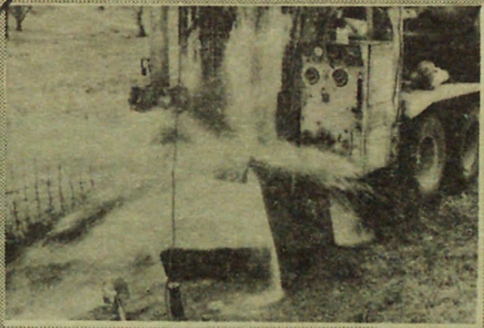
GROUND WATER IN THE CARBONATE ROCKS OF THE FRANKLIN AREA, TENNESSEE

U. S. GEOLOGICAL SURVEY
Water Resources Investigations
Open-file Report 80-410



Prepared in cooperation
with the City of Franklin

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1980

UNITED STATES DEPARTMENT OF THE INTERIOR

Cecil D. Andrus, Secretary

U. S. GEOLOGICAL SURVEY

H. William Menard, Director

FOR ADDITIONAL INFORMATION WRITE TO:

U. S. Geological Survey
A-413 Federal Building -
U. S. Courthouse
Nashville, Tennessee 37203

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FACTORS FOR CONVERTING U.S. CUSTOMARY SYSTEM UNITS TO S.I. UNITS

Multiply U.S. Customary System Units	by	To obtain S.I. Units
ft (foot)	0.3048	m (meter)
ft^3/s (cubic foot per second)	0.02832	m^3/s (cubic meter)
gal/min (gallon per minute)	0.06309	L/s (liter per second)
(gal/min)/ft (gallon per minute per foot)	0.2070	(L/s)/m (liter per second per meter)
in (inch)	25.40	mm (millimeter)
mi (mile)	1.609	km (kilometer)

GROUND WATER IN THE CARBONATE ROCKS

OF THE FRANKLIN AREA, TENNESSEE

BY

Ann Zurawski and Charles R. Burchett

ABSTRACT

A study of ground water in the Franklin area, Tennessee, was undertaken to fill a growing need for information on ground-water occurrence in the carbonate rocks of central Tennessee. Fifteen drilling sites were selected that had one or more of the following characteristics; medium- to thick-bedded limestones within 200 feet of land surface, structural lows, significant streamflow gains and losses, elongated sinkholes, straight stream reaches, linear features or other surface indications of solution cavities at depth.

The 15 test wells produced from less than 1 to about 600 gallons per minute and had an average yield of 68 gallons per minute, measured while pumping the wells with compressed air. The average driller-reported yield for the area was five gallons per minute. Specific capacities for the four highest yielding wells ranged from 0.6 to 357 gallons per minute per foot of drawdown after 8 hours of pumping at rates ranging from 70 to 225 gallons per minute. Additional drilling at two sites revealed extensive solution openings. At one site, drawdown in five observation wells did not exceed 8.5 feet during 48 hours of pumping at an average rate of 502 gallons per minute.

Raw water in the test wells meets most drinking-water standards and is of rather uniform quality from well to well and throughout the year.

1.0 INTRODUCTION

GROUND-WATER OCCURRENCE IN CARBONATE ROCKS IS SUBJECT OF FRANKLIN AREA STUDY

There is a growing need for information on the occurrence of ground water in the Central Basin of Tennessee. This report summarizes the findings of a ground-water study, including test drilling, pumping tests, and water-quality sampling, in the Franklin area.

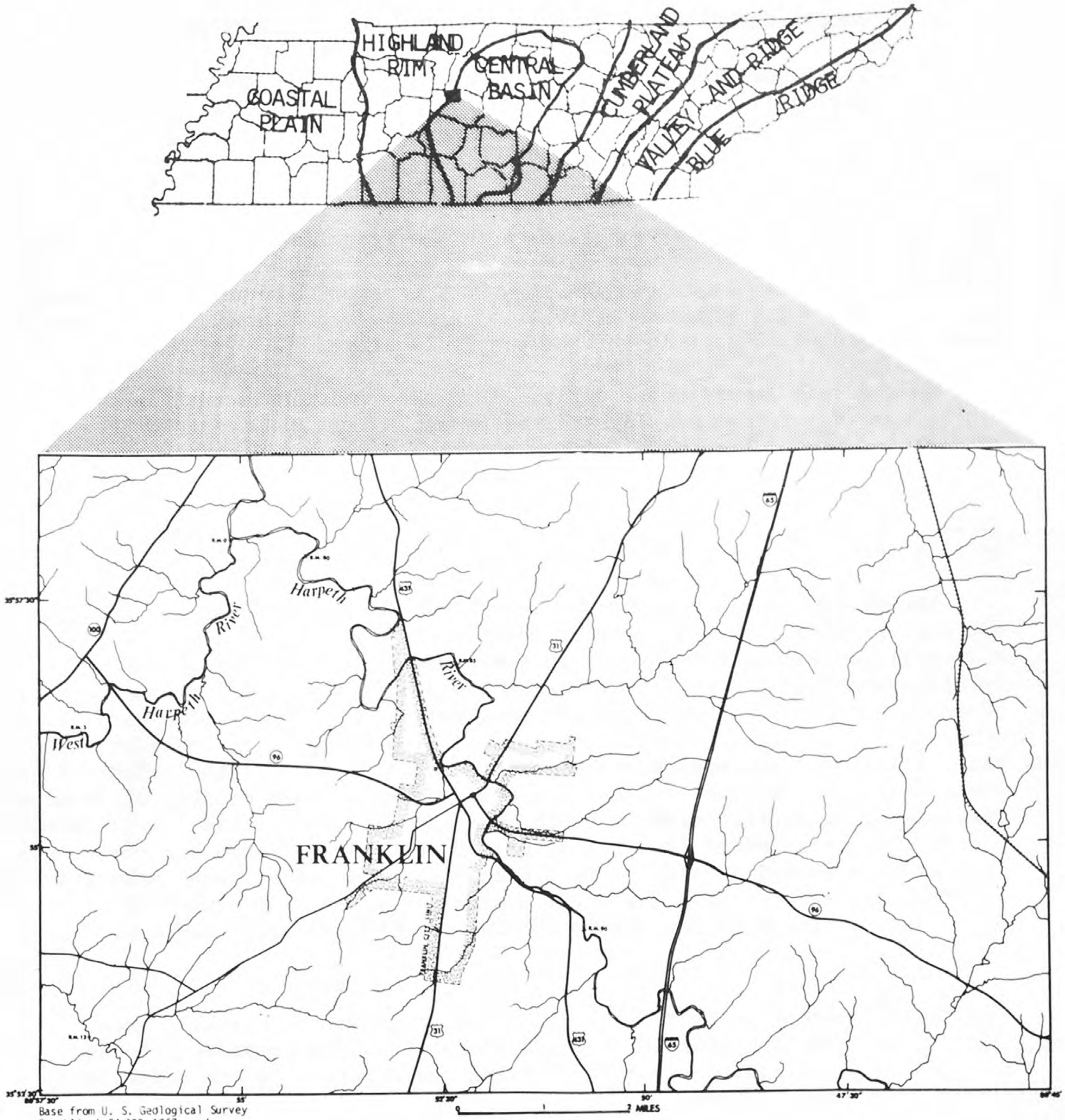
Urban growth in central Tennessee has increasingly taxed both the traditional surface-water supplies and existing treatment and distribution systems. The interest of water managers in alternative water sources has emphasized a critical lack of information on the occurrence of ground water in carbonate rocks. In the past, these aquifers have been used mostly as rural domestic water sources. Their development is deterred by their highly variable water-bearing properties; low-yielding wells are common and the occurrence of large supplies unpredictable. However, a better understanding of the ground-water system in such areas would do much to diminish the uncertainty of locating large ground-water supplies.

A two-year study of ground-water occurrence in the Franklin area by the U.S. Geological Survey, in cooperation with the City of Franklin, began in the spring of 1975. The study had three objectives:

1. Define the ground-water hydrology of the Harpeth River basin in the vicinity of Franklin.
2. Test concepts of ground-water occurrence by drilling test wells at sites selected on the basis of hydrologic criteria.
3. Acquire data on the quantity and quality of ground water and on the geologic environment in which it occurs.

The study included well and spring inventories, three stream surveys, study of aerial photography and geologic data, drilling of 25 test wells, six aquifer tests, and chemical analysis of more than 60 water samples. The purpose of this report is to summarize these data and present conclusions about the hydrogeologic system in the Franklin area.

The Franklin area (fig. 1) is located in Central Tennessee and lies completely within Williamson County. Franklin is approximately 17 miles south of Nashville. The study area lies mostly in the gently-rolling lowlands of the Central Basin, a section of the Interior Low Plateaus physiographic province. Outliers of the Highland Rim in the western edge of the area provide about 300 feet of relief. The major streams are the Harpeth River and its tributary, the West Harpeth River.



Base from U. S. Geological Survey
Franklin 1:24 000, 1967, and
Leipers Fork 1:24 000, 1967

Figure 1.-- Location of the Franklin area.

2.0 POTENTIAL AQUIFERS

2.1 Bedrock and solution openings

GROUND WATER OCCURS IN SOLUTION OPENINGS IN LIMESTONE

The Franklin area is underlain by a series of Ordovician limestones covered by thin overburden. The bedding characteristics of the rock affect their water-bearing potential by controlling the size of solution openings.

The rocks exposed at land surface in the Franklin area and underlying it to a depth of several thousand feet are dense limestones and dolomites with minor amounts of shale. The sequence, exposed thickness, and bedding characteristics are given in table 1. The rocks are covered by thin overburden exceeding 20 feet in thickness only locally.

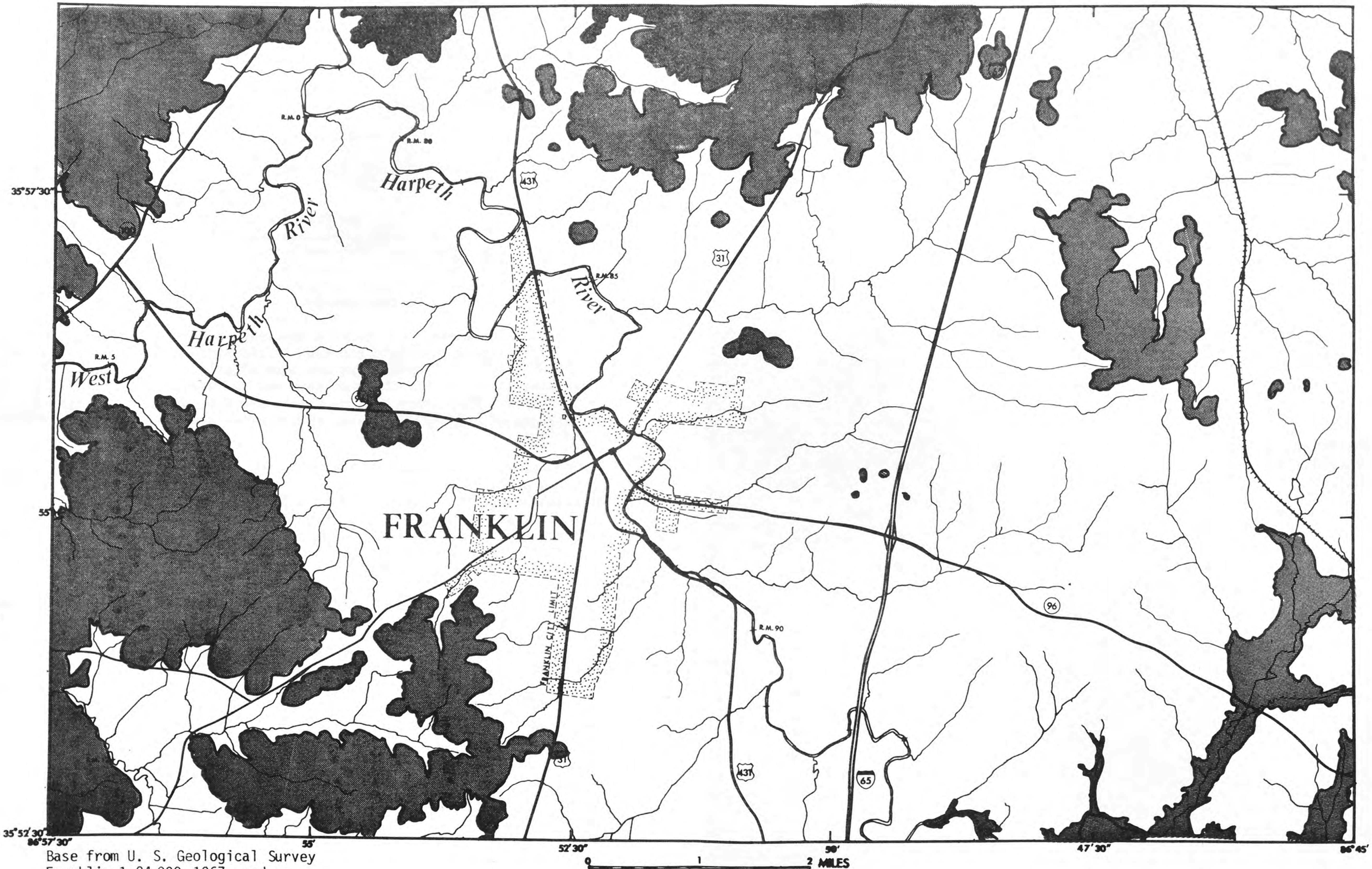
Most of the ground water derived from the limestone occurs in irregularly spaced solution openings formed by water from precipitation seeping through joints and bedding planes in the rock. The circulating water dissolves calcium carbonate and enlarges the openings to allow freer passage of ground water. Because ground water circulation is most vigorous within 50 to 100 feet of land surface, solution openings are most likely to occur in this interval. Openings are less abundant at greater depths.

The size of the horizontal and vertical solution openings is an important factor controlling the rate at which water can be produced by wells. Most wells obtain water from horizontal openings along bedding planes. Solution openings in the Franklin area range in height from cracks a fraction of an inch high that produce less than 1 gal/min to water-filled cavities as much as 10 feet high. In order for solution openings to increase in size, the surrounding rock mass must be strong enough to support the weight of the overlying rock. Medium- and thick-bedded limestones are capable of developing openings of sufficient size to yield large amounts (more than 100 gal/min) of water. The thin-bedded limestones contain solution openings but these openings usually do not develop to more than a fraction of an inch in height before subsidence occurs. The areal distribution of the medium- and thick-bedded limestones are shown in figure 2 as potential aquifers.

Table 1.--Rock units exposed at land surface in the Franklin area. Medium- and thick-bedded formations are considered to be potential aquifers. Bedding characteristics are indicated as follows:
S = thin- bedded, M = medium- bedded, T = thick- bedded

Age	Mississippian	Devonian	Silurian	Ordovician					
Formation(1)	Fort Payne Formation	Chattanooga Shale	Brassfield Limestone	Sequatchie Formation	Leipers & Catheys Fms.	Bigby-Cannon Limestones	Hermitage Formation	Carters Limestone	Lebanon Limestone
Maximum exposed thickness in feet.	220	10	30	15	200	130	100	80	30
Bedding	(2)	S	S	S	S	S to M	S to M	S to T	S

(1)Nomenclature is that used by the Tennessee Division of Geology.
(2)Mostly weathered to chert blocks and clay.



