ERRATA

Florida Geological Survey

Report of Investigations No. 10
Ground Water in
Central and Northern Florida

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Page 7 - (1st line of footnote) PART IV, not Part V.

Page 13 - (9th and 15th lines) WITHLACOOCHEE, not Withlacooche.

Page 14 - (Figure 6) ALAPAHA, not Alpha River.
WACASASSA, not Wicissa River.
OKLAWAHA, not Okkawaha River.

Page 15 - (Bottom line) WITHLACOOCHEE, not Withlacooche.

Page 21 - (Title to fig. 12) GEOLOGY, not Gology.

Page 30 - (Figure 21) FERNANDINA, not Fernandia.
(Third line of explanation of fig. 21) 60, not 600.

Page 34 - (Title to fig. 23) KISSENGEN, not Kissingen Spring.

FLORIDA

STATE BOARD OF CONSERVATION

FLORIDA GEOLOGICAL SURVEY

Herman Gunter, Director

REPORT OF INVESTIGATIONS

No. 10

GROUND WATER IN CENTRAL AND NORTHERN FLORIDA

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by

H. H. Cooper, Jr., W. E. Kenner and Eugene Brown

UNITED STATES GEOLOGICAL SURVEY

Published for

THE FLORIDA GEOLOGICAL SURVEY

Tallahassee, 1953

LETTER OF TRANSMITTAL

Florida Geological Survey
Tallahassee

November 10, 1953

Mr. Charles Bevis, *Supervisor*
Florida State Board of Conservation
Tallahassee, Florida

Dear Mr. Bevis:

The Interior and Insular Affairs Committee of the House of Representatives, United States Congress, encouraged members of the United States Geological Survey, and the United States Weather Bureau, "to prepare graphic descriptions of the geologic, topographic and hydrologic features of eight type areas, chosen to show in detail on a sample area basis characteristics which are typical of extensive areas," throughout the United States.

Florida was fortunate in being selected as the type area of artesian groundwater occurring in carbonate aquifers. The report on the central and northern Florida area was prepared by Messrs. Cooper, Kenner and Brown of the United States Geological Survey and was considered to be so readable, factually true, and excellently illustrated that it should be made available to the citizens of Florida, as part of the service by this Department.

I am pleased to submit this fine report with the request that it be published as Report of Investigations No. 10.

Respectfully,

Herman Gunter, *Director*

FLORIDA STATE BOARD

OF

CONSERVATION

TABLE OF CONTENTS

ILLUSTRATIONS

ACKNOWLEDGEMENTS

This report was published as Chapter Nine of part four of the series of studies of natural resources prepared for the Interior and Insular Affairs Committee, House of Representatives, United States Congress. Part four of the series was prepared under the supervision of Arthur M. Piper of the Federal Survey.

The permission to publish the chapter on Florida was kindly given by Dr. Nelson Sayre, Chief, Groundwater Branch, U. S. Geological Survey. The subject matter and the scope of the project is at the heart of the delegated responsibilities of the United States Geological Survey, but heavy responsibilities and limited manpower keep the Survey from making many studies that are needed.

The activities required in the preparation of these reports were undertaken by members of the regular staffs of the various branches of the U. S. Geological Survey, but much of the work accomplished was a result of overtime activity.

Many individuals have participated in the preparation of the report, "Ground Water in Central and Northern Florida." Those with the chief responsibility for preparing the report are listed as authors, but many individuals in the various offices prepared diagrams, tabulated data or contributed to the report in other ways. In particular A. O. Patterson, District Engineer, Surface Water Branch, Ocala, Florida, and Ralph Heath, Acting District Geologist, Groundwater Branch, Tallahassee, Florida, contributed specific items to the report.

Ground Water in Central and Northern Florida*

By H. H. COOPER, Jr., W. E. KENNER and EUGENE BROWN,
United States Geological Survey

THE GENERAL SETTING

Florida affords a happy contrast to thirsty regions of the Southwest. Over most of the State vast quantities of water await development. Precipitation is abundant. Streams empty substantial volumes of water into the ocean, their flows virtually undiminished by man's minor extractions. Numerous limestone springs, some among the largest in the world, contribute their share to the water that escapes unused. Myriad lakes and large swamps yield an untold levy to evaporation and to the transpiration of native vegetation.

Beneath the State lies a part of one of the most extensive and productive ground-water reservoirs in the Nation—the Floridan aquifer. This aquifer plays a dual role in the water-resources picture. On one hand it serves as a giant reservoir, storing water in periods of excessive rainfall against gradual release during droughts. On the other, it acts as a system of pipelines, transmitting water to points distant from the areas of recharge and distributing it conveniently to cities and industries and to isolated farms and rural homes.

Although the total available supply of water is very large as compared with the present demand, water of good quality is not adequate in some localized areas. The lack is becoming especially acute at some places along the coast where most of the ground water is too salty for ordinary uses, and where the surface supplies are scanty or are themselves salty.

Florida's economy is expanding rapidly. Ranking first among sources of income is the State's tourist trade, but other sources, including citrus growing and citrus processing, truck farming, cattle raising, mining of phosphate and heavy minerals, and timber

* Reprinted from Part IV, **Subsurface facilities of water management and patterns of supply—Type area studies**: The Physical and Economic Foundation of Natural Resources, Interior and Insular Affairs Committee, House of Representatives, United States Congress, 1953, 206 pp.

and pulpwood production, contribute substantially. Attracted in part by the availability of large dependable supplies of water, manufacturers of paper, rayon, and nylon are establishing many mills in the northern part of the State.

The State's mild climate has, of course, been predominantly instrumental to its agricultural development and to its popularity as a winter resort. Generally, the State is frost free more than 9 months of the year. With average temperatures of 81° F. in July and 59° F. in January, the climate is usually neither excessively hot nor excessively cold. Only once has a subzero temperature been recorded in the State: a low of -2° F. nipped Tallahassee during the unprecedented, nationwide cold wave of February 1899. The highest temperature on record is 107° F., but yearly maxima of 100° F. and minima of 20° F. are by no means common anywhere in the State. Snow is so rare that many adult natives have never seen it.

The 1950 census recorded in Florida a permanent population of 2,770,000, which represents a growth of 46 percent since 1940. Part of the growth has come from an influx of elderly people, who are retiring and establishing permanent residence in the State.

PRECIPITATION

As shown in figure 1, no part of the State has been slighted in the distribution of rain. In the extreme southeastern and northwestern sections of the State the average is 64 inches and at other places is generally more than 48 inches. The average over the State as a whole is 53 inches a year.

Although there are well-defined wet seasons and occasional droughts, ordinarily the rainfall is fairly well distributed through the year. The seasonal distribution at Gainesville is typical of that at most stations (fig. 2). The period of greatest rainfall generally begins in June and ends in September but extends into October on the southeast coast, owing to the far-reaching influences of tropical disturbances in the Atlantic Ocean.

Long-term trends of rainfall at Gainesville are represented in figure 3. During the 50-year period from 1901 to 1950 the yearly rainfall averaged 50 inches but ranged from as little as 32 inches in 1917 to as much as 65 inches in 1941. From 1901 through 1918 the rainfall was generally less than average; from 1919 through 1943 it was about average; and from 1944 through 1950 it was generally higher than average.

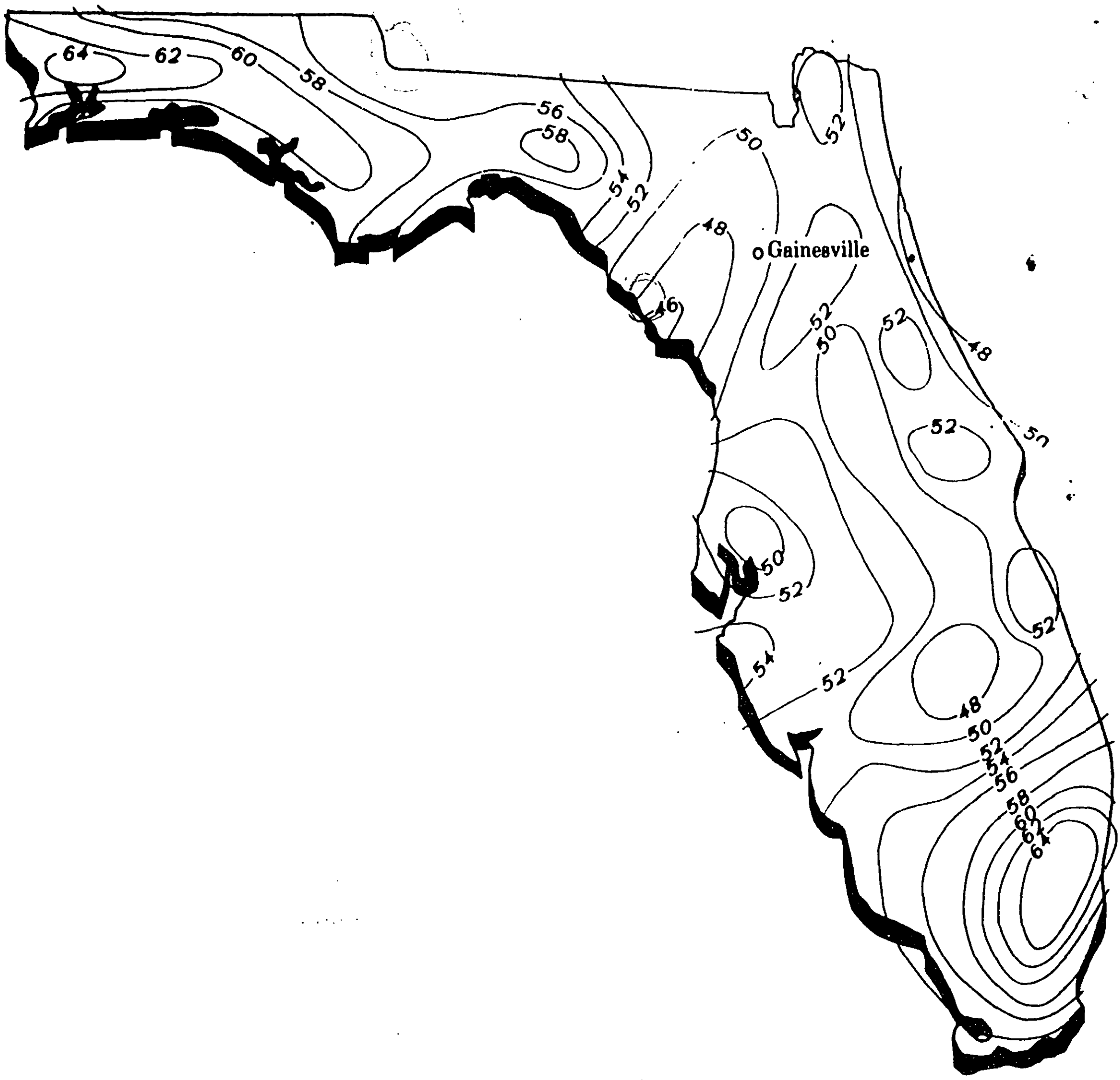


FIGURE 1.—Florida's rainfall is plentiful.

The lines define zones of equal average yearly rainfall, which ranges from 46 to 64 inches. From "Climate and man," U. S. Department of Agriculture yearbook, 1941.

STREAMS IN NORTHERN AND CENTRAL FLORIDA

The area which will be discussed comprises about 22,000 square miles in the north-central part of Florida, including all or parts of 32 of the State's 67 counties. This area consists principally of low coastal lands divided slightly east of center by Trail Ridge, a series of rolling hills that rise no higher than about 200 feet above sea level.

In few other areas of the United States is the distinction between surface water (streams, lakes, and ponds) and ground water more transient. Also, in few other areas is the land surface more obviously drained in part by movement of water underground. The water of a stream or lake may infiltrate through the bed of that stream or lake and become ground water. Elsewhere, perhaps miles

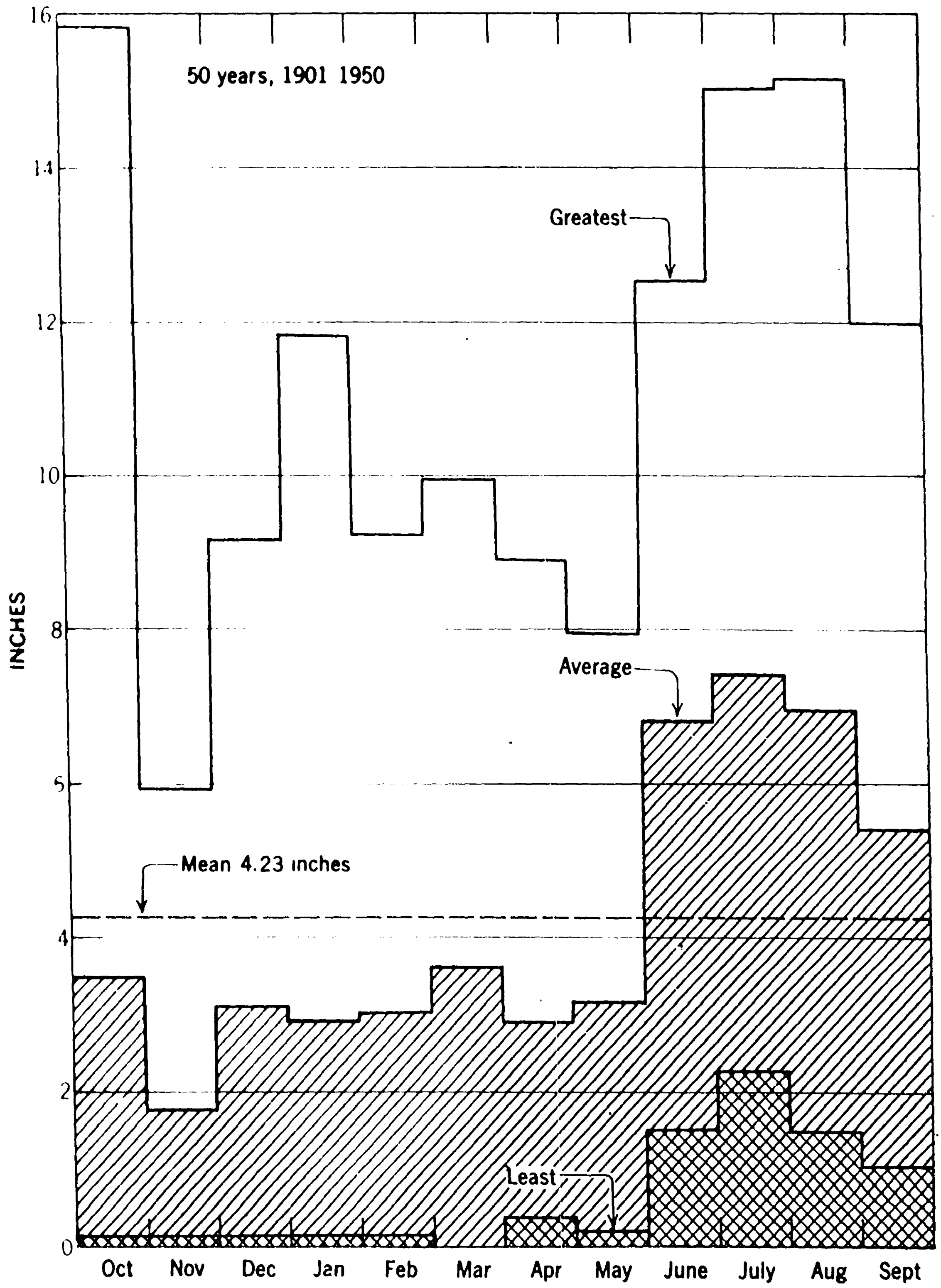


FIGURE 2.—Variations in monthly precipitation at Gainesville.

