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UNITED STATES DEPARTMENT OF THE INTERIOR

GROUND WATER IN THE UNITED STATES, A SUMMARY

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 836-D

UNITED STATES DEPARTMENT OF THE INTERIOR
Harold L. Ickes, Secretary

GEOLOGICAL SURVEY
W. C. Mendenhall, Director

Water-Supply Paper 836-D

GROUND WATER IN THE UNITED STATES

A SUMMARY OF GROUND-WATER CONDITIONS AND RESOURCES UTILIZATION OF WATER FROM WELLS AND SPRINGS METHODS OF SCIENTIFIC INVESTIGATION, AND LITERATURE RELATING TO THE SUBJECT

BY
OSCAR EDWARD MEINZER

Contributions to the hydrology of the United States, 1938-39
(Pages 157-229)

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RELIEF MAP OF THE UNITED STATES

;ROUND WATER IN THE UNITED STATES—A SUMMARY

By Oscar Edward Meinzer

ABSTRACT

Water-bearing formations and their geographic distribution.—The United States ın be divided into four regions with respect to ground water, that is, the water ıat supplies the springs and wells—(1) the East-Central old-rock region, (2) the tlantic and Gulf Coastal Plain region, (3) the Great Plains region, and (4) the /estern Mountain region.

The East-Central region includes about one-third of the area and two-thirds ' the population of the country. Most of the region is underlain by Paleozoic ›cks, including water-bearing sandstones and limestones and unproductive shales; ıe deep water from these rocks is highly mineralized. Parts of this region are nderlain by Pre-Cambrian or Triassic rocks that yield small supplies. The glacial rift, in the northern part, and the glacial outwash sands and gravels beyond the rift border yield numerous large water supplies.

The wide and well populated coastal plain bordering the Atlantic Ocean and ulf of Mexico is underlain by Cretaceous, Tertiary, and Pleistocene formations, cluding many beds of sand and limestone that yield numerous supplies of water, .any of which are large.

The semiarid or subhumid plains region lying east of the Rocky Mountains con- .ins extensive Tertiary and Pleistocene deposits of water-bearing sand and gravel ıd Cretaceous sands that yield highly mineralized artesian water, especially in orth Dakota and South Dakota; also water-bearing glacial drift in the north and ·oductive Permian limestone in the Roswell artesian basin in New Mexico. In .e areas of Cretaceous shale the water supplies are scarce.

The Western Mountain region, which occupies about one-third of the area the country, is chiefly arid and contains extensive tracts in which water supies are scarce. Its principal water-bearing beds are the sand and gravel in e Pleistocene or Tertiary valley fill, which in some parts, especially in Calirnia, yield very large supplies. In some places in the Northwest the Tertiary ılcanic rocks yield much water to springs and wells.

Water-table conditions.—The water supplies of the springs and wells in the ıited States are largely derived from formations that have essentially waterble conditions. These are the surficial deposits of sand and gravel; the sand- ›nes and limestones in their outcrop areas; the extrusive volcanic rocks of the ›rthwest; and the dense igneous and metamorphic rocks and clays and shales, ıich are commonly rendered somewhat permeable by weathering near the rface. As these formations are extensively exposed at the surface, their sup- es are readily replenished by the water from rain and snow. The largest pplies of water come from the deposits of sand and gravel, and these may grouped as follows: (1) Glacial outwash from the continental ice sheets occur- .g from the Atlantic to the Pacific, (2) Valley fill in the Western Mountain ;ion (in part artesian), (3) Tertiary and Quaternary deposits in the Great ıins region, and (4) Tertiary and Quaternary terrace and lowland deposits the Atlantic and Gulf Coastal Plain.

Artesian conditions.—The principal artesian systems in the United States a as follows: (1) the extensive Paleozoic artesian system occupying a large part the East-Central region, in which the shales confine water under artesian pressu in the sandstones and limestones; (2) the small but productive Roswell artesi basin, in New Mexico, in which cavernous Permian limestone is the artesian fo mation; (3) the artesian system formed by the entire Atlantic and Gulf Coast Plain, in which Cretaceous and Tertiary strata dip toward the sea, and t water in the sands and limestones is held under artesian pressure by the interbedd shales; (4) the Cretaceous artesian system of the northern and central parts the Great Plains region, in which water is confined in the sandstones, under gre artesian pressure, by the thick, dense, overlying shales; (5) numerous small a imperfect artesian systems in the glacial drift; and (6) numerous artesian syste in the valley fill of the Western Mountain region, the largest of which are in t San Joaquin Valley, in California, and the San Luis Valley, in Colorado.

In most areas of artesian flow the pressure has greatly diminished, and lar supplies are generally obtained by pumping.

Discharge of ground water through springs and by evaporation and transpiration. In the relatively humid eastern part of the United States, the streams are genera fed by numerous branches that receive effluent seepage at many points, exce in the limestone terranes, in which the springs are larger but less numerous. the arid and semiarid western parts of the country, the recharge and hence also t discharge of ground water are reduced in even greater proportion than the preci tation, as compared with the humid East, and the discharge is largely by transpi tion of the plants known as phreatophytes.

According to available data, there are in the United States 65 springs of t first magnitude, that is, springs yielding more than 100 second-feet. Of these, rise in volcanic rock or associated gravel in the Northwest; 24 rise in limesto chiefly in Florida, Missouri, and Texas; and 3 rise in sandstone in Monta Silver Spring, Florida, which is the largest limestone spring in the country, has average discharge of 808 second-feet. The springs that issue from volcanic ro and associated gravel along a 50-mile stretch of Snake River, Idaho, have an agg gate discharge that averages 5,085 second-feet.

In a recently published report (Water-Supply Paper 679–B) are listed 1,0 thermal springs or spring localities, all of which are in the Western Mounta region except 52 in the East-Central region, and 3 in the Great Plains regi (Black Hills). Yellowstone National Park exceeds all other areas in the abu dance of springs of high temperature. Nearly two-thirds of the thermal sprin issue from igneous rock, chiefly intrusive magmas, deriving their heat large from magmatic sources and their water largely from surface sources. Those the eastern part of the country are largely due to artesian structure.

There are in the United States 23 known periodic or ebbing and flowing sprin of which 9 are in Virginia and 4 in Missouri. All or nearly all are in limestone

Utilization of ground water.—About 10,000 communities, with about 75,000,0 inhabitants (1930 census), have public waterworks, of which about 6,500 co munities, with about 20,000,000 inhabitants, are supplied with ground wat from wells. The total yielded by wells for public supplies is estimated at 2,00 000,000 gallons a day.

One of the greatest achievements in American history has been the develo ment of water supplies of good quality for domestic use, that is, for drinki cooking, and laundry and toilet purposes. A very large proportion of the 75,00 000 people in communities served by public waterworks have ample and perenn supplies of safe water delivered under pressure. About 47,000,000 people livi in several thousand small communities and on about 6,500,000 farms have priva water supplies, chiefly from wells, supplemented in hard-water areas with ra water cisterns for toilet and laundry uses. Much progress has been made in improvement of supplies from private wells but much remains to be done, largely through advances in well drilling practices.

Water supplies for livestock are partly the same as the domestic supplies but many additional supplies have been developed to make it possible for the livestock to utilize all the available forage. This has been done chiefly by sinking wells but also by improving springs and building small reservoirs.

Numerous large and small private water supplies have been developed from wells for industries and institutions in areas not reached by public waterworks and also to a considerable extent in the large cities.

Over 2,100,000 acres was irrigated in 1929 with water from wells, about two-thirds of which was in California. Only 2 or 3 percent of this acreage was irrigated with water from flowing wells, the rest from pumped wells. The area irrigated with water from wells is about 11 percent of the total irrigated area, but the value of the product is proportionately greater because it consists largely of fruits and vegetables. About twice as much water from wells is used annually for irrigation as for public supplies.

In the United States there are some well-equipped health resorts at watering places and many that are only modestly or poorly equipped. A total of 184 thermal springs are reported to be used for resorts, including sanitariums. In 1923 about 45,000,000 gallons of natural waters were sold, from 433 commercial springs, for table and medicinal uses. The American people rank high in the personal use of water, both external and internal. From a broad viewpoint, they doubtless rank higher than is generally assumed in its therapeutic use.

Methods and results of ground-water investigations.—The ground-water investigations have been of two principal kinds—(1) systematic areal surveys and (2) special investigations, which are generally more intensive and contribute to a more detailed knowledge of hydrologic principles. It has not been possible to carry out a uniform ground-water survey of the entire country, but more or less standardized methods are applied as opportunity is afforded.

The intensive studies have related largely to the quantities of ground water that can be obtained from underground storage and from recharge. Quantitative methods are grouped as intake, discharge, storage, and transmission methods. Water-bearing formations are studied with respect to their functions as reservoirs and as conduits.

Studies have been made of the infiltration of rain and stream water, the retention of the water in the root zone, and its transmission to the water table; the rate of discharge of ground water by springs, effluent seepage, evaporation, and transpiration from phreatophytes; specific yield, or changes in storage corresponding to changes in the level of the water table; permeability and the laws of ground-water flow; and changes in storage in confined formations due to their elasticity. Studies have been made of the balance between fresh ground water and the heavier salty water; deep wells have been explored with current meters and salinity apparatus to determine inflow and outflow of fresh and salty water; and geophysical methods, especially the electric resistivity method, have been studied as to their availability for locating salty water and permeable water-bearing beds.

The principal instruments of precision in ground-water investigations have come to be the automatic water-stage recorders, of which several hundred are installed over wells—200 by the Geological Survey and cooperating parties. A nation-wide program including several thousand observation wells has been developed, and a report is published annually giving water levels or artesian pressures in these wells. Emphasis has also been placed on obtaining corresponding records of pumpage and artesian flow.

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In 1917 the Geological Survey reestablished its laboratory for making chemica analyses of water. In 1923 it established a hydrologic laboratory, in whicl natural rock materials are tested for mechanical composition, permeability porosity, and moisture equivalent—the last two as a means of computing specifi retention and specific yield. Similar work is done in various other laboratorie in the country.

Work of the Geological Survey and cooperating agencies.—Ground-water investigations were actively conducted near the close of the past century and in the early years of this century. Then there was a notable curtailment. In the past twenty years there has been progressive and large increase in the funds made available for ground-water investigations and a corresponding improvement in the quality of the technical work done. The demand came first from the States, many of which supplied funds for cooperation with the Ground Water Division of the Geological Survey. Later these funds were met by increased Federal appropriations. In the fiscal year 1939 about $380,000 was expended for ground-water investigations by the Geological Survey and cooperating State, Territorial, county, and municipal organizations.

Literature relating to ground water.—The Geological Survey has published about 700 papers that contain information on ground water, of which about 400 relate primarily to this subject. The technical literature relating to ground water published by other investigators is extensive and widely scattered. In the fiscal year 1938 the Geological Survey and cooperating agencies released about 100 papers relating to ground water, of which 9 were published by the Geological Survey, the rest being published by cooperating agencies or in scientific journals or released in mimeographed or typewritten form.

INTRODUCTION

The 48 States that constitute the United States of America cover an area of a little more than 3,000,000 square miles. (See pl. 15.) This vast area comprises a geologic section of great aggregate thick-

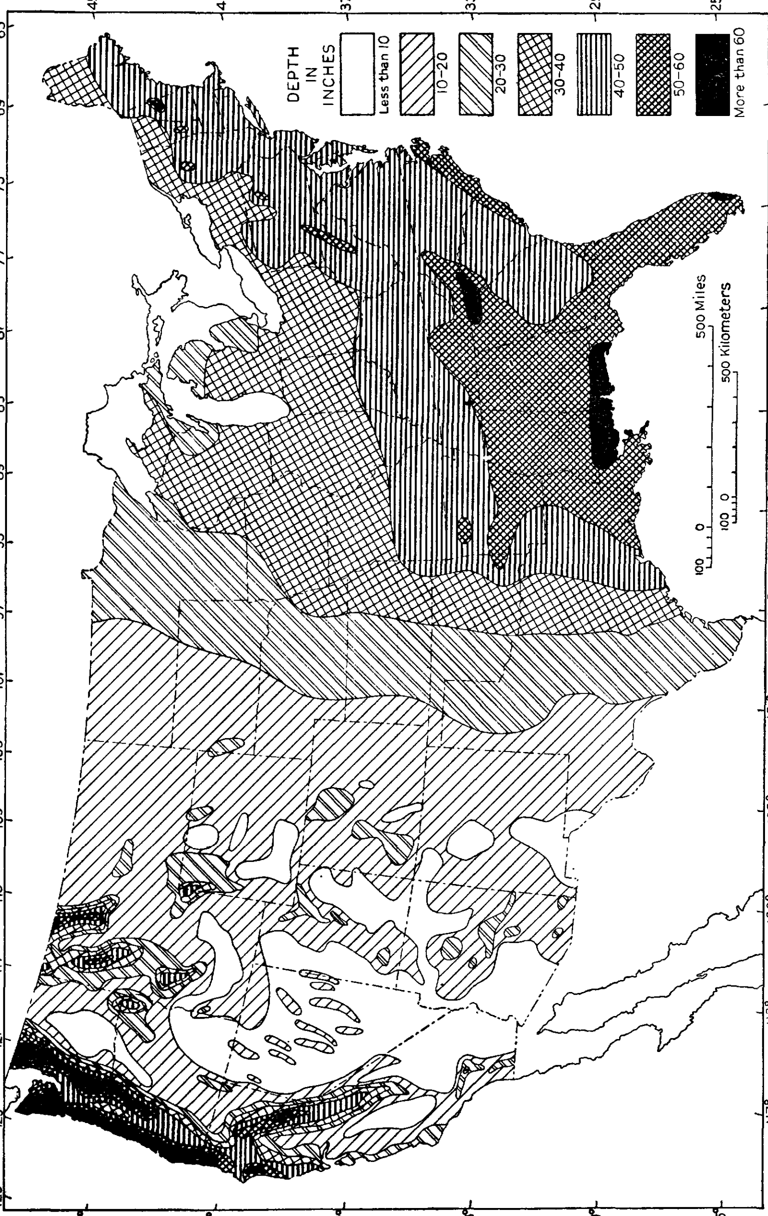


FIGURE 11.—Map of the United States showing mean annual precipitation. Based chiefly on records of the United States Weather Bureau. Compiled from map published by the National Resources Board, Water Resources Committee, 1934, with much simplification.

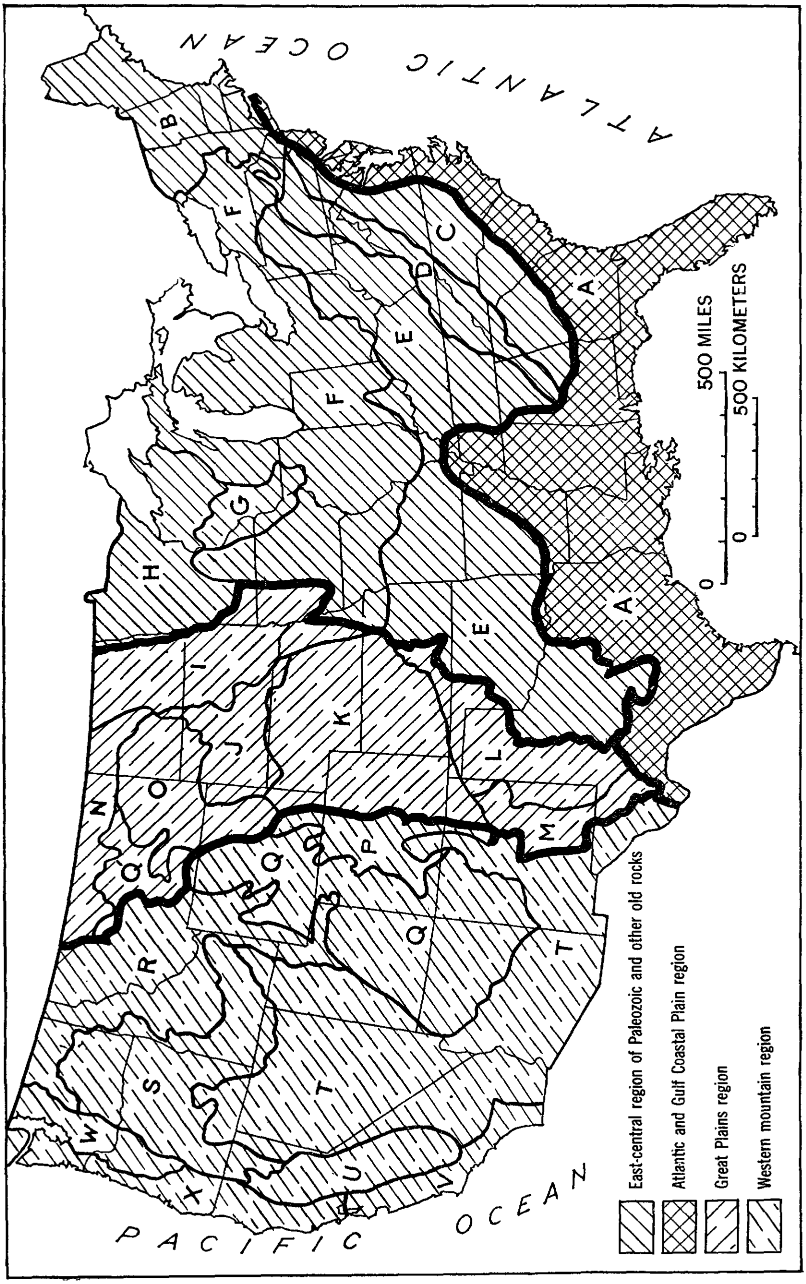


FIGURE 12.—Map of the United States showing the four major regions with respect to ground water and their subdivision into ground-water provinces. (After Geol. Survey Water-Supply Paper 489, pl. 31, with some revision of provinces in the West, in part after C. F. Tolman.)

EXPLANATION

East-Central region of Paleozoic and other old rocks

Province C is underlain by igneous and metamorphic rocks (chiefly pre-Cambrian) and Triassic sandstone. These rocks yield many small supplies of good water. Province D is mountainous and is underlain by folded and faulted Paleozoic strata, pre-Cambrian metamorphic rocks, and associated igneous rocks. These rocks supply water of good quality to numerous springs, spring-fed streams, and shallow wells. In province B the bed rocks (chiefly metamorphic) are overlain by glacial drift. The bed rock and boulder clay yield many small supplies of good water, and glacial sand and gravel yield large supplies in some places.

Provinces E, F, and G are underlain by Paleozoic rocks. The sandstones and limestones yield good water to shallow wells, but deep wells strike mineralized water, much of which is unfit for use. The shales yield meager supplies. The glacial drift in province F yields many supplies, both large and small. The outwash sand and gravel in valleys in province G and the northern part of province E yield large supplies.

In province H glacial drift yields many water supplies, but where the drift is thin only meager supplies are obtained from the underlying granite or other pre-Cambrian rocks. The water ranges in quality from soft and good in the eastern part of the province to highly mineralized and even unfit for use in the western part.

Atlantic and Gulf Coastal Plain Region

In province A Cretaceous, Tertiary, and younger strata of sand and limestone yield many small and many large water supplies. Much of the water is of good quality, but some is salty.

Great Plains Region

Provinces I, J, K, N, O, and Q are in general underlain by Cretaceous formations—chiefly unproductive shale with interbedded or underlying sandstone that yields highly mineralized artesian water. Flowing wells are especially abundant in province I. In large areas in province Q′ and in most of province J, except in the Black Hills, thick Cretaceous shales occur at the surface and are barren of water or yield only meager supplies of poor water. In province O and the eastern part of province N the Cretaceous strata are overlain by strata of early Tertiary and perhaps in part late Cretaceous age, which include sand, gravel, and coal that in most places yield small to moderate supplies. In provinces I and N the glacial drift generally yields supplies of hard but otherwise fairly good water.

In provinces K and L Tertiary and Quaternary sand and gravel yield abundant supplies of somewhat hard but otherwise good water in most places. The underlying Cretaceous formations in province K and the underlying Permian or Triassic "Red Beds" in province L furnish water supplies in some places but generally are not of much value, and where they occur at or near the surface water may be scarce.

In the Roswell artesian basin, in province M, Permian limestone yields large supplies of hard but usable water. Elsewhere the Carboniferous rocks underlying this province generally yield only meager supplies of poor quality, but in certain areas alluvial sand and gravel furnish abundant supplies.

Western Mountain Region

In the Rocky Mountains (provinces P and R) and the Sierra Nevada (part of province U), water supplies are furnished by springs, streams, and shallow wells. In province Q more or less flat-lying Paleozoic, Mesozoic, and younger strata form dissected plateaus with generally meager water supplies. In province S extensive lava beds and associated gravel give rise to very large springs and in some places yield large supplies of good water to wells. In provinces T, U, V, W, and X, sand and gravel in the broad valleys between mountain ranges yield numerous supplies of generally good water, at many places in large quantities. In parts of these provinces water supplies are obtained also from lava beds, glacial outwash, and other formations.

ness, including rocks of almost every kind that range in age from pre-Cambrian to Recent. It also has great diversity in geologic structure, altitude and form of land surface, and climatic conditions.

In the eastern part of the United States the mean annual precipitation ranges from less than 40 to more than 60 inches. (See fig. 11.) In general the precipitation decreases toward the west, and in most parts of the Great Plains the annual mean is between 15 and 30 inches. In the extensive Western Mountain region the climate is generally arid, but the range in mean annual precipitation is from more than 100 inches in a few localities in the extreme Northwest to less than 5 inches in parts of southwestern Arizona and southeastern California.

The great diversity in geology, topography, and climate has resulted in a corresponding great diversity of conditions with respect to the ground water, that is, the water in the zone of saturation, which supplies the springs and wells. Thus there is great variety in the intake, quantity, movement, artesian pressure, chemical character, and mode of discharge of the ground water.

In the present paper the effort is made to give a brief but comprehensive summary of the complex ground water conditions in the United States (not including the outlying territories), and of the utilization of the ground water, its value as a natural resource, and the scientific investigation that has been and is at present being made of this subject.

In previous studies the United States has been divided into ground-water provinces. For the purpose of this paper these provinces are grouped into four major regions. (See fig. 12.)

As this paper covers a comprehensive field it is necessarily based on the work of many scientists. Some of the data have not heretofore been published. Much of the information is taken directly from the author's previously published papers on ground water, but those were to a considerable extent based on publications by others. The list of publications on pages 223–229 includes the principal works used in the preparation of this paper and also other representative publications relating to the different subdivisions of the subject. In the text these publications are cited by their serial numbers as given in the list. Some of the publications contain bibliographies or numerous references to other published works.

