UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

SUMMARY APPRAISALS OF THE NATION'S GROUND-WATER RESOURCES - TENNESSEE REGION, INCLUDING PARTS OF TENNESSEE AND ADJACENT STATES

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METRIC UNITS

English	Multiply by	Metric
acre-ft (acre-foot)	1233	m^3 (cubic meter)
ft (feet)	3.048×10^{-1}	m (meters)
$(ft^3/s)/mi^2$ (cubic feet per second per square mile)	1.093×10^{-2}	$(m^3/s)/km^2$ (cubic meter per second per square kilometer)
ft^2/d (foot squared per day)	9.29×10^{-2}	m^2/d (meter square per day)
gal/min (gallons per minute)	6.309×10^{-2}	L/s (liters per second)
(gal/min)/ft (gallons per minute per foot)	2.070×10^{-1}	(L/s)/m (liters per second per meter)
in (inches)	$2.540 \times 10^{+1}$	mm (millimeters)
in/yr (inches per year)	$2.540 \times 10^{+1}$	mm/yr (millimeters per year)
Mgal/d (million gallons per day)	$3.785 \times 10^{+3}$	m^3/d (cubic meters per day)
mi (miles)	1.609	km (kilometers)
mi^2 (square miles)	2.590	km^2 (square kilometers)

ABSTRACT

Ground water is an abundant and little-used resource in the Tennessee Region, a 41,000 square mile area dominated by the Tennessee River system and including parts of Alabama, Georgia, Kentucky, Mississippi, North Carolina, Tennessee, and Virginia. One-fifth to one-quarter of the precipitation that falls on the region enters the ground-water reservoirs. During the year approximately the same amount of water leaves the ground-water system, sustaining the dry-weather flow of streams. Recharge for the region is about 22,000 million gallons per day or 0.5 million gallons per day per square mile.

The major types of aquifers in the region are unconsolidated material (including sand and regolith), carbonate rocks, and fractured noncarbonate rocks. One or more of these aquifer types occurs in each of the six physiographic subdivisions of the region. The productivity of these aquifers depends on their hydraulic properties and on the distribution of these properties. The unconsolidated sand aquifers are the most homogeneous in composition and most predictable in occurrence. These aquifers commonly yield as much as 200 to 600 gallons per minute per well depending on the thickness of sand penetrated.

The most difficult aquifers to predict in regard to depth and yield are the carbonate rocks. In these aquifers it is possible to drill dry holes within a few hundred feet of wells capable of producing several thousand gallons per minute. However, with an adequate reconnaissance study to determine the occurrence of ground water and a planned test drilling program, yields of 300 gallons per minute per well can be expected in the carbonate aquifers. Potential yields from the fractured noncarbonate aquifers are lower than in the carbonate rocks.

The chemical and physical properties of ground water in the Tennessee Region are usually within the limits recommended by the Environmental Protection Agency for drinking water, and the ground water in all but some very shallow aquifers tends to be free of pathogenic microorganisms. Saline water is not known to occur in significant quantities in the region.

In 1970, 173 million gallons per day of ground water were used in the Tennessee Region. This was less than eight percent of the total quantity of water used in the region and only 0.8 percent of the estimated ground-water recharge. Ground water is used chiefly as a source of water supply for rural areas and small towns. A lesser amount is used by industries and commercial establishments located beyond the limits of municipal water-supply systems. However, there is potential for significantly increased use in order to augment surface-water supplies and to utilize the total water resource more efficiently.

Hydrologic studies and adequate test drilling would greatly increase the chances of locating large amounts of ground water, especially in the nine-tenths of the Tennessee Region that is underlain by either carbonate rocks or fractured noncarbonate rocks which have highly variable water-bearing properties. Collectively, such studies are useful in developing a concept of the hydrologic system which would permit the development of criteria for selecting well sites in other areas with a similar geological and hydrological setting. Hydrologic studies that include test drilling have been undertaken in all parts of the region except the Cumberland Plateau.