Average rainfall in the driest month, November, is 24 percent of that in the wettest month, July. Extremes vary widely in each month, especially from October through April.

away, it may issue from a large spring and form a stream. In north Florida, for example, the Santa Fe River disappears underground to reappear several miles away and continue again as a surface stream (see figs. 4 and 5). The water is the same; only

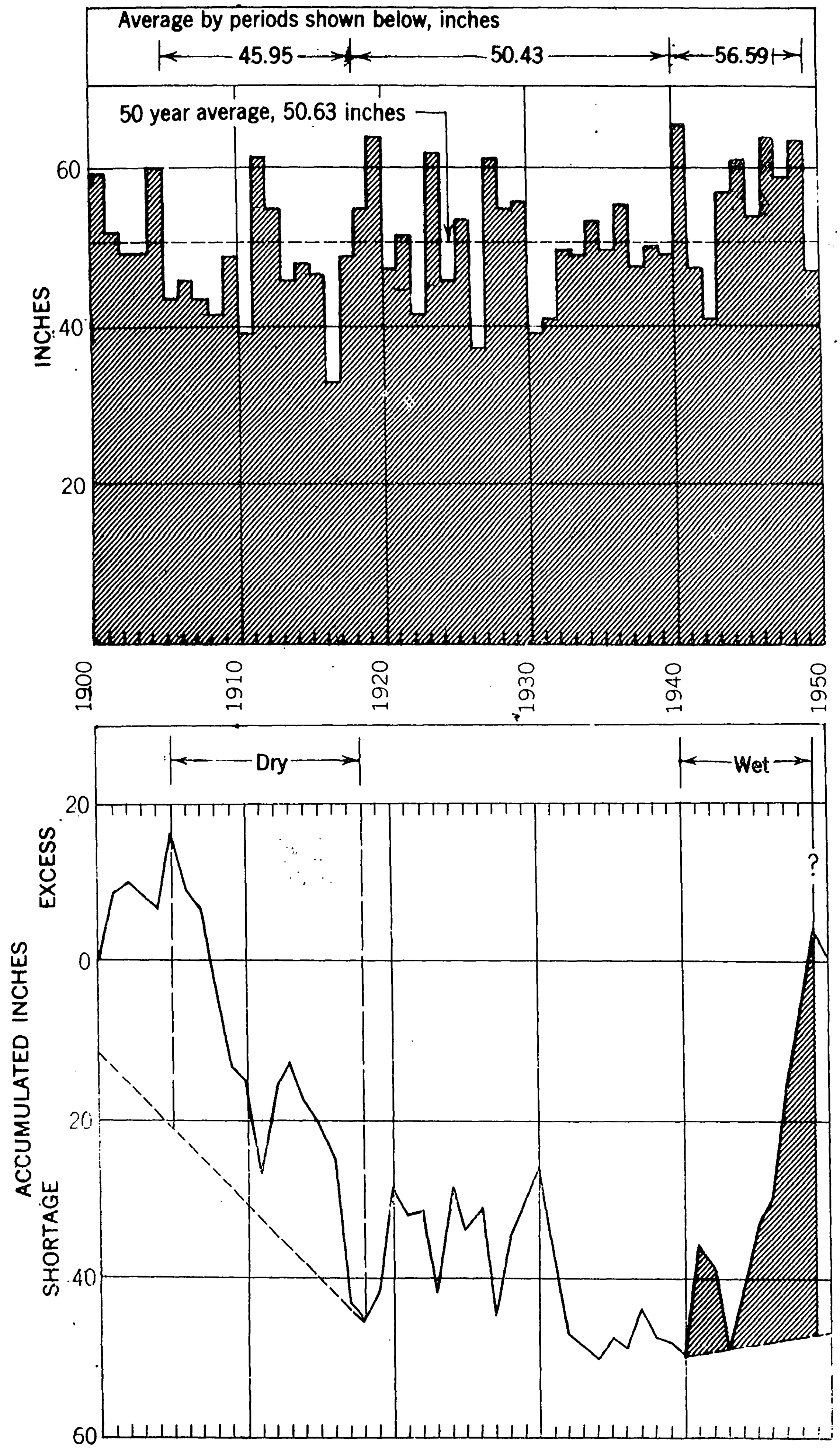


FIGURE 3.—Variations in yearly rainfall at Gainesville, 1901-50.

In the last half century, yearly rainfall has ranged from 65 percent of average in 1917 to 128 percent of average in 1941; this percentage range is much less than is common in the drier parts of the Nation. The lower graph shows a dry period from 1906 through 1918 and a wet period beginning with 1941; the intervening period was neither notably wet nor notably dry.

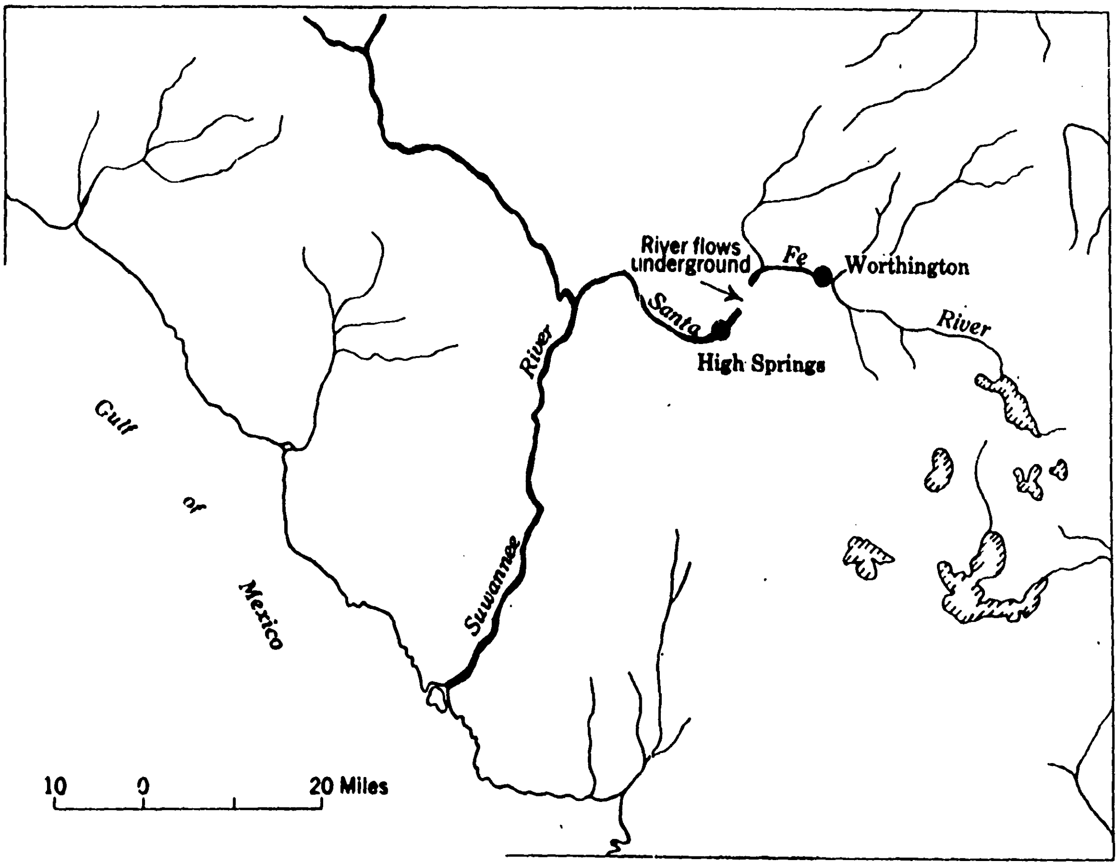


FIGURE 4.—Flow of the Santa Fe River passes underground in a 3-mile reach between Worthington and High Springs.

Several of the rivers in northern Florida, including the Santa Fe and the Suwannee, have cut channels into the limestone formations that compose the principal ground-water reservoir. During low flows, these rivers are fed by the ground water. During high flows, water from the rivers pours into the limestone.

its name, "surface water" or "ground water," changes according to mode of occurrence at the moment.

Lakes and ponds, scattered over the area, number in the thousands. Large swamps border most of the west coast and occupy much of the St. Johns River basin. The principal streams of the area include the Suwannee, St. Marys, St. Johns, Oklawaha, Santa Fe, Hillsborough, and Waccasassa Rivers, two rivers named Withlacoochee, and Olustee and Black Creeks (see fig. 6). The St. Johns River is one of the few rivers of the world that flow northward throughout their courses.

The figure shows the average flows of these streams so far as is indicated by the few data available. A notable deficiency is the lack of records on the flow of the lower St. Johns River—the flow is unknown over a reach of 150 miles. The flow of the Suwannee River near Bell, Fla., averaging 8,000 cubic feet a second, is by far the largest of any on which adequate data are available, but

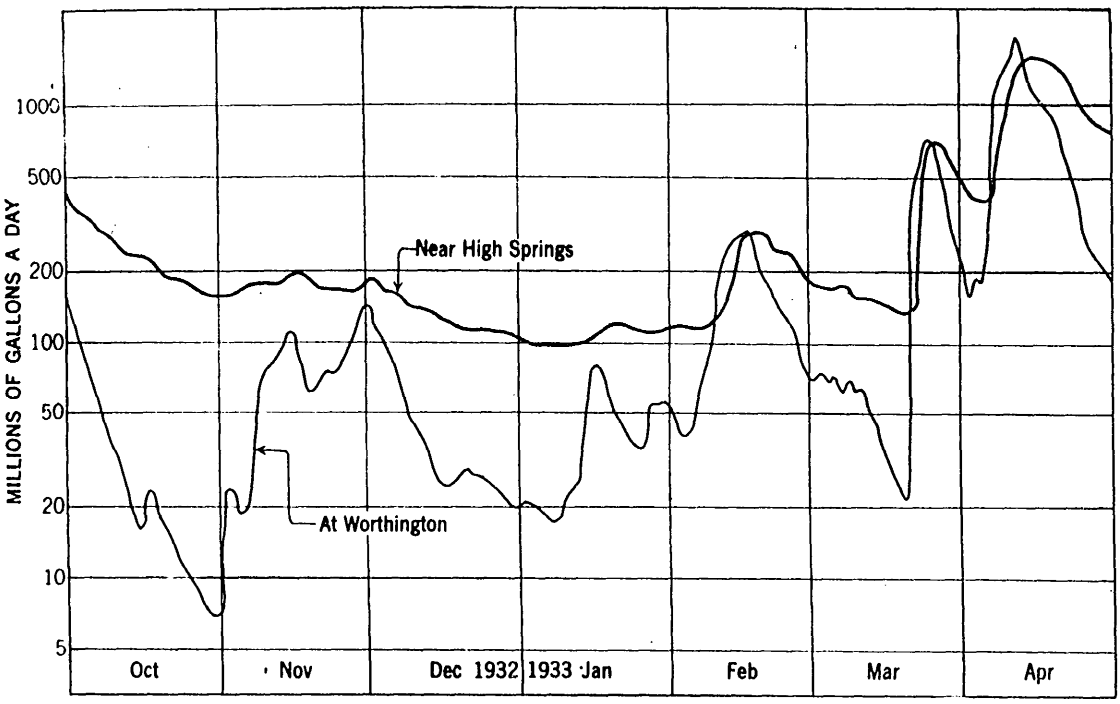


FIGURE 5.—Flow of Santa Fe River upstream and downstream from its underground reach.

During the 7 months covered, flow of the river at Worthington, upstream from the underground reach, ranged from 7 to 1,930 mgd (million gallons a day), or 11 to 2,980 cfs. Near High Springs, downstream, it ranged from 94 to 1,630 mgd, or 146 to 2,520 cfs. Evidently, during low flow and falling stages at high flow this reach of the river gains very substantially from ground water. During rising stages at high flow, it loses moderately to ground water.

the flow of the lower St. Johns may turn out to be even larger when determined.