Base from U. S. Geological Survey
Franklin 1:24 000, 1967, and
Leipers Fork 1:24 000, 1967

Figure 2.--Areal distribution of potential aquifers in the Franklin area. The unshaded areas contains medium- or thick-bedded rock units which, at the optimum depth below land surface, may provide large ground-water supplies. Shaded areas contain thin-bedded rock units units and clay size material which is unlikely to yield large amounts of ground-water. (See Table 1 for formal name and age of the rock units)

2.0 POTENTIAL AQUIFERS

2.2 Structure and ground-water movement

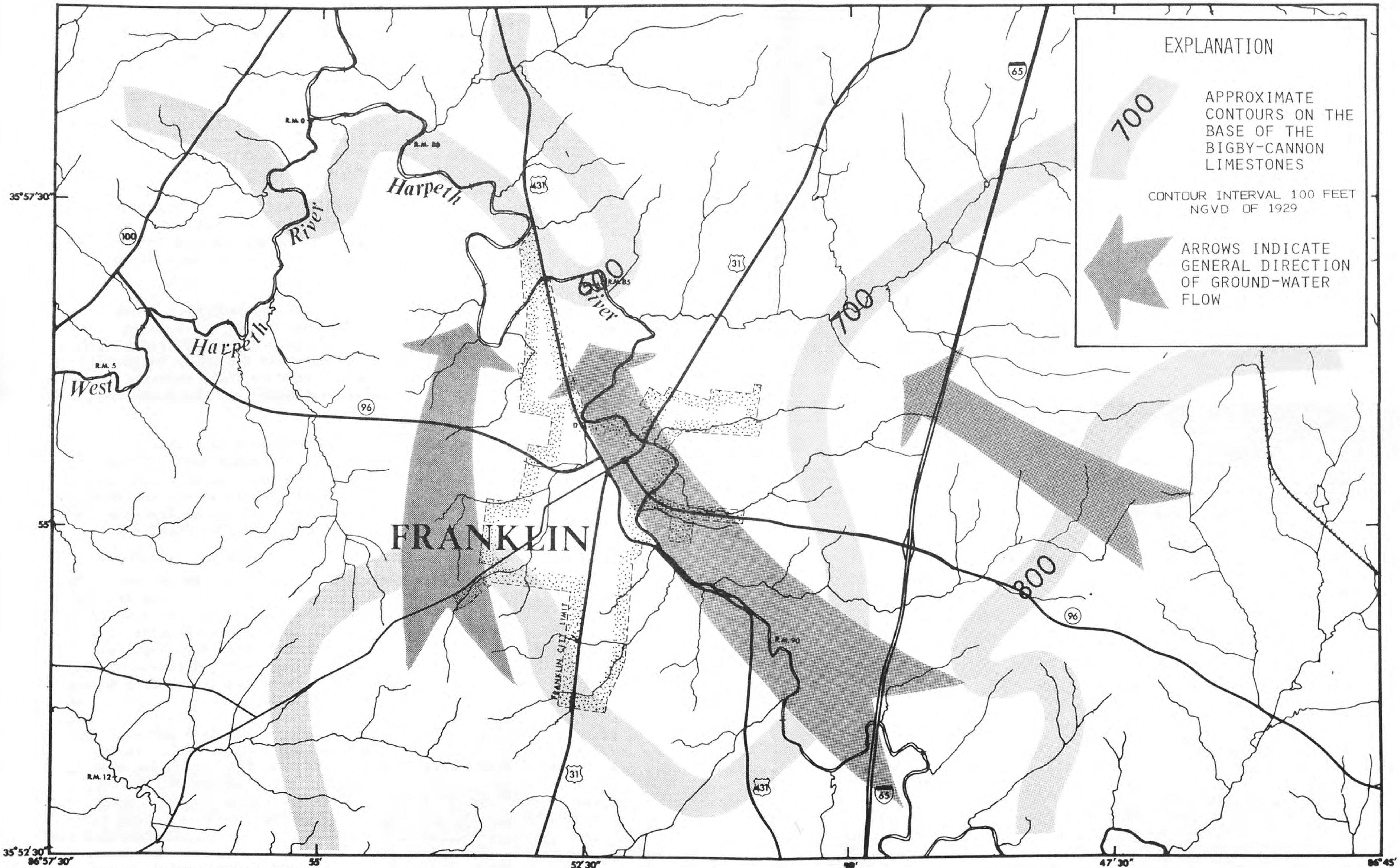
GROUND-WATER FLOW PATHS ARE RELATED TO TOPOGRAPHY AND BEDROCK STRUCTURE

Ground water in the Franklin area moves from highland areas to lowland discharge points following the irregular flow paths provided by bedding planes and fractures in the rock. Structural highs and lows in the bedrock enhance or retard ground-water flow depending on their relation to flow patterns.

The carbonate rocks beneath Franklin are mostly flat lying. However, structural highs and lows in the bedrock can be detected and mapped (fig. 3). These highs and lows control the orientation of bedding planes within the rock unit and the distribution of stress fractures. When these bedding planes and fractures are enlarged by solution of calcium carbonate, they provide avenues for ground-water movement.

Ground water moves from areas where water levels are high toward areas where they are low. In limestone, it must follow the irregularities of the flow paths formed by openings in the rock. It appears that larger solution openings tend to develop in structural lows. It is not known, however, to what degree the structural lows influence ground-water flow or to what extent the lows are actually produced by subsidence of solution channels rather than tectonic activity.

Ground water in the Franklin area is under water-table conditions; recharge occurs fairly uniformly throughout the area. The major discharge points are springs and streams in low-lying areas. Thus, directions of ground-water movement tend to be similar to those of surface streams, from the highlands to the lowlands and along major stream valleys. Areas where structural lows coincide with topographic lows are favorable areas for the development of large solution openings.



Base from U. S. Geological Survey Franklin 1:24 000, 1967, and Leipers Fork 1:24 000, 1967

Figure 3.-- Altitude of the base of the Bigby-Cannon Limestones, showing general direction of ground-water movement. Contours generalized from contact altitudes shown on geologic maps(Wilson and Miller, 1963, and Morrow and Wilson, 1963.)

2.0 POTENTIAL AQUIFERS

2.3 Well inventory

RECORDS FOR DOMESTIC WELLS ARE NOT A RELIABLE INDICATOR OF AQUIFER POTENTIAL

The average reported yield of 100 wells in the Franklin area is 5 gal/min. However, these wells commonly do not penetrate the full aquifer thickness and are not located at sites hydrologically favorable for obtaining maximum yields.

Most wells in the Franklin area are drilled only to a depth where a domestic supply is obtained; the well sites are located near a dwelling rather than in a spot that is the most hydrologically suitable place for ground water; and yields are generally estimated rather than measured. All these factors tend to limit reported yields to less water than is actually available from the limestone aquifers.

Since 1963, most new water wells in Tennessee have been reported to the Division of Water Resources by State-licensed well drillers. The driller's report includes information on total depth of the well, overburden thickness, depth to the water-bearing zone, and estimated well yield. One hundred wells have been reported in the Franklin and Leipers Fork 7½ minute quadrangles. Almost all these wells are for domestic use.

Depths of reported wells average 220 feet. They range from 25 feet to 1,936 feet in depth. However, 87 percent of the wells are drilled deeper than 50 feet and only 24 percent are deeper than 200 feet (fig. 4). Well depths of 50 to 200 feet may be considered representative of the effort required to obtain a domestic water supply of 3 to 5 gal/min. Because the wells commonly do not penetrate the full thickness of the water-bearing formation and underlying potential aquifers, they do not define the maximum depth at which ground water occurs.

Average yield for wells in the two quadrangles is 5 gal/min. The maximum reported yield is 40 gal/min and the minimum is 0. Forty percent of the wells are reported to yield more than 3 gal/min whereas only 6 percent are reported to yield more than 24 gal/min (fig. 4). Of the seven wells that produced 25 gal/min or more, four obtained water from the Bigby-Cannon Limestones. The sources of water for the other three were the Hermitage Formation, the Lebanon Limestone, and the Leipers and Catheys Formations (undifferentiated).

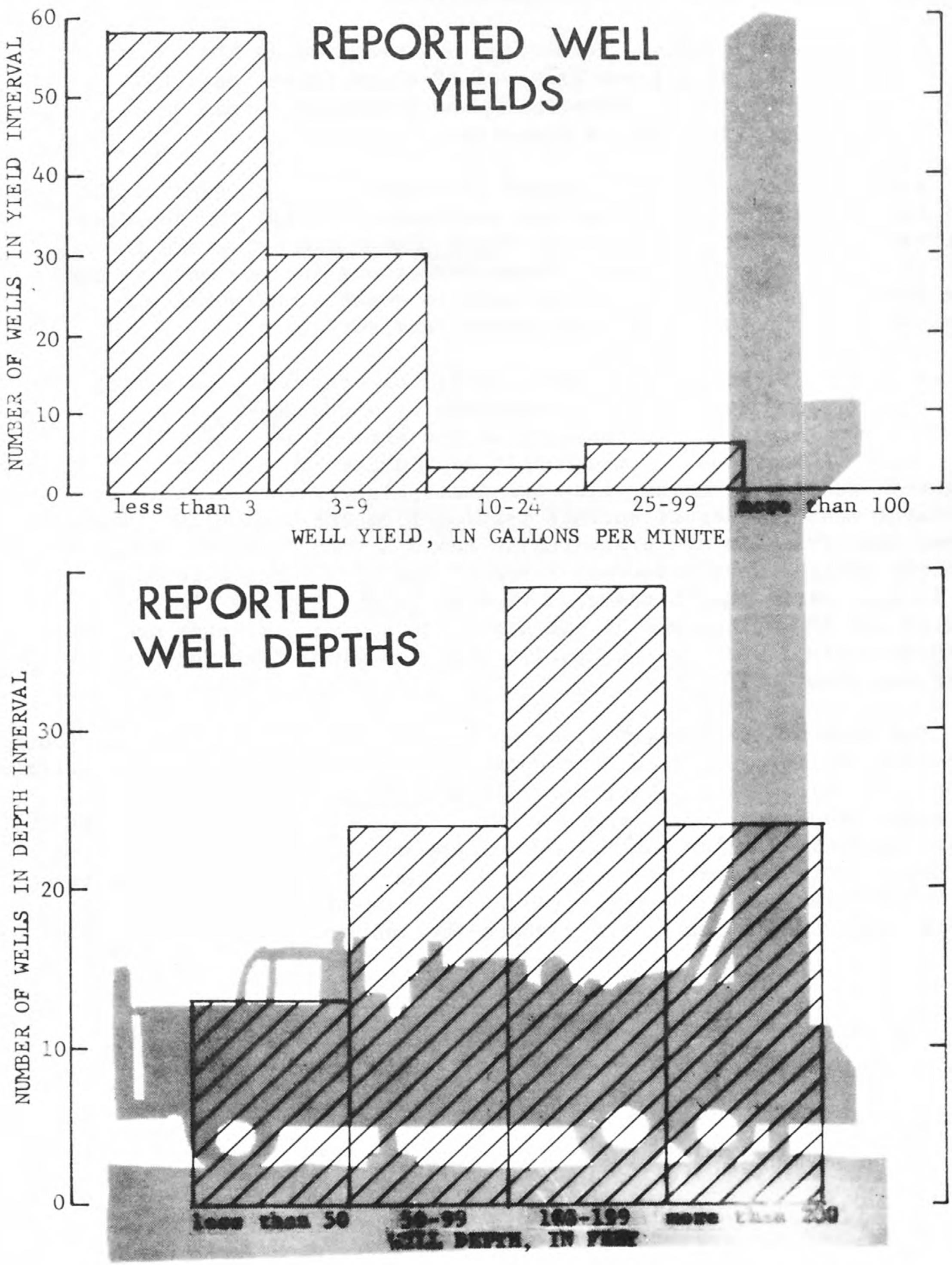


Figure 4.--Reported well yields and depths in the Franklin and Leipers Fork quadrangles.

2.0 POTENTIAL AQUIFERS

2.4 Spring inventory

SPRINGS INDICATE POTENTIAL AQUIFERS

Seventeen springs identified and measured in the Franklin area issue from one of three formations: the Bigby-Cannon Limestones, the Hermitage Formation, or the Carters Limestone.

Figure 5 shows the locations of 17 springs. It is significant that the outlets of all the springs are located within the geologic interval between the middle of the Bigby-Cannon Limestones and the base of the Carters Limestone. These formations include massive beds that have the potential to develop solution-opening networks when they are less than about 200 feet below land surface.

According to Rima and Goddard (1979) the presence of a spring is a positive indication of the existence of a ground-water reservoir, and the type, yield, and variability of the springs are reliable indicators of the magnitude of the supply available. Unfortunately, no long-term records of spring flow are available for the Franklin area. Discharge measurements of springs issuing from the Ordovician limestones near Franklin are presented in table 2. On June 16, 1975, when the springs were measured, three of the 17 springs were dry. The largest spring had a measured flow of 79 gal/min and the average flow of all 17 springs was 21 gal/min. The spring discharge measurements in table 2 were made at a time when the flow of the Harpeth River was about half of average.

The Head of the Harpeth River Spring is about 20 miles to the southeast of Franklin. The flow from this spring was 2.04 ft^3/s (915 gal/min) on July 3, 1975. This spring provides a major part of the flow in the upper reaches of the Harpeth River. The source of this water is the Ridley Limestone, which underlies the Lebanon Limestone and occurs at depths of 50 to several hundred feet or more beneath the Franklin area. The Ridley Limestone, therefore, is also believed to be a potential aquifer where it is sufficiently close to land surface.

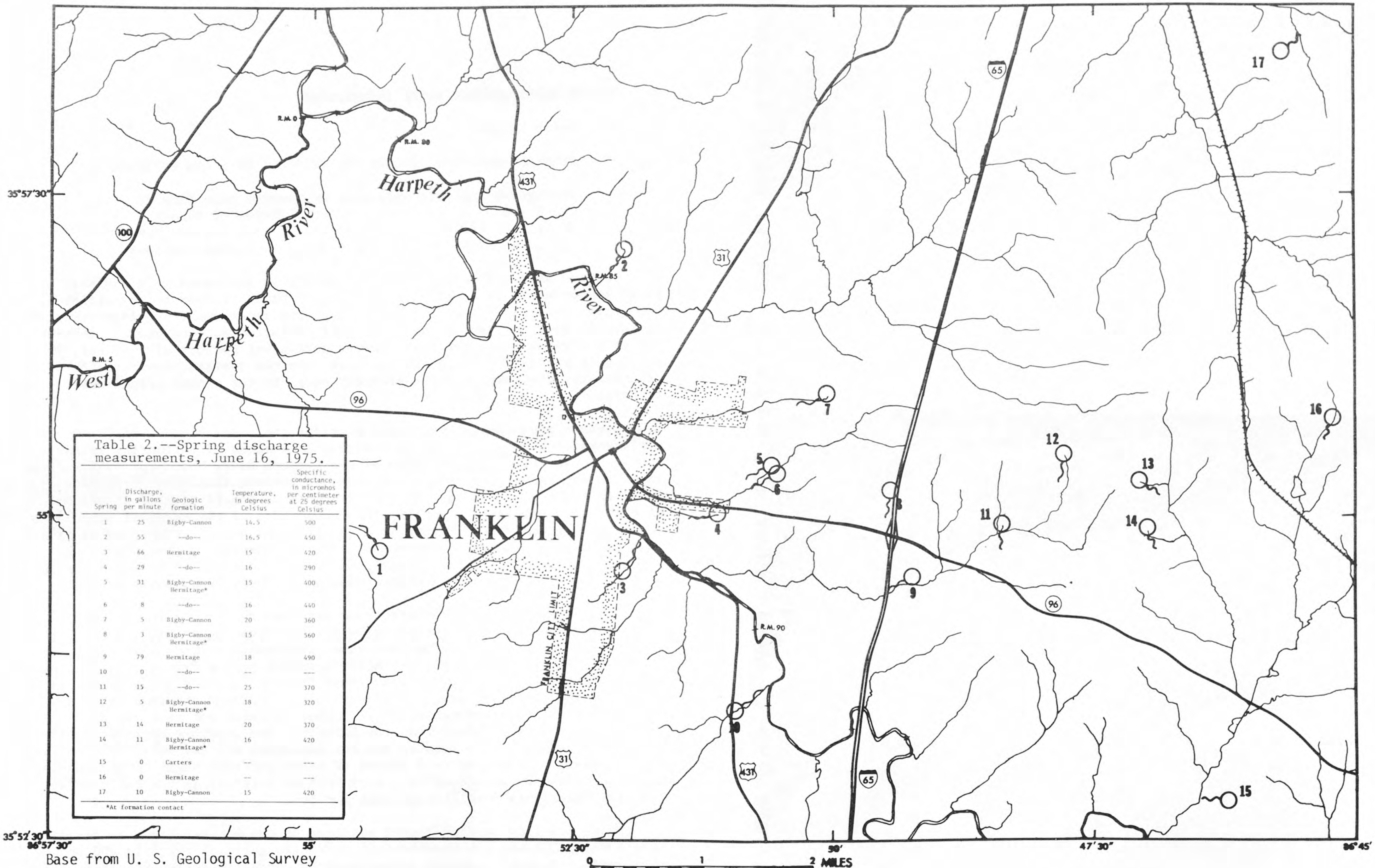


Table 2.--Spring discharge measurements, June 16, 1975.

Spring	Discharge, in gallons per minute	Geologic formation	Temperature, in degrees Celsius	Specific conductance, in micromhos per centimeter at 25 degrees Celsius
1	25	Bigby-Cannon	14.5	500
2	55	--do--	16.5	450
3	66	Hermitage	15	420
4	29	--do--	16	290
5	31	Bigby-Cannon Hermitage*	15	400
6	8	--do--	16	440
7	5	Bigby-Cannon	20	360
8	3	Bigby-Cannon Hermitage*	15	560
9	79	Hermitage	18	490
10	0	--do--	--	---
11	15	--do--	25	370
12	5	Bigby-Cannon Hermitage*	18	320
13	14	Hermitage	20	370
14	11	Bigby-Cannon Hermitage*	16	420
15	0	Carters	--	---
16	0	Hermitage	--	---
17	10	Bigby-Cannon	15	420

*At formation contact

Base from U. S. Geological Survey
Franklin 1:24 000, 1967, and
Leipers Fork 1:24 000, 1967

Figure 5.-- Location of springs in the Franklin area.

