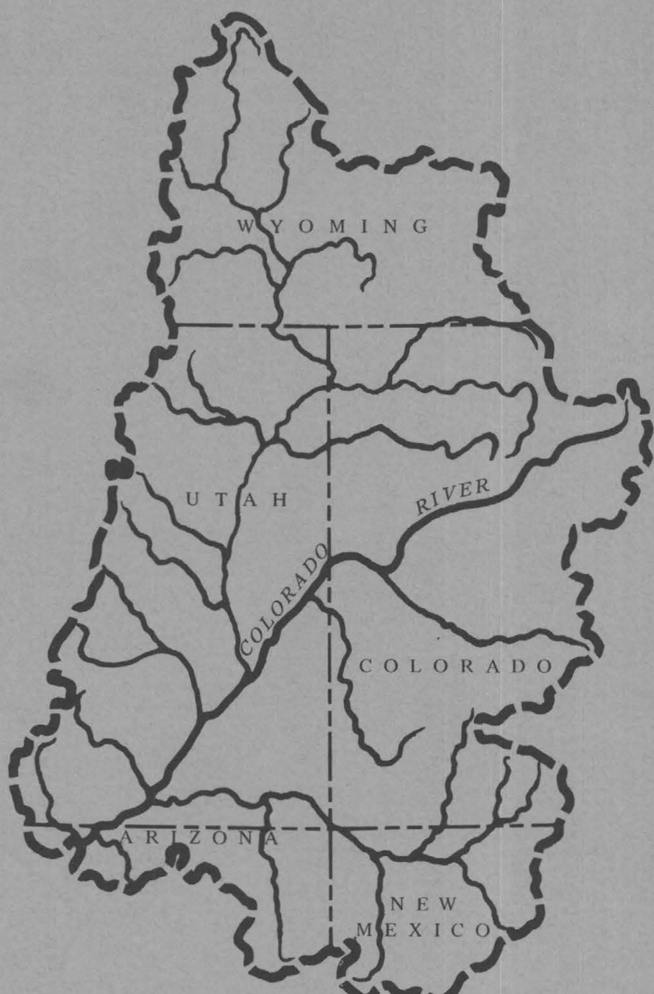
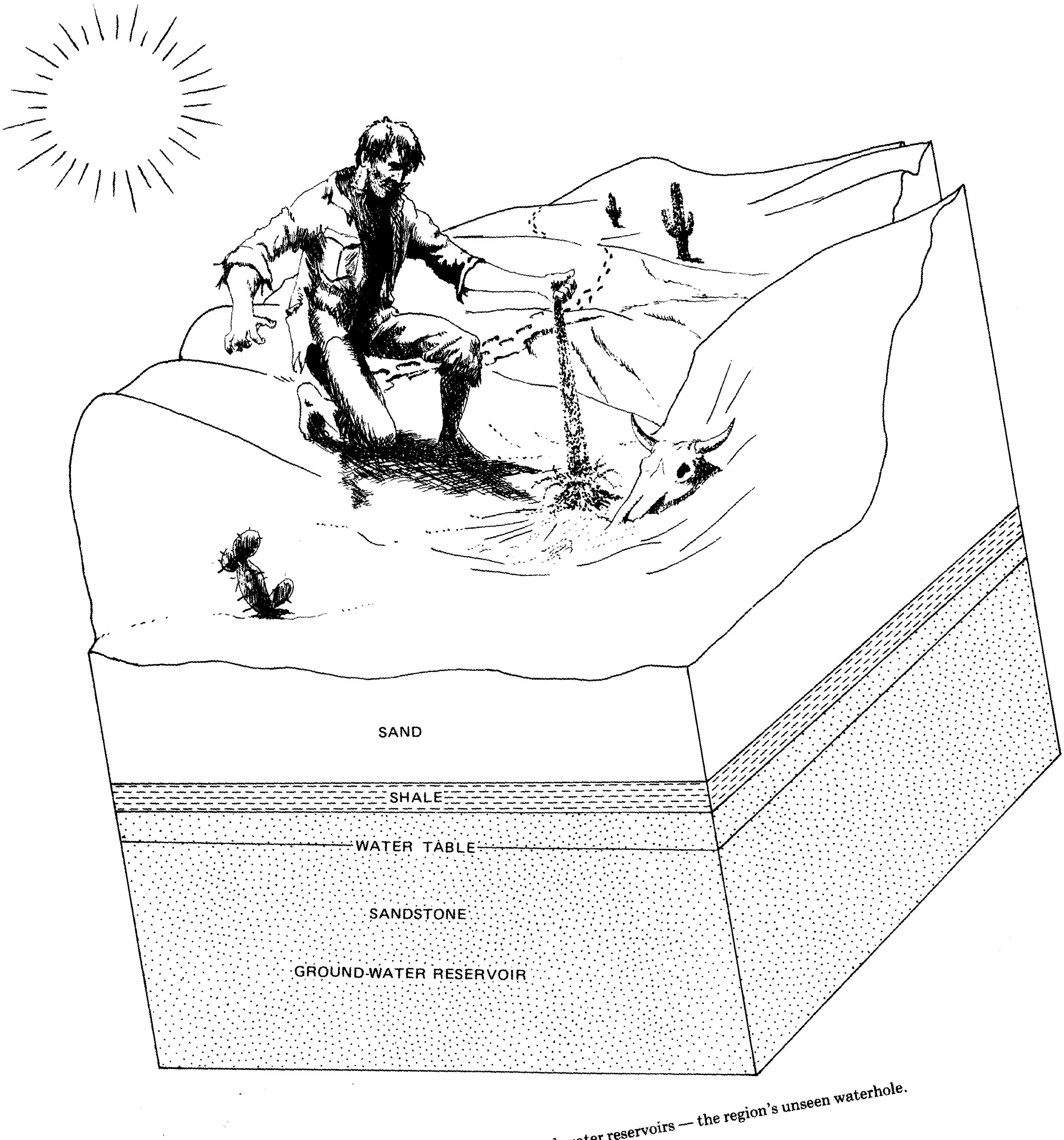
Summary Appraisals of the Nation's Ground-Water Resources—Upper Colorado Region

GEOLOGICAL SURVEY PROFESSIONAL PAPER 813-C



UPPER COLORADO REGION



FRONTISPIECE. — Ground-water reservoirs — the region's unseen waterhole.

Summary Appraisals of the Nation's Ground-Water Resources — Upper Colorado Region

By DON PRICE *and* TED ARNOW

GEOLOGICAL SURVEY PROFESSIONAL PAPER 813-C

Relevance of ground water to water-management alternatives in the region

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1974

UNITED STATES DEPARTMENT OF THE INTERIOR

THOMAS S. KLEPPE, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

First printing 1974
Second printing 1976

Library of Congress Cataloging in Publication Data
Price, Don, 1929-
Summary appraisals of the Nation's ground-water resources—Upper Colorado Region.
(Geological Survey Professional Paper 813-C)
Bibliography: p.
Supt. of Docs. No.: I 19.16:813-C
1. Water supply—Colorado River watershed. 2. Water, underground—Colorado River watershed.
I. Arnow, Theodore, 1921- joint author. II. Title. III. Series: United States Geological Survey Professional Paper 813-C.
TD225.C665P74 333.9'104'097641 74-17019

For sale by Branch of Distribution, U.S. Geological Survey
1200 South Eads Street, Arlington, VA 22202
Stock Number 2401-02561

CONTENTS

	Page
Abstract	C1
Introduction	1
Purpose and scope	1
Setting	2
Ground water in overall water-resources management	7
The water bank	7
Utility of ground water	8
Assessment of the ground-water resource	8
Quantity and availability of ground water	8
Quality of the ground water	11
Relation of surface water and ground water	11
Use of ground water	16
Increasing the usable supply of ground water	16
Artificial recharge	16
Reduction of natural discharge	21
Demineralization	22
Recycling	24
Availability of ground water to meet future water needs	24
Selected development options	26
Conjunctive use of surface water and ground water	26
Use of ground water only	26
Sustained ground-water supply	28
Time-limited ground-water supply	28
Ground water in overall water-resources management — Continued	
Other use of underground space	C30
Fluid-waste disposal	30
Flood control	30
Underground storage	30
Problems and constraints associated with ground-water development	30
Physical problems	30
Declines in water levels	31
Depletion of streamflow	31
Deterioration of water quality	31
Land subsidence	33
Effect on the environment	33
Constraints	33
Water rights	33
The Colorado River Compact	33
Ecological considerations	34
Limit of scientific knowledge	34
Information needed for project design	34
Summary	37
Selected references	38

ILLUSTRATIONS

	Page
FRONTISPIECE. Ground-water reservoirs — the region's unseen waterhole.	
PLATE 1. Maps showing quantity and availability of ground water, Upper Colorado Region	In pocket
A. Geohydrologic units based on water-bearing properties of the rocks.	
B. Average annual precipitation (1931-60) and evaporation (1940-55).	
C. Average annual runoff (1914-65).	
D. Areas of ground-water recharge and ground-water discharge.	
E. Areas of recoverable ground water.	
F. Potential yields to properly located, properly constructed wells.	
G. Depths to ground water.	
2. Maps showing quality of water, Upper Colorado Region	In pocket
A. Concentrations of dissolved solids in ground water.	
B. Sources of potential ground-water contamination.	
C. Ground-water temperature.	
D. Concentration of dissolved solids in streams.	
FIGURE 1. Graph showing estimated annual exports and consumptive use of water within the region by the year 2020	C2
2. Relief map of the Upper Colorado Region, showing drainage and principal physiographic subdivisions	3
3. Photograph showing a deep narrow intricate canyon, such as those in the Canyon Lands, characteristic of much of the region	4
4. Photograph showing high rugged peaks of the San Juan Mountains, one of the headwater areas in the Upper Colorado River system	4
5. Map showing that most of the land in the region is owned or administered by the Federal Government	5
6. Map showing principal population centers in the region in 1970	6
7. Diagram of the hydrologic system	7
8. Diagram showing examples of how ground water occurs under water-table or artesian conditions in the region	12
9. Diagrams showing the close relationship of ground water and surface water	14

Page

FIGURE 10. Hydrograph showing the rising ground-water levels near Lake Powell ---- C15
11. Diagram showing the total withdrawal and consumptive use of ground water compared with the total withdrawal and consumptive use of water from all sources in 1970 ---- 17
12. Map showing the few scattered areas in the region in which the annual withdrawals from wells exceeded 500 acre-feet 18
13. Hydrographs showing the minor effect of ground-water development on ground-water levels ---- 19
14. Map showing areas where water-management practices can be used singly or in combination to increase the usable ground-water supply ---- 20
15. Diagrams showing how artificial recharge is accomplished by surface spreading and by subsurface injection ---- 21
16. Diagram showing how artificial recharge can increase the ground-water supply in water-deficient regions ---- 22
17. Graph showing the effect of evapotranspiration on fluctuations of the stage of the Green River ---- 23
18. Photograph of greasewood, a common phreatophyte which covers many square miles of the region ---- 23
19. Photograph of saltcedar, which lines many perennial streams in the region ---- 23
20. Map showing areas where aquifers are known or assumed to be sufficiently productive for conjunctive use with surface water in water-resources development ---- 27
21. Map showing areas where aquifers are known or assumed to be sufficiently productive for use as a sole water supply in water-resources development ---- 29
22. Diagram showing how deterioration of water quality can result from large-scale withdrawals from freshwater aquifers in the region ---- 32
23. Map showing areas in the region in which ground-water resources have been studied in detail ---- 35
24. Map showing areas of the region that have potential for implementation of ground water and for use of subsurface space in overall water-resources management ---- 36

TABLES

Page

TABLE 1. Average annual discharge of the three largest tributaries of the Colorado River — the Green, San Juan, and Gunnison Rivers C4
2. Principal water-bearing formations, Upper Colorado Region ---- 8
3. Estimated recoverable ground water in storage, Upper Colorado Region ---- 10
4. Data requirements for prediction model studies ---- 37
5. Summary of problems that could be analyzed with a model ---- 37

SUMMARY APPRAISALS OF THE NATION'S GROUND-WATER RESOURCES — UPPER COLORADO REGION

By DON PRICE and TED ARNOW

ABSTRACT

The Upper Colorado Region covers about 113,500 square miles (293,965 km²) in parts of Arizona, Colorado, New Mexico, Utah, and Wyoming. Drainage from about 97 percent of the region is to the Colorado River. About 60 percent of the land is owned or administered by the Federal Government, and another 15 percent is in Indian trust. The predominantly arid to semiarid region is sparsely populated (averaging about three persons per square mile, or about two and one-half persons per km²) and is used chiefly for grazing, recreation, and mineral development.

The water supply for the region comes from precipitation within the region, which averages about 95 million acre-feet (117,182.5 hm³) per year. Development of the region's water supply has been limited almost entirely to surface water. Only about 2 percent of the total estimated volume of water withdrawn (about 5.7 million acre-ft, or 7,030.9 hm³) and consumed (about 3.6 million acre-ft, or 4,440.6 hm³) in the region in 1970 came directly from ground-water sources.

By the year 2020 consumptive use of water within the region and water exports to adjacent regions are expected to total more than 6.5 million acre-feet (8,017.8 hm³) per year. Use of the ground-water resources of the Upper Colorado Region in water-resources management can help to meet these water needs.

A tremendous amount of water is stored in the rocks (ground-water reservoirs) of the Upper Colorado Region. Recoverable water in just the upper 100 feet (30.5 m) of saturated rocks is estimated to be as much as 115 million acre-feet (141,852.5 hm³). That amount is nearly four times the total active storage capacity of all surface-water reservoirs in the region. The average annual replenishable supply of the ground-water reservoir is about 4 million acre-feet (4,934 hm³). This amount of water could irrigate about 1.3 million acres (526,110 ha) of crops having an annual water requirement of 3 feet per acre (0.9 m/ha), or it could provide about 3,600 million gallons (13,627,440 m³) per day for industrial use.

Most of the ground water is in consolidated rocks, which generally yield water to wells slowly. Much of the ground water is saline and, in some places, occurs at great depths. Nevertheless, the ground water is more uniformly distributed than is surface water, both areally and with time; therefore, it can be used advantageously in overall water-resources management. Recent advancements in the field of demineralization and in evaluation and development of ground water make this possible.

Options available for use of ground water in water-resources management in the region include conjunctive use with surface water or development of ground water as an independent supply. The latter option could be for a perennial supply or for a time-limited supply (mining ground water), depending on the need and the existing ground-water conditions. All options can be carried out so as to meet the requirements of the Colorado River Compact. The options could be implemented to optimally develop the Upper Colorado River Basin's allocation of Colorado River water while meeting the Compact commitments to the Lower Basin.

INTRODUCTION

PURPOSE AND SCOPE

The history of the Western United States is replete with stories of settlers and travelers who suffered grievously or abandoned their homes when streams, springs, and waterholes went dry. Agony for many of them would have been even greater if they had realized that beneath their feet, under the parched land, were huge reservoirs of cool clear water.

The early settlers were unaware of the underground reservoirs, but, even if they had known of them, they would not have been able to reach much of the water because of lack of drilling equipment. Today's occupants of the West know that the underground reservoirs exist and have at their command the equipment to tap the hidden water supplies, but still, for the most part, the underground water remains untouched even when the streams and waterholes cannot supply all the water needed. Why is this so?

Water on the surface is obvious — it can be seen, tasted, readily measured, and diverted for man's use. But ground water is hidden in the earth, and knowledge about ground water and the development of suitable techniques for its measurement and withdrawal have lagged for hundreds of years behind similar techniques for surface water.

Even today many water planners believe that ground water cannot be evaluated adequately in terms of availability, quantity, quality, cost of development, or the effect of development on surface-water sources. Such belief is no longer valid because advances in the science of ground-water hydrology in the last half century have provided the knowledge and techniques necessary for planning, developing, and managing water supplies using ground water. This same knowledge also can be applied to the joint management of interrelated surface water and ground water to make full use of the total water resource.

Unless the total water resource of the Upper Colorado Region is fully used, it may not be possible to satisfy the projected water needs of the region and the exports from the region (fig. 1) because of constraints on the full

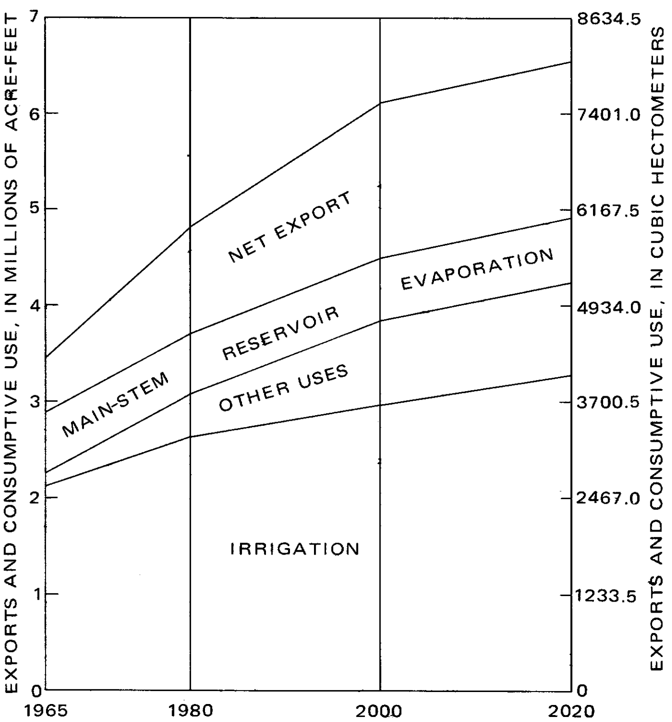


FIGURE 1. — Estimated annual exports and consumptive use of water within the region by the year 2020. Water needs and exports by then are expected to total more than 6.5 million acre-feet (8,017.8 hm³). (After Hedlund and others, 1971, p. 47, 54.)

development of the surface-water sources. Even if the needs could be met entirely from surface water, the full development of surface water alone may not be possible because of the increasing social pressure to preserve and enhance the environment, which continues to place greater constraints on construction of surface-water storage facilities. More emphasis, therefore, must be placed on evaluation and development of the region's ground-water supply because ground water is the region's "unseen waterhole."

Optimal use of the total water resource of the Upper Colorado Region can best be achieved by considering all the alternatives — surface water alone in some areas, ground water alone in other areas, either as a sustained supply or an exhaustible supply, and conjunctive use of surface and ground water in still other areas.

The following questions about ground water are most commonly asked by water planners and managers in the Upper Colorado Region:

1. How much ground water is available for development?
2. What is the quality of the ground water?
3. What effect will large-scale ground-water development have on streamflow in general and on the Colorado River in particular?
4. What effect will large-scale ground-water development have on the environment?

The purpose of this report is to supply the best possible answers to those questions by presenting a gross regional assessment of the ground-water resources in a manner that will show the availability and significance of ground water in the region, and how it might be used alone or conjunctively with surface water to meet future water needs. The report shows what additional ground-water information is needed for project planning, design, and management, and what can be done to obtain this information. It also discusses possible uses of underground space as related to water and environmental problems.

The maps and discussions in this report (one of a series of similar reports that describe the entire United States by water-resources regions) are in sufficient detail to evaluate broad concepts of water planning, development, and management. The detail is not intended to be suitable for the design of new projects or implementation of specific proposals in terms of quantity, quality, or economic feasibility.

Most numbers are given in this report in English units followed by metric units in parentheses. The conversion factors used are as follows:

English unit (multiply)	Conversion factor (by)	Metric unit (to obtain)	Metric abbreviation
Acre	0.4047	Hectare	ha
Acre-foot	.0012335	Cubic hectometer	hm³
Cubic foot	.02832	Cubic meter	m³
Foot	.3048	Meter	m
Gallon	3.7854	Liter	l
Gallon	.0037854	Cubic meter	m³
Inch	25.4	Millimeter	mm
Inch	2.54	Centimeter	cm
Mile	1.6093	Kilometer	km
Square mile	2.59	Square kilometer	km²

Chemical concentration and water temperature are given only in metric units. Chemical concentration is given in milligrams per liter (mg/l). For concentrations less than 7,000 mg/l, the numerical value is about the same as for concentrations given in parts per million.

Water temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit by the following equation: °F = 1.8 (°C)+32.

SETTING

The Upper Colorado Region includes the area drained by the Colorado River and its tributaries upstream from Lee Ferry, Ariz., and the area of the Great Divide Basin, a closed basin in Wyoming. The region covers about 113,500 square miles (293,965 km²) in parts of Arizona, Colorado, New Mexico, Utah, and Wyoming. Physiographic subdivisions that lie wholly or partly within the region are shown in figure 2.

The Upper Colorado Region is characterized by high rugged mountains, broad basins, and high plateaus that

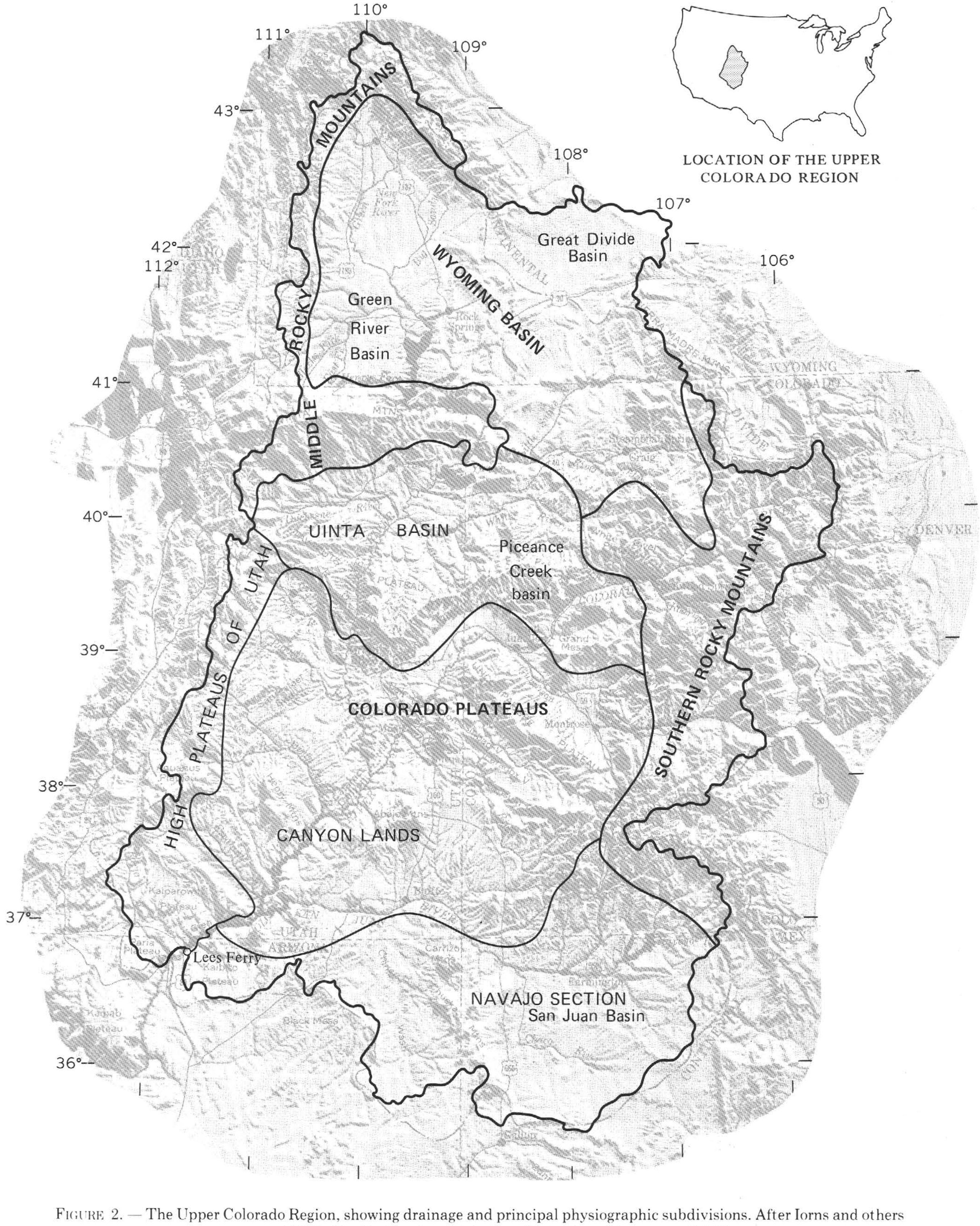


FIGURE 2. — The Upper Colorado Region, showing drainage and principal physiographic subdivisions. After Iorns and others (1965, fig. 1). Physiographic boundaries from Fenneman (1946).