Most of the major streams—including the Suwannee, St. Johns, Oklawaha, Santa Fe, Hillsborough, and Waccasassa Rivers and the two Withlacoochee Rivers—receive a part of their flow from artesian springs. At high stages, water from the Suwannee River backs into many of the numerous springs along its course. The flows of the Oklawaha and the southern Withlacoochee Rivers are sustained at medium and low stages by Silver Springs and Rainbow Springs, respectively—the State's largest two springs. The operation of a hydroelectric plant on the Withlacoochee owes its existence to the discharge of Rainbow Springs. The Hillsborough River is the source of supply for Tampa, the third largest city of the State.

Inundating floods of the Suwannee River (see fig. 7) doubtless have helped to retard economic development in the river basin. Optimum design of control structures will require an adequate understanding of the effects of water movement in the limestone formations through which the river has cut its channel. The flow of water through open solution channels in the limestone would cause difficulty in confining the flood waters to surface reservoirs, but, on the other hand, voids in the limestone would add substantially to the storage capacities of reservoirs.

The lakes are used extensively for irrigating citrus groves and truck farms during the winter and early spring, when rains are

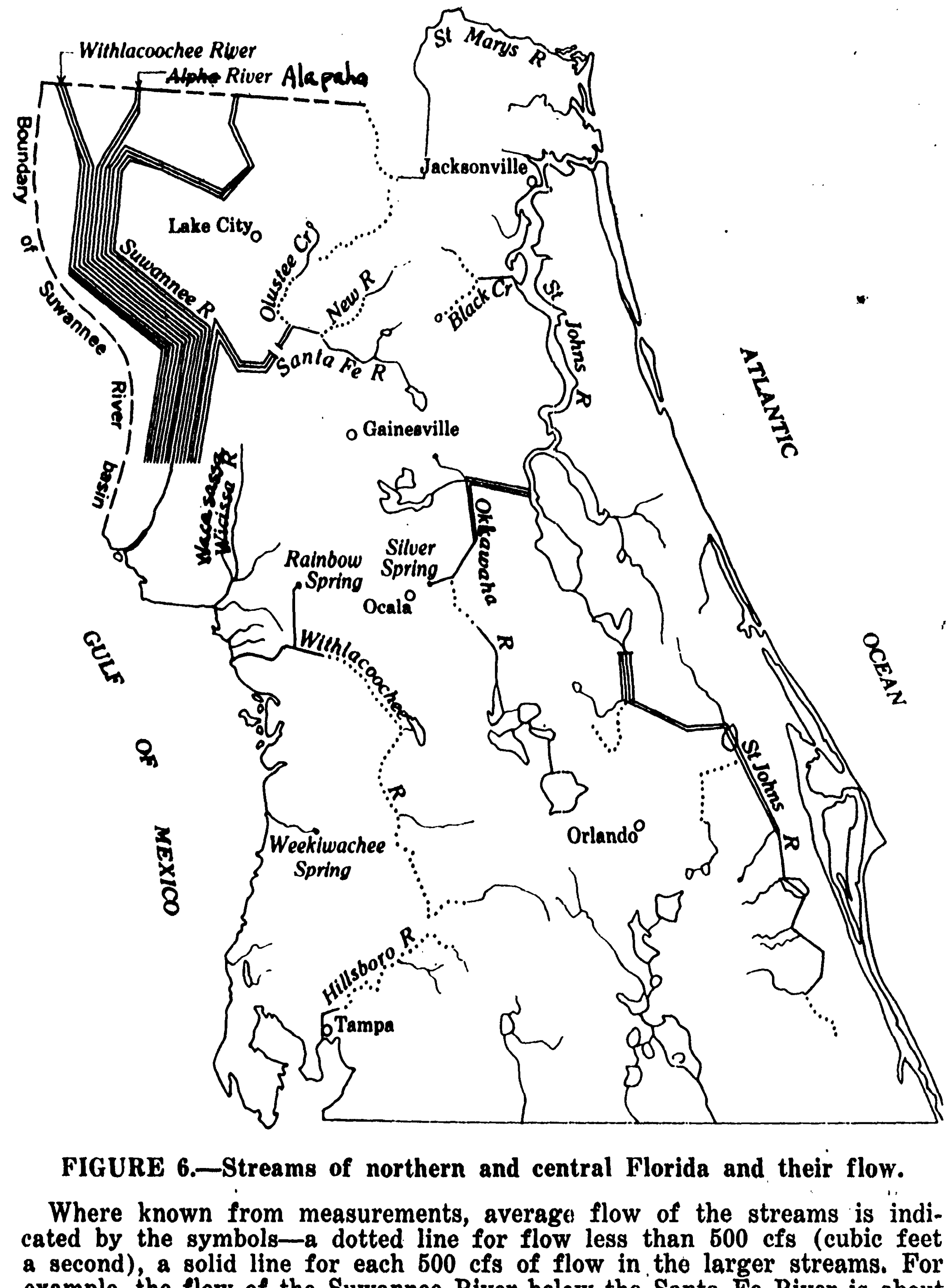


FIGURE 6.—Streams of northern and central Florida and their flow.

Where known from measurements, average flow of the streams is indicated by the symbols—a dotted line for flow less than 500 cfs (cubic feet a second), a solid line for each 500 cfs of flow in the larger streams. For example, the flow of the Suwannee River below the Santa Fe River is about 8,000 cfs. Flow is not measured in numerous long reaches of certain streams, and cannot be shown here.

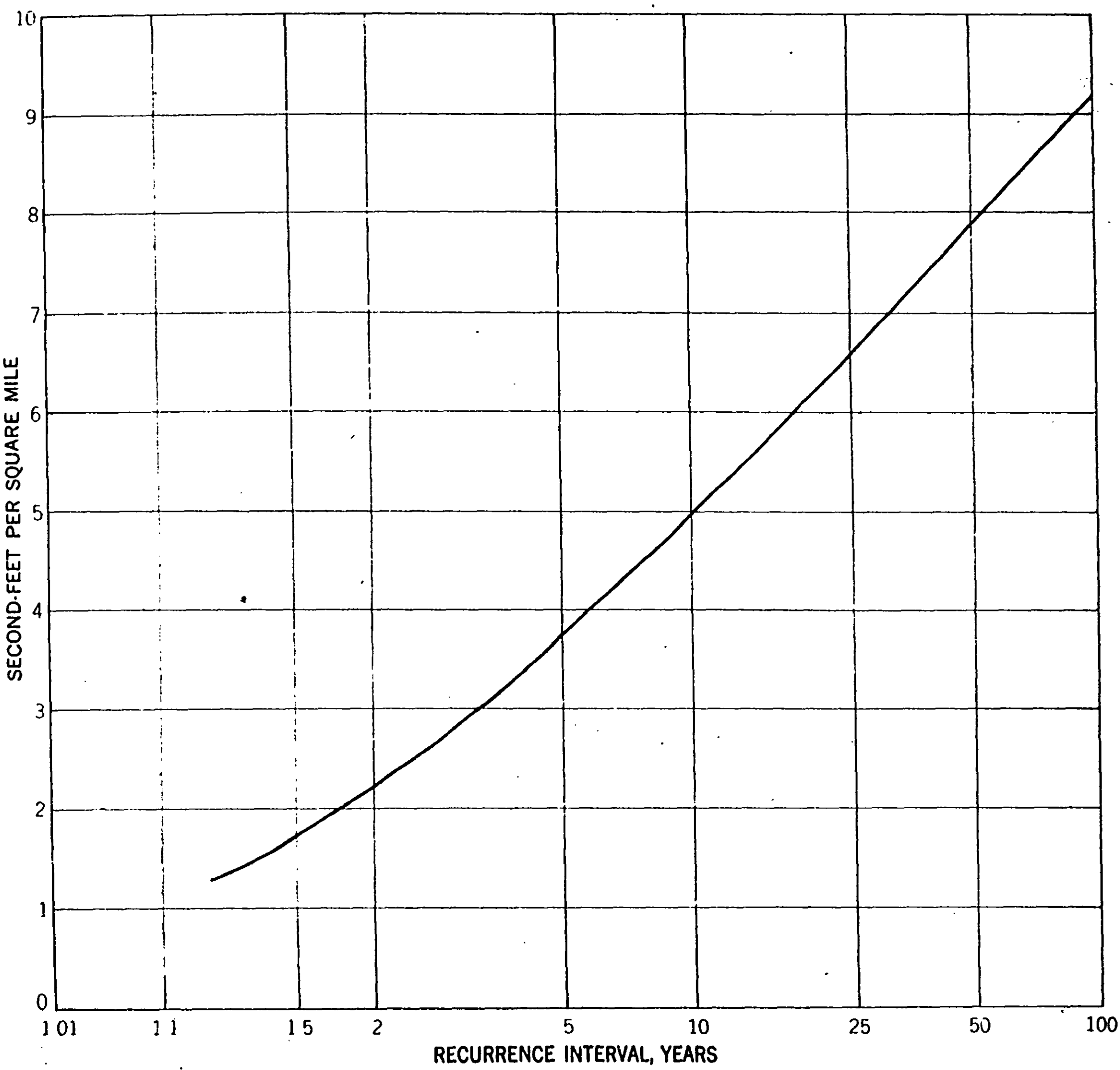


FIGURE 7.—Size and frequency of floods, Suwannee River near Bell.

Drainage area 9,260 square miles. Here, water yield per square mile is only moderate. For a flood of 10-year expectancy, flow near Bell would be about 46,000 cfs. In contrast, the 10-year flood of the St. Joe River at Calder, Idaho is 4.7 times larger per square mile. On the streams of Florida, flooding is more a result of low channel gradients and relatively slow runoff, than of the amount of runoff.

relatively infrequent. They serve also to moderate the temperature, providing frost protection for citrus and vegetables during cold waves.

The recreational facilities offered by the surface waters are substantial contributors to the economy of the area, and the large limestone springs of the area are among the State's major tourist attractions. Fishing in the lakes and streams lures many anglers from border States and other parts of the Nation. Pleasure boating on the Oklawaha River and its headwater lakes is a favorite recreation among local inhabitants and visitors.

The proposed Florida cross-State barge canal would run east from the Withlacoochee River to the Oklawaha and thence into the

St. Johns. The successful operation of the locks of the canal would depend on the flows of the large springs.

Gaging stations on the small streams of the area are far too few and have been operated only for short periods. Before these streams are developed for municipal, industrial, and agricultural supplies, records of their flows will be needed. Also, records of the flow of smaller streams are prerequisite to estimates of ground-water recharge.

The chemical character of Florida's lakes and streams is quite

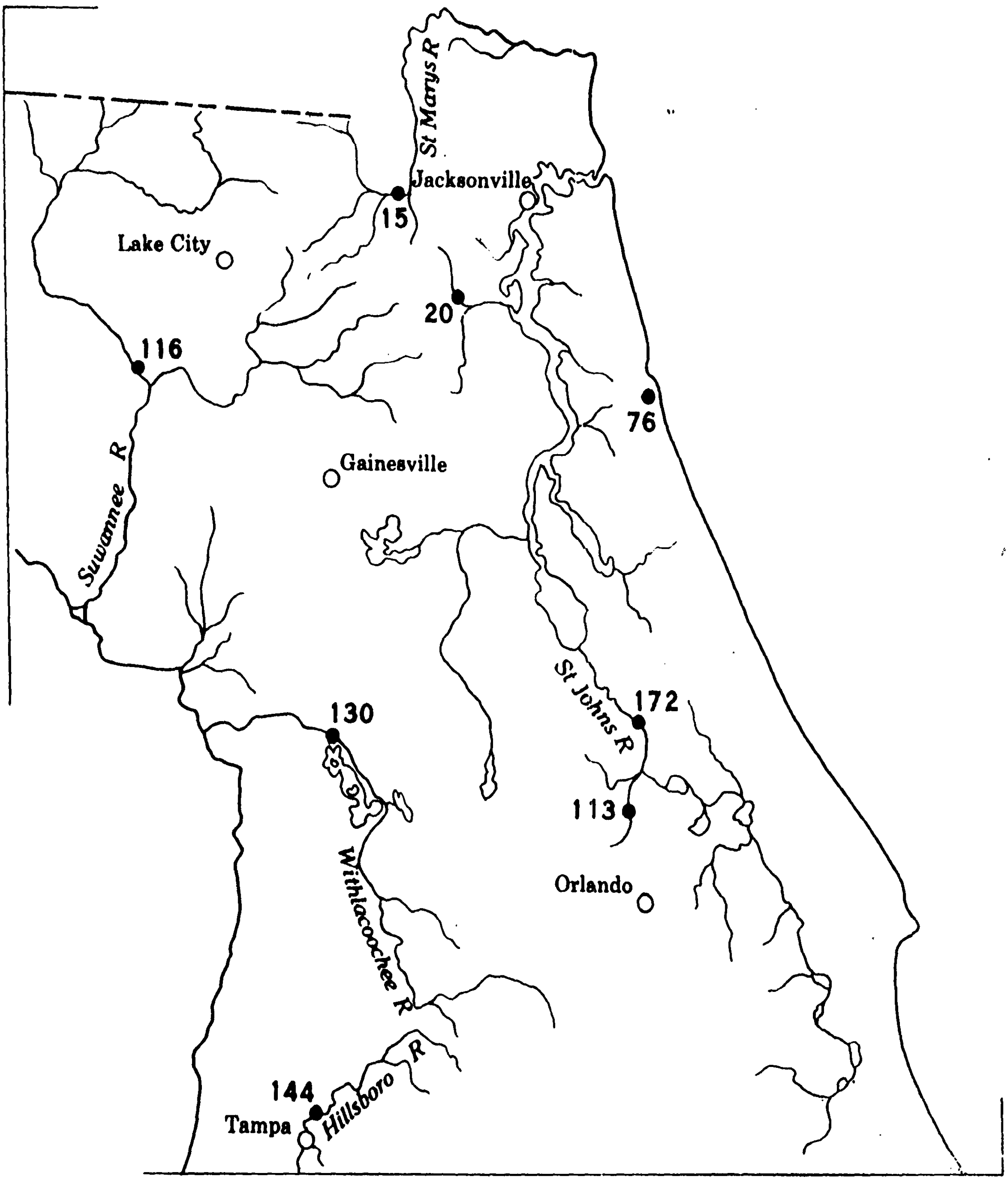


FIGURE 8.—Hardness of stream waters in central and northern Florida.