3.0 GROUND WATER-SURFACE WATER INTERACTION

3.1 Water budget

RECHARGE RATE OF 8 INCHES PER YEAR MAY BE A LOW ESTIMATE

Hydrograph analysis indicates an average base flow in the Harpeth River basin of about 8 inches of runoff per year. The ground-water recharge rate may be higher due to subsurface flow not measured by gaging stations.

In many ways, the ground-water reservoir is analogous to a surface-water impoundment; on an annual or long term basis, inflow to an outflow from a reservoir are approximately equal. The impoundment provides temporary storage to even out variations in streamflow throughout the year. Likewise the ground-water reservoir stores water during wet periods of the year, releasing it gradually throughout the year. On the average, however, the ground-water discharge is approximately equal to the annual ground-water recharge.

Because ground-water discharge provides the basic flow of streams, surface-water hydrographs can be analyzed as a means of estimating recharge rates. An analysis of streamflow of the Harpeth River basin for 1968, a year in which the annual streamflow was close to average throughout Tennessee, is shown in figure 6. The base flow of 8 inches of runoff equaled 18 percent of the year's rainfall. Probably this proportion of the rainfall circulates through the ground-water reservoir annually. The normal proportion of rainfall recharging the ground-water system may be somewhat higher due to the unusual distribution of the rainfall in 1968. A dry period occurred during the winter, at the time when most ground-water recharge normally occurs.

This estimate of the recharge rate may also be low due to the fact that significant amounts of subsurface flow may be occurring at the points where surface flow is measured. Two long-term, continuous record gaging stations have been operated on the Harpeth River downstream from Franklin. The annual average streamflow for these two stations is equivalent to 19 inches of rainfall over the basin per year. Stations on the Duck and Stones Rivers show that these streams discharge 21 to 26 inches of water per year yet have only 1 to 2 inches more rainfall than the Harpeth. One possible explanation is that the stations on the Harpeth are not measuring all the water that is leaving the basin. If so, up to 7 inches of water per year might be leaving the basin as ground-water underflow. Each inch of rainfall in the basin above Franklin represents 9 million gallons per day.

Three low-flow partial-record stations on the Harpeth River in Franklin have a 3-day 20-year low flow of 0.05 ft^3/s (20 gal/min) for this 200 square mile basin. However, seepage investigations conducted during the study indicated that all three of these low-flow stations are located in losing reaches of the river. Gaining reaches of the river would have substantially more water than this for the same frequency.

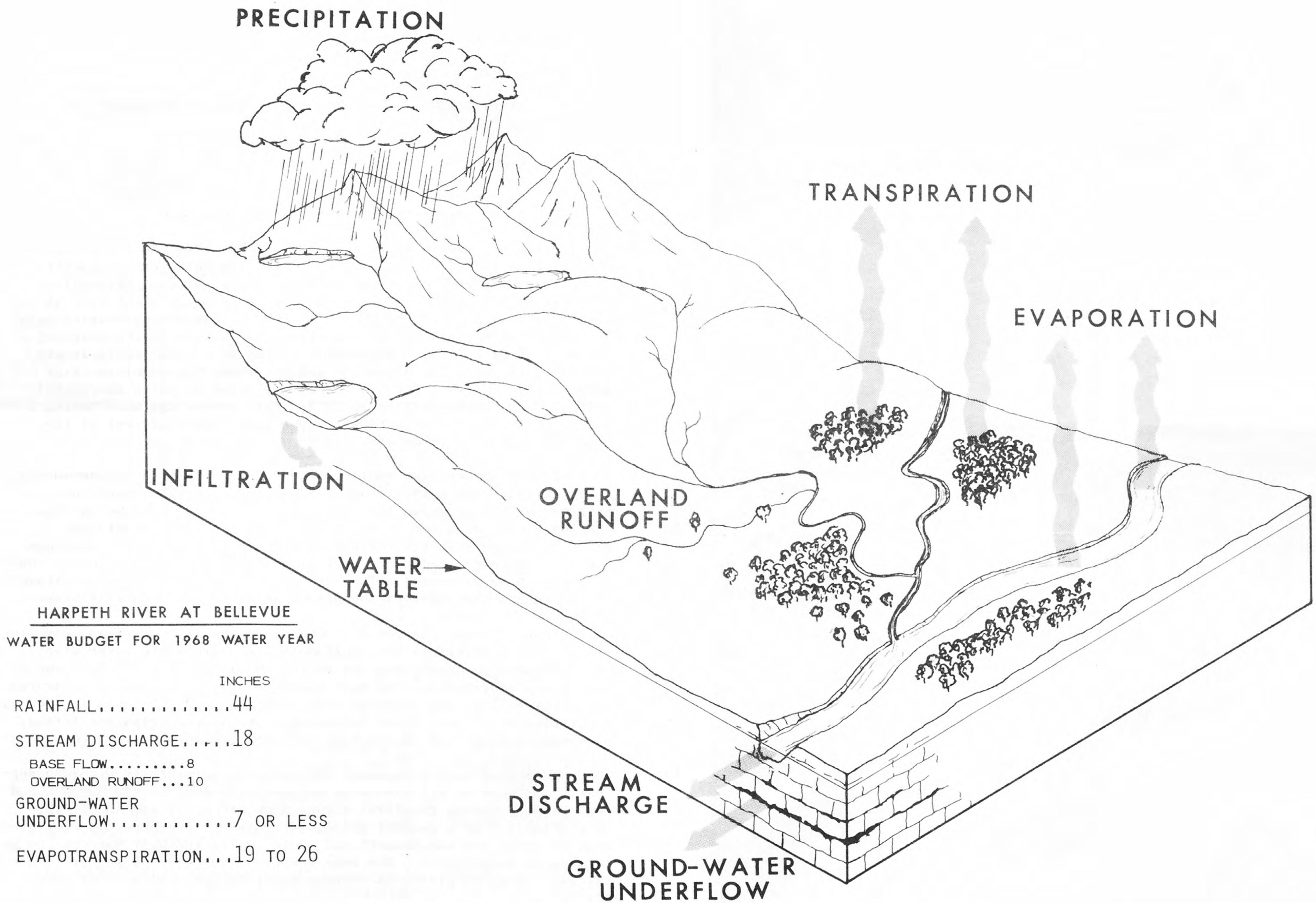


Figure 6.-- The hydrologic cycle and estimated water budget for 1968, a near-average year, in the Harpeth River basin. (modified from Rima and Goddard, 1979)

3.0 GROUND WATER - SURFACE WATER INTERACTION

3.2 Stream surveys

SIGNIFICANT GAINS AND LOSSES IN STREAMFLOW OCCUR IN THE FRANKLIN AREA

Gains and losses as great as 15 to 20 percent of streamflow indicate exchange of water between the rivers and solution openings in the Bigby-Cannon Limestones and upper part of the Hermitage Formation.

A stream survey was conducted May 21-22, 1975, during a high base flow period of the Harpeth and West Harpeth Rivers to identity areas where the streams are gaining and losing water. Streamflow was measured at 166 river and tributary sites along a total of 64 river miles. On August 2, 1976, a second stream survey covered only an 8-mile reach of the Harpeth River from Franklin to the mouth of the West Harpeth River. The second survey was conducted to locate points of ground-water discharge and determine the quantity of ground water entering the river near two sites at which successful test wells had been drilled in 1975. This survey was made during a period of low baseflow; streamflow was less than 5 percent of the flow during the previous stream survey.

Significant changes in flow were detected in both stream surveys. It is certain that most, if not all, of these changes cannot be attributed to unmeasured tributaries. These large changes in flow are indicative of water leaving or entering the stream through solution openings in the bedrock. The occurrence of these openings can be related to geologic intervals and their occurrence in the subsurface can be predicted. They are also indicative of the magnitude of the interaction between the stream and the ground-water system.

Figure 7 shows changes in flow at successive downstream measuring sites. The differences are plotted at the appropriate river mile (the distance upstream from the mouth, in miles) with the left end of each graph representing the most upstream site. Because all measured tributary inflows are deducted, the increases and decreases in flow can be atrributed to one of the following: unmeasured tributary inflow, measurement error, or interaction with the ground-water system.

The method used to measure discharge is accurate to within 5 percent. The mean of all discharge measurements made on the Harpeth and West Harpeth during the first survey was 140 ft^3/s and 100 ft^3/s, respectively. As a general guide, increases or decreases in flow greater than 12 ft^3/s for the Harpeth and 10 ft^3/s for the West Harpeth can be considered significant. The mean measured flow for the August 1976 survey was 7.5 ft^3/s giving an average error range of plus or minus 0.4 ft^3/s.

The most active reach of the West Harpeth River was between river mile 1.3 and 4.2 where the river alternately gained and lost 13 to 16 ft^3/s at five measurement sites. In the most active reach of the Harpeth River, between river mile 85.7 and 84.4, the greatest loss was 36 ft^3/s and the greatest increase was 31 ft^3/s. The locations of major increases and decreases of streamflow for the Harpeth and West Harpeth River occur where the rivers are flowing across the Bigby-Cannon Limestones or across the top of the Hermitage Formation near the contact with the overlying Bigby-Cannon.

Significant net increases in streamflow were measured August 1976 at both the F-3 and F-12 drilling sites (shown on fig. 7). The magnitude of the increases depends on where minimum and maximum streamflow is picked within each well's area of influence. Between river mile 86.3 and 84.7 there was an increase of 0.8 ft^3/s (20 to 57 percent). Between river mile 81.3 and 79.8, there was an increase of 1.6 ft^3/s to 2.4 ft^3/s (36 to 54 percent). These increases are equivalent to a ground-water discharge of 0.5 to 1.3 million gallons per day at the F-3 site and 1.0 to 1.5 million gallons per day at the F-12 site.

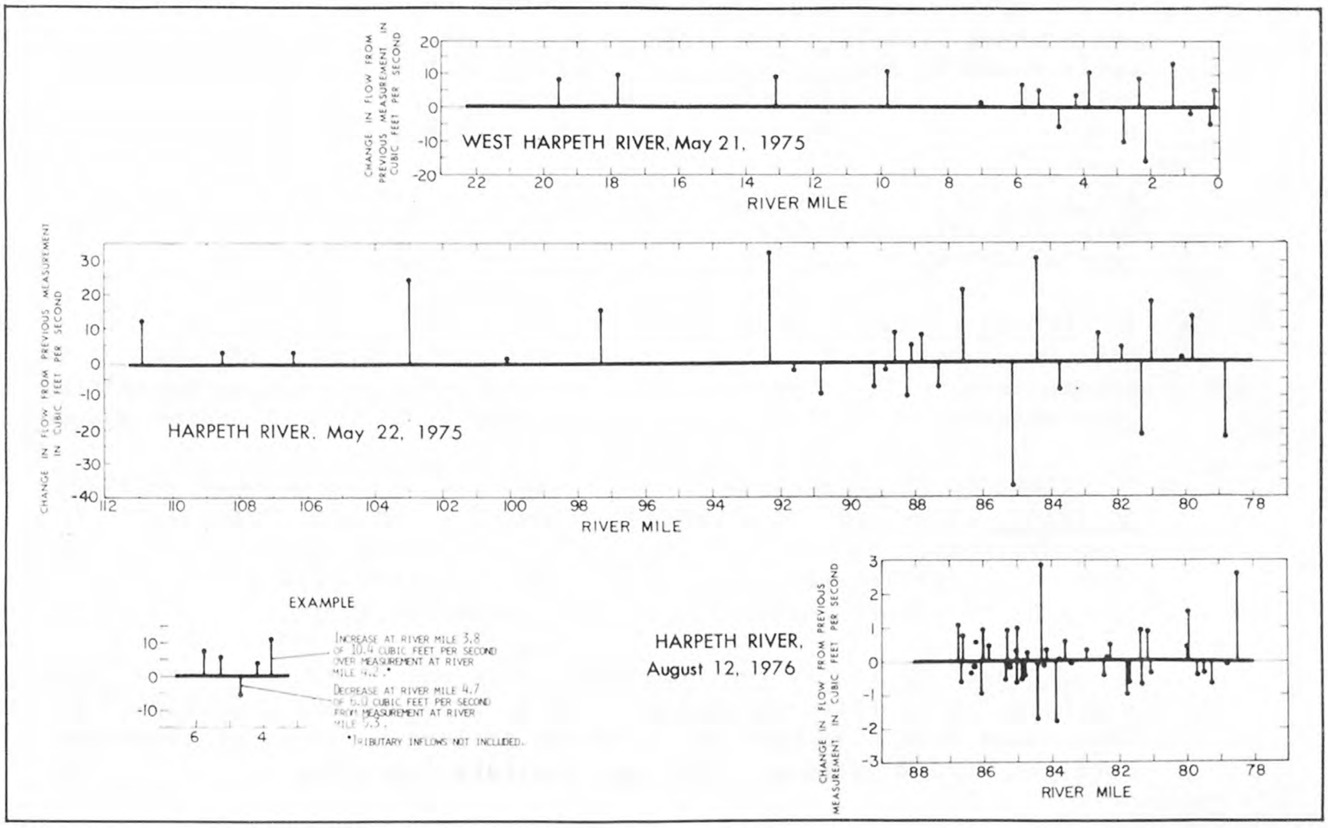


Figure 7.-- Streamflow gains and losses on the Harpeth and West Harpeth Rivers. Tributary inflows not included.

4.0 TEST WELLS AND HYDRAULIC RELATIONSHIPS AT TEST SITES

4.1 Site selection factors

HYDROLOGIC AND GEOLOGIC CRITERIA USED TO SELECT DRILLING SITES

Factors considered in site selection included presence of medium or thick-bedded limestones, location in a structural low, location near an active reach of Harpeth River, presence of topographic features such as straight streams and elongated sinkholes, and presence of linear features.

Twenty-five test wells were drilled in the Franklin area between November 1974 and November 1976 (fig. 8). Fifteen sites were chosen on the basis of hydrologic and geologic criteria. The additional 10 wells were drilled to determine the properties and the geometry of the aquifers at the F-3 and F-12 sites. F-3 and F-12 were the highest-yielding of the first 15 test wells.

Criteria for the selection of drilling sites were the following:

1. Presence of a medium- to thick-bedded limestone beginning 50 to 100 feet below land surface. Well and spring records and stream surveys indicated that the Bigby-Cannon Limestones would be a productive aquifer in the area. In the vicinity of Franklin, however, the Bigby-Cannon is not present at sufficient depth to supply water to wells. All of the wells began in Bigby-Cannon or the upper part of the Hermitage except well F-6 which begain in the Carters Limestone. Its target was the Ridley Limestone. The other wells tested the Hermitage and Carters.

2. Location in a structural low in the bedrock. The lowlands along the Harpeth River, where most of the wells are located, correspond in a general way to a curving, northwest-trending bedrock low.

3. Location near active reaches of the Harpeth River. From about river mile 90 to the mouth of the West Harpeth, considerable exchange of water occurs between the river and underlying solution openings, suggesting greater development of permeability in the rock than in upstream areas.

4. Presence of topographic features indicative of possible solution activity. Low-lying areas were considered to be favorable places for test drilling. In addition, small-scale features (less than 0.25 mile) such as elongated sink holes influenced the final selection of drilling sites as they were thought to indicate solution activity.

5. Presence of linear features observable on low-altitude areal photography. Linear features in the Franklin area are shown on figure 8. They range from 0.25 mile to 2.5 miles in length. Many of these are straight stream valleys. They may indicate fractures in the bedrock.

6. Other factors. Wells F-4, F-5, and F-15 are located near a building with a basement which must be pumped at rates up to 585 gal/min during wet weather. The wells were drilled to determine whether flow to the basement was from a shallow horizontal solution opening or whether ground-water occurred at depth and was discharging upward into the basement. Well F-14 was located in the vicinity of a reported high-yielding well.

Significant criteria at each drilling site are listed in table 3.