TABLE 1. — *Average annual discharge of the three largest tributaries of the Colorado River — the Green, San Juan, and Gunnison Rivers*

Stream	Years of record	Period	Average annual discharge[1] cfs	m^3/sec	Thousands of acre-feet	Thousands of hm^3
Green River (at Green River, Utah)	72	Oct. 1894-Oct. 1899 Oct. 1904-Sept. 1971	6,360	180.12	4,610	5,686.4
San Juan River (near Bluff, Utah)	57	Oct. 1914-Sept. 1971	2,600	73.63	1,880	2,319.0
Gunnison River (near Grand Junction, Colo.)	62	1896-99, 1901-06, 1916-71	2,580	73.07	1,870	2,306.6

[1]Values have been rounded.

have been deeply entrenched and dissected by the Colorado River and many of its tributaries. Perhaps the most striking, unique physiographic feature of the region is the deep narrow intricate canyons that have been carved by streams (many of which are intermittent and ephemeral) in the varicolored rocks that underlie broad basins and plateaus (fig. 3). Altitudes range from about 3,100 feet (944.9 m) above mean sea level near Lee Ferry to more than 14,000 feet (4,267.2 m) in the Central and Southern Rocky Mountains. Most of the region has an arid to semiarid climate, and some areas receive less than 5 inches (127 mm) of precipitation a year. The higher plateaus and mountains have subhumid to alpine climatic zones, and more than 40 inches (1,016 mm) of precipitation a year falls on the highest peaks (pl. 1*B*).

Nearly 97 percent of the region drains to the Colorado River; the rest drains to the Great Divide Basin. Average annual discharge of the Colorado River near Lees Ferry was 17,760 cfs (cubic feet per second) (502.96 m^3/sec), or 12,860,000 acre-feet (15,862.8 hm^3) per year, for 49 years of record prior to completion of Glen Canyon Dam in 1963. The river and its three largest tributaries — the Green, San Juan, and Gunnison Rivers — all head in the Southern and Central Rocky Mountains (fig. 4), and the average annual discharge of each of these tributaries exceeds 2,000 cfs (56.64 m^3/sec) (table 1).

About 60 percent of the land in the region is owned or administered by the Federal Government, and another 15 percent is in Indian trust. (See fig. 5.) The region is sparsely populated, averaging about three persons per square mile (2.6 persons per km^2). Grand Junction, Colo., and Farmington, N. Mex., were the only communities with populations of more than 20,000 in 1970. (See fig. 6.) Because of the growing popularity of the region for recreation, however, many of the communities have large seasonal influxes of population. Most of the land is used for grazing, recreation, and mineral development (mostly fossil fuels).

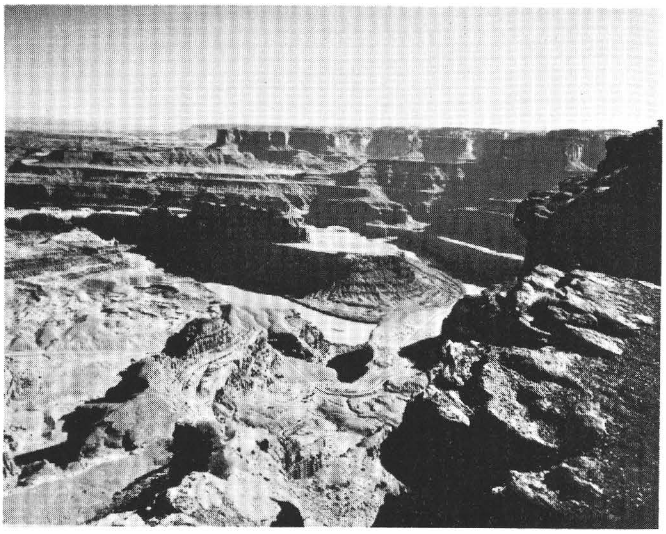


FIGURE 3. — Deep narrow intricate canyon, such as those in the Canyon Lands, characteristic of much of the region. (Photograph by U.S. Bureau of Reclamation.)

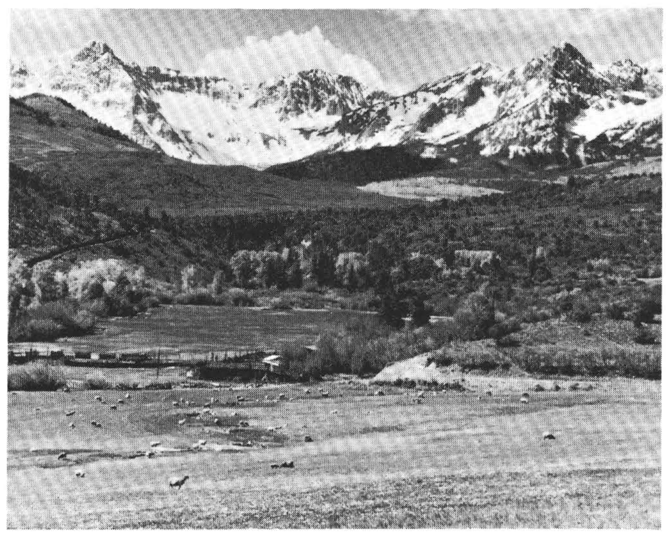


FIGURE 4. — High rugged peaks of the San Juan Mountains, one of the headwater areas in the Upper Colorado River system. (Photograph by U.S. Bureau of Reclamation.)

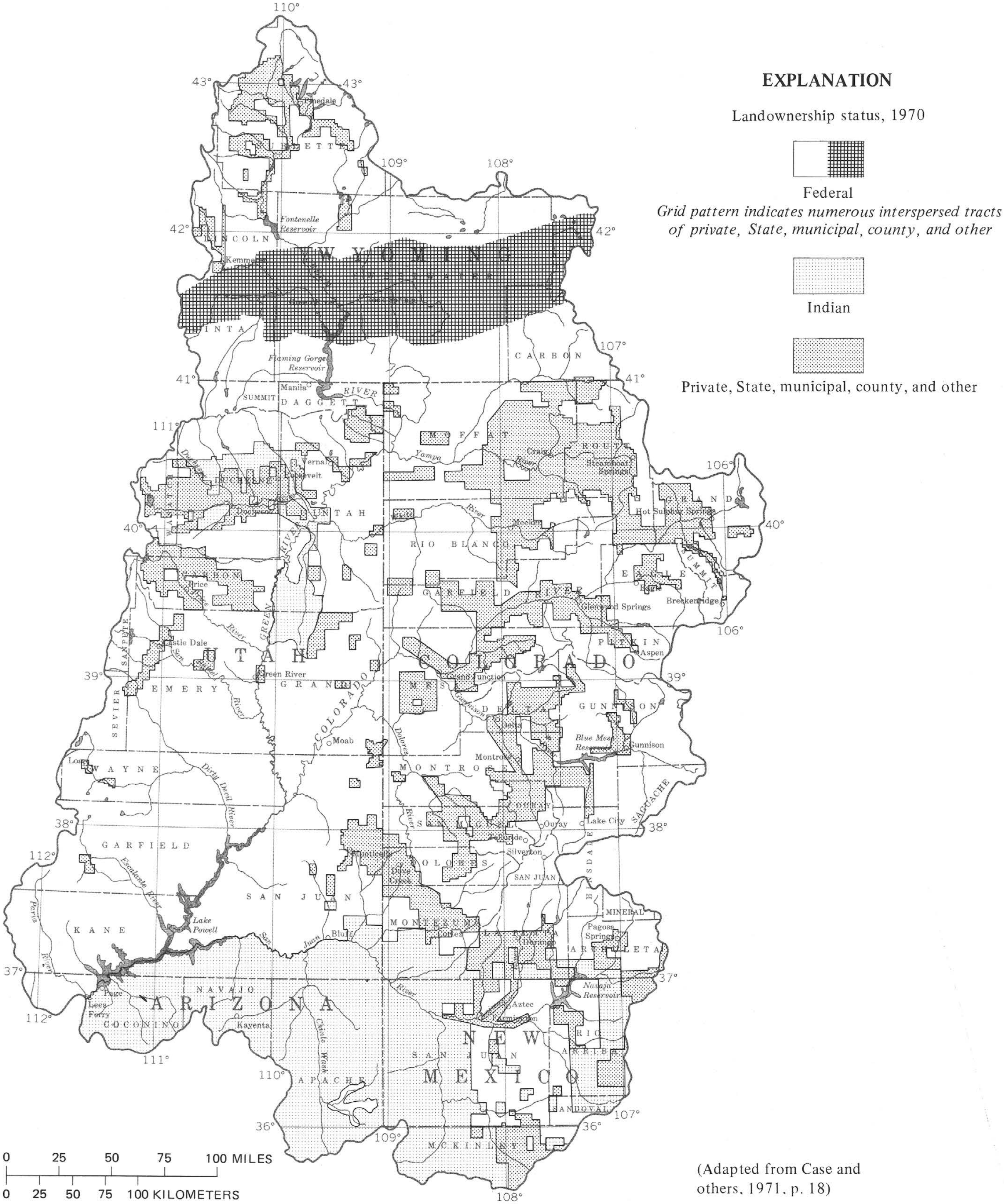


FIGURE 5. — Most of the land in the region is owned or administered by the Federal Government.

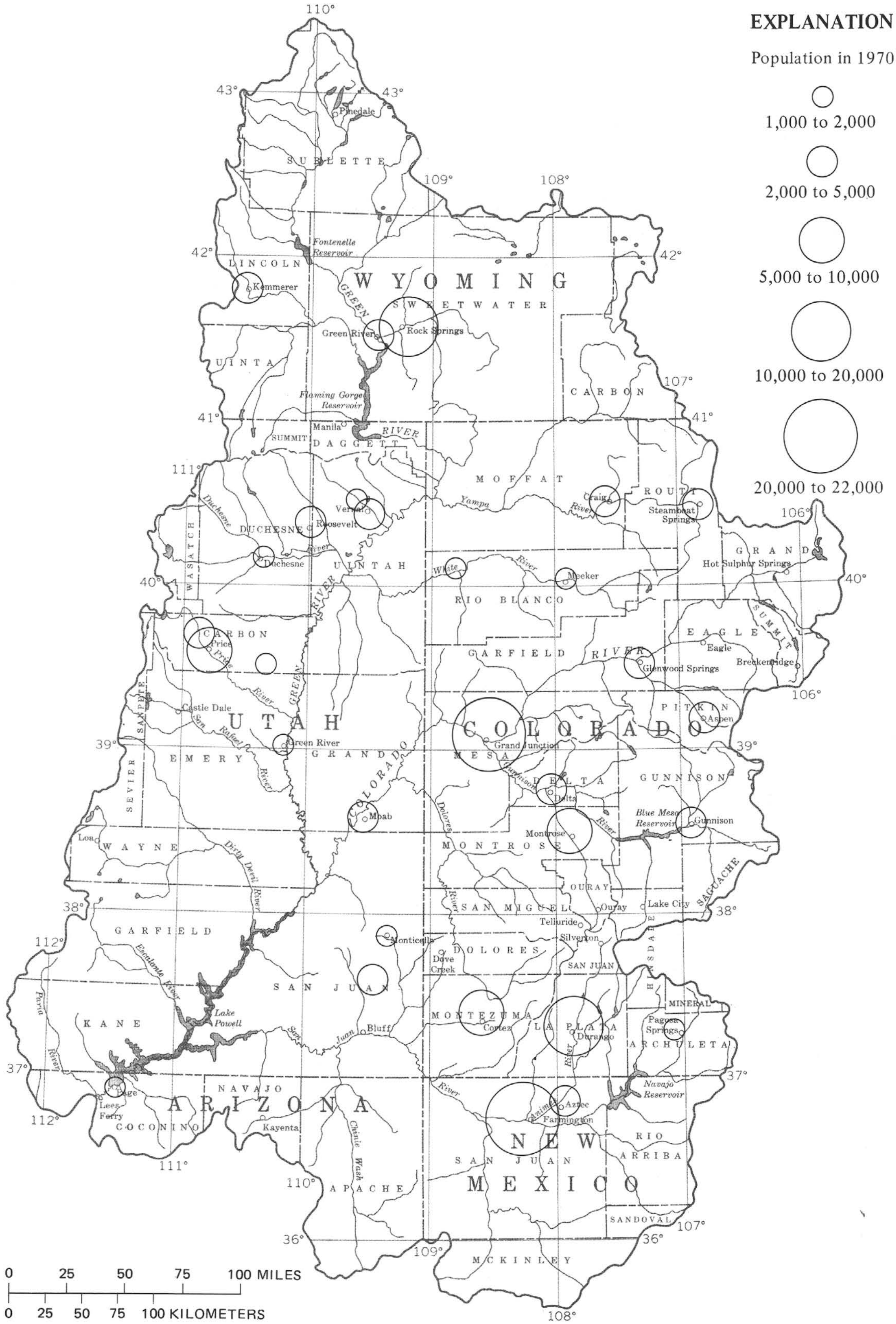
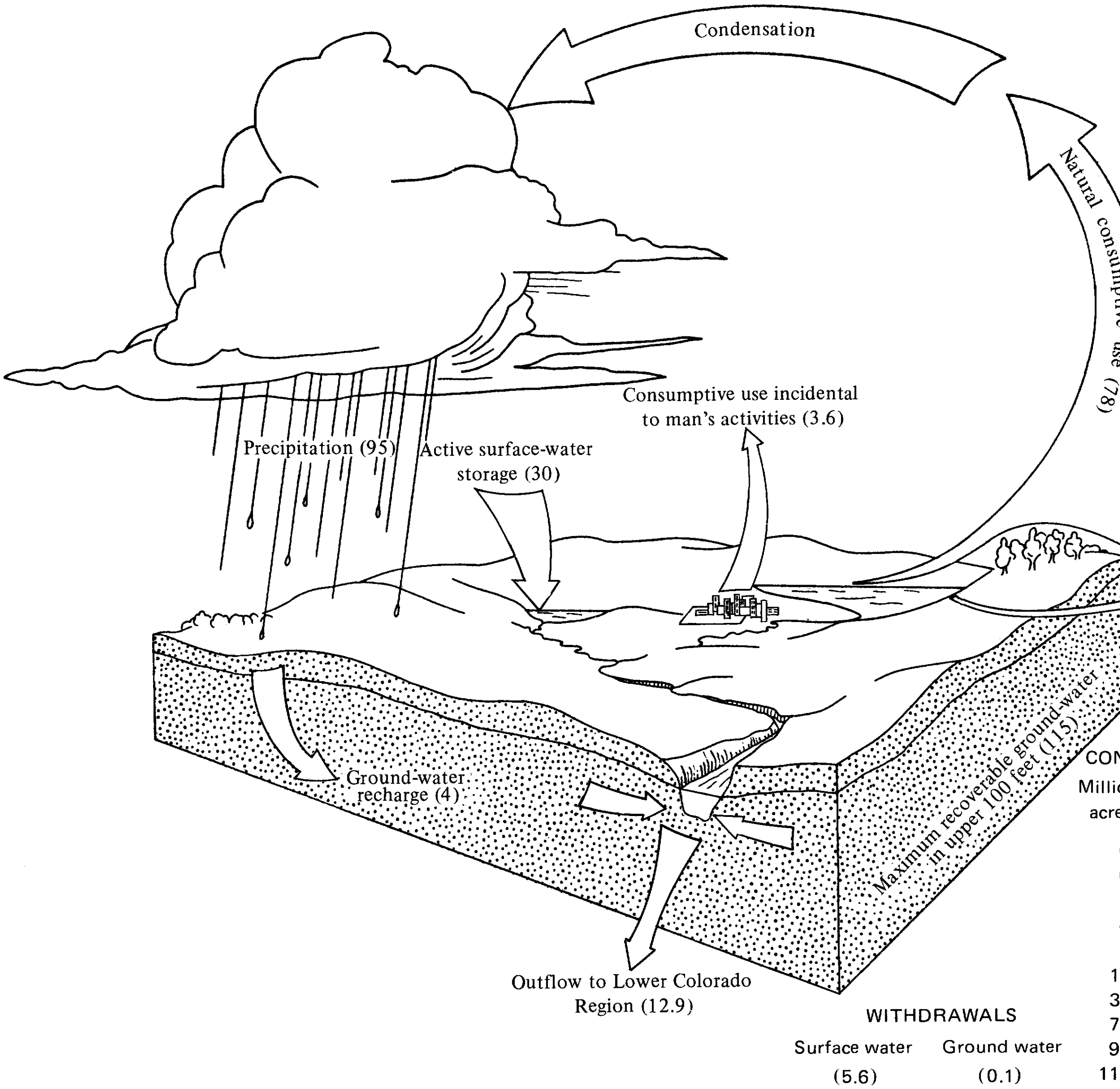


FIGURE 6. — Principal population centers in the region in 1970.



Millions of acre-feet	Cubic hectometers
0.1	123.4
0.6	740.1
3.6	4,440.6
4	4,934
5.6	6,907.6
12.9	15,912.2
30	37,005
78	96,213
95	117,182.5
115	141,852.5

FIGURE 7. — The hydrologic system — the region's "water bank." Most of the supply is in ground-water storage, yet direct withdrawals of ground water are comparatively small. (Numbers in parentheses are in millions of acre-ft per year except those for storage, which are in millions of acre-ft.) Values are for the 1970 level of development, in part after Hedlund and others (1971) and Murray and Reeves (1972).

Development of the water resources of the region has been limited almost entirely to the development of surface water — particularly in relation to the Colorado River Storage Project of the U.S. Bureau of Reclamation and its participating agencies. The completion of such multipurpose dams as Flaming Gorge (1964) and Glen Canyon (1963) under this project has greatly stimulated the economy of the region. Development of ground water to date (1973) has been on a small scale and is limited in most places to withdrawals for domestic and stock supplies.

GROUND WATER IN OVERALL WATER-RESOURCES MANAGEMENT

THE WATER BANK

The hydrologic system in the Upper Colorado Region is the "water bank" for the region. (See fig. 7.) Deposits are made from the precipitation that falls within the region; withdrawals are the returns to the atmosphere by consumptive use, outflow in the Colorado River near Lees Ferry, and exports to other regions. The largest amount of water by far in the bank is in the ground-water reservoirs of the region. Under natural conditions these reservoirs help provide a more uniform annual and long-term water supply for the region. The reservoirs accept wet-season deposits for release during dry seasons, and provide large carryover storage for release during periods of drought. Proper development and management of these underground reservoirs by man can provide an efficient utilization of the "water bank."

UTILITY OF GROUND WATER

Because it is generally expedient to use what can be seen and to shy away from that which is hidden and not fully understood, surface water, if available, has been used as the source of water supply in many parts of the country without consideration being given to the alternative sources for development of a supply. Advances in techniques in ground-water hydrology during recent years now provide methods for resolving some of the development and management problems that historically have bred reluctance to consider ground-water development.

In the Upper Colorado Region, as in many other parts of the country, ground water has certain advantages, which in many areas make it a logical source of supply. It is widely distributed throughout the region and is generally dependable throughout the year. It is not everywhere equal in volume or rate of availability, but it is almost everywhere present in some quantity and quality, so that in many places the point of withdrawal can be at the point of use, and the effect upon the environment is minimal. Its temperature and chemical quality are fairly uniform, making it desirable for use where these characteristics are necessary. It is generally silt free and is stored in a spacious reservoir that is not subject to excessive losses by evaporation. Its reservoirs are ready made and generally self-regulated, yet many can be manipulated for more advantageous and beneficial use. The reservoirs are not easily polluted and are not subject to damage or destruction by natural or man-caused disasters.

ASSESSMENT OF THE GROUND-WATER RESOURCE

QUANTITY AND AVAILABILITY OF GROUND WATER

Because of the varying hydrologic properties of rocks, the geology of the Upper Colorado Region is the principal factor controlling the quantity and availability of ground water for development. The rocks that underlie the region consist mostly of consolidated and semiconsolidated sedimentary strata. Igneous and metamorphic rocks underlie parts of the mountains, and unconsolidated alluvial deposits underlie reaches of major stream valleys.

Iorns and others (1965, p. 4-8) grouped the rocks into eight hydrologic units on the basis of their age and general hydrologic properties. These units are herein regrouped into five geohydrologic units on the basis chiefly of relative hydrologic properties of the rocks (pl. 1*A*). The better known water-bearing formations in the units are listed in table 2.

TABLE 2. — *Principal water-bearing formations*

[Unconsolidated deposits of Quaternary age are the most permeable water-bearing formations in most parts of the region; sandstone strata of Jurassic, Cretaceous, and Tertiary age contain the most extensive bedrock aquifers. Letters correspond to areas shown on pl. 1*A*]

WYOMING BASIN PROVINCE
A — West-central part of Green River basin[1]
Quaternary
Unconsolidated sedimentary deposits (mostly alluvial and lacustrine in origin)
Tertiary
Bridger Formation
Green River Formation
Wasatch Formation
Jurassic
Nugget Sandstone
Ordovician
Bighorn Dolomite
B — Great Divide and Washakie Basins[2]
Quaternary
Unconsolidated sedimentary deposits (mostly alluvial and lacustrine in origin)
Tertiary
Browns Park Formation
Green River Formation
Wasatch Formation-Battle Spring Formation
Cretaceous
Ericson Formation
Rock Springs Formation
Mesaverde Formation (east part of area)
Mississippian
Madison Limestone
MIDDLE ROCKY MOUNTAINS PROVINCE
C — South flank of Uinta Mountains[1]
Quaternary
Unconsolidated sedimentary deposits (mostly alluvium)
Cretaceous
Dakota Sandstone
Jurassic
Nugget Sandstone
Permian
Park City Formation
Pennsylvanian
Weber Quartzite
Morgan Formation
UINTA BASIN SECTION
D — Eastern and central parts[3]
Quaternary
Unconsolidated sedimentary deposits (mostly alluvium)
Tertiary
Duchesne River Formation
Uinta Formation
Green River Formation
Wasatch Formation
Cretaceous
Frontier Sandstone Member of Mancos Shale
Mowry Shale
Dakota Sandstone
Triassic(?) and Jurassic
Glen Canyon Sandstone
Permian
Park City Formation
Phosphoria Formation
Pennsylvanian
Weber Sandstone (Quartzite)
Morgan Formation
Round Valley Limestone

TABLE 2. — *Principal water-bearing formations* — Continued

HIGH PLATEAUS OF UTAH
E — Northern part[3]

Quaternary	
	Unconsolidated sedimentary deposits (mostly alluvium)
Tertiary	
	Crazy Hollow Formation
	Flagstaff Formation
Cretaceous and Tertiary	
	North Horn Formation
Cretaceous	
	Emery Sandstone Member of Mancos Shale
	Ferron Sandstone Member of Mancos Shale
Jurassic	
	Carmel Formation
Triassic(?) and Jurassic	
	Navajo Sandstone (Glen Canyon Group)
Triassic	
	Wingate Sandstone (Glen Canyon Group)

F — Southern part[3]

Quaternary	
	Unconsolidated alluvial and lacustrine deposits (probably some extrusive igneous rocks)
Tertiary	
	Igneous rocks
	Brian Head Formation
	Wasatch Formation
Cretaceous	
	Kaiparowits Formation
	Wahweap Sandstone
	Straight Cliffs Sandstone
Jurassic	
	Carmel Formation
Triassic(?) and Jurassic	
	Navajo Sandstone (Glen Canyon Group)
Triassic	
	Wingate Sandstone (Glen Canyon Group)

CANYON LANDS
G — Henry Mountains vicinity[4]

Quaternary	
	Unconsolidated sedimentary deposits (mostly alluvium and dune sand)
Cretaceous	
	Dakota Sandstone
Triassic(?) and Jurassic	
	Navajo Sandstone (Glen Canyon Group)
Triassic	
	Wingate Sandstone (Glen Canyon Group)

H — La Sal Mountains vicinity[5]

Quaternary	
	Unconsolidated sedimentary deposits (mostly alluvium and dune sand)
Cretaceous	
	Dakota Sandstone
	Burro Canyon Formation
Jurassic	
	Entrada Sandstone
Triassic(?) and Jurassic	
	Navajo Sandstone (Glen Canyon Group)
Triassic	
	Wingate Sandstone (Glen Canyon Group)
Permian	
	Cutler Formation

NAVAJO SECTION
I — North-central part[6]

Quaternary	
	Unconsolidated alluvium and dune sand (some igneous rocks)
Tertiary	
	Chuska Sandstone
Cretaceous	
	Dakota Sandstone

TABLE 2. — *Principal water-bearing formations* — Continued

NAVAJO SECTION — Continued
I — North-central part[6] — Continued

Jurassic	
	Recapture Shale Member of Morrison Formation
	Salt Wash Sandstone Member of Morrison Formation
	Summerville Formation
	Cow Springs Sandstone
	Bluff Sandstone
Triassic(?) and Jurassic	
	Navajo Sandstone (Glen Canyon Group)
Triassic(?)	
	Moenave Formation
Triassic	
	Owl Rock Member of Chinle Formation
	Shinarump Member of Chinle Formation
Permian	
	Cedar Mesa Sandstone Member of Cutler Formation

J — Northeast part[7]

Quaternary	
	Unconsolidated sedimentary deposits (mostly alluvium)
Tertiary	
	San Jose Formation
Cretaceous	
	Dakota Sandstone
Jurassic	
	Entrada Sandstone

SOUTHERN ROCKY MOUNTAIN PROVINCE
K — North Park and Middle Park vicinity[8]

Quaternary	
	Unconsolidated sedimentary deposits (mostly alluvium and glacial deposits)

L — Glenwood Springs-McCoy vicinity[9]

Quaternary	
	Unconsolidated alluvium
Mississippian	
	Leadville Limestone

From geologic columns and sections in:
[1]Oriel (1963).
[2]Welder and McGreevy (1966).
[3]Feltis (1966).
[4]Hunt and others (1953).
[5]Carter and Gualtieri (1965).
[6]Feltis (1966) and McGavock and others (1966).
[7]Baltz (1967) and McGavock and others (1966).
[8]Voegeli (1965) and Hall (1968).
[9]Boettcher (1972).