Points indicate sampling stations; numerals indicate hardness in parts per million. These are momentary values of hardness, from single "spot" samples; they are not average values.

varied. Streams whose flow consists principally of drainage from swamps are generally very low in hardness but high in organic color. In contrast, the water from most limestone springs is crystal clear but hard. Streams fed largely by these springs are therefore relatively hard and clear during low flows but soft and highly colored during high flows. Many of the streams, notably the St. Johns River, have gradients so low that sea water migrates many miles upstream from their mouths, contaminating the water and rendering it unfit for most uses.

Data on the variations in the chemical composition of the streams are few. Single "spot" samples from most streams have been analyzed (fig. 8), but these serve only to indicate what the character of the water was at the time of sampling. Industries considering the streams as sources of supply must know how the chemical composition varies between high and low flows—what the maximum concentrations of various critical constituents are—before they can determine whether the water is suitable for their purposes. Such information cannot be obtained quickly once the need for it has arisen—it must be collected over a period of years, in advance of the need.

GROUND WATER

About 70 percent of the water used for municipal, industrial, agricultural, and domestic supplies in Florida is drawn from the ground. Ground water is favored for two reasons. First, ordinarily it is more readily accessible, and second, its quality and temperature are generally constant. No accurate figures are available, but the total use of ground water in the State is estimated to be about 600 mgd (million gallons a day). Of this, about 250 mgd is being used by industries and 160 mgd for public supplies. The use for agricultural supplies is most difficult to estimate but probably is in the order of 150 mgd.

The ground water of Florida may be roughly divided into two classes: that known as the artesian water, which occurs in an extensive limestone system, and that in several shallow formations of relatively small areal extent.

Artesian Water

The Floridan aquifer, as the artesian aquifer is called, underlies almost all Florida, the coastal area of Georgia, and the southernmost parts of South Carolina and Alabama (fig. 9). It consists of a series of limestone formations having a total thickness of several thousand feet throughout most of Florida (Stringfield, 1936, p. 132). At some places the aquifer is exposed at the surface, but throughout most of the State its top is several hundred feet beneath the surface.

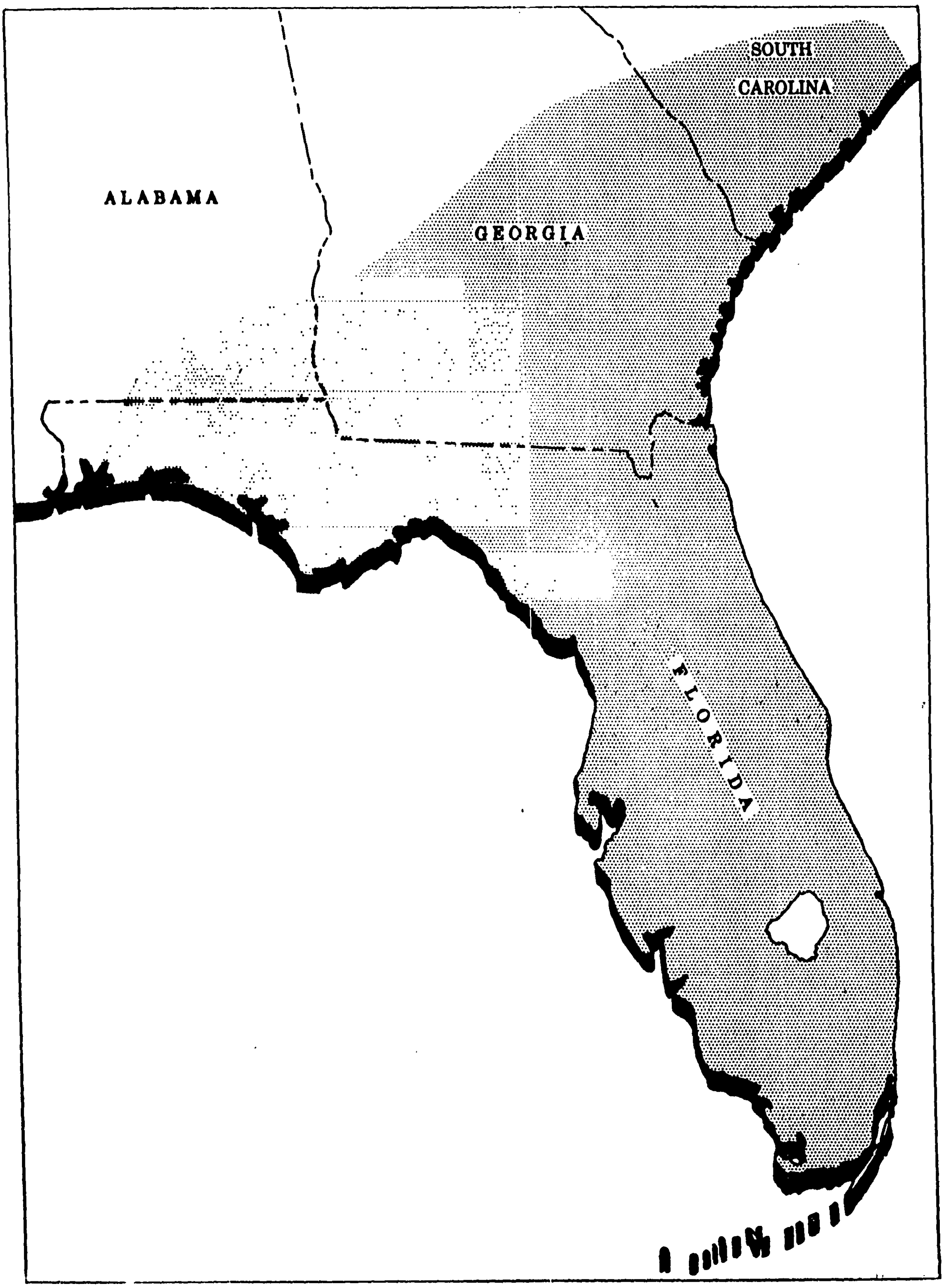


FIGURE 9.—Expanse of the Floridan aquifer.

Extending beneath almost all Florida, and smaller parts of three adjoining States, the artesian aquifer ranks among the Nation's largest and most productive natural underground reservoirs.

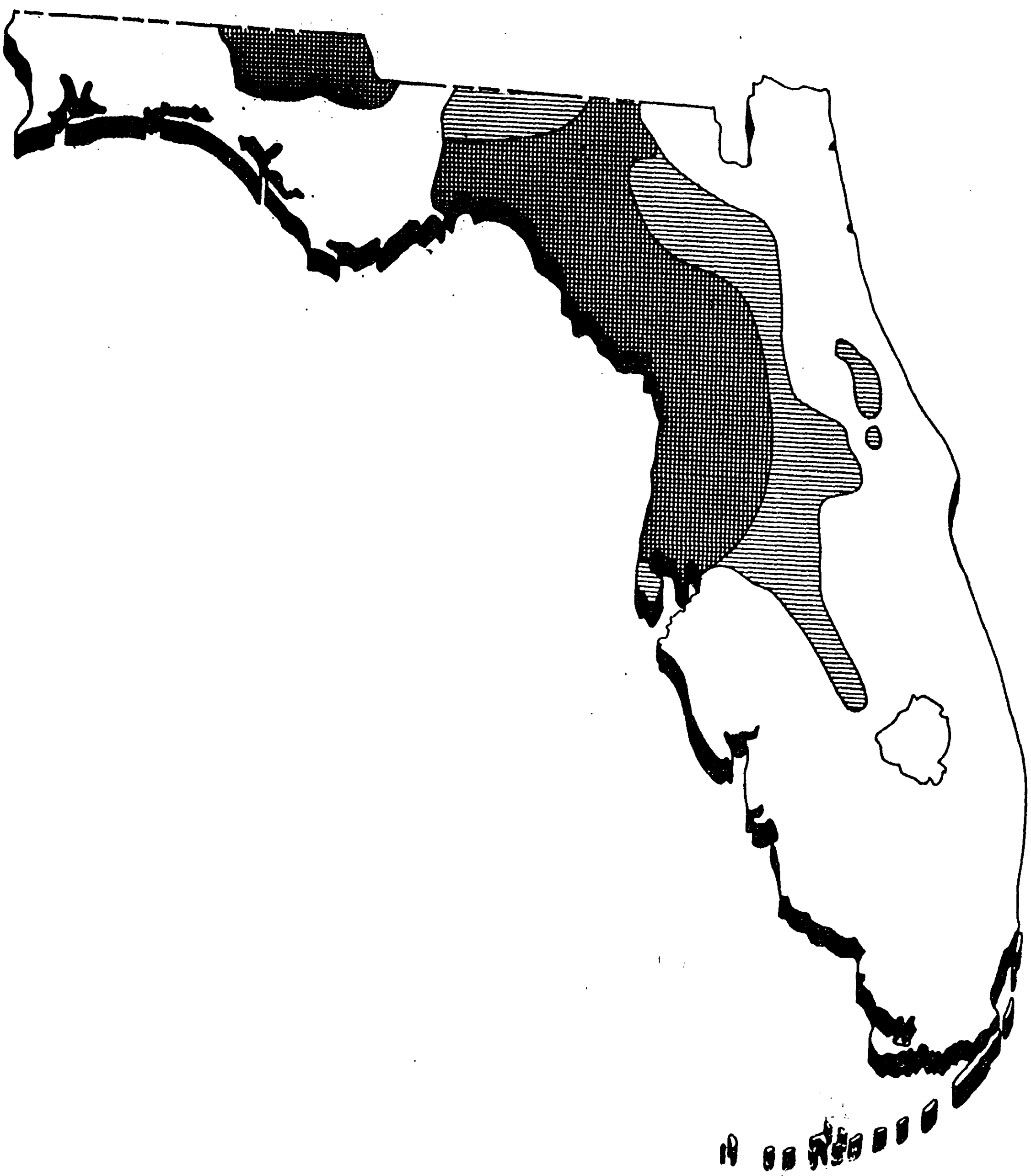


FIGURE 10.—Areas of recharge to the Floridan aquifer.

The aquifer is replenished by infiltration of rain over about 13,000 square miles. In the darkly-shaded areas almost all the rainfall is offered to the aquifer but some is rejected when the aquifer becomes full. In the lightly shaded areas the aquifer is blanketed by watertight material but receives recharge through sinkholes that penetrate the blanket.

This aquifer is the source of Florida's many large springs, such as Silver Springs, whose discharge averages 500 mgd, or 775 cfs. It is also the source of water from many thousand wells. In Seminole County alone it yields water to more than 2,500 irrigation wells. The natural flows of some of the wells are quite large; one well at Jacksonville, in Duval County, yielded a flow of almost 10 mgd, enough water to supply a city of 75,000 people.

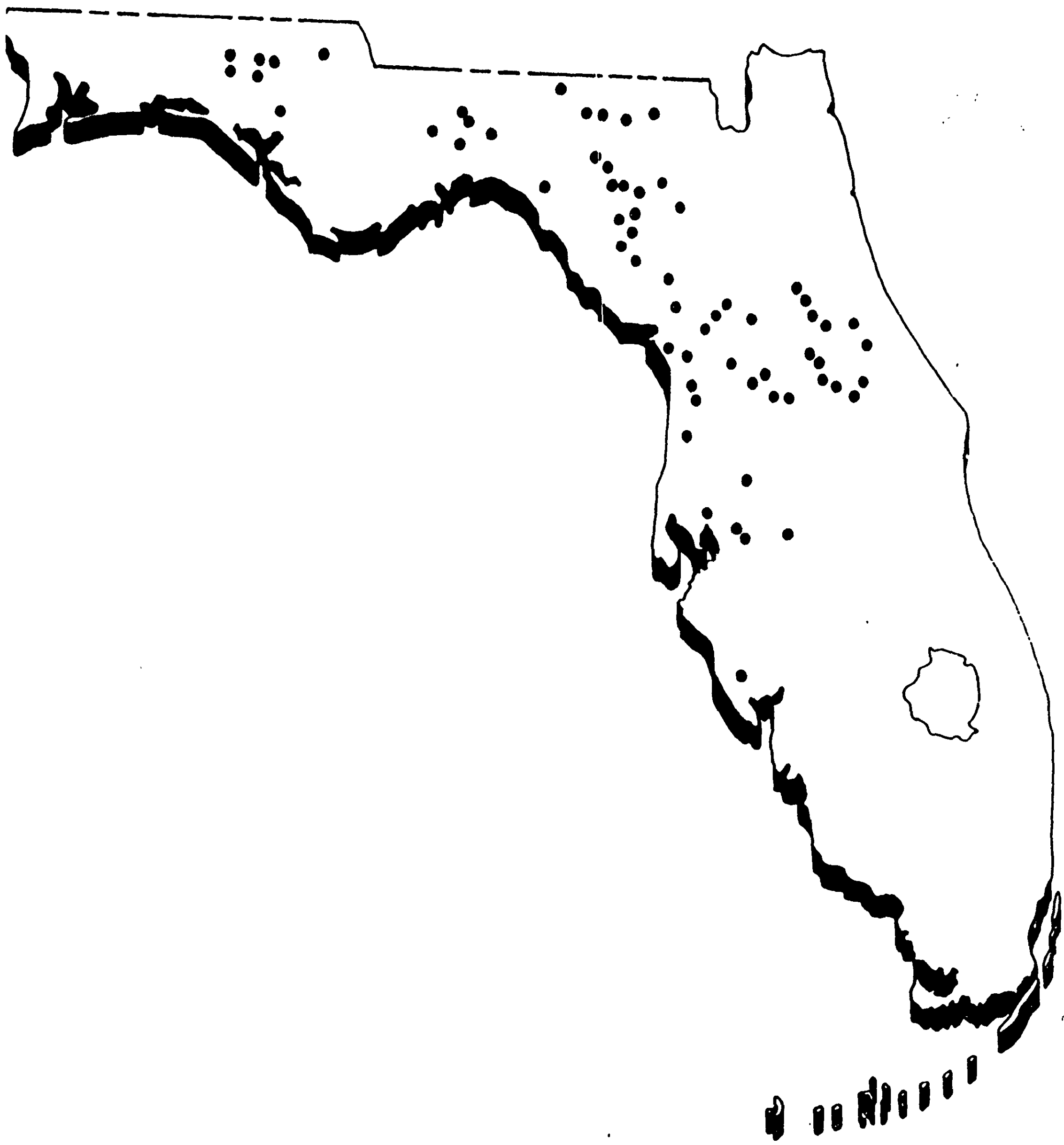


FIGURE 11.—Florida's large springs.

