wells rapidly deplete the stream rather than stored ground water and recharged water flows rapidly to the nearby stream rather than into storage in the aquifer. Water-quality problems may develop from reuse schemes. If dissolved solids remain as the water is consumed, the dissolved-solids concentration may become large.



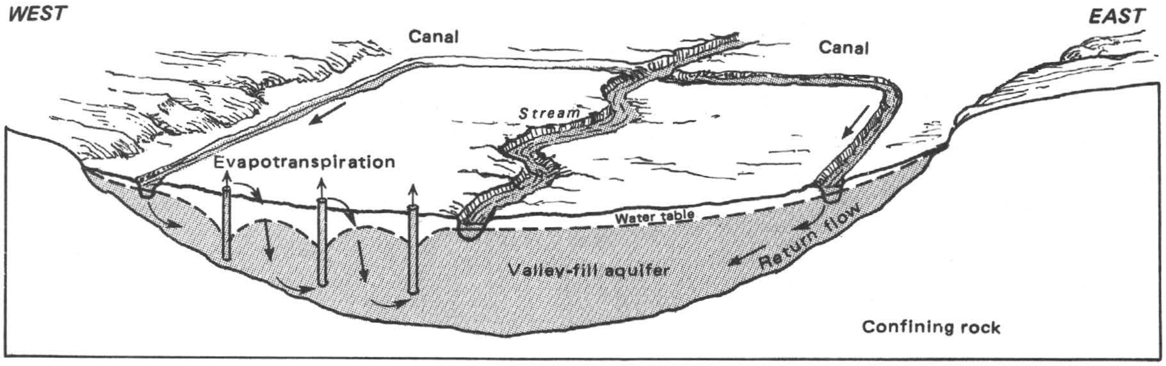
A. **Effect of well location on timing of depletion**



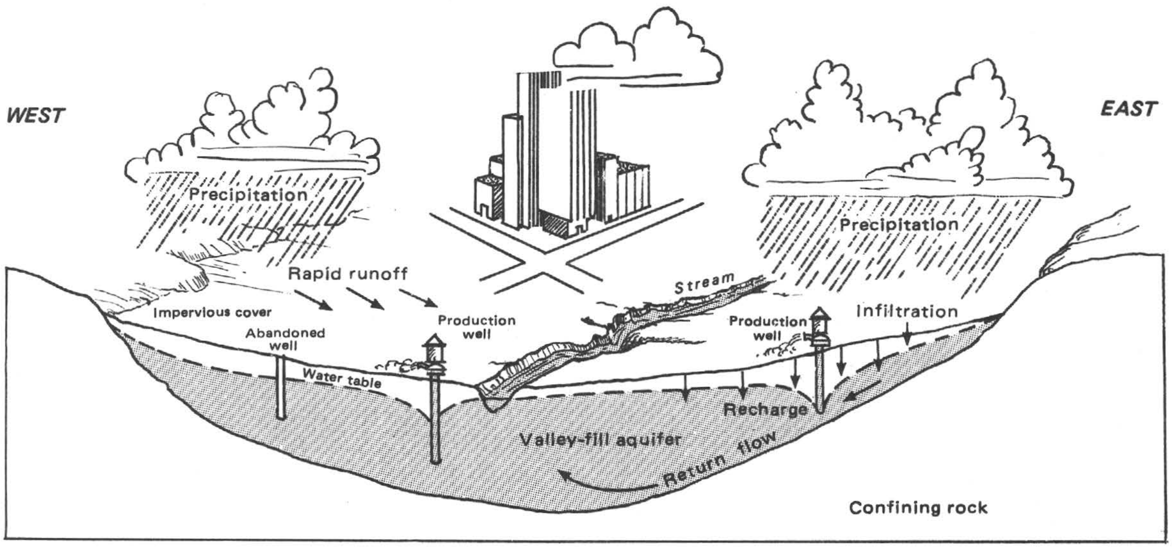
B. **Effect of aquifer boundary and well location on timing of depletion**

FIGURE 4—Effects of well location and aquifer boundary on depletion in a stream-aquifer system.

An urbanized area is sketched in figure 5B. Water supply is obtained from wells completed in the valley-fill aquifer. Yields to wells are maintained by natural recharge to the aquifer from precipitation and by depletion of the stream. However, as impervious cover is added to land in the urbanized area on the west side of the valley, natural recharge to the aquifer is decreased and overland flow to the stream is increased. The decrease in recharge reduces the yield of wells and the stored ground water. A change in well placement permits the water supply to be restored. Existing wells are abandoned, and new wells are drilled closer to the stream. The new wells deplete the stream more rapidly and derive less water from aquifer recharge and



A. **Reuse of water supply by successive recharge and discharge**



B. **Capture of rapid runoff from urbanized area by pumping well near stream**

FIGURE 5.—Reuse of water supply and capture of runoff from urbanized area.

storage. More rapid stream depletion captures the additional streamflow resulting from increased overland flow.

A specific water-management plan may be designed for any area in which water data and interpretive studies are available. For example, water-use regulations in the South Platte River Valley in Colorado are based on the known connection between surface and ground water. Conjunctive use of ground and surface water in the South Platte River Valley is related to the history of the development of water use in the valley. Prior to the beginning of irrigation the saturated thickness of the valley-fill deposits was small and the South Platte probably was not a gaining stream. After surface-water irrigation began in the middle 1800's, the recharge from irrigation raised the water table and increased the saturated thickness of the valley-fill aquifer. Resulting return flow to the South Platte has made it a gaining stream. However, the surface-water supply was extremely variable and undependable even when supplemented with imported surface water from the Colorado River and Laramie River basins. By 1970 more than 3,200 large capacity wells had been drilled for irrigation use (Hurr and others, 1975). The South Platte remains a gaining stream, in spite of the decrease in return flow that results from ground-water withdrawals that average 420,000 acre-ft/yr. An increase in withdrawal rate in the main valley would reduce further the return flow to the stream. However, flow of the South Platte River at the Nebraska State line averages 335,000 acre-ft/yr, and a reduction in streamflow may not harm downstream users because of normally adequate surface supplies. Present regulations of the State Engineer of Colorado require that a volume of water equal to 5 percent of streamflow depletion, caused by ground-water pumping during the year, be added to the stream or to surface-water storage from a supplemental source for use in augmenting streamflow the following year. The regulation was designed to protect senior water rights and eliminate water shortages in the overappropriated stream that occur about 5 percent of the time.

Management of water use in the South Platte River Valley might be improved by integrating forecasts of seasonal water supply with the known behavior of the hydrologic system. Predictions of surface runoff during the irrigation season are prepared monthly by the U.S. Soil Conservation Service and the National Oceanic and Atmospheric Administration, beginning in January. Magnitude of ground-water withdrawals depends on surface runoff because together they constitute the water supply. In years of above-normal runoff and recharge, ground-water withdrawals are usually small, and surplus supplies should be stored; in years of below-normal runoff and recharge, ground-water withdrawals are usually large, and stored supplies should be used. Therefore, the magnitude of ground-water withdrawals and the use of storage facilities can be anticipated from predictions of surface runoff.

Specially constructed artificial-recharge pits in the upper reaches of the tributary valleys could be used during periods of above-normal runoff in the South Platte River Basin. Minor surface-water irrigation in the tributary valleys provides little recharge. Mining of ground water in many tributary valleys has occurred because withdrawals from wells deplete ground water in storage rather than the flow of ephemeral tributaries. Surplus streamflow in tributaries could be diverted to recharge depleted valley-fill aquifers in the tributary valleys, rather than allowed to pass downstream to the main valley where it also may be surplus. Ground water could be withdrawn from the aquifers in tributary valleys and transmitted to the main valley through the tributary channels during periods of below-normal runoff (fig. 6). Aquifers in tributary valleys would function as off-channel reservoirs with the advantage of smaller evaporative losses than surface reservoirs, particularly if the water table were maintained at least 10 ft below the land surface.

The use of tributary valleys as off-channel reservoirs for the South Platte River Valley is permissible under the regulations of the South Platte River Compact between Colorado and Nebraska, and the Doctrine of Prior Appropriation. Briefly, the regulations state that during the irrigation season in the lower valley in Colorado, diversions from the river are forbidden for appropriators having adjudicated dates of priority after 1897 if Nebraska users diverting water from the river put their supply to beneficial use. However, during the winter season in the lower valley, Colorado may divert and store as much as 35,000 acre-ft of water in either surface or ground-water reservoirs.

ALLUVIAL AND DUNE-SAND AQUIFERS

Other unconsolidated aquifers in the Missouri Basin Region include alluvial and dune-sand aquifers. A transmissive and extensive sand and gravel alluvial aquifer occurs in south-central Nebraska and part of northeastern Kansas. The aquifer attains a thickness of several hundred feet and is hydraulically connected to valley-fill aquifers, dune-sand aquifers, the underlying Ogallala aquifer, and adjacent streams (pl. 1). Large-capacity wells in the aquifer yield as much as 2,000 gal/min for irrigation. Dissolved-solids concentration is normally less than 500 mg/L.

An extensive dune-sand aquifer in central Nebraska and southern South Dakota consists of fine sand and clay and has a maximum thickness of several hundred feet. Precipitation recharges the permeable aquifer at high rates, and surface runoff does not occur. Dissolved-solids concentration is only several hundred milligrams per liter. Streams that originate in the dune-sand area have steady flows because they consist of base flow from the ground-water reservoir. The water table in the dune-sand aquifer lies close to the land surface in many areas; evapotranspiration is about 10 million acre-ft/yr from natural lakes and from the shallow ground water. Increased use of ground water may salvage water that is normally evapotranspired. However, implementation of an incautiously designed plan for additional withdrawal of ground water might reduce streamflow, eliminate some natural vegetation, and allow wind erosion to increase (Keech and Bentall, 1971).

Salvage of water normally evapotranspired is portrayed schematically in figure 7. Lowering the water table by pumping reduces the losses due to transpiration by plants and evaporation from the soil and ground-water reservoir. Some pheatrophytes have roots that grow deeper as the water table is lowered, necessitating physical or chemical eradication of the plants to stop transpiration. The scheme shown in figure 7 does not work well near the stream in a stream-aquifer system because the wells mostly deplete the stream and do not lower the water table appreciably.

Several model studies of unconsolidated aquifers in Nebraska have been completed. An analog model of the Big Blue River Basin and Little Blue River Basin in southeastern Nebraska was prepared by Emery (1966). Results from the model study indicated that withdrawals from wells in Nebraska reduce base flow of the Big Blue and Little Blue Rivers by less than 5 percent. Knowledge of the simulated reduction in base flow is important to Nebraska and Kansas because the streams drain parts of both States. Huntoon (1974) prepared a mathematical model of the upper

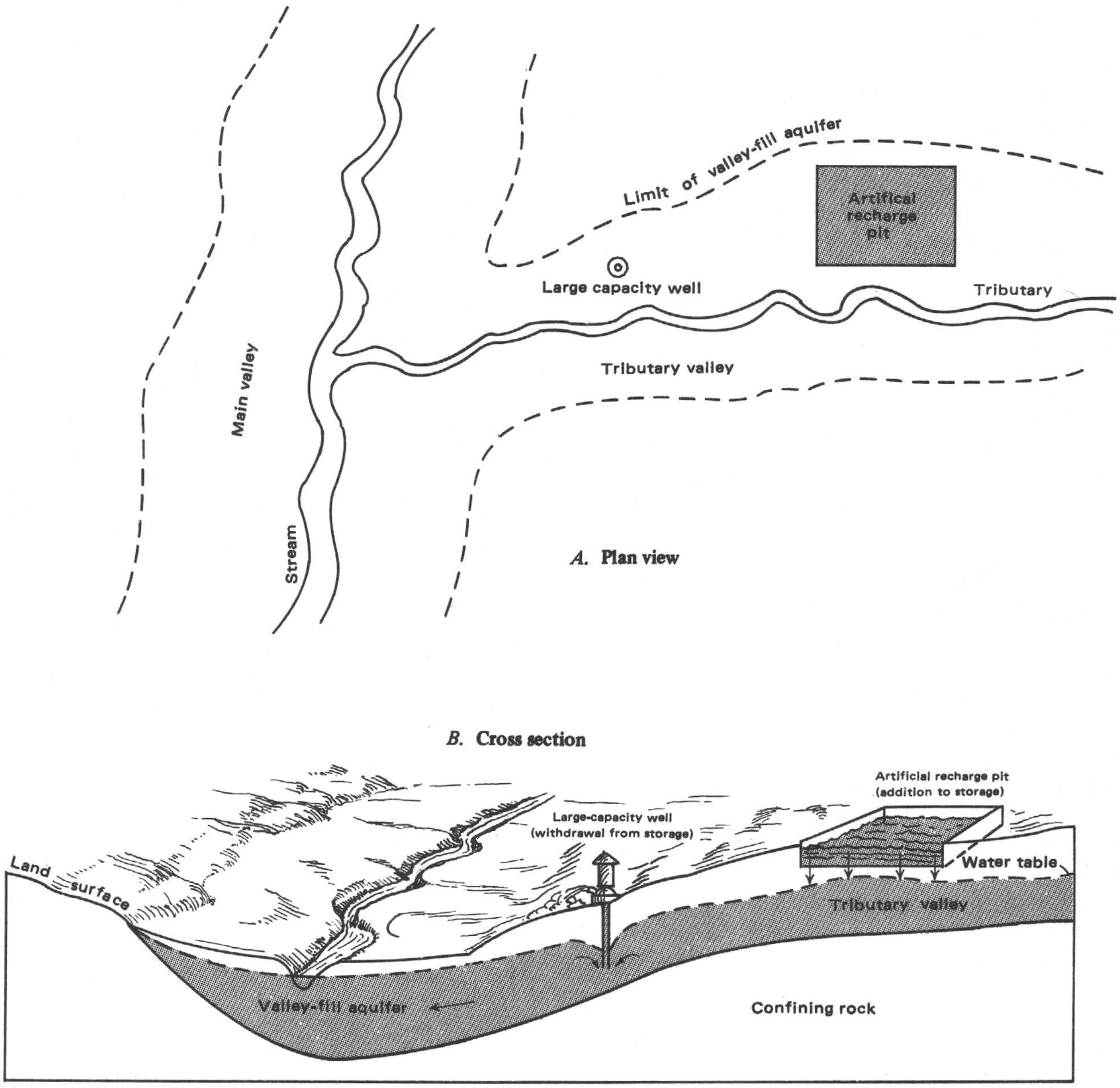
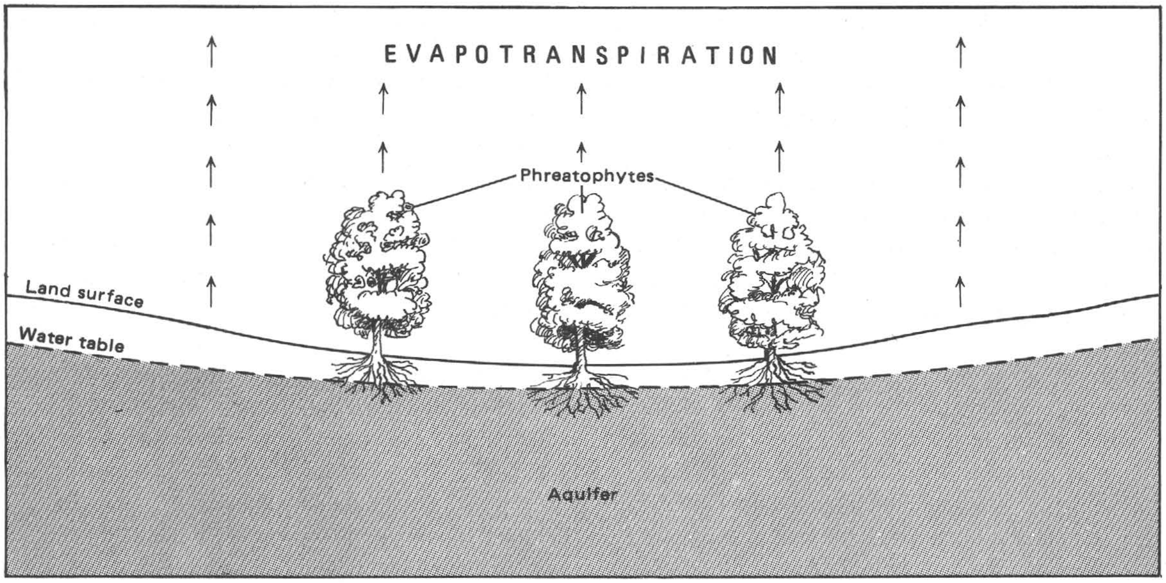
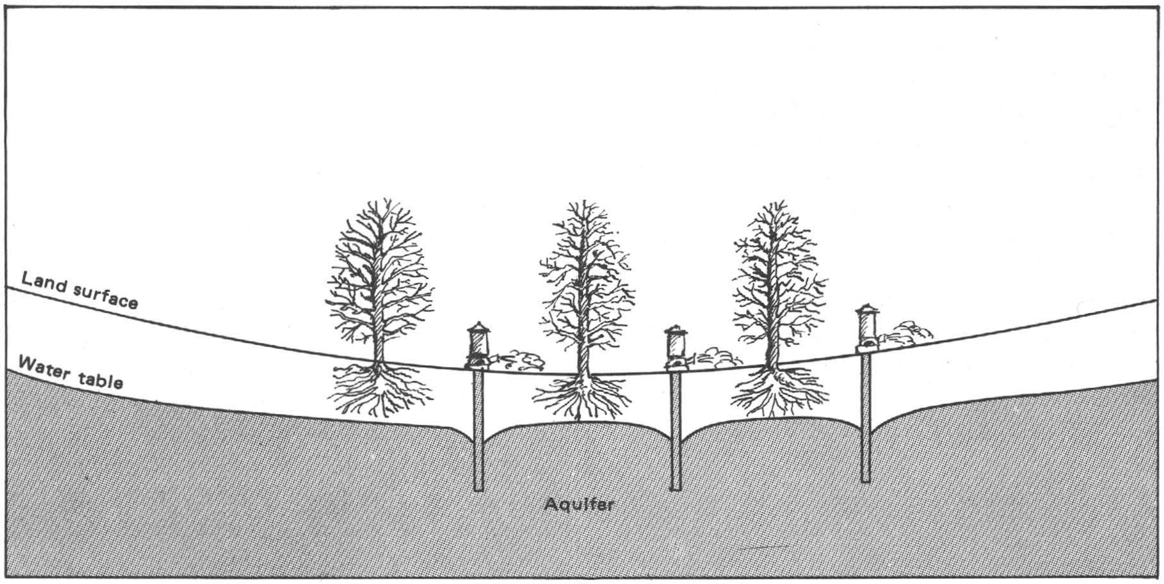


FIGURE 6.—Use of alluvial aquifer in tributary valley as off channel reservoir.