WATER-BEARING FORMATIONS AND THEIR GEOGRAPHIC DISTRIBUTION

EAST-CENTRAL REGION OF PALEOZOIC AND OTHER OLD ROCKS

The eastern and central parts of the United States consist chiefly of old rocks, underlain in the northern part by glacial drift. The old rocks are chiefly of Paleozoic age but include large areas of pre-Cambrian rocks, which are older than Paleozoic, and a few relatively small areas of Triassic rocks, which are younger than Paleozoic. (See figs.

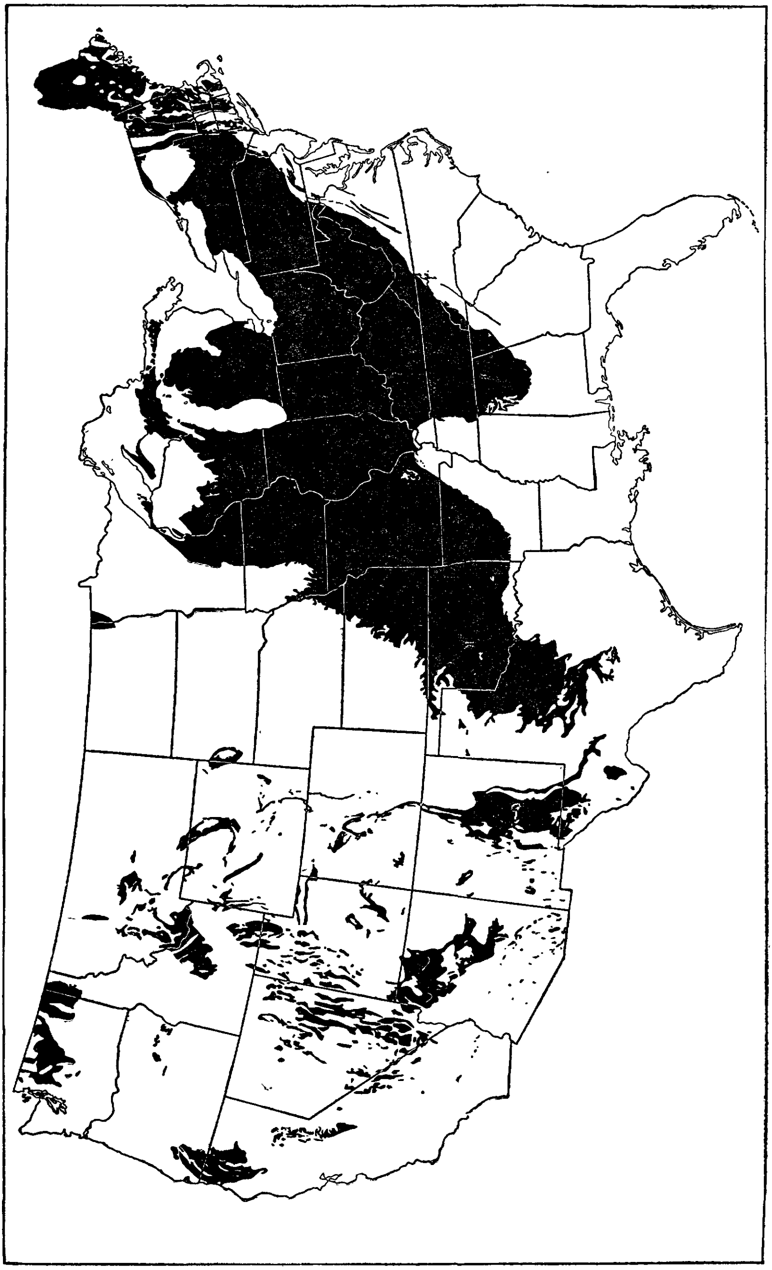


FIGURE 13.—Map of the United States showing areas in which Paleozoic rocks are at or near the surface. In the large areas the Paleozoic formations generally lie nearly horizontal and include a number of valuable sandstone and limestone aquifers. The deeper waters are in most places highly mineralized.

13, 14, and 15.) This region covers about one-third of the entire area of the country and contains fully two-thirds of the inhabitants.

All the Paleozoic rock systems are represented, from the Cambrian to the Permian (which is regarded by the Geological Survey as a part of the Carboniferous system). Together they form a succession of sedimentary strata, chiefly shale, sandstone, and limestone, having an aggregate thickness of many thousand feet. Over most of the region the rock strata lie nearly horizontal, but in the Appalachian Mountains

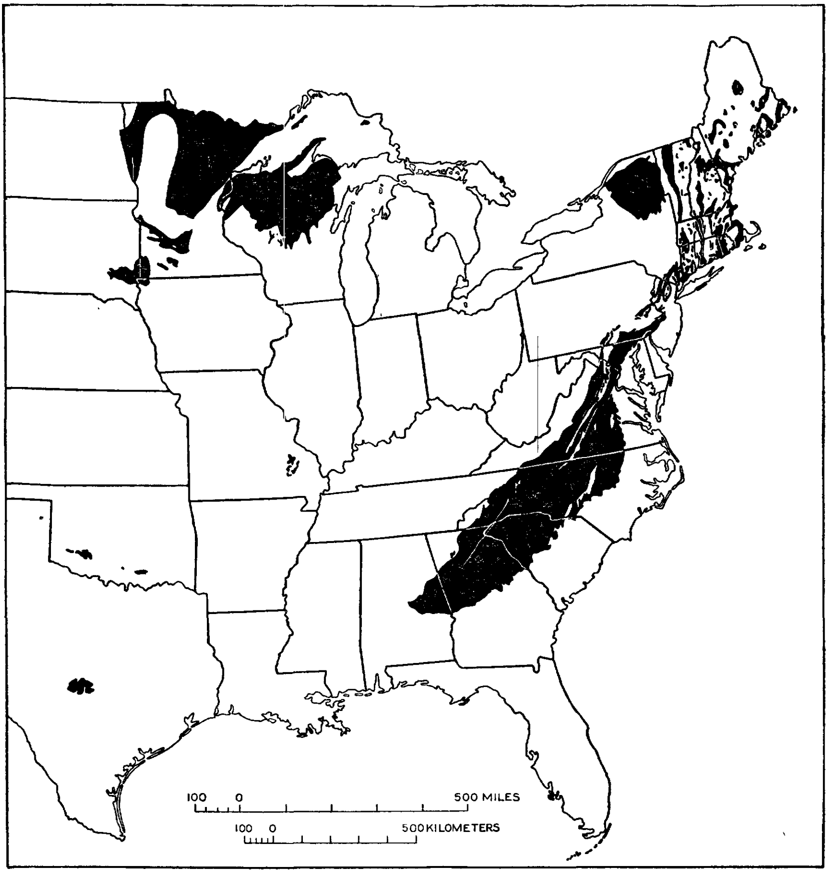


FIGURE 14.—Map of the eastern and central parts of the United States showing areas in which pre-Cambrian rocks or post-Cambrian intrusive or plutonic rocks are at or near the surface. These rocks yield small supplies of water to springs, to dug wells that end in the disintegrated surficial parts of the rocks, and to drilled wells that encounter water-bearing joints within a few hundred feet of the surface.

and in a few other places they are folded and faulted. From the many different formations of Paleozoic sandstone and limestone are obtained a great number of water supplies, both large and small, for domestic, livestock, municipal, and industrial uses. In most of the region the potable water comes from depths of not more than a few hundred feet, and the deeper water is salty. In some parts, however, especially in Wisconsin, Minnesota, Illinois, Iowa, and Missouri, the deeper water is potable, though highly mineralized, and furnishes large public and industrial supplies. The shales, which are especially abundant in the Pennsylvanian and Permian series of the Carboniferous system, are generally unproductive or yield only small supplies.

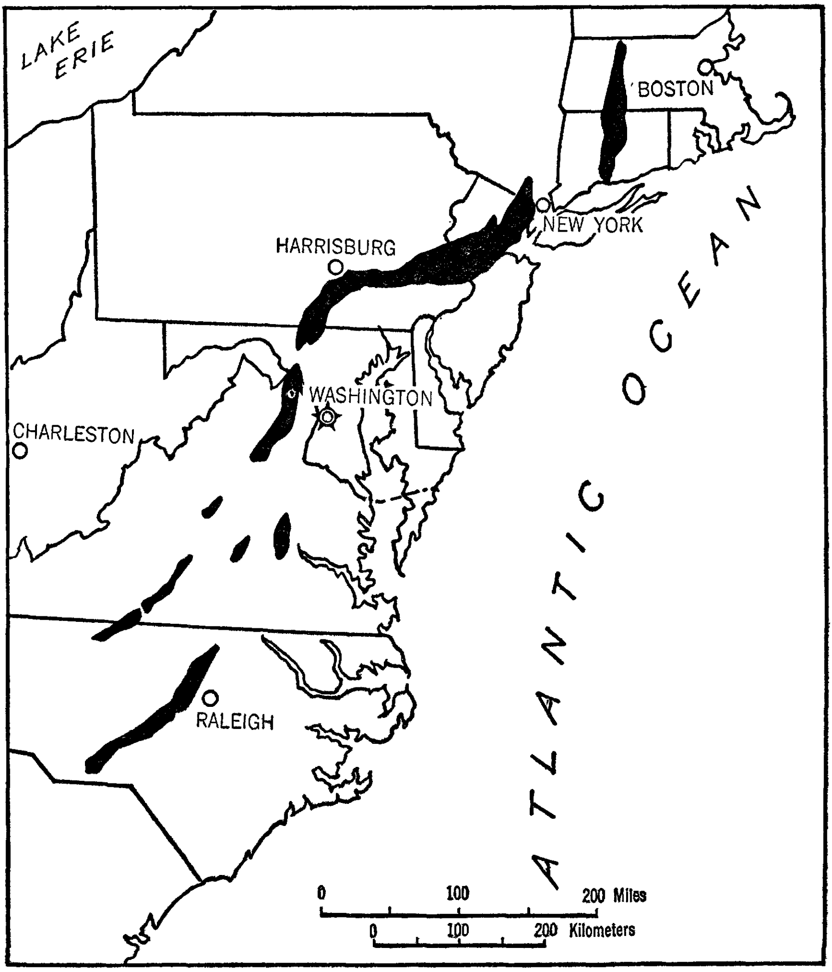


FIGURE 15.—Map of the eastern part of the United States showing areas in which Triassic rocks are at or near the surface. These rocks consist chiefly of red sandstone and other sedimentary beds that yield water in moderate quantities. They include some igneous rocks, commonly called trap, that are not productive of water.

Where they occur at the surface and the deeper water is salty, the problems of obtaining a satisfactory water supply are difficult.

Parts of the East-Central region are underlain by pre-Cambrian rocks, chiefly granite, gneiss, and schist, or by later intrusive or plutonic rocks. Such rocks occur at or near the surface in northern and western Minnesota, northern Wisconsin, and the northern peninsula of Michigan, in the Blue Ridge and the Piedmont Plateau from Alabama to New York, in the Adirondack Mountains of northeastern New York, and in New England. (See fig. 14.) Water supplies for domestic and stock use and for some small industries and public waterworks are obtained from the weathered and jointed parts of these rocks near the surface, and exceptionally at depths of several hundred feet, but in some places these rocks fail to yield even small supplies of water.

In the Piedmont Plateau and in New England there are several belts of Triassic rock, consisting largely of red sandstone that yields moderate supplies of water. (See fig. 15.)

Glacial drift of several successive ice sheets overlies the older rocks in the northern part of this region to depths ranging from a few feet to a few hundred feet. (See fig. 16.) The drift consists largely of boulder clay but includes many irregular beds of sand and gravel that underlie the boulder clay or are interbedded with it. The boulder clay yields small supplies of water to many shallow dug wells, whereas the sand and gravel yield abundant and permanent supplies to an ever-increasing number of deeper drilled wells for domestic, livestock, and industrial uses and for municipal waterworks.

Great quantities of sand and gravel were deposited in the valleys of streams that headed in the glacial ice. In the drainage basin of the Mississippi River the sand and gravel deposits extend down the northern tributaries, including the Ohio and the Missouri, and down the valley of the trunk stream far beyond the mouth of the Ohio. These deposits contain large quantities of water, which they yield freely to wells, and their storage is readily replenished by infiltration from the surface. They furnish many large water supplies for cities and industries.

ATLANTIC AND GULF COASTAL PLAIN REGION

A wide coastal plain, occupying fully one-seventh of the entire area of the United States, borders the Atlantic Ocean and the Gulf of Mexico. It extends from Martha's Vineyard, in Massachusetts, to the Rio Grande, and thence into Mexico. It includes the peninsula of Florida and extends up the Mississippi Valley to the mouth of the Ohio River. (See fig. 12.)

This region is well populated and teems with human activities of many kinds. It is underlain by Cretaceous, Tertiary, and Pleistocene sedimentary formations which include numerous beds of water-bearing sand with some gravel, and in parts of the region, especially Florida and Texas, beds of cavernous water-bearing limestone. In this region ground water is especially important in furnishing supplies not only for domestic and stock use but also for a large proportion of the industrial establishments and municipalities, including most of the large cities, and for irrigation, especially of vegetables and fruits in Texas and Florida and of rice in Texas, Louisiana, and Arkansas.

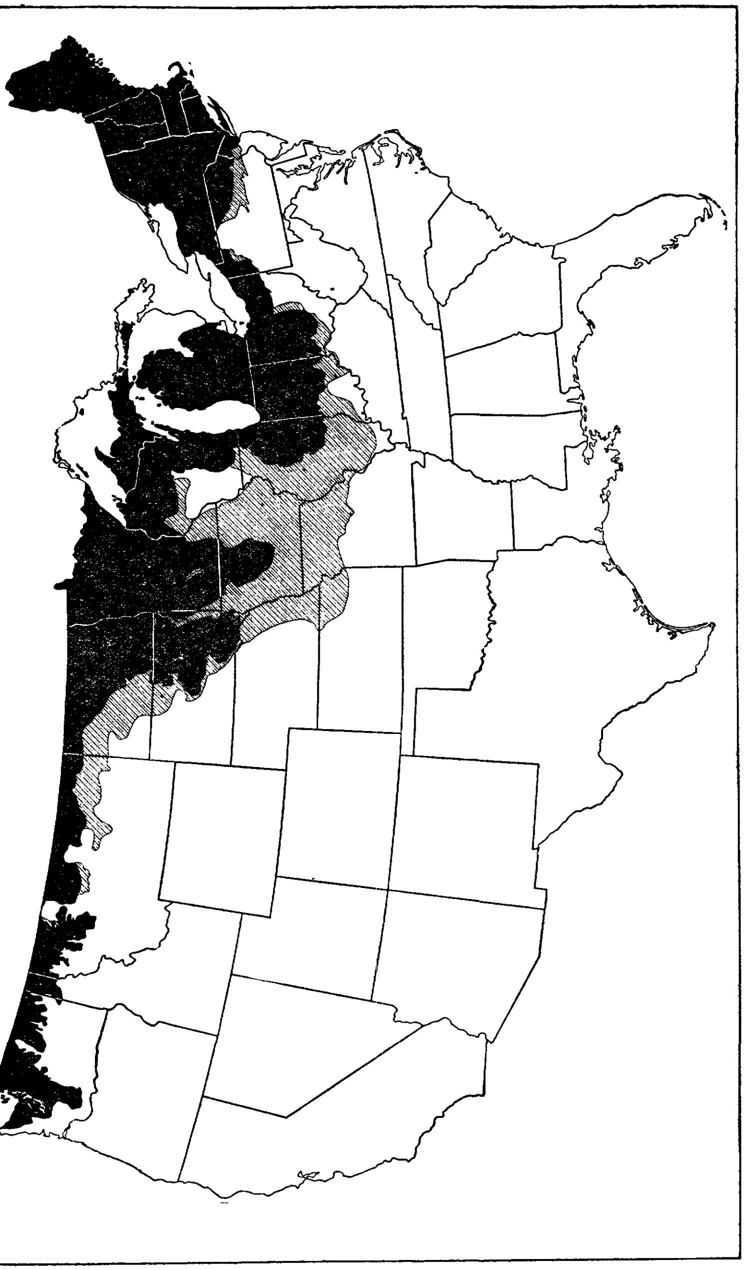


FIGURE 16.—Map of the United States showing principal areas underlain by glacial drift. (After unpublished map compiled by W. C. Alden.) Black indicates the Wisconsin or latest drift sheets; light shading indicates older drift. Many small patches covered by drift of local glaciers in the western mountains are not shown on this map. Outwash deposits and deposits of loess beyond the drift sheets are not shown. The glacial drift, including the outwash sand and gravel, constitutes one of the most important sources of water supply in the United States.

The glacial deposits impinge on the coastal plain in two areas where abundant water supply is especially valuable—Long Island and he Mississippi Valley. (See fig. 16.) The northern part of Long sland is occupied by moraines, the southern part by a plain of out-ash sand and gravel that yields very large supplies of water for

municipal and industrial uses. The very broad Mississippi Valle
from the mouth of the Ohio to the mouth of the Mississippi, con
tains extensive Pleistocene deposits of sand and gravel, mostly o
glacial outwash origin, that yield very large supplies, used especiall
for the irrigation of rice.

GREAT PLAINS REGION

In an extensive semiarid or subhumid agricultural region east o the Rocky Mountains, about 500 miles wide in the northern par and tapering toward the south, the Paleozoic and older rocks ar generally overlain by younger formations, including rocks of Triassic Jurassic, Cretaceous, Tertiary, and Pleistocene age. This regio corresponds in general but not exactly to the region that is commonl called the Great Plains. (See fig. 12.)

Nearly all of the northern and central parts of this region ar underlain by Cretaceous formations (chiefly Upper Cretaceous) consisting mostly of impermeable shale but with water-bearin sandstones interbedded with them or occurring at or near the base The water in the Cretaceous sandstones is generally under artesia pressure and supplies many flowing wells, especially in North Dakot and South Dakota. It is generally highly mineralized, and muc of it is unfit for ordinary use.

In the northwestern part of the region, chiefly in western Nort Dakota, eastern Montana, and eastern Wyoming, there are thic sedimentary deposits of early Tertiary and perhaps in part lat Cretaceous age, which include many irregular beds of sandstone tha yield potable water, generally in small quantities. Some wate supplies are also obtained from coal beds.

In most of the central and southern parts of the region the Cre taceous and older rocks are overlain by late Tertiary and Pleistocen deposits that consist largely of alluvial outwash from the Rock Mountains. The beds of sand and gravel in these deposits generall furnish ample supplies of water of good quality for domestic, stock municipal, and industrial uses, and locally for irrigation. Th Pleistocene deposits contain much coarse and well-assorted materia that yields water very freely. They extend down the valleys of th principal streams and merge to some extent with the outwash fron the continental ice sheets, covering extensive areas in the centra parts of Nebraska and Kansas.

The northeastern and extreme northern parts of this region ar overlain by glacial drift, which furnishes potable water to many well for domestic, stock, municipal, and industrial uses. (See fig. 16.)

In parts of the Great Plains region, especially where the Cretaceou shale is at the surface and the water of underlying sandstones i salty, supplies of potable ground water are lacking or very meage ıd recourse must be had to the generally unsatisfactory and uncertain ıpplies obtained by storing rain water or run-off. In the northern ırt of the valley of the Red River of the North, also, the ground ater is generally salty.

Over a considerable area on the east side of the mountains in New [exico and Texas, Paleozoic rocks are at the surface, and in the oswell basin cavernous Permian limestone yields large supplies of ·tesian water for irrigation.

WESTERN MOUNTAIN REGION

The Western Mountain region, which occupies about one-third ; the entire area of the United States (see fig. 12), has many diverse ɔnditions. Although generally arid, it experiences the country's ;tremes of humidity and aridity; although generally sparsely popu-.ted, it contains a number of large cities and great developments of ıining, stock raising, agriculture, and horticulture; although generally ıcking in water supply, it has some of the largest rivers and springs ıd some of the most copious of water supplies developed from wells. ı different parts of the region water is obtained from many different ɔrmations and under many different conditions.

In the Rocky Mountains, which occupy the eastern part of the ·gion, and in other areas of large and rugged mountains, the water ıpplies are obtained chiefly from springs and from streams fed by ɔrings and melted snow.

The High Plateau, in eastern and southern Utah, northern Arizona, ɔuthwestern Colorado, and northwestern New Mexico, is underlain y a great succession of more or less flat-lying sedimentary strata, ıcluding rocks of Carboniferous, Triassic, Jurassic, Cretaceous, and ertiary age. These rocks are deeply cut by the Grand Canyon of ıe Colorado River and the canyons of the tributary streams. Water ıpplies are obtained from many of these rocks, locally in abundance, ıt in general ground water is scarce, and much of the available water highly mineralized. Large parts of the plateau area are virtually ithout water supplies. Farther north, especially in western Wyo-.ing, there are extensive areas of Cretaceous and Tertiary strata ith variable ground-water conditions.

Much of the Western Mountain region, especially in southern and ·ntral California, Nevada, western Utah, southern Arizona, and rge parts of New Mexico, is characterized by isolated mountain ınges and broad intervening valleys that contain thick deposits of ·avel, sand, and clay derived by erosion of the mountains. (See ;. 17.) The upper part of this valley fill is generally of Quaternary ;e, but the deeper fill is largely Tertiary. The irregular beds of ınd and gravel receive water from the mountain streams, and they ·nerally yield abundant supplies of potable water for domestic, ·ock, municipal, and industrial uses and for desert watering places.

They furnish very large supplies for irrigation in some places, especially in California and Arizona. If the water pumped for irrigatio is included, the valley fill of this region furnishes more water to wel than any other group of formations in the United States.