The discharge of springs gives an inkling of the large potential yield of the Floridan aquifer. In the aggregate about 6,000 cfs flows from the springs represented here. But a much larger quantity of water escapes from the aquifer beneath the sea, unobserved and unmeasured.

Aquifer Functions as a Giant Reservoir

The artesian water is replenished by rain in areas where the limestone aquifer lies at the surface and where it is covered only by pervious material (fig. 10). Within these areas the water that falls as rain is stored over long periods of time sustaining the flow of springs and rivers during long droughts, and endowing a perennial supply to wells. No one knows how much recoverable water is stored in the aquifer—there is not sufficient information to enable a well-founded estimate—but we do know that it is very large. Rough calculations put the volume of fresh water in the aquifer at about 10 times the capacity of Lake Mead, the Nation's largest man-made reservoir, impounded behind Hoover Dam on the Colorado River. But only a fraction of the water stored can be claimed for use.

Neither do we know how much replenishment the aquifer receives each year, although the total discharge of the large springs indicates that it, too, is large. The aggregate discharge of the springs represented in figure 11 is about 6,000 cubic feet a second. But this is only a small fraction of the whole. Probably most of the discharge goes directly into the sea, through countless springs and widespread seepage. This submarine discharge cannot be observed or measured, but we believe that it exceeds by several times the discharge of the terrestrial springs. Thus, we conclude that the discharge from the aquifer, and hence the replenishment to it, must be reckoned in the tens of thousands of cubic feet a second, and that the replenishment easily exceeds the flow into Lake Mead.

The areas of recharge aggregate about 13,000 square miles in central and northern Florida. Full development and use of the ar-

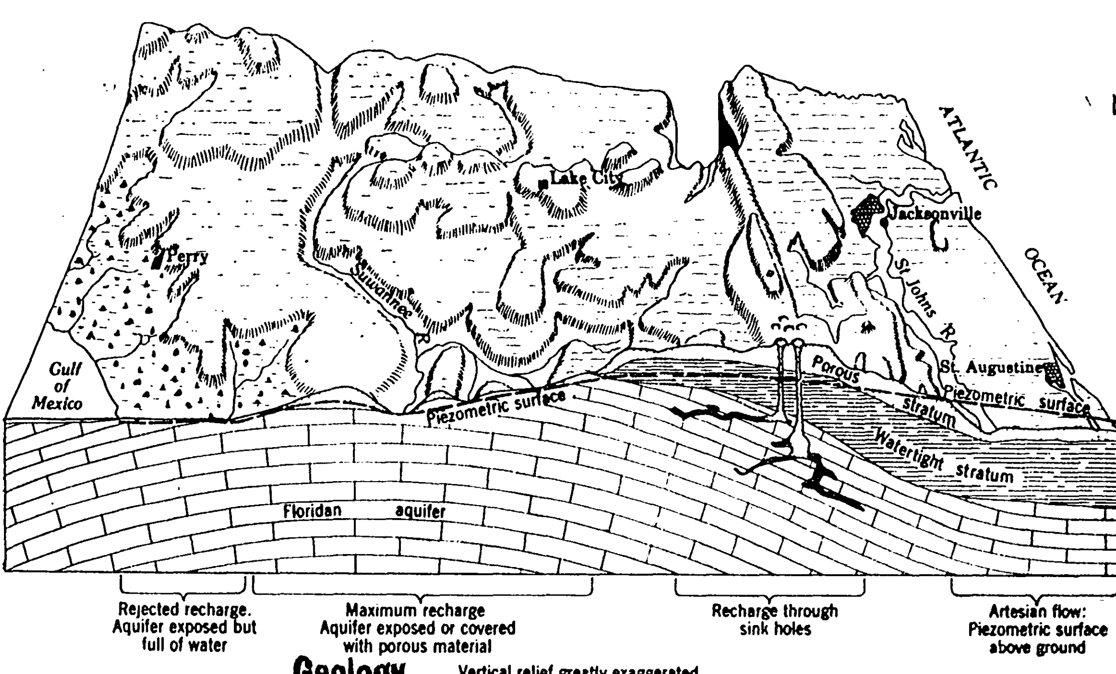


FIGURE 12.—[redacted] controls recharge and movement of the water.

The Floridan aquifer is a thick section of limestone which crops out at the land surface in some areas, but which is blanketed by watertight material in other areas. Recharge occurs most readily where the aquifer crops out, but a substantial amount of water enters through sinkholes which breach the watertight blanket.

Flowing wells may be obtained wherever the piezometric surface (see fig. 13) is above the land surface, as in the right-hand part of the section shown. Here the water is confined beneath the watertight blanket, and the aquifer is essentially a conduit. Where the aquifer is unconfined (left half of the section) it functions as a reservoir. At the far left of the section the aquifer is full and, therefore, is rejecting recharge.

tesian water will require that we distinguish between two types of recharge areas. In one, the aquifer is exposed at the land surface or is covered only with porous sand through which water may infiltrate to the aquifer quite readily. (See figs. 12 and 13.) In such an area a large percentage of the rainfall is available to the aquifer. Where the aquifer is not full, it accepts the water offered to it, leaving little or none to run off in streams. (See fig. 14.) Where the aquifer is full to overflowing, however, it rejects a part of the rainfall. Of that rejected, some runs off in streams and some returns to the atmosphere through evaporation and transpiration. Where the aquifer is rejecting water, recharge may be increased by the simple expedient of drilling wells and pumping water for use, thereby unwatering the aquifer and providing space to be occupied by additional recharge. When this is done, some of the streamflow and some of the water that otherwise would be evaporated or transpired is captured by the wells. Certain species of vegetation, when so robbed of their perennial supply of water, become sparse.

In the second type of recharge area the aquifer is overlain by a blanket of relatively impervious material that tends to confine the aquifer and preclude recharge. Here it is only where the blanket is breached that appreciable quantities of water reach the aquifer. In certain areas the blanket of impervious material is perforated with sinkholes, which form when limestone caverns, growing ever larger as the limestone gradually dissolves away, eventually collapse (fig. 15). These sinkholes are the avenues through which water finds its way down into the artesian aquifer (String-

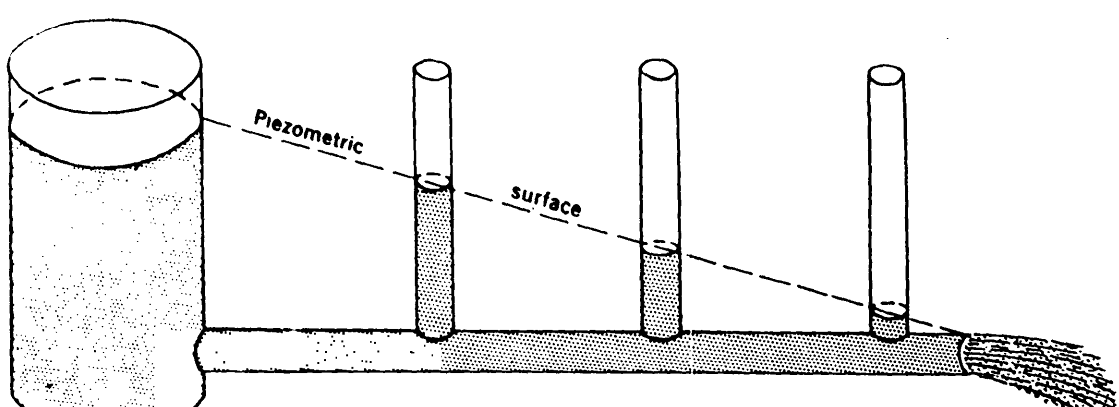


FIGURE 13.—Model explaining the piezometric surface.

In this laboratory model, the piezometric surface is the plane passing through the water surfaces in the tank and in the vertical tubes. In nature, it is an imaginary surface coinciding everywhere with the height to which water will rise in wells, owing to its pressure head. Water moves in the direction of downward slope on the piezometric surface.

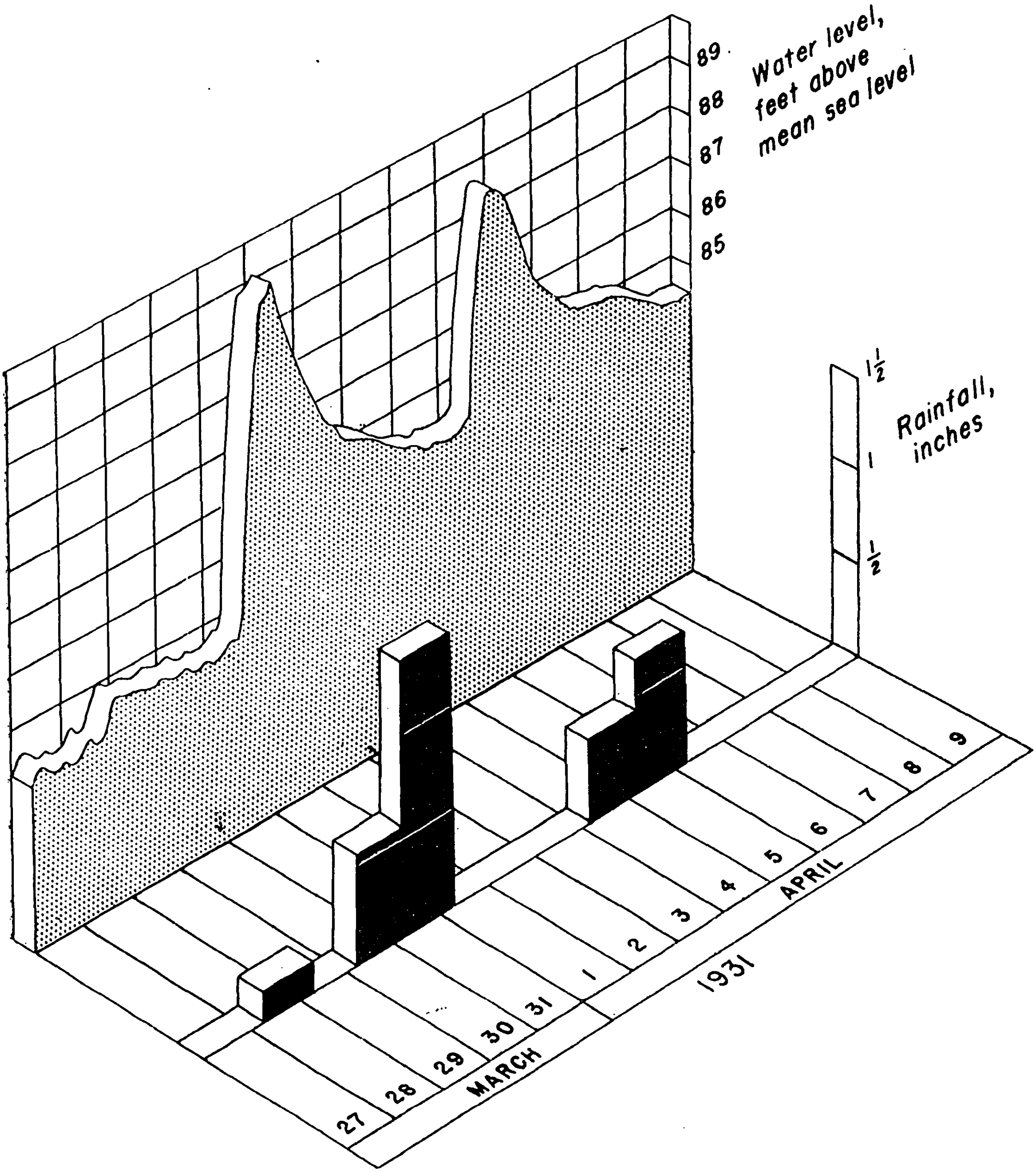


FIGURE 14.—Effect of rain on ground-water levels.

In the area of free recharge ground-water levels rise quickly owing to local rain. As shown, in a well east of Orlando the water level rose more than 6 feet in less than 24 hours after 2 inches of rain fell. A rise so rapid indicates that water infilters readily to the aquifer. In most wells the water level responds to rainfall more slowly.

field, 1936, p. 148). Ordinarily, they are not open holes but are floored with sand, and the sand allows water to filter through slowly (fig. 16). Thus, the rate of recharge is limited by the number of sinkholes and by the permeability of the sand and other material they contain. It may be observed that in this case the recharge is limited neither by the amount of rainfall nor by the capacity of the aquifer to receive water, but by the rate at which water may seep through the overlying material. The aquifer would receive more water if it were offered. Accordingly, the water running off in surface streams and being evaporated and transpired cannot be regarded as having been rejected by the aquifer. One could not expect, then, to induce much additional recharge merely by pumping. Additional recharge can be effected only by causing more water to pass through the water-tight blanket. This might be done by drilling artificial-recharge wells, through which surplus water may be diverted from the land surface into the aquifer.