The source of virtually all ground water in transient storage in the Upper Colorado Region is the precipitation that falls within the region. Total annual precipitation in the region averages about 95 million acre-feet (117,182.5 hm^3) (Hedlund and others, 1971, p. i). Practically all this water is consumed at or near the place of fall by sublimation and evapotranspiration or becomes overland runoff. Only about 4 percent, or about 4 million acre-feet (4,934 hm^3), is estimated to become ground-water recharge. This includes percolation through the soil zone as well as seepage from streams and lands irrigated by streams. It is regarded as the peren-

TABLE 3. — *Estimated recoverable ground water in storage,*[1] *Upper Colorado Region*

Geohydrologic unit (pl. 1*A*)	Rock type	Area (thousands of acres)	Estimated specific yield[2] (percent)	Saturated thickness[3] (ft)	Estimated amount of water in storage (thousands of acre-ft)	
					Minimum	Maximum
1	Unconsolidated deposits	800	5-15	50	2,000	6,000
2	Volcanic rocks	2,200	2-5	100	4,400	11,000
3	Sedimentary rocks	40,000	1-2	100	40,300	80,600
4	do	24,300	0.2-0.7	100	4,900	17,000
5	Igneous and metamorphic rocks	5,100	0-0.3	100	0	1,500
Total (rounded)					50,000	115,000

[1]About 85 percent of the recoverable ground water stored in the upper 100 feet of saturated rocks occurs in sedimentary rocks which have relatively low permeability and yield water slowly.

[2]The ratio of the volume of water that a saturated rock will yield by gravity to the volume of the rock.

[3]Ground-water storage is estimated for only 50 feet of the unconsolidated deposits because in many places the saturated thickness of this unit does not greatly exceed 50 feet. Ground-water storage is estimated for only 100 feet of the other geohydrologic units because the saturated thickness of the units is not known. In many places throughout the region the saturated thickness is much more than 100 feet; thus, total recoverable ground-water storage in the region greatly exceeds the maximum amount shown in this table.

nial yield[1] of the ground-water reservoirs or perennial ground-water supply for the region under the existing climatic and hydrologic conditions.

A perennial water supply of 4 million acre-feet (4,934 hm^3) could support a population of about 24 million people having an average daily per capita consumption of 150 gallons (568 l). It could irrigate about 1.3 million acres (526,110 ha) of crops having an average annual water requirement of 3 feet per acre (0.9 m/ha), or it could provide about 3,600 mgd (million gallons per day) (13,627,440 m^3) for industrial use. It should be noted, however, that, over a long period of years, the natural ground-water discharge balances the natural ground-water recharge. Consequently, any diversion by wells and consumptive use of ground water will cause some form of natural ground-water discharge, such as seepage to streams, to decrease proportionately.

The principal areas of natural ground-water recharge are in the higher mountains and plateaus, which receive the largest amount of annual precipitation (pl. 1*B*) and produce most of the runoff (pl. 1*C*). The ground water moves from the areas of recharge to areas of natural discharge, which include numerous widely scattered springs, gaining reaches of streams, and areas of phreatophyte growth. The principal areas of ground-water recharge and natural ground-water discharge are shown on plate 1*D*.

Ground water occurs under both water-table (unconfined) and artesian (confined) conditions, as illustrated in figure 8. Water-table conditions commonly exist in shallow alluvial aquifers along the larger streams, in principal recharge areas, and in the relatively flat-lying rocks that prevail in the Canyon Lands and Navajo sections (fig. 2) of the region. Artesian conditions occur locally throughout the region but are prevalent in the bedrock aquifers of the major structural basins, such as the Green River, Uinta, Piceance Creek, and San Juan Basins.

The volume of recoverable ground water in storage in the upper 100 feet (30.5 m) of the saturated rocks is estimated to be between about 50 and 115 million acre-feet (61,675 and 141,852.5 hm^3) (table 3). The maximum figure is nearly four times the total active storage capacity of all surface-water impoundments in the region, including Lake Powell and Flaming Gorge and Navajo Reservoirs. Total recoverable ground-water storage in the region — that is, in the complete section of saturated rocks — is many times the amount stored in the upper 100 feet (30.5 m) of saturated rocks. Plate 1*E* shows that the amount of recoverable storage per square mile (2.6 km^2) in the upper 100 feet (30.5 m) of saturated rocks varies considerably from place to place.

Although the total volume of recoverable ground water in storage is great, the water cannot be recovered in large quantities from wells at all places. For example, about 85 percent of the estimated maximum recoverable water in storage occurs in sedimentary rocks (table 3), which have relatively low permeability and yield water slowly. Only about 5 percent of the estimated maximum recoverable water in storage occurs in unconsolidated deposits, which includes permeable alluvium. Wells that yield more than 50 gpm (gallons per minute) (189 l/min) generally can be expected only along reaches of larger streams and in small widely scattered alluvium-filled basins (pl. 1*F*).

The depth to ground water and the depth from which it must be pumped have a great economic effect on the availability of ground water. In much of the Canyon Lands and Navajo sections of the region, ground-water levels are several hundred to more than 1,000 feet (several tens to more than 304.8 m) below the land surface,

[1]Perennial yield of a ground-water reservoir, as used in this report, is the maximum amount of water of suitable chemical quality that can be withdrawn from the reservoir each year for an indefinite period of years without causing a continuing depletion of storage. The perennial yield cannot exceed the average annual natural recharge to, or discharge from, the reservoir.

whereas ground water in alluvium of the larger perennial streams generally is within 50 feet (15.2 m) of the land surface (pl. 1*G*). As illustrated in figure 8 and shown on plate 1*G*, wells will flow under artesian pressure in a number of areas, but in most, several hundred feet of drilling through unsaturated rocks is required before the artesian aquifers are reached.

QUALITY OF THE GROUND WATER

Plate 2*A* shows the general chemical quality of the water with regard to its dissolved-solids content. Water containing less than 1,000 mg/l (milligrams per liter) of dissolved solids is fresh; water containing more than 1,000 mg/l is saline according to the following classification used by the U.S. Geological Survey:

Class	*Dissolved solids (mg/l)*
Fresh	0- 1,000
Slightly saline	1,000- 3,000
Moderately saline	3,000-10,000
Very saline	10,000-35,000
Briny	>35,000

Freshwater is generally available from shallow aquifers in most rock units in areas above an altitude of about 7,000 feet (2,133.6 m). At lower altitudes, fresh water most commonly occurs in the relatively permeable sandstone, such as the Navajo and Dakota Sandstones. Freshwater is also found in carbonate rocks, such as the Madison Limestone and Morgan Formation, which have good hydrologic connection with the principal recharge areas in the mountains.

Saline water commonly occurs in shale and siltstone strata that underlie most of the Green River, Great Divide, Washakie, Uinta, Piceance Creek, and San Juan Basins, but even in those areas some of the aquifers locally contain freshwater.

The quality of ground water in many parts of the region may be greatly altered by man's activities. Areas where fresh ground water might be contaminated by man's activities are shown on plate 2*B*.

Temperature is an important property of ground water, particularly with regard to artificial recharge, to use of the water for certain industries, and to possible development of geothermal energy. The degree of success of most artificial-recharge operations (or fluid-waste disposal) depends largely on the thermal compatability of the recharge water and the natural ground water. The success of industries that require cooling water (such as large thermal electric powerplants) depends at least in part on the initial temperature of the cooling water. Finally, the areal distribution of thermal water (water whose temperature is at least 5°C higher than the mean annual air temperature of the area in which the water occurs) is a guide in locating potential sites for development of geothermal energy.

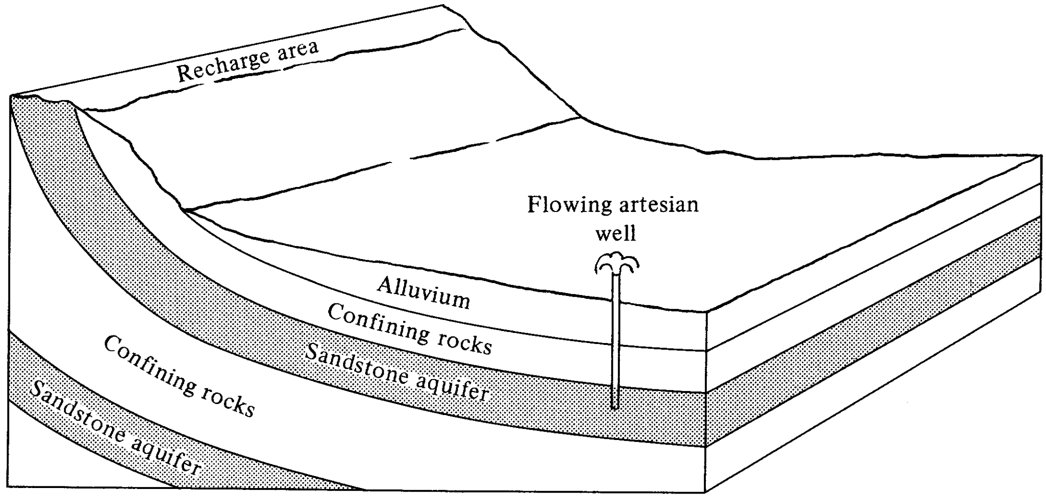
The temperature of water from most water wells less than 1,000 feet (304.8 m) deep and from nonthermal springs is about 5°-10°C in the mountainous parts of the region and about 10°-20°C in the lower basin and plateau areas (pl. 2*C*). Discharge of thermal ground water is relatively rare in the region and is confined chiefly to a few widely scattered thermal springs (pl. 2*C*).

RELATION OF SURFACE WATER AND GROUND WATER

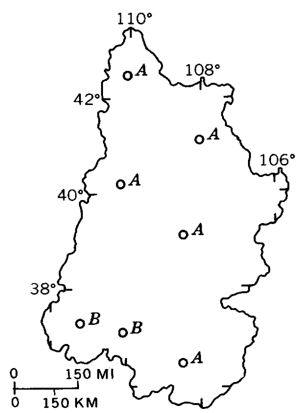
A close relation exists between surface water and ground water. This relation is shown diagrammatically in figure 9 and is known to exist throughout the Upper Colorado Region. Factors that control this relation include the degree of hydraulic connection between the aquifers and the stream channels, lakes, or reservoirs, the permeability of the aquifers, and the slope or gradient of the water table. As noted earlier, some recharge to aquifers occurs as seepage from certain reaches of streams in the region (fig. 9*A*); conversely, discharge from aquifers occurs as seepage to other reaches of the stream (fig. 9*B*). Aquifers in the permeable alluvial deposits along perennial streams receive recharge (bank storage) during peak runoff periods (fig. 9*D*) and release the water back to the streams as streamflow subsides. Ground-water withdrawal by wells or vegetation along streams depletes streamflow (fig. 9*C*).

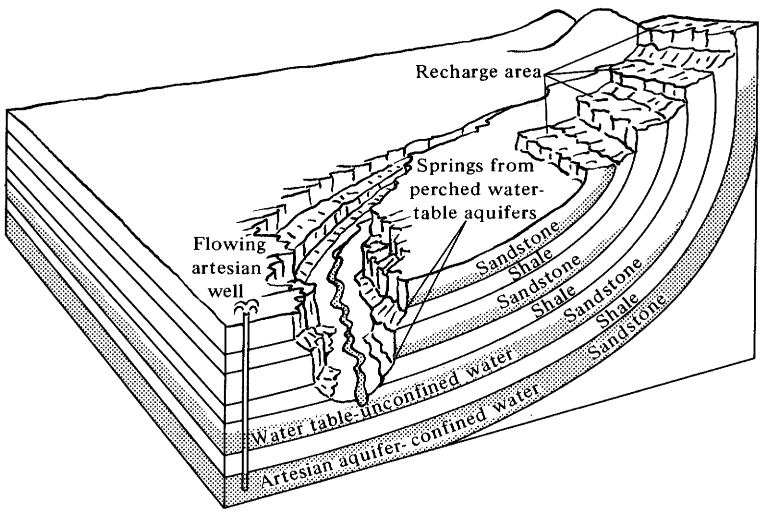
Bank storage at manmade reservoirs can involve considerable quantities of water. For example, Madison and Waddell (1973, p. C16) estimated that about 240,000 acre-feet (296 hm^3) of water went into bank storage, mostly into bedrock aquifers, at Flaming Gorge Reservoir during the period 1963-68; also, it has been estimated that as much as 6.7 million acre-feet (8,264.4 hm^3) has gone into bank storage (mostly into the Navajo Sandstone) at Lake Powell since filling of that reservoir began in 1963. This increased bank storage is reflected by a rise of water levels in wells near Lake Powell. (See fig. 10.)

The interchange of ground water and surface water also has an effect on water quality. For example, the relatively large discharge-weighted-average concentration of dissolved solids in the streamflow in various parts of the region (pl. 2*D*) results partly from inflow of saline ground water from such formations as the Mancos Shale and Paradox Formation to streams. In some areas, seepage of highly mineralized irrigation return flow from surface sources into aquifers can deteriorate the quality of water in those aquifers. (See pl. 2*B*.) Conversely, the chemical quality of ground water in some aquifers (as the Uinta and Duchesne River Formations in the Uinta Basin) has improved where irrigation developments have augmented natural ground-water recharge with fresher water diverted from surface sources.



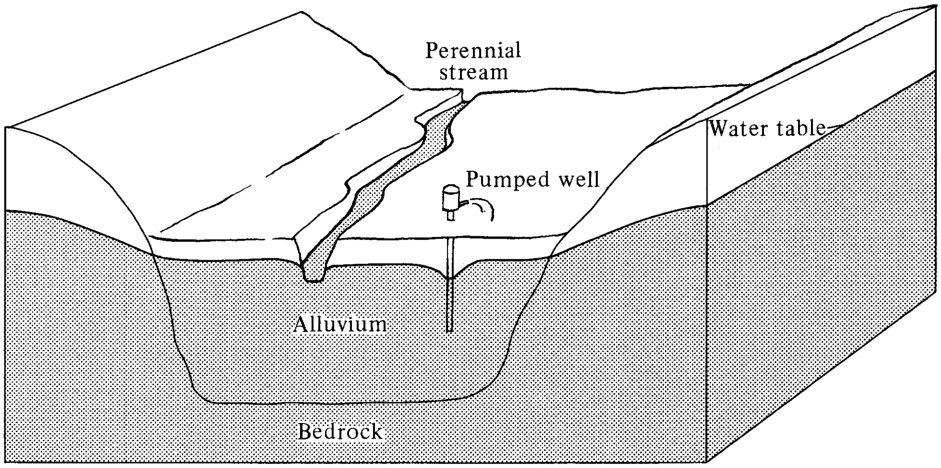
A. CONFINED GROUND WATER IN FOLDED ROCKS
Examples: Green River, Washakie, Uinta, Piceance Creek, and San Juan Basins



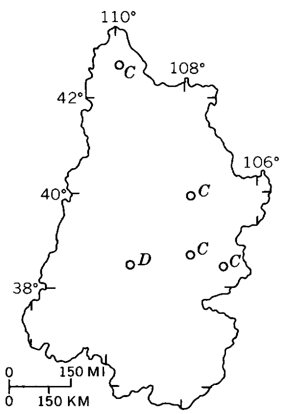


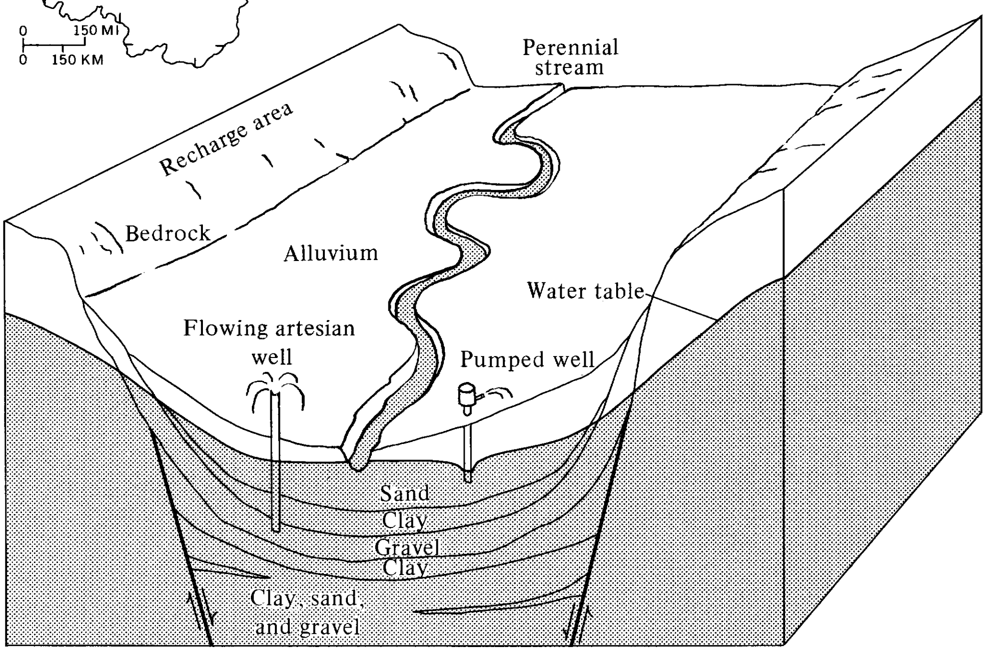
B. CONFINED AND UNCONFINED GROUND WATER
IN DEEPLY DISSECTED ROCKS
Example: Canyon Lands area

FIGURE 8 (above and facing page). — Examples of how ground water occurs under water-table (unconfined) or artesian (confined) conditions in the region.



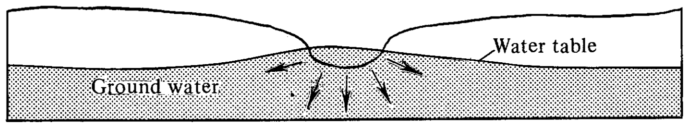
C. UNCONFINED GROUND WATER IN STREAM-VALLEY ALLUVIUM
Examples: Valley segments of the Green, Yampa, White, and Gunnison Rivers



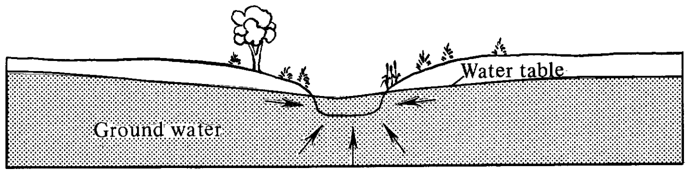


D. UNCONFINED AND LOCALLY CONFINED GROUND WATER
IN A DEEP ALLUVIUM-FILLED BASIN
Example: Spanish Valley

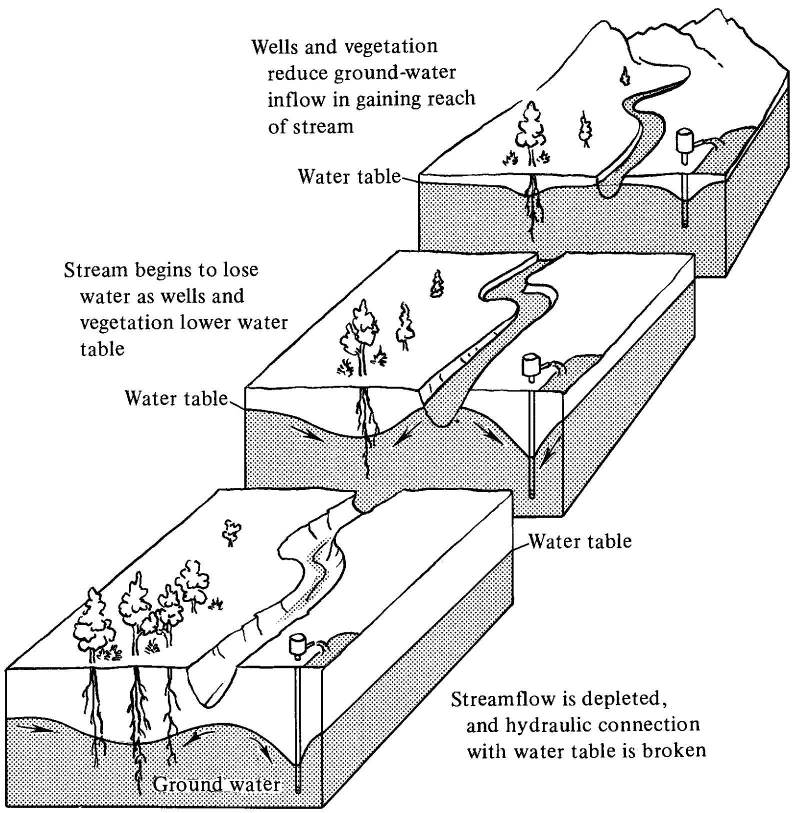
FIGURE 8. — Continued.



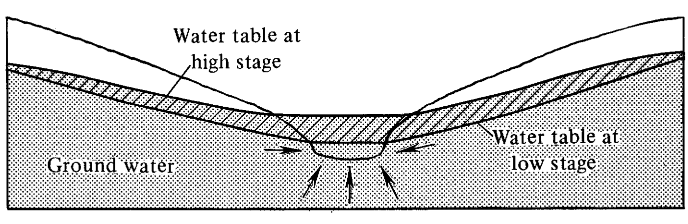
A. LOSING REACHES OF STREAMS LOSE WATER TO AQUIFERS



B. GAINING REACHES OF STREAMS GAIN WATER FROM AQUIFERS



C. GROUND WATER WITHDRAWN BY WELLS AND VEGETATION CAN DEPLETE STREAMFLOW



D. GROUND-WATER STORAGE IS INCREASED OR DEPLETED WITH THE INCREASE OR DEPLETION OF STORAGE IN THE BANKS OF STREAMS, LAKES, AND RESERVOIRS

FIGURE 9. — Surface water and ground water are closely related.

