STATE OF FLORIDA
DEPARTMENT OF NATURAL RESOURCES
Harmon Shields, *Executive Director*

DIVISION OF RESOURCE MANAGEMENT
Charles M. Sanders, *Director*

BUREAU OF GEOLOGY
Charles W. Hendry, Jr., *Chief*

REPORT OF INVESTIGATIONS NO. 72

# HYDROLOGIC CONCEPTS OF ARTIFICIALLY RECHARGING THE FLORIDAN AQUIFER IN EASTERN ORANGE COUNTY, FLORIDA— A FEASIBILITY STUDY

By
Darwin D. Knochenmus

Prepared by
UNITED STATES GEOLOGICAL SURVEY
in cooperation with the
BUREAU OF GEOLOGY
FLORIDA DEPARTMENT OF NATURAL RESOURCES
and the
CENTRAL AND SOUTHERN FLORIDA FLOOD CONTROL DISTRICT

Tallahassee, Florida
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**DEPARTMENT**
**OF**
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# LETTER OF TRANSMITTAL

Bureau of Geology
Tallahassee
August 28, 1975

Governor Reubin O'D. Askew, Chairman
Florida Department of Natural Resources
Tallahassee, FL 32304

Dear Governor Askew:

The Bureau of Geology of the Division of Resource Management, Florida Department of Natural Resources, is publishing as its Report of Investigations No. 72, a study, "Hydrologic Concepts of Artificially Recharging the Floridan Aquifer in Eastern Orange County, Florida—A Feasibility Study", by Darwin D. Knochenmus, of the U. S. Geological Survey.

Artificial recharge of the Floridan Aquifer is a most important water management tool in that it captures rainfall that otherwise would run off or be lost by evapotranspiration. This means of increasing the amount of water in storage and available for development from the Aquifer is one that will be looked at in substantially more detail in many areas of the State of Florida in the near future.

Respectfully yours,

Charles W. Hendry, Jr., *Chief*
Bureau of Geology

Completed manuscript received
May 7, 1975
Printed for the
Florida Department of Natural Resources
Division of Resource Management
Bureau of Geology

Tallahassee
1975

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# HYDROLOGIC CONCEPTS OF ARTIFICIALLY RECHARGING THE FLORIDAN AQUIFER IN EASTERN ORANGE COUNTY, FLORIDA— A FEASIBILITY STUDY

By
Darwin D. Knochenmus

## ABSTRACT

Artificial recharge in eastern Orange County is worth consideration. The hydrologic system is suitable for gravity flow through a network of connector wells to recharge the Floridan aquifer from the nonartesian aquifer. Also, the Floridan aquifer needs the additional fresh water to prevent migration of brackish water into the area as rates of withdrawal are increased.

The hydrologic system cycles about 55 inches of rainfall per year of which 10 to 15 inches runs off, 40 to 45 inches evapotranspires, and 0 to 2 inches recharges the Floridan aquifer. The hydrogeologic framework consists of a nonartesian aquifer that is separated from the underlying Floridan aquifer by a confining layer. The water table in the nonartesian aquifer is near land surface and as much as 30 feet above the altitude of the potentiometric surface of the Floridan aquifer. Dissolved-solids concentration of water in the nonartesian aquifer is less than that of the water in the Floridan.

The supply of water for artificially recharging the Floridan through a network of connector wells that also tap the nonartesian aquifer could be derived from the capture of potential water losses — evapotranspiration and runoff. This recharge water would be replaced in the nonartesian aquifer by the capture of rainfall that otherwise would run off or be lost to evapotranspiration. However, the water table must be lowered before capture can occur.

Systematically lowering the water table requires a network of connector wells. The spacing of the wells in the network depends on the transmissivity of the nonartesian aquifer, the available drawdown in the connector well, the well radius, and the capture-drawdown function. The average thickness of the nonartesian aquifer is 50 feet and its average transmissivity is estimated to be between 125 and 625 $ft^2$ per day (feet squared per day). The capture rate is estimated to be between 0.5 and 1.5 feet per year with an effective drawdown between 5 and 10 feet. The well spacing for a network of fully penetrating 6-inch connector wells would be 2,220 feet for an aquifer having a transmissivity of 625 $ft^2$ per day, a capture rate of 0.5 foot per year, and an effective drawdown of 5 feet. A higher capture rate would require additional wells and closer spacing.

The relation between the amount of capture and amount of drawdown, presently unknown, is a critical parameter in the analysis of connector-well recharge. An investigation of the capture-drawdown function in eastern Orange County would appear to be a logical step to provide the needed data.

# INTRODUCTION

## PURPOSE AND SCOPE

The largest dependable source of water in central Florida is the Floridan aquifer. Its water quality grades from fresh in the central region to brackish near the coast. The occurence of brackish water has forced coastal cities to find other less dependable sources such as lakes or shallow ground water. The city of Cocoa, in order to obtain a dependable source of water, drilled their public supply wells 25 miles inland where the aquifer contains fresh water.

In that part of east-central Florida where the water in the Floridan aquifer changes in quality from fresh to brackish, the terrain is swampy and of low relief. Potential ground-water recharge in this water-logged area is lost by surface runoff and evapotranspiration. If these water losses could be reduced and that water used to artificially recharge the aquifer, the transitional zone would be displaced toward the coast and greater amounts of fresh water could be withdrawn. With the availability of greater amounts of fresh water, coastal cities would not have to drill new wells farther and farther inland to satisfy growing demands, and legal conflicts between local governments over water rights would be reduced.

The purpose of this report is to present the hydrologic concepts involved in artificially recharging the Floridan aquifer through connector wells by gravity flow and to formulate and evaluate models of various connector-well networks.

The investigation was limited to eastern Orange County. an area whose general hydrology is known from previous investigations. There, a 1-year feasibility study need be concerned primarily with assembling and analyzing all readily available hydrologic and geologic information as it relates to artificial recharge. Eastern Orange County is considered an appropriate study area also because it is experiencing water problems associated with increased withdrawals from the Floridan aquifer. The dearth of geologic information on near-surface deposits made it necessary to drill some shallow test holes. Twelve test holes were drilled and about 100 cores were taken for laboratory analyses of aquifer characteristics.

The specific objectives of this investigation were to determine the quantity, quality, source and areal extent of water lost from the area by surface runoff and evapotranspiration; the quantity, quality and areal extent of water in the surficial sediments; the quantity of water that might be available for recharge; the means of inducing recharge; the areas most hydrologically favorable for construction of recharge works; and the probability of recharge water remaining in storage as a discrete volume for future recovery.

The feasibility study in eastern Orange County should have transfer value to other coastal areas in east-central Florida because many have similiar hydrologic systems and are in need of increasing their supply of fresh water.

## ACKNOWLEDGMENTS

This report was prepared by the U. S. Geological Survey in cooperation with the Central and Southern Florida Flood Control District. The investigation was under the direct supervision of Joel O. Kimrey, Chief, Winter Park Subdistrict and general supervision of Clyde S. Conover, District Chief, Water Resources Division, U. S. Geological Survey.

Personnel of the U. S. Geological Survey who contributed significantly to the project were: Peter Bush, hydraulic engineer, James Holly, engineering technician, who provided assistance during the test drilling program, Hilton Cooper, research engineer, and Stavros S. Papadopulos, research hydrologist, who provided valuable assistance in formulating and evaluating the mathematical models of the aquifer system.

To all who contributed to the project, the author expresses his sincere appreciation.

## GEOGRAPHY

### LOCATION

The study area encompasses about 300 square miles between latitude 28° 20′ and 28°40′ and longitude 81°00′ and 81°15′ in eastern Orange County. This area lies east of Orlando and west of the St. Johns River (fig. 1.) There is very little development in the eastern part of the county except in the northern sector along State Highway 50 where small businesses and subdivisions are spreading eastward from Orlando. Most of the area is in pine woods and cypress heads where major land use is forestry and natural pasture. A few sections in the vicinity of Wewahootee Road and Econlockhatchee River have recently been developed for grain farming and citrus. In this same general area the city of Cocoa has a well field for their municipal supply (fig. 1).

### CLIMATE

Orange County is in the north-central climatic division of Florida as segmented by the Environmental Data Service for the collection of climatic records. Complete temperature and rainfall records are collected at the Orlando station and supplementary rainfall records are collected at Bithlo and Hart Lake.

The area has a subtropical climate; its average annual temerature is 22°C (71°F) and its average rainfall is slightly more than 51 inches. These averages are computed from long-term records for the normal climatic period (1931-60) at Orlando. Eastern Orange County may have slightly more rainfall than Orlando as is suggested from a comparison with shorter-term records at Bithlo.

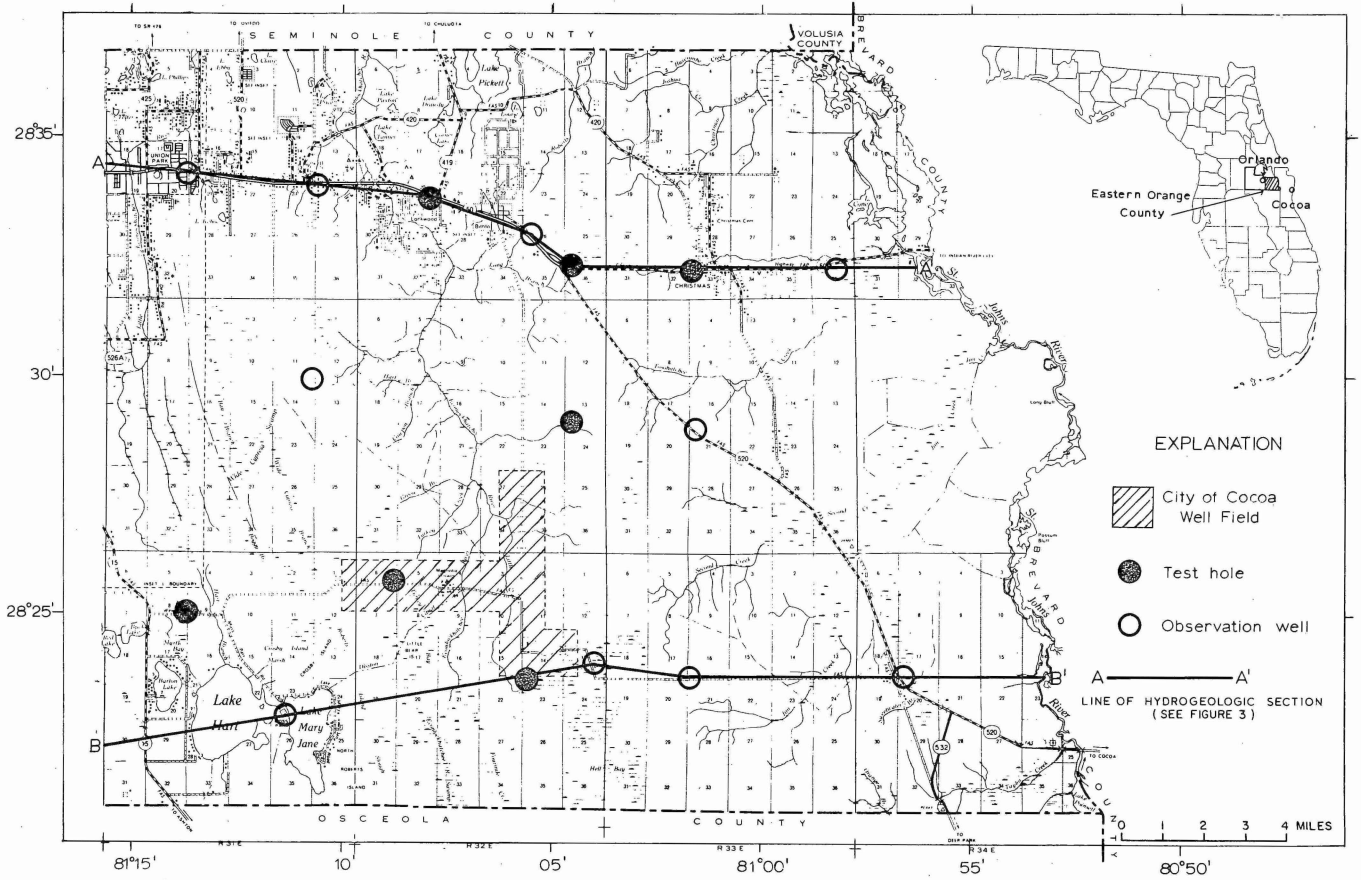



**Figure 1.—Location map of eastern Orange County.**

Records have been collected at Bithlo for the last 12 years (1960-71) and during that time annual rainfall has averaged about 4 inches more than at Orlando. For the same 12 years, the average annual rainfall at Orlando has been equal to the long-term average of 51 inches.

Rain on the area is not distributed equally with time. About 60 percent falls in June, July, August, and September, at an average rate of 7-8 inches per month.