Aquifer Functions as a System of Pipelines

One attractive feature of the artesian water, and of ground water in general, is its proximity to places where water is in demand. Generally, the isolated rural dweller, the farmer, the city or industry needs only to drill a few hundred feet to obtain an adequate supply. The aquifer through which the artesian water moves is a natural conduit, a distribution system reaching almost everywhere in the region. From where it enters the aquifer the water may travel long distances, commonly 50 miles and more, to where it is withdrawn for use. Not only does it move to the very premises of the consumers—over a large part of the State it is delivered under artesian pressure, so that the consumers are saved the expense of pumping.

We have learned the general directions in which the water moves by mapping the height of water levels in many wells

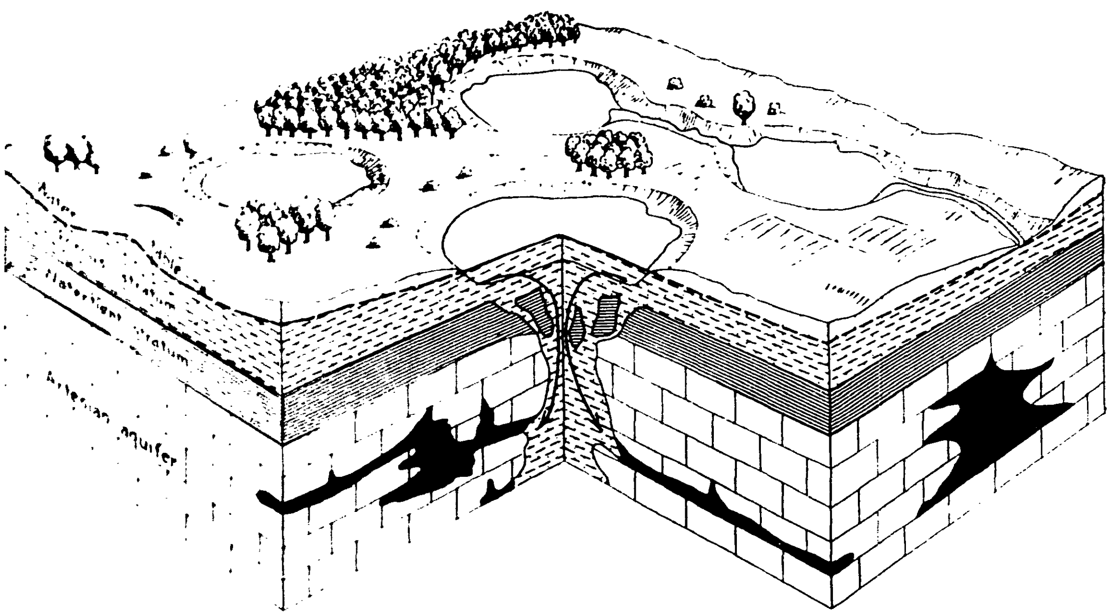


FIGURE 15.—Recharge through sinkhole.

Limestone is slightly soluble in water and gradually dissolves as water moves through it. Over the ages this process of solution creates large caverns, and forever enlarges them until ultimately they collapse under the load of rock and earth above. Collapse of a cavern causes the overlying material to subside, and so breaches the watertight blanket that confines the aquifer. Water from the land surface and in the thin sandy mantle then has a portal through which it may drain into the aquifer.

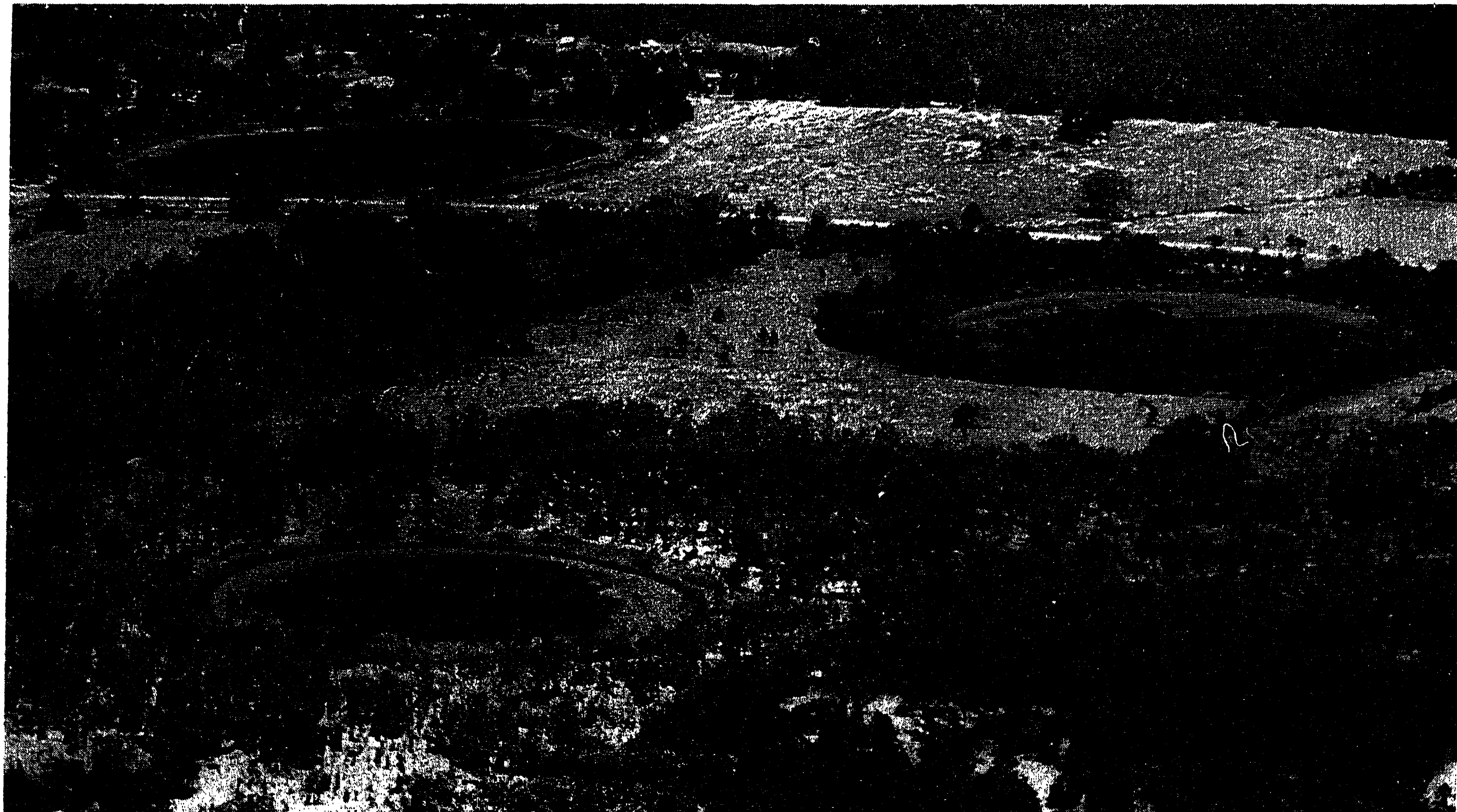


FIGURE 16.—Typical recharging sinkholes.

Florida's landscape is dotted with hundreds of sinkholes such as this. Some contain water and others do not. Those that are dry evidently drain freely and hence contribute a larger share of recharge to the Floridan aquifer. Those that contain water generally do so because their bottoms are covered with an accumulation of muck that slows drainage. Recharge to the aquifer might be increased by dredging the muck away.

throughout the State. The result is the map shown in figure 17, which represents approximately the height to which the artesian water will rise in a well at any given place (Stringfield, 1936, pp. 146-154). We may observe, for example, that near the center of the peninsula the water in wells stands 120 feet above sea level—higher than at any other place in the State. Generally, recharge occurs in areas such as this, where the water stands high, and discharge occurs where it stands low. The water moves laterally from the areas of recharge toward areas of discharge, generally at right angles to the lines shown on the map. The water passes, in some directions, beneath the blanket of relatively impervious material,

FIGURE 17.—Piezometric surface of the Floridan aquifer, 1952.

Lines connect points of equal head on the ground water, in feet above sea level. The piezometric surface, so shown, is highest where there is recharge and slopes downward in the direction that water moves toward places of escape. The general coastward slope of this surface indicates that most of the water moving in the aquifer wastes into the sea.

which not only impedes downward percolation from the land surface, but also confines the water within the aquifer and preserves its head. In low areas, water so confined has enough head to flow at the land surface when the confining blanket is punctured by a well. As indicated in figure 18, flowing wells may be obtained over roughly a third of the State.

Where the artesian water is confined, the aquifer cannot function efficiently as a reservoir, because it is already full and cannot store additional water in large quantity. An effort to conserve

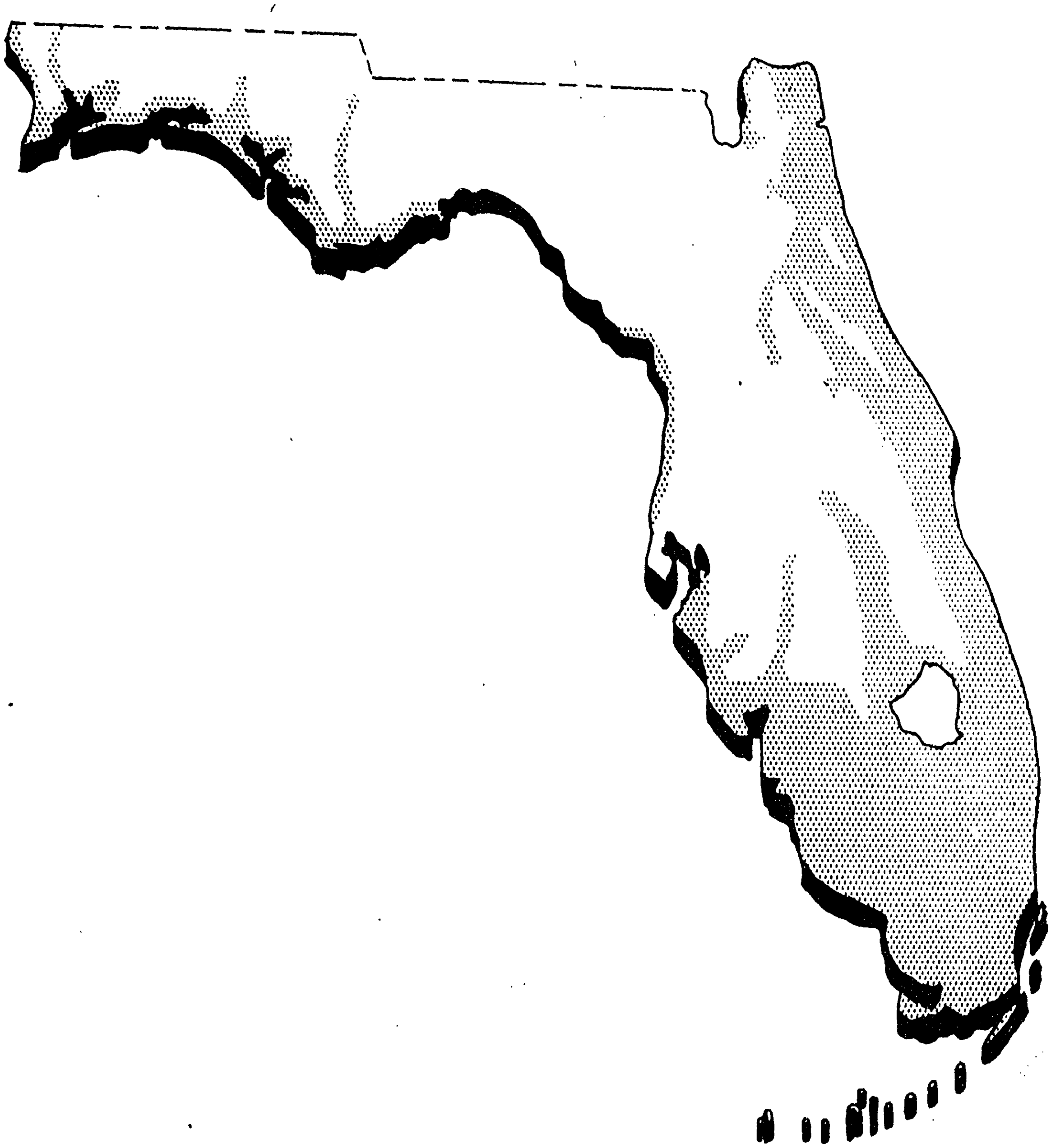


FIGURE 18.—Areas of artesian flow.