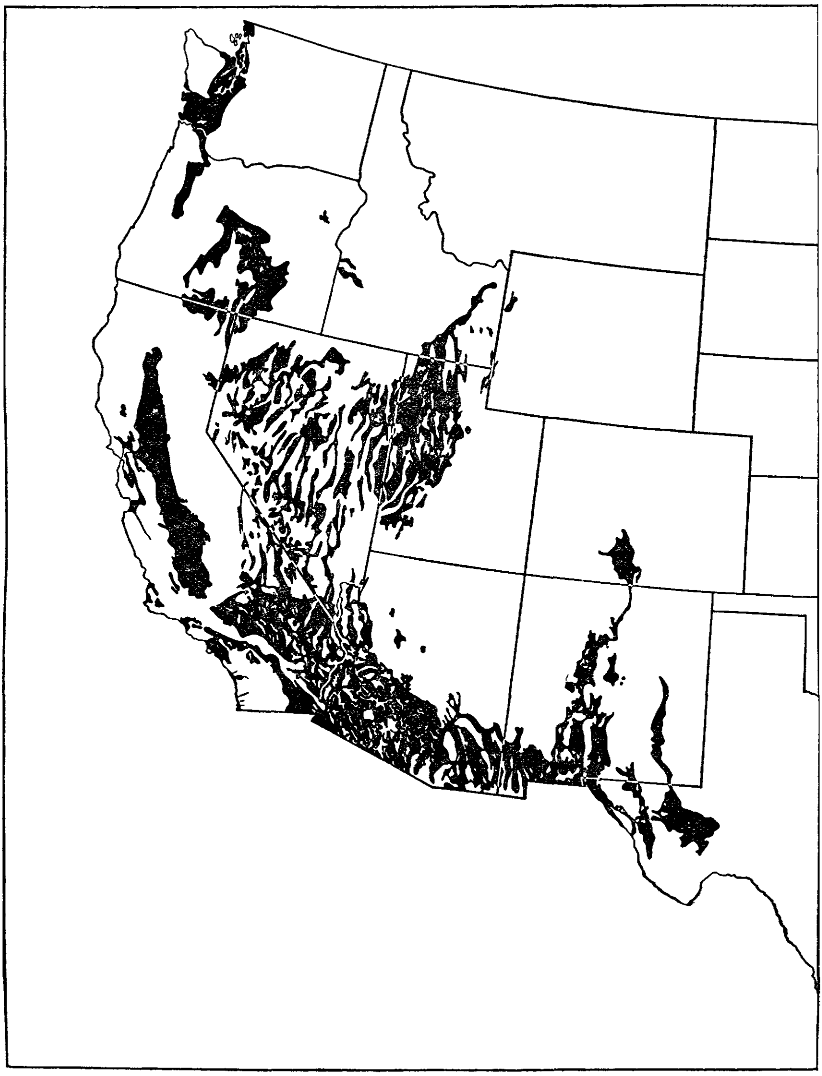
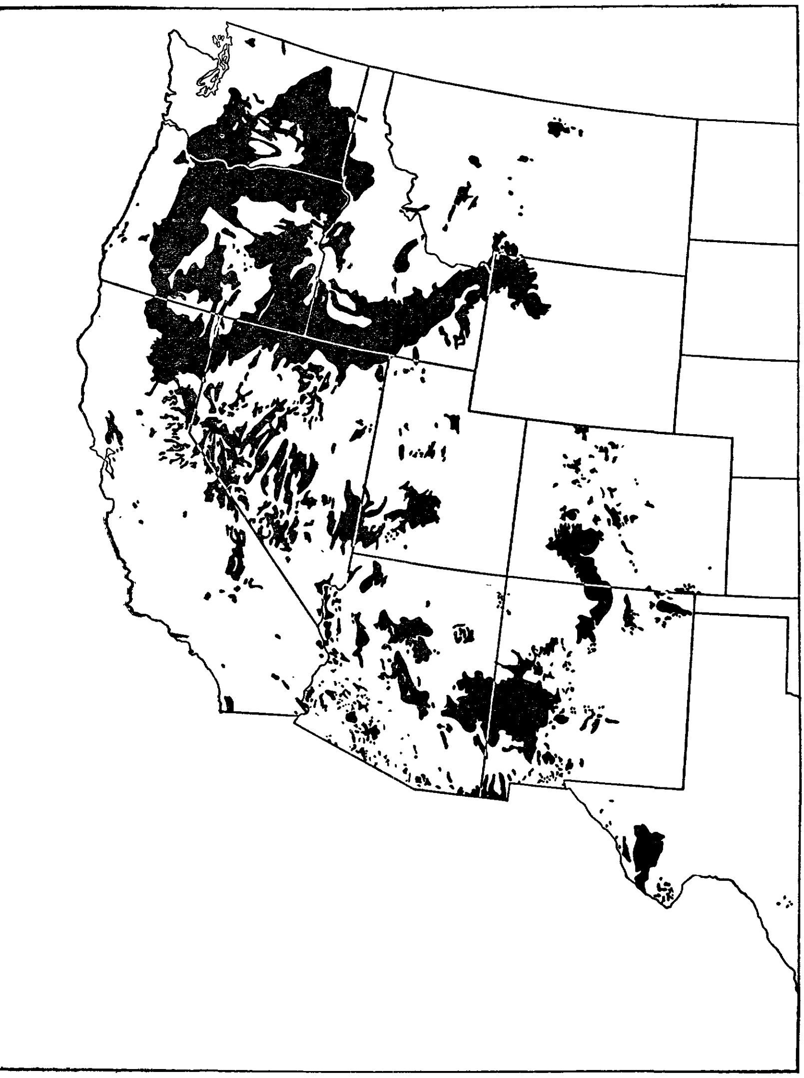


FIGURE 17.—Map of the western part of the United States showing the principal areas underlain by vall fill. This fill includes much sand and gravel that yield water freely and in large quantities. It co stitutes the most valuable group of aquifers in the Western Mountain region.

Gravel and other materials were washed out from the abundar mountain glaciers during the glacial stages of the Pleistocene an were in part deposited in the lakes that occupied many of the valley during the same stages. Locally the outwash and shore grave yield much water. In the extreme northern part of the region ther

great deposits of coarse glacial outwash that yield very large
pplies of water.

Extrusive volcanic rocks of Tertiary and Quaternary age, largely
salt, are abundant and widely distributed throughout the Western



URE 18.—Map of the western part of the United States showing areas in which Tertiary or Quaternary
lcanic rocks are at or near the surface. The extensive lava beds, especially in Idaho, Washington,
regon, and northern California consist chiefly of basalt; they yield abundant supplies to many drilled
ells and give rise to numerous springs, some of which are very large. No Tertiary or Quaternary
lcanic rocks are exposed in the eastern part of the United States.

ountain region, especially in Idaho, Washington, Oregon, and north-
n California. (See fig. 18.) These rocks are in part dense and
productive, but in part they take in the water from rain and snow

freely and discharge it through huge springs or through wells of larg capacity. The areas of volcanic rock are in most places only sparsel inhabited, and there is only moderate development of the large sup plies of good water that are available from these rocks. This is i contrast to the Hawaiian Islands, where very large developments hav been made from rocks of this kind.

WATER-TABLE CONDITIONS

Below a certain level the permeable rocks are generally saturate with water under hydrostatic pressure and are said to be in the zone o saturation. The upper surface of the zone of saturation, where i occurs in permeable materials, is called the water table (1, 40).[1] A greater depths water-bearing formations may lie below relativel impermeable confining beds and may consequently be under artesia conditions. In nearly all parts of the United States a water tabl occurs at greater or less depth below the land surface. Even th compact igneous and metamorphic rocks and the dense clay and shal formations have in most places become sufficiently permeable b weathering near the surface to have a water table.

The water supplies of the springs and wells in the United State are largely derived from formations in which the water is essentiall under water-table conditions. Nearly all the productive wate bearing formations occur at or near the surface over more or less ex tensive outcrop areas—not only the surficial deposits of sand and grave and the extrusive volcanic rocks (47), but also the older water-bearin formations. Thus in many parts of the country large areas ar underlain at or near the surface by weathered limestones or b sandstones that yield ample and perennial supplies of water to man relatively shallow pumped wells (6, 8, 13, 14, 21, 60, 61, 64). I other large areas the surface formations consist of relatively imper meable rocks, such as the compact igneous and metamorphic rocks the clay and shale formations, and the boulder clay of the glaci drift. In these areas there are many shallow pumped wells whic yield supplies that are relatively small but very valuable, especiall where no deeper water-bearing formations occur or where the deepe water is too highly mineralized for use. Some of these shallow well yield perennial supplies, whereas others fail in dry seasons throug the decline of the water table or the virtual disappearance of th meager supply of ground water (8, 32, 43, 57, 61).

Among the most productive of the formations that yield wate essentially under water-table conditions are the great surficial deposit of sand and gravel, as follows:

1. Extensive deposits of sand and gravel washed out from th fronts of continental ice sheets, which furnish large perennial supplie

[1] Numbers in parentheses refer to publications listed on pages 223–229.

› a great number of municipalities, institutions, and industrial stablishments all the way from the Atlantic Ocean to the Pacific ., 8, 21, 25, 43, 56, 57, 60, 89, 97).

2. Valley fill of the Western Mountain region, which, in many ırts of the region, furnishes large supplies for municipalities, industies, and irrigation, to some extent under artesian conditions (1, 15,), 22, 38, 58, 59, 65, 69, 75, 83, 90).

3. Tertiary and associated Quaternary deposits of sand and gravel ı the Great Plains region, which furnish almost the entire water ıpply for large parts of the region (1, 37).

4. Late Tertiary and Quaternary terrace and lowland deposits of ıe Atlantic and Gulf Coastal Plain, which largely mantle the older ırmations, yielding moderate supplies to many pumped wells throughıt the region and large supplies in some areas (1, 26, 28, 78).

As the formations that have water-table conditions generally lie at ıe surface over all or large parts of their extent, their intake facilities :e generally good, with the result that their supplies are readily :plenished by the water from rain and snow or from influent streams.

ARTESIAN CONDITIONS

ARTESIAN CONDITIONS IN GENERAL

The height to which the ground water will rise in wells varies not ıly from place to place but also, in nearly every locality, with the ɜpth of the water-bearing bed below the water table. These almost ıiversal variations in the head of the ground water are the result ' the complexity in the stratigraphy and structure of the rocks, the ·lief of the land, and the sources of intake. Where the head decreases ith depth the upper ground water tends to move downward to the ɜeper water-bearing beds, except as there are intervening beds ıat are entirely impermeable and continuous; where the head in·eases with depth the deeper water is under pressure transmitted om some more or less distant intake area at a higher altitude, and this ·tesian pressure tends to cause upward leakage unless the confining ɜd is entirely impermeable and continuous. Thus imperfect artesian ructure is of very common occurrence and produces flowing wells ith slight head in many low places (7, 18). In areas in which the ater-bearing beds are overlain by extensive and effective confining ɜds and have their intake areas at sufficiently high altitudes, large ·eas of artesian flow with considerable artesian pressure may result !). In figure 19 is given an ideal section which illustrates very simply ıe fundamental principle of artesian flow. In the following para·aphs only the principal artesian basins in the United States are :iefly described.

PALEOZOIC FORMATIONS OF EAST-CENTRAL REGION

The Paleozoic rock systems of the interior of the United States, w of the Appalachian Mountains, form an extensive artesian basin, which the sandstones and to some extent the limestones are t artesian aquifers, and the interbedded shales are the principal conf ing beds. The formations lie nearly horizontal over most of the in rior part of this region, but they rise gently in some areas, as northern Wisconsin and in Minnesota and in the Ozark Plateau, wh the aquifers crop out. Recharge occurs at these somewhat elevat outcrops and also, according to available evidence, by slow downwa percolation through overlying formations in wide areas where t aquifers are not at the surface (2, 8, 21, 60, 64).

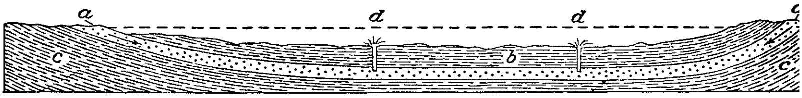


FIGURE 19.—Ideal section illustrating chief requisite conditions for artesian flows. *a*, Permeable wa bearing bed which constitutes the artesian aquifer; *b*, *c*, impermeable beds or beds with relatively permeability that constitute the confining beds above and below the artesian aquifer; *d*, flowing wells. piezometric surface, which shows the height to which the water from the artesian aquifer will ris tightly cased wells, is indicated by the dashed line. (After Chamberlin.)

The Mississippi River and its tributaries have cut rather bro valleys that are as much as several hundred feet below the gene level of the land surface. Many flowing wells have been obtained these valleys, chiefly from the Cambrian and Ordovician sandston but the flowing wells are virtually confined to the valleys. Hence map of the area of artesian flow resembles a map of the drainage syste

The strongest wells originally flowed several hundred gallons more than a thousand gallons a minute, but the head and rate of fl have generally diminished, and in areas of heavy pumping the sta water levels have receded below the surface. The water has be extensively used for municipal and industrial supplies since the fi wells were drilled, more than 60 years ago, but because of the hi mineral content of much of the water and the receding head, there h been a tendency in recent years to replace these supplies with wa from other sources.

To a large extent the Paleozoic formations of the interior are bel sea level and have perhaps never been above the present level of t sea. Over much of the region there is almost no means of esca for the deep water and almost no head to induce movement. Throug out most of the region the deep water is salty, though different composition from the sea water. Thus there is reason to believe th through the ages, there has been only very sluggish circulation throu the deep-lying parts of the Paleozoic rocks and that the salty wa is largely connate or at least very ancient (9).

Within a few hundred feet of the surface there is more vigoro movement of the ground water from the upland areas of intake towa the stream valleys; consequently, the water in the Paleozoic rocks ne he surface is generally resh, and much of it is f excellent quality (60).

The fact that the deep rtesian water is not so ıeavily mineralized in he areas adjacent to he Mississippi River as n most other parts of he region suggests that reshening may have ›een in progress ever ince the valleys were ut, as a result of upvard leakage of the rtesian water in the alleys and its replacenent by percolation of vater from intake areas n northern Wisconsin nd Minnesota, the)zark area, and elsevhere.

ROSWELL ARTESIAN BASIN

In the broad lowland ›elt in southeastern New Mexico through vhich the Pecos River lows southward occurs ›ne of the most producive and interesting of he artesian basins in he United States. (See ig. 20.) The area of ırtesian flow extends vith a north-south trend hrough a distance of ıbout 65 miles and orignally had an average vidth of about 10 miles. The artesian aquifer is a cavernous limestone of Permian age, which is at the surface over an extensive upland west of the valley, where it freely takes in water from the rain and snow and from the streams that head in the mountains still farther west.

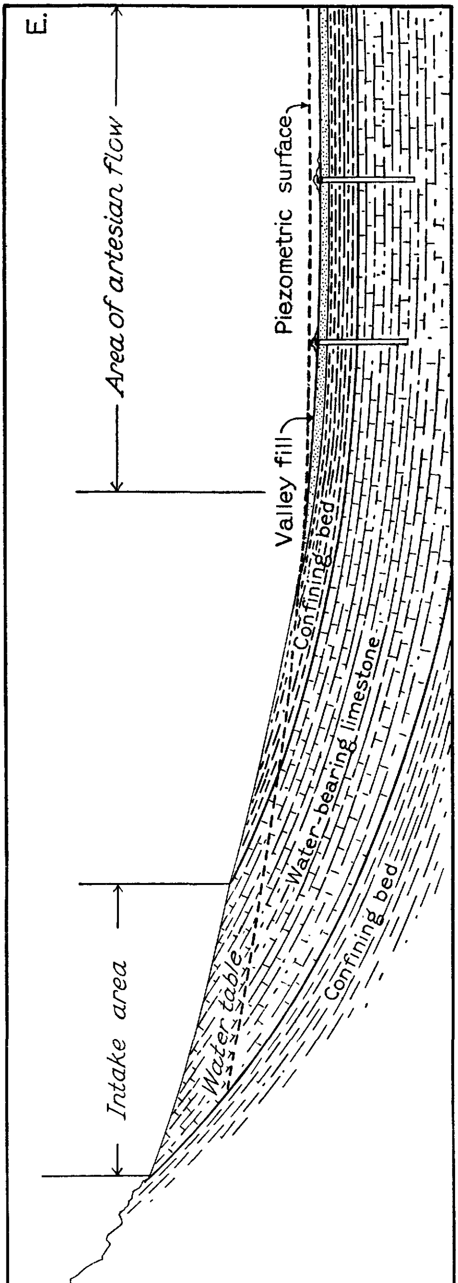


FIGURE 20.—Generalized section of the Roswell artesian basin. The artesian aquifer is a cavernous limestone of Permian age, which obtains large supplies of water from rain and snow on its elevated outcrop area and from the streams that flow over the outcrop area. Horizontal distance is about 80 miles; vertical scale is greatly exaggerated. (After Fiedler and Nye.)

The confining member consists chiefly of Permian red beds that cover the limestone east of its outcrop area (6).

The artesian water is used for the irrigation of about 60,000 acres of land. Much of the water is pumped from wells that no longer overflow. Between 1905 and 1925 the head was notably lowered by the artesian discharge and pumpage from many wells of large capacity. At the same time the lowest lands became water-logged because of the large quantities of artesian water that were wasted at the surface or by underground leakage from the wells. However, as a result of effective legal control and a program of repairing or sealing defective wells, most of the waste has been stopped, and the rate of withdrawal of artesian water by artesian flow or pumping is being kept close to the rate of recharge, with very beneficial results to agriculture and horticulture.

The flowing wells in the low parts of the area are still capable of very large yield. The rate of natural artesian flow from a well drilled in 1931, as measured, was 9,225 gallons a minute, or about 13,000,000 gallons a day. Such wells, however, are now under strict control, as is obviously necessary.

FORMATIONS OF ATLANTIC AND GULF COASTAL PLAIN

The great succession of sedimentary beds ranging in age from Lower Cretaceous to Quaternary that underlies the Atlantic and Gulf Coastal Plain is stratigraphically and structurally favorable for the accumulation of artesian pressure (3, 13, 14, 26, 27, 28, 94). The artesian aquifers are the water-bearing sandstones and limestones, and the confining members are the shales and other strata of low permeability. As a rule the formations dip gently toward the sea or gulf. The intake of each formation is along the landward margin, where it is at or near the surface, and the formation passes thence to greater and greater depths in the direction of the coast. These conditions are illustrated in figures 21 and 22.

It is believed that some of the artesian aquifers have submarine outcrops that form potential outlets for the artesian water, whereas others pinch out or become impermeable at their seaward edge. In the aquifers that have outlets the fresh artesian water presses against the heavier sea water. If the head of the fresh water is relatively high and the submarine outlet is not too far below sea level, the fresh water discharges into the sea. Otherwise the sea water backs up into the aquifer and maintains a static condition, except as the fresh water may escape upward through the confining beds. In some places aquifers containing water of excellent quality occur below salt-water beds. Much of the fresh artesian water has been softened by natural base exchange. Flowing and pumped wells reduce the head and may thus cause the sea water to percolate toward them. To some extent the existing conditions may have been inherited from the Pleistocene epoch, when the sea stood at times higher and other times lower than at present. This entire complex subject is receiving much critical study and will require much more.

Flowing wells, generally of low head, are obtained throughout a coastal lowland that ranges from a very narrow strip to a belt many

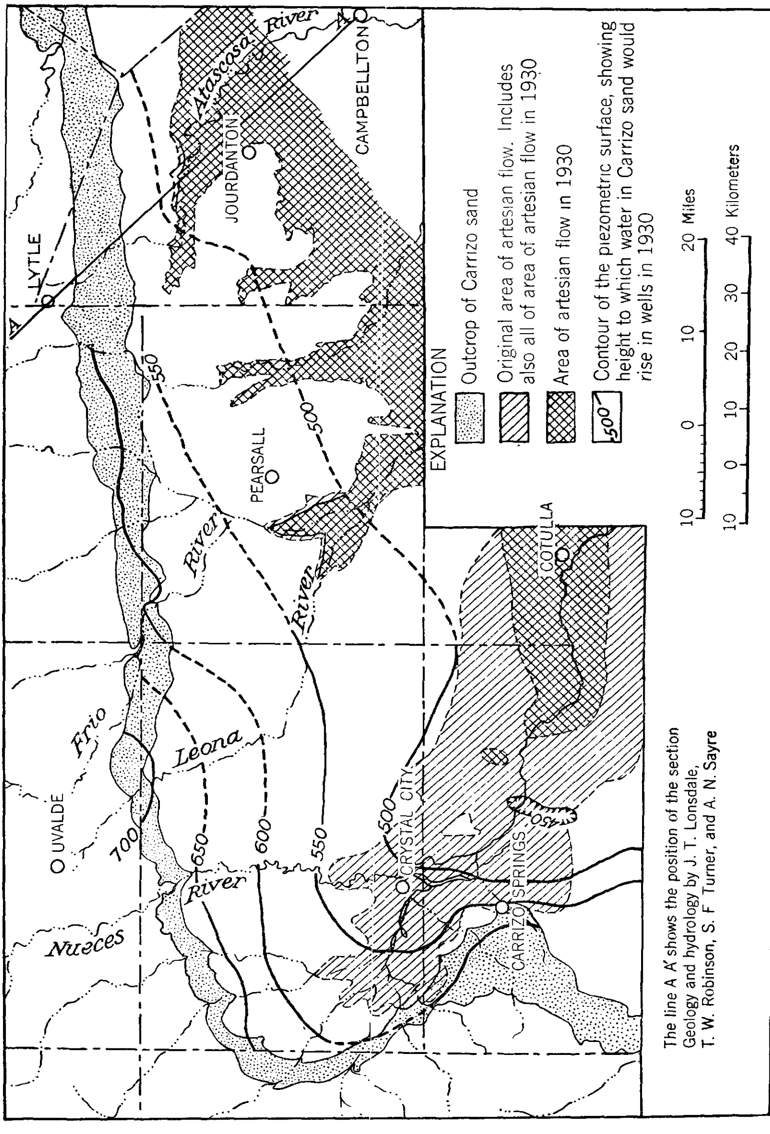


FIGURE 21.—Map of the Winter Garden district of the Coastal Plain in Texas, showing the original artesian conditions and the conditions as affected by heavy withdrawals through wells. For section, see fig. 22.

miles wide and also extends up the valleys of the rivers that cross the coastal plain and their tributaries. Flowing wells are therefore numerous and widely distributed. Most of them are of small diameter and rather small discharge and are used chiefly for domestic supplies. Many of them, however, originally flowed hundreds of gallons a minute.