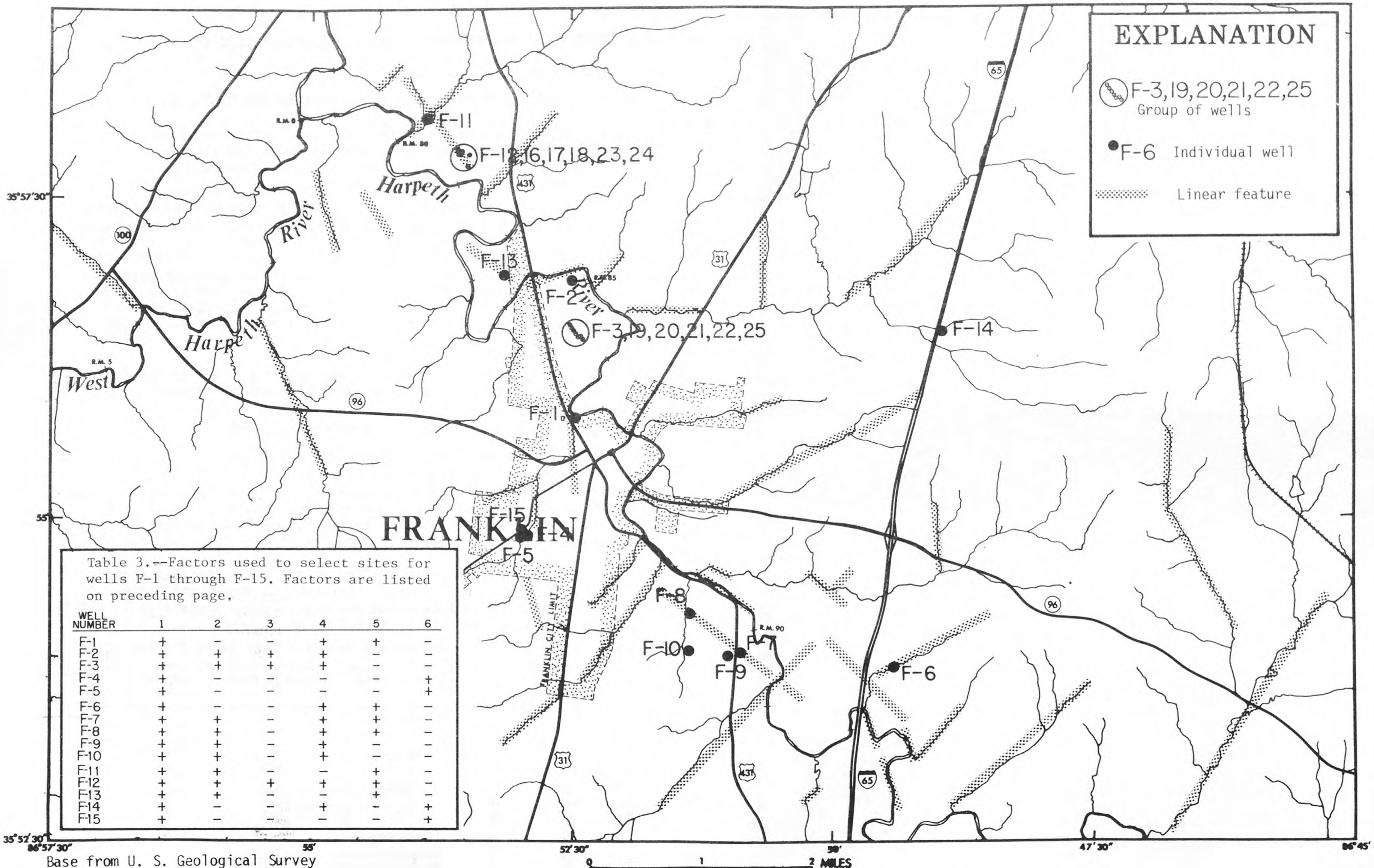


Table 3.--Factors used to select sites for wells F-1 through F-15. Factors are listed on preceding page.

WELL NUMBER	1	2	3	4	5	6
F-1	+	−	−	+	+	−
F-2	+	+	+	+	−	−
F-3	+	+	+	+	−	−
F-4	+	−	−	−	−	+
F-5	+	−	−	−	−	+
F-6	+	−	−	+	+	−
F-7	+	+	−	+	+	−
F-8	+	+	−	+	+	−
F-9	+	+	−	+	−	−
F-10	+	+	−	+	−	−
F-11	+	+	−	−	+	−
F-12	+	+	+	+	+	−
F-13	+	+	−	−	+	−
F-14	+	−	−	+	−	+
F-15	+	−	−	−	−	+

Base from U. S. Geological Survey
Franklin 1:24 000, 1967, and
Leipers Fork 1:24 000, 1967

Figure 8.-- Location of test wells and linear features.

4.2 Wells 1 through 15

TEST WELLS PRODUCE OVER 100 GALLONS PER MINUTE AT TWO SITES

Average production from the first 15 test wells was 68 gal/min; maximum production was about 600 gal/min. Solution openings occurred over a wide range of depths in all of the formations tested.

Production from the first 15 test wells, measured while blowing water from the hole with compressed air immediately after completion of the well, ranged from less than 1 to about 600 gal/min (table 4). The average production was 68 gal/min. One third of the test wells produced over 25 gal/min; only six percent of the wells reported by drillers had yields that great. Well F-3 produced 180 gal/min and F-12 produced an estimated 600 gal/min, which is 15 times the maximum reported yield for the area. The F-3 and F-12 sites were chosen for further investigation.

The average depth of the wells was 225 feet. All except F-12 were drilled to at least 50 feet below the lowest solution opening to assure full penetration of the solution-opening system. Overburden thickness ranged from 4 to 43 feet with an average of 17 feet.

Solution openings occurred at a variety of depths. For example, well F-4 penetrated an opening at 10 to 12 feet below land surface. This opening also supplied water to a nearby basement at rates exceeding 500 gal/min. However, no additional water-bearing zones were penetrated below 92 feet. Wells F-3, F-6, and F-12, however, produced considerable amounts of water from depths greater than 100 feet.

High yielding wells were drilled in all the formations tested, including the Hermitage Formation, Carters Limestone, and Ridley Limestone. None of the test wells penetrated the Bigby-Cannon Limestones in sufficient thickness to test its potential as an aquifer.

Table 4.--Geologic and hydrologic data for test wells F-1 through F-15.

Well number	Depth of well (ft)	Depth of overburden (ft)	Water-bearing formations	Depth to water-bearing zones (ft)	Well diameter (in)	Production rate 1/ (gal/min)
F-1	253	13	Carters	94	6¼	0.5
F-2	228	23		none	6¼	0
F-3	153	16	Carters	103	10½	180
F-4	203	8	Hermitage	10-12	6¼	80
F-5	203	13		none	6¼	0
F-6	253	4	Ridley	128	10½	90
F-7	278	23		none	6¼	0
F-8	253	16		none	6¼	0
F-9	252	43		unknown	6¼	1
F-10	278	10	Carters	71	6¼	5
F-11	250	9	Hermitage,Carters	99,123,195	6¼	8
F-12	192	40	Hermitage,Carters	60-170	10½	600(est)
F-13	225	12	Carters	182?	6¼	1
F-14	175	9	Hermitage	7-9	6¼	40
F-15	173	15	Hermitage	18,20,22	6¼	20

1/ measured while blowing water from the well with compressed air

Figure 9 consists of lithologic and geophysical logs for the first 15 wells. They are included both for their descriptive value and for comparison between wells.

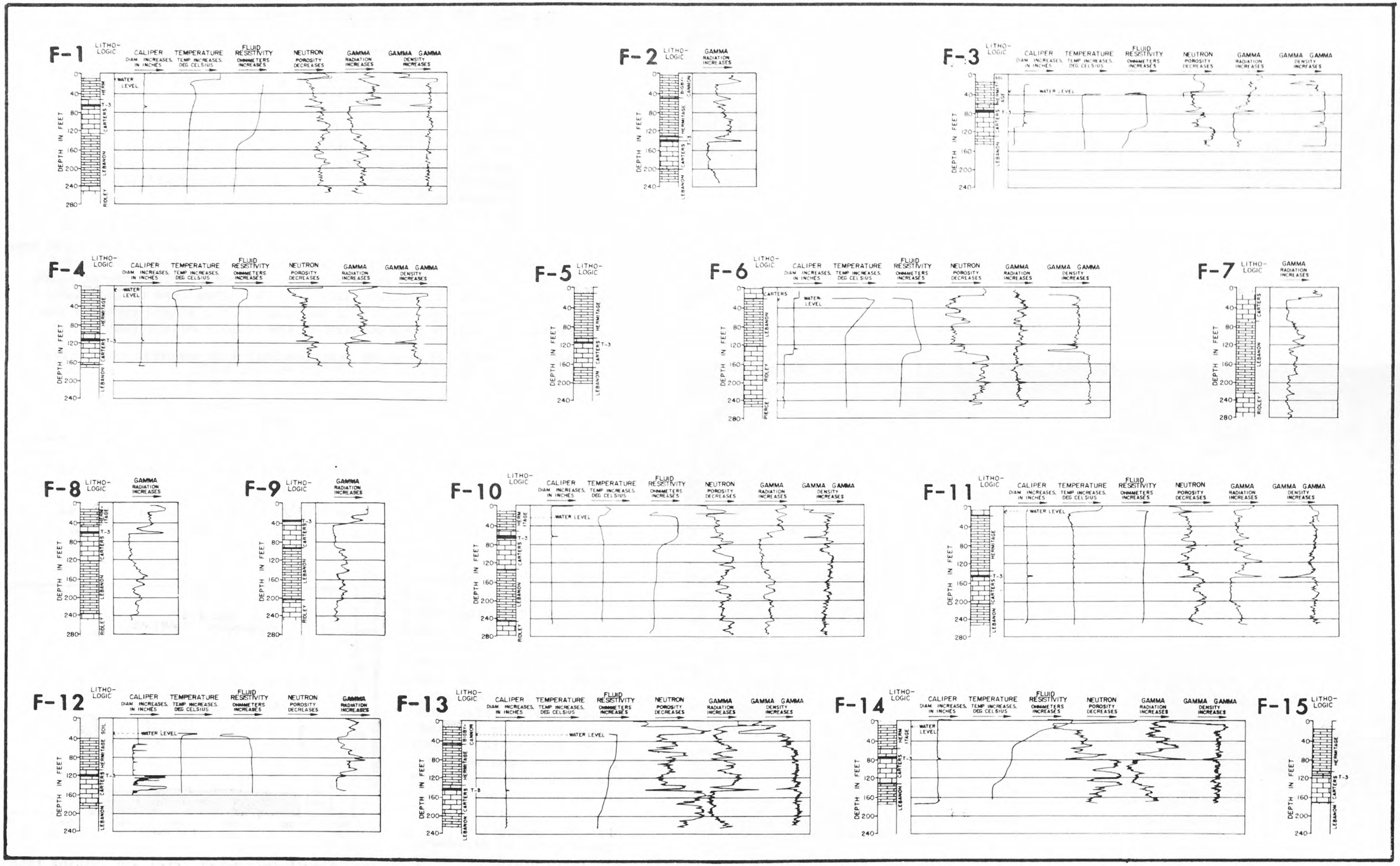


Figure 9.-- Lithologic and geophysical logs for test wells F-1 through F-15. Those unfamiliar with the application of geophysical logs to hydrologic studies are referred to Keys and MacCary, 1971.

4.3 Pumping tests of wells F-3, F-4, F-6, and F-12

SPECIFIC CAPACITIES FROM 0.6 to 357 GALLONS PER MINUTE PER FOOT OF DRAWDOWN AFTER 8 HOURS

Eight-hour pumping tests of the four most productive test wells indicated wide variation in capacity. Pumping rates ranged from 70 to 225 gal/min. Specific capacities after 8 hours ranged from 0.6 (gal/min)/ft of drawdown for F-6 to 357 (gal/min)/ft for F-12 which had a drawdown of only 0.56 feet.

Of the first 15 test wells, the four best were pumped for eight hours each to determine their specific capacities. Wells F-3, F-4, and F-6 were pumped at various rates to find the maximum pumping rate at which water levels would stabilize. This level was then used to calculate the specific capacity. Well F-12 was pumped at a single rate for the entire test. Table 5 is a summary of the results of the tests.

Table 5.--Summary of pumping test results, with specific capacities, for test wells F-3, F-4, F-6, and F-12.

Well Number	Date of test	Duration of test, in hours	Prepumping water level, in feet below land surface	Pumping rates, in gallons per minute	Maximum drawdown, in feet	Drawdown, in feet, after 8 hours	Average pumping rate, in gallons per minute	Specific capacity, in gallons per minute per foot of drawdown
F-3	1-6-76	8	30.27	200, 225	45.74	37.48	204	5.4
F-4	1-9-76	8	4.29	70-200	9.76	2.54	107	42
F-6	1-4-76	8	18.5	100-200	107.5	68.76	111	0.6
F-12	6-24-76	8	31.91	200	0.56	0.56	200	357

Well F-3 was pumped at nearly 200 gal/min for four hours (fig. 10) after which the discharge was increased to 225 gal/min. However, because of the limitations of the equipment, the discharge could not be kept steady at this rate. Consequently, after 1.5 hours it was reduced to 200 gal/min for the remainder of the 8-hour test. Drawdown at the end of the test was 37.5 feet, giving a specific capacity of 5.4 (gal/min)/ft of drawdown. Available drawdown during the test was 72.7 feet.

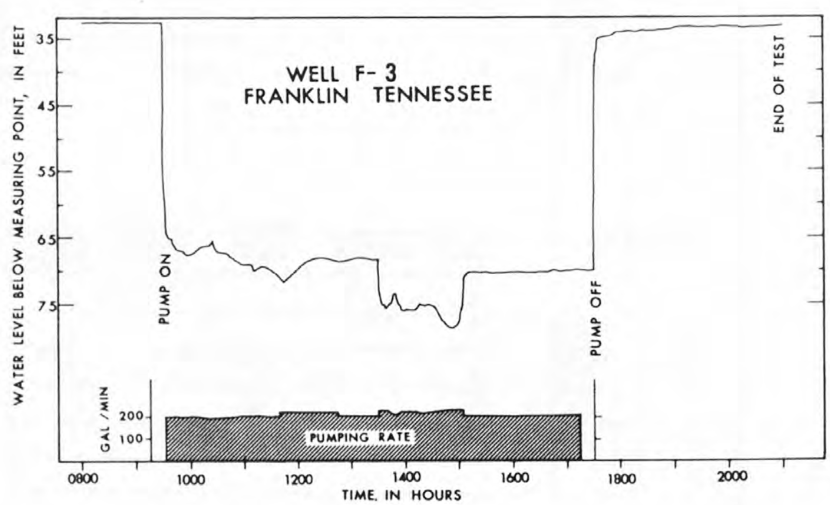


Figure 10.--Water level and pumping rate during test of well F-3.

Thirty minutes af the pump was turned off, the water level in the well had recovered 1.52 feet below the prepumping level. The following day it rose to 0.55 feet above the prepumping level, most likely because of recharge from the 1.5 inches of rain that fell during the night.

The initial pumping rate for well F-4 was 70 gal/min (fig. 11). After 1.5 hours the discharge was increased to 150 gal/min. It was pumped at this rate for 3.5 hours. At 1400 hours the discharge was increased to 200 gal/min but within four minutes after increasing the pumping rate, the discharge had declined to 167 gal/min and steadily decreased to 164 gal/min until 1415 hours.

During this period of pumping, the water level in the well declined to 11.22 feet below the measuring point, which is within 0.24 feet of the water-bearing solution opening. In addition, the water became relatively muddy. At 1415 hours the discharge was adjusted to 150 gal/min and was held there until 1532 hours. Water levels at this time were 11.18 feet below the measuring point. At 1532 the discharge was decreased to 100 gal/min for the rest of the 8 hour test. By the end of the test, the water level in the well had recovered 3.89 feet to 7.29 feet below the measuring point. This is 2.54 feet of drawdown, giving a specific capacity of 39 (gal/min)/ft at a discharge rate of 100 gal/min.

One minute after the pump was turned off the water level in the well had recovered to 0.78 feet below the prepumping water level. The water level had recovered to within 0.05 feet of the prepumping level in 185 minutes.

During the pumping test of well F-4 a basement which is 75 feet from the well was pumped at alternating rates of approximately 100 to 200 gal/min continuously. The average pumping rate from the basement was about 130 gal/min throughout the test. Pumping well F-4 had little or no effect on the discharge from the basement during the 8 hour aquifer test.

The initial pumping rate of well F-6 was 220 gal/min. At minute 2 the discharge was adjusted down to 100 gal/min and pumping continued at that rate for 5 hours (fig. 12). Based on a pumping rate of 100 gal/min for 5 hours and 68.76 feet of drawdown, the specific capacity of well F-6 is 1.5 (gal/min)/ft of drawdown. At 1330 the discharge was increased to 150 gal/min. Within 13 minutes the pump had broken suction with the water level at the pump intake, 126 feet below land surface. At 1345 hours the pumping rate was lowered to 125 gal/min for the remainder of the test. When the pump was turned off, recovery was rapid initially. However, 270 minutes after the pump was turned off, the water level was 1.08 feet below the prepumping level; after 1005 minutes it was 0.13 feet below the prepumping level.