Flowing wells may be obtained over roughly a third of Florida, commonly with yields of several hundred gallons a minute. Such wells are a boon to farmers and citrus growers as they obviate an expense of pumping water for irrigation. Flowing wells used for irrigation number in the tens of thousands. The area of flow is contracting locally because of the heavy draft of water.

flood water by artificially recharging a confined aquifer would be comparable to an attempt on the part of a city to use the pipes of its distribution system as a storage reservoir. True, the artesian pressure would be increased around the area of artificial recharge so long as the injection of water were continued, and to this extent beneficial results would accrue, but these effects would dissipate rapidly whenever the injection were interrupted. Thus, if surplus water is available for recharge only intermittently, as dur-

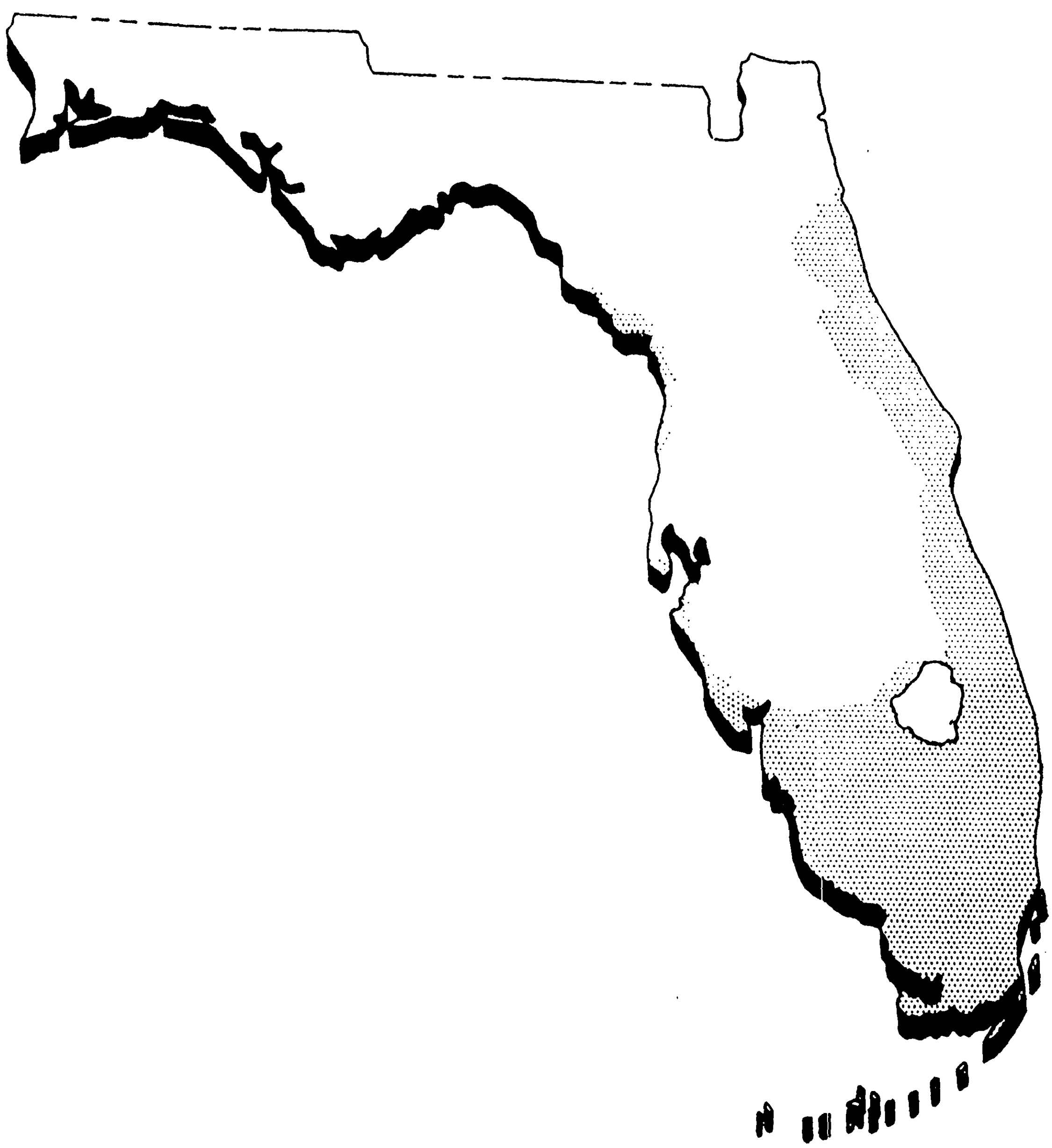


FIGURE 19.—Salty water in the Floridan aquifer.

Shaded area is that within which the water contains more than 1000 ppm of chloride at moderate depths. This is almost as large as the area of artesian flow. At some places the water is only slightly salty and is being used for irrigation and municipal supply, but only because better water is lacking. At other places the water is much too salty for all but a few unusual purposes. Some hydrologists think the salty water is a remainder of sea water that moved into the aquifer thousands of years ago when the sea stood higher than today.

ing wet seasons, it ordinarily cannot be stored in a confined aquifer for withdrawal during subsequent droughts.

Chemical Quality of Ground Water

At times in the geologic past the sea has stood much higher than it stands today. At those times, the salty water of the sea, under the thrust of the sea's stronger pressure, moved considerable distances into the aquifer. Some ground-water hydrologists believe that it is a consequence of this ancient invasion that the artesian water is now salty over much of Florida (see fig. 19). Since the sea was last high, possibly 10,000 to 20,000 years ago, the seaward circulation of fresh water has been gradually flushing the salty water out. Eventually the artesian water may become fresh almost everywhere, but that is too far in the future to be of much interest to us.

Over most of the State deep wells drilled for oil have penetrated very salty water, some of it much saltier than the sea, at depths of several thousand feet. We infer from this that such water may occur everywhere beneath the State, but our information is too scanty for us to be sure. Wherever it does occur, the salty water menaces the fresh artesian water that lies above, for unwise

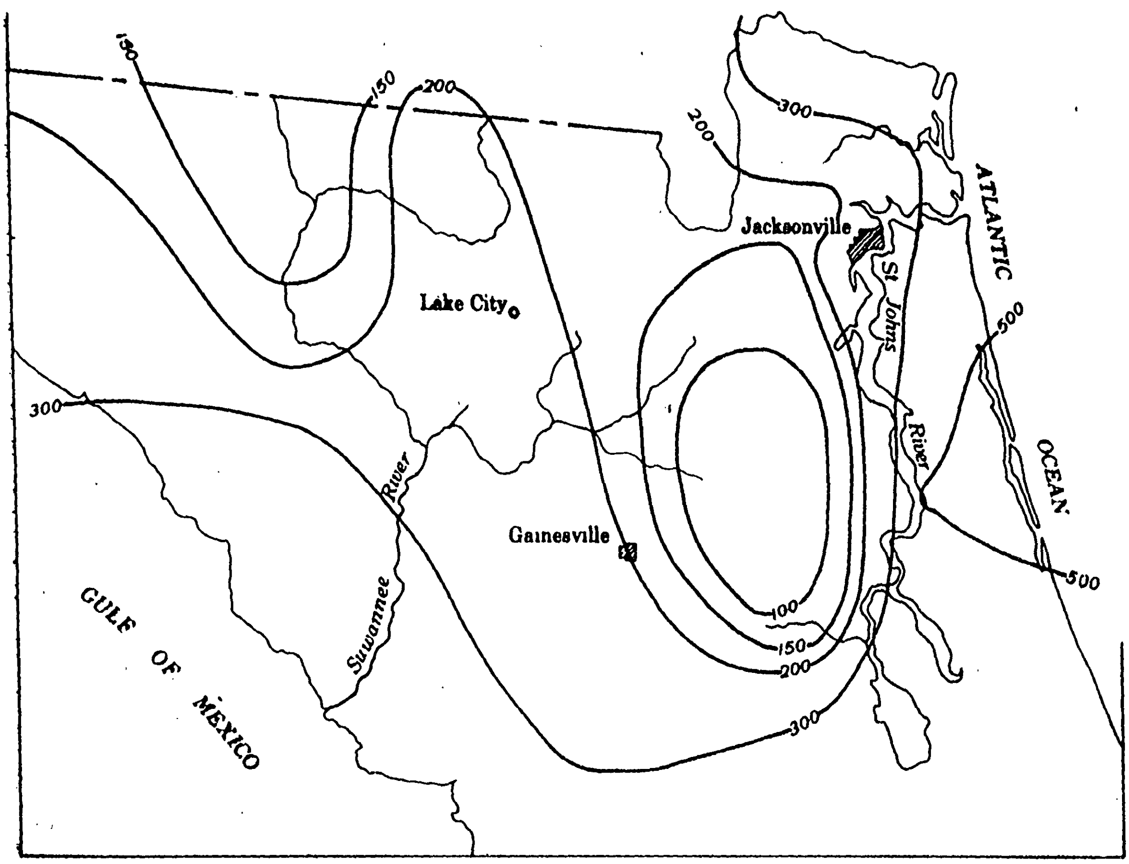


FIGURE 20.—Hardness of water from upper part of the Floridan aquifer.

Lines connect points of equal hardness, in parts per million.

development might cause the salty water to move up and contaminate the fresh-water resource.

The hardness of the artesian water varies considerably from one place to another (see fig. 20). It is less than 100 parts per million in an area west of Gainesville, where recharge enters the aquifer through sinkholes, but increases progressively as the water moves away from this area. The hardness is derived mainly by solution of the limestone and dolomite that make up the Floridan aquifer. As the water enters the aquifer, it is quite soft but contains carbon dioxide and organic acids that enable it to dissolve the rocks more readily. During its long journey from the area of recharge, always in intimate contact with the rocks, the water picks up several hundred parts per million of hardness.

Where the artesian water is too salty for use, the shallow ground water and the streams, lakes, and ponds constitute the principal sources of supply. In some such areas, as around Miami, the shallow aquifers are highly productive and will very likely supply the local needs for many years to come. On the other hand, in areas such as those along the middle east coast, the shallow formations and surface sources do not yield an adequate supply, and eventually the municipalities must pipe water from sources in adjoining areas to supply their steadily growing requirements.

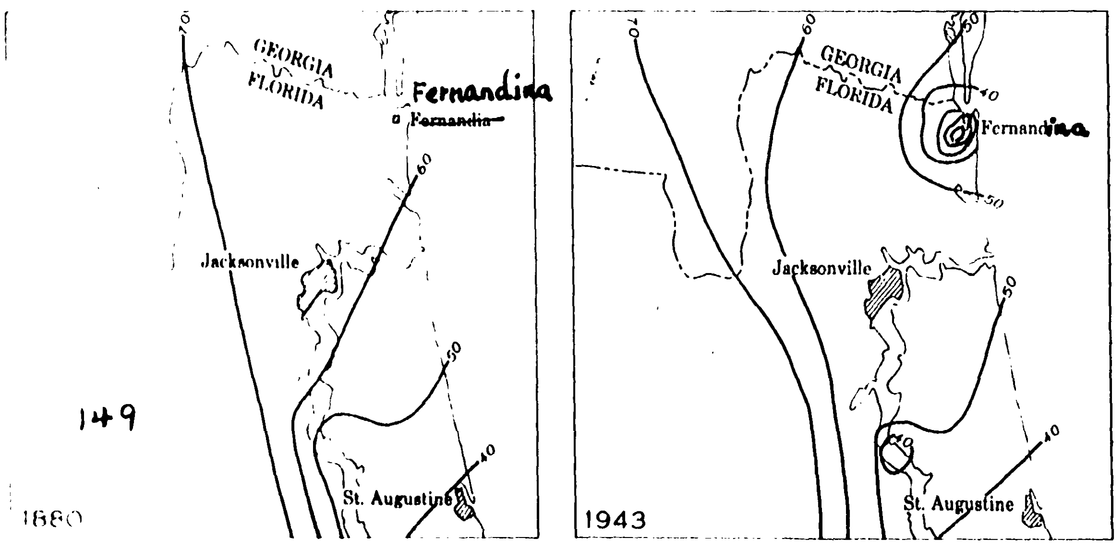


FIGURE 21.—Artesian pressures have diminished at Jacksonville.

Lines connect points of equal artesian head, in feet above sea level. When the first wells were drilled, about 1880, the artesian pressure in the vicinity of Jacksonville was sufficient to raise water 60 feet above sea level (map at left). Now, owing to a draft of 80 mgd, the pressure is substantially less (map at right). Large additional supplies of artesian water may be developed, but at the cost of a further decrease in pressure.

Current Draft of Water Has Made Only Minor Subtractions From the Total Supply

Considered as a whole, the available supply of artesian water is scarcely touched by current draft. It is only in certain localities that the demands for water are approaching the capacity of the aquifer to supply it.

For example, about 100 million gallons a day is currently being drawn from wells in the vicinity of Jacksonville for municipal and industrial uses. As indicated in figure 21, this draft has caused substantial lessening of artesian pressures, especially around the town of Fernandina, north of Jacksonville. The decline of water levels does not, however, indicate a depletion of the reserve, as it would in some other areas. It merely indicates that the aquifer lacks sufficient capacity for transmitting water from the area of recharge. Around Jacksonville the aquifer is confined and is functioning principally as a conduit rather than a reservoir. Just as the size of a pipeline limits the quantity of water that will flow through it, so does the capacity of the aquifer to transmit water—its "transmissibility"—determine the rate of flow of the artesian water. But the rate of flow is determined also by the steepness of the piezometric surface; when the piezometric surface is steepened, water moves through the aquifer more rapidly. Thus, the lessening of artesian pressures in the Jacksonville area, by steepening the piezometric surface, has induced more water to move in from the recharge area. Each time the draft is increased, the pressures will be further lessened and the gradient steepened proportionately. The maximum yield of the wells will have been realized when the draft has grown to the extent that no further lowering is economically feasible. Other factors being equal, the maximum yield will be larger if the wells are distributed over a wide area. Also, more yield may be obtained by drilling wells closer to the recharge area, thereby shortening the distance the water must travel.

It appears unlikely that any alarming consequences will develop from heavy withdrawal in the Jacksonville area, providing wells are not drilled too deep. More likely economic expedience, rather than disastrous experience, will eventually call a halt to further development of the artesian water and motivate the development of a supplemental supply from other sources.

But not everywhere is the outlook so happy. An excessive draft of ground water can be ruinous if it causes encroachment of salt water from the sea. A notable example of the places where salt-water encroachment is becoming acute is the Pinellas County peninsula, on the west coast of Florida. Here, sea water is gradually moving into the aquifer, destroying its worth to the farmers, municipalities, and industries that have grown to rely on it. One by one the wells are beginning to yield water unfit for use. Because of the encroachment, St. Petersburg was forced to develop a new water supply on the mainland as early as 1928, and indications are that the other municipalities of the county must follow suit before many more years. Other places at which salt water has encroached to a greater or lesser extent are Miami, Fort Myers, Fort Pierce, Tampa, Daytona Beach, Panama City, and Pensacola. The encroachment at Tampa forced the abandonment of the old municipal wells about 25 years ago, and since then Tampa has obtained its water from the Hillsborough River. However, available information indicates that an adequate supply of ground water for Tampa may yet be obtained close to the city. The encroachment at Miami was caused, not by pumping of wells, but by drainage operations (Parker, Ferguson, and Love, 1953).