Big Blue River Basin to consider alternative methods to halt the continuous decline in the water table caused by ground-water withdrawals for irrigation. Artificial recharge was the only simulated alternative that would halt the decline. An areally extensive mathematical model that covers the Platte, Loup, and Elkhorn River Basins was prepared by the Missouri River Basin Commission (1975). The model was formulated for the streams and hydraulically connected alluvial, dune-sand, and Ogallala aquifers which have a maximum saturated thickness of 1,100 ft. Effects of recharge and discharge on the stream-aquifer system were simulated to predict the effect of additional ground-water use for irrigation. Results indicate that additional ground-water use will have one or more of the following effects: increased depletion of ground water, increased depletion of streamflow, or increased salvage of water normally evapotranspired. Of the three effects, salvage of water normally evapotranspired is preferred because water is obtained by intercepting a normal loss from the stream-aquifer system, rather than by depleting existing supplies. Additional model study is needed to determine optimal withdrawal of available supplies for improved water use. A study of optimal operation would determine the best sources of irrigation water obtainable under stated



A. **Evapotranspiration due to high water table**



B. **Salvage of water evapotranspired by lowering water table**

FIGURE 7—Salvage of evapotranspired water.

conservation and production goals and within legal and economic constraints.

GLACIAL AQUIFERS

Unconsolidated aquifers also occur in glacial deposits that extend in a belt as much as 200 mi wide, as shown on plate 1. The deposits reach a maximum thickness of about 800 ft and contain sand and gravel aquifers in the form of buried channel deposits, extensive outwash deposits, and lenticular outwash deposits. Aquifers in glacial deposits may be formed during various stages of glaciation, complicating the geologic interpretation of their origin and distribution. Glacial aquifers are recharged by precipitation, streams, or leakage from bedrock aquifers below the glacial deposits. Ground water in the glacial aquifers is discharged to streams, springs, underlying bedrock, evapotranspiration, or wells. Well yields are extremely variable and are as much as 2,000 gal/min. Flowing wells derive water from aquifers confined by clay beds. Withdrawals from wells are used for domestic, livestock, municipal, and irrigation purposes.

Water quality in the glacial aquifers is extremely variable, and the dissolved-solids concentration ranges from 300 to 30,000 mg/L. Saline seeps from glacial aquifers in northern Montana have affected a growing area that currently is about 170,000 acres of land; the seeps make the land too saline for most uses (Marvin Miller, Montana Bureau of Mines and Geology, oral commun., 1976). Water-quality sampling of ground water and streamflow under low-flow conditions helps to delineate reaches of the streams affected by the seeps. Water-table maps and depth-to-water maps help to delineate areas that may be subject to future damage and help to develop schemes to reduce or halt the spread to the seep areas. Reducing recharge to the glacial aquifers by planting crops that transpire more water helps to moderate the problem. In some cases it may be possible to remove the saline water by wells or drains and evaporate the water from ponds. The residue could be processed to separate trace elements that are known to be present in unusually high concentrations. The elements include selenium, lead, cadmium, copper, zinc, nickel, tin, chromium, aluminum, silver, molybdenum, and vanadium.

Many aquifers in the glacial deposits are not mappable at the surface and must be located by test drilling, geologic interpretation, or geophysical exploration. Several States in the Missouri Basin Region have drilling programs to define aquifers in glacial deposits, but more extensive and ordered exploration is needed. Exploration procedures for aquifers in glacial deposits have been discussed by Winter (1975). Statistical analyses of data describing drillers' logs, rock types, well yields, well dependability, and aquifer transmissivity are needed to provide information useful in locating the aquifers and to describe areal variations in the hydraulic properties of the aquifers.

BASIN-FILL AQUIFERS

Basin-fill aquifers in southwestern Montana consist mostly of poorly consolidated deposits of gravel, sand, silt, and clay of Tertiary age and attain a maximum thickness of about 6,000 ft in intermontane valleys. Basin-fill aquifers are overlain by valley-fill alluvial aquifers in many areas. Basin-fill aquifers are recharged by precipitation, irrigation water, and streams. Ground water moves in the downstream direction. Aquifers discharge to streams, to the atmosphere by evapotranspiration where the water table is close to the land surface, and to wells drilled for irrigation, domestic, livestock, and industrial purposes. Although basin-fill aquifers are not as transmissive as the overlying valley-fill alluvium, wells yield as much as 1,000 gal/min. Dissolved-solids concentration is normally less than 1,000 mg/L, making the water suitable for most purposes.

An extensive analysis of the ground-water resources in the basin-fill aquifers of the Gallatin Valley near Bozeman, Montana, was prepared by Hackett and others (1960). The authors proposed greater conjunctive use of ground water and surface water to intercept more of the water that passes downstream. Artificial recharge is proposed by the authors as a means to store the occasional surface-water surplus in the ground-water reservoir. Similar studies should be made for each of the basin-fill aquifers shown on plate 1.

A comprehensive water-management plan could be designed so that each year a water supply could be obtained efficiently from a combination of available sources. The combination would depend on the current available supply in each source, the known behavior of the hydrologic system, snowmelt forecasts, and runoff forecasts. The large thickness of the basin-fill deposits indicates that a large volume of ground water is available, which would be particularly useful if temporary depletion of stored supplies became necessary during a drought of several years duration.

OGALLALA, ARIKAREE, AND BRULE AQUIFERS

The Ogallala aquifer is widespread over parts of Colorado, Nebraska, and Kansas and present in small areas of Wyoming and South Dakota. The Ogallala Formation consists of semiconsolidated gravel, sand, silt, caliche, and clay and attains a maximum thickness of about 400 ft. Recharge to the Ogallala occurs directly from precipitation and by leakage through the overlying alluvial and dune-sand aquifers. Average annual recharge ranges from about ½ to about 3 in. where the aquifer is exposed, according to numerous analyses. Jenkins and Hofstra (1970) concluded that part of the recharge to the Ogallala is from ephemeral streams. The water table slopes toward the east, indicating that water in the Ogallala moves slowly from Wyoming and Colorado into Nebraska and Kansas. Discharge from the Ogallala is to streams or to wells. Large-capacity wells yield as much as 3,600 gal/min for irrigation, municipal, domestic, and livestock purposes. Average well yield is about 1,000 gal/min. Dissolved-solids concentration ranges from about 200 to 600 mg/L.

Continual declines of the water table of the Ogallala aquifer in Colorado, Kansas, Nebraska, and Wyoming indicate that ground water is being depleted as the result of discharge exceeding the long-term recharge. In Colorado the water-table decline averages about 3 ft/yr; in Kansas the decline averages about 0.7 ft/yr. A small decline of the water table in extreme southeastern Wyoming is due to withdrawals from the aquifer that began in 1968. Decline in the water table at some places in southwestern Nebraska is about 0.2 ft/yr. Withdrawal from the Ogallala in South Dakota is small. The Colorado Ground Water Commission has established standards that limit well spacing and storage depletion for any new wells completed in the Ogallala in Colorado. However, model studies of the Ogallala in Colorado indicate that the water table will continue to decline even if the withdrawal from wells is reduced gradually as the water table declines (Luckey and Hofstra, 1973, 1974; Kapple and others, 1976).

A needed regional water-management and economic study of the Ogallala aquifer covering Colorado, Kansas, Nebraska, and Wyoming would require data on the areal distribution of the following:

1. Specific yield of the aquifer.
2. Saturated thickness of the aquifer.
3. Hydraulic conductivity of the aquifer.
4. Depth to water below land surface.
5. Ground-water withdrawal.
6. Recharge from precipitation and applied irrigation water.
7. Artificial-recharge capability.
8. Cost of pumping from the aquifer.
9. Expected yield from, and value of, various crops.

The study could search for methods of operation that would reduce ground-water mining, increase the beneficial use of the supply, and extend the life of the aquifer. A regional aquifer system analysis for the Ogallala aquifer was begun by the U.S. Geological Survey in 1977.

The Arikaree aquifer occurs in parts of Wyoming, South Dakota, Colorado, and Nebraska and underlies the Ogallala aquifer. The Arikaree Formation consists of semiconsolidated sandstone, siltstone, and claystone and attains a maximum thickness of about 600 ft. Aquifer recharge is largely from precipitation and irrigation. The Arikaree aquifer may be recharged also by leakage from the overlying Ogallala aquifer in some areas. Discharge is to streams and to irrigation, municipal, stock, and domestic wells. Some wells yield as much as 2,000 gal/min. Ground-water mining has occurred in the Arikaree in northwestern Nebraska, as evidenced by a progressive decline in the water table. Continued decline in the water table will gradually increase the cost of lifting water from the aquifer to the land surface and may discourage use of the aquifer. The dissolved-solids concentration in the Arikaree aquifer is only several hundred milligrams per liter. A mathematical model study (Lines, 1976) of the Arikaree aquifer along the Laramie River in Wyoming indicated that part of the natural discharge from the aquifer to the river could be captured with wells. Additional water-table maps, aquifer testing, and gain-and-loss studies in streams would help in the design of plans to capture more natural discharge from the aquifer and reduce ground-water depletion.

The Brule Formation of the White River Group underlies the Arikaree Formation and is exposed over parts of Wyoming, South Dakota, Colorado, and Nebraska. The Brule Formation consists of siltstone and fractured sandy clay with a maximum thickness of about 450 ft. Precipitation and streamflow recharge the Brule aquifer. Ground-water movement occurs in the siltstone and in the fractures in the sandy clay. Therefore, the Brule aquifer is transmissive even though the aquifer material is fine grained. Extensive vertical and horizontal fractures in the Brule are described by Rapp and others (1953) and Babcock and Bjorklund (1956). Discharge is to streams and to wells that yield as much as 2,000 gal/min. Withdrawals from wells have caused minor ground-water depletion in Wyoming and Nebraska. The dissolved-solids concentration is normally only several hundred milligrams per liter. Artificial-recharge experiments in the Brule aquifer would determine if the fracture system in the aquifer could facilitate rapid recharge. Conceivably the vertical fractures could transmit the recharged water rapidly downward, and the horizontal fractures could transmit the water rapidly laterally through the extent of the aquifer. Successful artificial-recharge operations, using occasionally surplus streamflow, could result in a greatly improved water supply in the Brule aquifer.

Water supplies in unconsolidated and semiconsolidated aquifers of the Missouri Basin Region are summarized in table 3. Included in the table are summaries of water-management suggestions for each aquifer.

SANDSTONE AQUIFERS

Sandstone aquifers are widespread in the Missouri Basin Region except in southwestern Montana and most of Nebraska, Kansas, Missouri, and parts of Wyoming and Colorado (pl. 2). Some sandstone aquifers are exposed at the land surface; others are in structural basins of various depths and alternate with relatively impervious beds of shale and limestone.

AQUIFERS IN STRUCTURAL BASINS

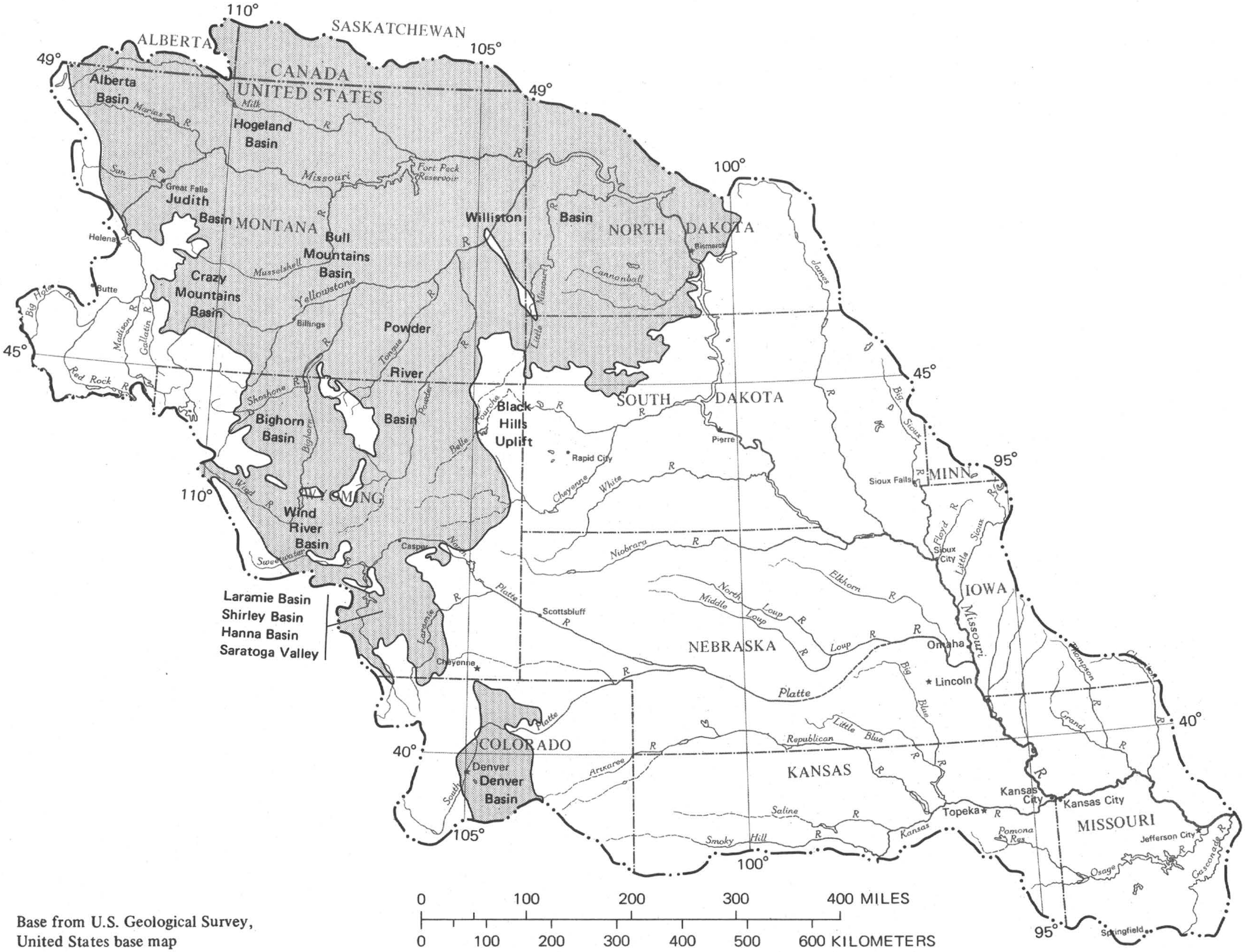
Structural basins are depressions that result from folding, faulting, subsidence, or nearby uplifting. Many structural basins in the region contain thick accumulations of sediment. Extensive accumulations of

TABLE 3.—*Summary of water supplies in unconsolidated and semiconsolidated aquifers, Missouri Basin Region*