## TOPOGRAPHY

Eastern Orange County was included in the Coastal Lowlands division of Cooke's (1939) generalized physiographic description of Florida. Puri and Vernon (1964), while describing the landforms of Florida in greater detail, called the section of the Coastal Lowlands that includes most of eastern Orange County, the Osceola Plain. It extends from the central highlands eastward to the coastal lowlands. The study area is wholly within the Osceola Plain except for a small part along the St. Johns River that is in the Eastern Valley (fig. 2).

This gently sloping plain is highest, just over 90 feet above msl (mean sea level), along a north-south line of rolling hills which form a drainage divide between the Little Econlockhatchee and Econlockhatchee Rivers. From the divide the land slopes westward to an altitude of 40 feet in the Little Econlockhatchee River valley and eastward to an altitude of 30 feet in the Econlockhatchee River valley. The divide between the Econlockhatchee drainage and the St. Johns River basin is a flat plain with altitudes just over 75 feet.

The landforms, such as the gently rolling hills, the sloping plains, the river valleys and the escarpment separating the Osceola Plain from the Eastern Valley are all aligned parallel to the Atlantic Coast suggesting a coast-related origin.

## DRAINAGE

The principal form of drainage is by surface streams, but due to a poorly developed system the area is wet and swampy much of the time. The most poorly developed part of the drainage system, and therefore the wettest, is along the broad basin divides. The St. Johns River forms the east boundary of Orange County and 45 percent of the study area drains eastward through small tributaries directly into the St. Johns. Thirty percent—in the middle of the study area—drains to the north by the Econlockhatchee River. The northwestern section—14 percent—is drained to the north by the Little Econlockhatchee River and the southwestern section—11 percent—to the south by the headwaters of the Kissimmee River (fig. 2),

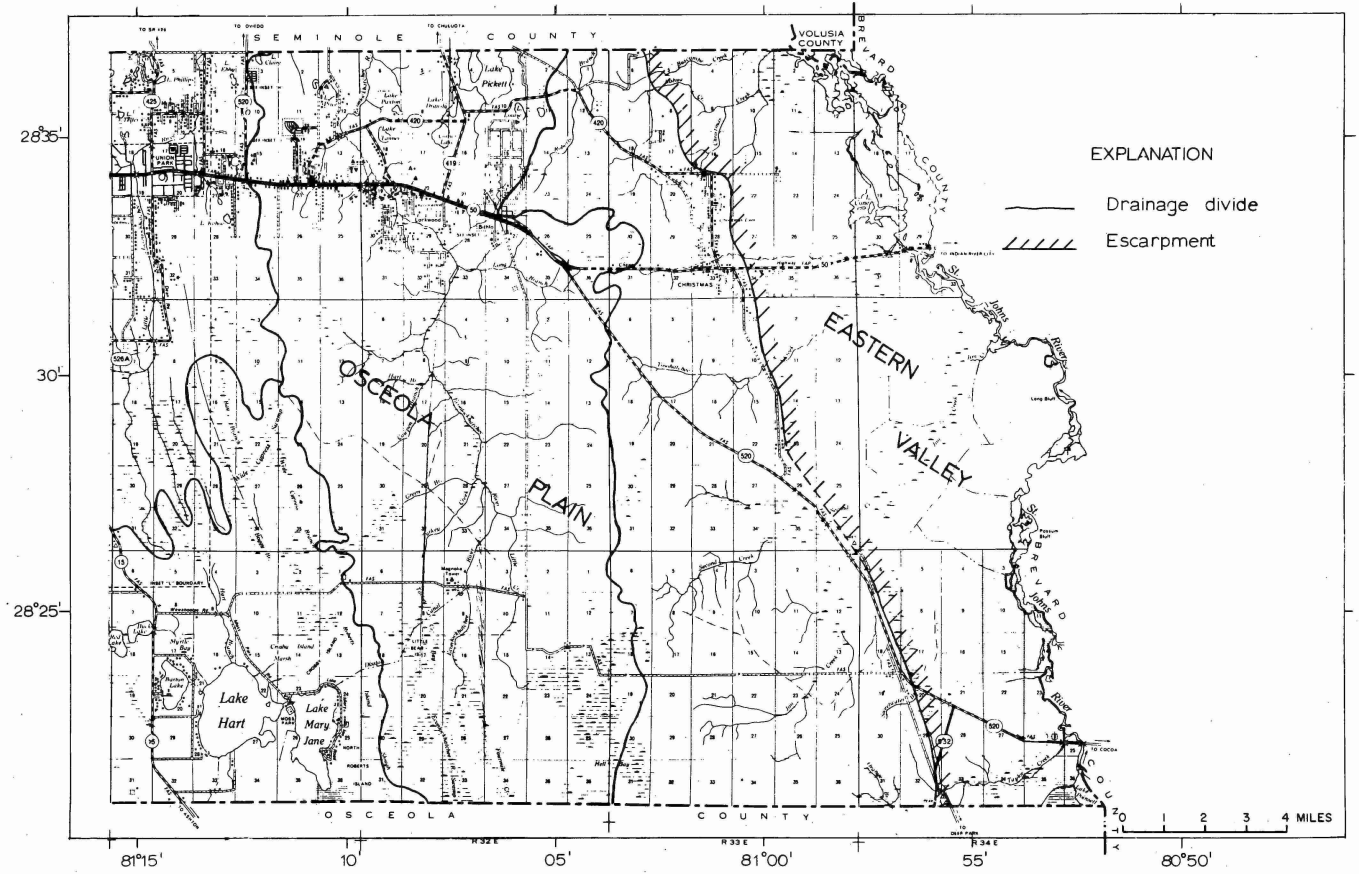



**Figure 2.—Map showing drainage basin boundaries and physiographic divisions.**

The Osceola Plain is dissected in varying degree by these four drainage systems. The small tributaries to the St. Johns River flow through the eastern edge of the Osceola Plain, cut through the escarpment and debouch into the swamps of the Eastern Valley. The valleys of the Econlockhatchee and Little Econlockhatchee Rivers become more dissected near the north edge of the county as the streams flow northward out of swamps in the south. Dissection is least where the headwaters of the Kissimmee consist of north trending elongate swamps separated by slightly raised knobs of land.

## HYDROLOGIC SYSTEM

### HYDROGEOLOGIC FRAMEWORK

The hydrogeology in eastern Orange County is simple. The groundwater system consists of a nonartesian aquifer lying above the Floridan aquifer but separated from it by a thick confining layer (fig. 3). Within the confining layer are discontinuous shell beds, sand lenses and limestone layers which form secondary artesian aquifers. The hydrogeologic sections on figure 3 were adapted from the geologic sections of Lichtler and others (1968, fig. 6).

The nonartesian aquifer extends throughout the area and ranges in thickness from 40 to 80 feet. At land surface the aquifer material is a fine sand which becomes progressively finer grained with depth until the material is predominantly clay at which point it is appropriately classified as a confining bed. Generally at depths below 20 feet the aquifer contains layers which consist partly, or in some cases, entirely of shells. The layers that consist predominantly of shells have the greatest permeability of any of the material in the nonartesian aquifer. Permeability is a measure of the ease with which a porous medium can transmit a fluid—in this case water. The sand in the upper part of the aquifer is the second most permeable material, after which the permeability decreases with depth as the clay content increases. The geologic age of the materials comprising the nonartesian aquifer ranges from Holocene to upper Miocene (Lichtler, 1968).

Except under the areas of greatest relief and highest altitude, the water table in the nonartesian aquifer is generally within 5 feet of the land surface and fluctuates within this range (fig. 4). This high water table in combination with the flat terrain creates a very wet and swampy area.

Water-level declines are small and primarily the result of evapotranspiration as surface drainage is not greatly incised, and downward leakage is considerably negligible.

The confining layer that separates the nonartesian aquifer from the Floridan aquifer ranges in thickness from 60 to 300 feet (fig. 3). It is composed

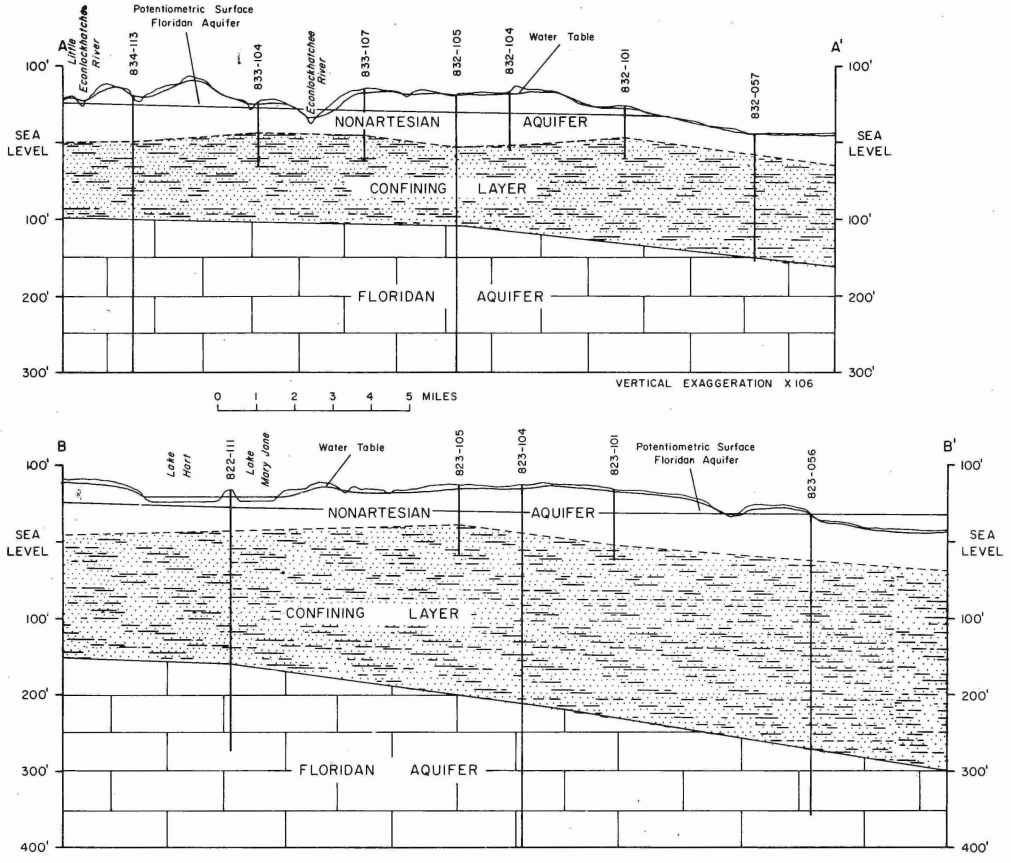
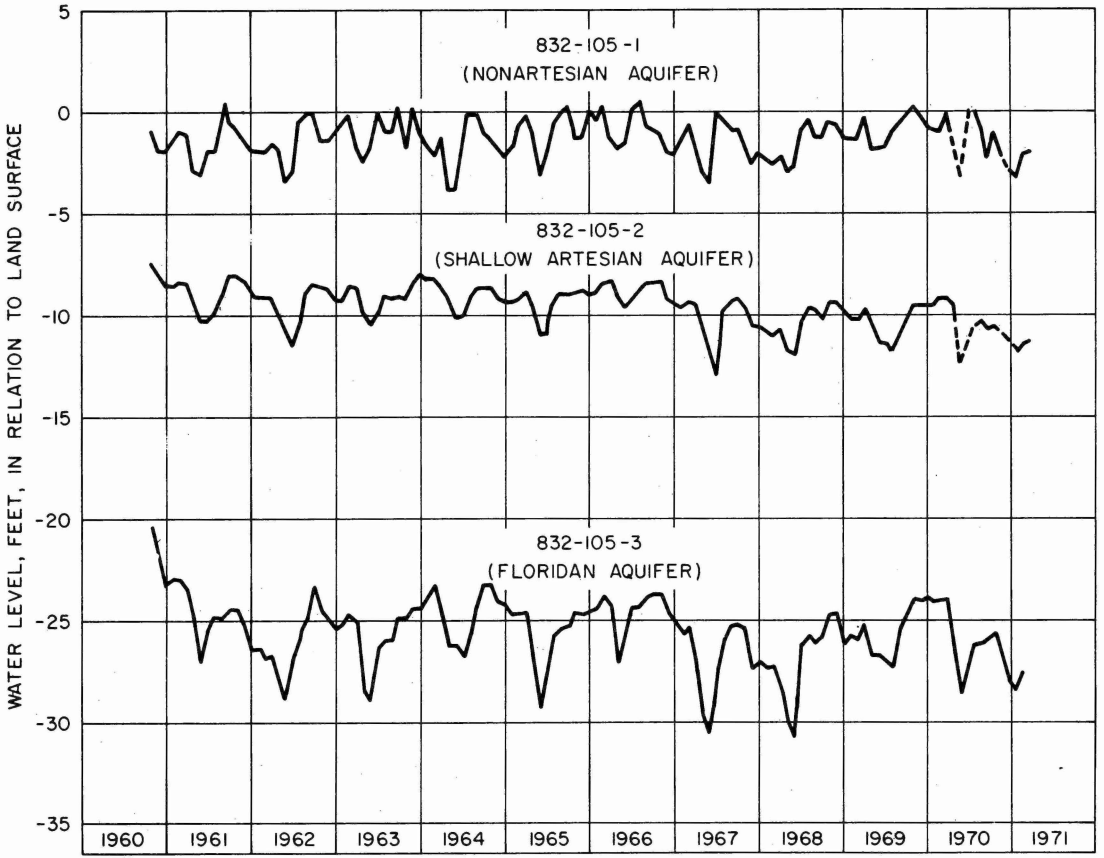



**Figure 3.—Hydrogeologic sections across eastern Orange County.**

principally of a mixture of sand, shell and clay, all of the Hawthorn Formation of Miocene age. Where the sand and shell constitute discrete strata within the confining layer they yield water to wells. These strata are referred to collectively as the secondary artesian aquifers. One such shell bed is 25 feet thick. The finer-grained strata of the confining layer and of the material above it retard the downward movement of water from the nonartesian aquifer to the Floridan. In the artesian-flow area along the St. Johns River the confining layer retards the upward movement of water from the Floridan aquifer.