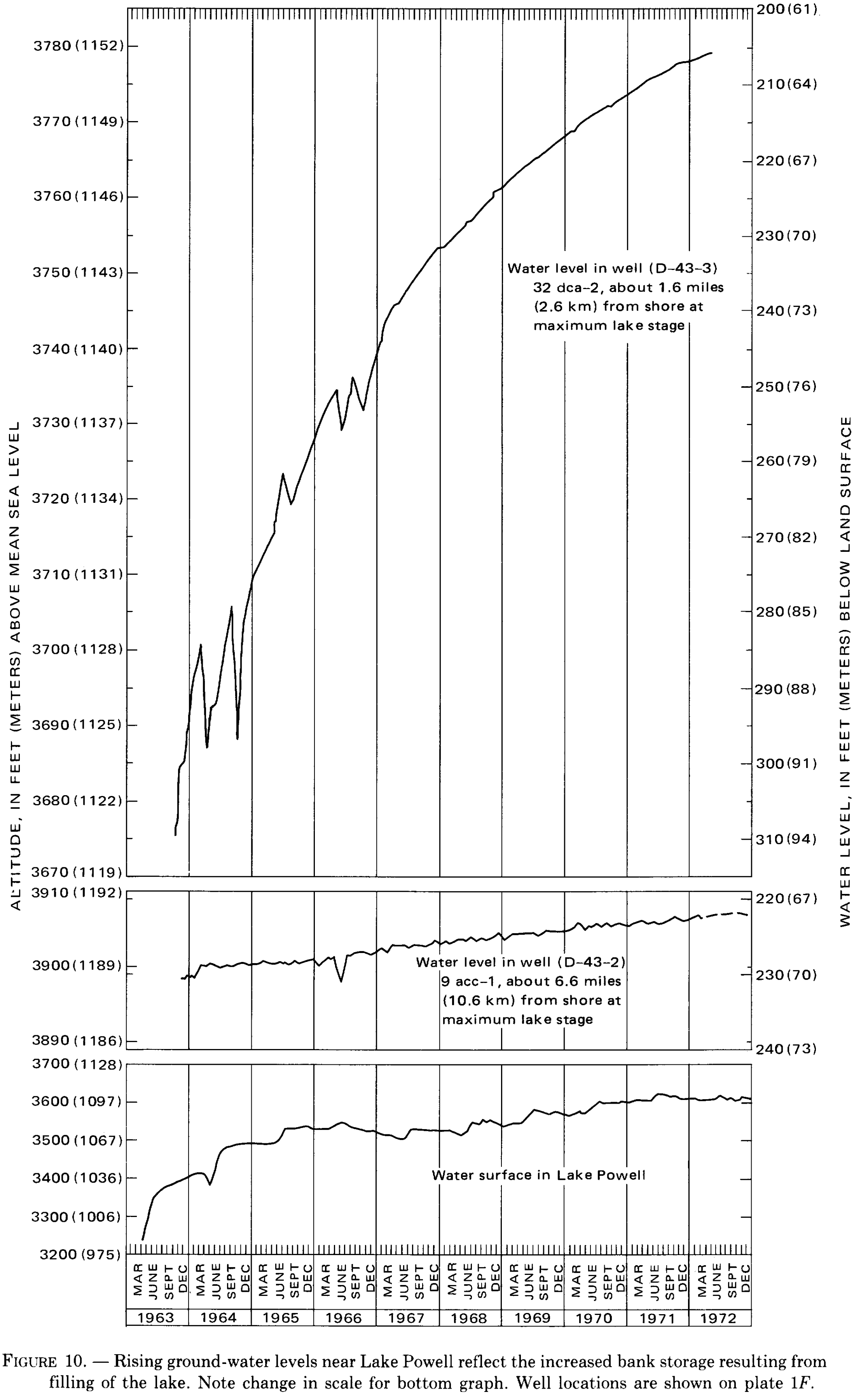


FIGURE 10. — Rising ground-water levels near Lake Powell reflect the increased bank storage resulting from filling of the lake. Note change in scale for bottom graph. Well locations are shown on plate 1*F*.

USE OF GROUND WATER

Use of ground water in the Upper Colorado Region is negligible compared with use of surface water. For example, estimated withdrawals and consumptive use of ground water in 1970 amounted to only about 122,000 and 63,000 acre-feet (150.5 and 77.7 hm^3), respectively (fig. 11). Total withdrawals and consumptive use of water from all sources (including main-stem reservoir evaporation) were about 5.7 million and about 3.6 million acre-feet (7,030.9 and 4,440.6 hm^3), respectively. Most of this water was from the Colorado River system, including the ground-water component to streamflow.

The following tabulation of estimated total annual withdrawal of ground water by States in 1970 was compiled from unpublished data used by Murray and Reeves (1972) to estimate the use of water in the United States:

State	Withdrawal	
	Acre-feet	hm^3
Arizona	12,000	14.8
Colorado	27,000	33.3
New Mexico	9,000	11.1
Utah	38,000	46.9
Wyoming	36,000	44.4

There are few areas of concentrated ground-water withdrawals from wells in the region. Local areas in which total annual withdrawals exceed 500 acre-feet (0.6 hm^3) are shown in figure 12. The areas of largest withdrawals are Ashley Valley and upper Fremont River valley, Utah, where the water is used chiefly to supplement surface water for irrigation, and the Gunnison, Colo., area, where the water is used chiefly for public supply.

Withdrawals of ground water by wells apparently have not had widespread significant effect on ground-water levels. The few long-term water-level records available for various parts of the region indicate that the changes in ground-water levels (which reflect changes in ground-water storage) are caused chiefly by changes in the annual supply of natural recharge from precipitation. (See fig. 13.) Local depletions of ground-water storage by pumping, as in the Uinta Basin (indicated by well U(D-1-1)14bbc-1 in fig. 13) and in the Grand Junction area (Lohman, 1965, p. 113), are probably more than offset regionally by the increased storage resulting from bank storage around new reservoirs, such as Lake Powell and Flaming Gorge and Navajo Reservoirs. Because of the close relation between surface water and ground water (fig. 9*C*), however, large-scale ground-water withdrawal over a long period of time would intercept water that naturally enters streams, and this would ultimately reduce the flow of the Colorado River.

INCREASING THE USABLE SUPPLY OF GROUND WATER

In any given area of the region, the available supply of ground water is not necessarily the usable supply. In many places, for example, a large percentage of the available supply is too saline for most uses. In other places, much of the available supply is consumed by vegetation that generally is considered to be nonbeneficial economically. Even in areas where all the available supply is of usable quality, it may not be in sufficient quantity to sustain withdrawals for an intended use.

A number of water-management practices are available to increase the usable ground-water supply. They include (1) artificial recharge, (2) reduction of natural discharge by nonbeneficial vegetation, (3) demineralization, and (4) recycling. (See fig. 14.)

ARTIFICIAL RECHARGE

Artificial recharge is the augmentation of natural ground-water recharge by the activities of man. It may be used either to replace ground water where water levels have been drawn down or to temporarily increase local ground-water storage for later recovery. Artificial recharge can also serve to help even out streamflow — that is, aquifers can be used to absorb flood runoff, which will be released slowly back to the stream as runoff subsides.

Artificial recharge can be accomplished by two basic methods — surface spreading and subsurface injection. (See fig. 15.) Both methods are described by Price and others (1965) for parts of the Columbia North Pacific Region, with specific examples and associated problems. Both methods are also being practiced in the Upper Colorado Region, but neither is part of a water-resources development project. Recharge by surface spreading is incidental with most irrigation projects in the region, and subsurface injection is used to repressurize oil fields and for brine disposal at oil fields.

Successful artificial recharge requires an adequate supply of recharge water and suitable reservoir space. Water generally is available during storm runoff or peak seasonal runoff periods. Reservoir space, if not naturally present, can be created by dewatering an aquifer. Areas in the region that have the greatest potential for the use of artificial recharge are designated in figure 20 as having promise for water-resource development involving the conjunctive use of ground and surface waters.

Natural reservoir space exists in permeable unsaturated terrace deposits and extensive strata of unsaturated rocks, such as the sandstones in the Canyon Lands and Navajo sections. In these areas, perched ground-water bodies might be created by artificial recharge (fig. 16). The success of this type of artificial recharge would depend on the percentage of recharge water that could be recovered, which in turn depends largely on the retaining

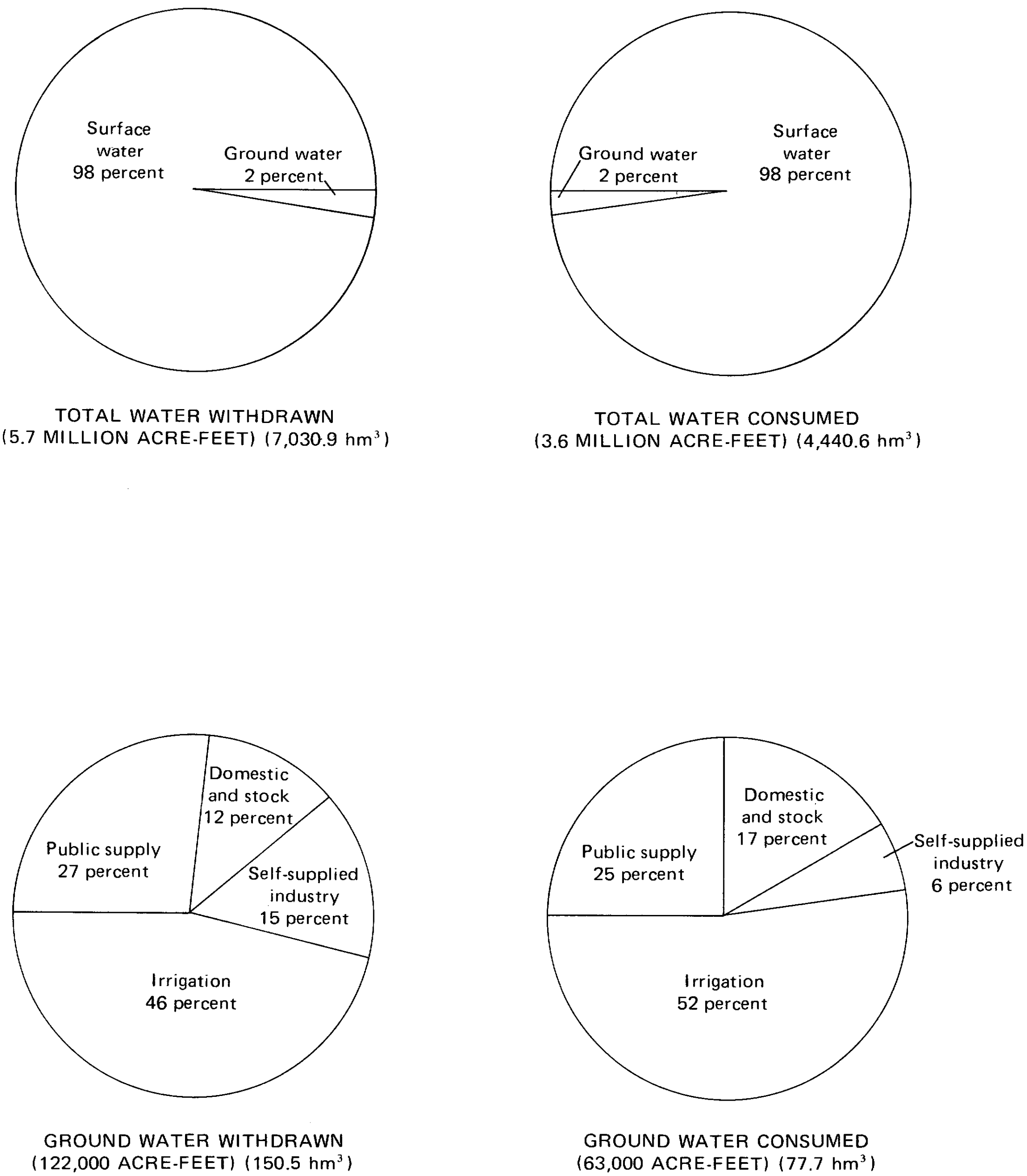


FIGURE 11. — Total withdrawal and consumptive use of ground water compared with the total withdrawal and consumptive use of water from all sources in 1970.

time of the reservoir rock. Some of the water will be lost by leakage from the artificial-recharge area, and some will be retained in the finer grained parts of the newly formed aquifer.

Deeper saline-water aquifers in the Canyon Lands and Navajo sections might also be used for recharge and later recovery from the freshwater bubbles (fig. 16). The freshwater source might be from natural runoff or it might be treated effluent. Injection and recovery of freshwater in saline aquifers is somewhat similar to injection and recovery of natural gas in aquifers, and it holds promise of utilizing some of the extensive saline-water aquifers in the region.

Reservoir space for artificial recharge can also be created by overpumping — that is, withdrawing ground water at a rate faster than it is replaced by natural recharge over an extended period of time. Overpumping is not uncommon in highly developed areas, such as many of the ground-water basins in the California and Lower Colorado Regions. It is practically nonexistent in the Upper Colorado Region, but it might be a desirable practice in some areas of the region where surface water

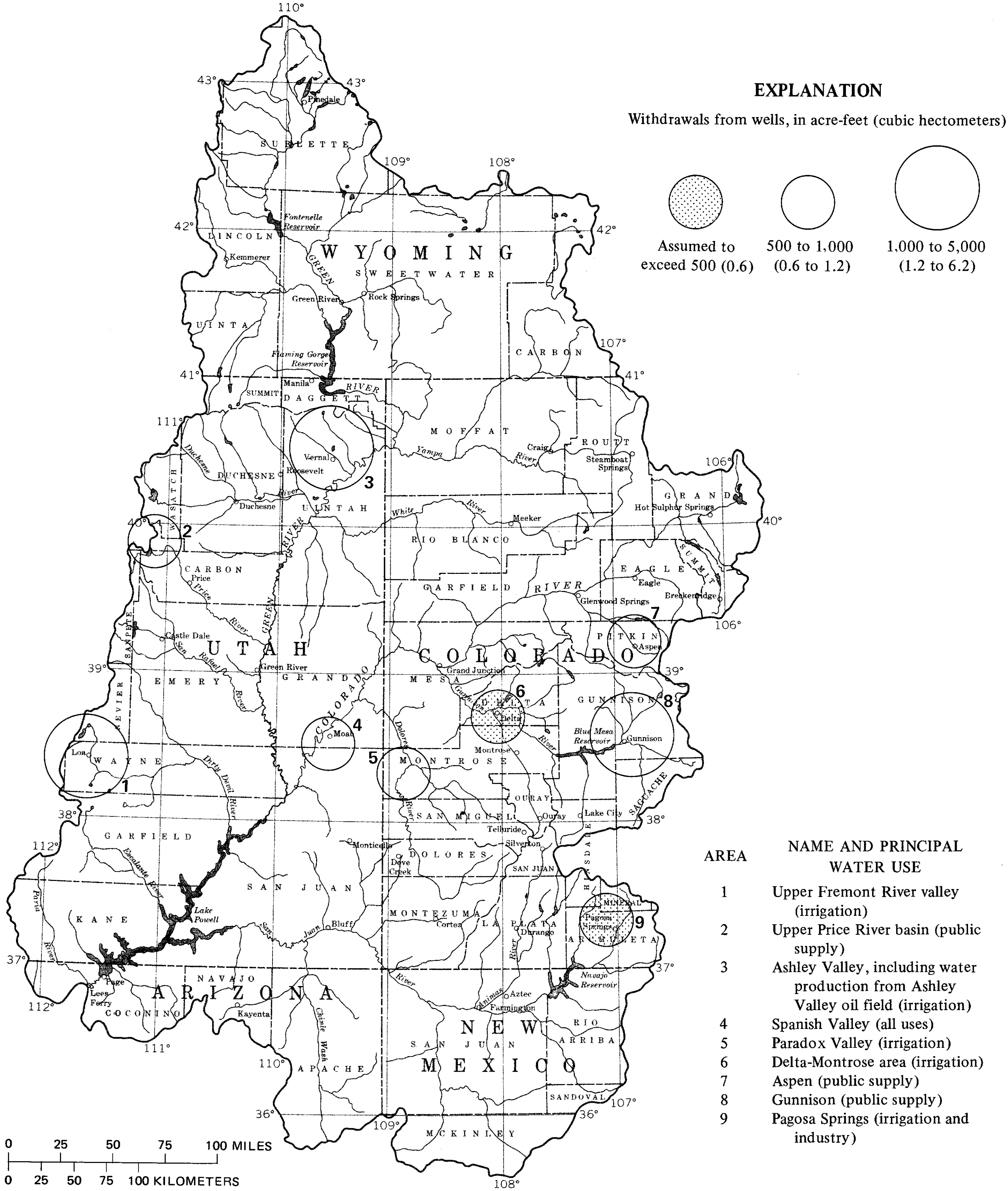


FIGURE 12. — Annual withdrawals from wells exceeded 500 acre-feet (0.6 hm^3) in 1970 in only a few scattered areas in the region.

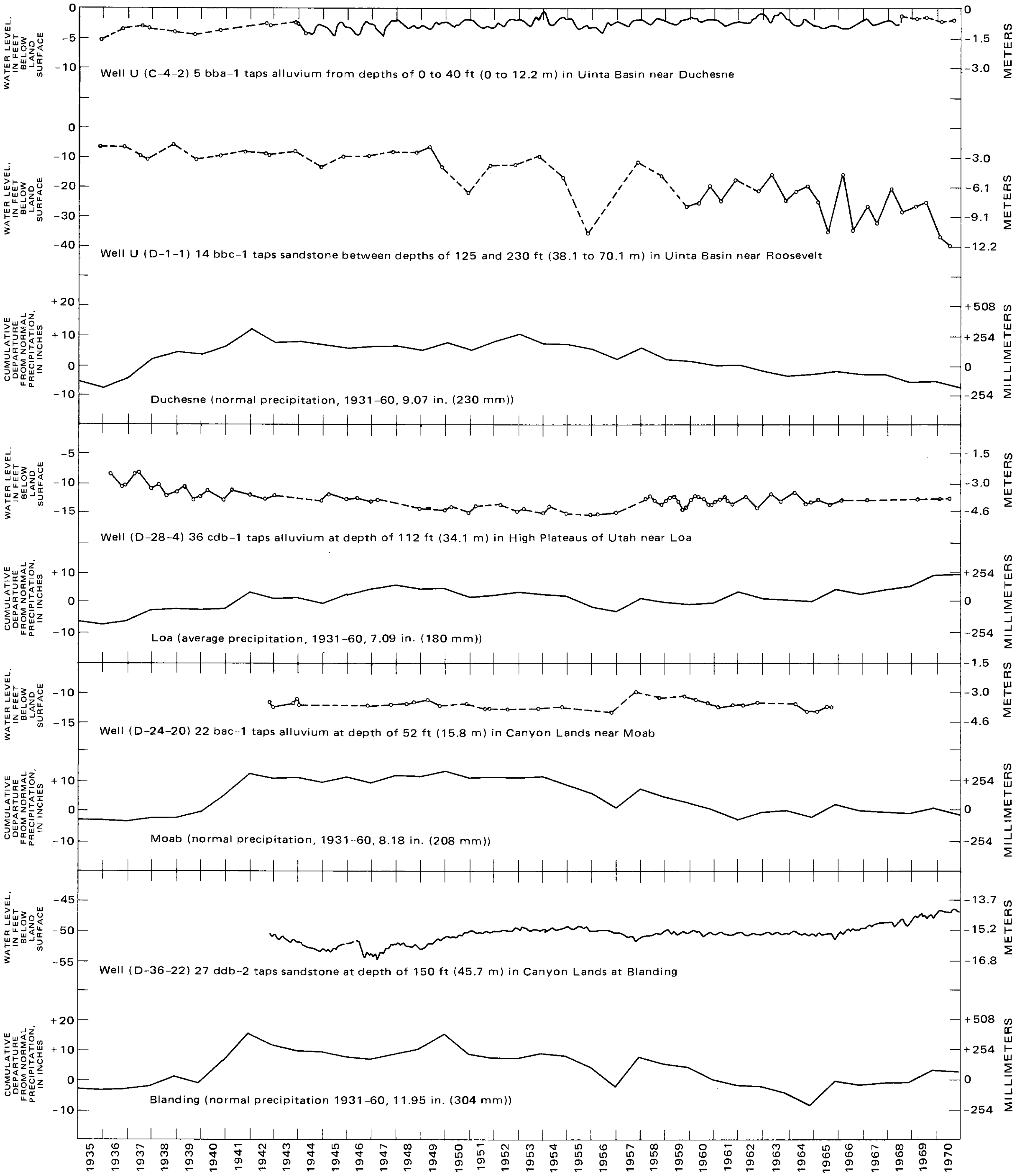


FIGURE 13. — Ground-water developments has had little effect on ground-water levels; changes in water levels reflect above- or below-average (normal) precipitation. Well locations are shown on plate 1*F*. Precipitation data are from National Weather Service.