Well F-12 was pumped at 200 gal/min the maximum output of the pump used for 8 hours (fig. 13). At the end of the pumping period, the water level was 0.56 feet below the prepumping level. Thirty minutes after the pump was turned off the water level had recovered to within 0.03 feet of the prepumping level. Ninety minutes later the water level had recovered to its prepumping level.

These data indicate that at 200 gal/min well F-12 has a specific capacity of 357 (gal/min)/ft of drawdown. Inasmuch as the principal water-producing zone in the well is 141 feet below land surface, the available drawdown (depth of water-bearing zone minus the prepumping water level) for this well is greater than 100 feet.

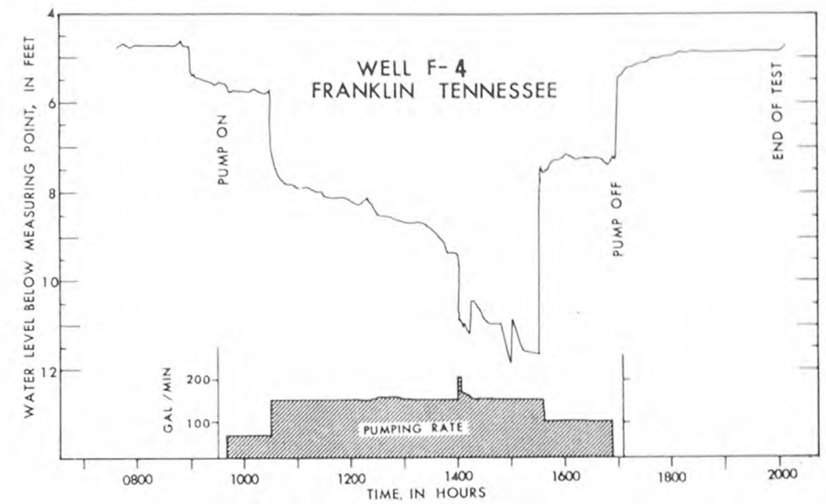


Figure 11.--Water level and pumping rate during test of well F-4.

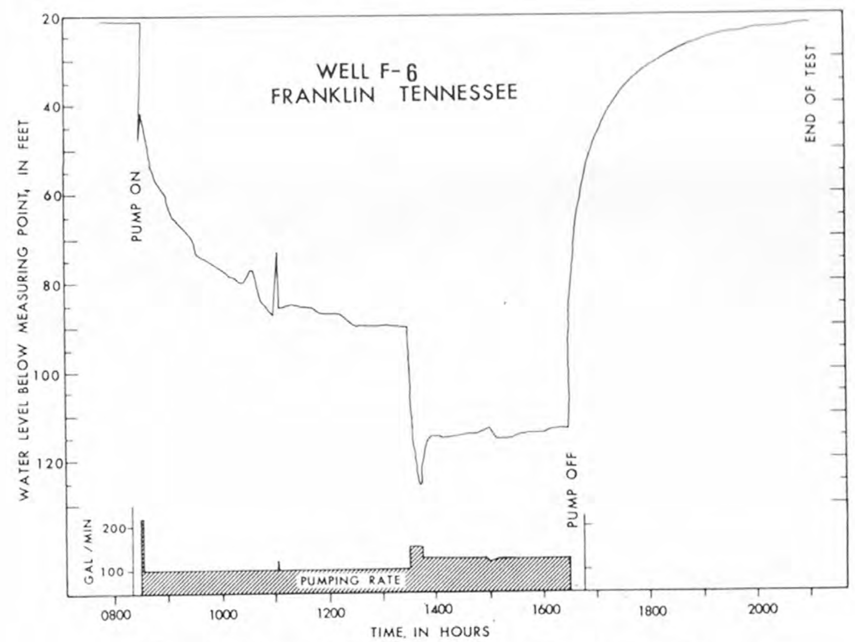


Figure 12.--Water level and pumping rate during test of well F-6.

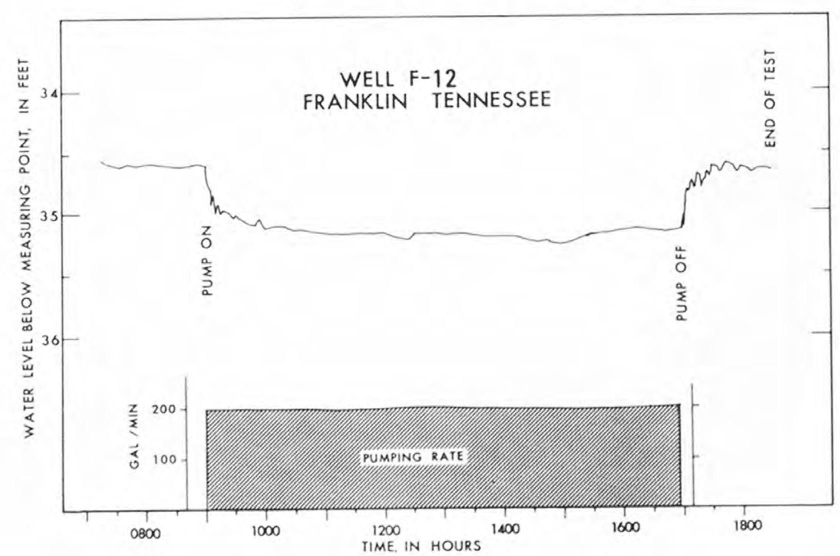


Figure 13.--Water level and pumping rate during test of well F-12.

4.4 Additional drilling near well F-3

TEST HOLES PENETRATE EXTENSIVE HORIZONTAL SOLUTION OPENING

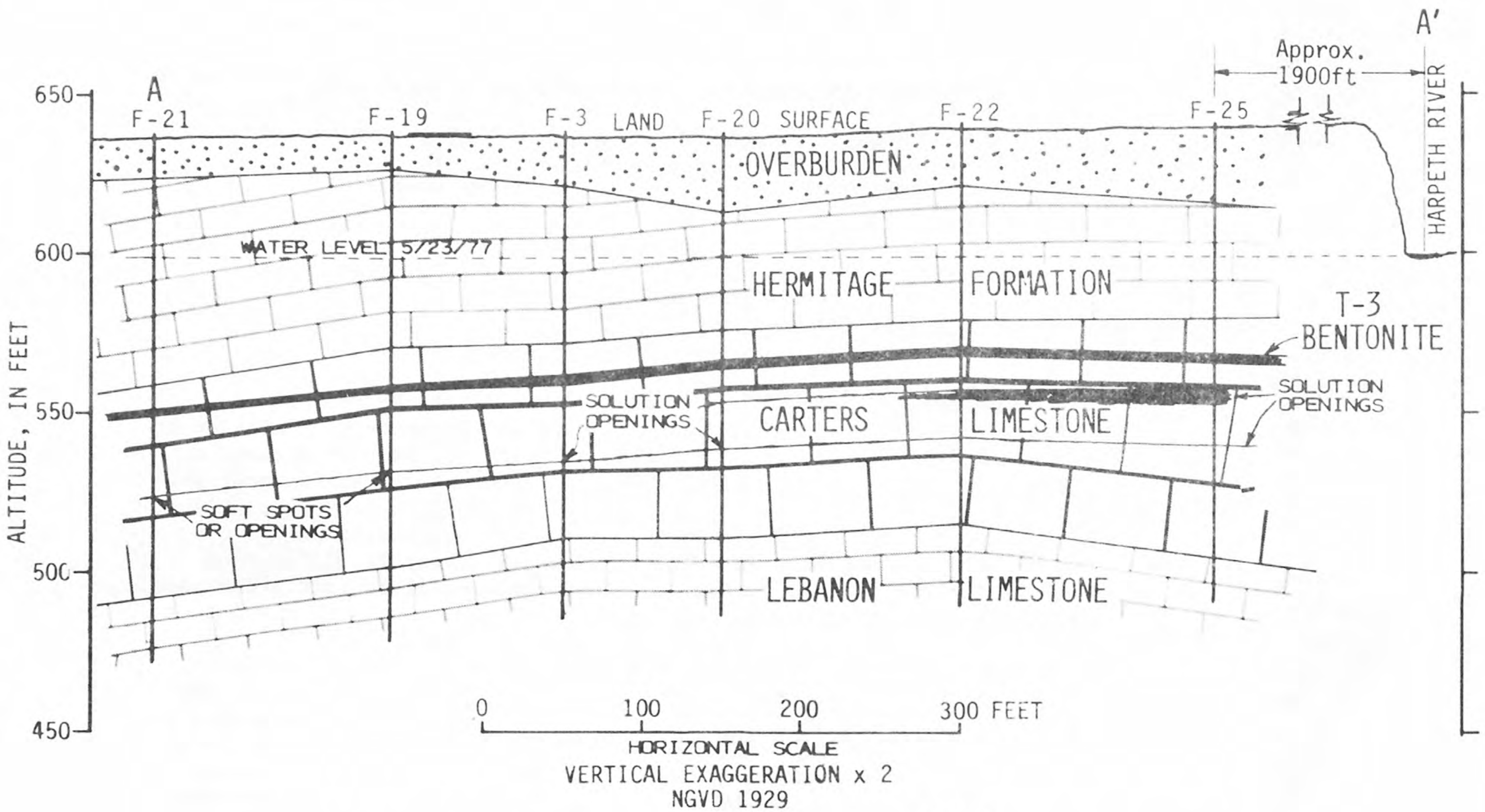
Production from test wells in an elongated sinkhole ranged from 3 to about 400 gal/min. The wells all penetrated a laterally extensive solution opening which appeared to be stratigraphically controlled.

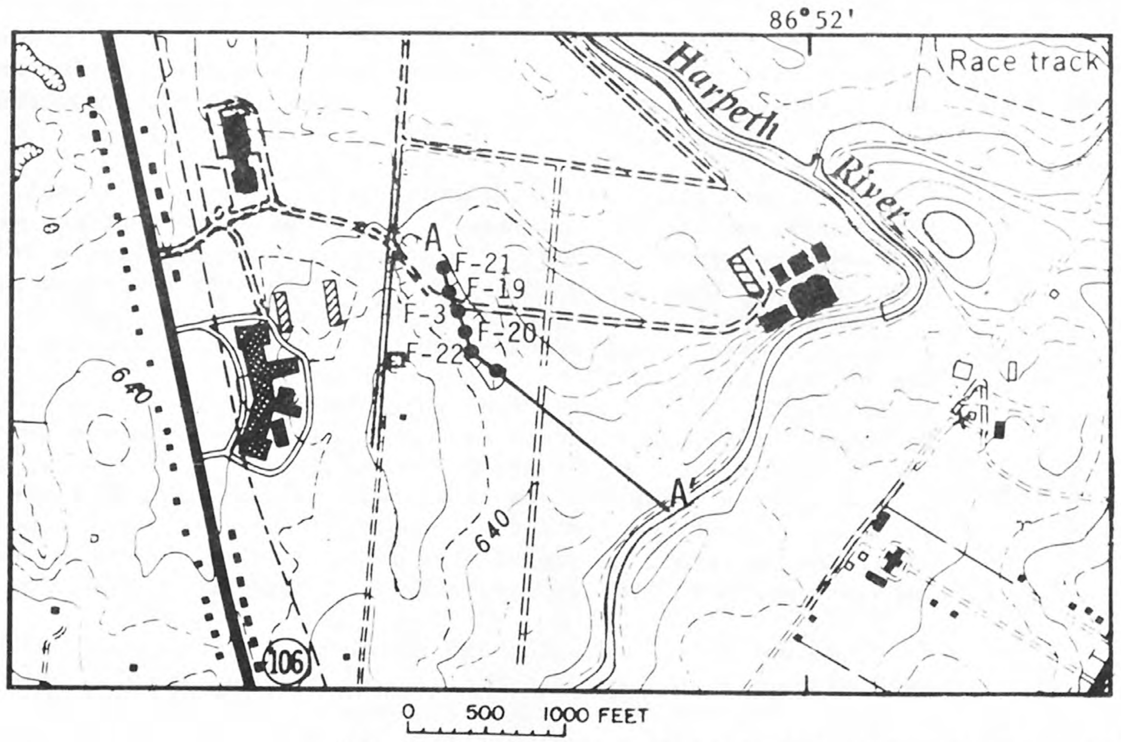
Five additional test wells were drilled at the F-3 site along the longitudinal axis of the sinkhole (fig. 14). The wells, including F-3, range in depth from 150 to 165 feet and produced from 3 to 400 gal/min, measured while blowing the wells with compressed air (table 6). The lowest yielding well, F-21, is nearest the center of the sinkhole, possibly indicating that the solution opening has collapsed or filled beneath the deepest part of the sinkhole. The well yields generally increase toward the southern end of the sinkhole as do the size of the solution openings; well F-25, farthest to the southeast, has a 5.5-foot opening.

All the wells penetrate one or both solution openings shown in the geologic cross section. The more extensive opening continues at least 650 feet in one direction; its total extent is not known. It appears to have developed at one stratigraphic horizon, as it occurs at 23 to 26 feet below the T-3 bentonite in all the wells, and it increases in size southward.

Table 6.-- Physical characteristics of Franklin test wells at F-3 site.

Well No.	Total depth in feet	Overburden in feet	Water-bearing formations	Depth to top of T-3 Bentonite, in feet	Depth to water bearing interval in feet	Yield by blowing, in gal/min	Diameter, in inches
F-3	153	16	Carters	76	103	180	8.5
F-19	160	11	Carters	79	105	18	6.25
F-20	150	23	Carters	70	83,98	57	6.25
F-21	165	12	Hermitage	85	76(?)	3	6.25
F-22	150	17	Carters	67	81-83,96	400 97	8.5 6.25
F-25	150	24	Carters	71	76,81-86, 100	400 100	10 6.25





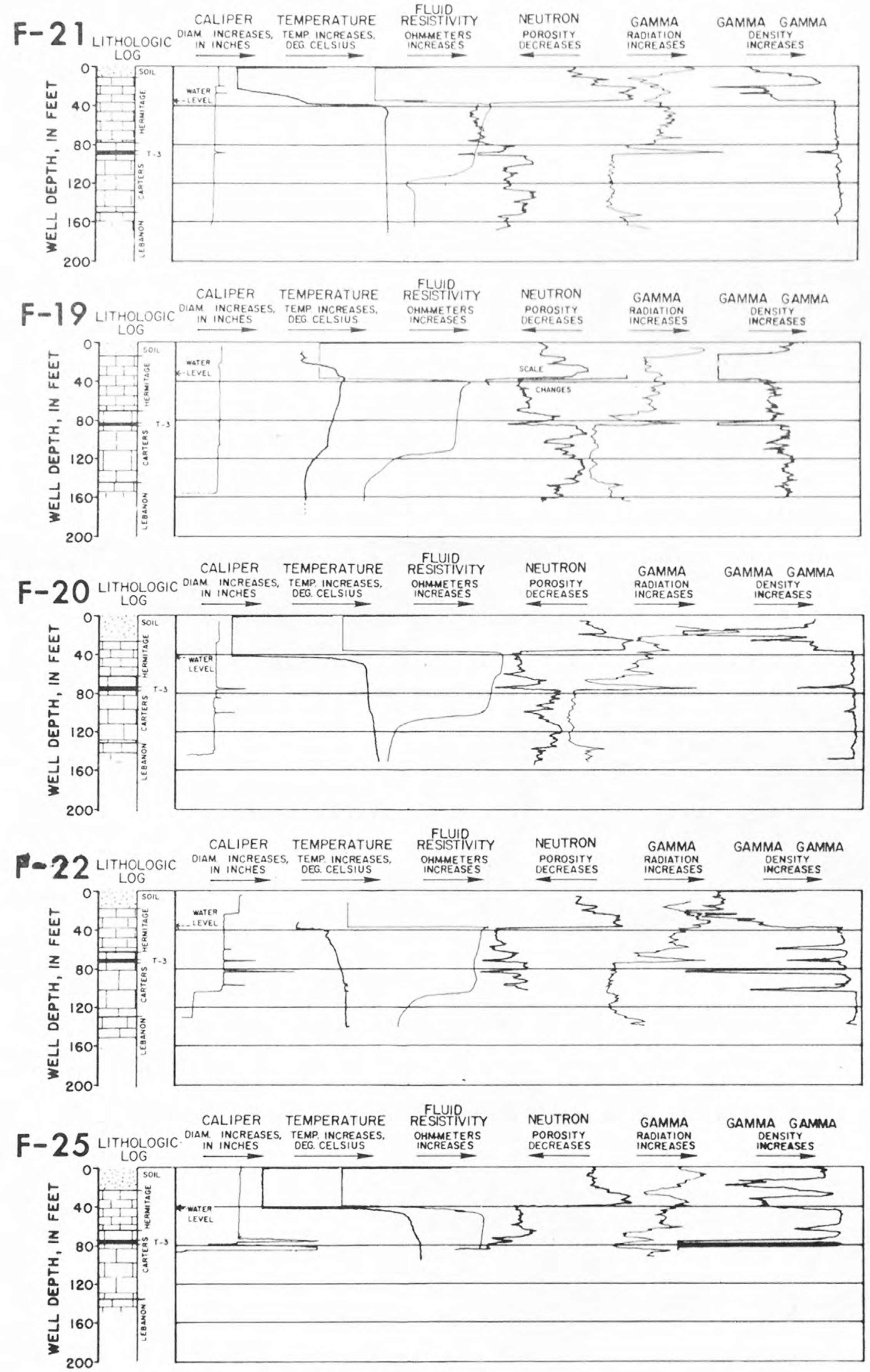


Figure 14.--Geologic cross section through test wells at the F-3 site, with location map and geophysical logs for the additional test wells. The structural high shown on the cross section is a localized feature and is contained within a regional structural low.