The contact between the nonartesian aquifer and the confining layer is transitional: the beds become finer grained with depth. Thus the placement of the contact on figure 3 was arbitrarily selected, depending upon the degree of fine-grained material. The lower contact, that with the Floridan aquifer, is placed at the top of the Eocene limestones. In a few places 5 to 10 feet of




**Figue 4.—Hydrographs of wells tapping the nonartesian, shallow artesian and Floridan aquifer near Bithlo.**

limestone at the base of the Hawthorn Formation is hydraulically part of the Floridan aquifer.

The potentiometric level of the secondary artesian aquifer fluctuates slightly less than 5 feet, similiar to the magnitude of the fluctuation in the nonartesian aquifer (fig. 4). Response of the potentiometric surface to rainfall is less rapid than the response of the water table but in general, both rise and decline similarly during wet and dry seasons.

The Floridan aquifer is the principal aquifer in the area, both in its hydraulic capability and areal extent. It is highly permeable and large wells may yield as much as 4,000 gpm (gallons per minute). The aquifer consists of nearly 2,000 feet of dolomitic limestone of Eocene age (Lichtler and others, 1968). Solutional processes in this limestone have produced a highly cavernous aquifer having a high secondary permeability. Solution of the carbonate minerals has not been uniform throughout the aquifer and in central Orange County two major producing zones, 150 to 600 feet and 1,100 to 1,500 feet, separated by a less permeable zone, have been mapped. In eastern Orange County, most wells penetrate only the upper producing zone as the lower zone contains brackish water. In water samples from a 1,350-foot salinity monitoring well of the city of Cocoa, chloride concentration has been as high as 1,400 milligrams per liter.

The depth to the top of the Floridan aquifer ranges from 100 to 350 feet (fig. 5). Near the Seminole County line the overburden is about 100 feet thick and increases to its maximum thickness in the southeast part of the area. This increasing depth to the top of the aquifer corresponds to the increasing thickness of the confining layer.

The Floridan aquifer is artesian; thus water in the aquifer is under artesian pressure and its potentiometric surface is above the top of the aquifer. (The level to which the water will rise in a tightly cased well open to the aquifer constitutes its potentiometric surface). The potentiometric surface of the Floridan aquifer fluctuates about 10 feet (fig. 4) or about twice the magnitude of fluctuation of the potentiometric surface of the nonartesian aquifer. The altitude of the potentiometric surface of the Floridan is highest on the west side of the area and the surface slopes toward the St. Johns River (fig. 6.) The general slope of the land surface is greater than the slope of the potentiometric surface, thus the potentiometric surface intersects land surface along the escarpment of the Osceola Plain (fig. 2) and rises above it toward the St. Johns River. Therefore, the area east of the escarpment is one of artesian flow. (fig. 6).

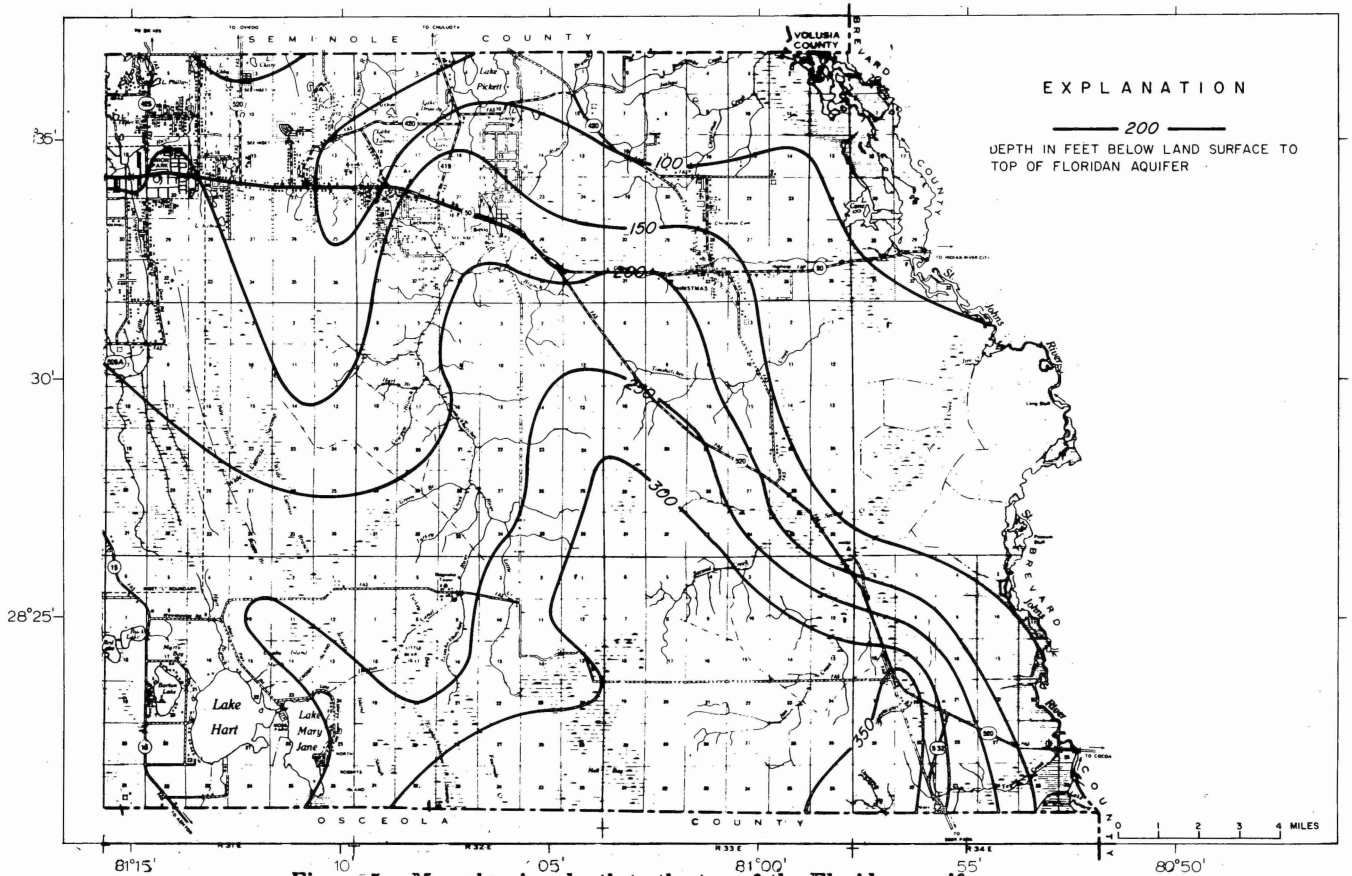



**Figure 5.—Map showing depth to the top of the Floridan aquifer.**

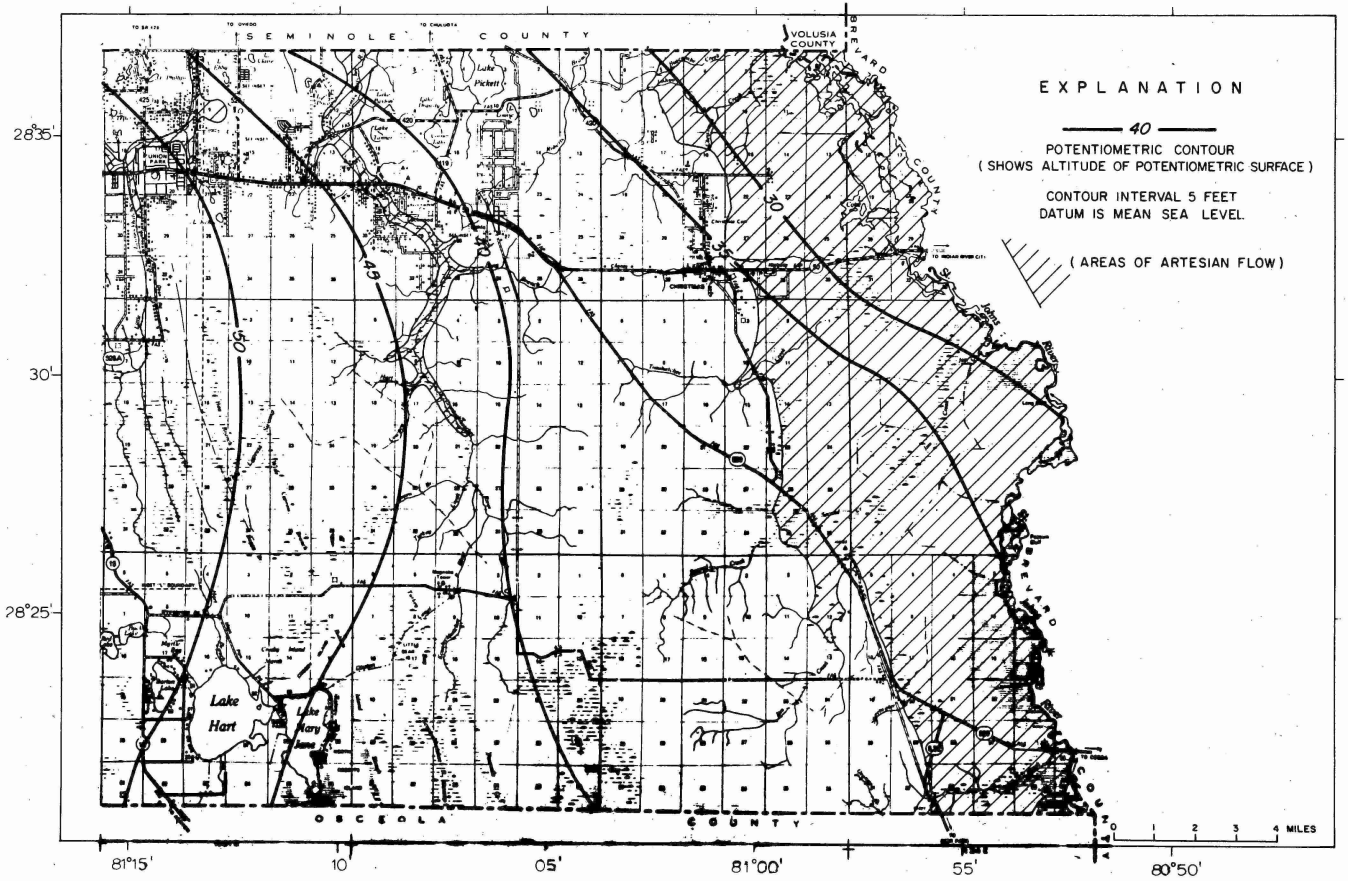



**Figure 6.—Potentiometric map of the Floridan aquifer at normal conditions, July 1961.**

## HYDROLOGY OF SURFICIAL WATER

### RAINFALL

In this report, surficial water means water that occurs at or near the land surface. It includes rainfall, water lost from the area by runoff and evapotranspiration, water stored on the land surface, and shallow ground water.

Most of the surficial water in eastern Orange County is derived directly from rainfall. Minor amounts are derived from streamflow in the St. Johns River and surface inflow from the Econlockhatchee River swamp in Osceola County. It is estimated that the average annual rainfall in the eastern part of the county is about 55 inches, slightly more than at Orlando.

The path water follows after it has fallen as rain is very dependent upon antecedent moisture conditions. If enough rain has fallen so that the water table is at the land surface, rain is stored on the land surface in swamps from which it evaporates or runs off overland. After a dry period when the water table is several feet below the land surface, rain will infiltrate the land surface and be stored in the nonartesian aquifer from which it evaporates, transpires, or discharges to streams as base flow. The rate at which water is lost from the area through evapotranspiration is much greater when water is stored on the surface than when it is stored in the subsurface.