Source of supply	Location	Yield to wells (gal/min)	Suggestions for improved hydrologic data, analyses, and water management	Outlook for future use if suggestions are followed
Valley-fill alluvial aquifers.	Montana, Wyoming, North Dakota, South Dakota, Colorado, Nebraska, Minnesota, Iowa, Kansas, Missouri.	10–4,000	Mapping and test drilling to determine location and type of boundaries, aquifer thickness and extent. Aquifer testing to prepare maps of transmissivity and specific yield. Preparation of water-table maps. Gain-and-loss studies in streams. Water-management analysis of stream-aquifer system.	Improved water supply by controlled changes in streamflow and ground-water storage. Additional reuse of available supply. Storage benefits from artificial recharge.
Alluvial aquifer, dune-sand aquifer.	Nebraska, Kansas.	50–2,000	Mathematical model studies designed to determine optimal development of available supplies.	Increased water supply by additional salvage of water evapotranspired. Reduced shortages during periods of drought.
Glacial-deposit aquifers.	Alberta, Saskatchewan, Montana, North Dakota, South Dakota, Nebraska, Minnesota, Iowa, Kansas, Missouri.	10–2,000	Test drilling to locate aquifers. Statistical analyses of drillers' logs, aquifer transmissivity, well yield, well dependability, and water quality to define major aquifers and saline ground-water resources. In northern Montana, ground water and streamflow sampling under low-flow conditions. Preparation of water-table maps and depth-to-water maps. Changes in agricultural practices to reduce recharge. Withdrawal and disposal of saline water from areas where conditions permit.	Increased and more dependable water supply. Reclamation of land in northern Montana affected by saline seeps. Use of saline ground water.
Basin-fill Aquifers.	Southwestern Montana.	15–1,000	Incorporation of ground water into water-management plans that include all water supplies, current status of each, and known behavior of hydrologic system. Exploration for additional basin-fill aquifers.	Reduced shortages, even during drought of several years' duration. Possible discovery of additional ground-water supplies.
Ogallala aquifer.	Wyoming, South Dakota, Colorado.	10–3,600	Regional water-management and economic studies to determine availability and best use of supply.	Reduced ground-water mining and increased benefit from available supply. Increased aquifer life.
Arikaree aquifer.	Wyoming, South Dakota, Colorado, Nebraska.	10–2,000	Preparation of additional water-table maps. Aquifer testing to determine transmissivity and specific yield. Gain-and-loss studies along streams hydraulically connected to the aquifer.	Improved understanding of aquifer potential. Conjunctive use of ground and surface water. Reduced ground-water mining.
Brule aquifer.	Wyoming, South Dakota, Colorado, Nebraska.	10–2,000	Artificial-recharge experiments to determine if fractures in aquifer will facilitate rapid recharge.	Increased ground-water storage and decreased shortages during extensive drought. Reduction of pumping lift in wells.

fine sediment form confining beds; accumlations of coarser sediment form aquifers. Numerous freshwater aquifers that alternate with confining beds occur in structural basins in Montana, Wyoming, North Dakota, South Dakota, and Colorado. In some cases, a shallow sandstone aquifer may be exposed over the areal extent of the structural basin. Normally, the sandstone aquifers and confining formations are exposed at the land surface at the margin of the basin. Confined conditions are common, and in many cases flowing wells may be obtained in the sandstone aquifers. Principal structural basins that contain freshwater aquifers in the Missouri Basin Region are shown in figure 8 (Rocky Mountain Association of Geologists, 1972). Intervening areas between basins are uplifted domes or arches and volcanic rocks. Margins are not shown for most basins on plate 2 and figure 8 because they tend to merge and exact basin margins are arbitrary. Local sandstone aquifers that occur in western Montana and northwestern Wyoming are not shown because they lie in an area of complex geologic structure and have not been mapped thoroughly. All principal aquifers in structural basins of the region are shown on plate 2 and tabulated in table 8 at the end of the report.

The Virgelle Sandstone occurs in northwestern Montana in the southern part of the Alberta Basin. In other parts of Montana the Virgelle is the basal member of the Eagle Formation; in southern Alberta the virgelle is known as the Milk River Sandstone (Meyboom, 1960). The Virgelle consists of sandstone and shale and attains a maximum thickness of about 180 ft. Precipitation and leakage from overlying glacial deposits recharge the Virgelle aquifer (Zimmerman, 1967). A potentiometric map of the Virgelle indicates a ground-water divide about 12 mi south of the Canadian border. Ground water moves north and south from the divide. The ground water moving north is leaving the Missouri River Basin and entering the Saskatchewan River Basin in Alberta. Discharge in Montana and Alberta is to streams and springs and to wells that yield as much as 250 gal/min for industrial, municipal, domestic, and livestock uses. The aquifer is confined in parts of Alberta, and a large number of flowing wells have been drilled. Withdrawals from pumped and flowing wells in the aquifer have caused continuing declines in water levels in wells. Meyboom (1960) suggested the implementation of conservation practices to protect the ground-water supply, even though the current riparian laws discourage conservation. Location and plugging of flowing wells would help to preserve the supply in the aquifer, but the wells are not located easily. Zimmerman (1967) suggested that industrial demands might be supplied



Base from U.S. Geological Survey, United States base map

FIGURE 8.—Structural basins that contain freshwater aquifers in the Missouri Basin Region.

from Cut Bank Creek or aquifers in the Madison Group. Dissolved-solids concentration in the aquifer reaches a maximum of about 2,500 mg/L and varies widely over the aquifer.

Maximum transmissivity of the Virgelle aquifer in Montana (Zimmerman, 1967) is about 25 times greater than the maximum transmissivity of the Milk River aquifer in Alberta (Meyboom, 1960). The greater maximum transmissivity of the Virgelle aquifer in Montana is probably due to extensive fracturing of the aquifer, which facilitates water movement. Laboratory tests of horizontal and vertical hydraulic conductivity of samples of the Milk River aquifer from Alberta indicated that the vertical conductivity of the sandstone is nearly as great as the horizontal conductivity. Therefore, the feasibility of artificial recharge of the aquifer should be investigated. The reported small storage coefficient of the confined zone of the Milk River aquifer in Alberta indicates that recharge will cause a large rise in water levels. Uncontrolled flowing wells would have to be plugged before beginning artificial-recharge operations. The water supply for artificial-recharge operations could be obtained from the Milk River when streamflow exceeds demands.

The Blood Reserve and Judith River Formations are sandstone aquifers that overlie the Milk River Sandstone in the Alberta Basin in southern Alberta (McLean, 1971; Tokarsky, 1974). The dissolved-solids concentration in the Blood Reserve and Judith River aquifers ranges from about 1,000 to 4,000 mg/L. Additional potentiometric maps and aquifer testing are needed in order to understand the flow system in each aquifer, including the possibility of interaquifer leakage, and to design plans for water management.

The Judith Basin lies in central Montana near the headwaters of the Missouri River and many of its upstream tributaries. Reconnaissance geologic and hydrologic studies of the basin were made by Zimmerman (1966) and Feltis (1973). Sandstone aquifers include the Judith River Formation, Eagle Sandstone, Dakota Sandstone, Kootenai Formation, Swift Formation, Amsden Group, and Kibbey Formation. The sandstone aquifers are recharged by precipitation, streams, and irrigation water. Direction of ground-water movement is poorly understood because not enough wells exist to allow preparation of potentiometric maps. Discharge is to wells, streams, or by evapotranspiration in areas where the water table is near the land surface. Wells completed in the Judith River, Eagle, and Dakota aquifers yield as much as 70 gal/min; wells completed in the Kootenai and Swift aquifers yield as much as 300 gal/min. Flowing wells are obtained where the aquifers are confined. Few wells have been completed in the Amsden or Kibbey aquifers.

Additional potentiometric maps, aquifer testing, and water-quality sampling are needed for the Judith Basin. Improved understanding of the ground-water resources could lead to comprehensive conjunctive use of ground and surface water.

The Hogeland Basin lies in southern Saskatchewan and north-central Montana. However, the sandstone aquifers present in the basin extend over a wide area (pl. 2) beyond the limit of the basin (fig. 8). Sandstone aquifers described by Whitaker (1967, 1974) and McLean (1971) include the Frenchman, Whitemud, Eastend, and Judith River Formations. Sandstone aquifers of the Hogeland Basin in north-central Montana described by Alverson (1965) and Osterkamp (1968) include the Judith River Formation, Eagle Sandstone, Dakota Sandstone, Kootenai Formation, and Swift Formation. Undoubtedly formations in Montana have stratigraphic equivalents in Saskatchewan, but such correlation is beyond the scope of this report. Toward the east in northeastern Montana, the Eagle Sandstone and the Swift Formation become less permeable and are not aquifers. Where exposed, the sandstone aquifers are recharged by precipitation and elsewhere probably by leakage from the overlying glacial aquifers. Discharge from the aquifers is to springs, streams, wells, possibly to the atmosphere by evapotranspiration, and to other aquifers. Flowing wells are obtained in some places where the aquifers are confined. Wells completed in the Judith River aquifer yield as much as 200 gal/min; wells in the Eagle yield as much as 75 gal/min. A potentiometric map prepared by Osterkamp (1968) indicates discharge from the Judith River aquifer to Fort Peck Reservoir and the Missouri River.

Additional hydrologic information is needed for the Hogeland Basin and surrounding areas in order to conserve or develop the water resources. Aquifers that are continuous across the United States-Canadian border need to be identified because effects of water use may be transmitted across the border. Potentiometric maps and aquifer testing of extensive areas are needed to provide information on direction and rate of ground-water movement, as well as areas of recharge and discharge. Additional water-quality sampling and interpretation are needed. Currently (1977) the vast ground-water resources are barely used because of the small population and small demand.

The Crazy Mountains Basin and the Bull Mountains Basin contain numerous sandstone formations that are known to be aquifers in other areas of the Missouri Basin Region. Hydrologic properties of the basins are poorly known, and hydrologic investigations are needed in both basins to obtain the information required for planning any development of the largely unused ground-water supplies.

The Bighorn Basin lies mostly in Wyoming but extends slightly into Montana. Principal sandstone formations in Wyoming are described by Lowry and others (1975); principal sandstone formations in Montana are described by Hamilton and Paulson (1968). Some of the sandstone formations in Montana correlate with formations in Wyoming. The sandstone aquifers are recharged by precipitation, streamflow, and leakage from other aquifers. Discharge is to springs, streamflow, to the atmosphere by evapotranspiration, other aquifers, and wells. Flowing wells completed in the Tensleep and Amsden aquifers have yielded 2,000 gal/min. Uses of the ground water include municipal, industrial, irrigation, and fish culture.

Potentiometric maps and aquifer testing are needed for each extensive sandstone aquifer in the Bighorn Basin. Collection and interpretation of water-quality data are needed also. Improved understanding of the ground-water resources in the Bighorn Basin is needed in order to plan for conjunctive use of ground water with surface water in the adjacent reaches of Clarks Fork of the Yellowstone River, the Shoshone, and the Bighorn Rivers.

Ground-water resources of the Wind River Basin were summarized by Whitcomb and Lowry (1968). The aquifers probably are recharged by precipitation or by interaquifer leakage. Measured gains in streamflow indicate that the aquifers discharge to streams, as well as to springs and wells. Some of the sandstone aquifers are fractured, increasing aquifer transmissivity and well yield. Maximum well yield is about 1,100 gal/min (an industrial well completed in the Arikaree aquifer). The concentration of dissolved solids or of a particular chemical constituent is very high in several aquifers. Water-quality mapping is needed to locate saline water zones so that they may be avoided or developed as saline water resources.

Numerous extensive sandstone aquifers in the Wind River Basin contain large volumes of ground water. Additional data on the hydrologic properties of the aquifers are necessary before additional ground water can be developed properly. The Wind River Basin might serve as a storage reservoir common to the two major streams that drain the basin, the Wind River and the Sweetwater River. Conceivably, the ground-water reservoir could be used to reduce shortages in water supply in each of the surface drainage areas through water-management procedures for storage, transfer, and withdrawal. During periods of below-normal runoff, ground-water withdrawals could be increased. During periods of above-normal runoff, surplus streamflow could be artificially recharged to the ground-water reservoirs.

Ground-water resources of the Laramie, Shirley, and Hanna Basins and Saratoga Valley were appraised by Lowry and others (1973). The basins contain large number of formations that consist partly or completely of sandstone. All of the sandstone aquifers are not present in each basin or valley, but the presence of several aquifers in any basin may represent a large thickness of sandstone and a correspondingly large volume of stored ground water. Most of the sandstone aquifers are recharged by precipitation where exposed. Interaquifer leakage is likely but remains untested. Measured gains in streamflow indicate that some of the aquifers discharge to streams. Wells yield as much as 1,000 gal/min especially where fracturing has increased the permeability of the aquifers. Water quality is variable, although the water is generally suitable for most purposes. Potentiometric maps, aquifer testing, and gain-and-loss studies along streams are needed.

The Laramie, Shirley, and Hanna Basins and Saratoga Valley lie near the headwaters of the North Platte River in northern Colorado. Ground-water reservoirs in the basins could be used in total water management in the main valley downstream. For example, in some areas a water surplus might be artificially recharged to the basins for later withdrawal and use. However, careful planning would be required to insure that the recharged water would be available when needed and not discharged from the aquifer or transmitted beyond the area influenced by recovery wells. Ground water in storage is subject to virtually no evaporative losses compared to lake evaporation of 36 to 42 in./yr for surface reservoirs in this area (see fig. 3). However, full use of the ground water would include conjunctive use with streamflow and surface-water reservoirs. Because of the large reserves, mining of ground water in storage may be feasible.

The Powder River Basin contains sandstone aquifers that extend over a large area in northeastern Wyoming and southeastern Montana (Hodson and others, 1973). The Wasatch Formation is an aquifer that yields as much as 500 gal/min to wells in Wyoming, but it is mostly absent in Montana. The dissolved-solids concentration commonly ranges from 500 to 1,500 mg/L. Aquifers in the Fort Union Formation are sandstone and coal beds. Wells in Wyoming in the Fort Union yield as much as 150 gal/min of water with a normal dissolved-solids concentration of 500 to 1,500 mg/L. The Fox Hills Sandstone and overlying sandstone beds of the Lance or Hell Creek Formations form an areally extensive and persistent aquifer. The aquifer is probably recharged where exposed at the edge of the basin and by leakage from other aquifers. In southeastern Montana ground water in the Fox Hills-basal Hell Creek aquifer moves toward the northwest, away from the Black Hills Uplift. Discharge is to the Yellowstone River and the Powder River. The ground-water movement is very slow; the transit time from the outcrop of the Fox Hills-basal Hell Creek aquifer in the Black Hills to the Yellowstone River is about 400,000 yr (Taylor, 1968). In contrast, the transit time for surface water over approximately the same distance is only several days. In northern Wyoming, water in the Fox Hills moves north into Montana. Industrial, municipal, and domestic wells yield as much as 200 gal/min. Dissolved-solids concentration is normally less than 2,000 mg/L. More aquifer testing and potentiometric maps are needed for the Fox Hills and overlying sandstone beds in order to predict the hydrologic response of the aquifer to future development.

Additional sandstone aquifers lie below the Fox Hills in the Powder River Basin. The Mesaverde and Frontier aquifers yield as much as 50 gal/min to wells; the Inyan Kara aquifer may yield 200 gal/min. Dissolved-solids concentration in the Mesaverde, Frontier, and Inyan Kara aquifers is normally less than 3,000 mg/L. Wells completed in the Sundance aquifer yield a maximum of 50 gal/min. Dissolved-solids concentration ranges from about 500 to 2,000 mg/L in the Sundance. The Tensleep Sandstone is partly equivalent to the Minnelusa Formation in the Black Hills. Wells completed in the Tensleep aquifer yield from 20 to 1,200 gal/min. Higher yields are obtained where the Tensleep is fractured, because of the resulting increase in transmissivity. Dissolved solids in water from the Tensleep aquifer commonly range from 200 to 500 mg/L and consist mostly of calcium and bicarbonate. A hydrologic model of the Powder River Basin would help to indicate ways of developing the ground-water resources. Potentiometric maps and aquifer testing are lacking for all aquifers. Data describing the vertical hydraulic conductivity of intervening layers between aquifers would help to predict the rate of interaquifer leakage.

The Williston Basin extends over western North Dakota, eastern Montana, northwestern South Dakota,and southern Saskatchewan. Sandstone aquifers occur in the Fort Union Formation, Fox Hills Sandstone, Hell Creek Formation, and Dakota Sandstone. The Fort Union Formation consists of shale, sandstone, siltstone, lignite, and clinker beds. Sandstone aquifers in the Fort Union are recharged principally by precipitation. Ground water in southwestern North Dakota generally moves northeast, in the direction of surface drainage. Discharge is to streams and to domestic and stock wells that yield as much as 200 gal/min, but generally much less. Dissolved-solids concentration normally is less than 2,000 mg/L but may be as high as 7,000 mg/L. Dependable sandstone aquifers in the Fort Union are difficult to locate because of their discontinuous and irregular nature. A statistical compilation and analysis of well logs, aquifer properties, well characteristics, and water quality is needed to improve the level of understanding of ground-water occurrence in the Fort Union.

The Fox Hills-basal Hell Creek aquifer is an extensive aquifer in the Williston Basin. Recharge occurs through outcrops of the aquifer near the Black Hills Uplift and seepage from overlying aquifers in part of the area. Ground-water movement is to the north, northeast, and east. Natural discharge is by upward leakage through confining beds or by evapotranspiration where the aquifer crops out, as in central North Dakota. Apparently the water moving to the north and northeast passes from the Missouri Basin Region into the Souris-Red-Rainy Region where it is discharged in north-central North Dakota and possibly in Saskatchewan and Manitoba. In south-central North Dakota east of the Missouri River the potentiometric surface slopes westward, indicating that ground water moves from east to west. Wells in the aquifer yield as much as 700 gal/min. Uncontrolled or partly controlled flow from wells in the aquifer has caused water-level declines of about 30 ft in Mercer County, N. Dak. Dissolved-solids concentration generally ranges from 1,000 to 2,000 mg/L. An areally extensive mathematical model is needed for evaluation of the Fox Hills-basal Hell Creek aquifer. The model could provide information on suspected leakage from aquifers in the overlying Fort Union Formation and aid in the design of plans for optimal use of the supply.