4.5 Hydraulic relationships at the F-3 site

INTERCONNECTED WELLS DRAWDOWN AT THE SAME RATE

During a 44-hour aquifer test with an average pumping rate of 327 gal/min, synchronous drawdown occurred in six wells including the pumped well; the most distant observation well was 650 feet away. Recovery took six days.

Water-level elevations in the test wells at the F-3 site on May 23, 1977, were 2.0 to 2.2 feet above the water-level elevation in the Harpeth River at its nearest point, with 0.2 feet of variation among wells. On December 14, 1976, the water level varied among the wells by 0.3 feet. These variations do not indicate any hydraulic gradient along the sinkhole axis. Extreme water levels in F-3 over a 12-month period from July 1976 to June 1977 were 17.33 feet and 39.13 feet below land surface, a fluctuation of 21.80 feet. The base level for the low periods was about 38 feet, or approximately 3 feet above the river bed.

An aquifer test was run at the F-3 site in December 1976. The test was 44 hours in duration and five observation wells were used to monitor water levels. The observation wells were spaced from 159 to 650 feet from the pumped well, F-25, along a line to the northwest. The test began December 14 at 1400 hours and consisted of five steps (fig. 15). During the first step, an average pumping rate of 122 gal/min was maintained for 7 hours. The pumping rate was increased to an average of 225 gal/min for the next 14 hours. During these two steps, the water level declined a similar amount in the pumped well and all of the observation wells (table 7).

The third step, with an average pumping rate of 517 gal/min, was to have continued for the remainder of the test. However, the rate of drawdown increased at about 2130 hours on December 15. In order to prevent the pump from breaking suction a fourth step was begun by reducing the pumping rate to 395 gal/min at 0100 hours on December 16. The water level recovered slightly, then began to decline again. The pumping rate was reduced less than 2 hours later. For the next 7 hours the water level oscillated, with the pump finally breaking suction at 1012 hours on December 16, 44 hours after the test began. The pump was turned on again the following day for 2 hours and 40 minutes so that a water sample could be collected. Table 6 gives the drawdown in each well at the end of each of the five steps and the recovery 1 hour after the pump was turned off. The wells all recovered at a steady rate of about 0.2 feet per hour. Recovery was complete six days after the pump was turned off.

The synchronous decline and recovery in the wells could be the result of partial or complete draining of a large, open solution-cavity system during the test. The cavity was refilled at a steady rate significantly less than the pumping rate. The rate of refilling limits the long-term yield of this group of wells.

Until the rate of drawdown increased (after 31.5 hours of pumping at an average of 300 gal/min), the test indicated a specific capacity of 8.6 (gal/min)/ft for F-25. The specific capacity declined in the latter part of the test. Two possible causes for the decline are drainage of the large solution cavity or collapse and partial blockage of the cavity. The latter explanation is supported by the increasing turbidity of the water during the second day of the test and the fact that the well, originally 150 feet deep, was found to be filled to 90 feet below land surface two weeks after the test.

With adequate consideration of the slow recovery, higher pumping rates from these wells are feasible on an occasional basis. In addition, because the solution cavities increase in size to the south, additional wells in this direction could be pumped at high rates and might have better-maintained yields.

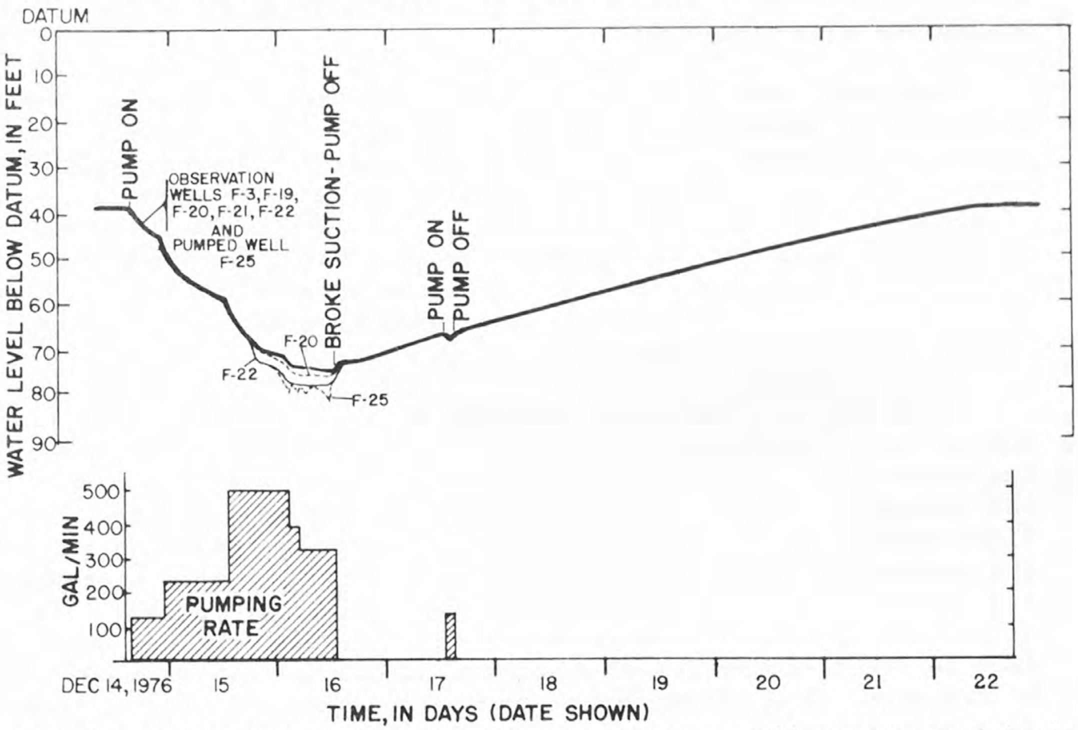


Figure 15.--Water levels and pumping rate during aquifer test at F-3 site.

Table 7.--F-3 site aquifer test showing distance of observation wells from pumped well with drawdown and recovery for pumped well and five observation wells.

Well number	F-25 1/	F-22	F-20	F-3 2/	F-19	F-21
Distance from pumping well, in feet	(pumping well)	159	305	400	509	650
Prepumping water level, in feet above mean sea level	603.5	603.1	603.1	603.2 (est)	603.5	603.1
Total drawdown from prepumping level, in feet, at end of step						
Step 1, 122 gal/min (average) for 7 hours	6.95	7.06	7.02	7	6.98	6.94
Step 2, 225 gal/min (average) for 14 hours	20.33	20.66	20.58	20	20.51	20.48
Step 3, 517 gal/min (average) for 14 hours	40.79	38.58	36.43	34	34.78	34.67
Step 4, 395 gal/min for 1.8 hours	40.98	39.25	37.04	35	35.34	35.13
Step 5, 336 gal/min (average) for 7.4 hours	42.34	39.40	37.47	36	36.08	35.91
Recovery, in feet, 1 hour after pump off	4.39	1.33	0.92	0.52	0.5 (est)	0.52

1/ Lesser drawdown in pumped well than observation wells for steps 1 and 2 is probably due to measurement error.

2/ Exact values for drawdown in well F-3 unavailable due to recorder tape slippage.

4.0 TEST WELLS AND HYDRAULIC RELATIONSHIPS AT TEST SITES

4.6 Comparison of pumping tests of wells F-3 and F-25

WELL EFFICIENCY, A DETERMINING FACTOR IN PUMPING TEST RESULTS

Seemingly great differences in the response of wells F-3 and F-25 to pumping can be accounted for by differences in well performance rather than by changes in the hydraulic characteristics of the aquifer.

Wells F-3 and F-25 were pumped in January 1976, and December, 1976, respectively. Figure 16 shows water levels in the two wells during and after pumping.

Well F-25 taps a 5-foot high solution opening. Because there is almost no resistance to the entry of water into the well, water levels in F-25 perfectly reflect the gradual drawdown in hydraulically connected parts of the solution opening system. F-3 however, displays an immediate drawdown than can be attributed to turbulent flow in the solution opening near the well bore; the cavity penetrated by F-3 is less than a foot high. Had the observation wells been in existance when F-3 was pumped, they would have experienced significantly less drawdown than F-3.

Well F-3 had a specific capacity of 5.4 (gal/min)/ft of drawdown after 8 hours pumping at an average rate of 204 gal/min. The water level dropped 21.52 feet in the first minute after the pump was turned on. Similarly, water levels recovered 30.42 feet in the first minute after pumping ceased. The water was within a foot of the prepumping level in 90 minutes. Well F-25, on the other hand, had a specific capacity of 13.4 (gal/min)/ft after pumping 8 hours at an average rate of 140 gal/min. Water levels declined only 0.20 feet in the first minute of pumping. Recovery took place over a period of six days. The difference in specific capacity indicates that F-25 is a more efficient well than F-3. However, for long-term pumping, both are subject to the limitations of the solution-opening system itself.

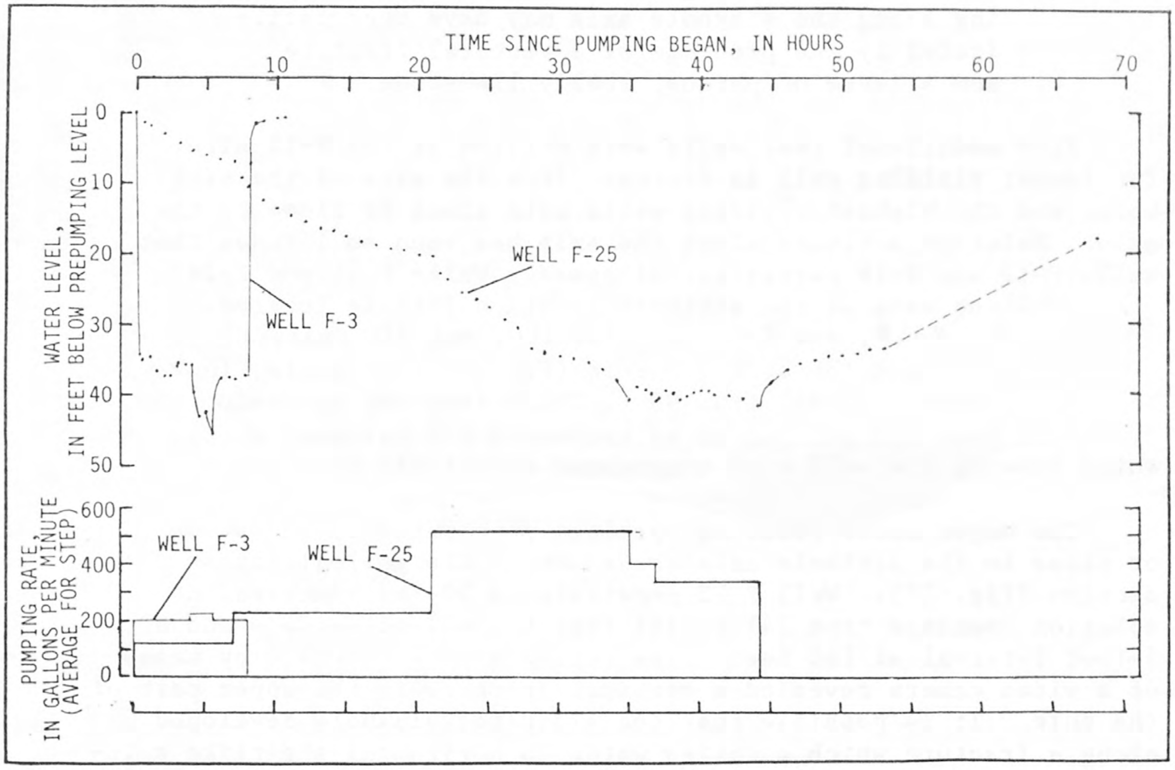


Figure 16.--Rate of pumping and water levels in wells F-3 (January 1976) and F-25 (December 1976).

4.7 Additional drilling near well F-12

HIGH-YIELDING TEST WELLS REVEAL INTENSE SOLUTION ACTIVITY ALONG SINKHOLE AXIS

Wells near the sinkhole axis produced as much as 600 gal/min; and those farthest from the axis as low as 0.5 gal/min. Intense solutioning along the sinkhole axis may have been facilitated by the presence of a vertical fracture and a lense of porous, shelly limestone.

Five additional test wells were drilled at the F-12 site. The lowest yielding well is farthest from the axis of the sinkhole, and the highest yielding wells were along or close to the axis. Solution activity along the axis has been so intense that wells F-12 and F-16 partially collapsed. Wells F-16 and F-24 are along the axis of the sinkhole in which F-12 is located. **Wells F-23, F-18, and F-17 are** 50, 100, and 370 feet, **respectively, from the sinkhole axis** (fig 17). The wells, including F-12, range in depth from 99 to 214.5 feet and in production from less than 0.5 gal/min to an estimated 600 gal/min, measured while blowing the well with compressed air (table 8).

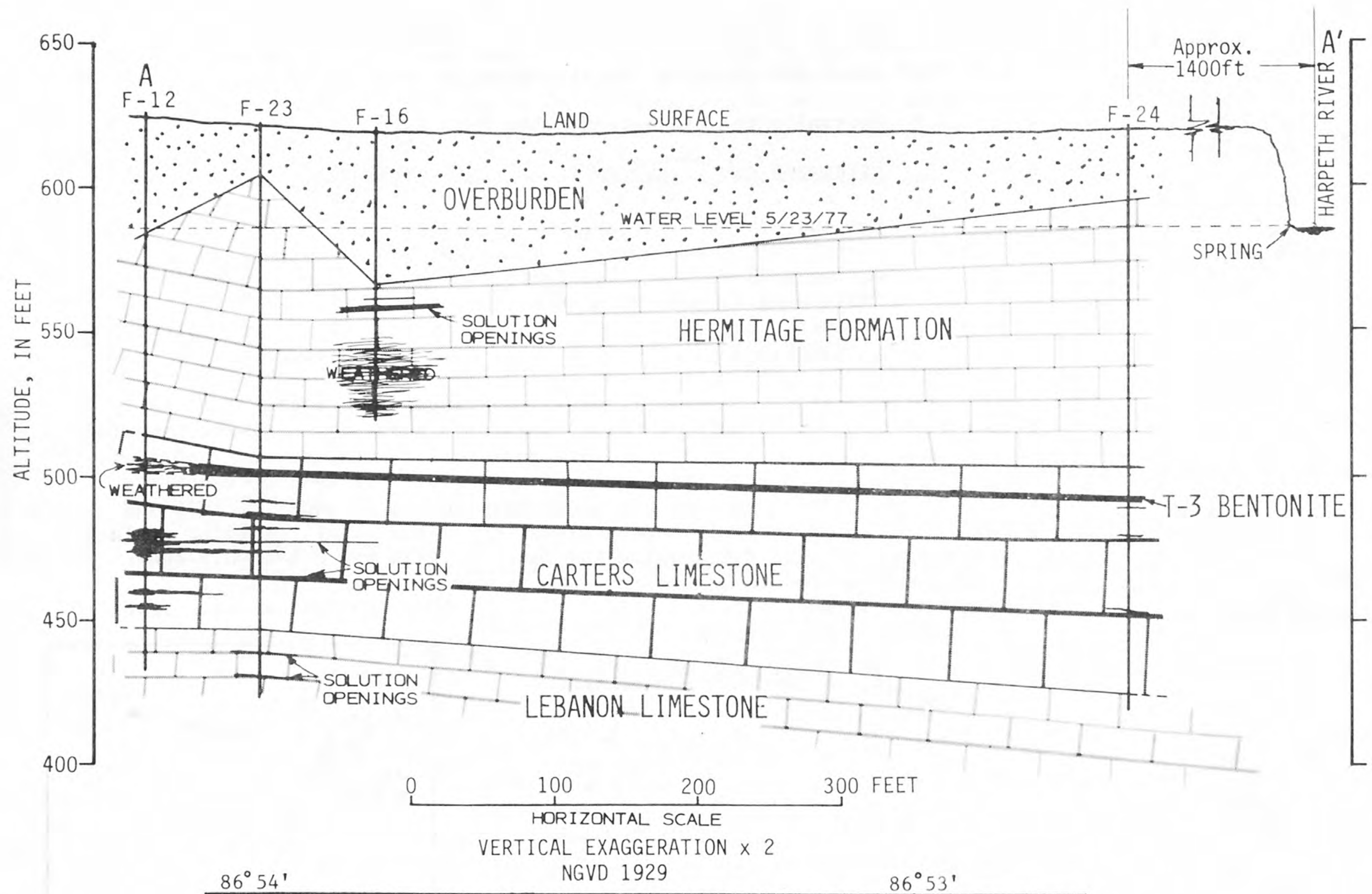
The major water-yielding openings penetrated by the wells on or close to the sinkhole axis are shown in the geologic cross section (fig. 17). Well F-12 penetrated a 10-foot interval of solution openings from 141 to 151 feet below land surface and a 5-foot interval at 160 feet. Inspection of the borehole by means of a video camera revealed a vertical fracture in the upper part of the hole. It is possible that the elongated sinkhole developed along a fracture which supplies water to horizontal sheetlike solution openings at depth.