Some of the basic data necessary for hydrologic studies, such as geologic maps, well records, and streamflow records are available throughout the region. However, detailed information on ground-water levels, ground-water quality and aquifer characteristics are not equally available throughout the region. This type of information cannot be obtained quickly when it is needed; it must be the product of a continuing program to evaluate the Tennessee Region's ground-water resource.

Because of the interdependence of ground water and surface water, water management efforts can be fully effective only if they involve the whole water resource. In the Tennessee Region, surface water is highly controlled, but there is at present no regionwide water-resources management plan that includes ground water.

INTRODUCTION

The significance of ground water as a resource is often not fully recognized in areas where surface water is abundant. Ground water is hidden from view, and requires special techniques to define its occurrence and availability. Planners and water managers who make decisions affecting development of water resources do not always have adequate information with which to evaluate ground water as an alternate or supplemental source of water.

In order to demonstrate that the Nation's ground water is a large and important resource, the U.S. Geological Survey has undertaken a broad-perspective appraisal of the ground-water resources in each of the twenty-one regions into which the United States has been divided by the Water Resources Council (fig. 1). The purpose of these regional appraisals is to show that in many parts of the Nation ground water can play a significant role in regional water supply and that it warrants further study and consideration in regional developmental planning.

The Tennessee Region coincides with the Tennessee River basin, an area of 41,000 mi^2 which lies mainly in Tennessee, Alabama and North Carolina but includes small parts of Virginia, Georgia, Kentucky and Mississippi. This diverse area includes parts of six physiographic provinces each having distinctive topography and geology (fig. 2).