The Ravenscrag, Frenchman, Whitemud, and Eastend Formations of southern Saskatchewan in the Williston Basin probably are stratigraphically equivalent to the Fort Union Formation, Fox Hills Sandstone, and Hell Creek Formation. The Ravenscrag Formation consists of 600 ft of sand, silt, clay, and lignite. Sandstone and coal aquifers of the Ravenscrag Formation yield as much as 500 gal/min to wells. Extensive dewatering of a Ravenscrag aquifer for coal mining in southern Saskatchewan may affect water levels in aquifers in northern Montana. Dissolved-solids concentration ranges from 260 to 3,770 mg/L. The Frenchman, Whitemud, and Eastend aquifers together consist of 280 ft of sand, silt, and clay. Dissolved-solids concentration ranges from 560 to 5,350 mg/L. Any areally extensive hydrologic analysis of the Williston Basin should include equivalent aquifers in Saskatchewan.

The Dakota Sandstone is a principal aquifer in the Williston Basin. At the deepest part of the basin near Williston, N. Dak., the top of the Dakota aquifer is more than 5,600 ft below the land surface. In western North Dakota, shale predominates over sandstone in the aquifer; in eastern North Dakota the sandstone predominates over shale. Natural recharge, movement, and natural discharge for the Dakota are not well understood in the Williston Basin. Large artesian pressures in the Dakota led to the drilling of numerous flowing wells, many of which were allowed to flow continuously and wasted ground water from the Dakota aquifer. Water levels declined an estimated 200 feet from 1902 to 1923 in LaMoure and Dickey Counties of North Dakota (North Dakota Geological Survey, 1973). The Dakota aquifer may be hydraulically connected to other aquifers whose supply is also being depleted by uncontrolled discharges from wells completed in the Dakota. Dissolved-solids concentration is as much as 11,000 mg/L in western North Dakota but generally ranges from 2,000 to 3,000 mg/L in areas of greatest use. Principal ions include sodium, chloride, and sulfate.

A detailed potentiometric map and additional aquifer tests are needed for the Dakota aquifer. A mathematical model of the aquifer would help to define areas of natural recharge and provide information necessary to extend the life of the water supply. Delineations of saline zones in the aquifer by water-quality mapping would be useful in avoiding withdrawals of saline water or in developing saline-water resources.

The Denver Basin lies in northeastern Colorado and extends over parts of the Missouri River Basin and the Arkansas River Basin. However, most of the Denver Basin is included in the Missouri Basin Region. Potentiometric maps of the sandstone aquifers in the Denver Basin indicate that the potentiometric surfaces are similar and slope to the north in the direction of surface drainage, indicating ground-water movement toward the north. However, the general pattern of natural recharge to and discharge from the aquifers is unknown. Long-term measurements indicate a decline in the water levels in wells completed in the aquifers of the Denver Basin. The greatest declines are in areas where withdrawals from wells are concentrated. Wells yield a maximum of about 300 gal/min. Withdrawals are for domestic, municipal, and industrial uses. Discharge from naturally flowing wells has been reduced, and in many areas the flow has ceased and wells must be pumped to obtain a water supply. Dissolved-solids concentration ranges from about 170 to 3,700 mg/L.

Ground-water supplies in the Denver Basin lie in the area east of the Front Range in Colorado where population growth is rapid, water demands are large, and much of the surface-water supply is imported. The lack of hydrologic data and interpretive hydrologic studies of the aquifers in the Denver Basin limits the design of water-management plans for developing the ground-water supply. Potentiometric maps and aquifer testing are needed for the sandstone aquifers, as well as information on the recharge to, movement through, and discharge from each aquifer. Data describing the hydraulic properties of confining layers between aquifers are also needed to analyze possible flow from one aquifer to another. A hydrologic model of the aquifer system could simulate the response of the system to expected withdrawals and provide information that could lead to better utilization of the existing ground-water resources.

Development of a water supply from sandstone aquifers in structural basins may induce ground-water movement that helps to sustain the yield of wells, as portrayed in figure 9. Aquifer A is unconfined; aquifers B and C are confined. However, the confined aquifers have unconfined zones wherever the aquifers are exposed, often ring-shaped zones near the periphery of the basin. The confined and unconfined zones have different storage characteristics that affect withdrawals by wells. For example, in the confined zone of a typical sandstone aquifer, a relatively small volume of water may be derived from storage by lowering the water level a few feet. In the unconfined zone of the same aquifer, a relatively large volume of water may be derived from storage by lowering the water level a few feet. Induced ground-water movement from the unconfined region to the confined region may help to sustain well yields as water supplies are developed in the structural basins.

Well 1 in figure 9A is completed in the confined zone of aquifer B but near the unconfined zone of the aquifer. Withdrawal from well 1 will initially yield water by expansion of water in the aquifer and by compression of the aquifer skeleton. In time drawdown will induce ground-water movement from the unconfined zone to the confined zone of aquifer B, as shown in figure 9B. The relatively large volume of water released from the unconfined zone helps to maintain the water levels and yield of well 1 in the confined zone. The decline of the water table in the unconfined zone of aquifer B causes the unconfined zone to migrate toward the well and helps to sustain the yield of well 1. Well 2 is completed in aquifer B at a greater distance from the unconfined zone than well 1. Withdrawals from well 2 and well 1 with time may induce leakage from the confining shale beds, and with greater time

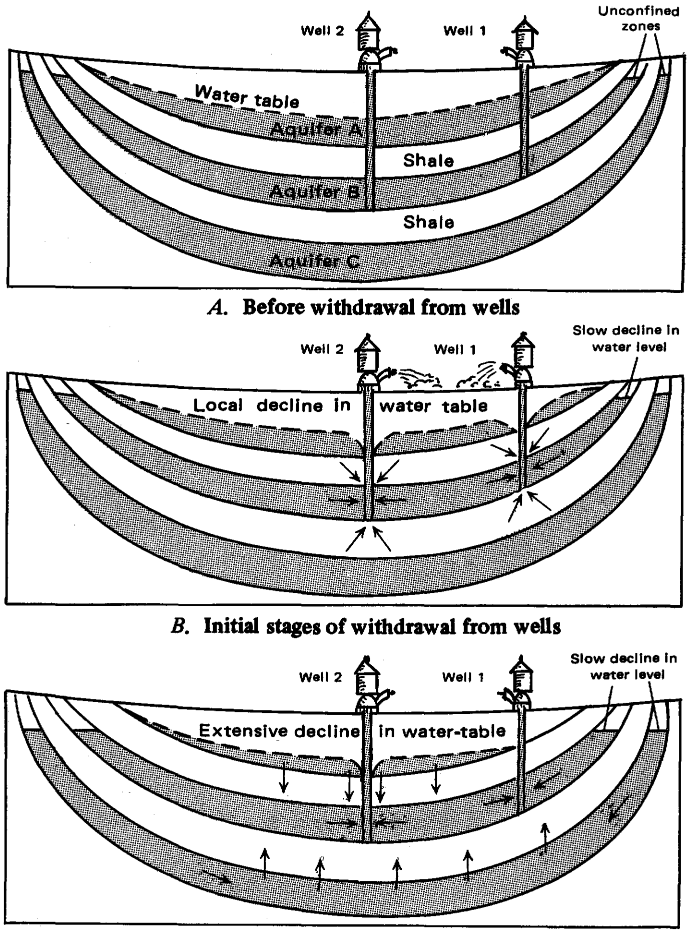


FIGURE 9.—Possible effects of withdrawal from aquifer in structural basin.

water may be induced through shale beds from aquifer A above and aquifer C below, into aquifer B. Leakage from and through shale beds may be substantial over the large areas covered by the structural basins. Eventually the leakage into aquifer B may replenish some of the ground water being lost from storage by pumping and will help to sustain the water level in the unconfined zone of aquifer B as shown in figure 9C. However, a continued withdrawal from wells will exhaust the supply to the wells.

Increased withdrawal of water from sandstone aquifers in the basins is likely because of expected increase in demands for energy development, agriculture, and municipal use throughout the Missouri Basin Region. The hypothetical example portrayed in figure 9 illustrates how the properties and hydrologic response of a basin may help to sustain the yield of wells.

DAKOTA, INYAN KARA, SUNDANCE, MINNELUSA, AND DEADWOOD AQUIFERS

Important sandstone aquifers in the Missouri Basin Region include the Dakota Sandstone, Inyan Kara Group, Sundance Formation, Minnelusa Formation, and Deadwood Formation. The Dakota Sandstone crops out in eastern Nebraska, western Iowa, central Kansas, possibly southwestern Minnesota, and near uplifted areas. Maximum aquifer thickness, where the aquifer crops out, is about 400 ft. At depth, west of the outcrop area, the maximum thickness is about 700 ft. Recharge is from precipitation and streams on the exposed sandstone and by leakage from shallow aquifers to the underlying Dakota. Direction of ground-water movement is not well known, because in most areas insufficient data are available to construct potentiometric maps. However, a potentiometric map prepared from available data indicates that in southwestern Kansas the water in the Dakota aquifer passes from the Arkansas-White-Red Region into the Missouri Basin Region. Discharge is to streams, springs, or into valley-fill aquifers in local areas. Wells completed in the exposed Dakota Sandstone yield as much as 1,500 gal/min. Dissolved-solids concentration is variable and ranges from about 300 to 30,000 mg/L. The concentration is low at shallow depths where the aquifer is exposed but high at depth and toward the west. Large concentrations of chloride and sulfate are reported in some areas. In parts of Kansas the water quality of some streams has been impaired by base flow from the Dakota. Additional potentiometric maps and water-quality maps are needed for the Dakota aquifer. Mapping of saline zones in the Dakota aquifer will delineate areas in which wells should not be drilled. Streamflow sampling under low-flow conditions will help to locate reaches where saline base flow is degrading the quality of streams that cross the Dakota aquifer. Well fields carefully designed to withdraw the saline ground water may reduce the saline base flow and improve water quality in the stream. Saline ground water pumped from the Dakota could be evaporated or flushed downstream during periods of above-normal runoff. Conjunctive use of ground water from the Dakota and other aquifers could lead to increased efficiency in use of water supplies. For example, near Lincoln, Nebr., ground water is pumped from wells in alluvium, treated, and recharged through injection wells into the Dakota aquifer during the winter. The ground water is withdrawn from the Dakota in the summer demand period.

Principal sandstone units that underlie the Dakota Sandstone primarily in central South Dakota and south-central North Dakota include the Inyan Kara Group and Sundance, Minnelusa, and Deadwood Formations. Inyan Kara is not recognized in North Dakota, but the Dakota Sandstone of North Dakota is partly equivalent to the Inyan Kara Group of South Dakota. The Sundance Formation is not recognized in North Dakota (Sandberg, 1962), although an equivalent unit may be present.

The geology and hydrology of the Dakota aquifer in South Dakota have been described by Schoon (1971). The potentiometric surface of the Dakota slopes from the Black Hills Uplift toward southeastern and northeastern South Dakota. Recharge is from precipitation and streamflow on outcrops near the Black Hills and from leakage from other aquifers. Ground water moves toward the east and partly into the Souris-Red-Rainy Region of northern and eastern North Dakota and Upper Mississippi Region of Minnesota. Natural discharge from the Dakota is to overlying glacial deposits or possibly other aquifers. Numerous flowing wells have been drilled in the Dakota since the late 1800's. Wells yield as much as 1,500 gal/min but average about 15 gal/min. An estimated 25 percent of the population of South Dakota obtains water supplies from the Dakota. Uncontrolled flowing wells have lowered the potentiometric surface, especially along the Missouri River Valley where wells are relatively shallow and artesian pressures are high. Dissolved-solids concentration ranges from 1,700 to 8,000 mg/L.

Casings of uncontrolled flowing wells should be sealed if necessary and the flow of the wells regulated with valves to preserve the ground-water supply. For example, consider the possible effect of withdrawals on the water levels of a typical artesian aquifer. Assume that an uncontrolled flowing well discharges only 1 gal/min for a period of 1 yr and that discharge depletes ground water in storage over an area of 1 mi^2. The average decline in water levels in wells over the area may be about 13 ft at the end of 1 yr, and the rate of decline will continue in successive years if the discharge is allowed to continue. The decline represents a decrease in ground water in storage and eventually will cause a reduction in the yield of flowing wells. The flows will eventually cease and continual lowering of water levels will require continually increasing energy to lift water to the land surface. The well owner that permits his well to flow uncontrolled is depleting not only his own water supply but the supplies of others nearby.

The Inyan Kara aquifer and Sundance aquifer lie directly below the Dakota aquifer in South Dakota. Flowing wells are obtained in both aquifers, but few wells have been drilled. Water quality is variable, and dissolved-solids concentrations range from less than 1,000 mg/L to more than 10,000 mg/L. Combined use of water from the Dakota, Inyan Kara, and Sundance aquifers should be investigated because wells completed in all three aquifers may have large yields.

The Minnelusa and Deadwood aquifers are mostly undeveloped. A well completed in the Minnelusa aquifer yielded 4,000 gal/min when drilled. Water in the Deadwood aquifer may be saline, but the aquifer is mostly untested. Additional drilling to the Minnelusa and Deadwood aquifers is needed to determine well yields and to prepare potentiometric maps. Aquifer testing and water-quality sampling should be conducted to appraise the potential water supply.

PRAIRIE DU CHIEN AND JORDAN AQUIFERS

The Jordan Sandstone is the most productive sandstone and dolomite aquifer in the part of Iowa within the Missouri Basin Region. The Jordan aquifer is hydraulically connected to an overlying dolomite, the Prairie du Chien Formation, and the two units form a single aquifer with a combined thickness that ranges from 300 to 600 ft. Recharge, movement, and discharge for the combined aquifers are poorly understood. Municipal wells yield as much as 1,000 gal/min. Dissolved-solids concentration ranges from about 1,500 to 2,000 mg/L. Care should be taken when constructing wells in southwestern Iowa to insure that saline water from the overlying limestone does not leak into the Jordan or Prairie du Chien aquifers. A potentiometric map is needed for the combined aquifers, as well as additional aquifer testing, to improve understanding of recharge, movement, and discharge and help design plans to sustain the water supply.

Water supplies in sandstone aquifers of the Missouri Basin Region are summarized in table 4. The sandstone aquifers are numerous and of diverse types, but water supplies can be improved greatly if the hydrologic characteristics of each aquifer are known and incorporated into management plans.

LIMESTONE AND DOLOMITE AQUIFERS

The few limestone and dolomite aquifers that occur in the Missouri Basin Region are areally extensive, as shown on plate 3, and capable of large yields where cavernous. Ground water in limestone or dolomite aquifers occurs in openings that range in size from

TABLE 4.—*Summary of water supplies in sandstone aquifers, Missouri Basin Region*

Source of supply	Location	Yield to wells (gal/min)	Suggestions for improved hydrologic data, analyses, and water management	Outlook for future use if suggestions are followed
Virgelle aquifer. Milk River aquifer.	Montana, Alberta	5–250	Control of flowing wells and implementation of other conservation practices. Use of other supplies for industry. Artificial-recharge experiments to determine if fractures and vertical hydraulic conductivity of aquifer will facilitate rapid recharge.	Reduction of ground-water mining and pumping lift in wells.
Blood Reserve, Judith River, and Milk River aquifers.	Alberta	5–120(?)	Preparation of potentiometric maps and aquifer testing for each aquifer.	Development of ground-water supply designed to take advantage of possible interaquifer leakage.
Judith Basin	Montana	5–300	Additional potentiometric maps, aquifer testing, and water-quality sampling for sandstone aquifers of Judith Basin and adjacent areas to northwest and southwest.	Conjunctive use of ground and surface water in upper reach of the Missouri Basin Region.
Hogeland Basin	Saskatchewan	10–200	Identification of aquifers that are continuous across the United States-Canadian border. Extensive aquifer testing, preparation of potentiometric maps, and water-quality appraisal.	Development of water supplies in vast area in which water resources are barely used.
Crazy Mountains and Bull Mountains Basins.	Montana	?	Complete hydrologic investigation.	Development of unused ground-water supplies.
Bighorn Basin	Wyoming, Montana.	5–2,000	Aquifer testing and preparation of potentiometric maps for each aquifer. Water-quality data and interpretation.	Conjunctive use with surface water in adjacent reaches of Clarks Fork, Shoshone River, and Bighorn River.
Wind River Basin.	Wyoming	5–1,100	Preparation of potentiometric maps. Aquifer testing to prepare maps of transmissivity and storage. Preparation of water-quality maps.	Conjunctive use of ground water and surface water from Wind River and Sweetwater River. Improved quality of water supplies and use of saline water.
Laramie, Shirley, and Hanna Basins and Saratoga Valley.	Wyoming	5–1,000	Conjunctive use of ground water, streamflow, and surface-water reservoirs. Artificial recharge to, and mining from, the large ground-water supplies.	Improved water management North Platte River valley. Reduction of evaporative losses.
Powder River Basin.	Montana, Wyoming.	5–1,200	Preparation of potentiometric maps and aquifer testing of all aquifers. Determination of vertical hydraulic conductivity of intervening layers between aquifers. Construction of mathematical model of entire basin.	Development of water-management plan for optimal development of ground-water resources.
Williston Basin.	Montana, North Dakota, South Dakota.	5–700	Statistical compilation of well logs, aquifer properties, well characteristics, and water quality for aquifers in Fort Union Formation. Preparation of areally extensive model for Fox Hills-basal Hell Creek aquifer. Control of flowing wells that discharge from Fox Hills-basal Hell Creek and Dakota aquifers. Potentiometric maps, aquifer testing, mathematical modeling, and water-quality mapping for Dakota aquifer.	Increased success in drilling dependable wells in Fort Union. Improved water supply in Fox Hills-basal Hell Creek aquifer. Extended life and improved quality of water supplies for Dakota aquifer. Development of saline-water resources in Dakota aquifer.
Denver Basin	Colorado	10–300	Preparation of potentiometric maps and aquifer testing of all aquifers. Determination of vertical hydraulic conductivity of intervening layers between aquifers. Construction of mathematical model of entire basin.	Better utilization of existing ground-water resources in area of large demands and frequent shortages.
Dakota aquifer.	Nebraska, Iowa, Kansas, Minnesota(?).	5–1,500	Preparation of potentiometric maps and water-quality maps. Streamflow sampling under low-flow conditions to locate saline base flow. Conjunctive use with water supplies in other aquifers.	Improved quality of ground- and surface-water supplies. Increased water supplies.
Dakota, Inyan Kara, Sundance, Minnelusa, and Deadwood aquifers.	North Dakota, South Dakota.	5–4,000	Preparation of up-to-date potentiometric map and additional aquifer testing of Dakota aquifer. Preparation of mathematical model of Dakota aquifer. Preparation of water-quality maps. Control of flowing wells that discharge from Dakota aquifer. Combined use of water from Dakota, Inyan Kara, and Sundance aquifers. Additional drilling, aquifer testing, and water-quality sampling of Minnelusa and Deadwood aquifers.	Improved understanding of natural recharge to Dakota aquifer. Improved quality of water supplies and development of saline water. Extended life of Dakota aquifer. Development of large yields from combined use of water from several aquifers. Development of additional ground-water supplies.
Prairie du Chien and Jordan aquifers.	Iowa	100–1,000	Preparation of potentiometric map and additional aquifer testing. Identification of recharge and discharge areas.	Sustained municipal supply.

small pores, joints, and other fractures to large caverns formed by the solution and removal of rock by ground water. Fractures also may increase the storage and transmissive properties of limestone and dolomite aquifers.