### EVAPOTRANSPIRATION

The greatest loss of water from the area is through evapotranspiration. It is estimated that 70 percent of rainfall on Orange County (36 inches per year) is returned to the atmosphere (Lichtler and others, 1968). In the eastern part of the county where wetlands and a high water table prevail, evapotranspiration is believed to be slightly more than 70 percent, or from 40 to 45 inches per year.

### RUNOFF

The second largest water loss occurs through surface runoff which has been estimated by Anderson (Lichtler and others, 1968) at 10 inches per year for Econlockhatchee and Little Econlockhatchee River basins. The 10 inches of runoff represents an average value for the entire basin. It is estimated that as much as 15 inches per year runs off areas adjacent to streams where secondary and tertiary drainage lines have developed. Runoff is much less from interbasin areas (basin divides) where little or no drainage lines have developed. Less runoff from interbasin areas is also inferred from the fact that these are also the wet and swampy areas where water remains on the surface until it evaporates.

The average annual water loss from evapotranspiration plus surface runoff is probably nearly uniform throughout the area: areas having lower rates

of surface runoff have higher rates of evaporation. The areal distribution of water losses in percent of rainfall is shown in figure 7.

### INFILTRATION AND AQUIFER STORAGE

The infiltration capacity of the surficial sand is as high as 3.5 inches per hour (Powell and Lewis in Lichtler and others, 1968). This rate will accommodate most rain intensities and probably could be sustained except for aquifer storage limitations. The water table does not decline much more than 5 feet below land surface and less than that in some periods (fig. 4). Normally the water table would be only 2 to 3 feet below land surface. Three feet of unsaturated aquifer would hold about 10 inches of water. This amount of water falls in a normal 45-day period during the wet summer season.

At the beginning of the wet season the nonartesian aquifer is quickly recharged to capacity and then begins to reject recharge. Between rains and during dry season, water is discharged from the nonartesian aquifer to supply evapotranspiration and base flow streams. In most places a little water percolated downward through the nonartesian aquifer and confining layer to recharge the underlying Floridan aquifer. This recharge probably amounts to less than 3 percent of annual rainfall.

## WATER QUALITY

In a general way the water in the hydrologic system increases in dissolved-solids concentration with depth. The water in the Floridan aquifer also increases in dissolved-solids concentration toward the east; that is, to the St. Johns River (fig. 8).

Surface water, in the upper part of the hydrologic system, contains the smallest quantity of dissolved solids. It is generally soft, somewhat acidic, highly colored, and each dissolved constituent is low in concentration. This discussion does not pertain to the St. Johns River, for the river includes water from other hydrologic systems outside the area. Summaries of the chemical analyses of water from Econlockhatchee and Little Econlockhatchee Rivers are given in table 1. Even though surface water is low in dissolved-solids concentration, its range in concentration is greater than in the nonartesian aquifer. This greater range in water in streams is related to the flow characteristics of the streams. During high flow, the water in streams is derived predominantly from overland flow. In chemical character it is similar to rainfall but its quality is slightly inferior because as the water flows over the land surface it picks up dissolved and suspended material. The organic matter included in the suspended material forms complexes which color the water. At low flow or base flow the water in the streams is derived from the nonartesian aquifer and its dissolved-solids concentration is greater than during high flow.

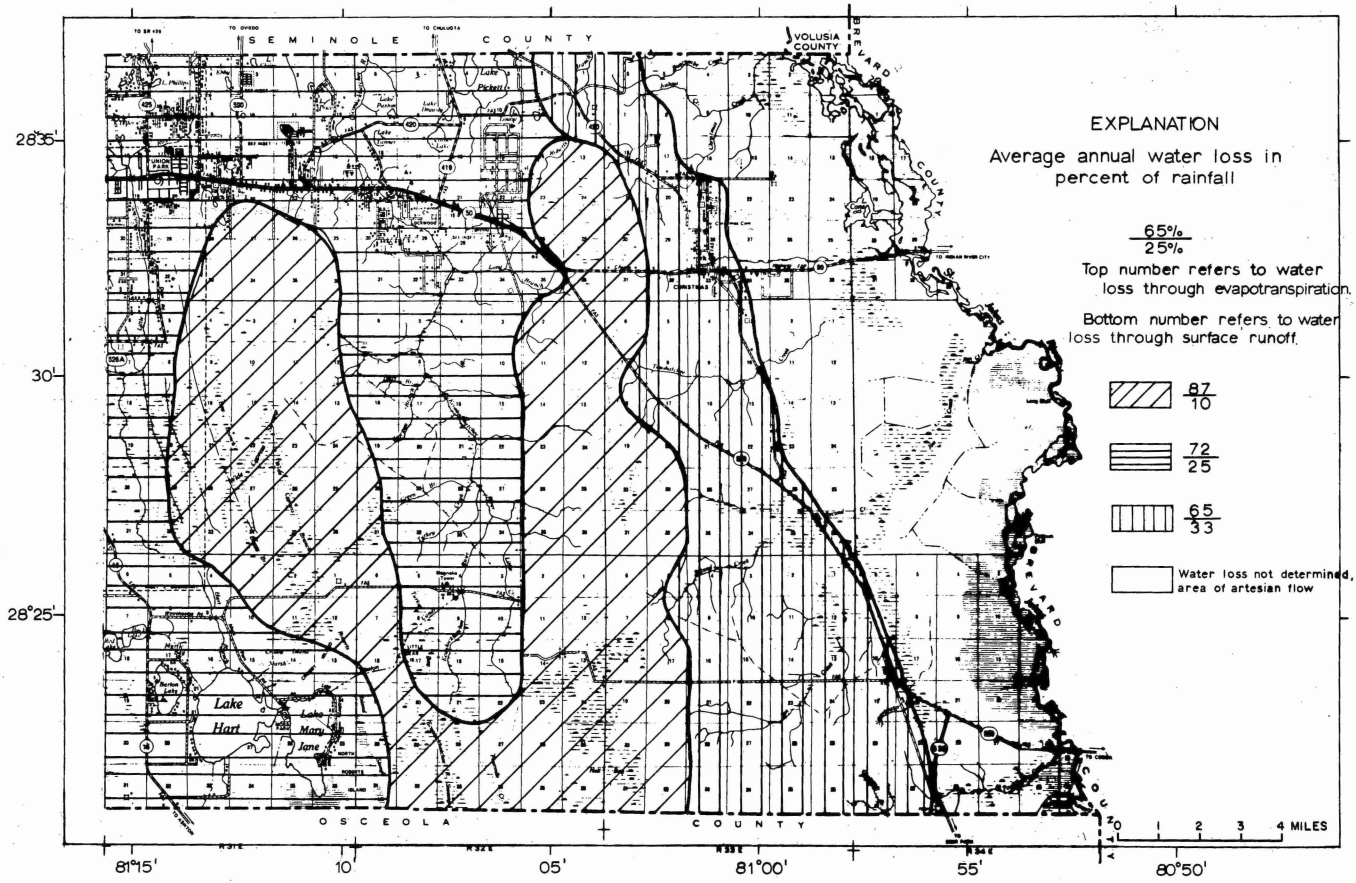



**Figure 7.—Map showing areal distribution of average annual water losses through evapotranspiration and runoff.**

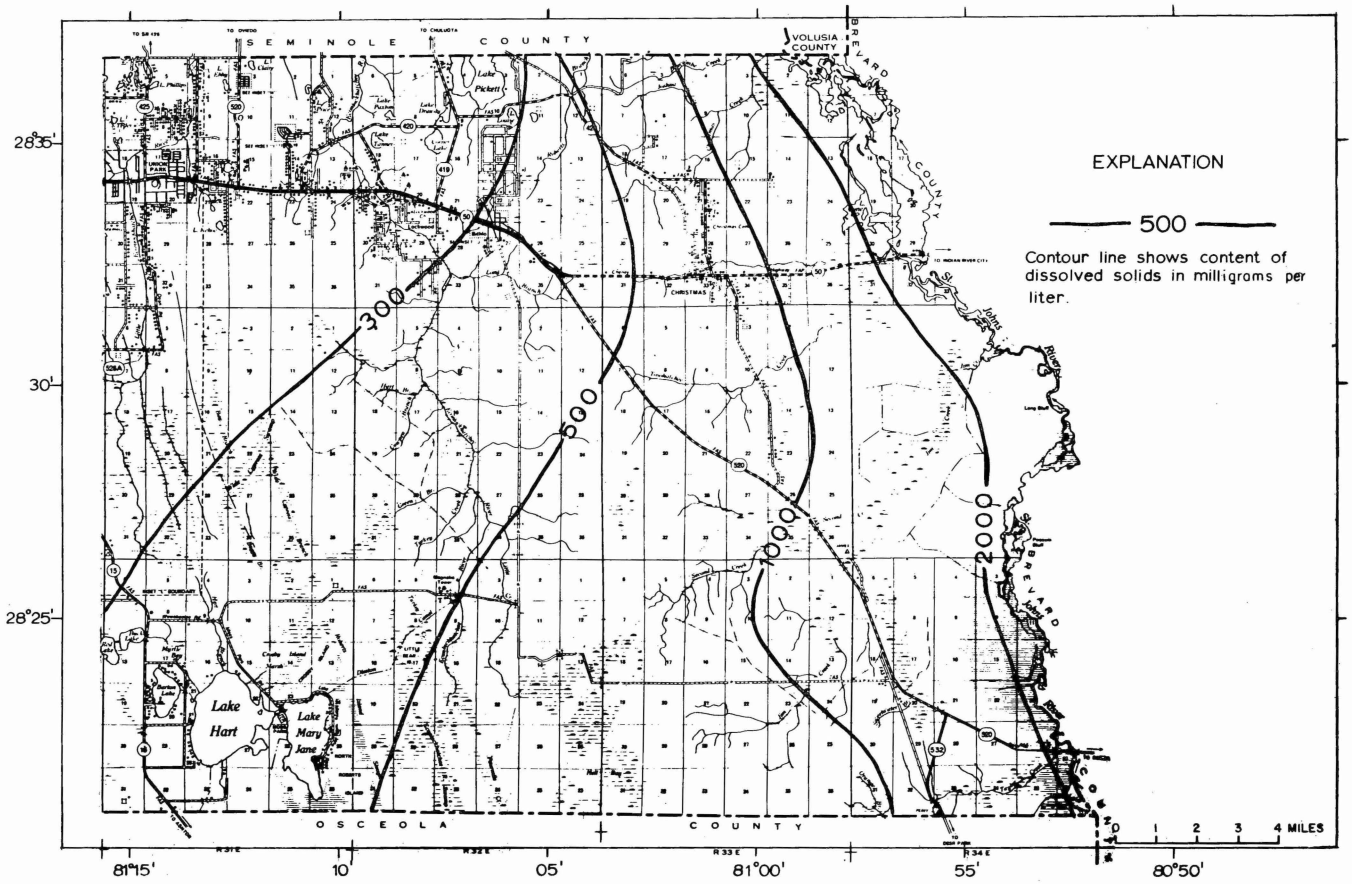



**Figure 8.—Map of the dissolved-solids concentration of water in the upper part of the Floridan aquifer, 1960-62.**

The chemical character of the water in the nonartesian aquifer is generally similar to the water in streams except that the water is harder, contains more dissolved solids, and is less colored. The variation in water quality at a particular site is small with respect to time but does vary with respect to different zones in the aquifer. In the upper part where the material is predominantly sand, the water is soft, low in dissolved-solids concentration, neutral, and slightly colored. At depths where shell beds occur, the water is hard from the presence of calcium and magnesium ions, is alkaline, and is less colored.

Chemical analyses of water from two wells that tap shell beds in the secondary artesian aquifer indicate that the water is almost as highly mineralized as the water in the Floridan aquifer in the western part of the study area (fig. 8). The dissolved-solids concentration in the water from the shell beds is as high as 400 mg/l (milligrams per liter), although the chloride concentration is much lower than that in the Floridan aquifer.

In the western part of the study area, water in the Floridan aquifer has a dissolved-solids concentration of 200 mg/l. It becomes progressively poorer in quality toward the east until near the St. Johns River the dissolved-solids concentration is greater than 2,000 mg/l (fig. 8). The limit of dissolved-solids concentration suggested by the Public Health Service (1962) for drinking water is 500 mg/l. The 500-mg/l line runs down through the middle of the study area and indicates the transitional zone between fresh and brackish water. Water-quality maps of Lichtler and others (1966) indicate that water of poor quality has migrated westward under the influence of pumping of wells in the vicinity of the Cocoa well field. However, more recent studies (Tibbals, 1973) indicate that the salty water has migrated upward from depth rather than laterally. Thus, the salt water intrusion in the Cocoa well field is a local phenomenon and its effects do not extend outward from the well field in any direction for any significant distance. The balance between fresh and brackish water in the aquifer is delicate in the well-field vicinity.