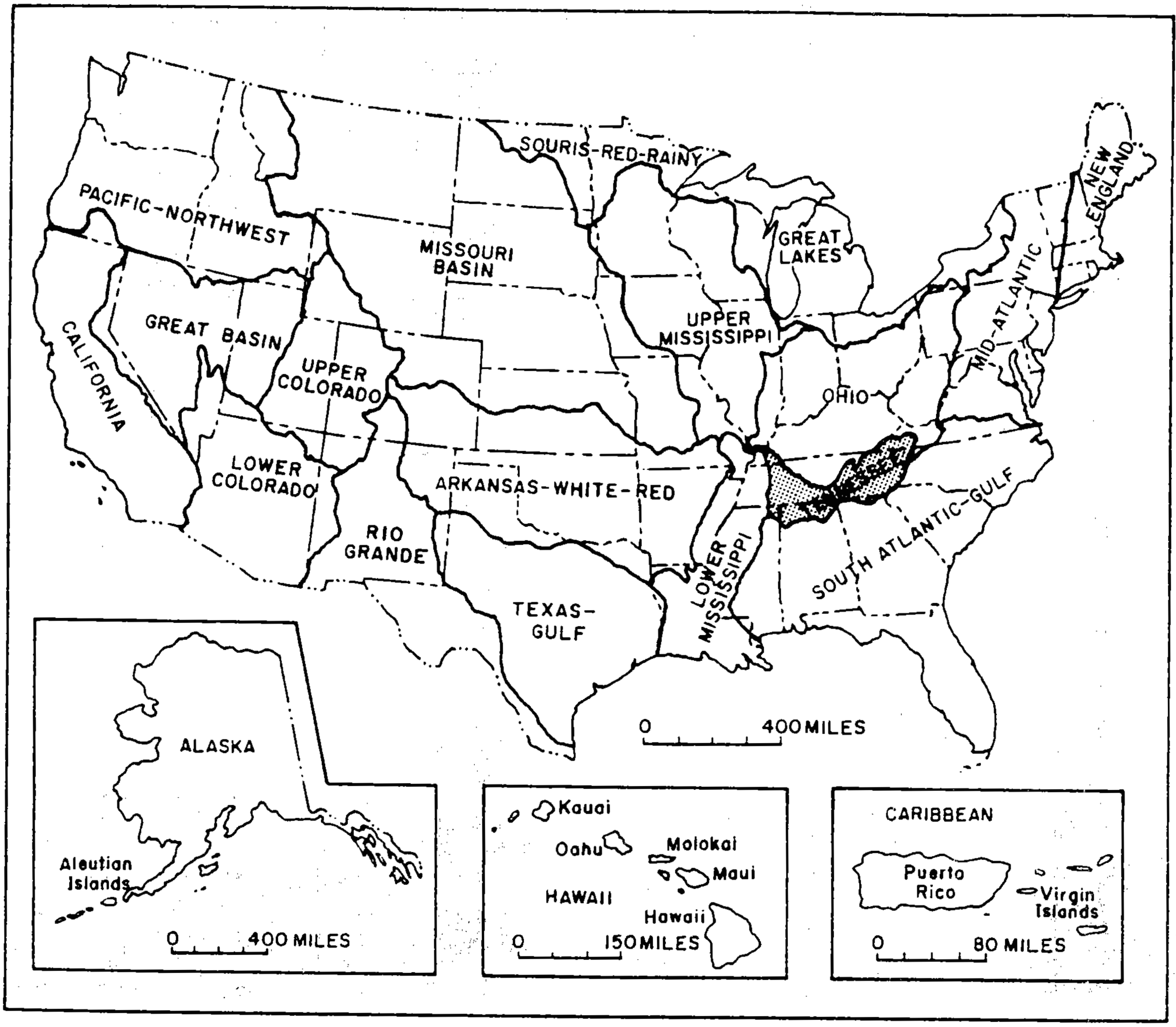


Figure 1.--Water Resources Council regions of the United States.