MADISON AQUIFER

The Madison Group (also Madison Limestone) is an extensive limestone aquifer that occurs in parts of Alberta, Saskatchewan, Montana, Wyoming, North Dakota, South Dakota, Nebraska, and Colorado. The

Madison is partly equivalent to the Pahasapa Limestone. A regional description of the Madison aquifer was prepared by Swenson and others (1978). Thickness of the Madison Group increases toward the center of the Williston Basin in northwestern North Dakota, where it is about 2,300 ft thick. The Madison is exposed near major structural uplifts in the Missouri Basin Region, but at the deepest location, about 40 mi northeast of Casper, Wyo., it is about 16,000 ft below land surface. The areal extent of the Madison aquifer, as shown on plate 3, is only approximate because the geologic structure in Montana and Wyoming is complex and few drillers' logs are available.

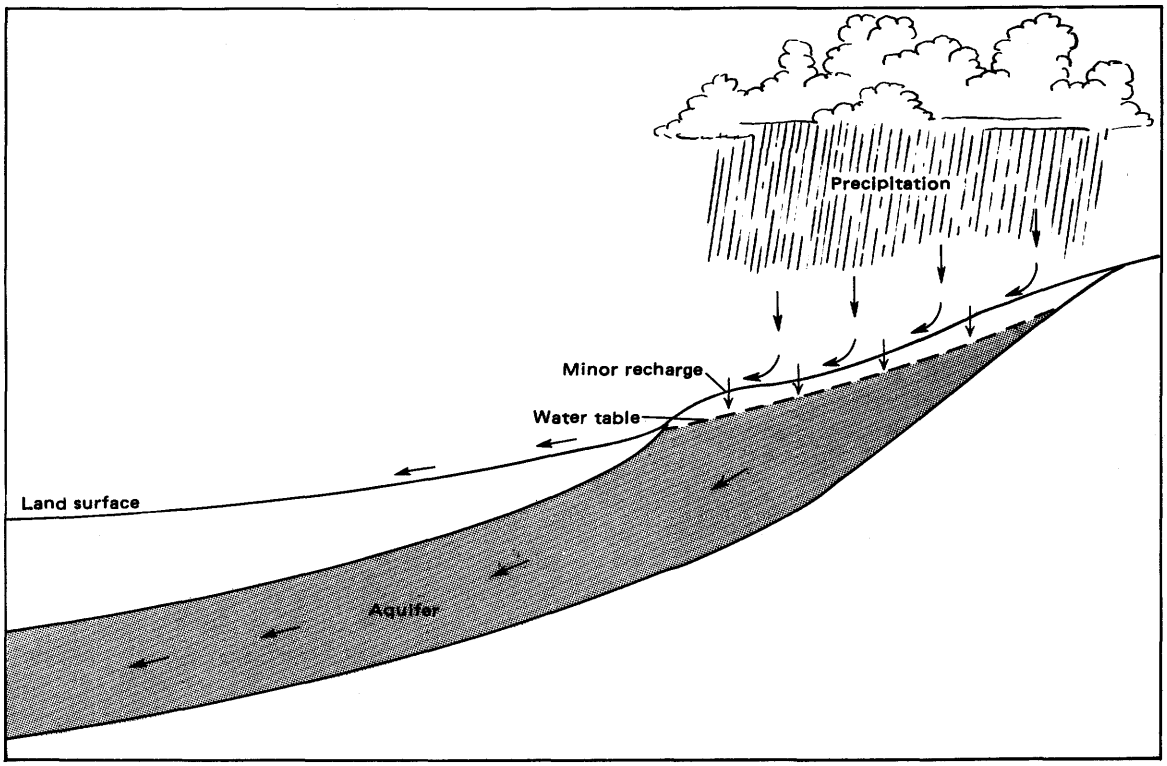
Streamflow and precipitation recharge the Madison aquifer where it is exposed; leakage from adjacent aquifers also may recharge the aquifer. Ground-water movement is generally to the north and northeast in northern Wyoming and Montana. Movement is generally toward the east in North Dakota and South Dakota. Discharge is to streams, springs, other aquifers, or wells. Numerous springs discharge from the Madison in Montana, and Giant Spring near Great Falls, Mont., flows about 300 ft^3/s. Wells yield from several hundred to several thousand gallons per minute. Industrial wells that withdraw water for use in oil fields have caused declines of water levels of as much as several hundred feet at places in Wyoming. Water temperature in the Madison aquifer increases with depth below land surface and ranges from about 50°F to 250°F. Large concentrations of dissolved solids are often associated with high water temperatures because of increased mineral solubilities. Dissolved-solids concentration in the Madison aquifer ranges from about 300 mg/L near Lewistown, Mont., to 350,000 mg/L in the Williston Basin.

A preliminary model of the Madison aquifer in the Powder River Basin and adjacent areas was prepared by Konikow (1976). The model simulated the effect of proposed withdrawals of water from wells at the rate of 20 ft^3/s for 100 yr, for use in coal transportation. An estimated 200 ft^3/s flows through the Madison, mostly from recharge along outcrops in the Bighorn Mountains and the Black Hills; the presence of springs in the Black Hills suggests that part of the recharge is rejected because the water table is shallow. Sources of withdrawn water in the model included salvaged rejected recharge, ground water in storage, and water otherwise lost by natural discharge. The model was used to predict declines in water levels in the Madison after 100 years of hypothetical pumping. Maximum predicted declines are 300 ft at a distance of approximately 5 mi from the pumped wells, presuming leakage from other aquifers into the Madison, and 600 ft, presuming no leakage from other aquifers.

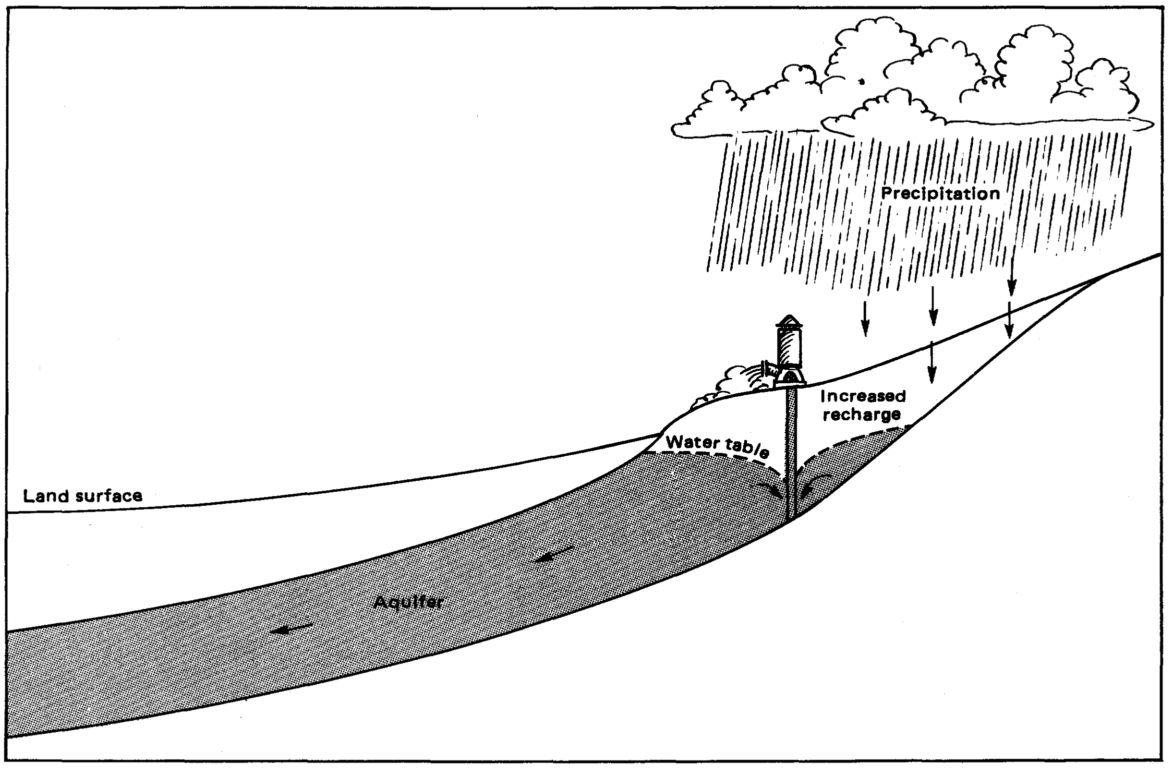
More hydrologic data are needed if the Madison aquifer is to be developed properly. Additional observation wells are required for a more accurate potentiometric map. Aquifer testing is needed to prepare maps showing the areal distribution of transmissivity and storage. Inventory and discharge measurements of springs are necessary to provide information on natural discharge. Identification of aquifers that are hydraulically connected to the Madison and measurement of water levels in observation wells in the aquifers would provide information regarding leakage to and from the Madison aquifer. A regional aquifer system analysis for the Madison aquifer was begun by the U.S. Geological Survey in 1975. The analysis should supply much of the needed data. Development of water in the Madison aquifer will be more efficient if development plans are based on the known behavior of the aquifer, as determined from field measurements and hydrologic models. The high water temperatures at depth in the Madison aquifer may indicate a potential source of thermal energy. Figure 10 shows how recharge to the aquifer may be increased. Natural recharge is normally low where the water table is high, reducing space available for recharge and permitting evapotranspiration from the water table (fig. 10A).The use of wells to lower the water table increases space for recharge and captures water formerly occurring as surface runoff or evapotranspiration (fig. 10B). Normally only part of the rejected recharge can be converted to recharge.

AQUIFERS IN ROCKS OF PERMIAN AND PENNSYLVANIAN AGE

Limestone and sandstone aquifers occur in rocks of Permian and Pennsylvanian age in Nebraska and Kansas. Similar aquifers occur in rocks of Pennsylvanian age in Iowa and Missouri. Total thickness of the limestone and sandstone ranges widely; maximum thickness is several thousand feet. Ground water occurs in pores, caverns, and fractures of the limestone and in interbedded sandstone. Aquifers are recharged by precipitation and are discharged to streams, springs, and wells. Direction of ground-water movement is poorly understood because few potentiometric maps have been prepared. Reported well yields range from 3 to 500 gal/min. Water quality is variable. In Iowa and Missouri the dissolved-solids concentration generally increases with depth below land surface. In Kansas the dissolved-solids concentration in the sandstone aquifers increases toward the west. Saline water discharges from mineralized shale, included with aquifers of Permian age, to streams in central Kansas and impairs the quality of surface water. In a



A. **Minor recharge due to high water table**



B. **Increase in recharge induced by lowering water table**

FIGURE 10—Induced increase in recharge.

few places in Kansas, high concentrations of sulfate, chloride, and nitrate have been detected in water from the aquifers in Permian and Pennsylvanian rocks.

Zones in the limestone aquifers that transmit and store water readily are difficult to locate because of their random occurrence. Therefore, a statistical compilation of data describing well logs, aquifer performance, and water quality is needed to search for trends and improve our understanding of the location of the most productive zones in the limestone. A water-quality investigation would help to determine the cause of saline zones in the aquifers. Water-management plans based on improved understanding could be designed to either (1) eliminate the saline ground water by withdrawing it through wells and using it or disposing of it or (2) avoid the withdrawal of saline water through carefully designed well fields.

BIGHORN, RED RIVER, AND WHITEWOOD AQUIFER

An areally extensive dolomite aquifer lies beneath the Madison aquifer in eastern Montana, northern Wyoming, and the Williston Basin. The aquifer lies at great depths except near uplifts; therefore, it is not shown on plate 3. The dolomite aquifer is known as the Bighorn Dolomite in northern Wyoming and southern Montana, the Red River Formation in the Williston Basin, and the Whitewood Dolomite near the Black Hills. However, the Bighorn, Red River, and Whitewood are only approximately equivalent. Maximum thickness of the aquifer is about 550 ft. Water temperatures as much as 250°F have been measured, and high artesian pressures are reported in the aquifer in South Dakota. Locally, the aquifer may yield several hundred gallons per minute to wells. The aquifer might furnish water to the overlying Madison aquifer through leakage if large amounts of water were withdrawn from the Madison. An observation-well network would provide data on suspected leakage. A potentiometric map is needed to define the recharge, movement, and discharge for the aquifer.

ROUBIDOUX, GASCONADE, EMINENCE, AND POTOSI AQUIFERS

The Roubidoux Formation, Gasconade Dolomite, Eminence Dolomite, and Potosi Dolomite in south-central Missouri and southeastern Kansas are utilized for water supplies where shown in plate 3. The formations are primarily dolomite and represent the principal aquifers of the Ozarks area (Missouri Geological Survey and Water Resources, 1963). The formations constitute a series of adjacent dolomite aquifers that are recharged by precipitation and streamflow. Normal monthly precipitation in Missouri ranges from 1.6 in. during February to 4.4 in. during June (Environmental Science Services Administration, 1968), assuring adequate recharge to the dolomite aquifers on a long-term basis. Ground-water movement is toward streams where the aquifers discharge naturally. Ground water is transmitted as rapidly as 1 mi/d through an extensive system of caverns. Relatively large and rapid ground-water movement is also indicated by the uniform cool temperatures of 56° to 65°F of ground water over a wide range in depth below land surface and the low dissolved-solids concentration (Feder, 1973). Most of the many large springs in Missouri issue from the Gasconade, Eminence, and Potosi aquifers (Vineyard and Feder, 1974). Bennett Spring in Missouri within the Missouri Basin Region discharges about 150 ft^3/s from the dolomite aquifers. Maximum yield of wells completed in the Roubidoux, Gasconade, Eminence, and Potosi aquifers is about 2,000 gal/min. The dissolved-solids concentration in the aquifers is normally less than 350 mg/L. Potentiometric maps and aquifer testing are needed to provide improved definition of the vertical and horizontal flow system for the aquifers. Tracer studies would be valuable in defining ground-water movement, transit time, and water mixing. An improved understanding of the flow system also would help to avoid pollution of the ground-water supply.

Limestone and dolomite aquifers are very productive as indicated by large spring flows and well yields. Transmission of ground water in the caverns is more like streamflow than like flow in a fine-grained aquifer. The presence of cavern systems gives the water developer the option of obtaining a large supply in some areas from sources other than the streamflow network. The advantages of the ground-water supply over a surface-water supply are greater protection from pollution and greater dependability because ground water in storage fluctuates less than streamflow. However, withdrawals from wells may deplete spring discharge and streamflow derived from springs. Water supplies in limestone and dolomite aquifers are summarized in table 5.