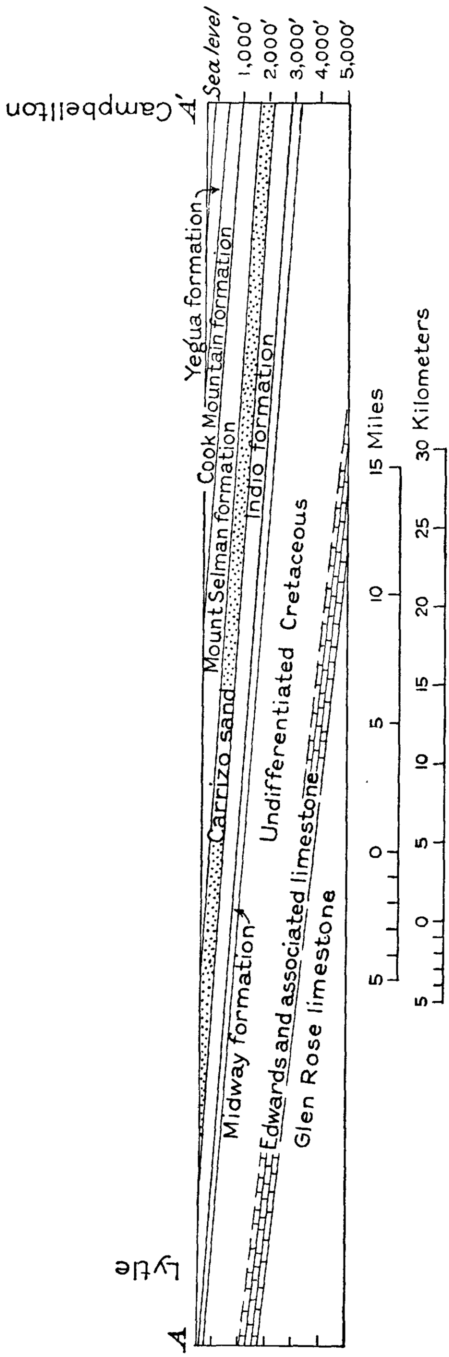


FIGURE 22.—Section along the line *A-A'* in figure 21.

A well in St. Augustine Florida, ending in cavernous limestone at a depth of 1,390 feet, was brought in with a natural artesian flow reported to be about 6,945 gallons a minute, or about 10,000,000 gallons a day. The numerous large supplies obtained from wells in many parts of the coastal plain are generally obtained by pumping, with considerable lowering of the head. However, some large supplies are still obtained by natural flow, as at Jacksonville, Florida, where flowing wells in permeable limestone furnish the entire public water supply of about 12,500,000 gallons a day.

CRETACEOUS FORMATIONS OF GREAT PLAINS REGION

The Cretaceous formations that underlie the northern and central parts of the Great Plains region with much continuity have a stratigraphy and structure that is favorable for the development of great artesian pressure (4, 5, 25). The strata of sandstone, which lie mostly at or near the base of the Cretaceous system, form the principal artesian aquifers. The thick formations of plastic impermeable shale are exceptionally effective in confining the water in these sandstones and permitting the development of great artesian head. The Cretaceous formations are generally flexed up around the Black Hills and along the flanks of the mountains farther west, exposing the sandstones in narrow belts, where they receive water from rain and snow and from the mountain streams that cross them. Elsewhere the Cretaceous formations generally lie nearly flat with only very gentle flexures, and the sandstones are deeply buried but reappear at the surface or below Pleistocene deposits in indefinite belts along the eastern margin of the region. The western outcrops occur at altitudes of a few thousand feet above sea level, but toward the east the surface in general slopes persistently though gradually downward to much lower altitudes. (See fig. 23.)

Flowing wells supplied from Cretaceous sandstones occur in widely separated localities throughout several States, but the notable area of artesian flow includes large parts of North Dakota and South Dakota and extends into adjacent States and into Canada. The original area in these two States was apparently about 45,000 square miles, and in most of this area the wells still overflow. In the last 55 years many thousands of flowing wells have been put down in this area.

Many of the early wells had pressures at the surface of more than 100 pounds to the square inch, and pressures of more than 200 pounds to the square inch were reported. Some of these wells had artesian flows of more than a thousand gallons a minute, and flows of several thousand gallons a minute were reported. A few of the wells got out of control, with spectacular and destructive results.

Near the end of the past century and in the early years of the present century a large number of flowing wells only 1¼ or 1½ inches in diameter were put down at very moderate cost, many of them to depths of more than a thousand feet. Eventually flowing wells were to be found on a large proportion of the farms in the area. This

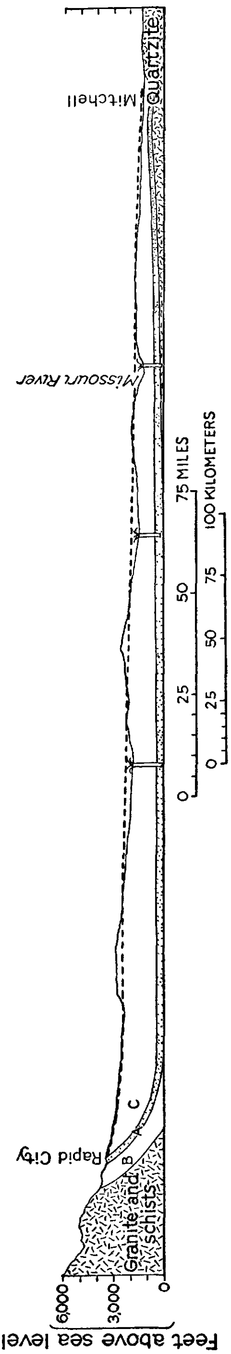


FIGURE 23.—Generalized section of the Dakota artesian basin in South Dakota. A, Sandstone of Cretaceous age, which constitutes the artesian aquifer; B, underlying sedimentary formations; C, overlying sedimentary formations, including thick beds of impermeable shale, which constitute the confining member. The broken line is the profile of the original piezometric surface of the Cretaceous sandstone; it shows the height to which the artesian water would rise originally in tightly cased wells. (After Darton.)

remarkable achievement was due to the ingenuity and enterprise of Peter Norbeck, who adapted the jetting method to this purpose and directed the drilling of most of the wells. Norbeck later became Governor of South Dakota and then United States Senator.

As the number of wells increased the head and the flow declined gradually but persistently. The area of artesian flow, however, has shrunk only moderately, and most of the wells are still flowing, though in most places the head is low and the flow relatively small. An investigation by the North Dakota Geological Survey showed that in 1935 there were about 4,400 flowing wells in that State, including a small proportion of wells drawing water from Tertiary and Pleistocene sources, and that these wells discharged by artesian pressure an average of somewhat less than 2 gallons a minute. Most of the Cretaceous wells were, however, throttled down, in accordance with the State law for the conservation of artesian water; otherwise the aggregate flow would have been considerably greater. In South Dakota the number of flowing wells is two to three times as great as in North Dakota, and the average discharge from a well is also greater.

Artesian sandstones occur at several horizons in most localities, but they have been only imperfectly correlated. In general, though with various exceptions, the strata that are first encountered yield rather soft water, high in sodium and in bicarbonate and chloride, whereas the deeper strata yield very hard water, higher in sulphate and lower in chloride. In many places the deeper water is still under great pressure, corroborating the chemical evidence of effective intervening confining beds.

The water is extensively used for livestock, but in many areas, and especially where it is high in fluoride, it is being replaced by water better for human consumption and industrial use. Some of the water, especially in Nebraska and Kansas, is too salty for any of the ordinary uses, though it is used to some extent for cooling installations. The soft water is generally unfit for use in irrigation.

The dynamics of the artesian system presents puzzling problems that require much more investigation. The artesian sandstones contain very large quantities of water, which, for the most part, is apparently moving very slowly from the western areas of outcrop, with their meager intake, in the direction of the hydraulic gradient—originally toward the natural areas of discharge but now more generally toward the wells. The natural course of the water from intake to discharge probably required thousands of years, and some of the water may be virtually stationary in synclinal troughs or encased lenses. There is evidence that a large part of the great quantity of water discharged by the flowing wells has come more or less locally from storage as a result of external compression of the aquifers when the artesian pressure within the aquifers was relieved (16, 17).

GLACIAL DRIFT

The glacial drift that covers much of the northern part of the United States gives rise to thousands of flowing wells (8, 11, 12, 21, 25). These wells are situated in several hundred small and irregular areas of artesian flow—chiefly but not exclusively within the area covered

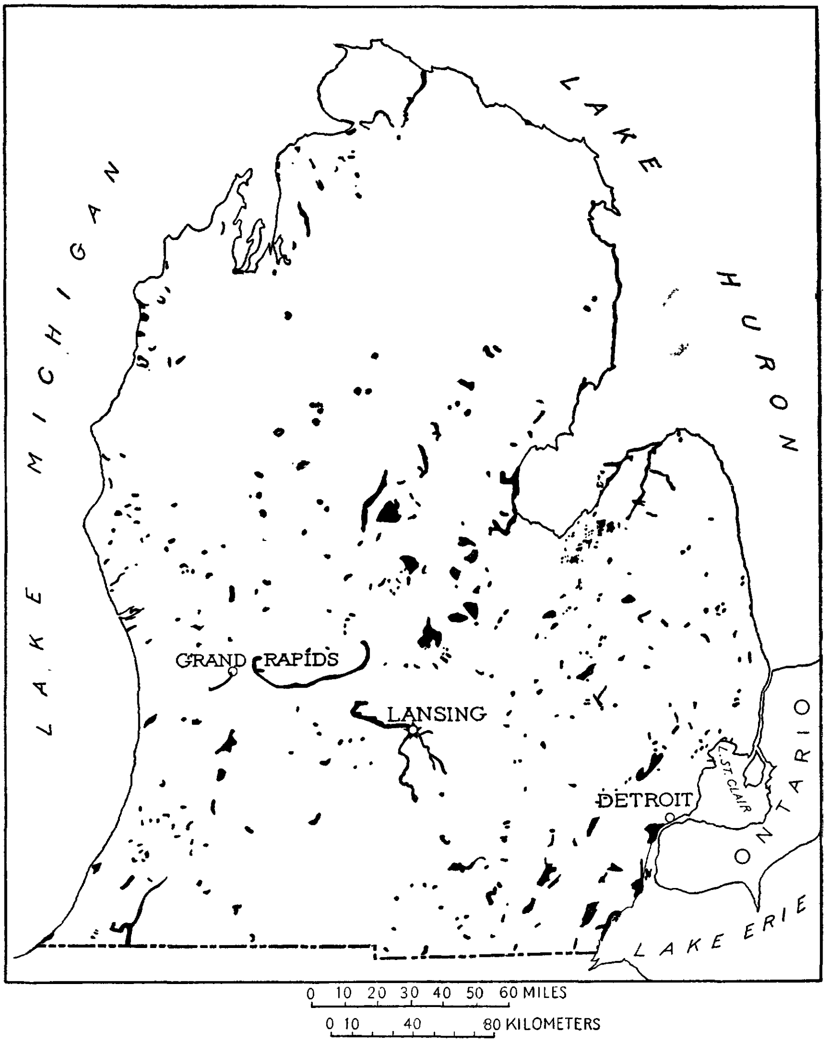


FIGURE 24.—Map of the lower peninsula of Michigan, showing areas of artesian flow, supplied chiefly from glacial drift. (After Leverett.)

by the Wisconsin or latest drift sheet. (See, for example, fig. 24.) The artesian aquifers are the numerous and irregular bodies of sand and gravel that occur in the drift. The confining beds are deposits of boulder clay, especially of the ground moraine, or clayey deposits of temporary glacial lakes. As the drift has a very irregular structure and includes much material that is more or less permeable, intake into the buried bodies of sand and gravel occurs in many indefinite areas where the water table is higher than the head of the water in these bodies, but the principal intake areas are the gravelly moraines that stand somewhat higher than the surrounding drift plains and in many places are connected with buried bodies of sand and gravel. The water that is absorbed by the moraines percolates slowly outward from them through the permeable materials beneath the boulder clay or lake beds, thereby creating artesian conditions.

Flowing wells are obtained in low places under a variety of conditions, largely at the base of moraines or in shallow stream valleys when the surface has been lowered somewhat without exposing the buried bodies of sand and gravel. The Wisconsin drift is so young that the area covered by it is very imperfectly drained, and the water table in this area is generally near the surface; hence a head in the deeper water only slightly greater than that at the water table produces artesian flows. As a rule there is upward leakage through the somewhat permeable confining beds, and consequently the head of flowing wells generally is low. Under exceptional conditions, however, there are wells with high head.

Throughout most of the Wisconsin drift area the water absorbed at the surface percolates through relatively unleached drift containing abundant organic matter. Hence the water from both flowing and pumped wells is commonly somewhat hard and iron-bearing but otherwise fairly satisfactory for domestic and other uses. There is, however, a wide range in the concentration of the dissolved constituents, corresponding to the character of the rocks from which the drift was derived.

Most of the flowing wells are of small diameter and yield, and they are found chiefly in villages and on farms, where they afford attractive and convenient supplies for domestic and stock use. Nearly all of the many large supplies obtained from glacial sand and gravel are pumped from wells of larger diameter and better construction.

VALLEY FILL OF WESTERN MOUNTAIN REGION

Flowing wells have been obtained in the low central parts of many of the valleys of the Western Mountain region that are underlain by detrital materials washed out from the adjacent mountains (10, 15, 19, 20, 22, 23, 24, 58, 65). The artesian aquifers are the beds or trains of sand and gravel that extend irregularly from the mouths of the canyons, where the streams emerge from the mountains upon the alluvial fans of their own construction. The confining beds are formed in part by the more clayey or loamy alluvial deposits that overlie or encase the deposits of sand and gravel, especially in the lower parts of the valleys, and in part by the extensive beds of plastic and impermeable clay deposited in the lakes that occupied many of these valleys during the glacial stages of the Pleistocene epoch. The streams that rise in the mountains lose much or all of their flow on the gravelly upper parts of their alluvial fans, where they build up the water table and thus furnish supplies, under artesian pressure, to the aquifers that extend below the confining beds in the low parts of the valleys. (See fig. 25.) As a rule, the largest and most productive areas of artesian flow are in the valleys that have not only Pleistocene lake beds or other effective confining beds but also abundant recharge from streams that drain large mountain areas with relatively heavy precipitation. Where lake beds are absent or poorly developed the confining beds generally permit considerable upward leakage and the flowing wells have only low or moderate head.

Notable for their size among the many areas of artesian flow are the extensive areas in the San Joaquin Valley, California (20), and

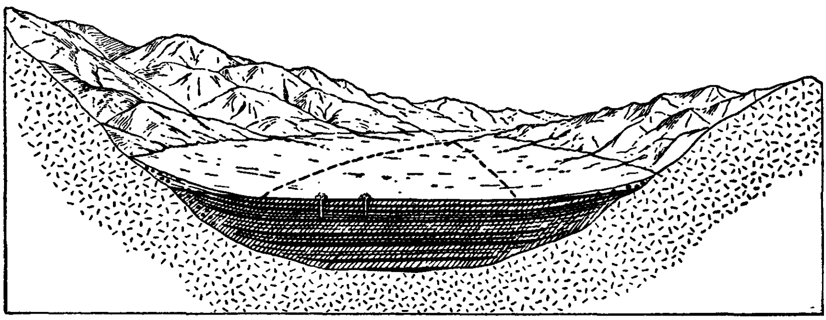


FIGURE 25.—Perspective view and section of a typical western valley showing artesian conditions. Cross ruling indicates saturated water-bearing beds; solid black indicates confining beds. Broken lines indicate boundaries of area of artesian flow.

in the San Luis Valley, Colorado (24). A survey made in 1936 showed that there are more than 6,000 flowing wells in the San Luis Valley and that these wells have an average artesian flow under regulation of about 12 gallons a minute, or an average unrestricted flow of about 15 gallons a minute (23).

The area of artesian flow in the San Luis Valley has been expanded somewhat in certain localities as a result of irrigation with surface water and consequent seepage from ditches and irrigated land in the higher parts of the valley. In many valleys, however, the artesian flow and especially the heavy pumping from wells have lowered the head greatly and have caused the areas of artesian flow to shrink or to disappear entirely. Flowing wells are still used extensively in many valleys for domestic and stock supplies and also for irrigation, generally on a small scale. Nearly all of the many large supplies from the valley fill are, however, obtained by pumping.

DISCHARGE OF GROUND WATER THROUGH SPRINGS AND BY EVAPORATION AND TRANSPIRATION

GROUND-WATER DISCHARGE IN GENERAL

In most terranes, regardless of geologic age, in the eastern part of the United States where the climate is fairly humid, the stream systems receive water from numerous branches, which are fed at many points by effluent seepage and gradually increase in flow downstream. In the limestone terranes, however, whether of Paleozoic, Cretaceous, or Tertiary age, the spring-fed branches are generally fewer but the springs are commonly bolder, that is, their water flows freely from a single opening or only a few large openings.

In the eastern part of the United States it is estimated that at least one-third of the total ground-water discharge occurs by evaporation from the soil and by transpiration of trees and other plants. In summer the discharge by evaporation and transpiration may greatly exceed the discharge through springs, and the flow of small streams may diminish sharply or cease entirely (43). In the areas of Wisconsin drift the stream systems are poorly developed, and accordingly the water table stands high and there are many swampy tracts except where extensive systems of artificial drainage have been constructed. In the poorly drained areas the discharge of ground water by evaporation and transpiration is relatively large; on the other hand, in the limestone areas, where underground drainage channels are well developed, it is doubtless relatively small.

In going toward the less humid parts of the country, the total water intake and discharge decrease even more rapidly than does the precipitation, whereas the proportion of discharge by evaporation and transpiration increases. Consequently in the Great Plains region and in the southwestern extension of the East-Central region, springs are scarce and small, except in a few areas in which the geologic structure is especially favorable for producing springs (37). In the extensive areas of Pennsylvanian, Permian, and Cretaceous shale the conditions are especially unfavorable.

Over large upland areas in the Western Mountain region, springs and streams are absent or very scarce. In the high mountains, however, there are many streams that are fed perennially or during large parts of each year by melting snow and by springs. The mountain springs are of many kinds, but they are largely seepage springs that discharge ground water from the surficial materials where this water in its percolation encounters outcrops of hard, impermeable rock (15, 31, 33).

After the streams leave the mountains they flow down over their alluvial fans and lose all or a large part of their water by influent seepage (38). A large proportion of the stream valleys are tributary to closed drainage basins, the lowest parts of which are occupied by playas, or clay flats, over which the water from storm run-off and perhaps from meager perennial stream flow is spread until it evaporates. During parts of the Pleistocene epoch many of the closed basins contained lakes of considerable size, but most of these lakes have disappeared entirely and the few that still exist are only remnants of the Pleistocene lakes (39).

With respect to ground water the closed basins are of two kinds—(1) those which lose all their ground water by subterranean leakage out of the basin, the water table being at considerable depth even in the lowest places; (2) those in which ground water is discharged in part by springs but generally in much greater quantities through evaporation and transpiration, the water table being at or near the surface in the low central areas. (See fig. 26.) Basins of the second kind are the most numerous, and economically they are by far the most important. The playas, which occupy the lowest parts of the basins, are underlain by nearly impermeable clay, of Pleistocene or Recent age, which permits only a small amount of upward percolation. Near the margins of the playas there are commonly belts of springs that discharge the overflow of the underground reservoir. Surrounding the playas are broad belts of characteristic desert plants, called phreatophytes, which habitually obtain their water supplies by sending their roots down to the water table. The phreatophyte vegetation is invariably arranged in concentric belts or zones, certain species, such as the common salt grass (*Distichlis spicata*), occupying the inner belt where the water table is near the surface, and other species, such as greasewood (*Sarcobatus vermiculatis*) in the northern basin and mesquite (*Prosopis*) in the southern basins, occupying the outer belt where the water table is farther below the surface but still within reach of these deep-rooted phreatophytes (42, 48, 65).

The great bodies of basalt and other volcanic rocks give rise to huge springs of excellent water that are the largest in the United States.

LARGE SPRINGS

In 1923 the author of this paper called attention to the need for a classification of springs according to their rate of discharge and proposed two systems of classification—one based on the metric system, the other on the units commonly used in the United States. According to the second system, a spring of the first magnitude is one that has an average discharge of not less than 100 cubic feet per second which amounts to an average daily discharge of 65,000,000 gallons, or 250,000 cubic meters (40).

According to a study completed about 10 years ago (41), there are in the United States 65 springs of the first magnitude. (See fig. 27.)

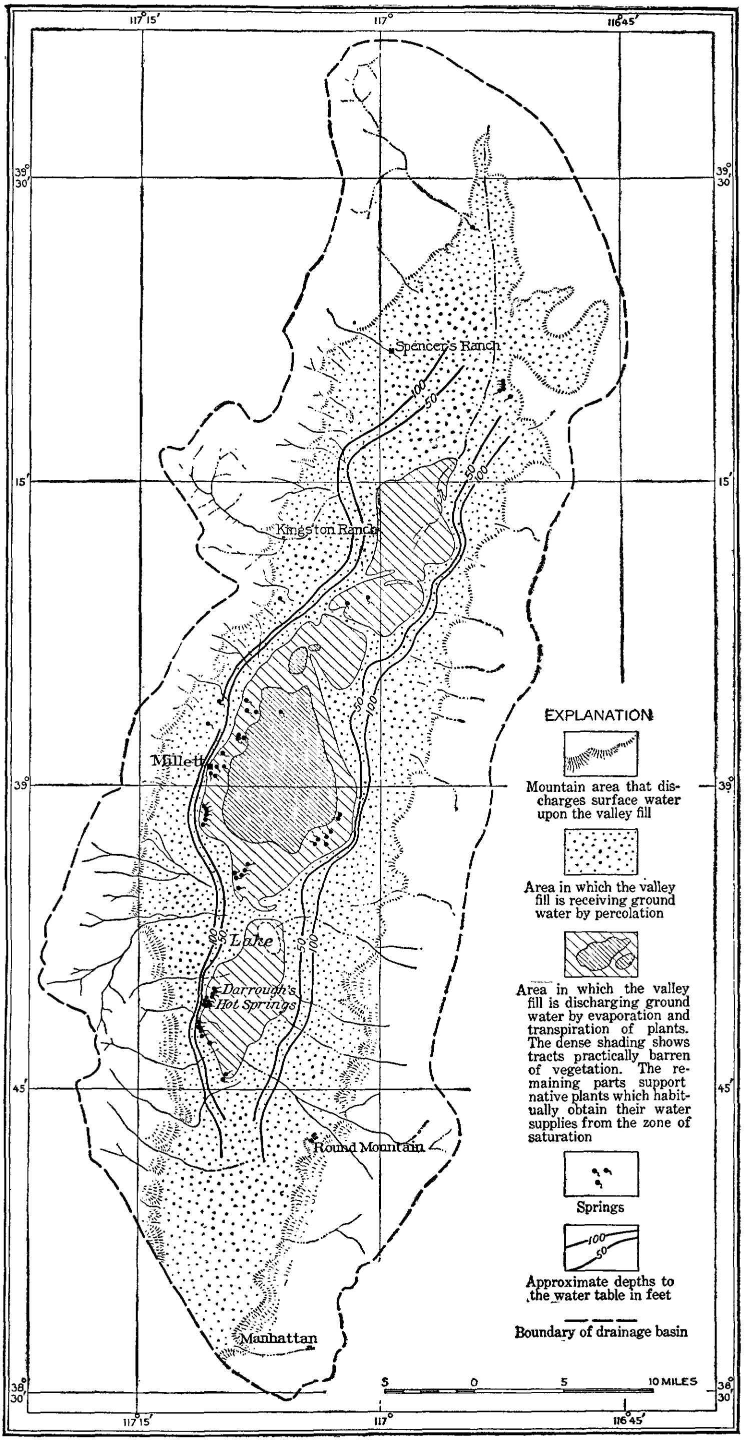


FIGURE 26.—Map of the northern drainage basin of Big Smoky Valley, Nevada, showing intake and discharge of ground water.