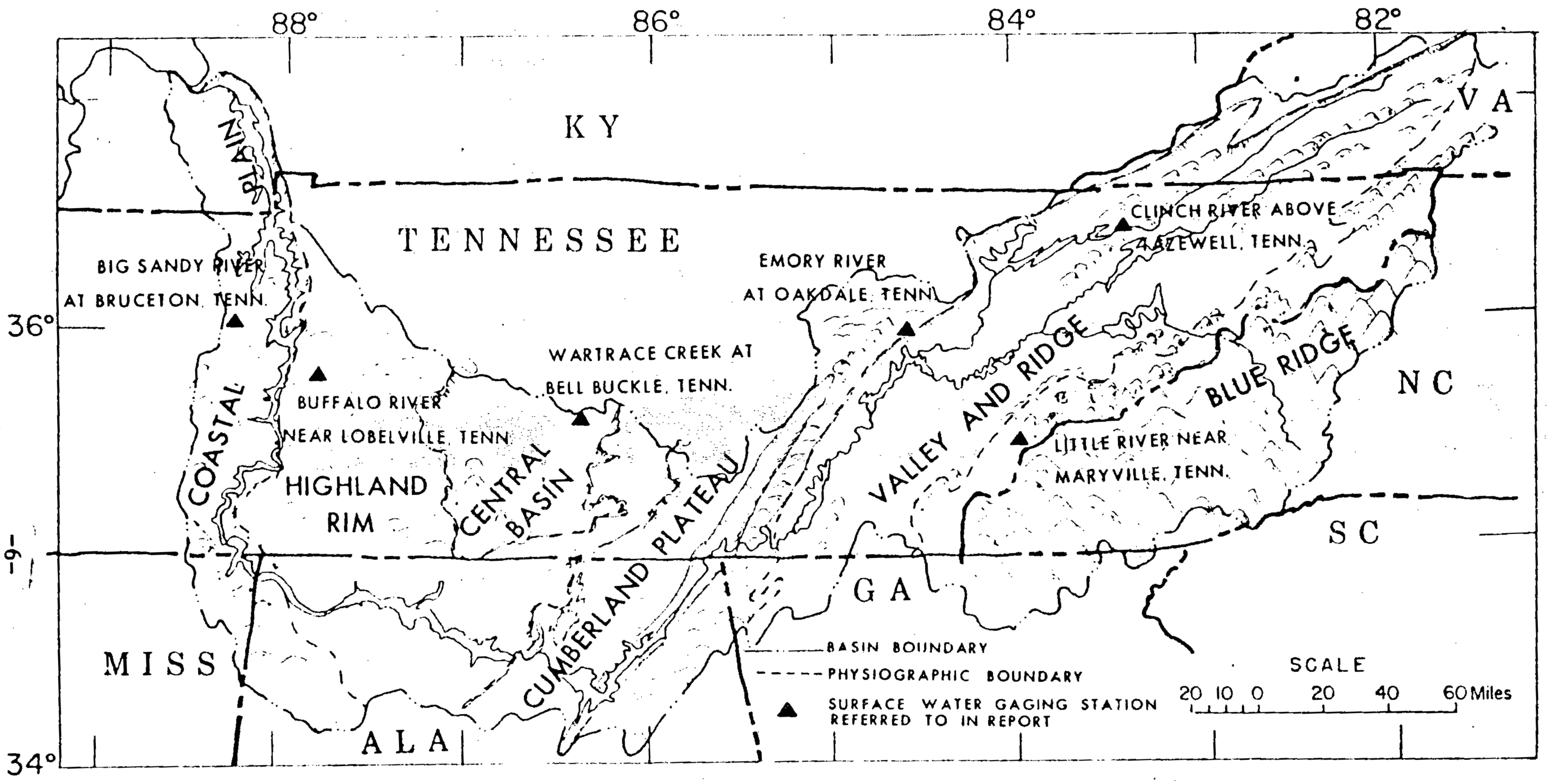


Figure 2.--Physiographic subdivisions of the Tennessee Region (modified from Hunt, 1967; Miller, 1974; Adams and others, 1926; Butts, 1933; and LaForge and others, 1925).

The Tennessee River system has played a major role in the region's development. Historically, severe flooding along the Tennessee River hindered industrialization of the region. The Tennessee Valley Authority, created by Congress in 1933 as a regional resource development agency, very early began to construct dams along the Tennessee to control flooding, promote navigation and produce electric power. The harnessing of the river was followed by industrialization, population growth, and a higher standard of living.

The flow of the Tennessee River and its tributaries, however, is only a small part of the region's water resources. In July of 1973, a record 10.3 million acre-ft of useable water was stored in the Tennessee River's reservoir system (TVA, 1973). This is 450 billion ft^3 of water. M. I. Kaufman (written comm. 1975) estimated that 25,800 billion ft^3 of ground water was available from storage in the Tennessee Region. While his figure is difficult to verify, it is indicative of the magnitude of difference between ground-water and surface-water storage even for a fully-regulated river system. In many areas where surface water is not available, large quantities of ground water are available for development. Ground water has been a neglected resource in the Tennessee Region, but because of increasing pressure to utilize all resources in the most efficient and productive manner, ground water is now being recognized as an integral part of the region's water resources.

This report synthesizes the results of previous studies in the Tennessee Region and appraises the role of ground water in the hydrologic systems of the Tennessee Region. It provides an overview of the occurrence of ground water, its present and potential use, and the need for management of ground water as an integral part of the water resources of the region.

THE GROUND-WATER RESOURCE

Ground Water and Streamflow

The source of both surface and ground water is precipitation. In an average year, precipitation in the Tennessee Region ranges from 85 in in the mountainous eastern part to 40 in in some locations (fig. 3). The average for the region is 52 in (Tennessee Valley Auth. 1975). In a normal year, most precipitation occurs in the winter and spring months, least in the summer and fall months. About 60 percent of the yearly precipitation returns to the atmosphere by evaporation and the transpiration of plants. Rates of evapotranspiration are highest during the hot, dry months when plants are growing. The remaining 40 percent of the precipitation either flows overland into streams or percolates into the ground to replenish, or recharge, the ground-water reservoirs (fig. 4).