SALINE GROUND WATER

Many possible uses of saline ground water are summarized by Kohout (1970). Desalinization may be used to obtain usable water of any quality, selected according to costs and needs. Minerals recovered as byproducts of the desalinization process may have economic value. Saline ground water may be used sometimes without treatment for cooling purposes in industry or for waterflooding in oil fields to increase

TABLE 5.—*Summary of water supplies in limestone and dolomite aquifers, Missouri Basin Region*

Source of supply	Location	Yield to wells (gal/min)	Suggestions for improved hydrologic data, analyses, and water management	Outlook for future use if suggestions are followed
Madison aquifer.	Alberta, Saskatchewan, Montana, Wyoming, North Dakota, South Dakota, Nebraska, Colorado.	20–9,000	Preparation of improved potentiometric map and additional aquifer testing to define areal distribution of transmissivity and storage. Inventory of springs and measurement of spring discharges. Identification of aquifers hydraulically connected to Madison aquifer and measurement of observation wells completed in the aquifers. Preparation of maps showing areal distribution of dissolved-solids concentration. Continued use of simulation models to determine optimal development plans.	Development of large supply derived from increased recharge, reduced discharge, storage, and leakage to the Madison from other aquifers. Development of saline water resources.
Limestone and sandstone aquifers in rocks of Permian and Pennsylvanian age.	Iowa, Nebraska, Kansas, Missouri.	3–500	Statistical compilation of well logs, aquifer performance, and water-quality data. Investigations to determine the cause of deterioration of water quality at depth and laterally. Design of water-management plans to eliminate or avoid saline ground water.	Improved success in drilling wells and maintaining well performance. Improvement of water quality.
Bighorn, Red River, and Whitewood aquifer.	Montana, Wyoming, North Dakota, South Dakota.	20–300	Establishment of observation-well network. Preparation of potentiometric map.	Development of local supplies where aquifer is shallow. Development of large supplies maintained by induced leakage from adjacent aquifers.
Roubidoux, Gasconade, Eminence, and Potosi aquifers.	Missouri, Kansas.	20–2,000	Preparation of potentiometric maps and aquifer testing. Tracer studies to define cavern systems in all aquifers.	Sustained municipal, industrial, and domestic supply. Reduced hazard of pollution of supply.

oil production. Hot saline water in deep aquifers may also be utilized as a geothermal resource from which energy may be extracted. Saline ground-water reservoirs may be used for storage of several types of materials. Toxic wastes may be stored in reservoirs if no other use of the ground water is planned. Natural gas may be stored in saline ground-water reservoirs for later withdrawal. Finally, freshwater may be stored in saline ground-water reservoirs for later use, probably with very little deterioration in quality (Moulder, 1970).

Saline ground water in this report is defined arbitrarily as ground water in which the maximum dissolved-solids concentration exceeds 4,000 mg/L. Saline ground-water resources of the Missouri Basin Region are listed in table 6. Data in table 6 are based on a relatively small amount of reported information.

TABLE 6.—*Saline ground-water resources of the Missouri Basin Region*

State or Province	Aquifer (listed in order of increasing depth below land surface in each area)	Maximim dissolved - solids concentration (mg/L)
Saskatchewan	Glacial deposits	5,600
	Frenchman, Whitemud, Eastend	5,400
Montana	Glacial deposits	30,000
	Virgelle	5,100
Wyoming	Wind River	6,500
	Mesaverde	16,300
	Frontier	20,000
	Cloverly	24,000
	Sundance	4,700
	Nugget	4,900
	Casper	9,600
	Tensleep	280,000
North Dakota	Glacial deposits	5,000
	Fort Union	7,000
	Dakota	11,000
	Madison	350,000
South Dakota	Glacial deposits	10,000
	Dakota	8,000
	Inyan Kara	10,000
	Sundance	7,600
	Minnelusa	4,300
	Madison	120,000
	Red River	130,000
	Deadwood	40,000
Nebraska	Dakota	30,000
Iowa	do	5,000
Kansas	do	30,000
Missouri	Limestone of Pennsylvanian age	20,000

Additional drilling and water-quality sampling in the region may indicate other saline ground-water resources. The most saline ground water in the Missouri Basin Region occurs in Wyoming, North Dakota, and South Dakota in aquifers that lie deep below the land surface. However, data in table 6 indicate that dissolved-solids concentration does not necessarily increase with the depth of aquifer below land surface and ground-water temperature. Salinity of ground water is controlled by a combination of mineral solubility, ground-water temperature, and rate of ground-water movement. Water-management plans developed for the Missouri Basin Region should include saline ground water as a valuable resource. Possible uses of the resource may expand in the future and are not limited to the desalinization, cooling, waterflooding, geothermal, and storage uses summarized in this report.

BASIS FOR WATER MANAGEMENT IN MISSOURI BASIN REGION

Although several water-management plans have been implemented in the Missouri Basin Region, numerous alternative plans for improvement in water supply may be designed. Management plans can be derived from information on all available sources of water supply, expected demands for current and future types of water use, constraints on desired use, and the effects of implemented use.

DEVELOPMENT OF GROUND-WATER SUPPLIES

Development of a water supply is accomplished by *intercepting* water from the hydrologic cycle, the natural circulation of water among the oceans, atmosphere, and continents. Examples of interception include diversion of streamflow using a canal or pumping ground water using wells. Development of a ground-water supply or incorporation of ground water into basinwide management of water procedures. A typical sequence of events is described below, although administrative, hydrologic, or legal constraints may dictate different sequences.

COLLECTION AND INTERPRETATION OF HYDROLOGIC DATA

Knowledge of location and type of lateral and vertical aquifer boundaries is needed to define the geometry of the flow systems. Types of boundaries include a stream or lake that is hydraulically connected to an aquifer, confining rock that completely or partially confines flow in an aquifer, or an areal change in aquifer properties. Boundaries are identified by data collection and interpretation. For example, boundaries of aquifers can be determined from geologic mapping, well logs, or the observed response of the aquifer to pumping or to other hydraulic stresses. If a stream forms a boundary of an aquifer (fig. 11*A*), the water interchange influences the stream and aquifer. Measurements of streamflow and the slope of the water table may indicate a gaining or losing stream. Valley-fill aquifers in the region commonly have stream boundaries. If tight confining rock forms a boundary of an aquifer (fig. 11*B*), as it does in most places in the region, little or no flow may cross the boundary. In some cases, however, confining layers of clay or shale between aquifers leak (fig. 11*C*) and allow water interchange between the aquifers. Leaky confining rock boundaries may occur in deep structural basins of the region. The contact between unconfined and confined zones of an aquifer (fig. 11*D*) also represents a type of boundary. The unconfined zone of an aquifer is subject to the draining of and filling with ground water; the confined zone is subject to pressure changes. A relatively large amount of ground water per unit volume of aquifer may be released from or taken into storage in the unconfined zone, compared to the amount that may be released from or taken into storage by pressure changes in the confined zone. Unconfined zone boundaries are common near uplifts such as the Black Hills.

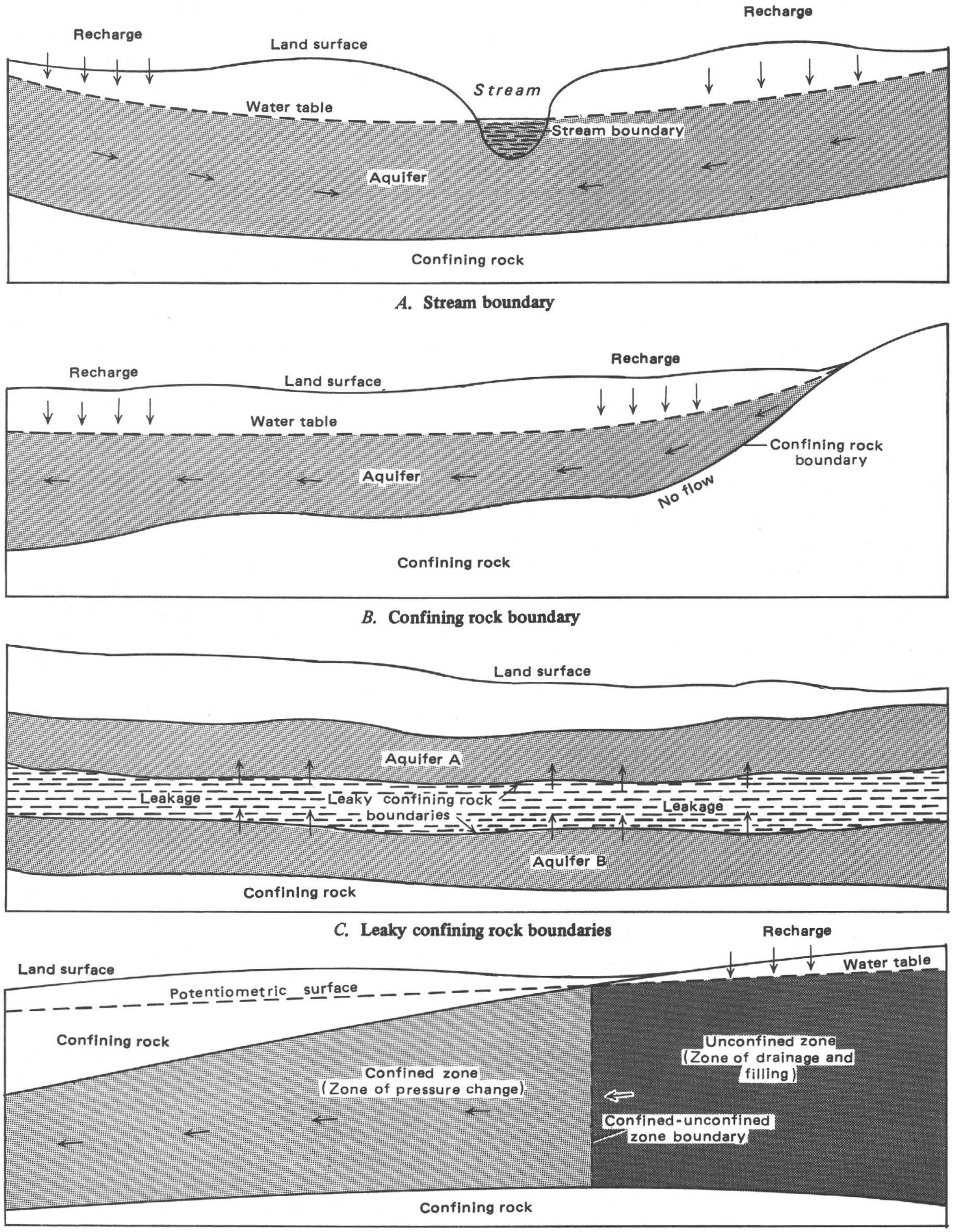
Inventory of existing wells and test holes followed by aquifer testing is needed to provide information on the geologic and hydraulic properties of the flow systems and on changes in ground-water storage with time. For example, logs of wells and test holes may be useful to determine the depth to the contacts between aquifers and confining beds. Water levels in observation wells may be used to prepare water-table or potentiometric maps that indicate direction of ground-water movement. Water-level changes measured in observation wells are useful to calculate changes in ground-water storage. Aquifer tests determine the hydraulic properties of the aquifers, such as the transmissivity and specific yield or storage coefficient. Data describing the hydraulic properties are necessary for calculations designed to predict the behavior of the aquifers in response to water use. Chemical analysis of water samples from the aquifer helps to define relations between the flow system and water quality.

An example of the interpretation of hydrologic data is shown schematically in figure 12. A sand and gravel aquifer lies beneath a stream and lake (fig. 12*A*). Additional wells are drilled into the aquifer to provide data for preparing the potentiometric map, shown in figure 12*B*. The potentiometric surface slopes toward the north, as shown by the altitudes on the contours. Arrows indicate the direction of ground-water movement toward the north, perpendicular to the contours. Flow from the lake to the stream boundary is indicated in the upper reach of the stream. Flow along the granite outcrop indicates the granite is a confined rock boundary. Aquifer testing provides data to subdivide the aquifer into three zones of transmissivity, as shown in figure 12*C*. Flow through the aquifer may be calculated using data from the potentiometric surface and the transmissivity value for each zone. The calculated flow from the aquifer to the stream may be checked by measurements of gain in the stream. The two zones of specific yield for the aquifer (fig. 12*D*) are also based on data from aquifer testing. The value of specific yield for each zone may be used to calculate changes in ground-water storage due to changes in the position of the potentiometric surface, as measured in wells.

After basic information is obtained, a water budget for the aquifers can be prepared from general data. Water budgets serve to indicate average recharge, changes in storage, and discharge, and they help to emphasize relative magnitudes of water sources, water uses, and water losses. Budgets may also provide information on the general long-term behavior of the aquifers and contribute to an understanding that may lead to better use of the aquifers.

DETERMINATION OF AQUIFER RESPONSE TO USE

Response of the aquifers to use may be determined using data describing the geologic and hydraulic properties of the aquifers. A simple problem may be solved with a few calculations by a skillful hydrologist. A



A. **Stream boundary**

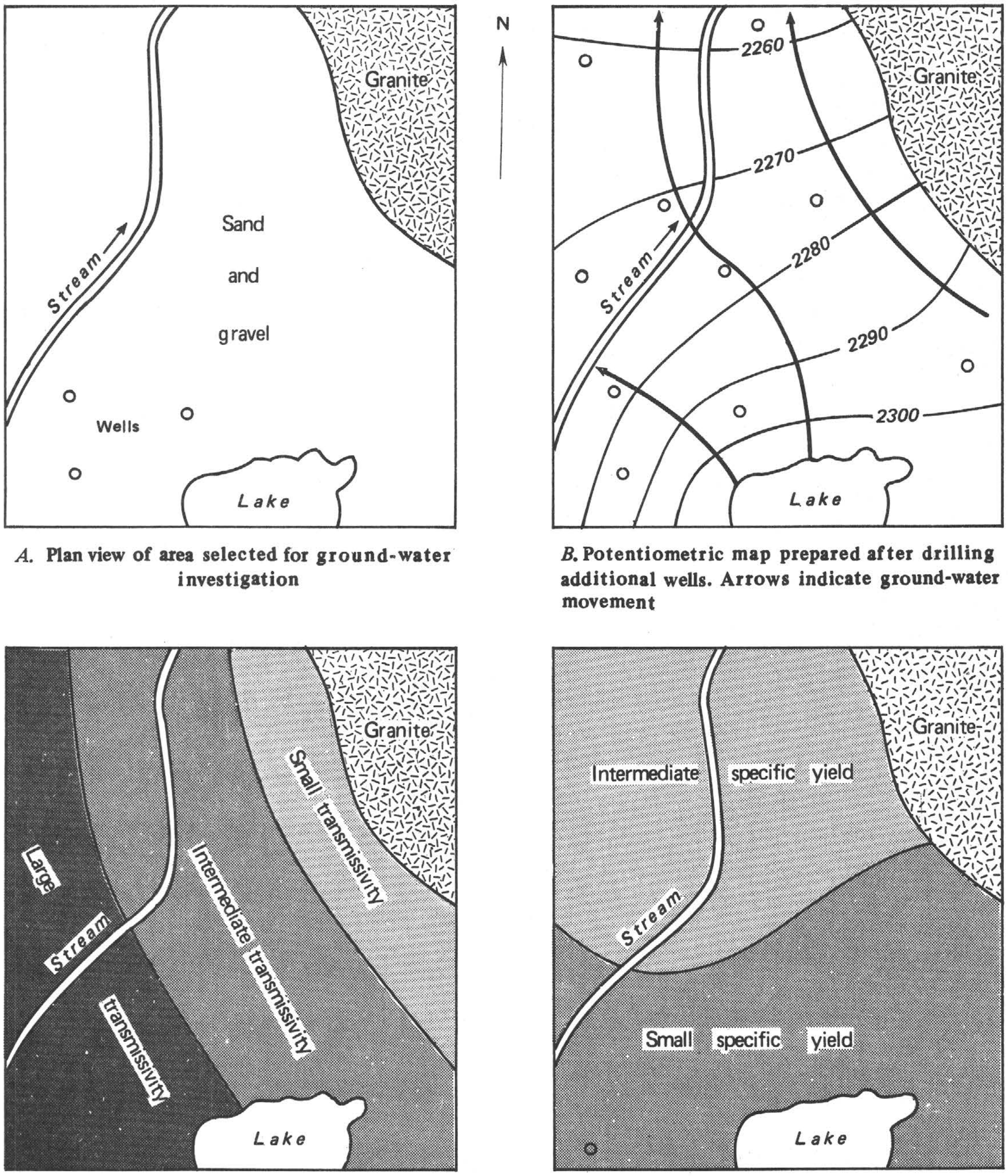
B. **Confining rock boundary**

C. **Leaky confining rock boundaries**

D. **Confined-unconfined zone boundary**

FIGURE 11.—Types of aquifer boundaries.

complex problem may require a simulation model in order to incorporate and integrate all data, including aquifer properties, necessary for an accurate solution. Various types of analog or mathematical simulation



A. **Plan view of area selected for ground-water investigation**

B. **Potentiometric map prepared after drilling additional wells. Arrows indicate ground-water movement**

C. **Distribution of aquifer transmissivity obtained from aquifer testing**

D. **Distribution of specific yield obtained from aquifer testing**

FIGURE 12.—Interpretation of collected hydrologic data.

models are used routinely to help understand and predict behavior of aquifers under hypothetical conditions.

WATER-MANAGEMENT PLANS

Hydrologic data and interpretation provide hydrogeologic understanding and predictive capability to aid the design of water-management plans that may lead to improved water use. A simple development plan may involve artificial recharge, withdrawals from wells, or ground-water mining. A comprehensive plan might include the use of ground water based on information on snowpack, surface runoff and storage, stream-aquifer interrelations, water quality, and expected fluctuations in water supply and demand. Design of water-management plans offers the challenge of integrating information on the known behavior of hydrologic systems with goals designed to improve water use. Variety of possible plans is limited only by the imagination and ingenuity of the analyst.

Most water-management plans are designed with the goals of alleviating shortages in water supply and reducing the harmful effects of saline water. The ground-water reservoir can contribute toward these goals in many ways, as discussed in this report. Most plans involve a redistribution of water supplies in time and location in order to improve availability. Water-management plans that utilize the ground-water reservoir are listed below to indicate the variety possible.