Of these springs, 38 rise in volcanic rock or in gravel associated with volcanic rock, 24 in limestone, and 3 in sandstone. Of the springs in

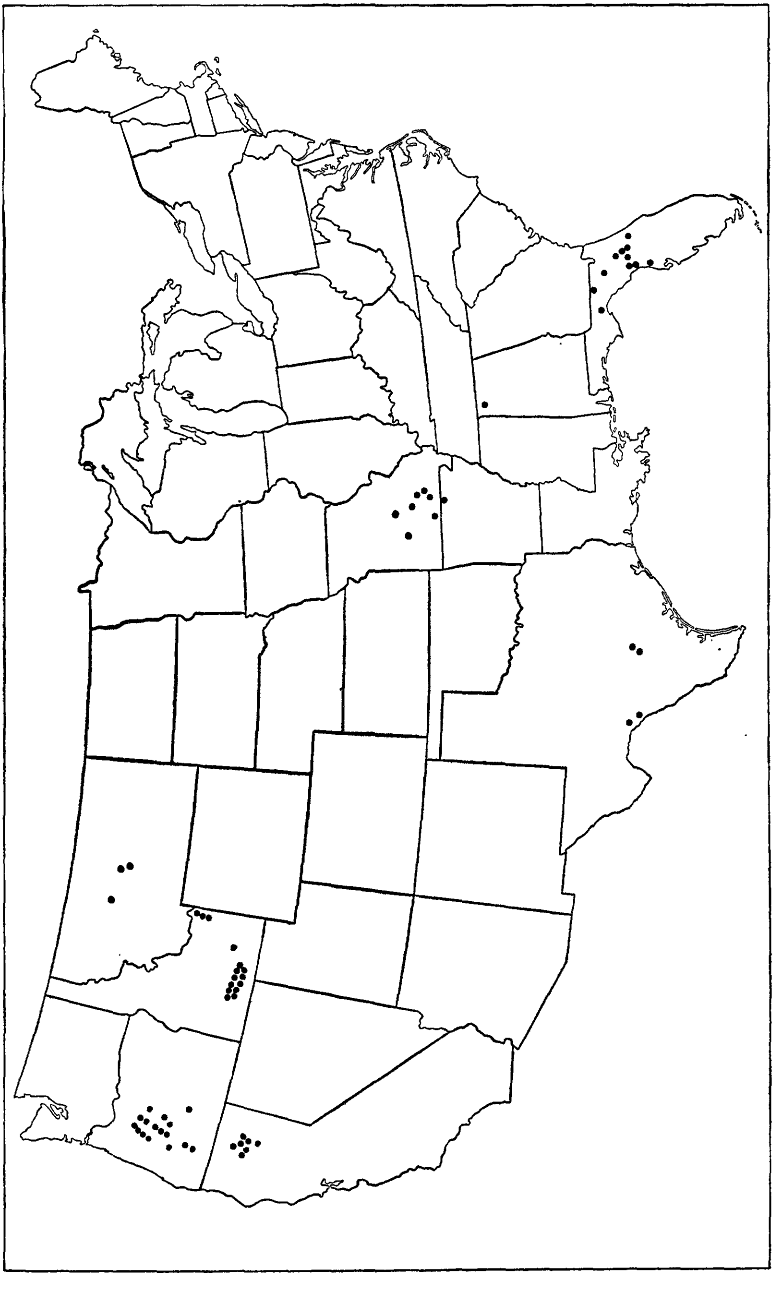


FIGURE 27.—Map of the United States showing springs of the first magnitude—that is, springs, which, according to available information, have an average discharge of more than 100 cubic feet a second, which amounts to more than 65,000,000 gallons (250,000 cubic meters) a day.

volcanic rock or associated gravel 16 are in Oregon, 15 in Idaho, and 7 in California (47). Of the springs in limestone, 9 rise in limestone of

Paleozoic age, 8 of them in the Ozark area of Missouri and Arkansas; 4 are in Lower Cretaceous limestone in the Balcones fault belt in Texas; and 11 are in Tertiary limestone in Florida. The 3 springs that issue from sandstone are in Montana. The great discharge of these springs is believed to be due to faults or to other special features. With the additional data now available, some revision of these figures could be made but it would be of minor character.

The recorded discharge (generally the average of available measurements) of a few of the largest springs and groups of springs is given in the following table.

Recorded discharge of very large springs and groups of springs in the United States

	Cubic feet a second	Gallons a day	Cubic meters a day
SPRINGS IN VOLCANIC ROCK OR ASSOCIATED GRAVEL:			
Sheep Bridge Spring, Oreg.	323	209,000,000	791,000
Springs along 10-mile stretch of Metrolius River, Oreg.	1,070	692,000,000	2,619,000
Springs along 10-mile stretch of Fall River, Calif.	1,400	905,000,000	3,425,000
Malade Springs, Idaho	1,133	732,000,000	2,761,000
Thousand Springs, Idaho	864	558,000,000	2,112,000
Springs along 50-mile stretch of Snake River, Idaho	5,085	3,787,000,000	14,334,000
SPRINGS IN LIMESTONE:			
Big Spring, Mo.	428	277,000,000	1,048,000
Comal Spring, Tex.	330	214,000,000	810,000
Silver Spring, Fla.	808	522,000,000	1,976,000
SPRINGS IN SANDSTONE:			
Giant Springs, Mont.	600	388,000,000	1,447,000

THERMAL SPRINGS

An exact statement of the number of thermal springs in the United States is, of course, arbitrary, depending upon the classification of springs that are only slightly warmer than the normal for their localities and upon the groupings of those recognized as thermal springs.

A recently published report (45) lists 1,059 thermal springs or spring localities. Of these 52 are in the East-Central region (46 in the Appalachian Highlands and 6 in the Ouachita area in Arkansas), 3 are in the Great Plains region (in the Black Hills of South Dakota), and all the rest are in the Western Mountain region. (See fig. 28) The States having the largest number of thermal springs, according to the listing in the report, are Idaho 203, California 184, Nevada 174, Wyoming 116, and Oregon 105. The geyser area of Yellowstone National Park, however, exceeds all others in the abundance of springs of high temperature (29). Indeed, the number of thermal springs in this area might be given as several thousand if the springs were counted individually instead of being grouped.

Nearly two-thirds of the recognized thermal springs issue from igneous rocks—chiefly from the large intrusive masses, such as the great Idaho batholith, which still retain some of their original heat. Few, if any, derive their heat from the extrusive lavas, which were widely spread out in relatively thin sheets that cooled quickly. Many of the

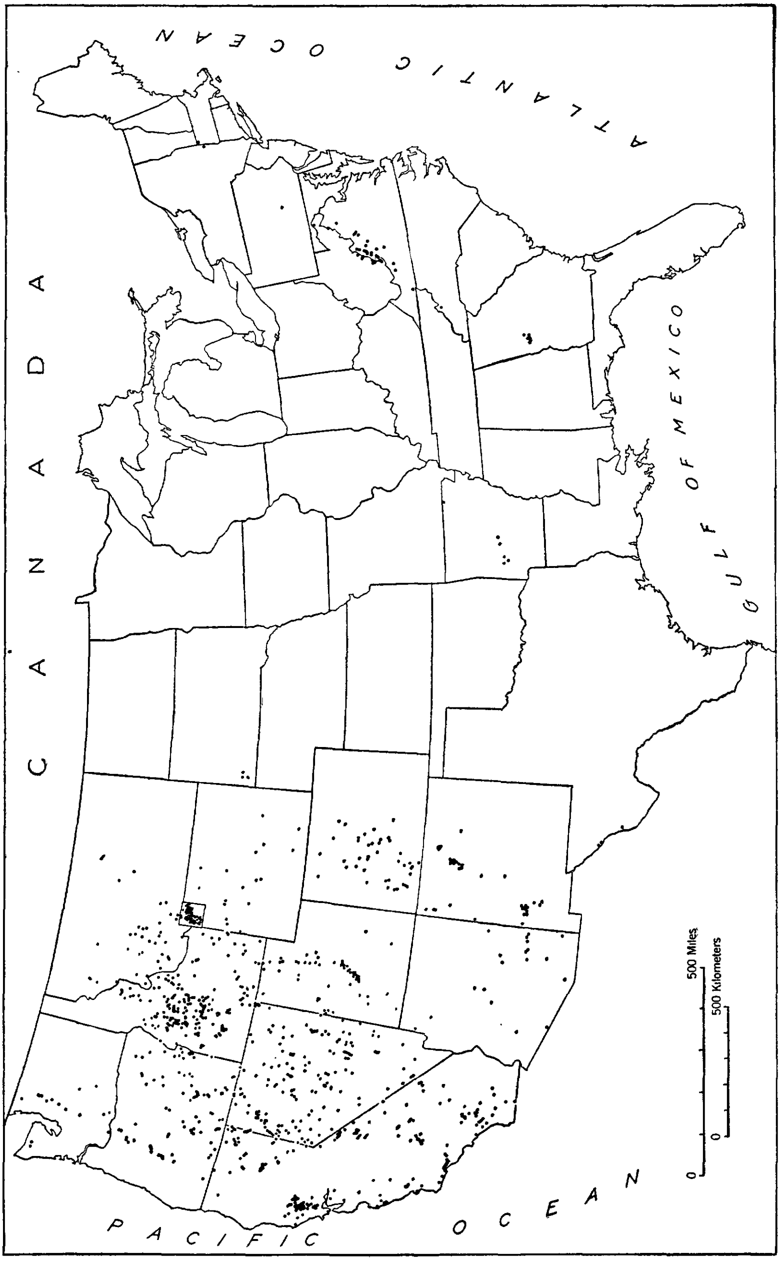


FIGURE 28.—Map of the United States showing thermal springs. After Norah D. Stearns, H. T. Stearns, and G. A. Waring.

thermal springs issue along faults, and some of these may be artesian in character, but most of them probably derive their heat from hot

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gases or liquids that rise from underlying bodies of intrusive rock. The available data indicate that the thermal springs of the Western Mountain region derive their water chiefly from surface sources, but their heat largely from magmatic sources (29, 45). The thermal springs in the Appalachian Highlands owe their heat to the artesian structure, the water entering the aquifer at a relatively high altitude, passing to considerable depth through a syncline or other inverted siphon, and reappearing at a lower altitude; in the deep part of its course the water is warmed by the normal heat of the deep-lying rocks (36, 44).

It has been estimated that the aggregate flow of all thermal springs in the United States is not more than 500,000 gallons a minute (45). The average discharge of 177 thermal springs in California on which data are available is 91 gallons a minute. The largest thermal spring in the United States is probably Warm Spring, in Montana, which has a temperature of only 68° F. (20° C.) but has a discharge of about 80,000 gallons a minute.

EBBING AND FLOWING SPRINGS

Ebbing and flowing or periodic springs are distinctly different in origin and operation from the ordinary intermittent springs that flow in wet seasons and disappear in dry seasons (30, 32, 34, 35, 46). An ebbing and flowing spring has periods of flow, when it flows vigorously, and periods of ebb, when it ceases to flow or flows at a greatly reduced rate. The periods of flow may occur at nearly regular intervals or at very irregular intervals; they may occur at intervals of a few minutes, a few hours, a few days, or even longer. All or nearly all of the springs of this type issue from limestone. Nearly all are situated far from the ocean, and they have no relation whatever to oceanic tides. In their periodic action they resemble geysers, but their water has the normal temperature of ordinary ground water, and they do not generally emit any noticeable amount of gas.

After many years of inquiry and search incidental to other work, there have been located in the United States a total of only 23 springs of this kind, of which 9 are in Virginia, 4 in Missouri, 3 in Tennessee, 2 in West Virginia, and 1 each in Nevada, New Mexico, Pennsylvania Utah, and Wyoming. The largest and most spectacular of these springs is the so-called "Geyser Spring" near Afton, Wyo., which at maximum flow on September 29, 1933, had a measured discharge of about 17,000 gallons a minute.

Automatic recorders have been maintained on several of these springs. A nearly continuous record for a period of more than 5 years was obtained for the so-called "tide spring," near Broadway, Va. (See fig. 29.) Study of the springs and of their perform-

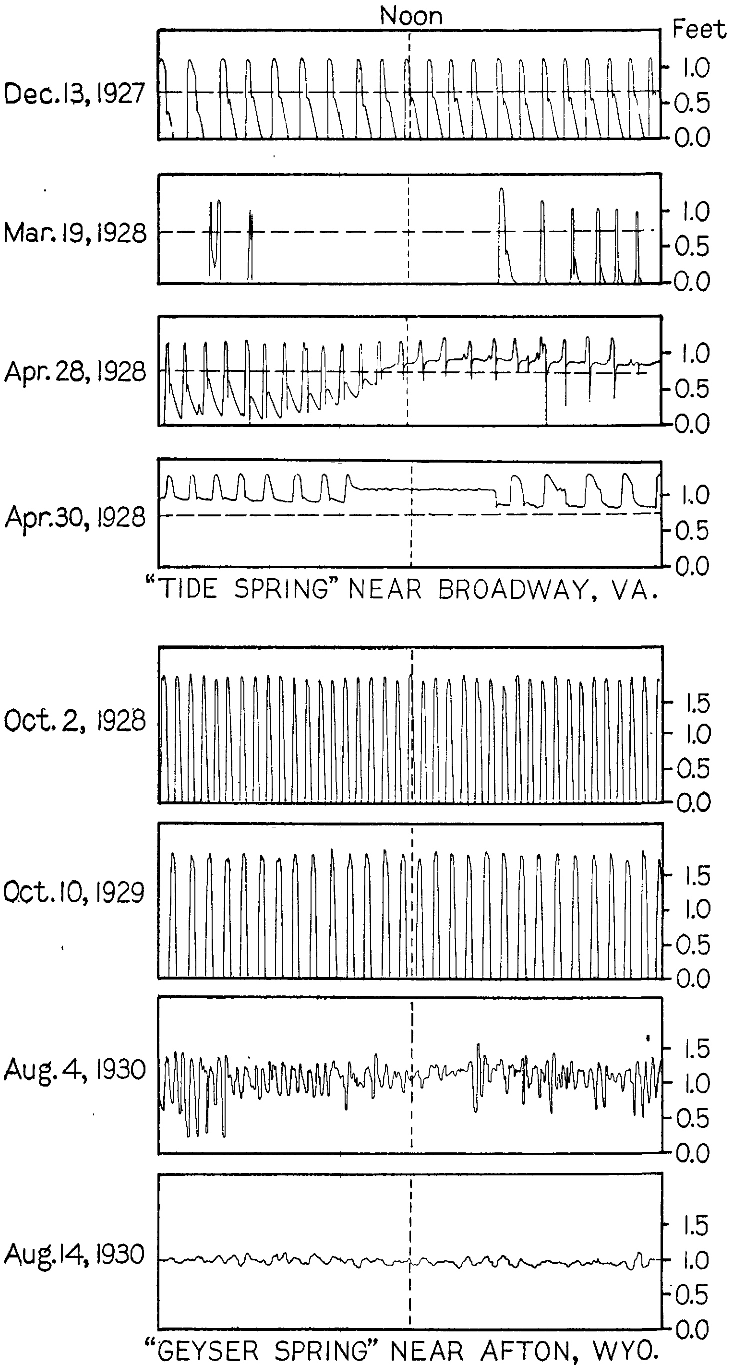

FIGURE 29.—Hydrographs, for selected days, of the ebbing and flowing springs near Broadway, Virginia, and Afton, Wyoming. The spring near Broadway was gaged under the direction of J. J. Dirzulaitis, and the spring near Afton under the direction of H. T. Stearns.

ances, as shown by the continuous records, seems to confirm the theory that this action is that of natural siphons and suggests that their irregularities are caused chiefly by variations in water supply and in air-tightness of the siphon system resulting from alternations of wet and dry seasons.

UTILIZATION OF GROUND WATER

PUBLIC WATERWORKS

The United States is notable for the large number of public waterworks, the high quality of the water that they serve, the generous and varied use that is made of the water, and the ample supplies that are furnished (50a).

Exact data in regard to the waterworks of the entire country are not available, but sufficient information has been obtained by the Geological Survey, chiefly from the State health departments, to serve as a basis for estimates that give an essentially correct perspective of the conditions. About 10,000 communities have public waterworks of some sort. As reported in the 1930 census, these communities have an aggregate population of about 75,000,000, out of a total population of the country of about 123,000,000. The per capita consumption of water in these communities probably averages as much as 125 gallons a day.

The large cities obtain their public water supplies chiefly from surface sources, and the small communities chiefly from wells. Of the 25 cities that have a population of more than 300,000 all obtain their supplies from streams or lakes, except that a few of these have supplementary supplies of ground water. In 1930 the aggregate population of these 25 cities was about 25,000,000, and the total population of all the cities supplied wholly or chiefly from surface sources or from springs is estimated to have been about 55,000,000. The supplies are generally ample, except for some of the smaller cities, and almost without exception the water, after treatment, is of good sanitary quality.

About 6,500 communities, with an aggregate population of about 20,000,000, having public waterworks supplied wholly or chiefly from wells or other structures for recovering ground water (54). This number includes 15 of the 68 cities having a population between 100,000 and 300,000; somewhat less than one-third of the 283 cities between 25,000 and 100,000; about one-half of the 1,457 cities between 5,000 and 25,000; and about two-thirds of the approximately 8,000 smaller communities that have public waterworks. The cities between 100,000 and 300,000 that have water supplies derived from wells or comparable structures, named in the order of their population, are as follows: Houston, Memphis, San Antonio, Dayton, Des Moines, Long Beach, Jacksonville, Camden, Spokane, Wichita, Miami, Peoria, Canton (Ohio), El Paso, and Lowell (Massachusetts). The proportional distribution of public waterworks supplied from wells is shown, by States, in figure 30.

It is roughly estimated that about 2,000,000,000 gallons of ground water are obtained daily through wells or similar structures for public water supplies in the United States. The largest ground-water development for public supplies is in the western part of Long Island, New York, in New York City and the adjacent county of Nassau (56). The average pumpage from wells and infiltration galleries for all purposes in that area during the period from 1904 to 1937, has been somewhat over 158,000,000 gallons a day, of which about 113,000,000 gallons

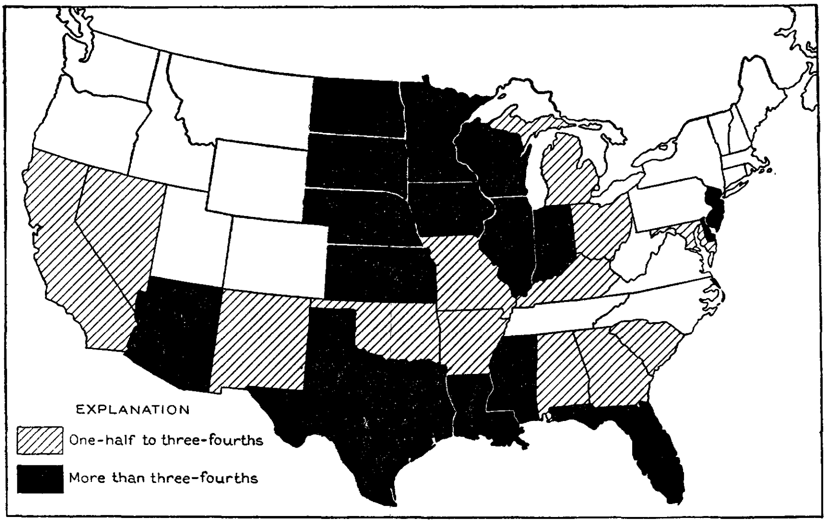

FIGURE 30.—Map showing the States in which most of the public water supplies are derived from wells. (From Eng. News-Record, vol. 110, p. 750.)

has been for the public supplies of New York City and suburbs. In the Houston-Galveston area, in Texas, the use of ground water has increased progressively since the beginning of this century, and in 1936 it averaged about 98,000,000 gallons a day, of which about 25,000,000 gallons was for the public supply of Houston.

As might be expected, the many small waterworks supplied with ground water vary greatly both as to quantity and quality of the water. However, with the constantly increasing vigilance of the State and local health departments, these supplies are with few exceptions of good sanitary quality. Moreover, in the recent droughts the public water supplies from wells have generally been adequate, and the difficulties on account of failing supplies have been chiefly in the smaller communities that depended on surface water without adequate storage.

DOMESTIC SUPPLIES

One of the greatest achievements in American history has been the progressive development of domestic water supplies of good quality—that is, the water supplies used by the people for drinking, cooking, and laundry and toilet purposes.

In the pioneer period the domestic supplies were obtained chiefly from springs or from shallow dug wells that were generally unreliable and exposed to pollution. In contrast, a very large proportion of the 75,000,000 people who now live in communities that are served by public waterworks have ample and perennial supplies of safe, acceptable water delivered under pressure to the taps in their kitchens, bathrooms, and laundries. Within the communities that have public waterworks, including large cities, there are still a considerable number of people who obtain their domestic supplies from private wells. The supplies from many of these wells are subject to pollution and are otherwise unsatisfactory, and they should for the most part be abandoned in favor of the supplies furnished by the public waterworks.