## HYDROLOGIC CONCEPTS OF ARTIFICIAL RECHARGE

### SOURCE OF RECHARGE WATER

In the humid eastern United States, rainfall is sufficient to supply water for artificial recharge. However, in eastern Orange County 95 to 100 percent of the rainfall is lost from the area by evapotranspiration and stream runoff (fig. 7). For an artificial recharge scheme to be effective it must include a means of salvaging water that otherwise would be lost and must also include a means of placing it underground beyond the reach of evapotranspiration.

**Table 1.—Chemical analyses of water from various environments in eastern Orange County.**

| Name or Well No. | Sample Date | Silica ($SiO_2$) | Iron (Fe) | Calcium (Ca) | Magnesium (Mg) | Sodium (Na) | Potassium (K) | Bicarbonate ($HCO_3$) | Sulfate ($SO_4$) | Chloride (Cl) | Fluoride (F) | Nitrate ($NO_3$) | Dissolved solids | Hardness | Specific conductance (micromhos at 26°C) | pH | Color | Well depth (feet) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Streams** | | | | | | | | | | | | | | | | | | |
| Econlockhatchee River nr. Bithlo | 10/59 - 7/63 (34 analyses) | 0.0 - 8.9 | 0.02 - .50 | 2.6 - 26 | 0.2 - 27 | 1.8 - 15 | 0.2 - 1.5 | 8 - 83 | 0.0 - 6.4 | 3.0 - 23 | 0.0 - .8 | 0.0 - 1.3 | 32 - 163 | 8 - 74 | 24 - 197 | 5.7 - 7.8 | 35 - 400 | — |
| Little Econlockhatchee River nr. Union Park | 1/60 - 7/63 (25 analyses) | .3 - 11 | .01 - .66 | 5.4 - 16 | .6 - 4.8 | 5.2 - 16 | .2 - 2.4 | 9 - 51 | 1.2 - 6.8 | 9.5 - 20 | .0 - .4 | .0 - .8 | 69 - 146 | 16 - 48 | 58 - 146 | 5.6 - 8.0 | 20 - 400 | — |
| **Nonartesian aquifer** | | | | | | | | | | | | | | | | | | |
| 283353N0811042.1 | 7/1/71 | 6.9 | .72 | 9.4 | 2.3 | 7.8 | .9 | 48 | 10 | 12 | .1 | .0 | 95 | 33 | 138 | 6.0 | 80 | 22 |
| 283249N0810532.3 | 10/63 - 4/70 (6 analyses) | 3.1 - 4.2 | .00 - .71 | 23 - 50 | 1.1 - 1.8 | 5.0 - 8.0 | .1 - .5 | 96 - 164 | .0 - 1.6 | 8.0 - 11 | .0 - .1 | .0 - 1.0 | 107 - 157 | 84 - 132 | 202 - 288 | 6.9 - 7.9 | 5 - 10 | 15 |
| 283212N0810107.1 | 12/20/63 | 9.9 | 4.5 | 26 | .7 | 7.4 | 1.2 | 78 | .6 | 15 | .0 | .2 | 98 | 68 | 175 | 7.0 | 5 | 24 |
| 283126N0811436.1 | 9/10/62 | 7.0 | 2.0 | 6.4 | .2 | 6.0 | 1.4 | 17 | 2.4 | 12 | .1 | .0 | 54 | .7 | 74 | 6.6 | 50 | 8 |
| 283127N0811439.1 | 9/10/62 | 20 | .79 | 70 | 1.8 | 9.2 | .7 | 218 | .0 | 12 | .4 | .0 | 252 | 182 | 366 | 7.8 | 45 | 19 |
| 282949N0811042.1 | 7/1/71 | 3.8 | 1.5 | .6 | 1.0 | 11 | .2 | 45 | .0 | 18 | .1 | .0 | 85 | 6 | 127 | 5.9 | 50 | 17 |
| 282952N0805952.1 | 12/20/63 | 2.5 | .00 | .4 | 1.0 | 4.3 | .6 | 5 | .0 | 8.0 | .1 | .0 | 26 | 5 | 39 | 6.9 | 5 | 22 |
| 282531N0810822.2 | 7/1/71 | 7.1 | 11 | 85 | 7.8 | 31 | 2.0 | 238 | 59 | 43 | .1 | .0 | 389 | 245 | 612 | 6.9 | 160 | 8 |
| 282510N0810545.4 | 7/1/71 | 3.0 | 26 | 16 | 7.0 | 38 | 9.6 | 40 | 83 | 29 | .1 | .0 | 225 | 69 | 377 | 6.1 | 5 | 40 |
| 282336N0810143.1 | 7/1/71 | 9.7 | 1.2 | 9.8 | 2.5 | 24 | 1.3 | 48 | .8 | 44 | .1 | .0 | 146 | 35 | 230 | 6.1 | 5 | 20 |
| **Secondary Artesian aquifer** | | | | | | | | | | | | | | | | | | |
| 283249N0810532.2 | 10/63 - 4/70 (5 analyses) | 12 - 18 | .00 - .47 | 107 - 120 | 1.1 - 2.9 | 8.4 - 13 | .9 - 2.7 | 352 - 382 | .0 - 7.2 | 9.0 - 22 | .2 - .6 | .0 - 1.6 | 321 - 400 | 279 - 316 | 550 - 620 | 7.5 - 8.2 | 0 - 20 | 75 |
| 282530N0810542.3 | 1/69 - 4/70 (6 analyses) | 18 - 20 | — | 63 - 112 | 3.4 - 3.7 | 15 - 16 | 1.0 - 4.1 | [illegible] - 368 | .0 - .4 | 15 - 18 | .1 - .2 | .0 - .7 | 237 - 360 | 172 - 296 | 386 - 602 | 7.9 - 8.4 | 0 - 10 | 172 |
| **Floridan aquifer** | | | | | | | | | | | | | | | | | | |
| 283407N0811341.1 | 4/27/70 | 13 | — | 36 | 7.2 | 7.4 | 1.0 | 120 | 8.8 | 10 | .2 | .0 | 153 | 120 | 275 | 7.3 | 0 | 434 |
| 283249N0810532.1 | 4/21/70 | 19 | — | 62 | 15 | 35 | 1.9 | 194 | 46 | 63 | .3 | .0 | 353 | 218 | 592 | 7.1 | 5 | 492 |
| 283214N0805835.1 | 5/12/69 | 20 | .09 | 155 | 55 | 350 | 13 | 218 | 268 | 660 | .4 | 2.0 | 1,640 | 619 | 2,810 | 7.9 | 0 | 200 |
| | | | | | | | | | | | | | | | | | | 225 |
| 282847N0810137.1 | 4/21/70 | 25 | — | 58 | 33 | 45 | 2.1 | 218 | 69 | 90 | .6 | .0 | 449 | 283 | 765 | 7.5 | 0 | 495 |
| 282623N0811438.1 | 4/20/70 | 32 | — | 61 | 8.8 | 16 | 1.3 | 236 | .4 | 21 | .5 | .0 | 267 | 189 | 423 | 7.7 | 5 | 435 |
| 282531N0810756.1 | 5/15/69 | 22 | .10 | 108 | 5.6 | 33 | 2.1 | 299 | 50 | 54 | .3 | .0 | 422 | 294 | 720 | 7.8 | 10 | 509 |
| 282348N0805647.1 | 4/27/70 | 27 | — | 93 | 27 | 162 | 3.0 | 204 | 51 | 348 | .9 | .0 | 995 | 345 | 1,500 | 7.6 | 5 | 390 |

1 Sample taken from water tap, maybe contaminated from plumbing.

## SCHEMES FOR CAPTURING WATER FROM POTENTIAL LOSSES

The two most readily conceived schemes for capturing potential water losses are those that involve impoundments and (or) shallow ground-water withdrawals. In both schemes, water losses are reduced because: (1) impounding water behind a dam in a surface reservoir will reduce runoff and (2) lowering the water table in the nonartesian (shallow) aquifer will reduce both runoff and evapotranspiration. The water impounded on the surface or withdrawn from the nonartesian aquifer by lowering its water level would serve to supply the wells used for artificial recharge to the Floridan aquifer.

### SURFACE IMPOUNDMENTS

The surface impoundment concept envisions dams constructed across the major streams to reduce runoff during high flow and to retain this water until it is artificially recharged to the Floridan aquifer. For example, constructing a dam across the Econlockhatchee River just upstream of State Highway 50 large enough to hold a 20-foot head of water would create a reservoir having the capacity of 20,000 acre-feet. A mean monthly discharge of 20,000 acre-feet or more occurs on the Econlockhatchee River at Highway 50 at least once each year, thus supplying sufficient water in 1 month to refill a reservoir of this capacity. Therefore, at least 20,000 acre-feet is available each year for recharge. This is equivalent to about 4.5 inches of water per year from the entire contributing area. If dams were constructed on the other streams, it is estimated that a comparable amount of water per unit area could be captured.

Because of the low relief, the total acreage necessary for surface reservoirs would be quite large. For instance, when the hypothetical reservoir on the Econlockhatchee River is full, it would inundate 7 percent of the total drainage area (fig. 9). This 7 percent, of course, would have no other use because the time of inundation would be dictated by the weather conditions.

A variation of the surface impoundment scheme envisions the containment of water in off-stream swampy areas of the basin divides during excessive rainfall. These constitute the area shown on figure 7 that has the highest rate of evapotranspiration — 87 percent of rainfall. Excess water that normally runs off could be contained in the area by levees which would increase surface storage in the swamps. Through a network of canals and ditches the water could be channeled to the deeper depressions. The amount of water that would be captured by this scheme is estimated to be 2 to 3 inches per year. Most of the water that normally runs off this area, estimated at 5 inches per year, could be captured but about one half of it would be lost to evapotranspiration before the water could be utilized for recharge.

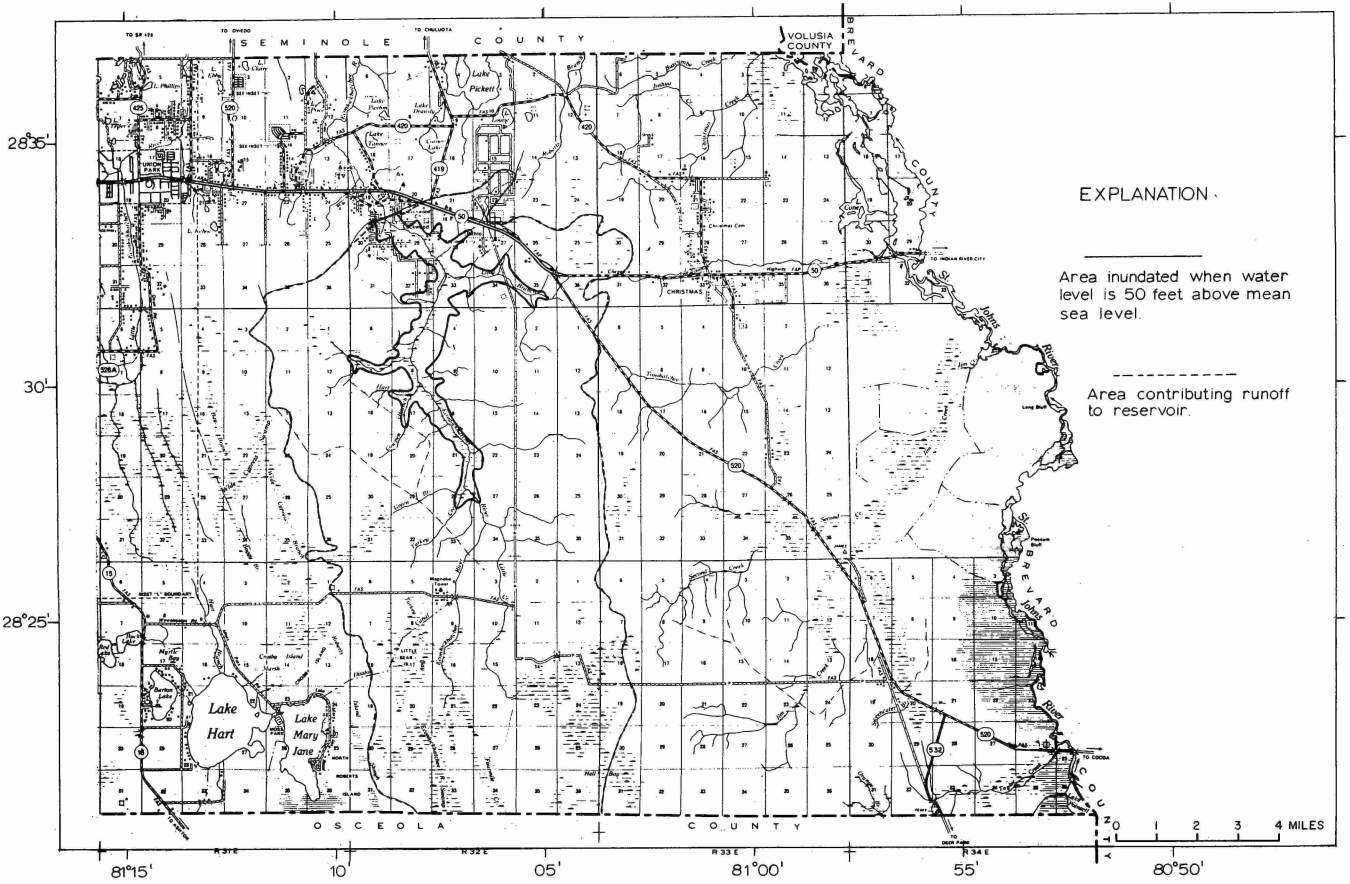



**Figure 9.—Map showing area of inundation and contributing area of surface impoundment scheme.**

## CONNECTOR WELLS

The second scheme for capturing water for artificial recharge—lowering water levels—involves the use of connector wells. These are wells that are open to both the nonartesian and Floridan aquifers and act to short circuit the flow through the confining layer (fig. 10). Water in the nonartesian aquifer would move laterally to the connector well, flow down through the well and recharge the Floridan aquifer. Under natural conditions, water would percolate very slowly, if at all, through the confining bed to the Floridan aquifer. The connector-well concept, where water flows by gravity from an upper aquifer to a lower one will work only when the water table of the nonartesian aquifer is higher than the altitude of the potentiometric surface of the Floridan aquifer. The areal distribution of the head difference in eastern Orange County is shown on figure 11.