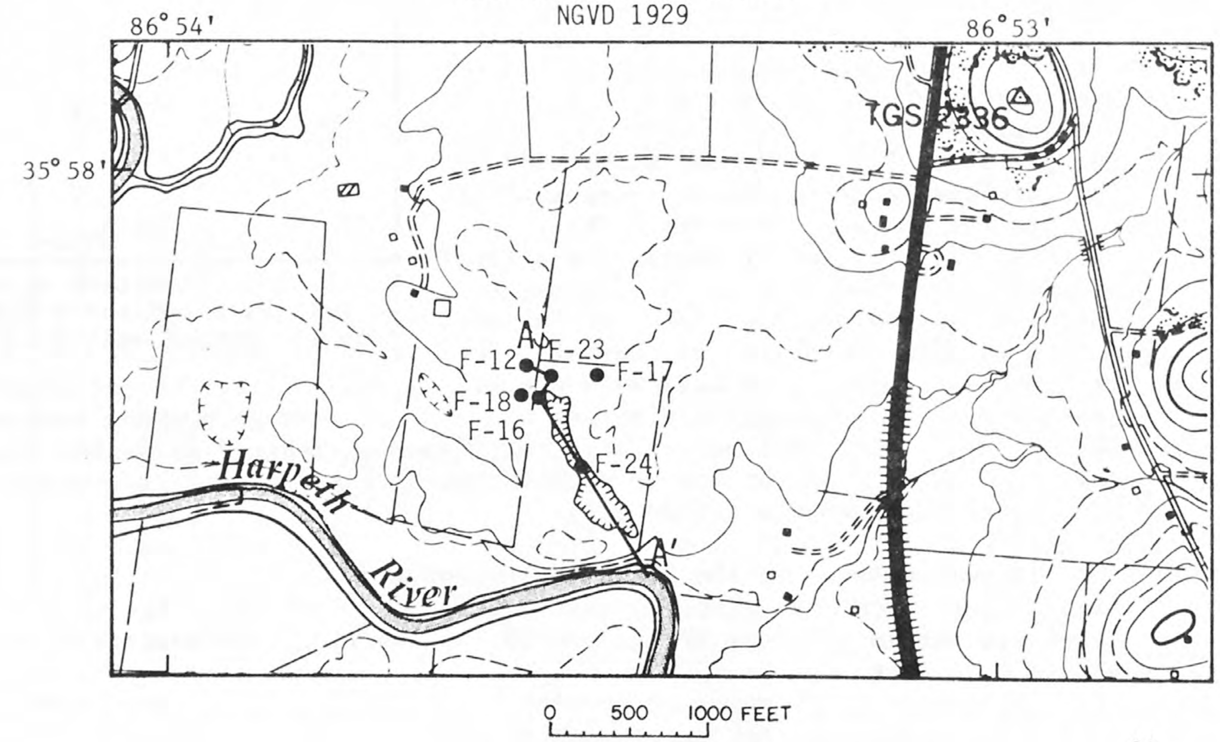
This area was the only test-well site in which the coquina or shelly facies of the Hermitage Formation was recognized. This porous limestone may provide a reservoir of ground water which is slowly released into the underlying solution openings.

Table 8.-- Physical characteristics of test wells at F-12 site.

Well No.	Total depth in feet	Overburden in feet	Water-bearing formations	Depth to top of T-3 Bentonite, in feet	Depth to water-bearing interval* in feet	Yield by blowing, in gal/min	Diameter, in inches
F-12	192	40	Hermitage, Carters	Approximately 120	60-170	600 160	10.5 6.25
F-16	99	52	Hermitage	-	55-99	150	6.25
F-17	200	18	?	127	?	<1/2	6.25
F-18	214	22	Carters	126	128-200	116	6.25
F-23	200	16	Carters	119	131-191	500 130	10.5 6.25
F-24	200	23	Carters	126	130-166	175	6.25

*Intervals contain multiple water-bearing openings.





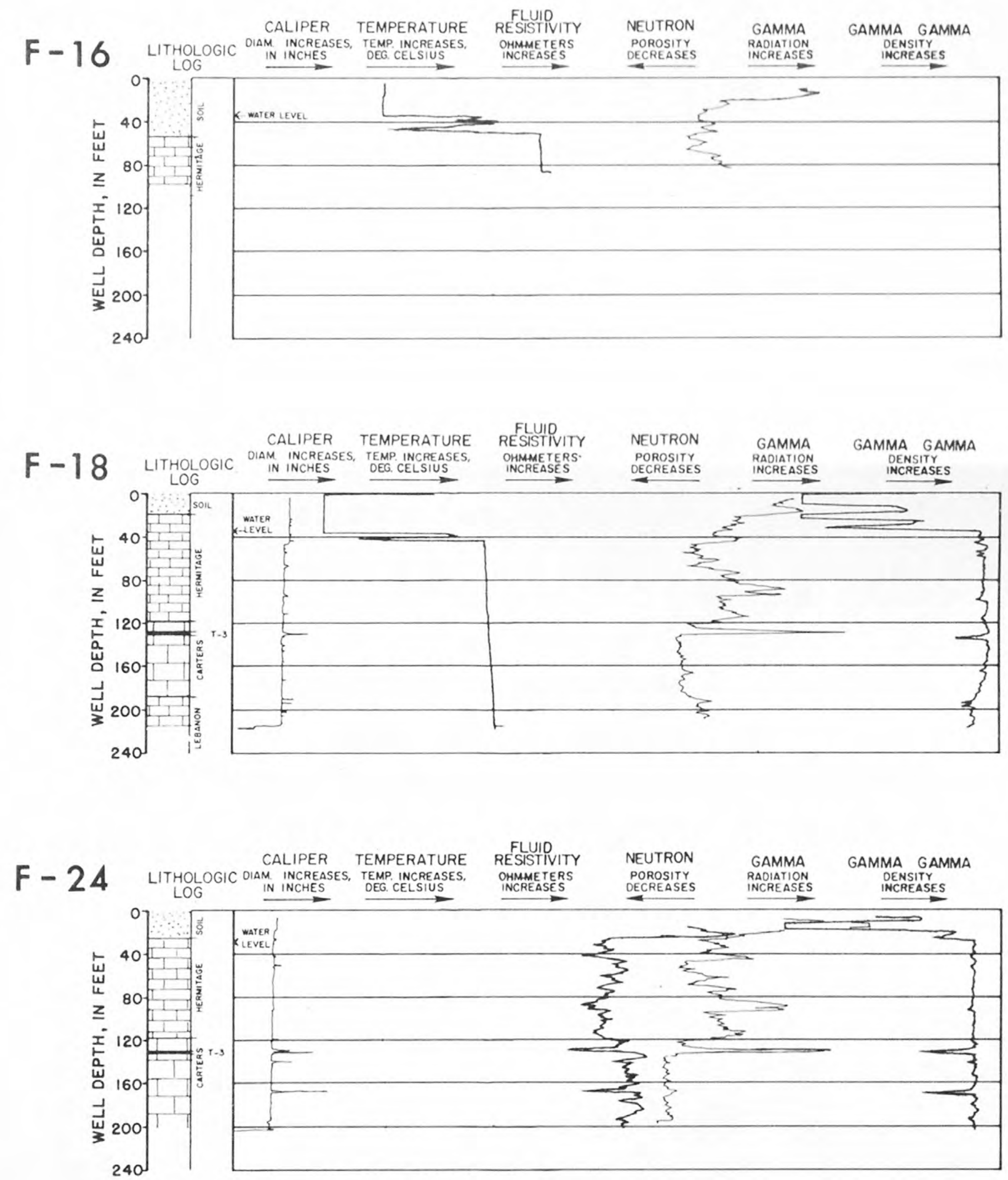


Figure 17.-- Geologic cross section through F-12 site, with location map and geophysical logs for three test wells.

4.0 TEST WELLS AND HYDRAULIC RELATIONSHIPS AT TEST SITES

4.8 Hydraulic relationships at the F-12 site

EXTENSIVE CAVITY SYSTEM IS A LARGE RESERVOIR FOR GROUND WATER

Pumping over 900,000 gallons of water from the cavity system caused less than 8.5 feet of drawdown in 5 observation wells during a 48-hour aquifer test. The wells recovered rapidly indicating the presence of a large ground-water reservoir. However, the rate of ground-water movement into the cavities is undefined.

The natural water level in well F-12 ranged from a low of 34.68 feet to a high of 17.00 feet below land surface during an 11-month period from August 1976 to June 1977. This is a total variation of 17.68 feet. The difference in water level elevation from well to well at the F-12 site was 0.65 feet and 0.59 feet when measured on December 8, 1976 and May 3, 1977, respectively. Both times the elevation of the water surface was highest in well F-17, while the level in F-24 was 0.4 to 0.5 feet lower, and the levels in the rest of the wells were 0.5 to 0.7 feet lower than in F-17. This gradient may indicate ground-water flow down the valley of the Harpeth.

An aquifer test was run at the F-12 site in December 1976. Well F-23 was pumped for 48 hours. Water levels were recorded in five observation wells spaced from 74.4 to 564 feet from the pumped well in different directions (fig. 18). The test began December 8, 1976 at 1330 hours and consisted of three steps. In the first step, the pumping rate ranged from 200 to 435 gal/min, but the average for the 7-hour step was 233 gal/min. For the second step, the pumping rate was increased to an average of 515 gal/min for the next 14 hours. The third step lasted for 27 hours, for a total pumping time of 48 hours. The discharge during this step declined from 580 gal/min to 560 gal/min at the end of the test. The specific capacity of well F-23 was 27 (gal/min)/ft at the end of step 1, declining to 7 (gal/min)/ft after 48 hours at an average pumping rate of 502 gal/min. This decline reflects well losses. Table 9 shows the drawdown in each well at the end of each of the three steps and recovery 1 hour after the pump was turned off.

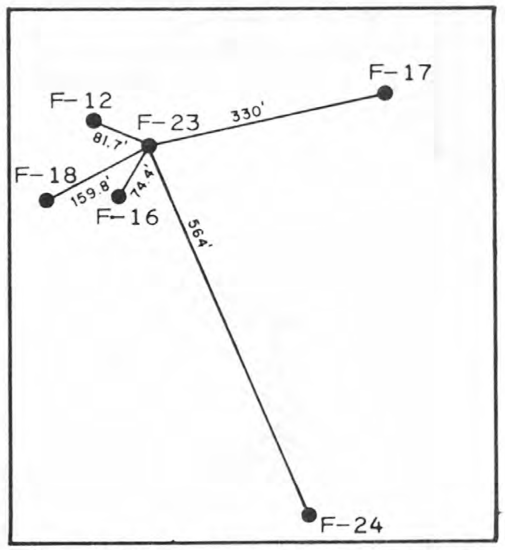


Figure 18.-- Location of wells at F-12 site and their distance from the pumped well F-23.

The water level in the pumped well recovered 68.4 feet within the first minute after the pump was turned off. One hour later the water level was within 1.4 feet of the prepumping level; at 100 minutes it was within 0.04 feet.

Water level declines in the aquifer were much less than in the pumped well. Figure 19 shows water levels in F-23 and the five observation wells during the test. Maximum drawdown in the three closest wells, F-16, F-12, and F-18, was 8.22 feet, 8.45 feet, and 8.22 feet, respectively. Water levels in these three wells declined simultaneously and almost equally. This indicates that a large open cavity is tapped by these wells. Wells F-24 and F-17 had slightly less drawdown. F-17 had a slow recovery compared to the other wells.

It is important to note that although over 900,000 gallons of water was pumped from the solution-opening system into the river, this test has not defined the rate of ground-water flow into the cavity system, which is the limit on long-term continuous pumping.

Table 9.--F-12 site aquifer test showing distance of observation wells from pumped well with drawdown and recovery for pumped well and five observation wells.

Well number------------------------------	F-23	F-16	F-12	F-18	F-17	F-24
Distance from pumping well, in feet------	(pumping well)	74.4	81.7	160	330	564
Prepumping water level, in feet above mean sea level--------------------	591.6	591.7	591.7	591.8	592.3	591.8
Total drawdown from prepumping level, in feet, at end of step						
Step 1, 233 gal/min (average) for 7 hours	8.59	0.75	0.80	0.75	0.48	0.45
Step 2, 515 gal/min (average) for 14 hours	58.02	4.86	5.06	4.87	3.75	3.92
Step 3, 566 gal/min (average) for 27 hours	75.02	8.22	8.45	8.22	6.77	7.12
Recovery, in feet, 1 hour after pump off-	73.57	5.97	6.11	5.88	0.93	5.06

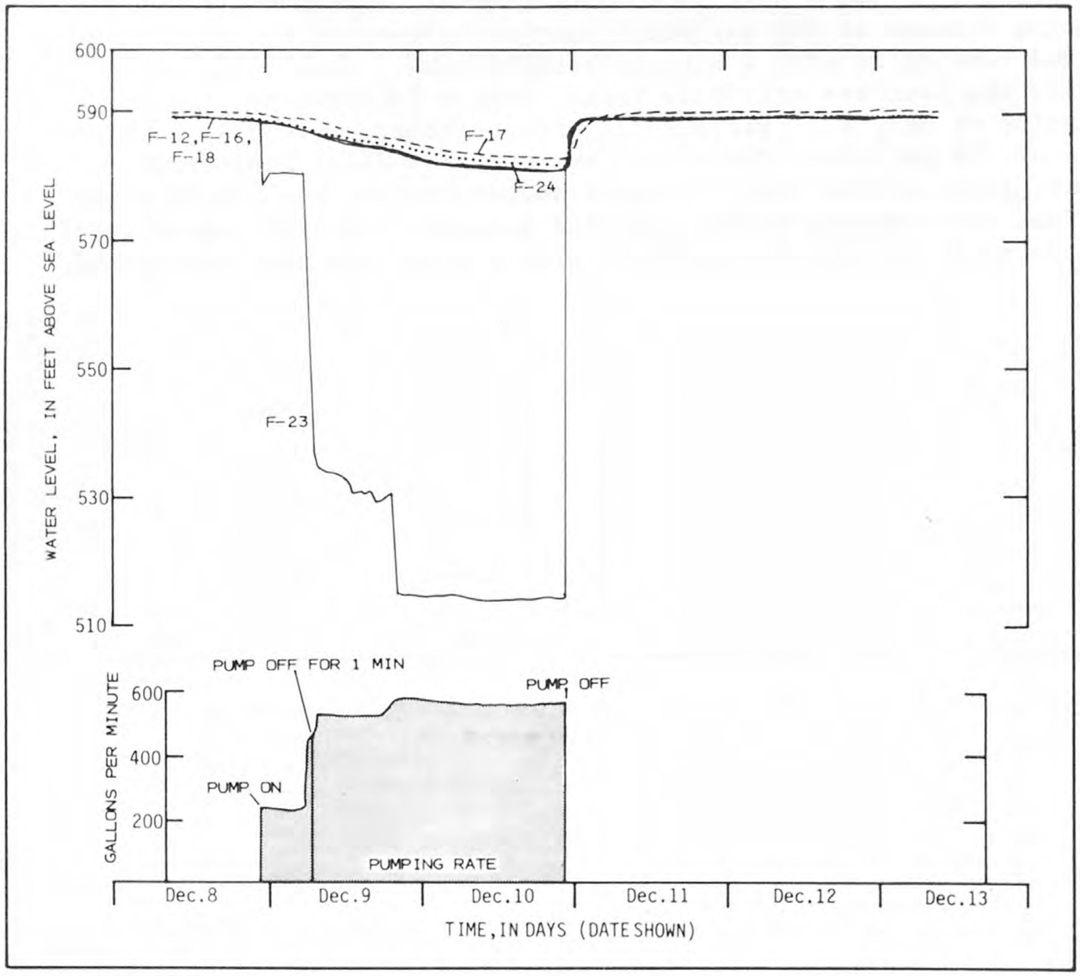


Figure 19.--Rate of pumping and water levels in F-23 and five observation wells at the F-12 site.