Water entering the ground-water reservoirs is stored in the pore spaces in unconsolidated deposits and weathered rock, or in fractures and solution openings in the bedrock. Characteristically, all ground water in storage moves toward areas of discharge such as springs, streams, and wells. Water levels are related to the amount of water available to the base flow of streams and the volume of water that can be stored in the ground-water reservoir.

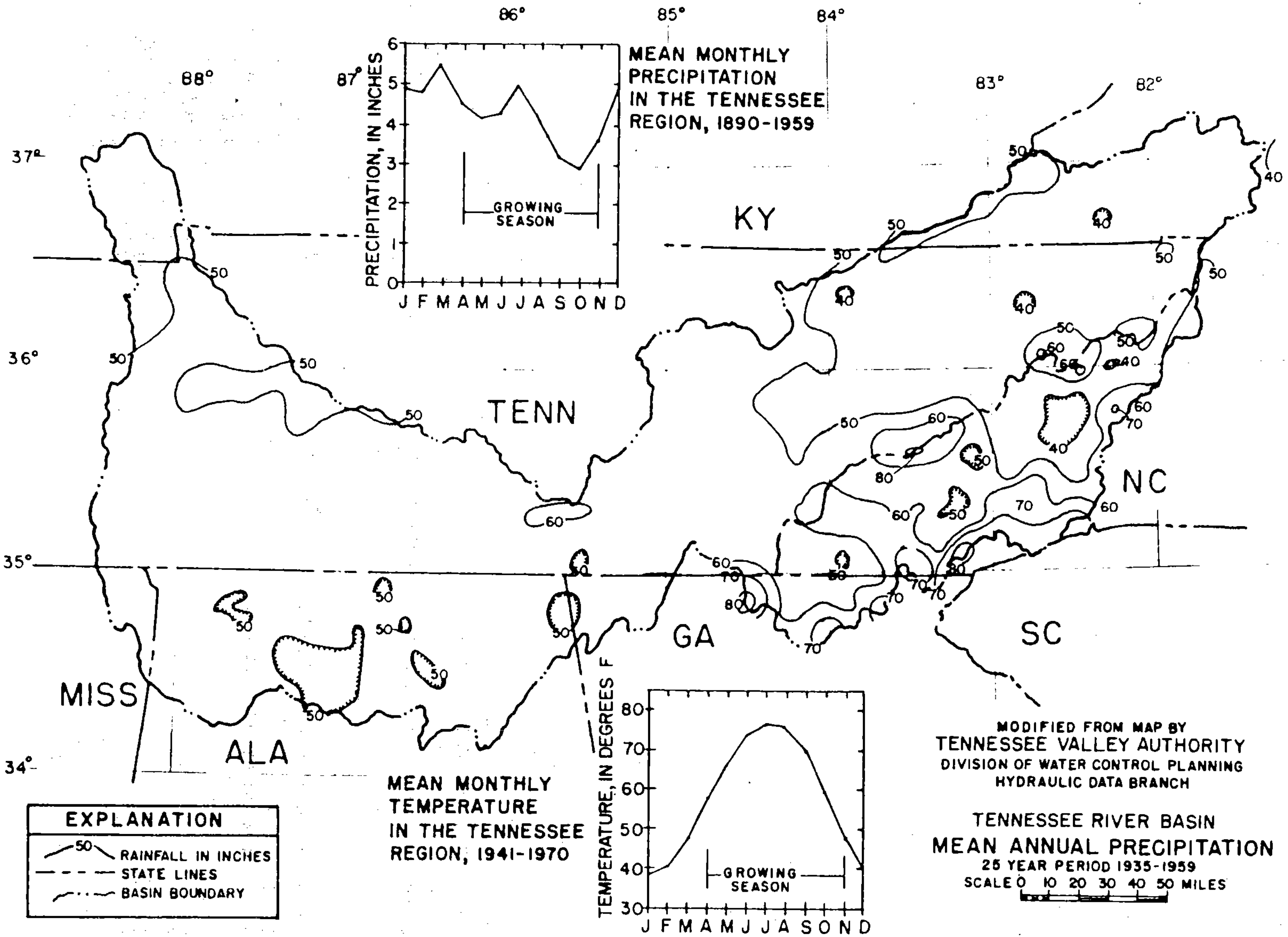
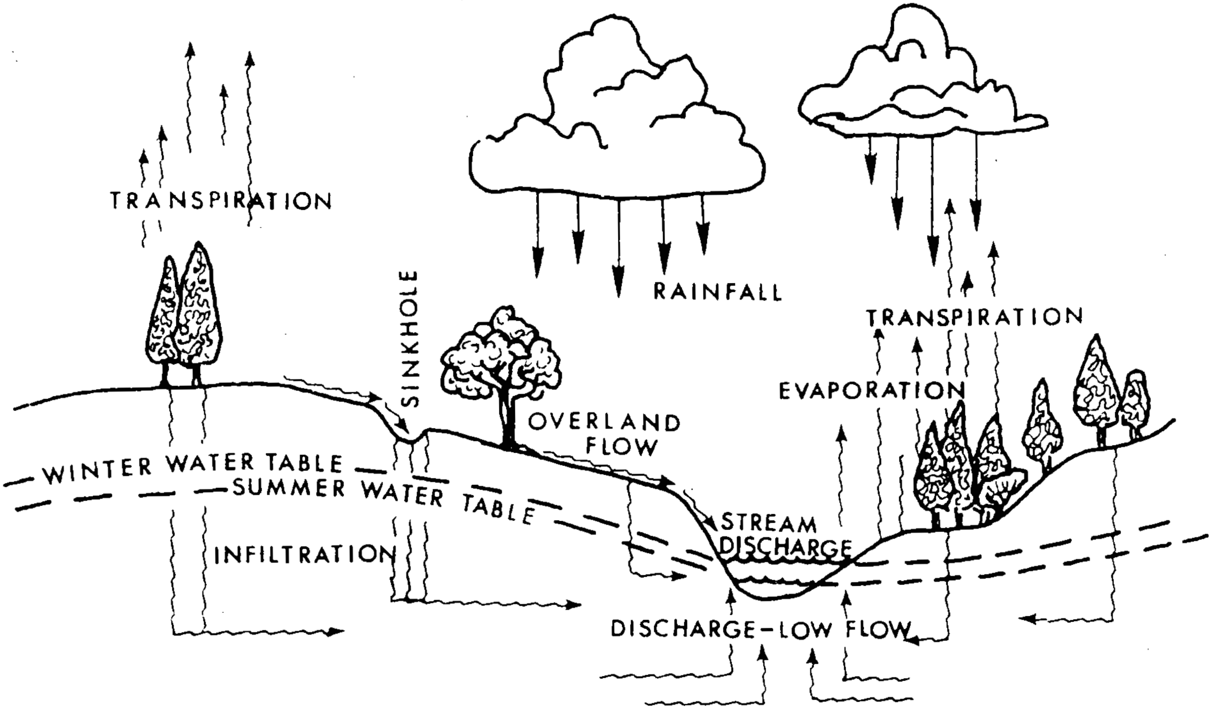