It is estimated that there are in the United States between 3,000 and 4,000 communities of less than 1,000 inhabitants that are provided with public water supplies. However, according to the 1930 census, the total number of incorporated places having less than 1,000 inhabitants is slightly over 10,000 and their aggregate population is somewhat more than 4,000,000. It may therefore be inferred that there are still several thousand of the smaller incorporated communities, with an aggregate population of perhaps 2,000,000, that do not have public water supplies. Most of the people in these communities have private wells.

According to the 1930 census there are nearly 45,000,000 people who live in rural territory—that is, in homes that are widely distributed on about 6,500,000 farms and in the very small rural communities that are not incorporated. It should be noted that the United States differs from most other countries in that the people engaged in agriculture do not generally live in compact communities but in widely separated homes on the individual farms. It is not generally practicable to supply these homes from public waterworks, but as a rule each farmer has developed a private supply for the household, or in some cases more than one household, on his farm.

By far the largest number of the rural inhabitants obtain their domestic water from private wells, but a considerable number obtain it from springs, and some depend on rain water stored in cisterns, water in irrigation ditches, or other sources. In the hard-water areas it is common practice for a household to have two distinct sources of supply—a well that provides hard but otherwise relatively acceptable water for drinking and cooking, and a cistern that provides soft water for laundry and toilet use.

Obviously it is, in the aggregate, a very large and difficult task to develop so many water supplies under the great variety of ground-water conditions that prevail throughout the country. Much progress has been made, not in any one year but through the successive decades since the different sections of the country were settled by the white men. The ideal is to provide every rural home with an ample, reliable, and convenient supply of water that is safe from pollution and otherwise of acceptable quality. Much work must yet be done before this ideal can be even approximately realized.

The development of improved private water supplies has been largely the work of many thousands of water-well drillers. Most of these drillers have operated on a small scale, in restricted territory, and until recently they have depended chiefly on their own ingenuity, with very little help from any outside source. In 1915 the well drillers in North Dakota organized an association with the help of H. E. Simpson, who later became the State geologist. Following this precedent, about 15 other State or regional associations of water-well drillers have been organized, and in 1929 was organized the American Association of Water Well Drillers. This movement is essentially an educational enterprise—to improve the condition of the industry and the welfare of the individual drillers through the application of better technical and business methods. The value of the movement to the public probably cannot easily be overestimated. Its effectiveness is largely due to the cordial cooperation of the Federal and State geological surveys and health departments, the State colleges and universities, other State organizations that are concerned with water supplies, and the National Research Council. An essential factor in the success of the movement has been the generous support given by the commercial supply houses, a few of which are publishing technical journals that are of great benefit to the drillers.

The development of satisfactory water supplies is not entirely a matter of deeper drilling, for much of the best water occurs near the surface. It is rather a matter of intelligent action, with due consideration of the problems of each specific locality, by men who are well informed and experienced in developing ground-water supplies—a matter of selecting the proper location and the proper water-bearing bed and of installing wells of the proper type and construction to give satisfactory perennial service and maximum protection from pollution.

As yet, only a small proportion of the rural homes are provided with adequate plumbing facilities and water-supply systems that deliver water under pressure to the kitchen, bathrooms, and laundry. However, the number of homes that are thus equipped is constantly increasing, and it may be expected that with the prospective general electrification of rural homes the greater part of the rural inhabitants will have water-supply facilities comparable to those of the city residents.

LIVESTOCK SUPPLIES

The livestock industry is a very important and widely distributed industry in the United States. It does not need any large individual supplies of water, and the requirements as to both sanitary and chemical quality are considered to be much less rigorous than for human use. However, supplies in adequate quantity are necessary at very many places to enable the livestock to utilize all the available forage. Moreover, the failure of the water supplies may cause serious inconvenience or financial loss to the stockmen, especially in times of drought, when the feed also is scarce. Consequently, the development of water supplies for livestock has been a large achievement for the country as a whole, and it still presents acute problems in some areas, especially in the shale areas of the Great Plains region and the southwestern part of the East-Central region and in the open range of the Western Mountain region.

The water supplies used for livestock are to a great extent the same as the rural domestic supplies, but on many farms the domestic supplies are obtained from wells whereas the animals obtain their water from springs or streams. Where ground water is scarce, as in the shale areas and parts of the arid region, many small earth dams are built to impound storm water. These supplies are valuable but many of them fail at times when water is most needed. Recently the Grazing Division of the United States Department of the Interior has been active in sinking wells, improving springs, and constructing small reservoirs on extensive tracts of the public domain in the arid parts of the country.

INDUSTRIAL SUPPLIES

Water supplies other than the public supplies are obtained from wells for a very large number of industrial and other establishments, including the many railroad systems, factories and mills of many kinds, metal and oil refineries, creameries and dairies, canneries, power plants, refrigerating and air-conditioning plants, public institutions, hotels, sanitariums, and recreational establishments. These supplies range from only a few thousand gallons to several million gallons a day. New supplies are constantly being developed from wells. Recently there have been developments in many places for air-conditioning projects and some very large developments for paper pulp mills.

The water supplies from wells are especially valuable in the many places where supplies are not available from any public waterworks. However, among the industrial establishments that are supplied with water from their own wells are many located in New York, Chicago, Philadelphia, and most of the other communities, both large and small, that have public waterworks. The water from the private wells is preferred to the public supplies chiefly where it is cheaper or where the constant low temperature of the ground water is an advantage, as in condensing, refrigerating, or air-conditioning. In many communities the water from the private wells is harder and less satisfactory for boiler use than is the water served by the public waterworks, but in some places it is preferred for certain industrial processes. In a very few places water from thermal springs or wells is used for heating buildings.

IRRIGATION SUPPLIES

According to the statistics obtained by the United States Census Bureau for the principal States in which irrigation is practiced, about 2,117,000 acres in these States was irrigated in 1929 with water from wells—about 11 percent of the total irrigated area (49). This irrigation was accomplished by the use of about 4,800 flowing wells and about 56,700 pumped wells, only between 2 and 3 percent of the area irrigated with ground water being supplied by flowing wells.

The aggregate capacity of the flowing wells in 1929 is recorded as about 877,000,000 gallons a day, and the aggregate capacity of the pumped wells as about 46,753,000,000 gallons a day. Because of the tendency of many well owners to overestimate the capacity of their wells, it is probable that this reported pumping capacity is considerably greater than the actual total capacity of the wells. At any rate, it gives no indication of the quantity of ground water actually used or actually available for irrigation. Thus, if it is assumed that in 1929 the average depth of water applied to the land that was irrigated by wells was 2 feet, the total quantity of water from wells actually used in that year was about 4,234,000 acre-feet, or an average throughout the year of about 3,777,000,000 gallons a day. This computation seems to indicate that, on the average, the irrigation wells were in use less than one-tenth of the total time. It indicates that the total quantity of water withdrawn from wells for irrigation was, very roughly, about twice the quantity withdrawn from wells for public waterworks and between one-third and one-half the total quantity of both surface and ground water furnished by all the public waterworks in the country. Since 1929 there has been a large increase in the use of water from wells for irrigation in some States and probably a substantial increase in the aggregate annual withdrawal for irrigation.

With respect to the areas irrigated with water from wells, the Census Bureau shows that in 1929 the States ranked as indicated in the following table:

Areas in States west of the Mississippi River, including Louisiana, irrigated with water from wells in 1929

	Area		Percent of total
	Acres	Hectares (approximate)	
California	1,464,960	593,000	69.2
Louisiana	175,787	71,000	8.3
Arkansas	142,978	58,000	6.8
Arizona	106,002	43,000	5.0
Texas	62,624	25,300	3.0
New Mexico	58,118	23,500	2.8
Nebraska	23,452	9,500	1.1
Washington	20,995	8,500	1.0
Utah	19,655	7,900	.9
Colorado	15,929	6,400	.8
Kansas	11,651	4,700	.6
Idaho, Oregon, Nevada, Montana, South Dakota, Wyoming, and Oklahoma	10,976	4,400	.5
	2,117,018	856,000	100

The water for irrigation obtained from wells is used largely for fruits, vegetables, and other relatively valuable crops. The valuable orchards of oranges and other citrus fruits in southern California are largely irrigated with water from wells. It has been estimated that in the intensively developed south coastal basin of California, in which Los Angeles is located, underground sources furnish about 90 percent of the water supply originating within the basin in the summer for irrigation and municipal purposes (69). A general study of the census statistics leads to the conclusion that for all irrigation in the States covered, the value of the water from wells is probably equal to about one-fourth the value of the surface water.

In some of the States the amount of irrigation with water from wells has been small, not so much because of lack of supply but rather because it has not been found profitable to pump the water for the crops of relatively low value that could be raised. In these States considerable additional developments can be made without exceeding the safe yield whenever methods can be developed that are economically feasible. More intensive quantitative studies are needed to determine the supplies of ground water that are available for irrigation and to find methods for utilizing the ground water to supplement rainfall and surface-water irrigation and to provide small-scale irrigation in connection with "dry-farming" and stock-raising.

In Arkansas, Louisiana, and eastern Texas the irrigation is nearly all for raising rice. In the eastern part of the United States water from wells is used on many small tracts for the commercial production of vegetables and fruits, especially in Florida, other parts of the Atlantic and Gulf Coastal Plain, and Michigan. Water from wells is also used extensively throughout the eastern part of the country for sprinkling lawns, golf courses, and domestic gardens.

The relatively small aggregate area irrigated with water from flowing wells in the western States is widely distributed among many low valley tracts. Nearly half of the area is in the Roswell artesian basin in New Mexico. In Florida several thousand flowing wells are used to supply water for irrigating celery and other vegetables and citrus fruits. Thus Florida ranks high in the number of flowing wells used for irrigation and in the value of the crops irrigated by flowing wells.

USES FOR HEALTH AND RECREATION

There are in the United States a number of health resorts at watering places that have excellent hotels and recreational facilities and are well equipped for treating disease. Some of these are at thermal springs; others, as Saratoga Springs, N. Y., are at springs that yield water of normal temperature. In addition to these well-known and well-appointed resorts, there are many that are only modestly or poorly equipped.

The earliest interest in thermal springs in the United States lay in their use as health resorts, and many of the health resorts that are at present widely known and patronized are located at thermal springs. Of 1,059 thermal springs listed in the recently published paper on thermal springs in the United States (45), a total of 184 are reported to be used as resorts, including sanitariums, and about 110 others are reported as having facilities for bathing. Of the remaining 765 thermal springs, about 175 are reported as being employed locally for domestic and public supplies, and a considerable number are used for irrigation and watering livestock. About 400 are reported as not used.

Resorts or sanitariums at thermal springs are reported in 18 States. California is reported to have 53, Montana 18, Colorado 17, Idaho 16, Nevada 15, and Oregon 14. Though the greater number are in the western part of the United States, some of the best known and best equipped are in the eastern part, as, for example, Hot Springs, in Arkansas (52); Warm Springs, in Georgia (36); and Hot Springs, in Virginia (52, 53).

The latest year for which statistics were obtained by the Government in regard to the production of mineral waters was 1923 (50). In that year sales were reported from 433 commercial springs, in 44 different States, amounting to about 45,000,000 gallons. The reports included natural waters that were sold for medicinal or table use but not waters that were used in the manufacture of soft drinks. The report for 1923 states that of the mineral waters as above defined, the medicinal waters represent only about 13 percent of the total in value and a much smaller proportion of the total quantity. The mineral-water trade is now largely in waters, in their natural state or carbonated, that are sold as pure and wholesome drinking water for offices and homes. The mineral-water industry is under strict control of the Food and Drug Administration of the United States Department of Agriculture (51, 55).

In the United States less attention is given to health resorts at watering places than in some other countries, and the sale of medicinal and table waters is also relatively small. These conditions are probably due largely to (1) the prevalence of adequate plumbing and bathroom facilities in a large proportion of the American homes, with ample supplies of hot and cold running water; (2) the abundant and convenient supplies of safe and palatable drinking water in nearly all cities and in a large number of the smaller communities and rural homes; and (3) the habit of most of the American people to drink freely the water from their own public or private supplies. The American people rank high in the personal use of water, both external and internal, and, they doubtless also rank higher than is generally assumed in its therapeutic use.

METHODS AND RESULTS OF GROUND-WATER INVESTIGATIONS IN THE UNITED STATES

Ground-water investigations are of two principal kinds—systematic areal surveys and special investigations, which are generally more intensive and contribute to a more detailed knowledge of hydrologic principles.

The earliest ground-water work necessarily consisted chiefly of reconnaissance over large regions that had not previously been investigated. Gradually the reconnaissance surveys were succeeded by more thorough and systematic surveys. As the ground-water surveys by the Federal Geological Survey are carried on only as financial cooperation is furnished by individual States, it has not been possible to cover all the States in accordance with any uniform plan, and in some parts of the country the ground-water conditions are still known only in a general way. However, the Ground Water Division of the Geological Survey has long visualized a systematic survey of the entire area of the United States with respect to the ground-water conditions and resources, and it has endeavored to standardize methods for carrying out this survey as opportunity is afforded.

SYSTEMATIC GROUND-WATER SURVEYS

The common units in the systematic ground-water survey are the counties, of which there are 3,070 in the United States, but in Connecticut the unit has been the town, and in many parts of the Western Mountain region such geomorphic units as valleys or drainage basins have been used. An individual water-supply paper may contain the results of the study of an entire State; it may cover a group of counties, in which case it generally contains a unit description of each county; or it may cover only a single county, in which case it generally includes a brief description of each township or geomorphic unit in the county.

Pennsylvania affords an example of a systematic ground-water survey in that the entire State has been covered by a survey that is relatively uniform and fairly adequate, although not so intensive as the surveys in some other parts of the country. Pennsylvania has an area of 45,126 square miles and a population of nearly 10,000,000. It is divided into 67 counties. The ground-water survey has been carried on somewhat intermittently since 1925 but is now completed. The results have been published by the State Geological Survey in a series of six volumes, designated Bulletins W1, W2, W3, W4, W5, and W6, each of which covers a group of counties and includes a unit description of each of these counties. On pages 223–227 are listed 24 representative papers that give the results of systematic ground-water surveys (4, 8, 14, 15, 20, 21, 22, 25, 26, 28, 32, 33, 37, 38, 47, 57–65).

A typical report of this kind consists of three parts—general discussion, stratigraphic description, and description by counties.

The general discussion covers briefly the geography, precipitation, stream flow, stratigraphy, and rock structure. It covers more fully the source, occurrence, quantity, quality, and temperature of the ground water; the head of the ground water and the artesian conditions; the distribution, character, and size of the springs; the recovery and utilization of the ground water; and the methods of constructing wells and improving springs. It generally includes a table of rock formations that has one column in which the quantity and quality of the water in each formation is concisely stated.

The stratigraphic description treats each formation in more detail—its occurrence, depth below the surface, stratigraphic and structural relations, thickness, lithologic character, and water-bearing properties; the head and quality of its water, and the development and value of the water for water supplies.

The county descriptions give more details concerning the ground-water conditions and the developments in each county and each locality. They generally include logs of specific wells, tables giving the available data in regard to individual wells and springs, and chemical analyses of the waters from some of them.

In 1917 the Geological Survey reestablished its water laboratory, in which chemical analyses of both surface and ground waters are made under rigorous control. In this laboratory several thousand samples of water have been analyzed, and analyses representing the water from a large number of water-bearing formations throughout the country have been published or placed in the open files of the Geological Survey.

In 1923 a hydrologic laboratory was established in the Geological Survey (91). In this laboratory tests have been made of certain physical properties of about 2,000 samples of material from many different water-bearing and non-water-bearing formations, the results of most of which have been published. The tests usually made are for mechanical composition, permeability, porosity, and moisture equivalent—the last two being used to compute the specific retention and specific yield (84, 91). The laboratory has also been used to a small extent for research work. There are, of course, many other laboratories in the United States in which are made chemical analyses of water and physical tests of natural earth materials.

A water-supply paper that presents the results of a systematic ground-water survey generally includes one or more maps showing the geology of the area covered, the location of wells and springs, and certain other features, such as depth to the principal aquifers and structure contours on them, depth to the water table and contours on the water table, contours on one or more of the piezometric or pressure surfaces, areas of artesian flow, areas of ground-water discharge by evaporation or by transpiration from plants of certain species, and areal variations in the chemical character of the water. Maps showing changes in ground-water conditions are found chiefly in the water-supply papers that are based on rather intensive investigations. Such papers may contain maps showing contours on the water table or on the piezometric surfaces on different dates and maps showing the original areas of artesian flow and the areas of artesian flow at specified subsequent dates.

INTENSIVE GROUND-WATER INVESTIGATIONS

Quantitative problems.—In many centers of population and industry and in many areas where water is needed for irrigation, ground water is being withdrawn from wells in such large quantities that the problems of overdraft and safe yield are becoming very serious and urgent. For many years the intensive studies of ground water have been chiefly quantitative. They involve for each formation and each area the problems of the quantity of water in storage, the proportion of the stored water that can be recovered through wells, the average rate of natural intake or recharge, the proportion of the recharge that can be recovered through wells, the effects of the withdrawals through wells upon water supplies derived from natural discharge of ground water, the extent to which the rate of recharge can be increased, and the effects of artificial methods for recharge upon the surface-water supplies.

Quantitative investigations were in progress in the early years of the present century, chiefly in California and on Long Island, New York (74, 75, 83, 87, 88, 89, 98). In subsequent years, even though the funds for ground-water investigations were extremely meager, the quantitative problems were being studied and steady progress was made in the analysis of these problems and the development of methods for their investigation. In 1919 the author of this paper presented before the Geological Society of America a paper on quantitative methods of estimating ground-water supplies (80). At that time this subject was still regarded as somewhat academic; since then its great practical importance has come to be generally recognized.

In the paper just cited, the methods of estimating ground-water supplies were classified in four groups—intake, discharge, water-table, and underflow methods. This classification has since served as a frame work for planning quantitative investigations.

In 1928 the author presented before the Society of Economic Geologists a more detailed paper which contained also references to the principal publications issued up to that time on the different phases of the subject. This paper was published in 1932 (81), and although substantial progress in the study has since been made, this paper still serves fairly well as an outline of available quantitative methods.

In this second paper the concept was developed that some of the water-bearing formations function chiefly as underground reservoirs and others chiefly as underground conduits but that to some extent all of them function in both ways. It was shown further that quantitative methods based on the reservoir concept are applicable chiefly, though not exclusively, to formations or parts of formations that have a water table, whereas methods based on the conduit concept are applicable chiefly to artesian formations, in which the water moves laterally under pressure for considerable distances from the intake area to the discharge area.

The exacting requirements of the quantitative studies have resulted in substantial clarification of the principles of ground-water hydrology and in the development of an effective technique for ground-water studies, thus opening a large field for further research.

Molecular attraction.—The rock formations consist largely of porous materials with small interstices. In some formations a cubic foot of the porous material contains a few acres of intersticial surface, and the molecular attraction of this aggregate surface exerts a powerful control over the ground water that has no equivalent in the hydraulics of surface water. Indeed, it is largely the force of molecular attraction that makes ground-water hydrology a distinct science requiring a technique of its own (1).

The molecular attraction may be strong enough to hold only a small part of the stored water, or a large part, or all of it. The *specific retention* of a porous material furnishes a quantitative expression of the effectiveness of molecular attraction in the material. It is the volume of water held against the pull of gravity, expressed as a percentage of the volume of material drained.

The counterpart of specific retention is *specific yield.* It is the volume of water that can be withdrawn from a water-bearing formation with a given lowering of the water table, also expressed in percentage of the volume of the material drained. The specific retention and the specific yield of a material together equal the porosity. Various methods have been devised for determining specific retention and specific yield, but the subject is complicated by the time factor and in other ways and should receive much more thorough investigation. (See references 1, 40, 69, 92, and 99.)

Recharge.—Considerable data are now available on the depletion of the moisture in the *belt of soil water,* or *root zone,* which comprises the surficial material from which water is withdrawn through evaporation or by the roots of plants; also on the relatively constant moisture content, approximating the specific retention, of the *intermediate belt,* which is next below the belt of soil moisture. The water absorbed from rain and snow is held in the root zone until the approximate limit of specific retention is reached; thereafter in permeable material it responds to the force of gravity and tends to move down to the water table. Recent investigations have shown impressively that with light precipitation the absorbed water may all, or nearly all, be held in the root zone even though the soil and rocks afford good intake facilities, whereas with heavier precipitation and similar intake facilities there may be large recharge of the ground-water supply. There is now evidence that recharge may occur by the inconspicuous process of gradual fattening and subsequent thinning of the moisture films on the interstitial surfaces in the intermediate belt, the thinning being in response to the force of gravity. (See references 40, 66, 72, 99.)

Investigations have shown that, under favorable conditions, the rate of recharge can be substantially increased by pumping, whereby the water table is lowered and underground storage is provided for surface water that would otherwise be rejected (10, 69, 75, 78, 89, 96). In California artificial recharge by spreading the flood waters of influent streams over permeable terranes has long been under investigation and is now practiced to a considerable extent (83a). Wells have long been used in some limestone terranes for draining swampy land and unfortunately also locally for disposal of sewage, but they have not been much used as intake openings to augment the water supplies of sand and gravel formations. Recently, however, recharge wells have come into use in certain places in California, and on Long Island the attempt has been made to return through wells water that has been used for air conditioning. The methods and problems of such operations are being studied. The recent droughts have created great interest in artificial recharge by the construction of small reservoirs, and the national program of soil conservation has raised questions as to the effects of terracing and of different methods of tilling, fertilizing, and cropping upon the amount of water from rain and snow that penetrates to the water table. Several investigations of these problems have been started, chiefly by obtaining records of fluctuations of water levels in wells, and it appears that in the near future the entire subject will receive the intensive study that it deserves.

Discharge of ground water.—A notable American contribution to ground-water hydrology is the recognition and study of the plant species called phreatophytes, which in the arid regions are rather sharply distinguished from the true xerophytes by their habit of obtaining their water supplies from the water table. Methods have been developed for determining the quantities of ground water discharged by such plants. The quantative determinations are based on daily fluctuations of the water table, the ratio of water consumed to dry vegetable matter produced by growth, and other factors. (See references 42, 48, 65, 66, 67, 75, and 96.)