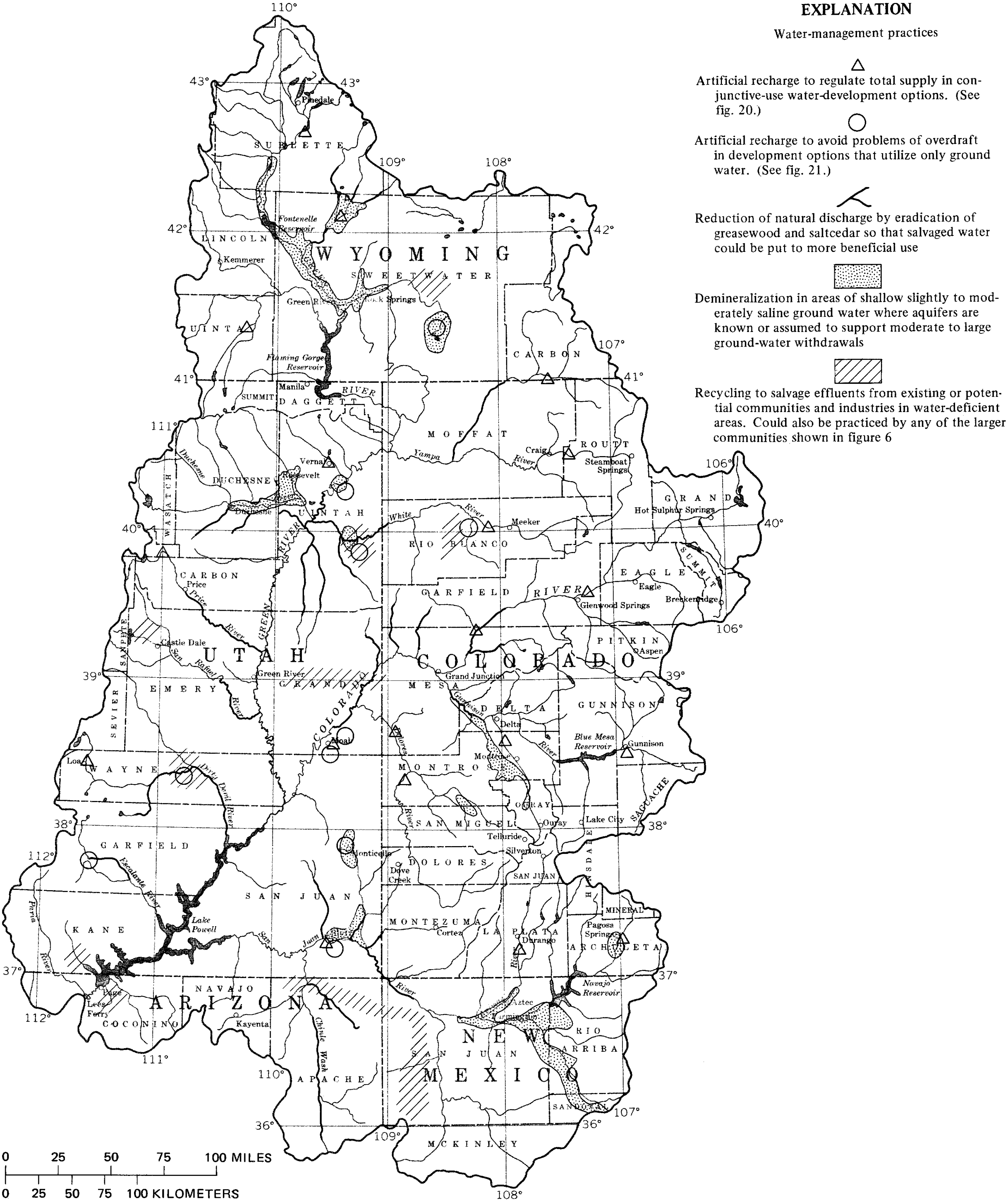
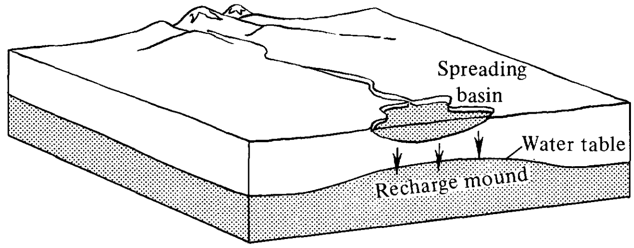
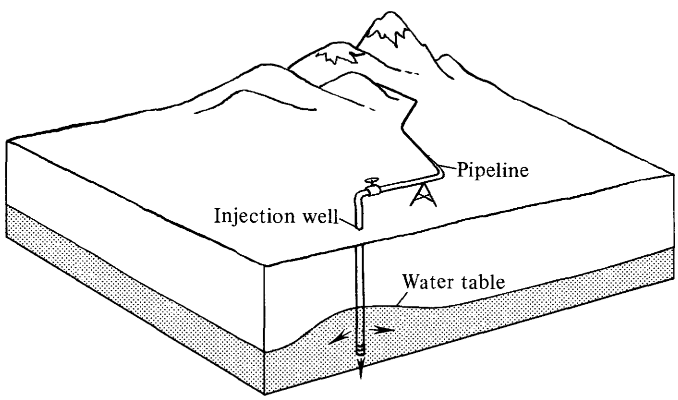


FIGURE 14. — Areas where water-management practices can be used singly or in combination to increase the usable ground-water supply. Map shows selected areas of existing or potential supply problems where these practices might be feasible.



ARTIFICIAL RECHARGE BY SURFACE SPREADING



ARTIFICIAL RECHARGE BY SUBSURFACE INJECTION

FIGURE 15. — Artificial recharge is accomplished by surface spreading or by subsurface injection.

might be available for recharge during periods of high runoff. For example, large quantities of water could be pumped from alluvium of the larger perennial streams for irrigation during critical periods of low flow in the late summer. Water removed by the increased late summer irrigation withdrawals could be replaced by artificial recharge using winter runoff, a time of low streamflow but of low seasonal demand, and spring and early summer runoff. Perhaps the wells used for withdrawal could also be used for injection — a recharge operation similar to that practiced near Klamath Falls, Oreg. (Price and others, 1965), or the recharge could be accomplished by surface spreading.

Artificial recharge not only is a means of increasing the usable water supply, but it also may prevent deterioration of ground-water quality which results from overpumping aquifers that are hydraulically connected with saline-water aquifers. This condition probably exists in Spanish and Castle Valleys, Utah, Paradox Valley, Colo., and in many other places throughout the region. The mound created by artificial recharge forms a barrier to encroachment of the saline water in the same fashion that artificial-recharge mounds successfully form barriers to the encroachment of sea water in the Long Beach area of California (Johnson and Lundeen, 1967).

REDUCTION OF NATURAL DISCHARGE

Consumptive use of ground water by phreatophytes (plants that rely directly on ground water for their moisture) and hydrophytes (plants that live in water, such as cattails and rushes) accounts for a major portion of the total natural ground-water discharge in the Upper Colorado Region. The phreatophytes, which are natural ground-water pumps, not only deplete ground-water storage but also have marked effect on streamflow. (See fig. 9.) The effect of evapotranspiration, largely by phreatophytes, on streamflow in part of the Green River basin is shown in figure 17. Consumption of water by phreatophytes also concentrates the mineral content of the remaining ground water and streamflow.

Phreatophytes commonly are found growing along the alluvial plains of both perennial and intermittent streams in the Upper Colorado Region. The most common ones in the region are cottonwood (*Populus* sp.), willow (*Salix* sp.), greasewood (*Sarcobatus vermiculatus*), rabbitbrush (*Chrysothamnus* sp.), saltcedar (*Tamarix* sp.), and saltgrass (*Distichlis stricta*). Greasewood and saltcedar (figs. 18, 19) probably are the most aggressive and least beneficial of the phreatophytes. They both are salt tolerant, and, although saltcedar is generally most adaptable to the southern part of the region, it has been observed growing in thick stands along many streams as far north as the Uinta Basin.

Consumptive use of water by phreatophytes varies depending on many factors, such as depth to water, water quality, and plant density. Under ideal growing conditions and 100-percent plant density, greasewood might consume on the order of 2 feet (0.6 m) of water and saltcedar might consume as much as 9 feet (2.7 m) annually. (See Mower and Nace, 1957, p. 21; Robinson, 1958, p. 75.)

The total volume of ground water consumed by phreatophytes in the region has not been estimated. Robinson (1968) estimated the consumptive use by phreatophytes and hydrophytes in the Colorado and Utah parts of the region alone to be more than 2 million acre-feet (2,467 hm^3) per year. Total consumptive use in the entire region probably approaches 2.5 million acre-feet (3,083.8 hm^3) per year. Part of this consumption, however, is from streamflow, as indicated by figure 9.

Some phreatophytes and hydrophytes are considered beneficial vegetation. The grasses provide forage for livestock, and the larger plants provide shade or add to the scenic value of the area in which they grow. Nevertheless, eradication of the least beneficial phreatophytes or their replacement with vegetation requiring less water

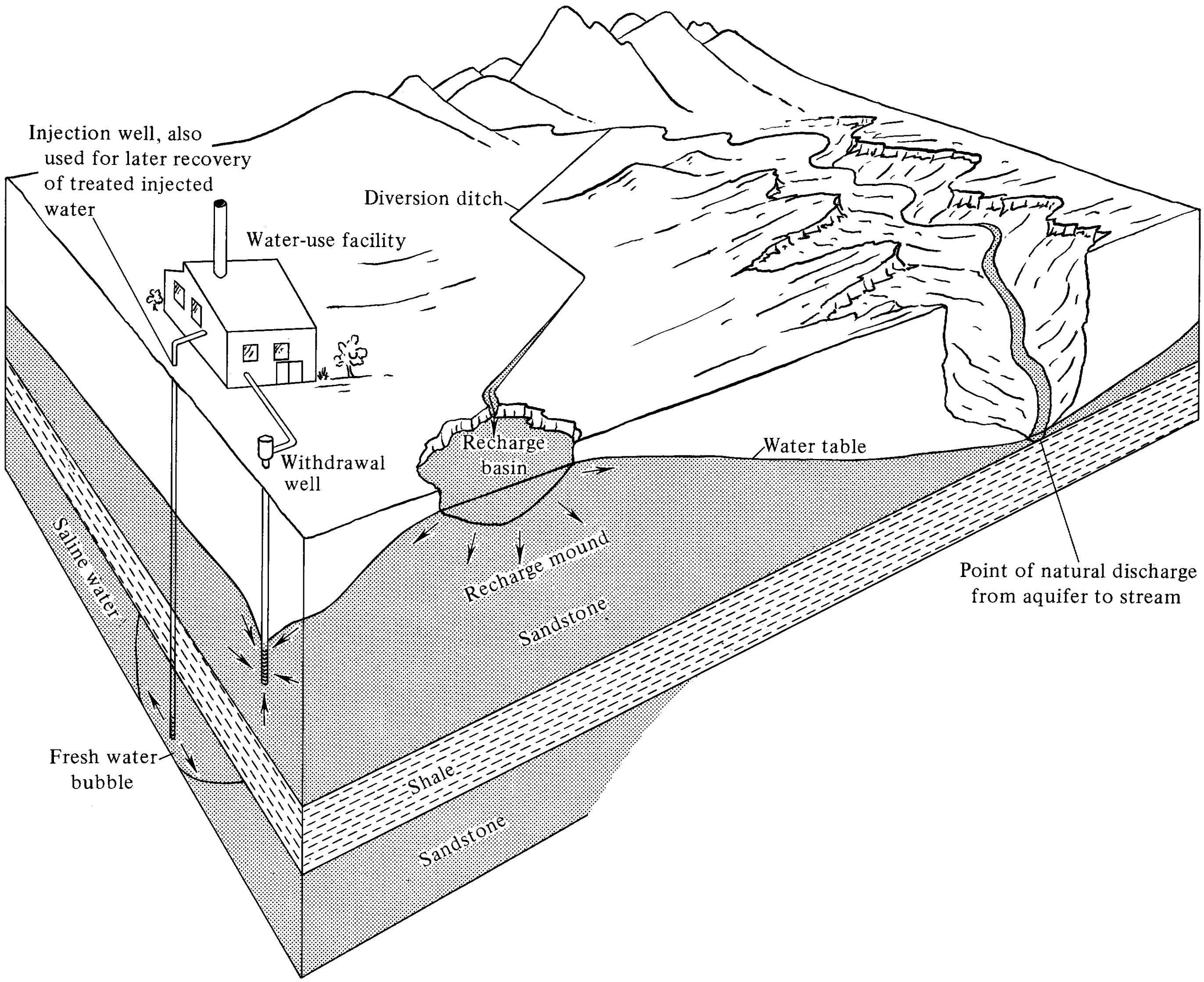


FIGURE 16. — Artificial recharge can increase the ground-water supply in water-deficient areas.

might add considerably to the total usable ground-water supply in some areas. In Spanish Valley, Utah, for example, an estimated 3,000 acre-feet (3.7 hm³) per year of ground water is consumed by phreatophytes (Sumsion, 1971a, p. 24). A large percentage of this water might be salvaged if the phreatophytes were eradicated or replaced. Even if there were no need for the water in the area in which phreatophytes had been removed or replaced, the salvaged ground water would eventually add to the total streamflow and could be used downstream.

DEMINERALIZATION

One of the principal limiting factors in the development of ground water in the Upper Colorado Region has been the widespread occurrence of generally undesirable saline ground water. (See pl. 2*A*.) Perhaps as much as 70 percent of the estimated maximum recoverable ground water stored in the upper 100 feet (30.5 m) of saturated sedimentary rocks is saline; this amounts to about 80 million acre-feet (98,680 hm³). If only 50 percent of this amount of water could be withdrawn and demineralized for beneficial uses, the total usable freshwater supply for the region could be increased by about 40 million acre-feet (49,340 hm³). This is considered a minimum figure, because considerably more recoverable saline water is stored at depths greater than 100 feet in the sedimentary rocks and in the other geohydrologic units shown on plate 1*A*.

Any development of saline water on a sustained basis, however, would be limited to the perennial yield of the saline-water aquifers. This might be only a few thousand

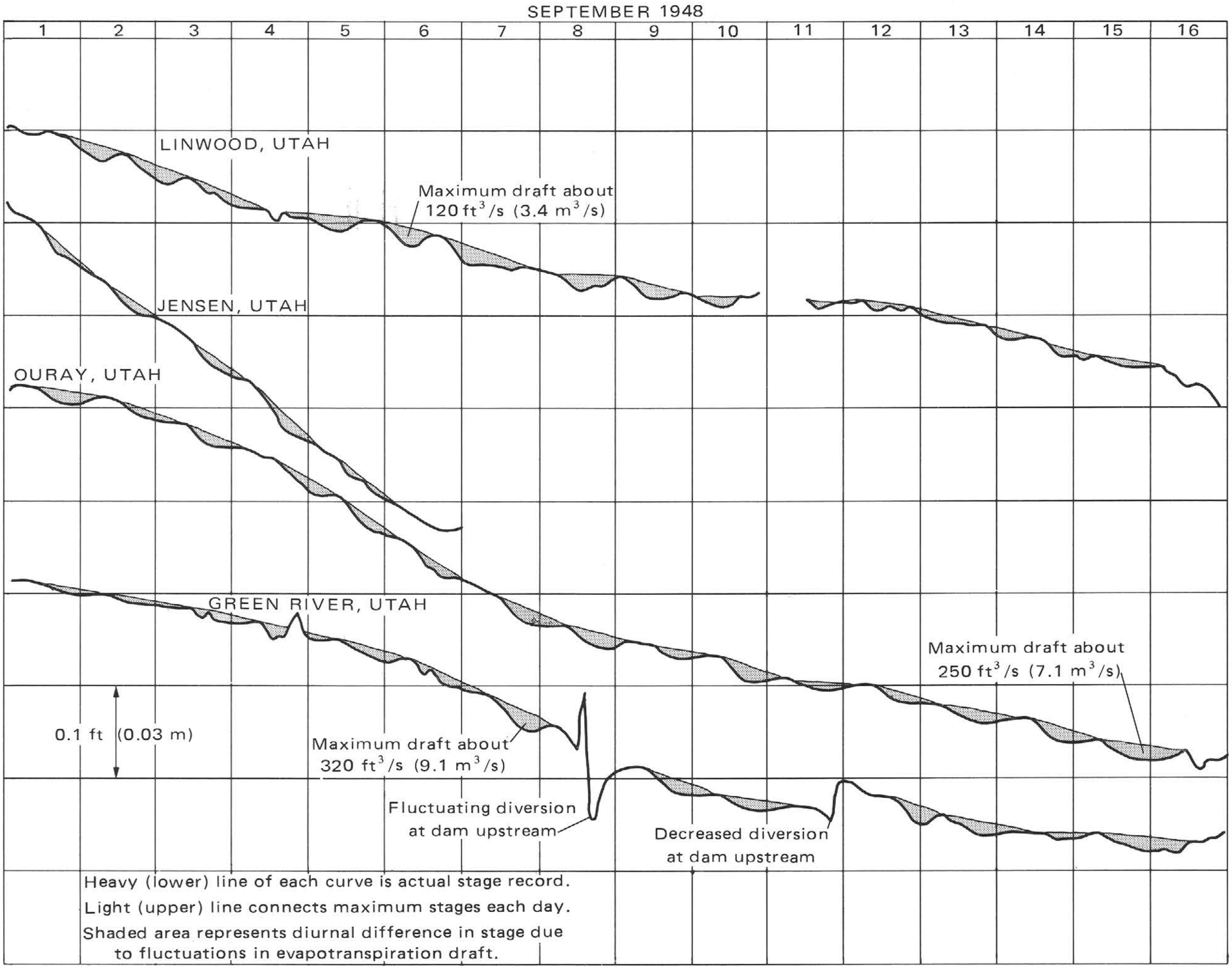


FIGURE 17. — The effect of evapotranspiration is reflected in fluctuations of the stage of the Green River (after Thomas, 1952, p. 20).

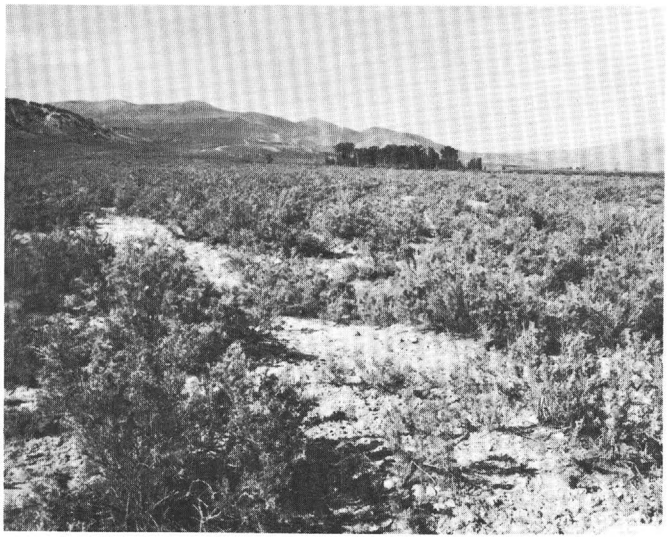


FIGURE 18. — Greasewood, a common phreatophyte which covers many square miles of the region (from Iorns and others, 1965).

FIGURE 19. — Saltcedar-lined perennial stream, one of many in the region.

acre-feet a year in many parts of the region, but it would provide an adequate supply for small communities and industries that use little water, and it probably would be the most feasible source to develop.

Demineralization is becoming an increasingly common practice throughout the world, and it should be adaptable to the Upper Colorado Region. According to the Office of Saline Water, more than 680 demineralization plants, with capacities ranging from as little as 25,000 gpd (gallons per day) to more than 7.5 mgd (94.6 to more than 28,390.5 m^3/day), were in operation in 1970. Existing commercial plants (in 1970), having capacities of 1 to 3 mgd (3,785 to 11,355 m^3/day), produce water in the general cost range of about $1 per 1,000 gallons (3.8 m^3). However, the status of large nuclear-powered dual-purpose plants, which produce both freshwater and electrical energy, indicates that a cost of 20 to 40 cents per 1,000 gallons (3.8 m^3) may be achieved before the year 2000 (Oak Ridge National Laboratory and Office of Saline Water, 1970).

Of the three basic demineralization processes — distillation, membrane, and vacuum freezing — distillation is most commonly used. This process can produce water with less than 25 mg/l of dissolved solids from natural supplies having a dissolved-solids content of 35,000 mg/l. The process might be well adapted to the Upper Colorado Region because it requires steam as its energy source, which might be produced from the vast fossil-fuel resources of the region. Because much of the recoverable saline water occurs near or in conjunction with major fossil-fuel reserves (as in the Green River, Uinta, Piceance Creek, and San Juan Basins), demineralization of saline water might be an ideal method of increasing the freshwater supply, if needed.

RECYCLING

Recycling of water is the reuse of water that has already been through a given supply system. The water might be recycled one or several times through the same system, or it may be taken from one system (such as a municipal supply) and put through another system (such as an industrial supply) where little or no treatment is required. Recycling does not physically increase the total usable water supply, but it does, in effect, "stretch" the supply by reducing nonbeneficial consumption of the effluent. It is becoming a common practice in many water-deficient areas of the world.

With recycling, it might be possible to develop sustained water supplies exceeding the natural sustained yields of certain aquifers. For example, an ore-processing plant might require a sustained water supply of 20,000 gpd (75.7 m^3/day), but the sustained perennial yield of the aquifers might be only 15,000 gpd (56.8 m^3/day). Assuming that the effluent from the plant is 10,000 gpd (37.8 m^3/day) and 50 percent could be recycled through the system, then the sustained yield of the aquifers plus the recycled water could support the industry on a perennial basis after the initial 20,000 gallons (75.7 m^3) has been withdrawn.

The amount of water that could be recycled depends on the consumptive use of the primary supply and on the percentage of the effluent that can be treated and reused. Many industries consume only a small percentage of the water withdrawn, but the effluent may be contaminated beyond treatment. For other industries, all the effluent may be economically treated and reused. The latter example is also true for effluents from municipal water supplies. In 1970 the difference between total withdrawals and total depletions of ground water for municipal use and self-supplied industry was about 32,000 acre-feet (39.5 hm^3). This, theoretically, is the volume of ground water regionally that might be recycled at least once at 100-percent recovery at the 1970 level of development.

AVAILABILITY OF GROUND WATER TO MEET FUTURE WATER NEEDS

As noted earlier, the perennial ground-water supply for the Upper Colorado Region is about 4 million acre-feet (4,934 hm^3); in addition, the recoverable reserve of ground water in storage in just the upper 100 feet (30.5 m) of saturated rocks may be as much as 115 million acre-feet (141,852.5 hm^3). Yet, in 1970, only about 2 percent of the estimated withdrawal and consumptive use of water for all uses in the region came directly from ground-water sources.

By the year 2020 the projected consumptive use of water for various uses in the region will be about 4.1 million acre-feet (5,057.4 hm^3) per year, as indicated in the following tabulation. Part of these needs could be met from ground-water sources.

Supply	Consumptive use[1]	
	Acre-feet	hm^3
Irrigation	[2]3,294,000	4,063.1
Thermal electric power	627,000	773.4
Municipal and industry	110,000	135.7
Minerals development	[3]85,000	104.8
Domestic and stock	25,000	30.8
Recreation	5,000	6.2

[1]All estimates except for domestic and stock supply and minerals development are after Hedlund and others (1971, p. 54). The estimate for domestic and stock supply assumes an increase of about 10 percent over the 1970 use.
[2]Includes reservoir and incidental evaporation.
[3]Assumes minimum additional requirement of 32,000 acre-feet (39.5 hm^3) for mining and processing oil shale (U.S. Dept. Interior, written commun., 1973).

The projected consumptive water need for irrigation annually by the year 2020 is estimated to be about 3.3

million acre-feet (4,070.6 hm^3). Although most of this need will be met with surface water, ground water is available in many of the irrigated areas to supplement surface water, particularly during periods of low flow and peak crop requirements. A minimum of 3,200 acre-feet (3.9 hm^3) of recoverable ground water per square mile is stored in alluvium in the irrigated areas along the Colorado and Green Rivers and other large streams. Most of these areas cover at least 10 square miles (25.9 km^2), indicating that at least 32,000 acre-feet (39.5 hm^3) of ground water is available to supplement the surface-water supply in each of the areas. If only half of this water were withdrawn in any given 10-square-mile (25.9 km^2) area, it could be used to irrigate about 16,000 acres (6,475.2 ha) during periods of low flow at a crop requirement of 1 foot per acre (0.3 m/ha).

An estimated 627,000 acre-feet (773.4 hm^3) of water will be needed annually for production of thermal-electric power by the year 2020 (Hanley and others, 1971, p. 65). The individual plants that will be producing this energy will require from about 6.6 to more than 130 million gallons (24,983.6 to 492,102 m^3) of water per day. Most will be located where ground water is plentiful (sites of plants are shown on pl. 2*B*) but where the aquifers yield water too slowly to meet the daily requirements on a sustained basis. However, ground water could be developed at some sites as supplemental or emergency supply.

The use of ground water for municipal and industrial supply has been inhibited in many areas by undesirable chemical characteristics of the water. Recent advancements in the field of demineralization and progressive decline in cost per unit volume of demineralized water, however, now make the cost such that ground water could be used to supply a large part of the projected water needs of 110,000 acre-feet (135.7 hm^3) per year for municipal and industrial use. The larger communities, such as Farmington, N. Mex., and Grand Junction, Colo., may require between 15,000 and 20,000 acre-feet (18.5 and 24.7 hm^3) per year for municipal and industrial supply by the year 2020. Most of the other communities probably will require between 100 and 5,000 acre-feet (0.1 and 6.2 hm^3) per year. Ground water (with optional demineralization) is available in most places to meet these requirements completely or, in some places, as a supplemental supply. Communities near the larger streams could obtain water from alluvium through shallow wells or infiltration galleries. Such communities as Price and Vernal, Utah, Green River, Wyo., and Grand Junction, Colo., are underlain by aquifers that contain slightly to moderately saline ground water that probably could be economically withdrawn and demineralized.

Mountain resort communities such as Aspen and Steamboat Springs, Colo., have a seasonal influx in population. For example, the permanent population served by the Aspen municipal water supply is about 4,000 (1970), but during the winter ski season the population increases to more than 20,000. With a trend to development of such communities for seasonal leisure and recreation, there will be a growing need for adequate seasonal public water supply. Most of the existing or potential mountain resort communities are on or near mountains streams. A seasonal water supply for those communities could be developed from the permeable alluvium of the streams, and the ground water withdrawn during the tourist influx could be replaced by natural or artificial recharge during the off-season.