Figure 3.--Mean annual and monthly precipitation and mean monthly temperatures for the Tennessee Region.



TYPICAL WATER BUDGET

	Inches	
Average rainfall over drainage area ---	50.2	
Stream discharge----------------------	21.5	42.8%
Low flow-------------------------	11.5	53.5% of Total Q
Overland flow--------------------	10.0	46.5% of total Q
Evaporation and transpiration---------	28.7	57.2

Figure 4.--Hydrologic cycle and water budget for a typical stream in the Tennessee Region based on average of values for six drainage basins. (Hydrologic cycle from Burchett, 1977).

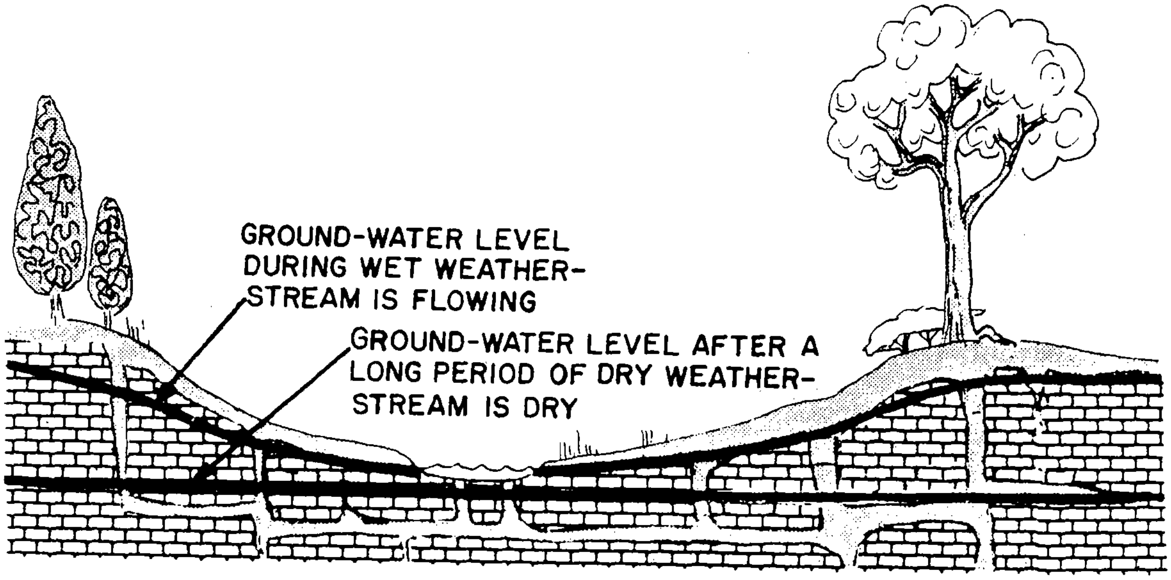


Figure 5.--Ground water levels affect streamflow. In this limestone aquifer, typical of the Central Basin, recharge is stored temporarily above stream level. When there is a gradient toward the stream, ground water is discharged to the stream, sustaining its flow. As solution openings are drained, the water table becomes almost flat at or below the stream level and streamflow ceases.

The effect that water-level fluctuation has on streamflow in areas underlain by a limestone aquifer with a thin soil cover is shown in figure 5. Ground water in these areas is discharged rapidly during periods of little or no rainfall, causing a decline in ground-water levels in the aquifer which results in the depletion of streamflow. Streams that cut deeply into thick, unconsolidated aquifers have sustained stream flow even through long periods of dry weather because of the slow release of ground water from these aquifers. In most aquifers, the replenishment of ground water at times exceeds the outflow or vice versa, but over a long period the recharge and discharge are about equal, so that ground-water discharge in a normal year can be approximately equated with the average annual base flow of streams.

The amount of ground-water recharge in the Tennessee Region was estimated using hydrographs of streamflow at six gaging stations during the 1968 water year, a year of nearly average streamflow across the region. Hydrograph separations were made to obtain maximum and minimum estimates of base flow (fig. 6). The values obtained ranged from 5 to 16 in/yr or 13 to 33 percent of the year's precipitation (fig. 7). The estimated average rate of recharge for the region as a whole is about 10 to 13 in/yr or 19 to 25 percent of the precipitation. This is about 0.5 $(\mathrm{Mgal/d})/\mathrm{mi}^2$ or 22,000 Mgal/d for the entire region. The water budget shown in figure 4 is an average for the region. The numbers agree with previous water budget studies in the Pomperaug River basin in Connecticut, a basin underlain by fractured crystalline rocks and thin glacial drift (Meinzer and Stearns, 1929) and Beaverdam Creek basin in Maryland, underlain by coastal plain deposits (Rasmussen and Andreasen, 1957, table 1). Since the hydrologic properties of the aquifers in the Tennessee Region are intermediate between those of the other two basins, it is reasonable that the water budget figures for the Tennessee Region as a whole fall between those of the other two studies. Average recharge figures can serve only as a rough guide to the amounts of ground water available for withdrawal because they describe only the annual amount of water passing through the system, only part of which is available to wells.