As water from the nonartesian aquifer flows downward through the connector well, the water table declines. This decline reduces evapotranspiration and creates additional storage in the aquifer which allows for greater infiltration, thus capturing water which would have run off or evapotranspired. Systematically lowering the water table over a specified area requires a network of connector wells. The actual rate of capture of water relative to the extent of lowering of the water table is not known. However, capture rates can be assumed for evaluation of the connector well scheme.

## EVALUATION OF SCHEMES

In both the surface impoundment and connector well schemes, the method of introducing water into the Floridan aquifer is the same. This method consists of the gravity flow of water through a well bore from either a surface water body or shallow aquifer to the Floridan aquifer. The difference in schemes is in the method of capturing water for recharge and in the hydrologic advantages and disadvantages.

The connector-well scheme has hydrologic advantages which make it more desirable than the surface impoundment scheme as a means of artificial recharge.

### CAPTURE OF WATER

Connector wells capture water that would be lost by evapotranspiration as well as from runoff, whereas an impoundment scheme would only decrease surface runoff and, probably, would even increase evapotranspiration.

### LAND UTILIZATION

The land used for a connector-well installation can also be developed for both urban and agricultural use; whereas the need for numerous reservoirs

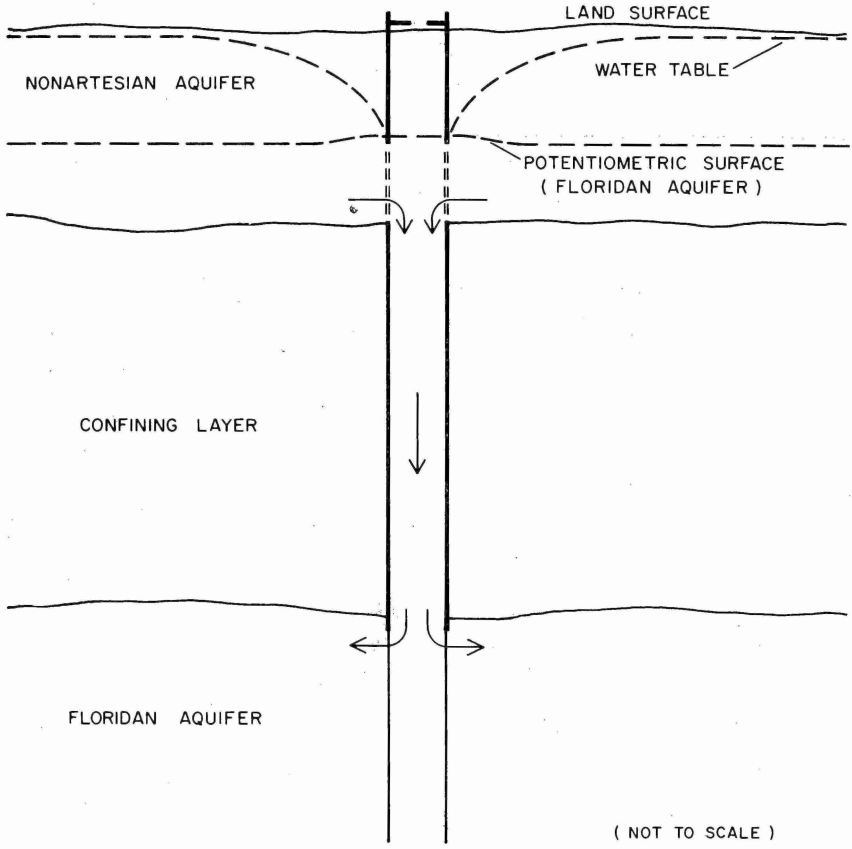



**Figure 10.—Schematic sectional view of a connector well between nonartesian and Floridan aquifers.**

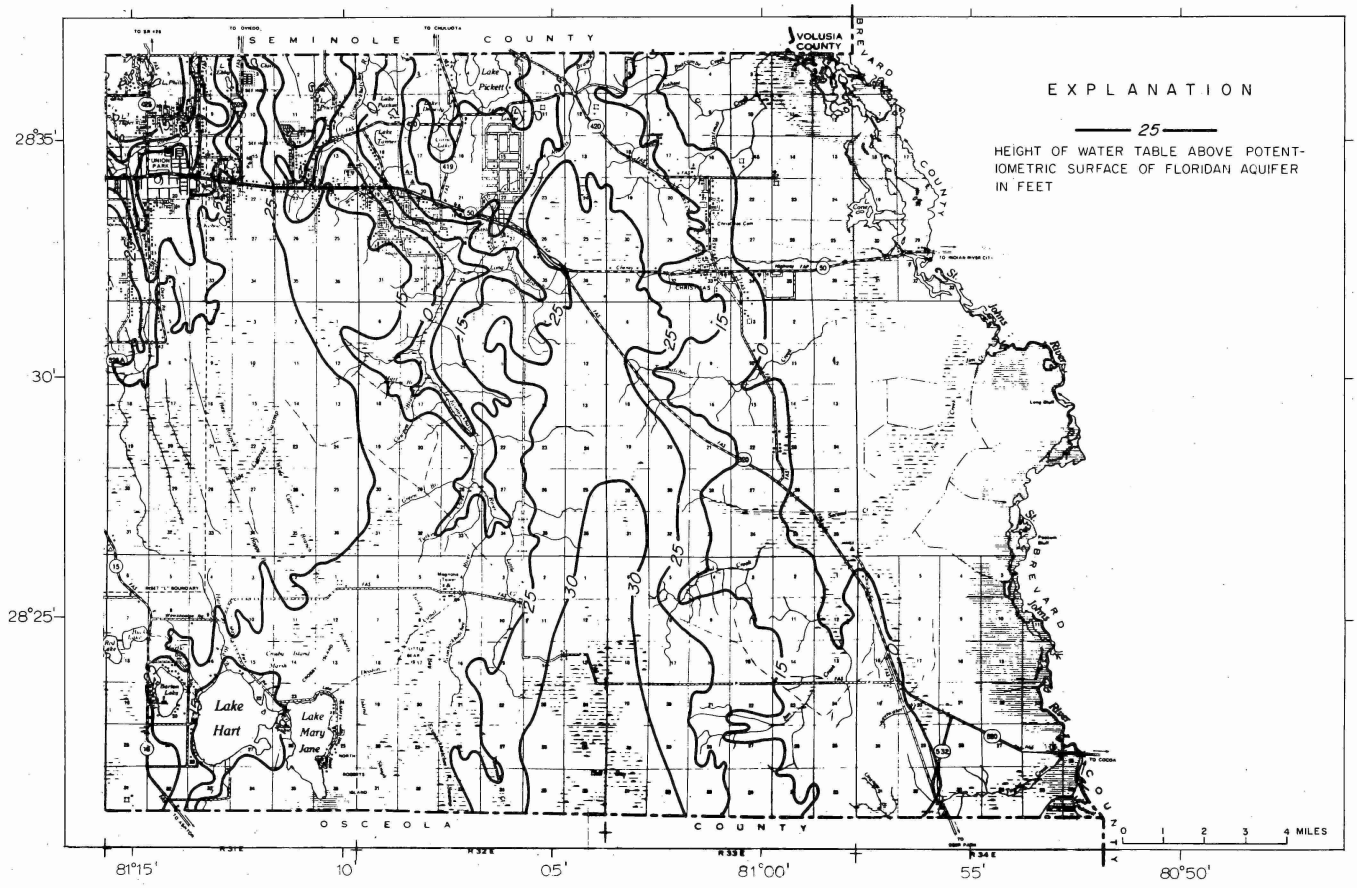



**Figure 11.—Contour map of head difference between nonartesian and Floridan aquifers.**

in a surface impoundment scheme would preclude any other use of the land because of the wide fluctuation in water level which would occur in a recharge project. A connector-well scheme would also dewater some areas that are now waterlogged making them suitable for land development.

### WATER TREATMENT

Recharge water in a connector-well scheme does not require treatment. The nonartesian aquifer would act as a large sand filter to purify and produce water similar in chemical character to water naturally recharged in other parts of the county. Recharge water from a surface impoundment requires treatment to avoid introducing suspended material and bacteria into the Floridan aquifer.

### LAND ACQUISITION

The cost of land for connector-well sites would be much less than the cost of land for reservoirs.

## ANALYSIS OF A CONNECTOR-WELL NETWORK

From general hydrologic concepts it was concluded that the connector-well scheme has more benefits than the surface impoundment scheme. But before such a system can be deemed feasible for a given area, it is necessary to analyze the hydraulic relationships of a connector-well network.

The infiltration capacities that exist in eastern Orange County are high enough to make capture of water possible if storage space can be created in the nonartesian aquifer. The discharge of water to connector wells will lower the water table and thus provide storage space in the nonartesian aquifer. The number of wells needed to lower the water table enough to make the project feasible is dependent upon the transmissivity of the nonartesian aquifer, the available drawdown in the well, and the rate of capture.

For a given set of atmospheric and geologic conditions, the rate of capture is a function of the depth to the water table. As the depth to water increases, the rate of capture will increase until the maximum capture rate is attained at which point further drawdown will not affect the capture rate (fig. 12). The drawdown that is associated with a particular rate of capture is the effective drawdown. A schematic model of the physical concepts of capture, drawdown, and contributing area of a connector-well network is shown on figure 13.

If there is available drawdown in the well, the drawdown in the aquifer will continue until discharge to the well equals the rate of capture, after which time no additional water is withdrawn from storage and the discharge-

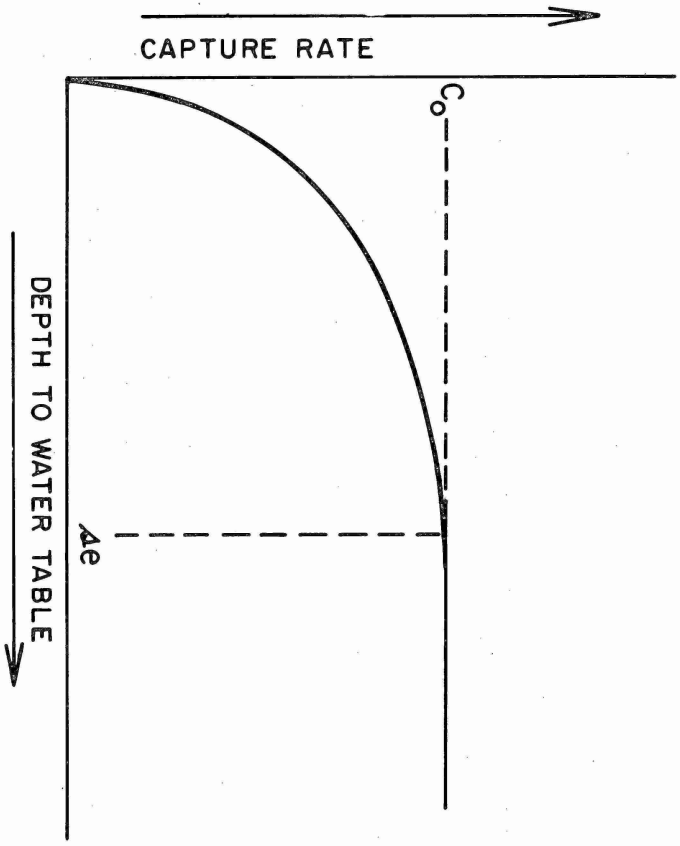



**Figure 12.—Schematic curve illustrating the capture-drawdown function.**

drawdown relation is said to be in a steady-state condition. A numerical analysis of the drawdown from a connector-well network in the nonartesian aquifer under steady-state conditions has been developed by Papadopulos and Cooper (written commun., 1973). This analysis uses the Dupuit-Forchheimer assumption of horizontal flow to the well. Deviation from this ideal condition may result in less accurate calculations of drawdown in the immediate vicinity of the well, especially if the drawdown is large compared to the thickness of the aquifer. However, equations derived on the basis of this assumption have been shown to be exact for discharge calculations (Hantush, 1962).