The so-called channel-storage method of determining effluent seepage appears to be opening a promising field of investigation (43, 73, 82). A continuous record of the quantity of ground water that seeps into a selected small drainage system is obtained by a single stream-gaging station that has been rated not only for discharge but also for channel storage, the channel-storage rating being accomplished by the use of many subsidiary gage-height stations that show the cross-section areas and hence the volume of water in successive segments of the streams. Except in periods of rain or melting of snow, when there is overland run-off, the method should give the rate of effluent seepage in each short interval of time, and should thus give a basis for studying the relation of this rate to many different factors, such as rainfall, melting of snow, freezing and thawing of the soil, amount of soil moisture, fluctuations of the water table in the valleys and on the uplands, bank storage, perched ground water, evaporation and transpiration, and fluctuations in atmospheric pressure.

Water table, capillary fringe, and piezometric surface.—The *water table* is of primary significance in the occurrence and movement of the ground water. If a well is sunk into a permeable material just to the point where water enters the well and forms a water surface in it, that surface marks the hydrostatic level of the water at the top of the zone of saturation; by definition, it indicates the position of the water table at that place. Wherever there is a body of permeable material that is saturated with water in its lower part, there is a zone of saturation and a water table—whether basal or perched; whether permanent, temporary, or very ephemeral.

The *capillary fringe* is immediately above the water table and may be as much as several feet in thickness. In it water under the control of molecular attraction may not merely cling in films on the interstitial surfaces but may fully occupy the interstitial chambers as in any other capillary tubes (1, 40). The force of molecular attraction becomes active in pulling up water through the capillary interstices whenever water is removed from the capillary fringe by evaporation or absorption by the roots and whenever the water table rises. The capillary fringe and the precise phenomena of its functioning have received considerable study but still present puzzling problems that bear in a large way on the practical problems of recharge and discharge.

In a permeable material that has interstices of capillary size, the water table is not a water surface such as the water surface in the well. It is an imaginary surface that marks the hydrostatic level of the water in the zone of saturation. The water surface in the permeable material is the upper surface of the capillary fringe. It is above the water table and is much more irregular, consisting of many little surfaces that are concave upward, each occupying an interstitial chamber that may be connected with its neighbor by a tiny strait or walled off from it by a grain of sand.

If a body of permeable material overlain by an impermeable formation is completely saturated with water under pressure, a well will strike water when it reaches the bottom of the impermeable formation and the water will rise in the well to its hydrostatic level, which may be below or above the land surface. The hydrostatic level marks the position of the *piezometric surface* of the confined water. Such a piezometric surface is functionally very different from a water table.

Impermeable bodies grade in size from that of a particle smaller than a grain of sand to that of the most extensive artesian confining bed. Therefore, although typical water-table conditions and typical artesian conditions are sharply differentiated, they grade into each other in a manner analogous to the gradation between the vegetable and animal kingdoms or between their major branches.

Movement of ground water.—The construction of contour maps of the water table and of the piezometric surfaces of the artesian aquifers has become a prominent part of ground-water investigations. These maps show the hydraulic gradient and the direction in which the ground water is moving in all localities that they cover, and hence, to a great extent, they show the source and destination of the ground water.

The development of the concept of the third dimension in the movement of ground water has resulted in a better understanding of artesian conditions. It is now recognized that there are vertical as well as lateral hydraulic gradients, that confining beds are generally not entirely impermeable, and that percolation across the strata is of major importance in the recharge and discharge of many of the artesian aquifers.

Water-bearing formations which throughout their extent have a water table generally have extensive intake areas and good intake facilities, and the discharge from many of them occurs in widely distributed localities relatively near to or even coinciding with the areas of intake (78, 89, 97). Such formations function chiefly as reservoirs, and if they have a considerable specific yield and lie in a region of abundant precipitation their perennial yield may be very large, as for example on Long Island. In the essentially artesian formations, which have a water table only in restricted areas and extend laterally beneath confining beds through long distances, the perennial yield may be limited by the rate of recharge in the intake areas or by the rate at which the water percolates laterally from the intake area to the area of natural discharge or to the wells where the water is utilized. If the intake area is in a region of abundant precipitation and the intake facilities are fairly good, the limiting condition is likely to be the rate of percolation and therefore the formation must be studied chiefly in its function as a conduit.

The simple law of laminar flow, developed by the French investigator Poiseuille and applied to water-bearing material by the French hydrologist Darcy, is one of the basic laws of ground-water hydrology on which the ground-water conduit investigations in the United States are based. It merely postulates that in any given material at a given temperature the rate of flow is directly proportional to the hydraulic gradient. Thus the capacity of any ground-water conduit can be computed as the product of its cross-section area, its coefficient of permeability (corrected for the existing temperature), and the hydraulic gradient of its water. Because of the fundamental importance of Darcy's law the range of its validity has been thoroughly studied in this country, and these studies have shown that the law holds for relatively high gradients in very permeable materials (104) and also for extremely low gradients and low velocities (70). Thus, in tests made in the hydrologic laboratory of the Geological Survey on a fine to medium sand, Darcy's law was found to hold with a gradient of only 2 or 3 inches to the mile (about 1:25,000).

Because of the urgent need for determining the perennial yield of the many artesian formations in the United States, it became necessary to develop practicable methods for obtaining the average permeability of these formations. The subject has been given much intensive study both in the laboratory and in the field, but it presents complex problems that will require more study. (See references 18, 74, 81, 87, 88, 91, 93, 94, 97, and 99.)

The limitations of the laboratory methods are due chiefly to the multitudinous difficulties encountered in obtaining representative samples. Some appreciation of these difficulties may be gained from the fact that the most permeable material tested in the hydrologic laboratory of the Geological Survey carries water at a rate about 450,000,000 times that of the least permeable material that was tested.

The early field work was based on the method of determining the rate of movement of salt introduced into the ground water, which was developed by the German hydrologist, Adolph Thiem, and was improved in this country by C. S. Slichter, who made effective use of an electric current instead of chemical tests (88). It was found, however, that this method, like the laboratory method, has many practical limitations. Later, the method developed by Gunter Thiem was introduced, and this has led to experiments in which observations have been made of the rate and amount of drawdown and recovery of water levels in numerous observation wells within the cones of depression of discharging wells under both water-table and artesian conditions (99). Intensive studies based on the data obtained in these experiments have been fruitful in determining not only permeability but also specific yield and elasticity of water-bearing formations. Mention should also be made of the successful results obtained in the use of uranin dye to trace in detail the course of ground water in sand under water-table conditions, and the course of bacteria introduced into the ground water (92).

Compression and expansion of aquifers.—One of the most significant of recent discoveries is that in some way many of the artesian aquifers have sufficient volume elasticity to yield large quantities of water from storage when the expansive force of the artesian pressure is reduced and to store large quantities when the artesian pressure is restored (16, 17). Thus it is recognized that until the reservoir function of the great artesian aquifers can be evaluated their perennial yield cannot be definitely determined, and estimates of perennial yield that do not take account of the withdrawal from storage in the early stages of development may be too optimistic. This subject is being actively investigated, and methods are becoming available for making quantitative determinations of change in storage by compression and expansion of the formation (93).

Contamination by salt water.—Problems relating to the contamination of supplies of fresh ground water by salt water are becoming increasingly important. The salt water is generally drawn into the formations in which fresh water is stored and thence into the producing wells by heavy pumping. The salt water may move laterally in a water-bearing stratum or vertically across the strata; it may be preexisting salty ground water or may come directly from the sea. The principle of the balance between the relatively heavy sea water and the lighter fresh ground water is expressed in what is called the Ghyben-Herzberg law, which was developed by Dutch and German investigators (68). This principle is being effectively applied in this country under a variety of water-table and artesian conditions (27, 63, 68, 78, 79, 89, 94). A recent method of study is to have observation wells, often called "pilot wells," from which samples are taken periodically for the determination of chloride, thus to obtain advance notice of the lateral or vertical encroachment of salt water.

Test wells.—Geologic study has been based chiefly on natural exposures of rock formations and on artificial exposures made in mining, well digging and drilling, grading for railroads and highways, and excavation for other purposes. From the observations made at such random exposures data have been obtained from which the stratigraphy and structure of the rocks at intervening points and at greater depths can be more or less accurately determined. Most of the natural exposures and many of the artificial exposures, however, are above the water table and therefore do not have the same determinative value for studies of the occurrence, quantity, head, and quality of ground water that they do for studies of stratigraphy and structure. Information in regard to ground water must be obtained largely from wells and other excavations that extend below the water table, and many ground-water studies have been severely handicapped by lack of adequate well data. In the past the funds available generally have not been sufficient to permit test drilling, but with the greatly increased appreciation of the value of ground water and of ground-water investigation, the sinking of test wells of some sort is now a part of the program of most of the ground-water work done by the Geological Survey.

Apparatus used in ground-water studies.—The study of artesian conditions and salt-water problems has been advanced by the development of current meters, electrical salinity apparatus, and samplers for use in wells (77, 79). With this apparatus it is feasible to detect leaks in the casings and to determine the sources of both fresh and salt water. A technique has also been developed for determining the source of salt water by frequent sampling of the water pumped from a well, especially at the beginning of pumping operations.

The possibilities of using different geophysical methods in ground-water studies are being investigated (71). Surveys of the electric resistivity of the earth are being made to determine the depth to bodies of salt water and their lateral extent; also to distinguish between beds of coarse materials that yield water freely and beds of fine-grained materials that yield little or no water. The salt water is detected by its low electric resistivity; the productive water-bearing materials are detected by their high resistivity as compared with that of the fine-grained, unproductive materials. Plans have been considered for using electric resistivity in place of pilot wells for detecting the encroachment of salt water; also, in investigations of rainfall penetration, for determining changes in the moisture content of the material between the land surface and the water table.

The principal instruments of precision in ground-water investigations in the United States have come to be the automatic water-stage recorders installed over observation wells (76). For a long time automatic recorders have been used occasionally on wells, but their systematic use and the critical study of the records was begun only about 15 years ago (94). Automatic recorders are now in operation on a few hundred wells in different sections of the country, representing a wide diversity of ground-water conditions. About 200 automatic recorders are being used on wells by the Geological Survey and cooperating agencies. Most of the instruments record water levels in wells by means of floats but some are pressure recorders. Improvements are constantly being made in the instruments to adapt them better to the conditions under which they must be used on wells.

Fluctuations of water levels.—The accurate continuous records obtained from these instruments have made almost sensational revelations, showing that both water tables and artesian pressures are constantly fluctuating in complicated fashion in response to a variety of impinging forces (81). Thus, the way has been opened for making exact and critical studies of the dynamics of the ground water and of the properties of the ground-water reservoirs and conduits. However, as the fluctuations are seldom the effects of simple forces acting singly, careful selection of the observation wells and painstaking analysis of the records are necessary for evaluation of the effects of specific forces. For example, great interest was aroused at first when hydrographs were obtained that closely resembled the barographs at the same place; then the fluctuations produced by changes in atmospheric pressure came to be regarded merely as a bothersome interference with the records of significant fluctuations; now it is becoming evident that much is yet to be learned from the differences in the degree of response to changes in atmospheric pressure. In figures 31 to 41 are given hydrographs showing fluctuations in water levels in wells produced by several different causes—precipitation, evaporation

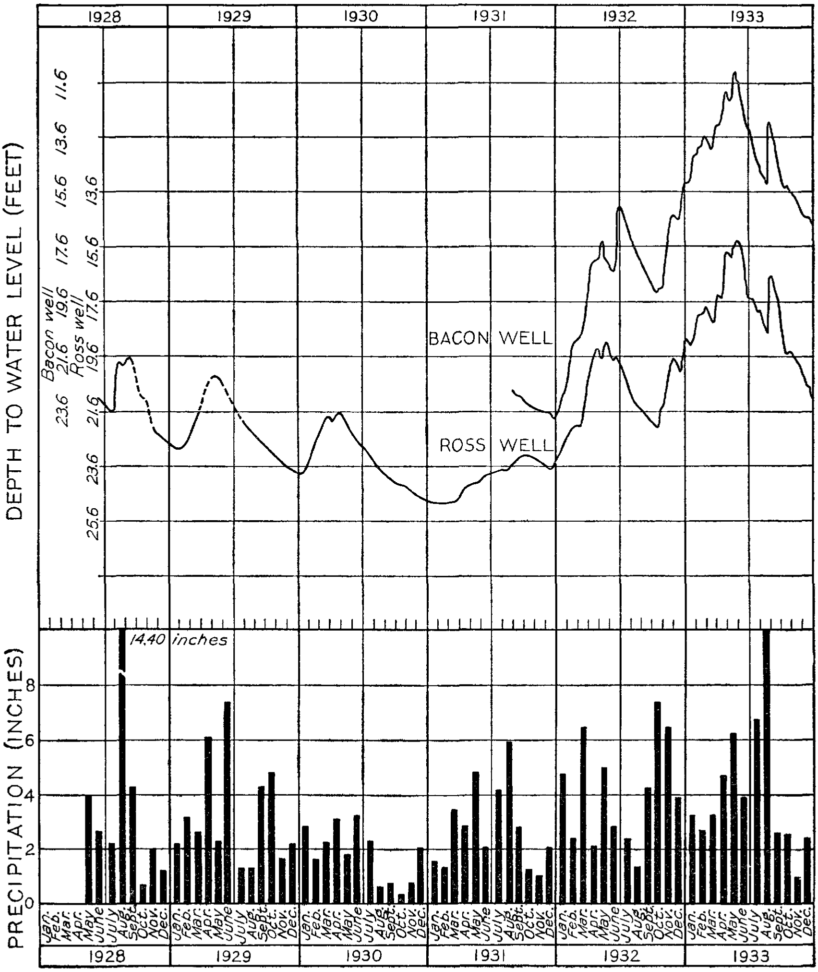

FIGURE 31.—Graphs of water levels in two shallow wells in Virginia, near Washington, D. C., showing fluctuations caused by precipitation and seasonal variations in evaporation and transpiration. The monthly precipitation is that recorded at Washington, by the U. S. Weather Bureau. (Geol. Survey Water-Supply Paper 840, pp. 618 and 619, 1938.)

and transpiration, pumping, variations in atmospheric pressure, ocean tides, earth tides, earthquakes, and railroad trains. All these hydrographs are reproductions of graphs obtained by the Geological Survey on automatic recorders.

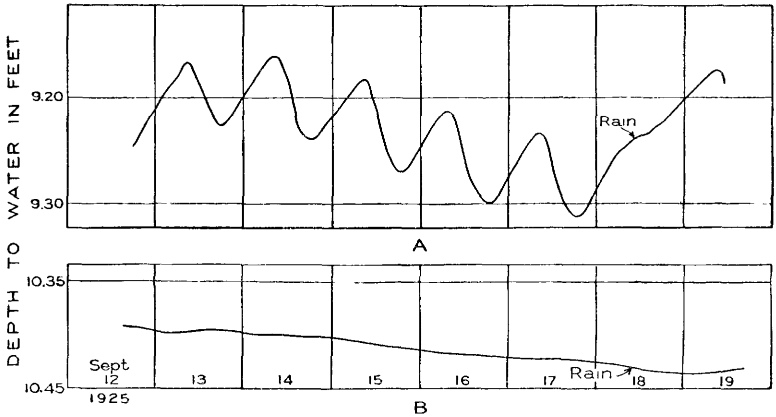

FIGURE 32.—Graphs of water levels in wells in Escalante Valley, Utah, showing discharge of ground water by transpiration. A, Shallow well in field of alfalfa; shows draw-down of the water table during a part of each day caused by transpiration. B, Shallow well in cleared field adjoining the alfalfa field; shows absence of discharge by transpiration. (After W. N. White. Geol. Survey Water-Supply Paper 659, p. 42, 1932.)

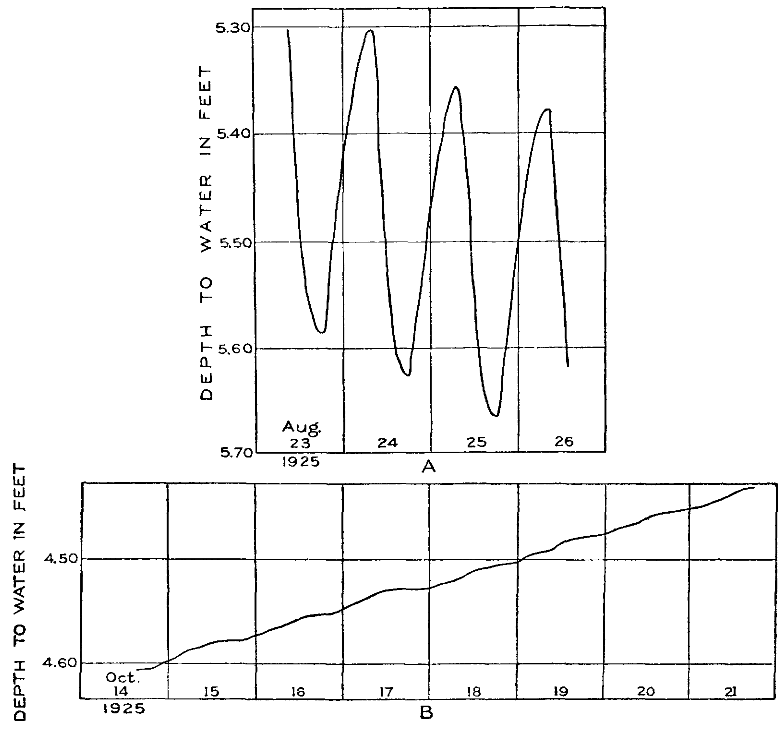

FIGURE 33.—Graphs of water level in a shallow well in Escalante Valley, Utah, showing discharge of ground water by transpiration. A, Shows discharge by transpiration of willows in the summer; B, shows absence of such discharge in the autumn, after the vegetation had become dormant. (After W. N. White. (Geol. Survey Water-Supply Paper 659, p. 40, 1932.)

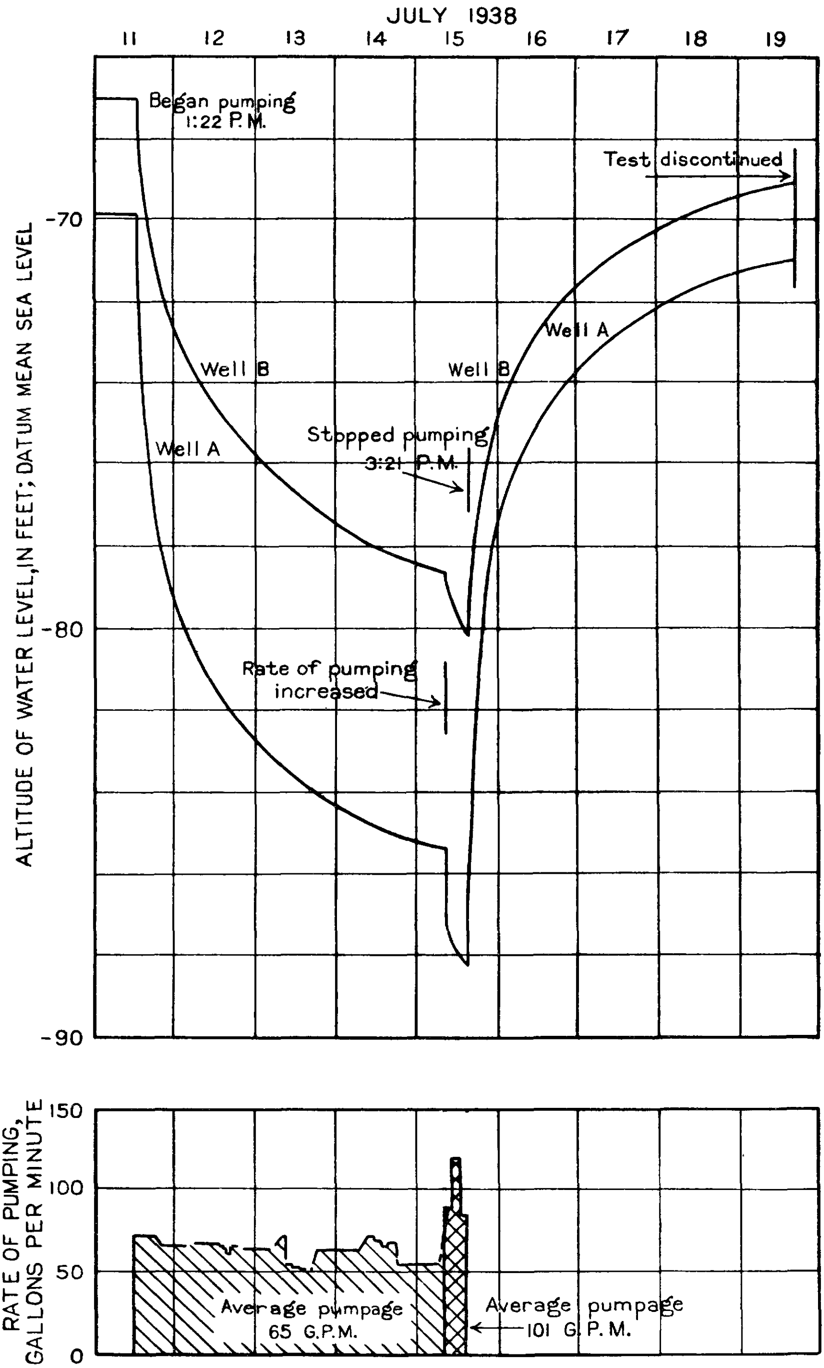

FIGURE 34.—Graphs of water levels in two observation wells showing fluctuations caused by pumping a third well. Well A is 256 feet from the pumped well; well B is 356 feet from the pumped well.

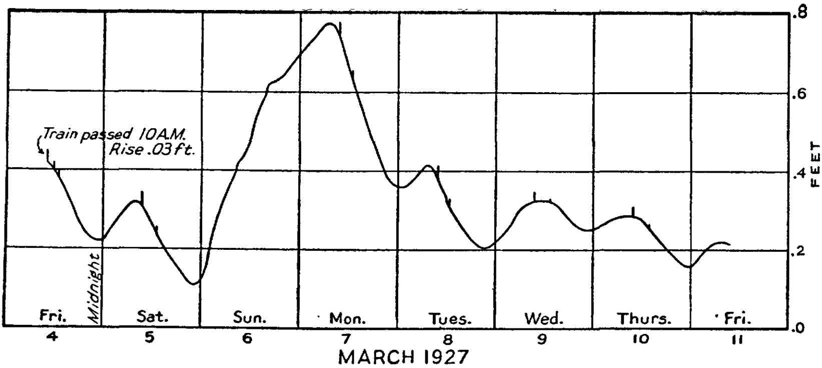

FIGURE 35.—Graph of water level in a well 200 feet deep, near Lodi, California, showing daily and weekly fluctuations caused by pumping from other wells for irrigation during the daytime, except on Sundays; also abrupt fluctuations caused by the passing of trains, except on Sundays, over a railroad 117 feet from the well. (After H. T. Stearns and T. W. Robinson. Economic Geology, vol. 23, p. 276, 1928.)