4.9 Comparison of pumping tests of wells F-12 and F-23

SOLUTION CAVITY SIZE AFFECTS WELL EFFICIENCY

Performance of nearby wells F-12 and F-23 differs greatly due to the large open cavities penetrated by F-12.

Wells F-12 and F-23 tap the same solution cavity system. Although the amount of ground water available at the site is determined by the characteristics of the cavity system, F-12 provides a far more efficient means of withdrawing it than does F-23. F-12 penetrated a vertical fracture and multiple openings including a 10-foot cavity 141 feet below land surface; F-23 produces water from a 6-inch cavity at 131 feet and a 2-inch cavity at 140 feet. Turbulent flow in the vicinity of F-23 caused much greater drawdown when the well was pumped in December 1976 than would have been expected from the test of well F-12 in June 1976, as shown in figure 20.

Well F-12 had a specific capacity of 357 (gal/min)/ft after pumping 8 hours at 200 gal/min. Partial cave-in of the well precluded testing it with a higher-capacity pump. Total drawdown during the test was only 0.56 feet. Well F-23, however, had a specific capacity of only 6.1 (gal/min)/ft after 8 hours pumping at an average rate of 250 gal/min. The water level dropped 28.97 feet during the first minute of the test. **Total drawdown for the 48-hour test was 75 feet with pumping rates up to 566 gal/min. However, water level recovered 68.36 feet in the first minute after the pump was** turned off.

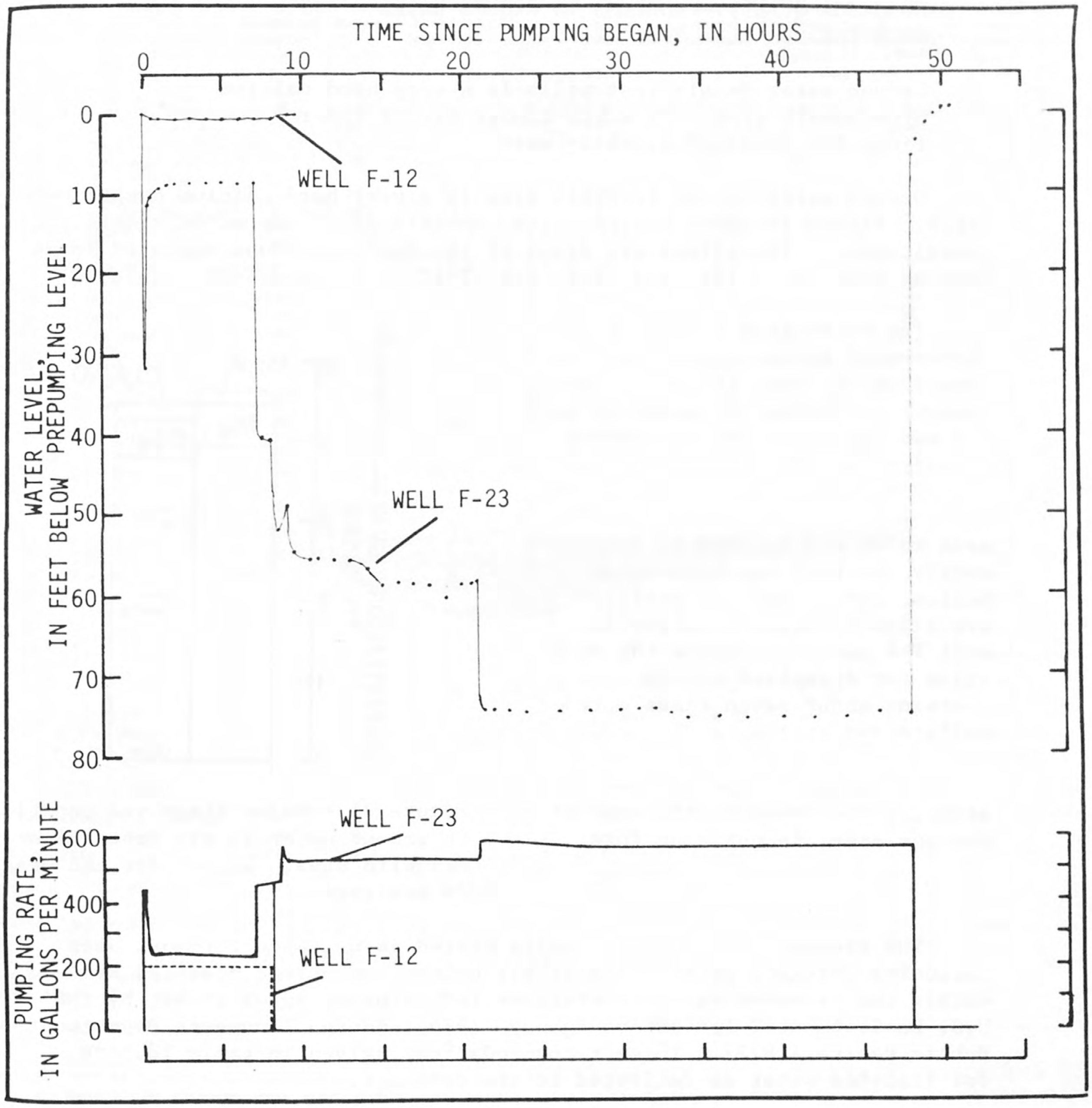


Figure 20.--Rate of pumping and water levels in wells F-12 (June,1976) and F-23 (December, 1976).

5.0 WATER QUALITY

NO MAJOR QUALITY PROBLEMS IN GROUND WATER FROM THE FRANKLIN TEST WELLS

Ground water in six test wells is a very hard calcium bicarbonate type. It meets almost all of the recommendations for finished drinking water.

Ground water in the Franklin area is a very hard calcium bicarbonate water. Figure 21 shows the relative proportions of the major mineral constituents. The values are means of the concentrations measured in 24 samples from six wells, F-3, F-4, F-6, F-12, F-23, and F-25 (table 10).

The water from F-4 and F-6, represented by one sample each, differs from the mean in the following manner: although the water in well F-6 has about the same amount of dissolved solids, magnesium makes up a significantly larger proportion. Magnesium is about four times the mean value and calcium is approximately one-half the mean value. Sodium, potassium, and sulfate are slightly higher. Water in well F-4 has about twice the mean value for dissolved solids. It contains about seven times more sulfate and sodium.

The water in the F-3 and F-12 areas, represented by the rest of the analyses, is quite uniform.

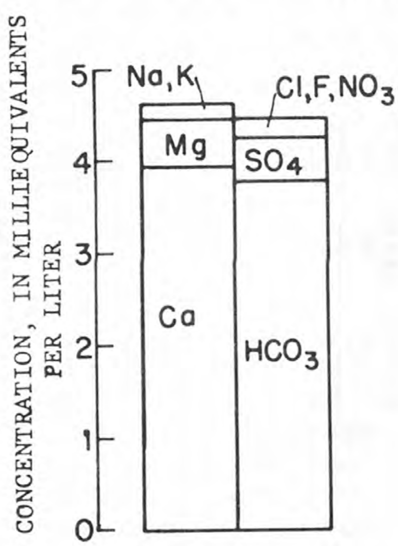


Figure 21.--Major dissolved constituents in ground water in six test wells in the Franklin area. Values are the mean of 24 analyses.

The ground water from the wells tested is suitable for most uses including drinking water. Almost all of the parameters measured are within the recommended concentrations for drinking water as set by the U.S. Environmental Protection Agency (1976) and the Tennessee Department of Public Health (1972). These recommendations, given in table 10, are for finished water as delivered to the consumer.

The two parameters which exceed recommended maximum levels in some samples are turbidity and phenols. One source of turbidity in the wells drilled into the Carters Limestone is the T-3 bentonite. Casing to prevent washing of the bentonite would reduce turbidity in these wells. Additional development of the wells might also bring about the improvement. Phenols exceeded the recommended limit in 44 percent of the samples. It is possible that phenols were introduced during sampling or processing. Possible sources of phenols in the samples are contaminated bottles or pumping equipment. Whenever more than one sample was taken from a well, phenols were at or below the recommended maximum level in at least one sample.

Table 10.--Mean values and statistical comparison of 24 analyses of water from six wells in the Franklin area with standards for maximum levels of constituents in finished drinking water. Analyses made by the U. S. Geological Survey. Values rounded to reflect accuracy of determinations.

Label	Number of samples	Mean	Standard deviation	Minimum value	Maximum value	Standard error of mean	Tennessee standards for public water supplies [1]		National drinking-water regulations [4]	
							Recommended maximum [2]	Approval limit [3]	Secondary maximum contaminant level [5]	Primary maximum contaminant level [6]
Alkalinity (Mg/L as $CaCO_3$)	24	189	19.8	150	217	4.05	-	-	-	-
Arsenic Total (ug/L as As)	18	1	1	0	4	0	10	50	-	50
Barium, total recoverable (ug/L as Ba)	18	50	70	0	200	17	-	1000	-	1000
Bicarbonate (Mg/L) as HCO_3)	24	230	24.4	177	264	4.00	-	-	-	-
Cadmium, total recoverable (ug/L as Cd)	18	0	1	0	4	0	10	10	-	10
Calcium, dissolved (Mg/L as Ca)	24	79	15	44	130	3.1	-	-	-	-
Carbon dioxide, dissolved (Mg/L as CO_2)	24	39	17	14	81	3.6	-	-	-	-
Carbon, organic total (Mg/L as C)	16	2.2	2.2	0.0	6.6	0.6	-	-	-	-
Carbonate (Mg/L as CO_3)	24	0	0	0	0	0	-	-	-	-
Chloride, dissolved (Mg/L as Cl)	24	4.9	5.6	2.4	31	1.2	250	-	250	-
Chromium, hexavalent, dis. (ug/L as Cr)	18	0	0	0	0	0	-	50	-	50
Color (platinumcobalt units)	18			0	15		-	15	15	-
Copper, total recoverable (ug/L as Cu)	18	4	4	0	15	1	1000	-	-	-
Cyanide, total (Mg/L as Cn)	17	0	0	0	0	0	0.01	0.2	1000	
Detergents, MBAS, (Mg/L)	17	0.01	0.03	0.00	0.10	0.01	0.5	-	-	-
Dissolved solids, residue at 180°C	24	258	56.0	196	494	11.4	500	-	500	-
Fluoride, dissolved (Mg/L as F)	24	0.2	0.2	0.1	0.9	0.0	1.3[7]	2.0	0.9[8]	1.6[9]
Hardness, noncarbonate (Mg/L) $CaCO_3$)	24	34	22	17	130	4.4	-	-	-	-
Hardness (Mg/L as $CaCO_3$)	24	223	31.6	180	330	6.44	-	-	-	-
Iron, dissolved (ug/L as Fe)	18	20	21	0	80	5	300	-	300	-
Iron, total recoverable (ug/L as Fe)	18	240	304	0	1100	72	-	-	-	-
Lead, total recoverable (ug/L as Pb)	18	8	6	0	24	1	-	50	-	50
Magnesium, dissolved (Mg/L) as Mg)	24	6.2	4.4	1.9	26	0.9	-	-	-	-
Manganese, dissolved (ug/L as Mn)	18	5	8	0	30	2	50	-	50	-
Manganese, total recoverable (ug/L as Mn)	18	10	9	0	40	2	-	-	-	-
Mercury, total recoverable (ug/L as Hg)	18	0.05	0.09	<0.05	0.3	0.02	-	5	-	2
Nitrogen, nitrate total (Mg/L as N)	18	2.6	1.2	0.0	4.4	0.3	35	-	-	10
Nitrogen, nitrite total (Mg/L as N)	18	0.01	0.02	0.00	0.09	0.01	-	-	-	-
pH (units)	24			6.7	7.4		-	-	$6.5 \le pH \le 8.5$	-
Phenols (ug/L)	18	2	3	0	10 [10]	1	1	-	-	-
Phosphorus, total (Mg/L as P)	18	0.34	0.10	0.04	0.49	0.02	-	-	-	-
Phosphorus, total (Mg/L as PO_4)	18	1.0	0.3	0.1	1.5	0.1	-	-	-	-
Potassium, dissolved (Mg/L as K)	24	0.9	0.9	0.6	5.0	0.2	-	-	-	-
Selenium, total (ug/L as Se)	18	1	1	0	3	0	-	10	-	10
Silica, dissolved (Mg/L as SiO_2)	24	9.0	0.7	7.0	9.9	0.1	-	-	-	-
Silver, total recoverable (ug/L as Ag)	18	0	0	0	0	0	-	50	-	50
Sodium, dissolved (Mg/L as Na)	24	3.1	4.7	1.2	22	1.0	-	-	-	-
Sodium adsorption ratio	24	0.1	0.1	0.0	0.5	0.0	-	-	-	-
Sodium percent	24	2.6	3.0	1.0	13	0.6	-	-	-	-
Specific conductance (Micromhos)	24	430	78.2	340	750	16.0	-	-	-	-
Sulfate dissolved (Mg/L as SO_4)	24	22	28	9.6	150	5.7	250	-	250	-
Turbidity (JTU)	24			0	15		-	2	-	1[11]
Temperature (Deg C)	24	15.5	0.60	14.0	16.5	0.12	-	-	-	-
Zinc, total recoverable (ug/L as Zn)	18	20	12	0	40	3	5000	-	-	-
Coliform, total, immed. (Cols./100 ML)	16	250	766	1.00	3100	192				
Coliform, fecal, 0.45 UM-MF (Cols./100 ML)	6	3	4	1	10	2				
Streptococci fecal, (Cols./100 ML)	6	20	28	1.0	77	12				

1. Tennessee Department of Public Health, 1972.
2. Concentration should not be exceeded where other more suitable supplies are or can be made available.
3. Presence in excess of this concentration constitutes grounds for rejection of the supply.
4. U.S. Environmental Protection Agency, 1976.
5. These are not Federally enforceable and are intended as guidelines.
6. Applies to all systems providing piped water for human consumption if such system has at least 15 service connections or regularly serves at least 25 individuals.
7. Maximum control limit.
8. Maximum control limit for Franklin area, based on annual average maximum daily temperature of 71.4°F (for 15 years of complete record between 1956 and 1978, recorded at Franklin Sewage Plant).
9. Based on average maximum daily temperatures (see footnote above).
10. Exceeds State limit in eight samples.
11. A value of five or fewer turbidity units is allowed if it does not interfere with disinfection or microbiological determinations.

6.0 CONCLUSIONS

1. Based on hydrologic data, the Bigby-Cannon Limestones, the Hermitage Formation, the Carters Limestone, and the Ridley Limestone are potential aquifers where they occur within about 200 feet of land surface. In the Franklin area, the Bigby-Cannon unit is exposed at land surface but is too thin to evaluate its potential as an aquifer; but the other three formations yield water.

2. Ground water occurs in solution openings in the carbonate rocks. Average recharge is 8 inches per year or more and is areally distributed. Ground water flow paths are similar to the surface drainage patterns, with discharge occurring from low-lying springs and into streams.

3. Significant gains and losses were measured in the flow of the Harpeth and West Harpeth Rivers, amounting to as much as 15 to 20 percent of streamflow. Active stream reaches are considered to be indicative of solution cavities in the underlying rock.

4. Drilling sites were selected on the basis of geologic criteria, active stream reaches, topography, and linear features.

5. Domestic well records are not reliable indicators of ground-water potential as the average production from the first 15 test wells was 68 gal/min and the reported average yield for wells in the area was 5 gal/min.

6. The first 15 test wells produced less than 1 to an estimated 600 gal/min. Specific capacities of the four highest-yielding wells ranged from 0.6 to 357 (gal/min)/ft of drawdown after pumping 8 hours at rates ranging from 70 to 225 gal/min.

7. Additional drilling at two sites revealed extensive solution openings. During an aquifer test at the F-3 site, water levels declined equally in all 6 wells and recovered slowly indicating a large cavity system with limited inflow. At the F-12 site, drawdown in the observation wells did not exceed 8.5 feet while one well was pumped for 48 hours at rates up to 570 gal/min. The rate of ground-water flow into the cavity system was not defined, but recovery was rapid.

8. Raw ground water in the test wells meets most of the recommendations for finished drinking water and is of rather uniform quality, both from well to well and throughout the year.

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