In a square-grid network the area contributing water to an individual connector well is a square with sides equal to the well spacing. If the network is designed to provide maximum capture with the least number of wells, the wells are placed at a spacing $\ell$ such that the minimum drawdown, which occurs at a point equidistant from the four nearest wells, is equal to the effective drawdown $s_e$ (fig.13).

An equation relating drawdown in the well $s_w$, effective drawdown $s_e$, aquifer thickness $h_o$, transmissivity T, maximum capture rate $C_o$, and well radius $r_w$ with the well spacing $\ell$, for a network of fully penetrating connector wells with negligible well losses, is given by Papadopulos and Cooper (written commun., 1973):

$$\frac{[(s_w - \frac{s_w^2}{2h_o}) - (s_e - \frac{s_e^2}{2h_o})]T}{C_o r_w^2} = f(\ell/r_w)$$

where

$$f(\ell/r_w) = \frac{\ell^2}{2\pi r_w^2}\left\{\frac{\pi}{4} + \sum_{n=1}^{\infty} \frac{1}{n \sinh n\pi}\left[\cosh n\pi \cos\frac{2n\pi r_w}{\ell} - (-1)^n\right]\right\}$$

If the parameters on the left side of the equation are known, the well spacing $\ell$ can be determined graphically from a plot of $\ell/r_w$ against $f(\ell/r_w)$ as shown on figure 14. With this spacing the discharge of each connector well will be $Q = C_o^2$.

Of the various parameters in the "well-spacing" equation, capture and effective drawdown ($s_e$) in the drawdown-capture function are quantitatively the least known. The transmissivity of the nonartesian aquifer has not been measured directly but is estimated from indirect methods. Aquifer thickness and available drawdown in the well have been determined. For those parameters whose values are not explicitly known, a range of values representing a reasonable upper and lower limit are used in the analysis.

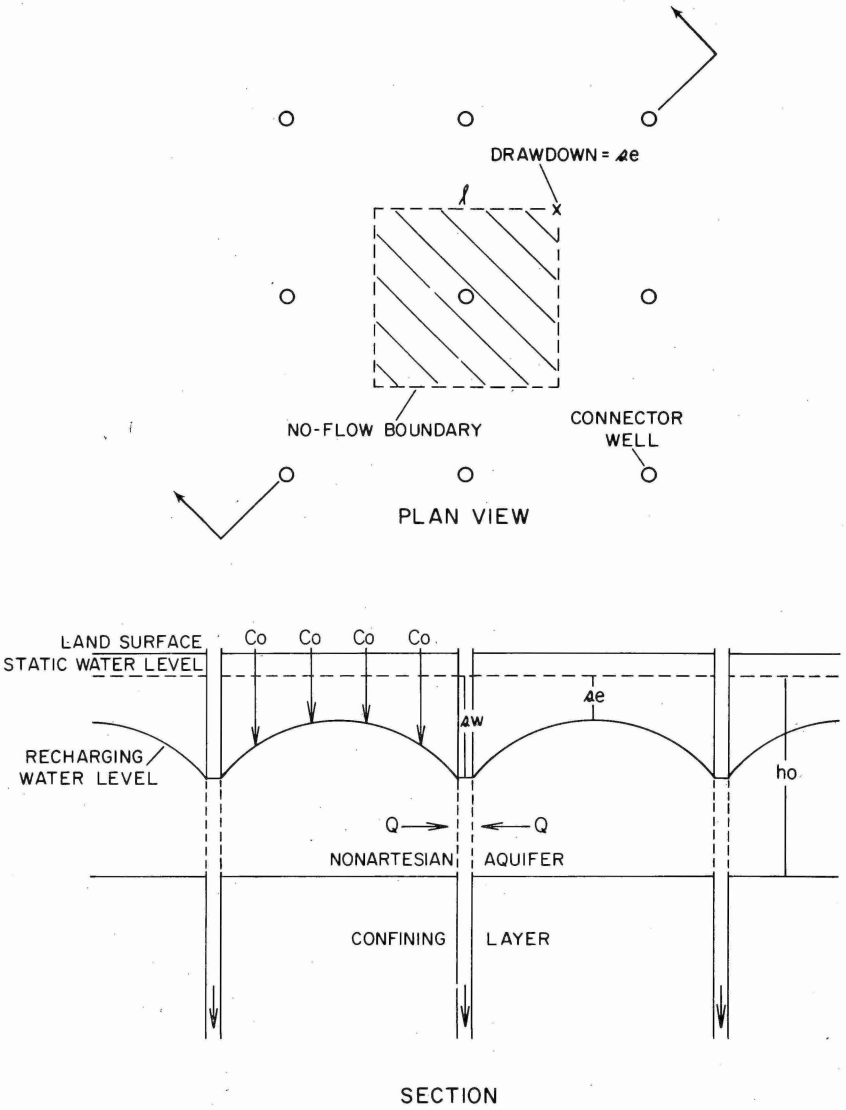



**Figure 13.—Diagrammatic plan view and section showing the physical concepts of a connector-well network.**

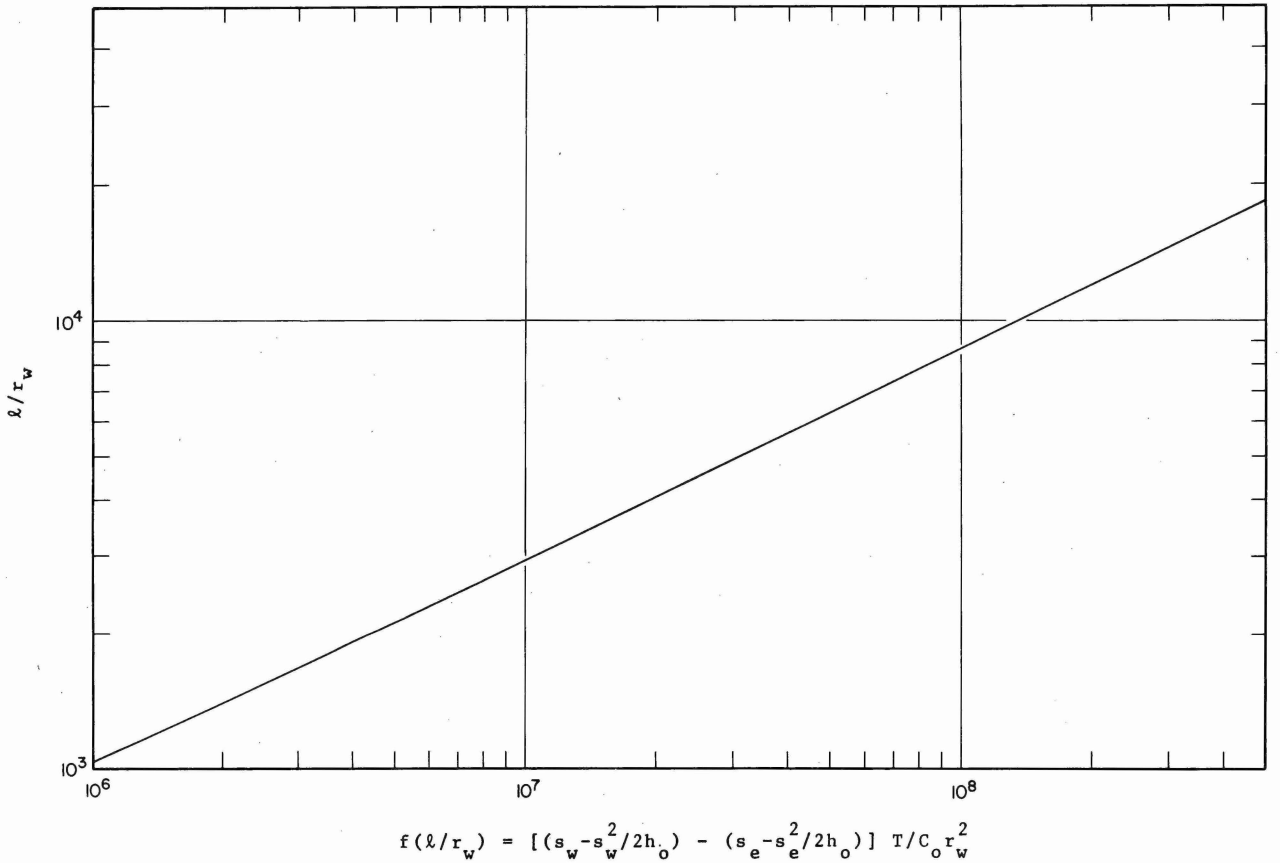



**Figure 14.—Graph for determining well spacing in a square-grid connector-well network.**

Estimates of the capture rate range from 0.5 to 1.5 feet per year. These rates would produce 38,200 $ft^3$ per day (0.3 mgd) and 114,600 $ft^3$ per day (0.9 mgd) of recharge water per square mile. Ripple and others (1972), using theoretical approaches, determined the relation between evaporation rates and water-table depths in the southwestern United States for given meteorological and bare soil conditions. For a given set of these conditions the evaporation rate decreases from 0.31 cm (centimenters) per day (3.7 feet per year) for a water-table depth of 200 cm (7.9 feet) to 0.10 cm per day (1.2 feet per year) for a depth of 250 cm (9.8 feet). Therefore it does not seem improbable that the rate of capture of water that otherwise would be lost by evapotranspiration and runoff could be between 0.5 and 1.5 feet per year.

Calculations of well spacing, discharge per well and number of wells per square mile using the upper and lower limits for each of the hydraulic parameters and well radii of 0.25 and 0.50 ft are given in table 2. As the well spacing equations and these calculations indicate, well spacing increases as the transmissivity and the difference between available and effective drawdown increases, and as the rate of capture and well radius decrease. However, the effect of well radius is relatively small. The reduction in the number of wells per square mile for larger diameter wells is small and on an areal basis the cost of the slightly greater number of small wells would be less than the cost of a smaller number of large wells. Therefore, connector-well networks designed with wells of the smallest practical diameter would be sufficient.

The average transmissivity of the nonartesian aquifer is estimated to be between 125 $ft^2$ per day and 625 $ft^2$ per day. To justify these estimates, samples of the aquifer material were collected for laboratory analysis of grain size and vertical hydraulic conductivity. The median grain size of the material in the nonartesian aquifer is 0.15 millimeter. Grains having this diameter are classified as fine sand (Johnson and others, 1966).

Various investigators have related soil class to hydraulic conductivity with some success. Todd (1959) shows a general relationship in which fine sand ranges in hydraulic conductivity from $10^{-1}$ to 20 feet per day. A relationship between median grain size and permeability of alluvial sediments from the Arkansas River Valley indicates a hydraulic conductivity of about 5 feet per day for fine sand (Bedinger, 1961). Well sorted, very fine sand may have a hydraulic conductivity as high as 25 feet per day (Davis, 1970). The fine sands of the nonartesian aquifer are fair to well sorted, thus it is not unreasonable to estimate a hydraulic conductivity between 2 and 12 feet per day for these sediments. Laboratory determinations of vertical hydraulic conductivity range from 0.02 to 20 feet per day for the aquifer materials. The rela-