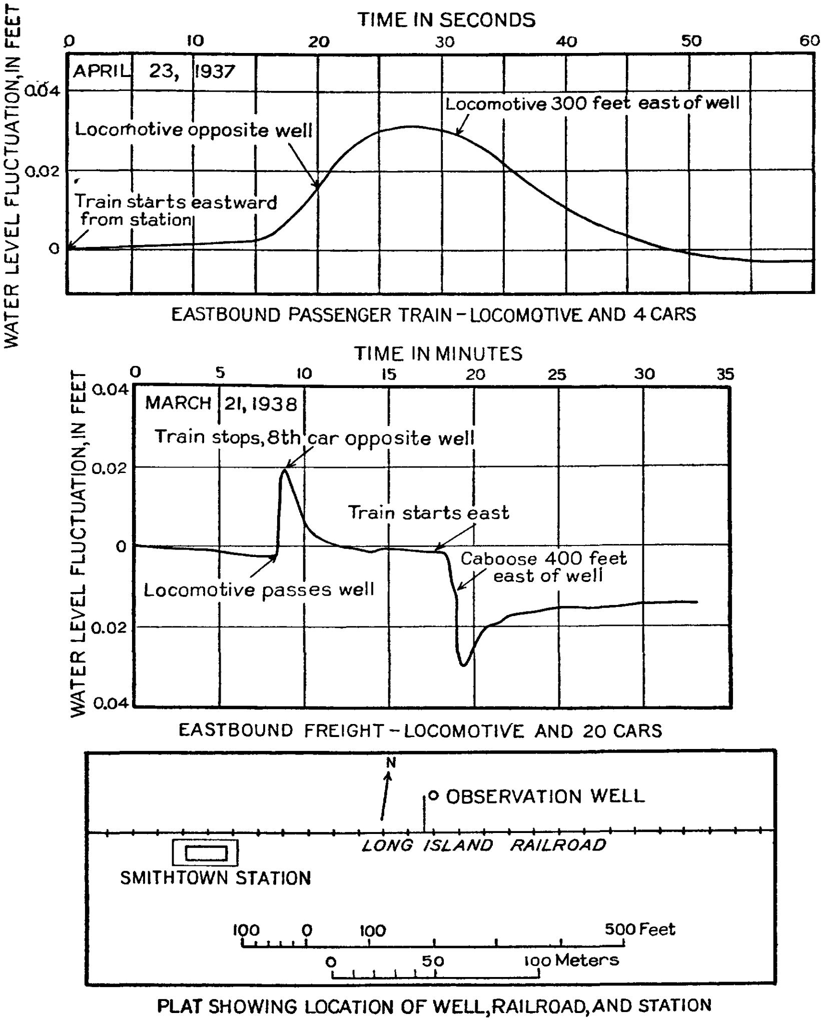

FIGURE 36.—Graphs of water levels in 90-foot artesian well at Smithtown, Long Island. New York, showing effects of passing railroad trains. (After C. E. Jacob. American Geoph. Union Trans. for 1939, in press.)

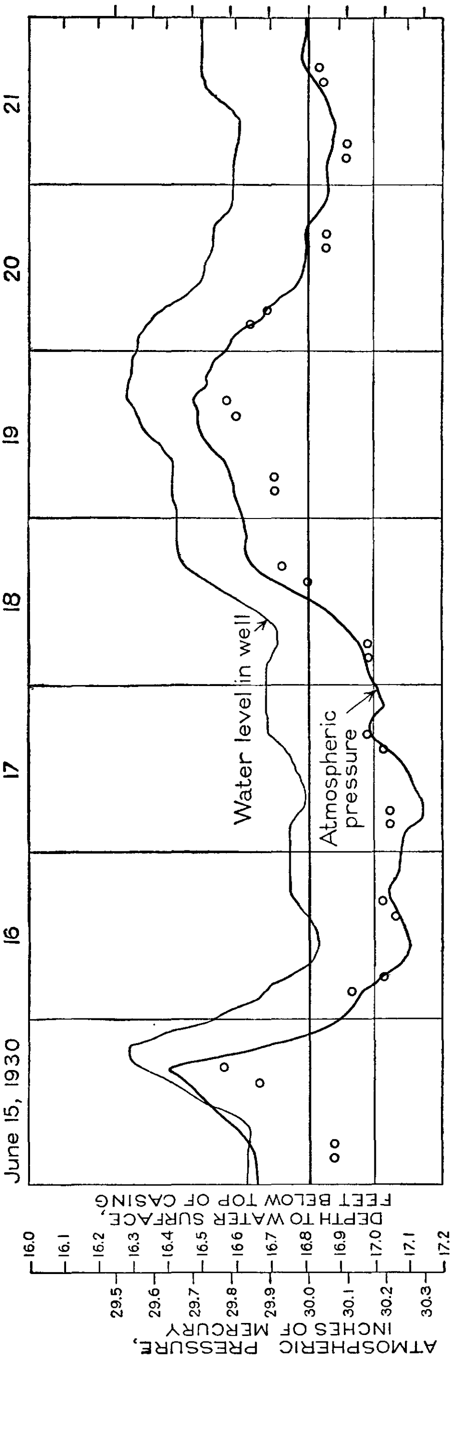

FIGURE 37.—Graph of water level in a well 200 feet deep at The Dalles, Oregon, showing fluctuations caused by variations in atmospheric pressure, as recorded by the United States Weather Bureau at The Dalles (circles) and at Portland (continuous line). The fluctuations in atmospheric pressure are shown on the same scale as fluctuations of the water level when converted from inches of mercury to feet of water. (After A. M. Piper. Geol. Survey Water-Supply Paper 659, p. 18, 1932.)

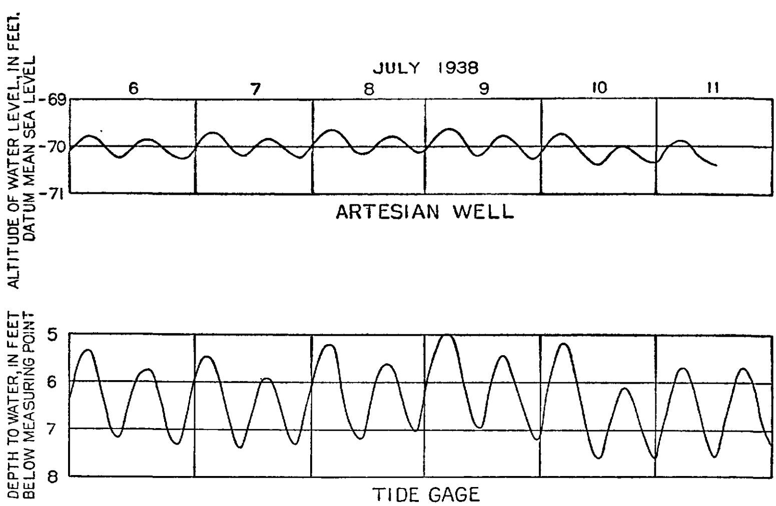

FIGURE 38.—Graph of water level in an artesian well 100 feet from the shore, showing fluctuations caused by the ocean tide that occurs in Mattawoman Creek, Maryland. During the period shown there was only slight change in the atmospheric pressure.

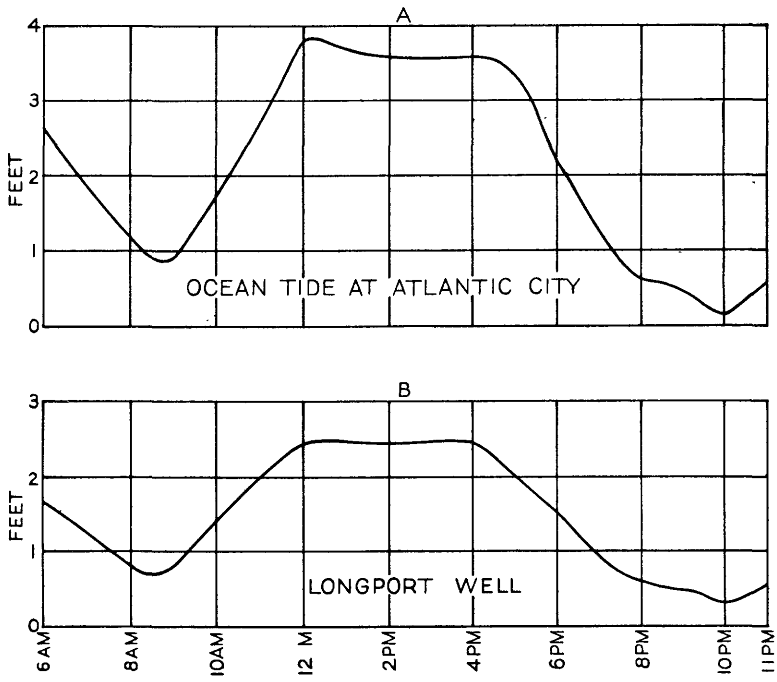

FIGURE 39.—Graph of water level in a well 800 feet deep near the coast at Atlantic City, New Jersey, showing fluctuations caused by the ocean tide on January 22, 1926, when the rising tide was interrupted by a strong northwest wind. The tide was recorded by a gage of the United States Coast and Geodetic Survey. (After Paul Schureman. Geog. Rev., p. 481, 1926.)

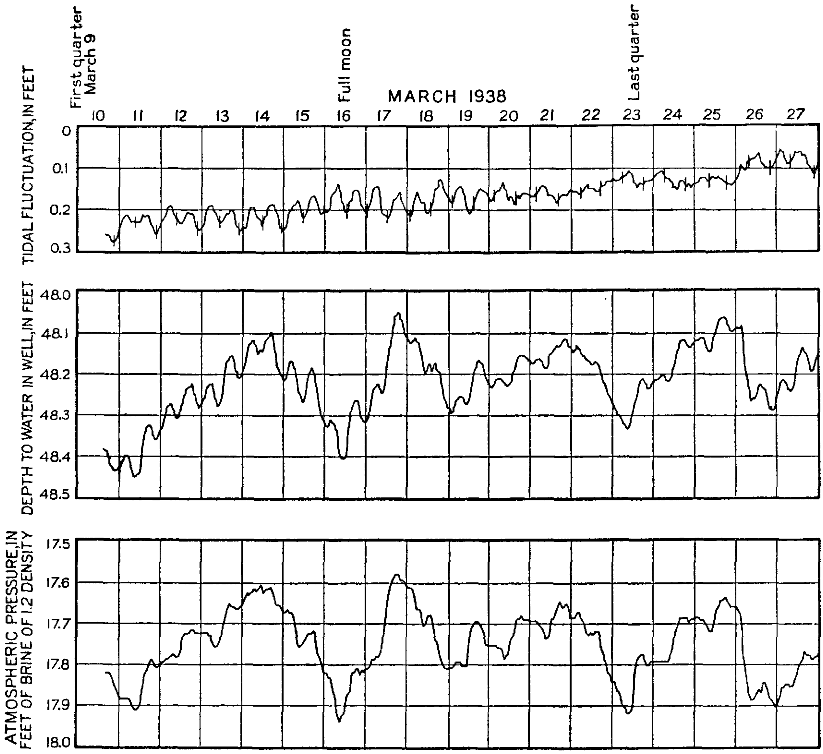

FIGURE 40.—Graph of water level in a 270-foot well near Carlsbad, New Mexico, about 500 miles from the sea, and supplementary graphs showing an earth tide. Curve at top is believed to show semidaily tidal fluctuations, more distinct at full moon than at first and last quarters; compiled from actual instrumental record (shown in the middle) by correcting for effects of fluctuations in atmospheric pressure. Water in well is a brine of 1.2 density. Barometric efficiency of the well, as determined by inspection, is about 70 percent. Curve at bottom, accordingly, shows 70 percent of the fluctuation in atmospheric pressure, expressed in feet of brine of 1.2 density. Vertical lines on the curve at the top show the time of the transit of the moon. (After T. W. Robinson and C. V. Theis. American Geophys. Union Trans. for 1939, in press.)

In recent years the Geological Survey and cooperating agencies have undertaken to develop a nation-wide program of observation wells. A permanent committee on observation wells has prepared a manual of methods (76), and annual reports are now being published that contain the records of water levels and artesian pressure in the wells equipped with automatic recorders and in several thousand wells that are observed periodically in different parts of the country. These reports are in the nature of inventories, showing from year to year the net depletion or replenishment of the ground-water supplies in different formations and different areas.

In the areas of large withdrawals by pumping or artesian flow, the ultimate answer to the question of maximum perennial yield must be obtained from records of monthly or annual withdrawals together with correlative records of fluctuations of water levels and artesian pressure.

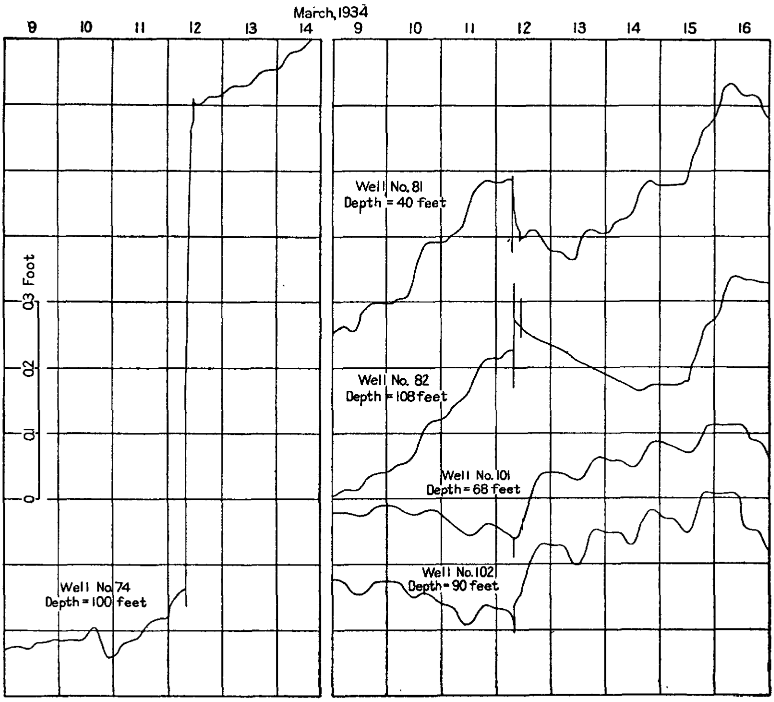

FIGURE 41.—Graphs of water levels in five wells in Ogden Valley, Utah, showing fluctuations caused by earthquakes on March 12, 1934. (After R. M. Leggette and G. H. Taylor. Geol. Survey Water-Supply Paper 796, p. 129, 1937.)

Neither withdrawal records nor water-level and pressure records alone are adequate to indicate the magnitude of the perennial supply. Therefore, a vigorous effort is being made to obtain both sets of data for the areas in which large use is made of the ground water.

WORK OF THE GEOLOGICAL SURVEY AND COOPERATING AGENCIES

In the period of rapid settlement of the country in the last third of the 19th century, there was widespread activity in well drilling, and flowing wells were obtained in many places. The interest in ground-water supplies led to numerous investigations, by both Federal and State geological surveys, of the ground-water conditions in the different parts of the country—largely reconnaissance surveys of extensive areas but also some intensive studies. The period of active ground-water investigation extended for several years into the 20th century. Then there was a reduction in the annual appropriation for the water-resources work of the Federal Geological Survey and, particularly, a great reduction in the allotment for ground-water investigations. It appears that about the same time there was also general curtailment by the State geological surveys of their ground-water work.

For many years after this decline, ground-water investigations were conducted on a meager scale, quite out of proportion to the importance and complexity of the subject. In the fiscal year 1918 a survey of desert watering places was made (Water-Supply Papers 490, 497, 498, 499, and 578), and exploratory drilling for irrigation supplies was done (Water-Supply Paper 467), both by the Ground ater Division of the Geological Survey as a result of special appro- riations by Congress. In that year and the following year there was much demand for ground-water investigations for special war pur- oses, investigations being made by the Ground Water Division at more than 100 military establishments.

Since 1918, there has been a progressively large increase in the funds annually made available for ground-water investigation and a corresponding improvement in the quality of the technical work done. The demand came first from the States, which supplied funds for cooperation with the Ground Water Division. At the same time there was a similar demand for more stream gaging, which likewise was supported chiefly by State funds. Since the fiscal year 1929 Congress has ecognized these needs by making increased appropriations for investigation of the water resources of the country by the Geological Survey. Congress has, however, restricted the major part of the water resources appropriations to use for cooperation with State, county, or municipal governments, and has provided further that in such cooperation the contribution from Federal funds should in no case exceed 50 percent. The growth of interest in the ground-water resources of the country is shown approximately by the increase in funds expended by the Geological Survey and cooperating State and local governmental organizations in the last 30 years. In the 10-year period covering the fiscal years 1908 to 1917 the expenditures for ground-water investigations by the Geological Survey and cooperating agencies averaged less than $20,000 a year; whereas in 1939, as a result of the interest and financial support of State and local agencies, the expenditures amounted to about $375,000.

LITERATURE RELATING TO GROUND WATER

GENERAL SUMMARY OF THE LITERATURE

The Geological Survey has published about 700 papers that contain information on the subject of ground water, of which about 400 relate primarily to this subject. See "List of publications of the Geological Survey, United States Department of the Interior" (reissued about every two years); also "Bibliography and index of publications of the United States Geological Survey relating to ground water" (Water Supply Paper 427, 1918). In the fiscal year 1937 the Geological Survey and cooperating agencies released 75 papers giving the results of technical studies regarding ground water. Of these, 5 were published by the Geological Survey as individual water-supply papers and 3 as contributions to hydrology; 6 were published by cooperating State or Territorial organizations; 17 were published in technical journals; 31 were mimeographed (chiefly by cooperating States); and 13 were released in typewritten form. In 1938 a total of about 100 ground-water papers were released, of which 4 were published as water-supply papers and 5 as contributions to hydrology.

The technical literature relating to ground water in the United States exclusive of that published by the Geological Survey, is extensive and widely scattered. Practically all technical ground-water papers published in this country since 1928, except those that are purely engineering in character, are listed in the "Annotated Bibliography of Economic Geology," which is issued semiannually under the auspices of the National Research Council. The principal ground-water papers published since 1935 are listed in the "Bibliography of Hydrology," which is to be published annually by the American Geophysical Union as a part of the international bibliography on the subject.

A list of representative papers relating to different phases of the subject is given on pages 223-229 of this paper for the use of those readers who wish to make further study of the subject. Many of the papers listed contain bibliographies or numerous references to other publications on the same phase of the subject.

SOURCES OF DATA FOR THIS PAPER

In the present paper the section relating to water-bearing formations is based chiefly on the author's paper entitled "The occurrence of ground water in the United States, with a discussion of principles" (No. 1 in the following list). That paper contains references to numerous substantial publications by many authors, covering different parts of this large subject. Many of the other papers in the list also contain systematic descriptions of water-bearing formations in different parts of the country.

Information on the principles of artesian water and on the artesian conditions in different parts of the country is widely scattered through many publications—chiefly reports by the Federal and State geological surveys. A number of representative reports are cited.

The section relating to springs and evaporation discharge of ground water is also based on many publications, some of which are cited in the list. The discussion of large springs is based chiefly on No. 41, and that of thermal springs on No. 45. The published information on ebbing and flowing springs is meager and scattered but there are unpublished records in the Geological Survey.

The section relating to the utilization of ground water is based chiefly on the publications cited but in part on other publications and on unpublished records in the Geological Survey. The statements regarding public waterworks are based in part on No. 54 and on other publications, of which No. 56 is representative; chiefly, however, on unpublished records collected by D. G. Thompson from the State health departments and other sources. The statements regarding use for irrigation are based chiefly on the census report (No. 49) but also on other sources. The statements regarding uses for health and recreation are based largely on Nos. 45 and 50. The papers listed as Nos. 51, 52, 53, and 55 were presented at a meeting of the American Chemical Society at Atlanta, Ga., in 1930, and were published in Industrial and Engineering Chemistry. Together they furnish a nearly up-to-date survey of conditions affecting the mineral-water business.

LIST OF REPRESENTATIVE PUBLICATIONS IN THE UNITED STATES RELATING TO GROUND WATER

Water-bearing formations and their geographic distribution

1. Meinzer, O. E., The occurrence of ground water in the United States, with a discussion of principles: Geol. Survey Water-Supply Paper 489, 1923. Contains reference to numerous publications that cover different parts of this subject. Many of the other publications in this list also contain systematic descriptions of water-bearing formations.

Water-table conditions

See especially the following papers in this list: Nos. 1, 6, 8, 13, 14, 15, 20, 21, 25, 26, 28, 32, 37, 38, 40, 43, 47, 56–61, 63–65, 69, 75, 78, 83, 89, 90, and 97.

Artesian conditions

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APPENDIX

Geologic time divisions and the corresponding rock systems and series

[Recognized by the Geological Survey, United States Department of the Interior]

Era	Period or system	Epoch or series
Cenozoic	Quaternary	Recent. Pleistocene (equivalent to "glacial").
	Tertiary	Pliocene. Miocene. Oligocene. Eocene.
Mesozoic	Cretaceous	Upper (Gulf in some areas). Lower (Comanche or Shasta in some areas).
	Jurassic.	
	Triassic.	
Paleozoic	Carboniferous	Permian. Pennsylvanian. Mississippian.
	Devonian.	
	Silurian.	
	Ordovician.	
	Cambrian.	
Proterozoic	Pre-Cambrian.	

Metric equivalents

1 inch = 2.540 centimeters.
1 foot = 0.305 meter.
1 mile = 1.609 kilometers.
1 acre = 0.405 hectare.
1 square mile = 259.00 hectares.
1 United States gallon = 3.785 liters.
1,000,000 United States gallons = 3,785.43 cubic meters.
1 cubic foot = 28.317 liters.
1 acre-foot = 1,233.49 cubic meters.
1 second-foot (1 cubic foot per second) = 1.699 cubic meters per minute = 2,446.58 cubic meters per day.

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