Most of the projected annual water need of 85,000 acre-feet (104.8 hm^3) by the year 2020 for minerals production could be obtained from ground-water sources. Most of the mineral production of the region is in areas where surface water is absent, inadequate, or used for other purposes. The ground water in the fossil-fuel-producing areas generally is saline, but it generally is suitable for such uses as repressuring oil and gas fields.

The amount of water needed to develop the vast oil-shale reserves in the Uinta, Piceance Creek, and Green River basins will depend on whether the oil is released by surface or in situ retorting. Mining and surface retorting of the shale may require large supplies of water. The actual volume required is not known, and it will depend on such factors as methods used to mine, crush, upgrade, and retort the shale, and the availability of electrical energy and the methods used to dispose of the spent shale. Preliminary estimates of the total volume of water needed range from as much as 189,000 to as little as 32,000 acre-feet (233.1 to as little as 39.5 hm^3) per year for an oil production capacity of 1 million barrels (158,987 m^3) per day. The estimated maximum need probably will have to be met largely from surface sources, but the minimum need probably can be met with ground water — part of which will be produced from the shale and part can be developed from local unaffected aquifers. In the Piceance Creek basin, however, water produced by mine dewatering activities might be sufficient to meet the entire estimated maximum need for the first few years of operation. In all areas, ground water could be used to supplement a surface-water supply for the life of the development. In situ retorting of the shale could reduce water requirements by more than 60 percent by eliminating water needs for mining, dust control, surface retorts, and disposal and revegetation of spent shale.

Only about 30,000 acre-feet (37.0 hm^3) of water will be needed annually for domestic, stock, and recreation supply by the year 2020. These needs can be met from ground water in most parts of the region.

SELECTED DEVELOPMENT OPTIONS

Various options for use of ground water in overall water management are possible in the Upper Colorado Region. In some areas, ground water might be used conjunctively with surface water. In other areas, ground water might be developed as the sole supply on a sustained basis or a time-limited basis. In order to approach optimal development of the total water resource of the region, the various options would include one or more of the practices for increasing the usable ground-water supply discussed in a preceding section of this report.

CONJUNCTIVE USE OF SURFACE WATER AND GROUND WATER

The opportunity to use ground water in conjunction with surface water exists locally along several of the larger perennial streams that are underlain by permeable alluvial aquifers, as illustrated in figures 8*C* and *D*. The areas are shown in figure 20. In these areas, ground water could be used to augment surface water during periods of low flow, which commonly coincide with periods of peak seasonal demand. Should the withdrawal of ground water exceed natural recharge during these periods, then artificial recharge could be implemented during peak runoff periods to facilitate ground-water replenishment.

Such a coordinated system would provide a more uniform year-round water supply without surface-reservoir construction. The well fields, regardless of their primary purpose, would also provide an emergency public water supply in populated areas. For example, the public water supply for Delta, Colo., is diverted from a stream and a spring which are 17 and 11 miles (27.4 and 17.7 km) north of the city, respectively. Should that supply be disrupted by a man-caused accident or a natural disaster, local well fields used to augment surface water for irrigation might serve as a temporary public supply for the city while the primary system is being restored.

Few areas in the region have been investigated in sufficient detail to determine their adaptability to a program of conjunctive development of ground and surface water. Selected potential areas for such development are shown in figure 20. One of these areas is the upper Fremont River valley of Utah, which might serve as a specific example of how ground water could be used to increase the total usable water supply for irrigation during seasonal low-flow periods. The ground-water resources of the upper Fremont River valley are described by Bjorklund (1969). Although only about 40 square miles (103.6 km^2) in areal extent, the valley contains one of the most productive ground-water reservoirs in the Upper Colorado Region. Yields to irrigation wells in the valley range from several hundred to more than 2,000 gpm (7.57 m^3/min). Total estimated recoverable storage in the upper 100 feet (30.5 m) of the ground-water reservoir in the valley is between 130,000 and 380,000 acre-feet (160.4 and 468.7 hm^3), and the perennial yield of the reservoir is on the order of 90,000 acre-feet (111 hm^3). Most of the water is fresh and suitable for irrigation and most other uses.

The surface-water supply for the valley is the Fremont River, and it is used primarily for irrigation. Flow of the river into the valley is regulated and has been measured during the period 1949-58, including the complete irrigation seasons during 1950-57. During those irrigation seasons, average monthly flow of the river was about 4,400 acre-feet (5.4 hm^3). However, the flow in September and October of some years was as low as 1,300 acre-feet (1.6 hm^3). This is an assumed deficiency of about 3,000 acre-feet (3.7 hm^3). Use of ground water in a management program for conjunctive use of water resources could make up this deficiency and perhaps provide enough water for irrigation of additional acreage.

Well fields could be located to deliver the water directly to the irrigated fields or to canals and distribution ditches. An inherent problem associated with large-scale ground-water development — well interference — could be minimized by proper well design and spacing. Any temporary overdraft could be replaced by artificial recharge during peak runoff periods.

A planned development that makes optimum conjunctive use of the ground- and surface-water resources in the upper Fremont River valley might provide a combined annual supply of more than 100,000 acre-feet (123.4 hm^3). This would consist of the perennial ground-water supply, plus surface-water inflow, plus irrigation-return flow, which could be as much as 25 percent of the total withdrawal. However, this type of development might virtually deplete the flow of the Fremont River.

USE OF GROUND WATER ONLY

Extensive areas of the Upper Colorado Region are far removed from the principal river systems. The supply from local intermittent and ephemeral streams supports some livestock but it is not sufficient to meet large-scale demands. Yet these areas are underlain by extensive bedrock aquifers that may be capable of supplying sufficient water for industry, public supply, or to irrigate small areas. Plans for development of this water might consider use on a sustained basis where the annual withdrawal would not exceed the perennial yield of the aquifers, or on a time-limited basis where the total recoverable ground-water storage would be withdrawn (mined) at a given annual rate for a given number of years. Because a large percentage of the water is saline, a demineralization process would be an integral part of most developments.

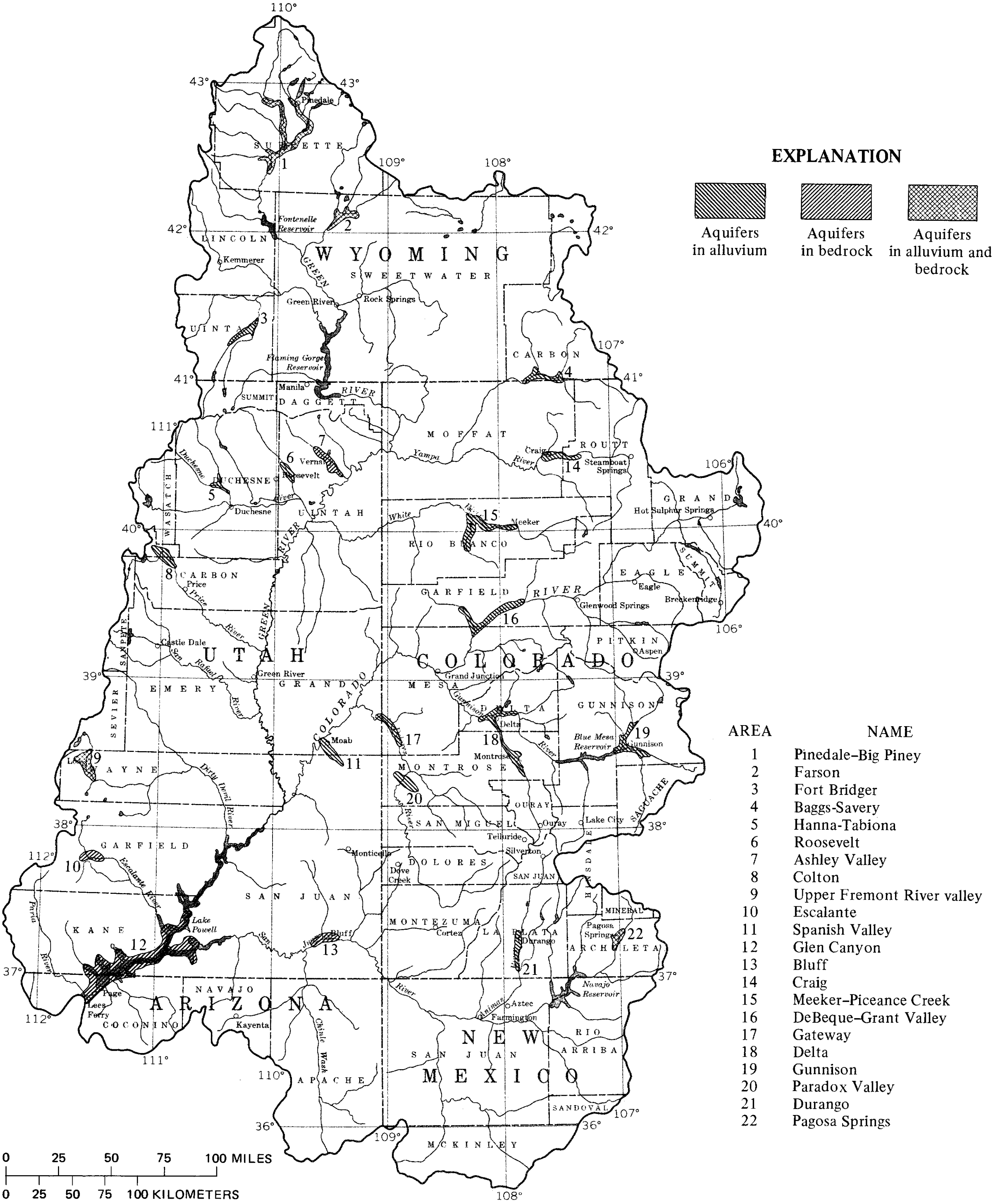


FIGURE 20. — Areas where aquifers are known or assumed to be sufficiently productive for conjunctive use with surface water in water-resources development.

SUSTAINED GROUND-WATER SUPPLY

A sustained ground-water supply is one where the planned annual withdrawal over a long time does not exceed the annual natural discharge of the aquifers. Successful development of ground water on a sustained basis requires that the size and character of the ground-water reservoirs be fairly accurately known and that the annual withdrawals be regulated to prevent excessive drawdowns and stream depletions. Short-term withdrawals exceeding the annual discharge rate might be tolerated if recycling or artificial recharge were a part of the development.

Areas that have some potential for moderate to large development (0.5 to 1.5 mgd or 1,892.7 to 5,678.1 m^3/day) of ground water as a sole supply are shown in figure 21. These areas appear to be underlain by aquifers that seem to have good sources of recharge. They have not been investigated in detail, however, so it is not possible to do more than speculate on the size or even the feasibility of such development in these areas.

A hypothetical development using ground water on a sustained basis as a sole source of supply is herein described using Spanish Valley, Utah, as an example. The water resources of Spanish Valley have been described by Sumsion (1971a). The valley covers about 18 square miles (46.6 km^2) and is underlain by permeable valley-fill deposits to depths of at least 360 feet (109.7 m). It is estimated that the ground-water reservoir will yield about 14,000 acre-feet (17.3 hm^3) per year and that about 58,000 to 173,000 acre-feet (71.5 to 213.4 hm^3) of water is recoverable from storage in the upper 100 feet (30.5 m) of the reservoir.

At the 1970 level of development, about 3,300 acre-feet (4.1 hm^3) of ground water was withdrawn from Spanish Valley for irrigation and public and domestic supply. About 8,000 acre-feet (9.9 hm^3) of ground water drained to the Colorado River, and another 3,000 acre-feet (3.7 hm^3) was consumed by phreatophytes and hydrophytes. Most of this 11,000 acre-feet (13.6 hm^3) of water could be put to beneficial use directly in Spanish Valley if it were withdrawn there from wells. An annual supply of about 11,000 acre-feet (13.6 hm^3) could be used by industry, or to supply a population of about 65,000 additional people at a per capita consumption rate of 150 gallons (0.57 m^3) per day, or to irrigate about 3,700 additional acres (1,497 ha) at an application rate of 3 feet per acre (0.9 m/ha) per year, or any combination of these. The water thus used would be of better chemical quality than it would be after seepage through the area of phreatophytes in the downstream part of the valley, where the dissolved-solids content increases as a result of evapotranspiration.

Sustained development of 14,000 acre-feet (17.3 hm^3) of ground water in Spanish Valley need not necessarily denude the area presently occupied by phreatophytes or completely terminate underflow to the Colorado River. The phreatophytes could be replaced by nonphreatophytic vegetation that uses less water and provides the same forage, shade, and scenic benefits. If the development were entirely for municipal and industrial supply, only about 54 percent (regional average in 1970) of the withdrawal would be consumed; thus, more than 7,500 acre-feet (9.2 hm^3) of water might still be allowed to reach the Colorado River. Withdrawals for irrigation or certain industries, which consume larger percentages of the diversions, would decrease proportionately the amount of water reaching the river; however, this could be offset to some extent by incorporating recycling systems in the development program.

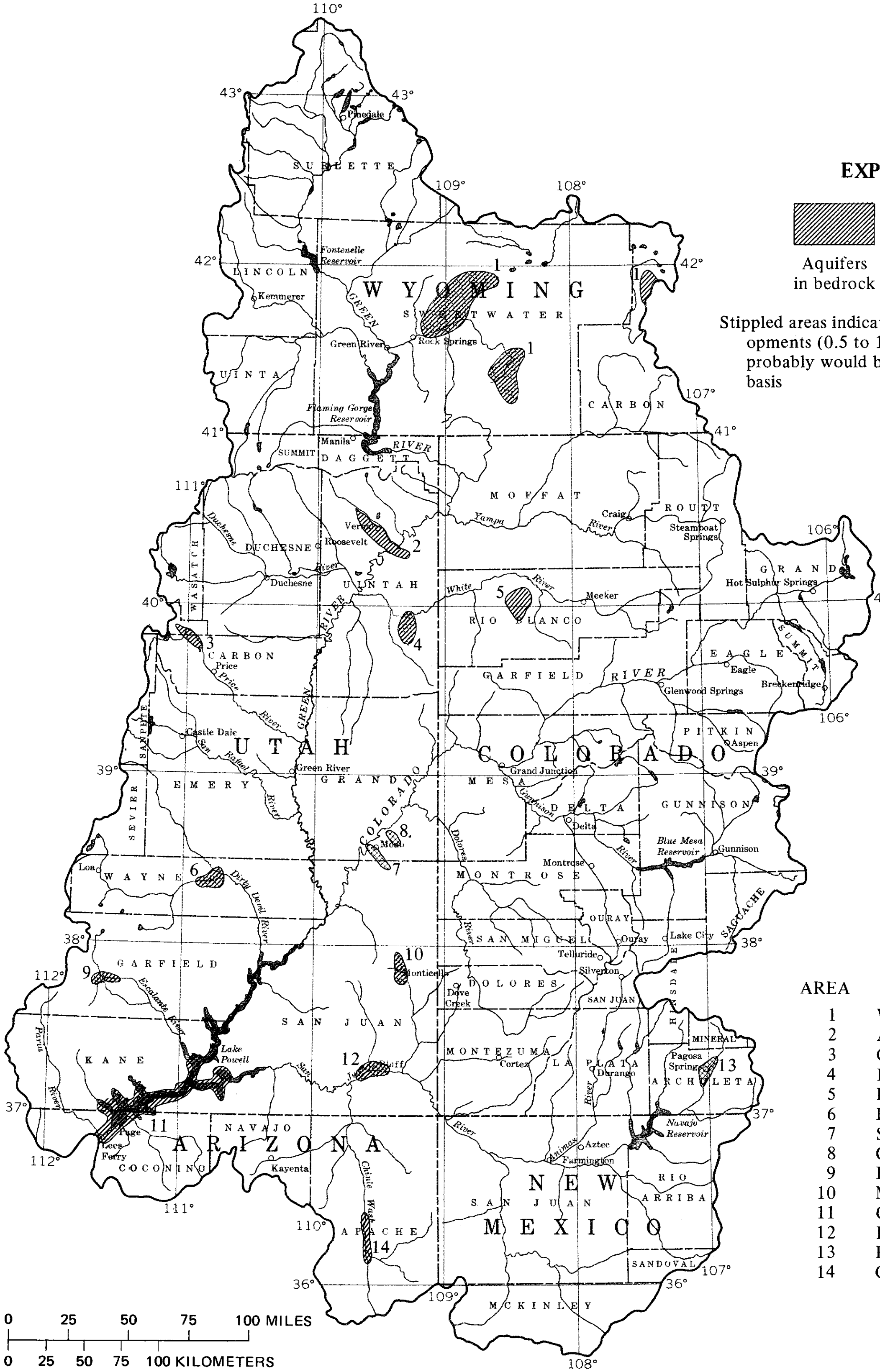
TIME-LIMITED GROUND-WATER SUPPLY

A time-limited ground-water supply is one where the planned annual withdrawal will exceed the annual natural discharge, the excess amount being obtained (mined) from the recoverable water in storage in the aquifers. This supply is limited in time by the number of years required to deplete the water in storage or to lower water levels to depths at which it is no longer economically feasible to withdraw the water.

Large-scale sustained ground-water developments generally are not possible in those parts of the Upper Colorado Region underlain by bedrock aquifers and far removed from principal areas of recharge. The rate of ground-water movement to the area of withdrawal would be too slow, even if a highly efficient recycling system were incorporated in the development. Nevertheless, large quantities of ground water in transient storage in these areas are either being wasted or becoming chemically degraded as they move to areas of natural discharge. Diversion of this water for beneficial use on a time-limited basis (ground-water mining) might be the best solution to water-supply problems in the arid Canyon Lands and Navajo sections of the region (fig. 21).

Little quantitative data are available for any of the areas shown in figure 21, but provisional estimates are made herein to illustrate the development of a time-limited ground-water supply in the Escalante area of Utah. The estimates are based on a reconnaissance by Goode (1969) of the ground-water resources of this area.

The ground water to be developed is under artesian pressure in the Navajo Sandstone, which is about 1,500 feet (457.2 m) thick in the area. Goode (1969, p. 31) estimated that if the sandstone were completely saturated, the total quantity of water in storage might be as much as 60,000 acre-feet per square mile (28.6 hm^3/km^2). Assuming that 60 percent of this water could be recovered by wells, then recoverable water in storage



EXPLANATION

Aquifers in bedrock

Aquifers in alluvium and bedrock

Stippled areas indicate that moderate to large developments (0.5 to 1.5 mgd)(1,892.7 to 5,678.1 m³/d) probably would be possible only on a time-limited basis

AREA	NAME
1	Washakie-Great Divide Basin
2	Ashley Valley
3	Colton
4	Bonanza (oil-shale area)
5	Piceance Creek (oil-shale area)
6	Hanksville
7	Spanish Valley
8	Castle Valley
9	Escalante
10	Monticello
11	Glen Canyon
12	Bluff
13	Pagosa Springs
14	Chinle-Many Farms

FIGURE 21. — Areas where aquifers are known or assumed to be sufficiently productive for use as a sole water supply in water-resources development.

would be about 36,000 acre-feet per square mile (17.1 hm^3/km^2) and would total about 360,000 acre-feet (444.1 hm^3) in a 10-square-mile (25.9 km^2) area from which the wells would most likely draw water. Average annual recharge to the Navajo Sandstone in this area probably is less than 2,000 acre-feet (2.5 hm^3) and, therefore, could be considered negligible. If the development is planned for a lifespan of 30 years, then the annual withdrawal would be nearly 12,000 acre-feet (14.8 hm^3). This much water could irrigate 4,000 acres (1,619 ha) of land at an annual crop requirement of 3 feet per acre (0.9 m/ha). If larger annual withdrawals are required, the lifespan of the development could be shortened. If smaller annual withdrawals are required, the lifespan of the development could be lengthened.

OTHER USE OF UNDERGROUND SPACE

Utilization of underground space for artificial recharge of ground water has already been discussed as a means of increasing the usable ground-water supply. Other uses of underground space include underground disposal of fluid waste, flood control, and underground storage of gas, liquid, and solid materials for later recovery and use.

FLUID-WASTE DISPOSAL

With increasing social pressures to reduce pollution of the surface environment, there has been an accelerated growth in underground disposal of fluid waste. According to Kohout (1970, p. 1445) the number of wells constructed for underground disposal of fluid industrial wastes in the country increased from 10 in 1950 to nearly 150 in 1969 and might approach 500 by 1980. The technique is used in the Upper Colorado Region almost exclusively for disposal of oil-field brines; it might also be used to dispose of blowdown water from the cooling towers of thermal-electric powerplants, waste brines from desalting plants, and other fluid industrial wastes.

Important requirements for successful underground disposal of fluid waste are that the reservoir rock be capable of accepting and retaining the waste indefinitely and that it be hydrologically isolated by impermeable strata from freshwater aquifers. Many areas in the Upper Colorado Region seem to meet these requirements. Deep aquifers in the Green River, Uinta, Piceance Creek, and San Juan Basins contain brines that are probably more highly mineralized than many untreated fluid wastes; therefore, they might not have a better use than as reservoirs for the fluid waste. They apparently transmit water very slowly and seem to be virtually isolated hydrologically from freshwater aquifers and streams. Areas in the region where underground disposal of fluid waste might be feasible are shown in figure 24. Before any underground fluid-waste disposal project is implemented, however, it should be preceded by detailed and careful study to insure that the waste remains out of the surface environment indefinitely and does not contaminate usable ground-water supplies.

FLOOD CONTROL

Underground space in the unsaturated zone can be used for the control of flash floods, which are a serious problem throughout the region. Floodwaters could be diverted over permeable unsaturated terrace deposits, which generally exist near mouths of canyons, to be absorbed and released gradually back to the stream channel. The cost of required diversion facilities and spreading basins might be minimal compared with the high cost of repeated repair or replacement of bridges and other structures generally damaged by floods.

UNDERGROUND STORAGE

Underground storage as used here is the emplacement underground of any material with the intent of recovering that material for later use. Underground storage of natural gas is a common practice in the Gulf Coast area and in other parts of the world. The space utilized for storage of gas generally is in depleted oil or gas reservoirs, but aquifers are also used. In aquifers, the gas is stored as a bubble below impermeable rock and above the heavier ground water. Such a reservoir has been created in the Paradox(?) Formation near Moab, Utah (C. T. Sumsion, oral commun., 1972), and others seem feasible in that general area.

A unique use of underground space for storage and recovery of water is the multiple-aquifer reverse-cycle heating and cooling system. This system has had considerable success in some large office buildings in Portland, Oreg., and Tacoma, Wash. It might be adaptable to the Upper Colorado Region because there are multiple-aquifer systems throughout the region (as illustrated in figs. 8*A*, *B*), and this method of heating and air conditioning consumes very little water.

A special use of the unsaturated zone in underground space is the storage in underground chambers of dangerous chemical and strategic war materials that must be isolated from densely populated areas. The great thicknesses of relatively unsaturated rock in the sparsely populated Canyon Lands section of the region might provide such space with a minimum of construction and security costs. Because of the widespread distribution of radioactive minerals in the rocks in the section, however, storage of materials that are affected by radiation might not be advisable.

PROBLEMS AND CONSTRAINTS ASSOCIATED WITH GROUND-WATER DEVELOPMENT

PHYSICAL PROBLEMS

Theis (1940, p. 280) listed some of the basic principles regarding ground-water development, and a summary of them follows:

1. All water discharged by a well is balanced by a loss of water somewhere in the system. The loss may be depletion of aquifer storage, reduction in streamflow, reduction of evapotranspiration, or reduced normal water flow from the region.
2. The loss is in many cases largely from aquifer storage. Some ground water is always mined. The ground-water reservoir is in effect bounded by time, by structural conditions, and by material boundaries. The amount of water removed is proportional to the drawdown, which, in turn, is proportional to the rate of pumping.
3. If the drawdown cone reaches an area of recharge, the well discharge will be made up, at least in part, by an increase in the recharge. If any recharge was previously rejected through nonbeneficial transpiration, no economic loss will probably occur. If the recharge was rejected through springs or by refusal of the aquifer to absorb surface water, an economic loss may result owing to resulting decrease in spring or stream discharge.
4. If the drawdown cone reaches areas of natural discharge, further discharge by wells will be made up, in part, by a reduction in natural discharge. If this natural discharge fed surface streams, prior rights to the surface water may be injured.
5. In artesian aquifers, because the cones of depression spread with great rapidity, each well in a short time has its maximum effect on the whole aquifer and obtains most of its water by increase of recharge or decrease of natural discharge.