An encroachment of salt water is especially lamentable because its effects are long lasting. Having once established inroads into the aquifer, the salty water will rinse out only very slowly, leaving traces for many years and perhaps for generations after remedial measures are undertaken. Convincing evidence of this is the fact that today, after thousands of years of rinsing, salty water that entered the aquifer during the ancient high seas is yet very much in evidence (fig. 19). It would seem, therefore, that among the various undesirable effects of excessive draft, an encroachment of salt water is the most hurtful. If it is not checked, it may destroy all or a part of an aquifer beyond practical recovery.

In the long run, salt-water encroachment can be avoided, whenever it impends, only by limiting the total draft from wells, but the limit can be raised by artificially recharging the aquifer. If geologic conditions are favorable, artificial recharge might be most effective if applied immediately adjacent to the coast, where it would build up a ground-water "ridge" to act as a barrier to the inland advance of sea water. This approach to the problem probably would be feasible only if the aquifer were underlain by a watertight formation at a reasonable depth. It is therefore important that the geology of the area be understood thoroughly before such remedial measures are undertaken.

As we have already observed, a withdrawal of water from the aquifer may, under favorable conditions, cause an increase in recharge. Another way in which nature adjusts to withdrawal is through a lessening of natural discharge. This process is exemplified by the cessation of flow at Kissengen Spring, near Bartow, formerly one of the large springs of the Florida Peninsula. For several decades Kissengen Spring was a favorite recreational center for out-of-State tourists and for residents of the Bartow area. In February 1950 it became the first of the large artesian springs of Florida to cease flowing completely (fig. 22). The cause of its demise was the increasingly heavy draft from wells in the surrounding region (see fig. 23). Currently, about 110 mgd (million gallons a day) is being drawn from the wells during periods of peak demand, principally for industrial and agricultural uses. Of this amount, about 20 mgd is derived from the capture of the flow of Kissengen Spring. The balance, or 90 mgd, evidently is made up partly from decreases in other discharge, partly from an increase in recharge, and—so long as the water levels continue to decline—partly from a slight reduction in the amount of water stored in the aquifer.

Like the lowering of pressures at Jacksonville, the cessation of the flow of Kissengen Spring reflects the capacity of the aquifer to transmit water from the area of recharge, and does not, in the main, indicate depletion of the resource. The flow will remain arrested as long as the current rate of draft continues, but would resume if, for any reason, the draft were curtailed sufficiently.

The large supplies of unappropriated artesian water in the area of recharge will doubtless play a prominent part in Florida's future development. They beckon to industries that must settle where large supplies can be had—industries whose thirsts can be satis-

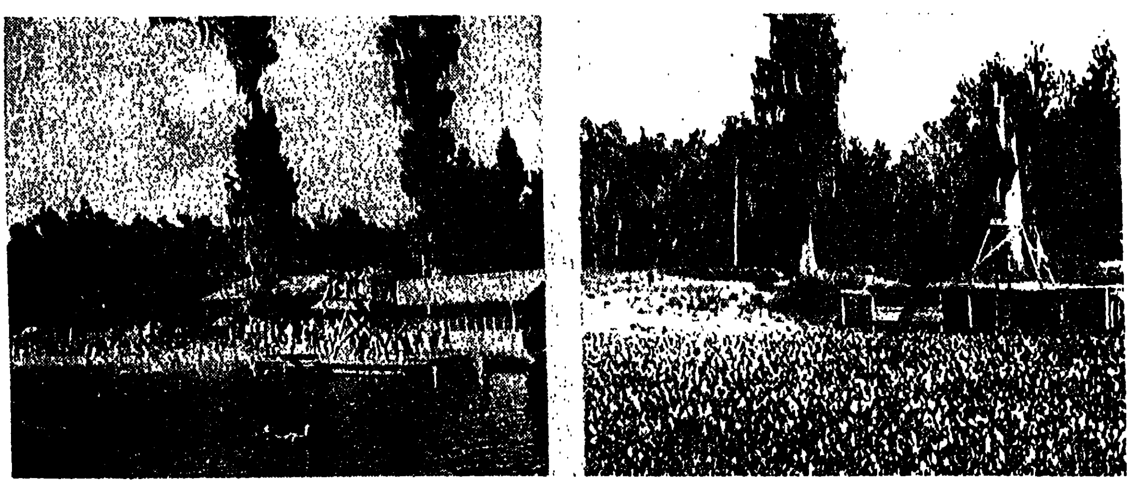


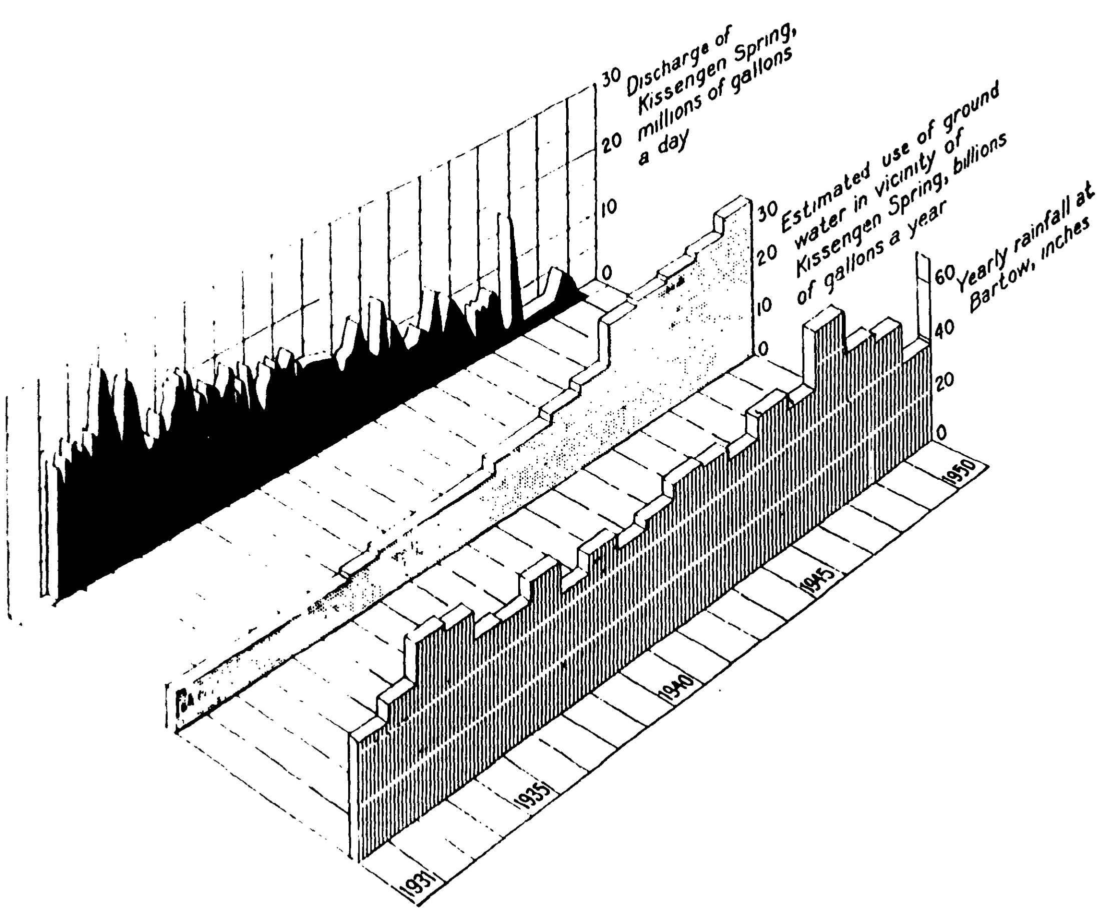
FIGURE 22.—A large spring ceases to flow.

Only a few years ago Kissengen Spring, near Bartow, was a well-known recreation center. Today it is a hyacinth-covered stagnant pool. **(See p. 37)**

fied only by drafts of tens of millions of gallons a day. If the trends of the past decade continue as they doubtless will, we may expect an accelerating influx of these industries into the State. Moreover, as the coastal cities grow until their water requirements exceed the local supplies, many will doubtless begin piping water from the recharge areas. Thus, however abundant the ground-water resources may appear today, it seems inevitable that they will eventually be fully appropriated—at least over much of the area.

Studies Needed

Anticipating full development of the artesian water, we should proceed to learn how much water can be claimed and what can be done to increase the water yield. But we have only an inkling of how much water enters the ground and a lesser idea of how much more recharge could be induced by pumping and by artificial recharge. We cannot obtain a reliable estimate of the rate of recharge until there is a more complete accounting of all factors in



FIGUE 23.—Why Kissengen Spring stopped flowing.

From about 1936 to 1950, pumpage of ground water in the region around the spring increased more than fourfold, from about 8 to 34 billion gallons a year (25,000 to 105,000 acre-feet a year). As a result, the artesian pressure diminished until it could no longer sustain the spring flow. There was no lasting deficiency in rainfall that might explain why the spring stopped flowing.

the water budget. We must first know how much water falls on the recharge area, how much runs off in streams, and how much returns to the atmosphere through transpiration and evaporation.

Much of Florida's rain comes in short, intense showers that drench a few square miles at a time while leaving surrounding areas undampened. Consequently, preciptation stations only a few miles apart commonly record substantially different quantities of rain in a given year. Existing stations are much too widely scattered to measure the volume of rainfall. Only when they have been greatly augmented can the gross supply of water in the recharge area be known as accurately as is needed.

We must know how much water runs off various parts of the recharge area. This means that we must gage the flow of many small tributaries. It means also that we must have topographic maps to enable us to define the drainage areas of these tributaries accurately.

Included in some of the larger drainage basins are sizable areas having no surface runoff at all—areas in which all the rainfall not evaporated or transpired filters into the ground. Lacking topographic maps that would enable us to delineate their boundaries, we cannot exclude these areas from the drainage basins of surface streams, although we know they do not contribute to the discharge of the streams. Accordingly, we are defeated in our effort to convert discharge records to meaningful figures representing runoff per unit area.

Another vexing complication is that many surface streams are fed by artesian springs whose water is derived from rain falling in the drainage basins of other streams. Obviously, we must evaluate and isolate the spring flow if we are to compute how much water is generated within a given drainage area. But the task of isolating spring flow will not be simple where the flow occurs in multitudinous vents along the bottoms of stream channels, as, for example, in the Suwannee River. The manner in which considerable quantities of water migrate underground without regard to surface basins has caused some hydrologists to ponder the wisdom of accepting surface basins as the logical hydrologic units in Florida.

The problem that will be the most difficult to solve is that of determining, within permissible limits of error, the amount of evaporation and transpiration from land surfaces. Techniques for estimating these quantities directly where manifold types of vegetation grow in varying densities have not yet been perfected. Until they are, progress can be made by studying selected areas wherein the other factors of the water budget are known. Ordinarily, if we subtract surface runoff from rainfall, we have a remainder consisting partly of ground-water recharge and partly of evapotranspiration, neither of which quantities can be measured. But if we select an area wherein ground-water recharge is known to be very small as compared with the other quantities, the difference between rainfall and runoff will provide an estimate of the evapotranspiration, which estimate can be applied to other areas having similar vegetation and topography to estimate ground-water recharge.

Although we know in general how and where the Floridan aquifer receives recharge, our knowledge is far from being adequate. The delineation of areas of recharge shown in figure 10 is based largely on inference, supported by observation and geologic mapping. An investigation, including extensive test drilling, of the geologic and hydrologic characteristics of the material overlying the aquifer in the areas of recharge must be made before we can have an adequate comprehension of the part that controlled recharge may play in optimum development of the artesian water.

We understand the recharge through sinkholes only in principle. We perceive that where sinkholes occur the piezometric surface stands high, and we infer that a substantial amount of recharge occurs through them. But beyond this we know very little. We wonder if appreciable recharge occurs through most of them or through only a small fraction of their number. Perhaps the gradual accumulation of muck has rendered a large percentage of them ineffective as recharge agents, and perhaps recharge could be increased materially by removing the muck. Studies of a representative number of the sinkholes would enable us to eliminate much of the guesswork from our present concepts.

Most of the wells currently being used for observations of water levels and artesian pressures in Florida are abandoned supply wells owned privately and by municipalities. They are used through the tolerance of the owners. Several valuable records have been interrupted when the owners rightfully elected to restore such wells to their own service. To the hydrologist, who recognizes long-term records as being indispensable to his studies, such interruptions are costly, especially when they terminate long records.

We have only a meager conception of how water moves about within the Floridan aquifer. For the sake of simplicity we have pictured the aquifer as though it were a hydrologic unit, a homogeneous mass of limestone through which water may move with equal ease in any direction, laterally or vertically. Actually its structure is far more complex. The aquifer is composed of layer upon layer of limestones that have different water-transmitting properties. Within some of these layers water moves quite freely, but it moves from one layer to another only very slowly and with considerable loss of pressure head. As a consequence, the artesian pressures vary considerably from one layer to another. Under this condition a single map of the piezometric surface, such as that in figure 17, obviously cannot be truly representative, although it is useful until more complete information is available. Before we can obtain an adequate comprehension of how the artesian water moves from the areas of recharge to areas of discharge, we must map the piezometric surfaces for the individual geologic formations that make up the aquifer. But we cannot do this by measuring water levels in existing supply wells. Such wells generally draw from several layers of limestone, and the water levels in them do not indicate the pressure in any one layer. To do the mapping will require numerous observation wells drilled under the control of trained hydrologists.

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Note added while in press:

From A. O. Patterson, District Engineer, Surface Water Branch, U. S. Geological Survey, Ocala, the following data was received February 1, 1954: "On January 13, 1954, a discharge measurement was made of Kissengen Springs and it was flowing 3.55 second-feet. This is the first time it has been found flowing since it stopped several years ago".