1. Withdrawal from wells in selected locations to control sources of water depleted with time.
2. Recharge to aquifers in selected locations to control movement and storage of water with time.
3. Reuse of available water supply through schemes that successively capture the part of the water supply that is not consumed with each use.
4. Use of valley-fill aquifers in tributary valleys as off-channel reservoirs by recharging surplus streamflow in the tributaries to the aquifers.
5. Salvage of water normally evapotranspired by plants, using discharging wells to lower the water table.
6. Reduction of saline discharge water from aquifers by planting crops that reduce recharge to the aquifers or by wells and surface drains that control movement of the saline water.
7. Plugging of flowing wells in confined aquifers to conserve ground water and to reduce the lowering of water levels.
8. Use of an aquifer that underlies two adjacent surface-drainage areas as a reservoir common to both areas by means of storage, withdrawal, and transfer techniques.
9. Mining of ground water to obtain a temporary water supply, even though the ground water may not be replenished for a long time.
10. Withdrawal from wells in an aquifer in a multi-aquifer system so that the aquifer boundaries and interaquifer leakage help to sustain the withdrawal rate.
11. Use of wells to lower a high water table in a recharge area of an aquifer, in order to increase the rate of recharge.

Normally a plan would not be implemented until tested in the field. Testing does not indicate lack of confidence in hydrologic data or analyses, only a desire to insure that the selected plan is sound, as evidenced by verification. Field testing of a selected water-management plan may proceed by trial in the area of analysis for a limited time period. For example, withdrawals from industrial wells in the Fox Hills Sandstone in eastern Montana were planned for 1964–84 and began on schedule in 1964. A hydrologic analysis was made, and the magnitude of declines in water levels was predicted (Taylor, 1965). However, periodic measurements in observation wells were made in order to compare predicted and observed declines before State agencies permitted the continuation of scheduled withdrawals. Alternatively a plan may be tried over part of the area for a limited time period. Field-measurement procedures must be designed and data collected carefully to insure that collected data are sensitive to the expected results of the plan. Data of the required accuracy must be obtainable with currently available field instruments and methods of procedure. Field verification of the expected response of the hydrologic system may prove the value of the selected plan. However, the decision to implement a water-management plan also requires economic justification, expressed as a proven net benefit from the plan (Howe, 1971). Net benefit is the sum of all benefits from the plan, less the sum of all costs of the plan and damages caused by the plan.

Optimal use of water supplies to meet water demands is defined as the best plan of use under stated goals and constraints. Frequently goals are conflicting, and the water manager may be tempted to make a decision that solves only part of the problem at the expense of the rest of the problem or that benefits part of a region at the expense of the rest of the region. Nevertheless, a plan can be designed that will be beneficial to water users as a group.

Establishment of goals is the first step in implementing optimal use of water resources. Typical hydrologic objectives toward the goal of adequate water supply might include:

1. Development of a new water supply.
2. Reduction of shortages in an existing water supply.
3. Reduction of surpluses in an existing water supply.
4. Improvement or maintenance of water quality.

Use of ground water might help meet any of the above objectives. A new water supply could be derived from ground water or conjunctive use of ground water and surface water (fig. 4). shortages may be reduced through ground-water salvage (figs. 7 and 10), reuse schemes that utilize ground water (fig. 5*A*), or ground-water storage for later withdrawal (fig. 6). Depletion of ground-water reservoirs may also help to relieve shortages (fig. 9). Reduction of water surpluses might be accomplished by artificial recharge to utilize the storage capacity of the ground-water reservoir (fig. 6) or by a comprehensive plan that utilizes stored ground water, stored surface water, and streamflow. The flow of saline water from the ground-water reservoir to streams may be eliminated by hydrologically planned withdrawals from wells and carefully designed use or disposal of the saline water withdrawn.

Water-management plans are the key to meeting goals set to improve a water supply. Effective plans of operation require inventories of currently available water supplies derived from precipitation, streamflow, stored surface water, and stored ground water. Hydrologic models can be prepared that will simulate the use of all available water supplies in the basin and the best overall use of the supplies at various times and in various parts of the basin (Taylor and Luckey, 1974). Alternatives in water management can be appraised through use of models, and contingency plans can be devised to cope with variations in water supply and water demand. Basinwide management of water resources must consider uncertain supplies and uncertain demands. Nevertheless, through statistical descriptions of the uncertainties and continual upgrading of information, sound decisions can be made, even though the decisions may be selected on probability rather than certainty of outcome.

The final step for incorporation of ground water into basinwide management of water resources is full implementation of a selected plan. However, the plan must conform to State or interstate regulations for water administration. Other possible constraints include availability of required capital and cooperation among participants. After implementation of a selected plan, a field monitoring program should be maintained to determine if the plan is producing the expected response in the hydrologic system and contributing benefits to the water users and managers.

SOURCES OF ADDITIONAL WATER INFORMATION

Additional specific information on water supplies, other than discussed in this report, is available for the Missouri Basin Region. Hydrologic data include historical, current, and forecasted data. Interpretive reports, which are available for some areas, provide detailed descriptions of water supplies. General sources of water-resource information include:

Forest Service of U.S. Department of Agriculture
National Oceanic and Atmospheric Administration
Soil Conservation Service of U.S. Department of Agriculture
State universities and colleges
State water-resource agencies
U.S. Army Corps of Engineers
U.S. Bureau of Reclamation
U.S. Department of Housing and Urban Development
U.S. Environmental Protection Agency
U.S. Geological Survey, Water Resources Division
Water-resource consultants

Specific sources of water-resource information by State and Province include:

Alberta

Alberta Research Council
Groundwater Division
3rd Floor, Campus Tower
8625 112th Street
Edmonton, Alberta
T6G 1K8

Alberta Research Council
Transportation and Surface Water
Engineering Division
301 Civil Electrical Engineering Building
University of Alberta
Edmonton, Alberta
T6G 2J2

Alberta Research Council
Department of the Environment
Oxbridge Place
9820 106th Street
Edmonton, Alberta
T6K 2J6

Alberta Research Council
Federal Government
Department of the Environment
Inland Waters Branch
4616 Valiant Drive N.W.
Calgary, Alberta
T3A 0X9

Federal Government
Department of the Environment
Northern Forest Research Center
5320 122d Street
Edmonton, Alberta
T6H 3S5

Saskatchewan

Chemistry Division
Saskatchewan Research Council
30 Campus Drive
Saskatoon, Saskatchewan
S7N 0X1

Family Farm Improvement Branch
Saskatchewan Department of Agriculture
1318 Winnipeg Street
Regina, Saskatchewan
S4R 1J6

Geology Division
Saskatchewan Research Council
30 Campus Drive
Saskatoon, Saskatchewan
S7N 0X1

Hydrology Branch
Saskatchewan Department of the Environment
1855 Victoria Avenue

Regina, Saskatchewan
S4P 3T1

Saskatchewan District Office
Water Survey of Canada
210-1102 8th Avenue
Regina, Saskatchewan
S4R 1C9

Water Pollution Control Branch
Saskatchewan Department of the Environment
1855 Victoria Avenue
Regina, Saskatchewan
S4P 3T1

Water Quality Branch
Inland Waters Directorate
Environment Canada
1901 Victoria Avenue
Regina, Saskatchewan
S4P 0R3

Water Rights Branch
Saskatchewan Department of the Environment
1855 Victoria Avenue
Regina, Saskatchewan
S4P 3T1

Montana

Montana Bureau of Mines and Geology
Room 203-B Main Hall
Montana College of Mineral Science and Technology
Butte, Montana 59701

Montana State Department of Health and Environmental Sciences
1400 11th Avenue
Helena, Montana 59601

Montana State Department of Natural Resources and Conservation
32 South Ewing
Helena, Montana 59601

U.S. Geological Survey
Water Resources Division
Montana District Office
P.O. Box 1696
421 Federal Building
Helena, Montana 59601

Wyoming

U.S. Geological Survey
Water Resources Division
Wyoming District Office
2120 Capitol Avenue
P.O. Box 1125
Cheyenne, Wyoming 82001

Wyoming State Engineer
Barrett Building
Central Avenue
Cheyenne, Wyoming 82002

North Dakota

North Dakota State Health Department
Capital Building
Bismarck, North Dakota 58501

North Dakota State Water Commission
900 E. Blvd. Avenue
Bismarck, North Dakota 58501

U.S. Geological Survey
Water Resources Division
North Dakota District Office
Room 332 New Federal Building
Third Street and Rosser Avenue
Bismarck, North Dakota 58501

South Dakota

City of Sioux Falls
Sioux Falls, South Dakota 57101

Division of Water Rights
Department of Natural Resource Development
Joe Foss Building
Pierre, South Dakota 57501

East Dakota Conservancy Sub-District
P.O. Box 68
Brookings, South Dakota 57006

South Dakota Department of Environmental Protection
Joe Foss Building
Pierre, South Dakota 57501

State Geologist
Division of Geological Survey
State University
Science Center
Vermillion, South Dakota 57069

U.S. Bureau of Reclamation
Missouri-Oahe Project Office
Federal Building
200 Fourth St. SW
Huron, South Dakota 57350

U.S. Geological Survey
Water Resources Division
South Dakota District Office
Federal Building Room 308
200 4th St. SW
Huron, South Dakota 57350

Colorado

Colorado Division of Water Resources
Office of the State Engineer
818 State Centennial Building
1313 Sherman Street
Denver, Colorado 80203

Colorado Geological Survey
715 State Centennial Building
1313 Sherman Street
Denver, Colorado 80203

Colorado Water Conservation Board
823 State Centennial Building
1313 Sherman Street
Denver, Colorado 80203

U.S. Geological Survey
Water Resources Division
Colorado District Office
Mail Stop 415, Box 25046
Denver Federal Center
Denver, Colorado 80225

Nebraska

Conservation and Survey Division
University of Nebraska at Lincoln
Room 113 Nebraska Hall
Lincoln, Nebraska 68588

Nebraska Department of Water Resources
301 Centennial Mall, South
P.O. Box 94676
Lincoln, Nebraska 68509

Nebraska Natural Resources Commission
301 Centennial Mall, South
P.O. Box 94876
Lincoln, Nebraska 68509

U.S. Geological Survey
Water Resources Division
Nebraska District Office
Room 406, Federal Building and U.S. Courthouse
100 Centennial Mall North
Lincoln, Nebraska 68508

Minnesota

Minnesota Department of Natural Resources
Division of Waters
Space Center Building, 444 Lafayette Road
St. Paul, Minnesota 55101

U.S. Geological Survey
Water Resources Division
Minnesota District Office
1033 Post Office Building
St. Paul, Minnesota 55101

Iowa

Department of Environmental Quality
Henry Wallace Office Building
Des Moines, Iowa 50319

Iowa Conservation Commission
Henry Wallace Office Building
Des Moines, Iowa 50319

Iowa Geological Survey
123 N. Capitol Street
Iowa City, Iowa 52240

Iowa Natural Resources Council
Grimes State Office Building
E. 14th Street and Grand Avenue
Des Moines, Iowa 50319

Iowa State Hygienic Laboratory
Medical Laboratories
University Hospital
University of Iowa
Iowa City, Iowa 52242

U.S. Geological Survey
Water Resources Division
Iowa District Office
Room 269 Federal Building
400 South Clinton Street
Iowa City, Iowa 52240

Kansas

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

Kansas State Department of Health and Environment
Building 740
Forbes Air Force Base
Topeka, Kansas 66620

Kansas Water Resources Board
Suite 303
503 Kansas Avenue
Topeka, Kansas 66603

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

Kansas State Board of Agriculture
Division of Water Resources
1720 South Topeka Avenue
Topeka, Kansas 66612

Missouri

Missouri Department of Conservation
P.O. Box 180
Jefferson City, Missouri 65101

Missouri Department of Natural Resources
Division of Environmental Quality
P.O. Box 1368
Jefferson City, Missouri 65101

Missouri Department of Natural Resources
Division of Geology and Land Survey
P.O. Box 250
Rolla, Missouri 65401

U.S. Corps of Engineers
Kansas City District
700 Federal Building
601 E. 12th Street
Kansas City, Missouri 64106

U.S. Geological Survey
Water Resources Division
Missouri District Office
1400 Independence Road
Rolla, Missouri 65401

CONCLUSIONS

The Missouri Basin Region is a large area that requires large water supplies to meet increasing demands for irrigation, industrial, public supply, and rural uses. Development of petroleum, coal, and oil shale reserves in the region also will require larger water supplies. Available supplies are obtained from precipitation, streamflow, stored surface water, and ground water. Although ground-water use is increasing, large supplies available in numerous aquifers are still not completely defined or completely developed. Effective and efficient use of ground water requires additional hydrologic information so that withdrawals from aquifers can be designed to furnish beneficial supplies without creating problems. A better understanding of ground-water resources will aid in the design of alternative water-management plans that consider all available supplies.

Ground-water reservoirs have unique storage properties that enable them to contribute to sound water-management practices in the region. Large quantities of water are stored in many aquifers because of the storage capacity of the aquifer material and the great areal extent of the aquifers. The stored ground water is not rapidly affected by fluctuations in seasonal precipitation, because recharge and movement of ground water are slow processes. Evaporation also affects ground water much less than surface water.

Ground water in storage can be withdrawn, replaced, or increased if the aquifer is not hydraulically connected to streams or surface-water reservoirs at numerous locations. For example, during a drought or any period in which water demand increases, water supplies can be obtained by pumping wells and mining ground water from storage. Mining eventually lowers the potentiometric surface throughout the extent of the aquifer, rather than locally. A large volume of water may result from a small lowering of the potentiometric surface over a large area. Surplus water supplies can be added to the ground water in storage by using artificial-recharge techniques. Water added to storage also eventually raises the potentiometric surface throughout the areal extent of the aquifer so that the increased quantity in storage is areally distributed.

The recharge, movement, and discharge of ground water also may facilitate water-management practices. Any technique that increases natural recharge to or decreases natural discharge from an aquifer will increase ground water in storage that can be withdrawn by pumping wells. Improved water supplies can be obtained by designed and induced changes in ground-water movement, especially if the aquifer is hydraulically connected to nearby streams. Production wells can be located according to aquifer properties and boundaries and pumped according to calculated time schedules. The resulting withdrawals induce changes in ground-water movement, control the distribution of ground water in storage, and affect the nearby streamflow. The resulting changes in ground water and surface water can result in an improved supply that is available at the desired time and location.

REFERENCES CITED

Alverson, D. C., 1965, Geology and hydrology of the Fort Belknap Indian Reservation Montana: U.S. Geol. Survey Water-Supply Paper 1576–F, 59 p.

Babcock, H. M., and Bjorklund, L. J., 1956, Ground-water geology of parts of Laramie and Albany Counties, Wyoming, and Weld County, Colorado: U.S. Geol. Survey Water-Supply Paper 1367, p. 14–15.

Ellis, M. J., and Pederson, D. T., 1977, Groundwater levels in Nebraska, 1976: Nebraska Water Survey Paper 44, 96 p.

Emery, P. A., 1966, Use of analog model to predict streamflow depletion, Big and Little Blue River basin, Nebraska: Ground Water, v. 4, no. 4, p. 13–19.

Environmental Science Services Administration, 1968, Climatic atlas of the United States: Environmental Data Service (repr. by Natl. Oceanic and Atmospheric Adm., 1974), 80 p.

Feder, G. L., 1973, A conceptual model of the hydrologic system supplying the large springs in the Ozarks: U.S. Geol. Survey Open-File Rept., 148 p.

Feltis, R. D., 1973, Geology and water resources of eastern part of Judith Basin, Montana: Montana Bur. Mines and Geology Bull. 87, 51 p.

Ferris, J. G., 1950, Quantitative method for determining ground-water characteristics for drainage design: Agr. Eng., v. 31, no. 6, p. 285–291.

Hackett, O. M., Visher, F. N., McMurtrey, R. G., and Steinhilber, W. L., 1960, Geology and ground-water resources of the Gallatin Valley, Gallatin County, Montana: U.S. Geol. Survey Water-Supply Paper 1482, 282 p.

Hamilton, L. J., and Paulson, Q. F., 1968, Geology and ground-water resources of the lower Bighorn valley, Montana: U.S. Geol. Survey Water-Supply Paper 1876, 39 p.

Hodson, W. G., Pearl, R. H., and Druse, S. A., 1973, Water resources of the Powder River Basin and adjacent areas, northeastern Wyoming: U.S. Geol. Survey Hydrol. Inv. Atlas HA–465.

Howe, C. W., 1971, Benefit-cost analysis for water system planning: American Geophys. Union Water Resources Mon. 2, 144 p.

Huntoon, P. W., 1974, Predicted water-level declines for alternative groundwater developments in the upper Big Blue River basin, Nebraska: Conserv. and Survey Div., Inst. Agr. and Nat. Resources, Univ. Nebraska, Lincoln, Resource Rept. 6, 105 p.

Hurr, R. T., Schneider, D. A., and Minges, D. R., 1975, Hydrology of the South Platte River valley, northeastern Colorado: Colorado Water Conserv. Board Circ. 28, 24 p.

Jenkins, C. T., and Hofstra, W. E., 1970, Problems of artificially recharging the Ogallala Formation in Colorado, *in* The Ogallala aquifer, a symposium: Lubbock, Tex., Tech. Univ. Spec. Rept. 39, p. 154–164.