DECLINES IN WATER LEVELS

Water levels in the vicinity of a discharging well or well field will decline as long as the rate of the well discharge exceeds the rate of recharge to the aquifers supplying the water. Decline in the water levels is in the form of an inverted cone (cone of depression), as shown in figure 16. As the cone expands, the amount of ground-water moving toward the well or well field will increase until it equals the amount of discharge from the wells; then, the water levels should cease to decline. The water levels will begin to rise once pumping ceases. In areas of closely spaced wells, however, even temporary water-level declines may create legal and economic problems, owing to the interference caused by a discharging well on the water levels in nearby wells.

If withdrawals exceed natural recharge over many years, water levels might decline until a level is reached where further drilling or pumping would be uneconomical. This possibility is readily apparent in areas of deep natural water levels (pl. 1*G*), where the cost of drilling and pumping might be greater than the benefits to be gained.

DEPLETION OF STREAMFLOW

The relation of ground water and surface water was discussed on page 00 and is illustrated in figure 9. As shown in figure 9*C*, pumping of ground water can deplete streamflow. This is true whether the well field is adjacent to a stream or some distance from a stream, as long as there is hydraulic connection between that stream and aquifers tapped by the wells.

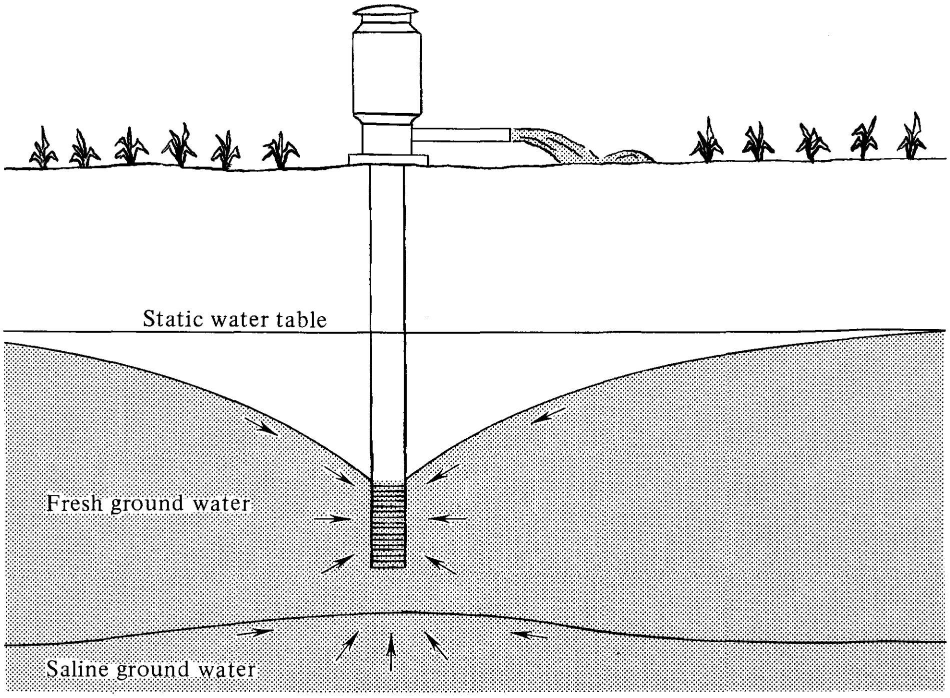
The amount of depletion would be proportional to the amount of ground water withdrawn provided that there is no return flow. Therefore, the effect of small ground-water withdrawals probably would be minuscule and could not be detected by current methods of streamflow measurement. In contrast, long periods of large-scale pumping, such as several tens of cubic feet per second during an irrigation season, from the alluvium of relatively small streams (average discharges of several hundred cubic feet per second during the irrigation season) would unquestionably cause a significant reduction of streamflow. This could result in legal problems related to local water rights and the Colorado River Compact, and it might also have an effect on the ecology of the stream and the water-related land resources.

DETERIORATION OF WATER QUALITY

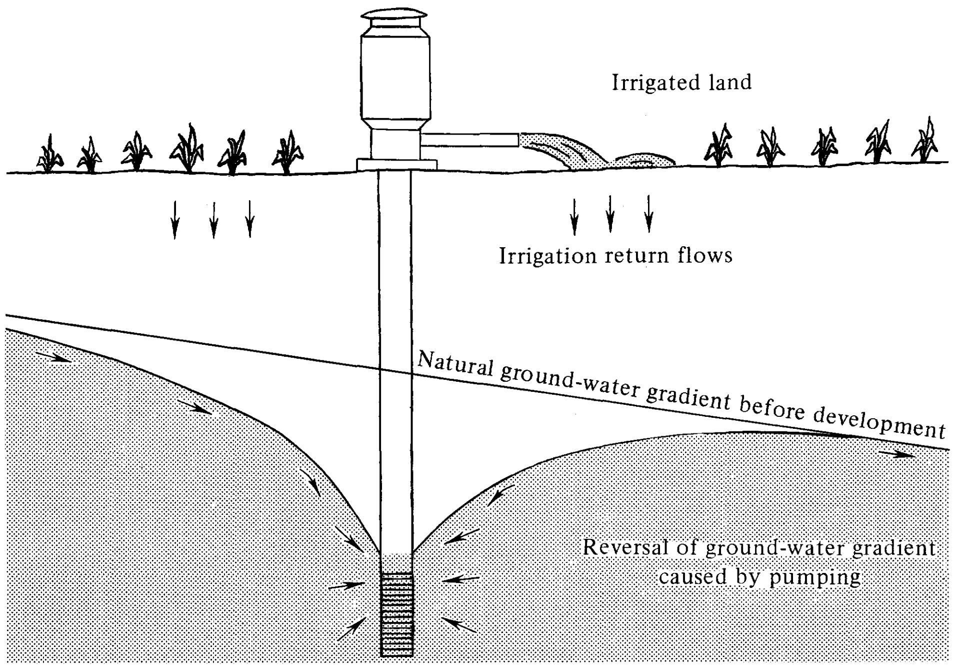
Plate 2*B* shows how ground water is subject to contamination or deterioration by activities that are not directly related to ground-water withdrawals. Deterioration of ground-water quality as a direct result of large-scale withdrawal can occur in two ways — inducement of saline water from adjacent aquifers and recycling of water whose quality has been deteriorated by use.

Some freshwater aquifers in the region are either overlain by, underlain by, or sandwiched between saline-water aquifers. Reduction of the hydrostatic pressure in the freshwater aquifer by pumping could allow saline water from an adjacent aquifer to move into the pumped aquifer, as illustrated in figure 22*A*. The possibility of this problem exists throughout the region because of the widespread occurrence of saline ground water. It might have its greatest impact in areas such as Spanish Valley, Utah, and Paradox Valley, Colo., where the Paradox Formation, which is composed largely of salt, gypsum, and other salines, seems to be in hydraulic connection with overlying unconsolidated valley deposits. The Paradox Formation also underlies sandstone aquifers throughout much of the Canyon Lands section.

Deterioration of water quality by recycling of previously used water can occur where withdrawal exceeds natural recharge. (See Handy and others, 1969.) Excessive pumping for irrigation, for example, can cause a reversal of the natural ground-water gradient, so that water seeping downward from irrigated fields no longer can move out of the area but instead percolates back



A. REDUCTION OF HEAD IN FRESH WATER AQUIFER CAN INDUCE ENCROACHMENT OF UNDERLYING SALINE WATER INTO THAT AQUIFER



B. PERMANENT CONE OF DEPRESSION AROUND WELL FIELD PREVENTS OUTFLOW OF IRRIGATION RETURN FLOWS AND THEREFORE CONCENTRATES MINERAL CONTENT OF WATER IN PUMPED AREA BY RECIRCULATION

FIGURE 22. — Large-scale withdrawals from freshwater aquifers can result in deterioration of water quality.

toward the well fields. (See fig. 22*B*.) This return flow from irrigation is concentrated by evapotranspiration, and it carries salts leached from the soil and chemicals from fertilizers and soil amendments. The return of this water to the well field, therefore, serves to increase the dissolved-solids content of the water. This problem is most likely to occur in the shallow unconfined aquifers of the region, such as the broader alluvial plains of the larger streams, where natural ground-water gradients are fairly flat.

LAND SUBSIDENCE

Land subsidence associated with ground-water development is well known in Arizona, California, and other areas where withdrawals of ground water have exceeded natural recharge. In many places, it has resulted in considerable inconvenience and damage. (See Poland and Davis, 1969.)

Subsidence results principally from the compaction of lenses or layers of fine-grained materials within unconsolidated aquifers that contain water under artesian pressure. Aquifers meeting these conditions are rare in the Upper Colorado Region; therefore, subsidence may not be a major problem in the region.

EFFECT ON THE ENVIRONMENT

Development of a ground-water supply directly within the desired area of use probably would cause less damage to the environment than the impoundment of a stream a great distance from the area and the construction of long pipelines or canals. Some damage to the environment might occur, however, from a ground-water development that is on a time-limited basis in which water levels are allowed to decline indefinitely. For example, the ecological balance of an area might be upset if ground-water withdrawals drastically depleted streamflow or dried up a natural wetland habitat. Similarly, the esthetic beauty of a natural spring area would be destroyed if the development dried up the spring.

Other ecological problems might result from developments that require demineralization of ground water. If distillation were used in the demineralization process, the burning of fossil fuel to create the necessary energy from steam may result in a source of air pollution. If a membrane process were used to demineralize the water, fuel might also have to be burned to produce the required electrical energy.

CONSTRAINTS

WATER RIGHTS

Each State in the Upper Colorado Region administers its water resources according to the appropriation doctrine. The basic concept of this doctrine is that ownership of land provides no inherent right to water from sources upon, contiguous to, or underlying his land, but that rights to these sources are based on priority in time of beneficial use. The doctrine originally applied to surface water, but it was later extended to include ground water. The general knowledge that a proposed ground-water development in a given area might affect existing water rights in the area, therefore, is a major constraint to large-scale ground-water development.

Utah, for example, has restricted Spanish Valley and has closed or restricted parts of the Uinta Basin to further ground-water withdrawal until more information can be obtained regarding the effects of such withdrawal on existing water rights. The State of Colorado generally will not issue permits for wells that divert more than 15 gpm (57 l/min) in areas where streamflow is fully appropriated and ground-water withdrawals would reduce the streamflow, unless the permit is to replace or change the point of diversion of an existing water right.

Nevertheless, large-scale surface-water development has successfully been implemented within the framework of the appropriation doctrine. It seems reasonable to believe, therefore, that planned large-scale ground-water development, such as a conjunctive-use development, might also be successfully implemented without major legal complications.

Differences in interpretation of various State water laws and the Federal "reserved-water doctrine" might impose some constraints to ground-water development in the region. The State water laws imply that all the water in the State is subject to appropriation, whereas the Federal reserved-water doctrine implies that when land is reserved by the Federal government (fig. 5), the water necessary for use of the land is simultaneously reserved.

THE COLORADO RIVER COMPACT

The Colorado River Compact, which was approved August 19, 1921, states: "There is hereby apportioned from the Colorado River system in perpetuity to the upper basin and to the lower basin, respectively, the exclusive beneficial consumptive use of 7,500,000 acre-feet [9,251.2 hm^3] of water per annum, which shall include all water necessary for the supply of any rights which may now exist." (Article III a.) The Compact further states: "The States of the upper division will not cause the flow of the river at Lee Ferry to be depleted below an aggregate of 75,000,000 acre-feet [92,512.5 hm^3] for any period of 10 consecutive years reckoned in continuing progressive series beginning with the 1st day of October next succeeding the ratification of this Compact." (Article III d.)

These statements could be construed by some to imply that the compact is a major constraint to large-scale ground-water development in the Upper Colorado Region, but this is not true. For example, no provision in the compact specifies that the allotted consumptive use of 7.5 million acre-feet (9,251.2 hm^3) per year must come directly from streams. The allotted consumptive use could come from streams, aquifers, or the combined sources in a conjunctive-use development. In fact, large-scale ground-water development in the region, particularly using saline water with demineralization, would reduce mineral inflow to the Colorado River. This would help to maintain better chemical quality of outflows to the Lower Colorado River Basin.

ECOLOGICAL CONSIDERATIONS

Growing social pressure to preserve the environment in its natural state is now a significant constraining factor to surface-water development. This type of constraint has not been felt in ground-water development, partly because ground water is an unseen resource and the effects of its development on the environment are not as obvious as a major surface-water development. Also, ground-water developments have grown in a piecemeal fashion, and any effects on the environment have been gradual. This is especially true in the Upper Colorado Region, where there is little large-scale withdrawal of ground water. Nevertheless, some of the problems associated with large-scale ground-water development, such as the land-subsidence problems of California, are well known. Thus, in addition to considering the benefits of a large-scale ground-water development, groups concerned with the environment quite surely will be evaluating the impact on the environment and will be prepared to contest the development if adverse effects on the ecology and environment are believed to outweight the benefits of the development.

LIMIT OF SCIENTIFIC KNOWLEDGE

Little detailed information about ground water is available for the Upper Colorado Region. Reconnaissance studies of the ground-water resources have been made in most parts of the region, but only in a few widely scattered areas have detailed studies been made (fig. 23). Few of these studies contain quantitative information, and only one (Sumsion, 1971a) has involved the use of a model to define the ground-water system and predict the effects of withdrawals on water levels.

Ironically, the major emphasis on ground-water development in all five of the Upper Colorado Region States has been in parts of those States that lie outside the region — the High Plains of Colorado, New Mexico, and Wyoming and the Basin and Range segments of Utah and Arizona. Consequently, very little of the States' available funds for ground-water study have been expended for detailed or comprehensive studies to evaluate the relatively undeveloped ground-water resources of the Upper Colorado Region.

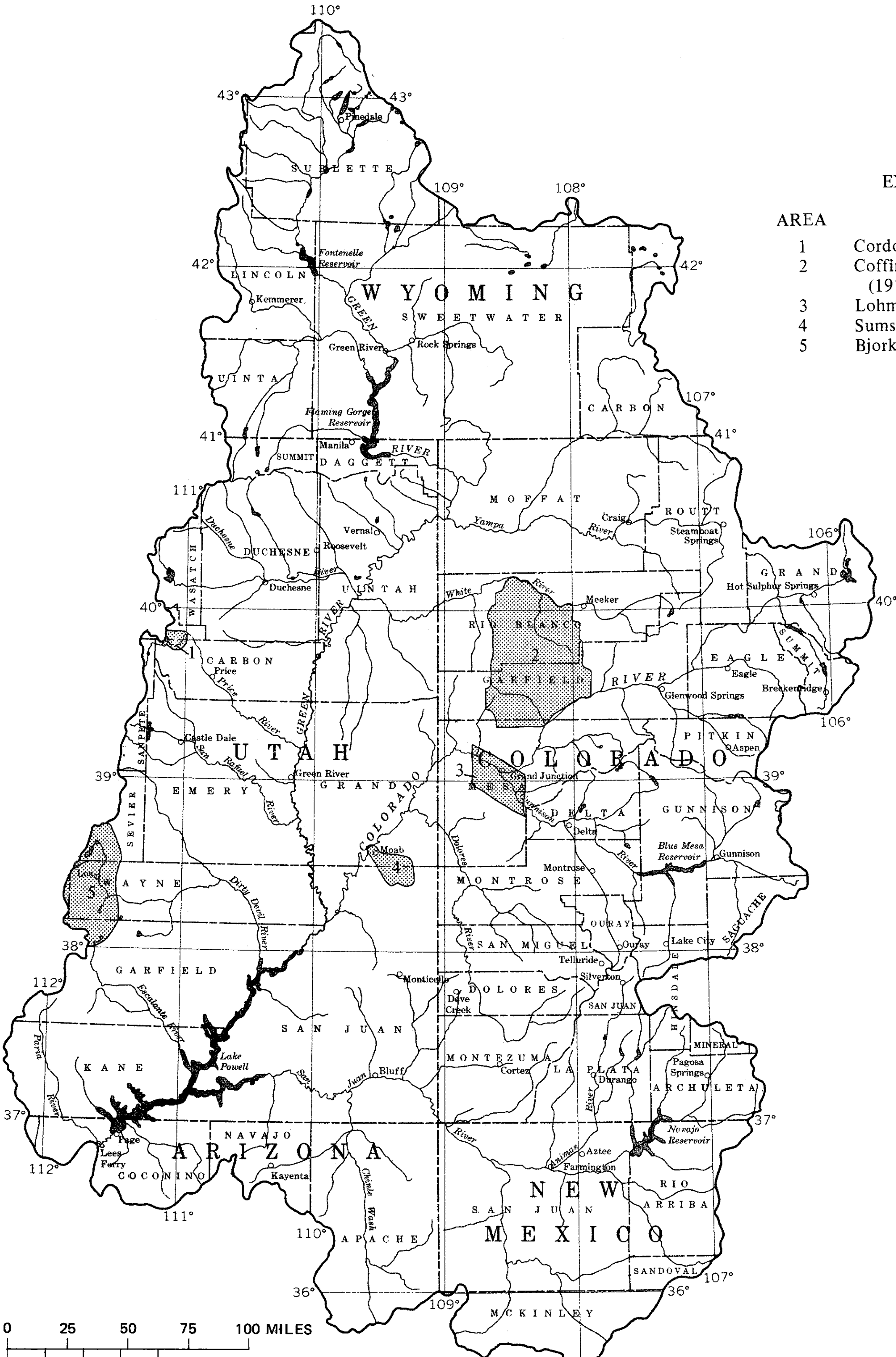
If large-scale ground-water development is to be implemented in the Upper Colorado Region, studies will be required that are similar in scope, magnitude, and cost to those that precede the planning and implementation of large-scale surface-water developments. These would involve feasibility studies, environmental-impact studies, and project design and implementation studies. Figure 24 shows selected types of studies that are needed in various parts of the region that have promise for use of ground water in overall water-resources management.

INFORMATION NEEDED FOR PROJECT DESIGN

Planned ground-water development, like planned surface-water development, requires considerable background information about the geohydrologic system in which the development is to function. The limitations or even the feasibility of the development cannot be determined until reasonable answers are obtained for such questions as:

1. How permeable are the aquifers? Will they support the required well yields?
2. How deep is the water? Will drilling and pumping costs be within the economic limit of the development?
3. What is the perennial yield of the ground-water reservoirs? Can the reservoirs support anticipated perennial withdrawals including peak seasonal or periodic requirements?
4. How much water is recoverable from storage within economic pumping limits? Is the storage adequate to support the anticipated perennial withdrawals for the life of the project, or until a supply can be imported?
5. How good is the water? Is it chemically and physically suitable for the anticipated needs, or will it require desalinization or treatment?
6. What effects will the development have on streamflow and the environment in general?

Because of the small amount of ground-water development to date (1973) in the region, there is little background data on which to base detailed studies. Such data must be acquired in the earliest possible stages of an investigation; thus, in essentially all parts of the region, detailed geologic mapping in conjunction with test and drilling and geophysical mapping is needed to determine the location, thickness, and extent of aquifers. Static water levels in the test holes would provide information about direction of ground-water movement and location of areas of natural recharge and discharge. Pumping tests, using the test wells as production wells



EXPLANATION

AREA	REFERENCE
1	Cordova (1964)
2	Coffin, Welder, and Glanzman (1971); model study in progress
3	Lohman (1965)
4	Sumsion (1971a)
5	Bjorklund (1969)

FIGURE 23. — The ground-water resources have been studied in detail in only a few widely scattered areas in the region.

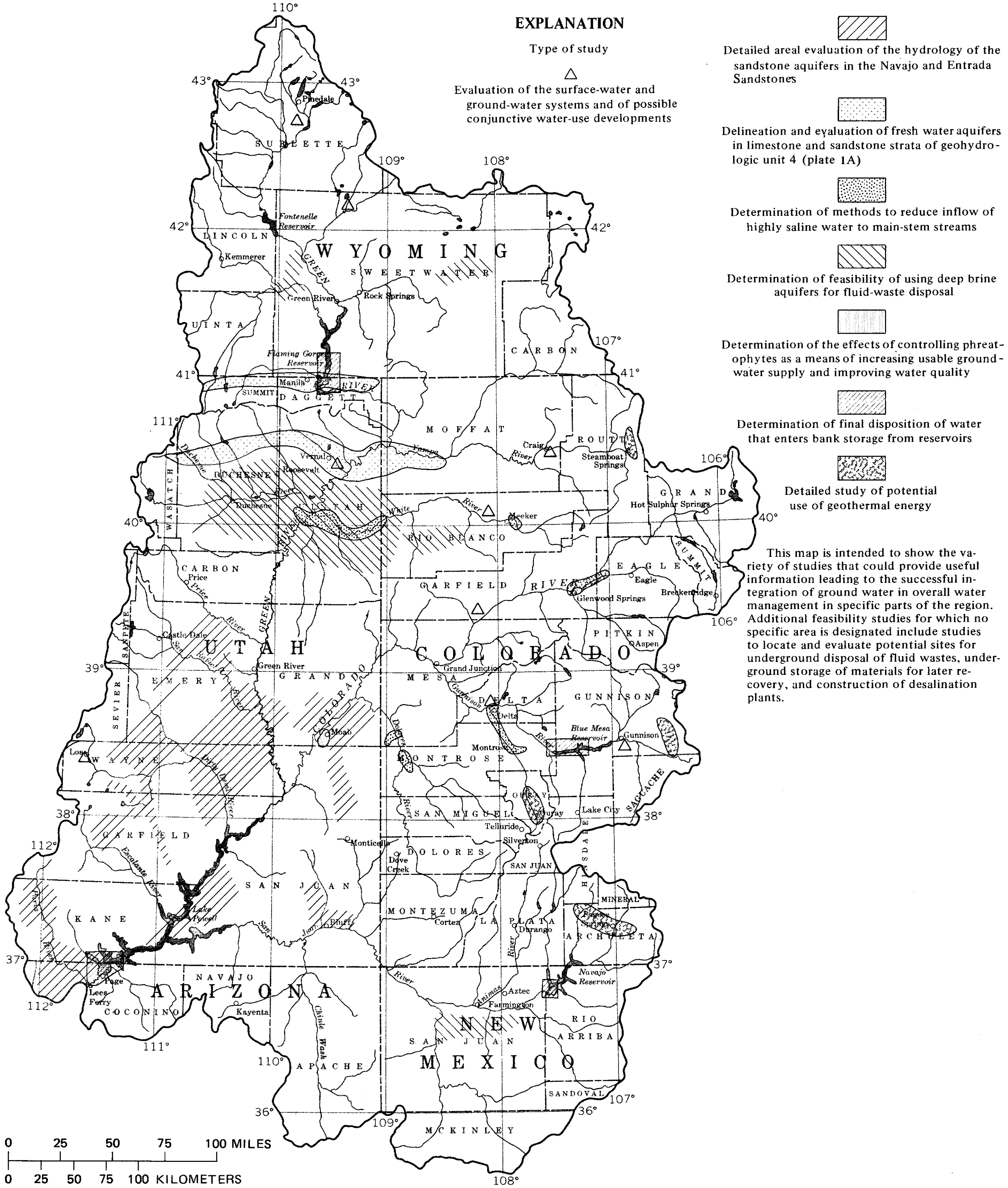


FIGURE 24. — Areas of the region that have potential for implementation of ground water and use of subsurface space in overall water-resources management.

and observation wells, would provide information about the hydraulic properties of the aquifers. Analyses of water samples collected from the test wells would provide information about the ground-water quality both areally and with depth.