**Table 2.—Well spacing $\ell$, well discharge Q, and numbers of wells per square mile $N_w$, for upper and lower limits of transmissivity T, capture rate $C_0$, effective drawdown $s_e$, and available drawdown $s_w$, and for well radii $r_w$ of 0.25 and 0.5 foot.**

| T ($ft^2$/day) | $C_0$ (ft/year) | $s_e$ (ft) | $f(\ell/r_w)$ (dimensionless) | $\ell$ (ft) | Q ($ft^3$/day) | $N_w$ (per $mi^2$) |
|---|---|---|---|---|---|---|
| | | | $s_w$=25 ft | | | |
| | | | $r_w$=0.25 ft | | | |
| 125 | 0.5 | 5 | $2.044 \times 10^7$ | 1,040 | 1,480 | 26 |
| 125 | .5 | 10 | $1.424 \times 10^7$ | 880 | 1,060 | 36 |
| 125 | 1.5 | 5 | $6.813 \times 10^6$ | 630 | 1,630 | 71 |
| 125 | 1.5 | 10 | $4.745 \times 10^6$ | 530 | 1,150 | 100 |
| 625 | .5 | 5 | $1.022 \times 10^8$ | 2,220 | 6,750 | 6 |
| 625 | .5 | 10 | $7.118 \times 10^7$ | 1,870 | 4,790 | 8 |
| 625 | 1.5 | 5 | $3.407 \times 10^7$ | 1,330 | 7,270 | 16 |
| 625 | 1.5 | 10 | $2.373 \times 10^7$ | 1,120 | 5,160 | 23 |
| | | | $r_w$=0.5 ft | | | |
| 125 | .5 | 5 | $5.110 \times 10^6$ | 1,090 | 1,630 | 24 |
| 125 | .5 | 10 | $3.559 \times 10^6$ | 920 | 1,160 | 33 |
| 125 | 1.5 | 5 | $1.703 \times 10^6$ | 660 | 1,790 | 64 |
| 125 | 1.5 | 10 | $1.186 \times 10^6$ | 560 | 1,290 | 89 |
| 625 | .5 | 5 | $2.555 \times 10^7$ | 2,320 | 7,370 | 6 |
| 625 | .5 | 10 | $1.779 \times 10^7$ | 1,960 | 5,260 | 8 |
| 625 | 1.5 | 5 | $8.517 \times 10^6$ | 1,390 | 7,940 | 15 |
| 625 | 1.5 | 10 | $5.931 \times 10^6$ | 1,170 | 5,630 | 21 |
| | | | $s_w$=50 ft | | | |
| | | | $r_w$=0.25 ft | | | |
| 125 | .5 | 5 | $2.957 \times 10^7$ | 1,240 | 2,110 | 19 |
| 125 | .5 | 10 | $2.336 \times 10^7$ | 1,110 | 1,690 | 23 |
| 125 | 1.5 | 5 | $9.855 \times 10^6$ | 740 | 2,250 | 51 |
| 125 | 1.5 | 10 | $7.787 \times 10^6$ | 670 | 1,840 | 63 |
| 625 | .5 | 5 | $1.478 \times 10^8$ | 2,640 | 9,550 | 4 |
| 625 | .5 | 10 | $1.168 \times 10^8$ | 2,360 | 7,630 | 6 |
| 625 | 1.5 | 5 | $4.928 \times 10^7$ | 1,580 | 10,260 | 12 |
| 625 | 1.5 | 10 | $3.893 \times 10^7$ | 1,410 | 8,170 | 15 |
| | | | $r_w$=0.5 ft | | | |
| 125 | .5 | 5 | $7.391 \times 10^6$ | 1,300 | 2,320 | 17 |
| 125 | .5 | 10 | $5.840 \times 10^6$ | 1,160 | 1,840 | 21 |
| 125 | 1.5 | 5 | $2.464 \times 10^6$ | 780 | 2,500 | 46 |
| 125 | 1.5 | 10 | $1.947 \times 10^6$ | 700 | 2,010 | 57 |
| 625 | .5 | 5 | $3.696 \times 10^7$ | 2,760 | 10,440 | 4 |
| 625 | .5 | 10 | $2.920 \times 10^7$ | 2,470 | 8,360 | 5 |
| 625 | 1.5 | 5 | $1.232 \times 10^7$ | 1,650 | 11,190 | 11 |
| 625 | 1.5 | 10 | $9.733 \times 10^6$ | 1,480 | 9,000 | 13 |

tion between vertical and horizontal conductivity is not known but generally horizontal conductivity is greater. The laboratory values also imply that the estimated values are reasonable.

The thickness of the nonartesian aquifer is 50 feet and the available drawdown under present conditions is about 25 feet. However, the maximum drawdown could be 50 feet if the potentiometric surface of the Floridan aquifer were lowered 25 feet or to the bottom of the nonartesian aquifer. It is unlikely, however, that in the foreseeable future pumpage from the Floridan aquifer will increase to a degree that will lower its potentiometric surface by an additional 25 feet. Evaluation of equations that describe nonsteady flow to multiaquifer wells (Papadopulos, 1966) indicates that because of the large differences in the transmissivities of the nonartesian and the Floridan aquifer, the water level in a connector well will stand very close to the potentiometric surface of the Floridan aquifer. The availability of drawdown will therefore be affected if pumpage from the Floridan aquifer does not increase to counteract the build-up that could be caused by the recharge. However, the needs for increase in pumpage is small, about 200 gpm for each 6 inches of capture over 1 square mile.

The well spacing, discharge per well and number of wells per square mile, for fully penetrating wells with negligible well losses, are calculated in example 1, below, for a given set of hydraulic parameters.

Example 1

Given: $C = 1.0$ foot per year $= 2.74 \times 10^{-3}$ feet per day

$s_w = 25$ feet

$s_e = 5$ feet

$T = 400$ ft$^2$ per day

$h_0 = 50$ feet

$r_w = 0.25$ ft.

$$f(\ell/r_w) = \frac{[(25 - \frac{625}{100}) - (5 - \frac{25}{100})] \times 400}{2.74 \times 10^{-3} \times 0.0625}$$

$$= 3.27 \times 10^7$$

From figure 14

$$\ell/r_w = 5.2 \times 10^3$$

and $\ell = 5.2 \times 10^3 \times 0.25 = 1300$ ft

Discharge per well

$$Q = C\ell^2 = 2.74 \times 10^{-3} \times 1.69 \times 10^6$$
$$Q = 4630 \text{ ft}^3 \text{ per day}$$

Number of wells per square mile

$$N_w = \frac{Q \text{ per sq. mi.}}{Q \text{ per well}} = \frac{7.64 \times 10^4}{4.63 \times 10^3}$$

$N_w$ = 17 wells on 1,300 foot centers.

## OPERATIONAL CONNECTOR WELLS

The connector-well concept has been utilized in other areas and hydrogeologic systems as a basis for designing recharge works. In Anchorage, Alaska, the U. S. Geological Survey experimented with a well connecting a shallow clastic aquifer to two deeper artesian aquifers (Cederstrom and others, 1964). The shallow aquifer is hydraulically connected to a creek. By lowering the water table, the rate at which water from the creek infiltrated the aquifer was increased. The additional water captured flowed into the connector well. The recharge operation was not as successful as anticipated due to the decrease in the rate at which the two artesian aquifers accepted the water. Recharge began at a rate of 135 gpm but diminished to 55 gpm after 5 months. The authors attributed the reduction in recharge rate to incomplete development of the well and clogging of the deeper aquifer with silt from the shallow aquifer.

Another experimental connector-well installation by the U. S. Geological Survey is located southwest of Orlando, Florida, in western Orange County. At this site the hydrologic system consists of a thin surficial sand aquifer separated by a confining layer (thick hardpan) from an intermediate sand aquifer, both of which are separated from the deeper Floridan aquifer by a thick confining layer. This experiment has been operational for about 18 months and the data to 1972 indicate that the flow through the well has stabilized at about 13 gpm. Drawdown has reached 6 feet in an observation well 105 feet from the connector well and that taps the sand aquifer. (Written commun., 1972, Frank Watkins, U. S. Geological Survey).

## WATER QUALITY CONSIDERATIONS

Pumping from the Floridan aquifer at an ever increasing rate in an area where the quality of the water is marginal to begin with has caused the quality to degrade still farther. If water of good quality were recharged to the Floridan, withdrawal could be increased without degrading water quality. Thus, it becomes important that only fresh water be used for recharge.

The source of water for recharge is the nonartesian aquifer. This water has a chloride concentration less than 25 mg/l (milligrams per liter), hardness less than 100 mg/l (except in shell beds) and sulfate less than 5 mg/l. In contrast, in the Cocoa well field where quality is marginal, water from the Floridan aquifer has a chloride concentration as high as 500 mg/l, hardness 480 mg/l, and sulfate 190 mg/l. The nonartesian water is more acidic than the Floridan which would probably have the desirable effect of increasing its permeability. The only constituent that may be undesirable and whose geochemistry would need investigating is iron. The iron concentration of the nonartesian water appears to be high in some areas (table 1). The slightly colored water would be no trouble; after recharge had been in operation for a time water would move downward more rapidly through the soil zone and the amount of color would probably decrease.

### SUBSEQUENT WITHDRAWAL OF RECHARGED WATER

The purpose of most recharge operations is to store potable water in an aquifer for subsequent withdrawal. No recharge operation is successful if the recharged water or a mixture thereof cannot be retrieved. Several recharge-withdrawal experiments were made in the Cocoa well field to investigate the retrievability of the water after injection into the Floridan aquifer (Tibbals, 1972).

Water for the recharge experiment was obtained from a secondary artesian aquifer. The water had a chloride concentration of about 20 mg/l. The Floridan aquifer normally contains water whose chloride concentration is in excess of 500 mg/l. After five recharge-withdrawal experiments, Tibbals concluded that a buffer zone between the fresh and salty water could be established and that greater amounts of the recharged water were recovered on each successive experiment. On the fifth experiment, 68 percent of the actual water recharged was recovered before the chloride concentration of the mixture that was being withdrawn reached 250 mg/l. On a volume basis, 75 percent of the quantity recharged was withdrawn before the chloride concentration of the mixture reached 250 mg/l and the experiment was terminated. The four previous cycles were also terminated when the chloride concentration of the discharge water reached 250 mg/l.

## SUMMARY AND CONCLUSIONS

Artificial recharge in eastern Orange County is a worthwhile consideration. Not only is the hydrologic system suitable for gravity flow through a well to recharge the Floridan aquifer but there is also the need for additional fresh water in the Floridan in this area. The present rate of withdrawal from

the Cocoa well field puts a stress on the aquifer such that brackish water has migrated upward into the pumped zone of the aquifer in the eastern section of the field.

The hydrologic system cycles about 55 inches of rainfall per year, of which 10 to 15 inches runs off, 40 to 45 inches evapotranspires and 0 to 2 inches recharges the Floridan aquifer. With such a large supply to and loss from the area, there is a sufficient source of water for artificial recharge. The hydrogeologic framework also enhances the feasibility of artificial recharge. It consists of a surficial (nonartesian) aquifer separated from the underlying Floridan aquifer by a confining layer. The water table in the nonartesian aquifer stands as much as 30 feet above the altitude of the potentiometric surface of the Floridan aquifer. The water in the nonartesian aquifer is generally soft and low in dissolved-solids concentration whereas water in the Floridan aquifer, especially where quality is marginal, is very hard and has a chloride concentration as high as 500 mg/l.

The supply of water for artificial recharge could be derived from a network of connector wells capturing water currently lost from the area. The network would consist of wells hydraulically connecting the nonartesian and Floridan aquifers. Because the water table in the nonartesian aquifer is higher than the potentiometric surface of the Floridan aquifer, water would flow into the wells from the nonartesian aquifer, down the wells and into the Floridan. Hydrologic advantages to the connector-well scheme make it more desireable means for recharging water to the Floridan aquifer. These advantages are: only one device (well) need be constructed for capturing water and injecting it to the Floridan aquifer; runoff and evapotranspiration losses are both reduced; hydrologic change to the environment is less; and the water needs no treatment before it is injected.

The water table must be lowered before capture can succeed. The amount of lowering caused by flow to a connector well is controlled by the available drawdown, the transmissivity of the nonartesian aquifer, and the rate of capture. The available drawdown is limited under present conditions by the difference in head between the water table and the potentiometric surface of the Floridan aquifer. The ultimate available drawdown, however, would be equal to just slightly less than the thickness of the nonartesian aquifer. The transmissivity of the nonartesian aquifer is estimated to be between 125 and 625 $ft^2$ per day. These values are considered reasonable from indirect correlations with grain size and laboratory permeability determinations.

Calculations from a numerical model developed by Papadopulos and Cooper (written commun., 1973) indicate that for a capture rate of 1.0 foot per year and an effective drawdown of 5 feet, 6-inch fully penetrating con-

nector wells located in a square-grid network should have spacing of 1,300 feet. The corresponding recharge rate would be 4,630 $ft^3$ per day per well or about 0.57 mgd per square mile. Higher capture rates would require additional wells and closer spacings, and the flow to each well would be slightly higher. Greater effective drawdowns would require closer well spacings and consequently a greater number of wells and a lower recharge rate per well.

From recharge-withdrawal experiments in the Cocoa well field, Tibbals (1972) concluded that a buffer zone between the fresh and salty water could be established and that a greater amount of the recharged waters was recovered on each successive experiment.

The conclusion of this study is that it is feasible to capture surficial waters and recharge them to the Floridan aquifer in eastern Orange County by using a connector well.

The critical parameters used in the numerical analysis are the transmissivity of the nonartesian aquifer and the capture-drawdown function. Verification of the values of transmissivity used in the analysis can be obtained from proven field test procedures (Boulton, 1963; Prickett, 1965). However, verification of the capture drawdown function is more difficult to obtain.

As a succeeding phase in this artificial recharge study, a connector well and associated observation wells could be installed. Through the use of this installation an experiment could be conducted to obtain the empirical data on capture rate and drawdown distribution. From the empirical data the capture-drawdown function would be investigated. If a relationship between capture and drawdown can be determined, the potential for artificial recharge by means of a connector well system can be evaluated for other areas.

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