Kapple, G. W., Luckey, R. R., and Hofstra, W. E., 1976, Digital ground-water model of the Ogallala aquifer in parts of Washington and Yuma Counties, northern High Plains of Colorado: Colorado Water Resources Circ. 34, 25 p.

Keech, C. F., and Bentall, Ray, 1971, Dunes on the plains, the sand hills region of Nebraska: Univ. Nebraska Conserv. and Survey Div., Resource Rept. 4, Feb. 1971, 18 p.

Kohout, F. A., 1970, Reorientation of our saline water resources thinking: Water Resources Research, v. 6, no. 5, p. 1442–1448.

Konikow, L. F., 1976, Preliminary digital model of ground-water flow in the Madison Group, Powder River Basin and adjacent areas, Wyoming, Montana, South Dakota, North Dakota, and Nebraska: U.S. Geol. Survey Water-Resources Inv. 63–75.

La Rocque, G. A., Jr., 1966, General availability of ground water and depth to water level in the Missouri River basin: U.S. Geol. Survey Hydrol. Inv. Atlas HA–217.

Lines, G. C., 1976, Digital model to predict effects of pumping from Arikaree aquifer in the Dwyer area, southeastern Wyoming: U.S. Geol. Survey Water Resources Inv. 8–76, 24 p.

Lowry, M. E., Lowham, H. W., and Lines, G. C., 1975, Water resources of the Bighorn Basin, northwestern Wyoming: U.S. Geol. Survey Hydrol. Inv. Atlas HA–512.

Lowry, M. E., Rucker, S. J., IV, and Wahl, K. L., 1973, Water resources of the Laramie, Shirley, Hanna Basins and adjacent areas, southeastern Wyoming: U.S. Geol. Survey Hydrol. Inv. Atlas HA–471.

Luckey, R. R., and Hofstra, W. E., 1973, Digital model of the hydrologic system, northern High Plains of Colorado: Colorado

Water Resources Circ. 19, 25 p.

——— 1974, Digital model of the Ogallala aquifer of the northern part of the northern High Plains of Colorado: Colorado Water Resources Circ. 24, 22 p.

McLean, J. R., 1971, Stratigraphy of the upper Cretaceous Judith River Formation in the Canadian Great Plains: Research Council Saskatchewan, Geol. Div., Rept. 11, 96 p.

Meyboom, Peter, 1960, Geology and groundwater resources of the Milk River Sandstone in southern Alberta: Alberta Research Council Mem. 2, 89 p.

Missouri Basin Inter-agency Committee, 1969a, Comprehensive framework study Missouri River basin: v. 1–7.

——— 1969b, Comprehensive framework study Missouri River basin: v. 1, 274 p.

——— 1969c, Comprehensive framework study Missouri River basin, *in* Hydrologic Analyses and Projections: v. 6, 143 p.

Missouri Geological Survey and Water Resources, 1963, Groundwater maps of Missouri.

Missouri River Basin Commission, 1975, Stream-aquifer hydrology, technical paper, Platte River basin, Nebraska Level B Study.

Moulder, E. A., 1970, Freshwater bubbles: A possibility for using saline aquifers to store water: Water Resources Research, v. 6, no. 5, p. 1528–1531.

Murray, C. R., 1968, Estimated use of water in the United States, 1965: U.S. Geol. Survey Circ. 556, 53 p.

Murray, C. R., and Reeves, E. B., 1972, Estimated use of water in the United States in 1970: U.S. Geol. Survey Circ. 676, 37 p.

North Dakota Geological Survey, 1973, Mineral and water resources of North Dakota: North Dakota Geol. Survey Bull. 63, 252 p.

Osterkamp, W. R., 1968, Occurrence of ground water in the Judith River Formation north-central Montana: U.S. Geol. Survey Hydrol. Inv. Atlas HA–308.

Rapp, J. R., Warner, D. A., and Morgan, A. M., 1953, Geology and ground-water resources of the Egbert-Pine Bluffs Carpenter area Laramie County, Wyoming: U.S. Geol. Survey Water-Supply Paper 1140, p. 40–42.

Rocky Mountain Association of Geologists, 1972, Geologic Atlas of the Rocky Mountain region: Denver, Colo., A. B. Hirschfeld Press, 331 p.

Sandberg, C. A., 1962, Geology of the Williston Basin, North Dakota, Montana, and South Dakota, with reference to subsurface disposal of radioactive wastes: U.S. Geol. Survey Rept. TEI-809, 148 p.

Schoon, R. A., 1971, Geology and hydrology of the Dakota Formation in South Dakota: South Dakota Geol. Survey Rept. Inv. 104, 55 p.

Swenson, F. A., Miller, W. R., Hodson, W. G., and Visher, F. H., 1978, Water in the Madison Group, Powder River Basin, Wyoming and Montana: U.S. Geol. Survey Inv. Map I–847–C (in press).

Taylor, O. J., 1965, Ground-water resources along Cedar Creek anticline in eastern Montana: Montana Bur. Mines and Geol. Mem. 40, 99 p.

——— 1968, Ground water resources of the northern Powder River valley, southeastern Montana: Montana Bur. Mines and Geol. Bull. 66, 34 p.

Taylor, O. J., and Luckey, R. R., 1974, Water-management studies of a stream-aquifer system, Arkansas River valley, Colorado: Ground Water, v. 12, no. 1, p. 22–38.

Tokarsky, O., 1974, Hydrogeology of the Lethbridge-Fernie area, Alberta: Alberta Research Council Rept. 74-1, 18 p.

Vineyard, J. D., and Feder, G. L., 1974, Springs of Missouri: Missouri Geol. Survey and Water Resources, Water Resources Rept. 29, 267 p.

Whitaker, S. H., 1967, Geology and groundwater resources of the Wood Mountain Area (72–G): Saskatchewan Research Council, Geology Div. Map 5.

——— 1974, Geology and groundwater resources of the Willow Bunch area (72–H): Saskatchewan Research Council, Geol. Div. Map 20.

Whitcomb, H. A., and Lowry, M. E., 1968, Ground-water resources and geology of the Wind River Basin area, central Wyoming: U.S. Geol. Survey Hydrol. Inv. Atlas HA–270, 13 p.

Winter, T. G., 1975, Delineation of buried glacial-drift aquifers: U.S. Geol. Survey Jour. Research, v. 3, no. 2, p. 137–148.

Zimmerman, E. A., 1966, Geology and ground-water resources of western and southern parts of Judith Basin, Montana: Montana Bur. Mines and Geol. Bull. 50–A, 33 p.

——— 1967, Water resources of the Cut Bank area, Glacier and Toole Counties, Montana: Montana Bur. Mines and Geol. Bull. 60, 37 p.

TABLE 7.—*Principal aquifers in States and Provinces and their geologic ages in the Missouri Basin Region*

Alberta:

Glacial deposits of Pleistocene age
Blood Reserve Formation—Cretaceous
Judith River Formation—Late Cretaceous
Milk River Sandstone—Late Cretaceous
Madison Group—Early Mississippian

Saskatchewan:

Glacial deposits of Pleistocene age
Ravenscrag Formation—Paleocene
Frenchman Formation—Late Cretaceous
Whitemud Formation—Late Cretaceous
Eastend Formation—Late Cretaceous
Judith River Formation—Late Cretaceous
Madison Group—Early Mississippian

Montana:

Alluvium—Pleistocene and Holocene
Glacial deposits of Pleistocene age
Basin-fill deposits of Tertiary age
Fort Union Formation—Late Cretaceous and Paleocene
Hell Creek Formation—Late Cretaceous
Fox Hills Sandstone—Late Cretaceous
Judith River Formation—Late Cretaceous
Eagle Sandstone—Late Cretaceous
Virgelle Member of Eagle Sandstone—Late Cretaceous
Dakota Sandstone—Cretaceous
Kootenai Formation—Early Cretaceous
Swift Formation—Middle and Late Jurassic
Tensleep Sandstone—Pennsylvanian
Amsden Group or Formation—Mississippian and Pennsylvanian
Kibbey Formation—Late Mississippian
Madison Group—Early Mississippian
Bighorn Dolomite—Middle and Late Ordovician

Wyoming:

Alluvium—Pleistocene and Holocene
Ogallala Formation—Miocene
North Park Formation—Late Miocene and Pliocene (?)
Arikaree Formation—Miocene
White River Formation—Oligocene
Brule Formation—Oligocene
Wagon Bed Formation—Eocene
Battle Spring Formation—Eocene
Wind River Formation—Eocene
Indian Meadows Formation—Eocene
Wasatch Formation—Eocene
Hanna Formation—Paleocene
Fort Union Formation—Paleocene
Ferris Formation—Late Cretaceous and Paleocene
Medicine Bow Formation—Late Cretaceous
Lance Formation—Late Cretaceous
Fox Hills Sandstone—Late Cretaceous
Lewis Shale—Late Cretaceous
Mesaverde Group or Formation—Late Cretaceous
Frontier Formation—Late Cretaceous
Inyan Kara Group—Early Cretaceous
Cloverly Formation—Early Cretaceous
Sundance Formation—Middle and Late Jurassic
Nugget Sandstone—Late Triassic (?) and Jurassic (?)
Jelm Formation of Chugwater Group—Late Triassic
Casper Formation—Pennsylvanian and Permian
Tensleep Sandstone—Pennsylvanian and Early Permian
Amsden Formation—Mississippian and Pennsylvanian
Madison Limestone—Early Mississippian
Bighorn Dolomite—Middle and Late Ordovician

North Dakota:

Alluvium—Pleistocene and Holocene
Glacial deposits of Pleistocene age
Fort Union Formation—Paleocene
Hell Creek Formation—Late Cretaceous
Fox Hills Sandstone—Late Cretaceous
Dakota Sandstone—Cretaceous

North Dakota—Continued:

Minnelusa Formation—Pennsylvanian and Permian
Madison Group—Early Mississippian
Red River Formation—Late Ordovician
Deadwood Formation—Late Cambrian and Early Ordovician

South Dakota:

Alluvium—Pleistocene and Holocene
Glacial deposits of Pleistocene age
Ogallala Formation—Miocene
Arikaree Formation—Miocene
Brule Formation—Oligocene
Hell Creek Formation—Late Cretaceous
Fox Hills Sandstone—Late Cretacous
Dakota Sandstone—Cretaceous
Inyan Kara Group—Early Cretaceous
Sundance Formation—Middle and Late Jurassic
Minnelusa Formation—Pennsylvanian and Permian
Madison Group—Early Mississippian
Red River Formation and Whitewood Dolomite—Late Ordovician
Deadwood Formation—Late Cambrian and Early Ordovician

Colorado:

Alluvium—Pleistocene and Holocene
Ogallala Formation—Miocene
Arikaree Formation—Miocene
Brule Clay—Oligocene
Dawson Formation—Late Cretaceous and Paleocene
Denver Formation—Late Cretaceous and Paleocene
Arapahoe Formation—Late Cretaceous
Laramie Formation—Late Cretaceous
Fox Hills Sandstone—Late Cretaceous
Madison Limestone—Early Mississippian

Nebraska:

Alluvium—Pleistocene and Holocene
Dune-sand deposits of Pleistocene and Holocene age
Glacial deposits of Pleistocene age
Ogallala Formation—Miocene
Arikaree Formation—Miocene
Brule Formation—Oligocene
Dakota Sandstone—Cretaceous
Limestone of Pennsylvanian and Permian age
Madison Limestone equivalent—Early Mississippian

Minnesota:

Alluvium—Pleistocene and Holocene
Glacial deposits of Pleistocene age

Iowa:

Alluvium—Pleistocene and Holocene
Glacial deposits of Pleistocene age
Dakota Sandstone—Cretaceous
Limestone of Pennsylvanian age
Prairie du Chien Formation—Early Ordovician
Jordan Sandstone—Late Cambrian

Kansas:

Alluvium—Pleistocene and Holocene
Glacial deposits of Pleistocene age
Ogallala Formation—Miocene
Dakota Sandstone—Cretaceous
Limestone and sandstone of Pennsylvanian and Permian age

Missouri:

Alluvium—Pleistocene and Holocene
Glacial deposits of Pleistocene age
Limestone of Pennsylvanian age
Roubidoux Formation—Early Ordovician
Gasconade Dolomite—Early Ordovician
Eminence Dolomite—Late Cambrian
Potosi Dolomite—Late Cambrian

TABLE 8.—*Principal aquifers in structural basins, their geologic ages and maximum thicknesses, Missouri Basin Region*

Formation and age	Maximum thickness (ft)	(m)
Alberta Basin, Alberta and Mont.:		
Blood Reserve Formation—Cretaceous	100	30
Judith River Formation—Late Cretaceous	1,200	370
Milk River Sandstone—Late Cretaceous	220	67
Bighorn Basin, Mont.:		
Hell Creek Formation—Late Cretaceous	600	180
Judith River Formation including Parkman Sandstone Member—Late Cretaceous	250	76
Kootenai Formation including Cloverly Formation—Early Cretaceous	400	120
Tensleep Sandstone—Pennsylvanian	100	30
Amsden Formation—Mississippian and Pennsylvanian	300	91
Bighorn Basin, Wyo.:		
Fort Union Formation—Paleocene	5,000	1,500
Lance Formation—Late Cretaceous	1,800	550
Mesaverde Formation—Late Cretaceous	1,800	550
Frontier Formation—Late Cretaceous	700	210
Cloverly Formation—Early Cretaceous	400	120
Tensleep Sandstone—Pennsylvanian and Early Permian	400	120
Amsden Formation—Mississippian and Pennsylvanian	350	110
Denver Basin, Colo.:		
Dawson Formation—Late Cretaceous and Paleocene	2,000	610
Denver Formation—Late Cretaceous and Paleocene	800	240
Arapahoe Formation—Late Cretaceous	600	180
Fox Hills Sandstone and basal Laramie Formation—Late Cretaceous	200	60
Hogeland Basin, Mont.:		
Judith River Formation—Late Cretaceous	460	140
Eagle Sandstone—Late Cretaceous	270	82
Dakota Sandstone—Cretaceous	60	18
Kootenai Formation—Early Cretaceous	190	58
Swift Formation—Middle and Late Jurassic	240	73
Hogeland Basin, Saskatchewan:		
Frenchman Formation—Late Cretaceous	130	40
Whitemud Formation—Late Cretaceous	60	18
Eastend Formation—Late Cretaceous	100	30
Judith River Formation—Late Cretaceous	650	200
Judith Basin, Mont.:		
Judith River Formation—Late Cretaceous	400	120
Eagle Sandstone—Late Cretaceous	300	91
Dakota Sandstone—Cretaceous	80	24
Kootenai Formation—Early Cretaceous	660	200
Swift Formation—Middle and Late Jurassic	185	56
Amsden Group—Mississippian and Pennsylvanian	920	280
Kibbey Formation—Late Mississippian	300	91
Laramie, Shirley, Hanna Basins, and Saratoga Valley, Wyo.:		
North Park Formation—Late Miocene and Pliocene (?)	1,500	460
Arikaree Formation—Miocene	1,400	430
White River Formation—Oligocene	400	120
Wagon Bed Formation—Eocene	150	46
Wind River Formation—Eocene	500	150
Hanna Formation—Paleocene	13,500	4,110
Ferris Formation—Late Cretaceous and Paleocene	6,500	2,000
Medicine Bow Formation—Late Cretaceous	6,200	1,900
Lewis Shale, including Fox Hills Sandstone—Late Cretaceous	3,900	1,200
Mesaverde Group—Late Cretaceous	4,000	1,200
Cloverly Formation—Early Cretaceous	100	30
Sundance Formation—Middle and Late Jurassic	230	70
Nugget Sandstone—Late Triassic (?) and Jurassic (?)	50	15
Jelm Formation—Late Jurassic	360	110
Casper Formation—Pennsylvanian and Permian	800	240
Powder River Basin, Wyo. and Mont.:		
Wasatch Formation—Eocene	2,000	610
Fort Union Formation—Late Cretaceous and Paleocene	3,450	1,050
Fox Hills Sandstone and Lance Formation, Wyo.—Late Cretaceous	700	210
Fox Hills Sandstone and basal Hell Creek Formation, Mont.—Late Cretaceous	250	76
Mesaverde Formation—Late Cretaceous	900	270
Frontier Formation—Late Cretaceous	830	250
Inyan Kara Group—Early Cretaceous	450	140
Sundance Formation—Middle and Late Jurassic	400	120
Tensleep Sandstone—Pennsylvanian and Early Permian	500	150
Williston Basin, N. Dak., Mont., S. Dak., and Saskatchewan:		
Fort Union Formation—Paleocene	1,100	340
Fox Hills Sandstone and basal Hell Creek Formation—Late Cretaceous	400	120
Dakota Sandstone—Cretaceous	460	140
Inyan Kara Group—Early Cretaceous	700	210
Sundance Formation—Middle and Late Jurassic	740	230
Minnelusa Formation—Pennsylvanian and Permian	1,400	430
Deadwood Formation—Late Cambrian and Early Ordovician	600	180
Wind River Basin, Wyo.:		
Arikaree Formation—Miocene	2,700	820
White River Formation—Oligocene	650	200
Wagon Bed Formation—Eocene	700	210
Battle Spring, Wind River, and Indian Meadows Formations—Eocene	8,000	2,400
Casper Formation—Pennsylvanian and Permian; Tensleep Formation—Pennsylvanian and Early Permian and Amsden Formation—Mississippian and Pennsylvanian	900	270