By use of mathematical, statistical, and electric-analog models the field data can be evaluated. Successful models can accurately portray the ground-water regimen and predict the effects and changes imposed by various types and stages of ground-water development. A mathematical model of the hydrologic system in the Piceance Creek basin is currently being developed. It will help planners evaluate the ground-water supply and to predict effects of oil-shale development on the water resources of the basin.

Basic information needed for accurate and successful model studies is listed in table 4, and some applications of models to specific problems are listed in table 5.

TABLE 4. — *Data requirements for prediction model studies*

[After Moore, 1971]

Physical framework

1. Geologic map showing areal extent and boundaries of all aquifers.
2. Topographic map showing surface-water bodies.
3. Water-table, bedrock-configuration, and saturated-thickness maps.
4. Transmissivity map showing aquifer and its boundaries.
5. Map showing variation in storage coefficient of aquifer.
6. Relation of saturated thickness to transmissivity.
7. Relation of stream and aquifer (hydraulic connection).

Hydrologic stress

1. Recharge areas (irrigated areas, recharge basins, recharge wells, and so forth).
2. Surface-water diversions.
3. Ground-water pumpage distributed in time and space.
4. Depth-to-water map (with evapotranspiration rate).
5. Tributary inflow (distribution in time and space).
6. Ground-water inflow and outflow.
7. Precipitation.
8. Distribution of water quality in aquifer.
9. Streamflow quality (distribution in time and space).

Model calibration

1. Water-level-change maps and hydrographs.
2. Streamflow (including gain and loss measurements).

Prediction and optimization analysis

1. Economic information on water supply.
2. Legal and administrative rules.
3. Environmental factors.

The model can be used for planning the project and for evaluation of development, use, and management plans. Some of the possible uses of the model are shown in table 5.

TABLE 5. — *Summary of problems that could be analyzed with a model*

[After Moore, 1971]

1. Assist in identifying deficiencies in hydrologic field data.
2. Quantitative evaluation of stream-aquifer relations.
3. Evaluation of the efficiency of the surface-water distribution system, including surface storage.
4. Define areas where additional pumping of ground water would be beneficial, such as salvage of ground water now consumed nonbeneficially.
5. Study the effect of increased pumpage of ground water on return flow to the river, on evapotranspiration, and on aquifer storage.
6. Aid in the selection of sites where large-capacity wells can be developed for use in satisfying surface-water rights.
7. Evaluation of the most efficient spacing of irrigation wells in different areas.
8. Outline areas where growth of phreatophytic plants can be controlled by lowering the water table by pumping from wells, determine the number and spacing of salvage wells that would be required, and evaluate the effect of these wells on seepage to and from the river.
9. Measure the effects of the importation of additional surface water.
10. Aid in the formulation of effective management criteria for the control and maintenance of favorable water quality.
11. Identify areas where additional water might be stored underground.
12. Provide a means of predicting water availability in different areas under varying schemes of surface-water delivery and ground-water pumpage.
13. Optimize plans for utilizing both ground water and surface water based on economic, legal, and social constraints.
14. Use of additional water in the tributary valleys.
15. Study the effect of lining canals.

SUMMARY

Ground water often has been neglected in water-resources planning and management. The reasons most commonly given are that ground water cannot be adequately evaluated in terms of quantity, quality, availability, and cost of development. These reasons are no longer valid. Advancements in the field of ground-water hydrology in the past half century have provided the knowledge and techniques to evaluate ground-water resources with considerable accuracy and reliability. Therefore, the resource should be considered in every phase of water-resources planning and included in management options. This is particularly true in the Upper Colorado Region, where limitations on surface-water development are imposed by the Colorado River Compact and by a growing demand for preservation and enhancement of the environment.

Tremendous quantities of ground water are available in the region. The volume of recoverable water stored in the upper 100 feet (30.5 m) of saturated rocks alone may be as much as 115 million acre-feet (141,852.5 hm^3), and many times this amount is available from greater depths. In addition, the annual replenishable supply of ground water of about 4 million acre-feet (4,934 hm^3) is enough water to support industries requiring 3,600 million gallons (13,627,440 m^3) of water a day, or to irrigate about 1.3 million acres (526,110 ha) of crops having an annual water requirement of 3 feet per acre (0.9 m/ha). Yet, in 1970 only about 2 percent of the water used in the region came directly from ground-water sources.

It is true that most of the ground water is in consolidated rocks which generally yield water to wells slowly, and it is also true that much of the ground water is saline and, in some places, occurs at great depths. Nevertheless, the ground water in the region has certain characteristics, such as its uniform areal and time distribution, that make it highly useful in overall water-resources management.

Under various development options, ground water can be used in conjunction with surface water or it can be developed as an independent supply where surface water is not available. The various development options all are possible within the framework of the Colorado River Compact; in fact, the full use of the ground-water resource could help the water users in the Upper Colorado River Basin to meet projected needs for water in the region and still satisfy the various provisions of the compact.

Benefits that could be gained by the optimal use of ground water in overall water-resources management in the region include:

1. A reduction of nonbeneficial discharge of water.
2. A more uniform water supply.
3. A means of meeting growing in-region water needs while satisfying the growing demand outside the region for water from the Colorado River.
4. A means of developing water supplies without the adverse effects on the environment that are commonly associated with large surface-water facilities.
5. A means of alleviating the salinity problems in the water in the Colorado River system.
6. Full use of the total water resource of the region.

The ground-water resources of those areas cited as having a potential for including ground water in overall water-resources management have had only cursory or reconnaissance study. Considerable more study, including the use of models, is needed to fully evaluate this potential and to determine the most feasible development options.

There is a great potential for use of underground space, such as for fluid-waste disposal and development of underground storage reservoirs and chambers, in the region. Special detailed studies are needed to locate and evaluate the potential sites.

SELECTED REFERENCES

[Astericks identify references that contain most useful information to water planning in various parts of the region]

Baltz, E. H., 1967, Stratigraphy and regional tectonic implications of part of Upper Cretaceous and Tertiary rocks, east-central San Juan Basin, New Mexico: U.S. Geol. Survey Prof. Paper 552, 101 p.

*Baltz, E. H., and West, S. W., 1967, Ground-water resources of the southern part of Jicarilla Apache Indian Reservation and adjacent areas, New Mexico: U.S. Geol. Survey Water-Supply Paper 1576-H, 89 p.

Berry, D. W., 1960, Geology and ground-water resources of the Rawlins area, Carbon County, Wyoming: U.S. Geol. Survey Water-Supply Paper 1458, 74 p.

*Bjorklund, L. J., 1969, Reconnaissance of the ground-water resources of the upper Fremont River valley, Wayne County, Utah: Utah Dept. Nat. Resources Tech. Pub. 22, 54 p.

Boettcher, A. J., 1971, Evaluation of the water supply at six sites in the Curecanti Recreation Area, southwestern Colorado: U.S. Geol. Survey open-file report, 28 p.

*______1972, Ground-water occurrence in the northern and central parts of western Colorado: Colorado Water Conserv. Board Water-Resources Circ. 15, 50 p.

Carter, W. D., and Gualtieri, J. L., 1965, Geology and uranium-vanadium deposits of the La Sal quadrangle, San Juan County, Utah, and Montrose County, Colorado: U.S. Geol. Survey Prof. Paper 508, 82 p.

*Case, F. O. [chm.], and others, 1971, Comprehensive framework study, Upper Colorado Region, Appendix VI (land resources and use): Pacific Southwest Interagency Committee, Water Resources Council open-file report, 142 p.

*Coffin, D. L., Welder, F. A., and Glanzman, R. K., 1971, Geohydrology of Piceance Creek structural basin between the White and Colorado Rivers, northwestern Colorado: U.S. Geol. Survey Hydrol. Inv. Atlas HA-370.

Coffin, D. L., Welder, F. A., Glanzman, R. K., and Dutton, X. W., 1968, Geohydrologic data from the Piceance Creek basin between the White and Colorado Rivers, northwestern Colorado: Colorado Water Conserv. Board Ground-Water Circ. 12, 38 p.

Connor, J. G., Mitchell, C. G., and others, 1958, A compilation of chemical quality data for ground and surface waters in Utah: Utah State Engineer Tech. Pub. 10, 276 p.

Cooley, M. E., 1965, Stratigraphic sections and records of springs in the Glen Canyon region of Utah and Arizona: Musem of Northern Arizona Tech. Ser. 6, 140 p.

Cooley, M. E., Akers, J. P., and Stevens, P. R., 1964, Geohydrologic data in the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah, Part III, Selected lithologic logs, drillers' logs, and stratigraphic sections: Arizona State Land Dept. Water-Resources Rept. 12-C, 157 p.

*Cooley, M. E., Harshbarger, J. W., Akers, J. P., and Hardt, W. F., 1969, Regional hydrology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah, *with a section on* Vegetation, by O. N. Hicks: U.S. Geol. Survey Prof. Paper 521-A, 61 p.

Cooley, M. E., and others, 1966, Geohydrologic data in the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah, Part IV, Maps showing locations of wells, springs, and stratigraphic sections: Arizona State Land Dept. Water-Resources Rept. 12-D.

*Cordova, R. M., 1964, Hydrogeologic reconnaissance of part of the head waters area of the Price River, Utah: Utah Geol. and Mineralog. Survey Water-Resources Bull. 4, 26 p.

Davis, G. E., Hardt, W. F., Thompson, L. K., and Cooley, M. E., 1963, Geohydrologic data in the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah, Part I, Records of ground-water supplies: Arizona State Land Dept. Water-Resources Rept. 12-A, 159 p.

Eisenlohr, W. S., and others, 1962, Explorations for water supplies on the public domain, 1960: U.S. Geol. Survey Circ. 461, 28 p.

*Feltis, R. D., 1966, Water from bedrock in the Colorado Plateau of Utah: Utah State Engineer Tech. Pub. 15, 82 p.

Feltis, R. D., and Goode, H. D., 1961, Production and use of fresh water from the Ashley Valley oil field, Uintah County, Utah, *in* Geological Survey Research 1961: U.S. Geol. Survey Prof. Paper 424-C, p. C90-C93.

Fenneman, N. M., 1931, Physiography of the Western United States: New York, McGraw-Hill Book Co., 534 p.

______1946, Physical divisions of the United States: U.S. Geol. Survey map, scale 1 : 7,000,000.

Feth, J. H., and others, 1965, Preliminary map oof the conterminous United States showing depth to and quality of shallowest ground water containing more than 1,000 parts per million dissolved solids: U.S. Geol. Survey Hydrol. Inv. Atlas HA-199.

Goode, H. D., 1958, The geology and distribution of aquifers in the southwestern part of San Juan County, Utah: U.S. Geol. Survey open-file report, 9 p.

*______1964, Reconnaissance of water resources of part of western Kane County, Utah: Utah Geol. and Mineralog. Survey Water-Resources Bull. 5, 63 p.

*______1966, Second reconnaissance of the water resources in western Kane County, Utah: Utah Geol. and Mineralog. Survey Water-Resources Bull. 8, 44 p.

*______1969, Reconnaissance appraisal of the water resources near Escalante, Garfield County, Utah: Utah Geol. and Mineralog. Survey Water-Resources Bull. 11, 38 p.

Goode, H. D., and Feltis, R. D., 1962, Water production from oil wells of the Uinta Basin, Uintah and Duchesne Counties, Utah: Utah Geol. and Mineralog. Survey Water-Resources Bull. 1, 30 p.

Gregg, D. O., Meyer, E. L., Targy, M. M., and Moulder, E. A., 1961, Public water supplies of Colorado, 1959-60: Colorado State Univ. Agr. Expt. Sta. Gen. Ser. Rept. 757, 128 p.

Gregory, H. E., 1916, The Navajo country — A geographic and hydrographic reconnaissance of parts of Arizona, New Mexico, and Utah: U.S. Geol. Survey Water-Supply Paper 380, 219 p.

______1951, The geology and geography of the Paunsaugunt region, Utah: U.S. Geol. Survey Prof. Paper 226, 116 p.

*Hagen, R. H. [chm.], and others, 1971, Comprehensive framework study, Upper Colorado Region, Appendix XV (water quality, pollution control, and health factors): Pacific Southwest Interagency Committee, Water Resources Council open-file report, 219 p.

Hale, W. E., Reiland, L. J., and Beverage, J. P., 1965, Characteristics of the water supply in New Mexico: New Mexico State Engineer Tech. Rept. 31, 131 p.

Hall, W. J., Jr., 1968, Geology of southwestern North Park and vicinity, Colorado: U.S. Geol. Survey Bull. 1257, 119 p.

Halpenny, L. C., 1954, Preliminary report on the ground-water resources of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: New Mexico Geol. Soc. Guidebook of the South and West Sides of the San Juan Basin, New Mexico and Arizona, p. 147-151.

Halpenny, L. C., and Harshbarger, J. W., 1952, Ground-water resources of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: Geol. Soc. America Bull., v. 63, p. 1330.

Handy, A. H., Mower, R. W., and Sandberg, G. W., 1969, Changes in chemical quality of ground water in three areas in the Great Basin, Utah, *in* Geological Survey Research 1969: U.S. Geol. Survey Prof. Paper 650-D, p. D228-D234.

Hanley, G. W. [chm.], and others, 1971, Comprehensive framework study, Upper Colorado Region, Appendix XIV (electric power): Pacific Southwest Interagency Committee, Water Resources Council open-file report, 92 p.

Harshbarger, J. W., and Repenning, C. A., 1954, Water resources of the Chuska Mountains area, Navajo Indian Reservation, Arizona and New Mexico, *with a section on* Quality of water, by J. L. Hatchett: U.S. Geol. Survey Circ. 308,, 16 p.

Haycock, E. B., and others, 1970, Interim report on the Utah water plan: Utah Div. Water Resources, Div. Planning Staff Rept. 6, 70 p.

*Hedlund, J. D. [chm.], and others, 1971, Comprehensive framework study, Upper Colorado Region, Appendix V (water resources): Pacific Southwest Interagency Committee, Water Resources Council open-file report, 66 p.

Hood, J. W., and Kister, L. R., 1962, Saline water resources of New Mexico: U.S. Geol. Survey Water-Supply Paper 1601, 70 p.

Hunt, C. B., Averitt, Paul, and Miller, R. L., 1953, Geology and geography of the Henry Mountains region, Utah: U.S. Geol. Survey Prof. Paper 228, 234 p.

Hurr, R. T., Wilson, W. W., Welder, F. A., and Emerson, R. L., 1969, Records of selected wells and springs in the Rulison Project area, Garfield and Mesa Counties, Colorado: U.S. Geol. Survey open-file report, Rulison-2, 17 p.

*Iorns, W. V., Hembree, C. H., and Oakland, G. L., 1965, Water resources of the Upper Colorado River Basin — Technical report: U.S. Geol. Survey Prof. Paper 441, 370 p.

Iorns, W. V., Hembree, C. H., Phoenix, D. A., and Oakland, G. L., 1964, Water resources of the Upper Colorado River Basin — Basic data: U.S. Geol. Survey Prof. Paper 442, 1036 p.

*Irwin, J. H., 1966, Geology and availability of ground water on the Ute Mountain Indian Reservation, Colorado and New Mexico: U.S. Geol. Survey Water-Supply Paper 1576-G, p. G1-G109.

Johnson, Michael, and Lundeen, E. W., 1967, Alamitos barrier project — Résumé of geohydrologic investigation and status of barrier construction: Eng. Geology, v. 4, no. 1, p. 37-49.

Kister, L. R., and Hatchett, J. L., 1963, Geohydrologic data in the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah, Part II, Selected chemical analyses of the ground water: Arizona State Land Dept. Water-Resources Rept. 12-B, 58 p.

Kohler, M. A., Nordenson, T. J., and Baker, D. R., 1959, Evaporation maps for the United States: U.S. Weather Bur. Tech. Paper, 37.

Kohout, F. A., 1970, Reorientation of our saline water resources thinking: Water Resources Research, v. 6, no. 5, p. 1442-1446.

Kume, Jack, Emmett, L. F., Bader, J. S., and Vorhis, R. C., 1974, Ground-water contamination, Central States — A preliminary inventory: U.S. Geol. Survey Circ. 00, 000 p. (in press).

Lofgren, B. E., 1954, Ground-water possibilities of bedrock aquifers in southwestern Utah, *in* Progress report on selected ground-water basins in Utah: Utah State Engineer Tech. Pub. 9, p. 105-118.

*Lohman, S. W., 1965, Geology and artesian-water supply, Grand Junction area, Colorado: U.S. Geol. Survey Prof. Paper 451, 149 p.

Madison, R. J., and Waddell, K. M., 1973, Chemical quality of surface water in the Flaming Gorge Reservoir area, Wyoming and Utah: U.S. Geol. Survey Water-Supply Paper 2009-C, 18 p.

Marine, I. W., 1962, Water-supply possibilities at Capitol Reef National Monument, Utah: U.S. Geol. Survey Water-Supply Paper 1475-G, p. 201-208.

______1963, Ground-water resources of the Bryce Canyon National Park area, Utah: U.S. Geol. Survey Water-Supply Paper 1475-M, p. 441-485.

*Maxwell, J. D., Bridges, B. L., Barker, D. A., and Moore, L. G., 1971, Hydrology of the eastern portion of the south slopes of the Uinta Mountains, Utah: Utah Dept. Nat. Resources Inf. Bull. 21, 54 p.

McConaghy, J. A., and Colburn, G. W., 1964, Records of wells in Colorado: Colorado Water Conserv. Board Basic-Data Release 17, 384 p.

McGavock, E. H., Edmonds, R. J., Gillespie, E. L., and Halpenny, P. C., 1966, Geohydrologic data in the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah, Part 1A, Supplemental records of ground-water supplies: Arizona State Land Dept. Water-Resources Rept. 12-E, 55 p.

McGuinness, C. L., 1963, The role of ground water in the national water situation: U.S. Geol. Survey Water-Supply Paper 1800, 1,121 p.

Miser, H. D., 1924, The San Juan Canyon, southwestern Utah — A geographic and hydrographic reconnaissance: U.S. Geol. Survey Water-Supply Paper 538, 80 p.

Moore, J. E., 1971, Integrating the use of ground water into water-resources planning: Minutes of Missouri Basin Interagency meeting, June 23, 1971.

Mower, R. W., and Nace, R. L., 1957, Water consumption by water-loving plants in Malad Valley, Oneida County, Idaho: U.S. Geol. Survey Water-Supply Paper 1412, 33 p.

Mundorff, J. C., 1970, Major thermal springs of Utah: Utah Geol. and Mineralog. Survey Water-Resources Bull. 13, 60 p.

______1971, Nonthermal springs of Utah: Utal Geol. and Mineralog. Survey Water-Resources Bull. 16, 70 p.

______1972, Reconnaissance of chemical quality of surface water and fluvial sediment in the Price River basin, Utah: Utah Dept. Nat. Resources Tech. Pub. 39, 55 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.

New Mexico State Engineer, 1967, Water resources of New Mexico, Occurrence, development, and use: New Mexico State Planning Office report, 321 p.

Oak Ridge National Laboratory and Office of Saline Water, 1970, Office of Saline Water special report of status of desalting, Comprehensive framework study: U.S. Dept. Interior open-file report, 111 p.

Oriel, S. S., 1963, Preliminary geologic map of the Fort Hill quadrangle, Lincoln County, Wyoming: U.S. Geol. Survey Oil and Gas Inv. Map OM-212.

Pearl, R. H., 1972, Geothermal resources of Colorado: Colorado Geol. Survey Spec. Pub. 2, 39 p.

Poland, J. F., and Davis, G. H., 1969, Land subsidence due to withdrawal of fluids: Geol. Soc. America Reviews in Engineering Geology, v. 2, p. 187-269.

Price, Don, Hart, D. H., and Foxworthy, B. L., 1965, Artificial recharge in Oregon and Washington, 1962: U.S. Geol. Survey Water-Supply Paper 1594-C, p. C1-C65.

Rapp, J. R., 1959, Reconnaissance of the geology and water resources of the Farmington area, San Juan County, New Mexico: U.S. Geol. Survey open-file report, 13 p.

*Robinove, C. J., and Cummings, T. R., 1963, Ground-water resources and geology of the Lyman-Mountain View area, Uinta County, Wyoming: U.S. Geol. Survey Water-Supply Paper 1669-E, p. E1-E43.

Robinson, T. W., 1958, Phreatophytes: U.S. Geol. Survey Water-Supply Paper 1423, 84 p.

______1968, Areal extent of phreatophytes and hydrophytes in the Western States (section on Arizona, Colorado, New Mexico, and Utah): U.S. Geol. Survey open-file report, 47 p.

*Sumsion, C. T., 1971a, Geology and water resources of the Spanish Valley area, Grand and San Juan Counties, Utah: Utah Dept. Nat. Resources Tech. Pub. 32, 45 p.

*______1971b, Water-resources investigations in Dinosaur National Monument, Utah-Colorado, fiscal year 1970: U.S. Geol. Survey open-file report, 52 p.

*Sumsion, C. T., and Bolke, E. L., 1972, Water resources of part of Canyonlands National Park, southeastern Utah: U.S. Geol. Survey open-file report, 75 p.

Theis, C. V., 1940, The source of water derived from wells: Civil Eng., v. 10, no. 5, p. 277-280.

Thomas, H. E., 1952, Hydrologic reconnaissance of the Green River in Utah and Colorado: U.S. Geol. Survey Circ. 129, 32 p.

______1962, Water and the Southwest — What is the future?: U.S. Geol. Survey Circ. 469, 15 p.

Thomas, H. E., and Wilson, M. T., 1952, Determination of total evapotranspiration in Ashley Valley, Utah, by the inflow-outflow method: U.S. Geol. Survey open-file report, 15 p.

U.S. Bureau of Reclamation and New Mexico Interstate Stream Commission, (no date), Preliminary situation assessment report, New Mexico State water plan: U.S. Bur. Reclamation open-file report, 166 p.

*Voegeli, P. T., Sr., 1965, Ground-water resources of North Park and Middle Park, Colorado — A reconnaissance: U.S. Geol. Survey Water-Supply Paper 1809-G, p. G1-G54.

Waring, G. A., 1935, Ground-water resources of northwestern New Mexico: U.S. Geol. Survey open-file report, 160 p.

Waring, G. A., and Knechtel, M. M., 1935, Ground water in part of southeastern Utah and southwestern Colorado: U.S. Geol. Survey open-file report, 119 p.

Waring, G. A. (revised by R. R. Blankenship and Ray Bentall), 1965, Thermal springs of the United States and other countries of the world — A summary: U.S. Geol. Survey Prof. Paper 492, 383 p.

Weir, J. E., Jr., 1970, Geohydrology of the area near WOSCO [Western Oil Shale Corp.] exploratory hole number 1, Uintah County, Utah: U.S. Geol. Survey open-file report, 27 p.

*Welder, G. E., 1968, Ground-water reconnaissance of the Green River basin, southwestern Wyoming: U.S. Geol. Survey Hydrol. Inv. Atlas HA-290.

Welder, F. A., 1971, Ground-water reconnaissance of selected sites in Rocky Mountain National Park and Shadow Mountain National Recreation Area: U.S. Geol. Survey open-file report, 47 p.

*Welder, G. E., and McGreevy, L. J., 1966, Ground-water reconnaissance of the Great Divide and Washakie Basins and some adjacent areas, southwestern Wyoming: U.S. Geol. Survey Hydrol. Inv. Atlas HA-219.

West, S. W., 1957, Possibility of developing a ground-water supply at the Chaco Canyon National Monument, San Juan County, New Mexico: U.S. Geol. Survey open-file report, 32 p.

Wilson, W. W., 1965, Pumping tests in Colorado: Colorado Water Conserv. Board Circ. 11, 361 p.

Wyoming State Engineer, 1970, Water and related land resources of the Green River basin, Wyoming: Wyoming Planning Program Rept. 3, 167 p.

☆U.S. GOVERNMENT PRINTING OFFICE: 1976—677-340/61