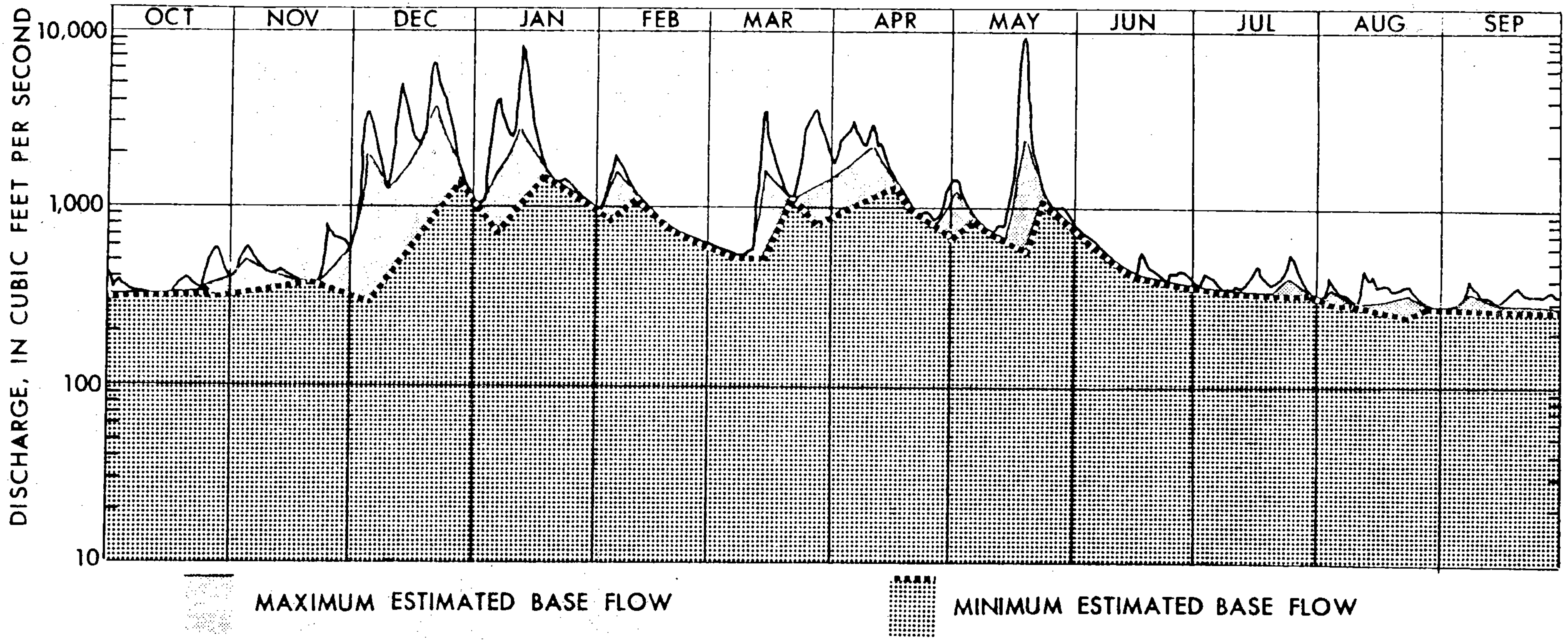


Figure 6.--Baseflow of Buffalo River near Lobelville during the 1968 water year, a year of average streamflow. After about 6 days overland runoff has left the basin and flow is supplied from the ground-water reservoir. Maximum and minimum ground-water contribution to streamflow was determined graphically for 1968 water year. For the maximum ground water outflow, the recession curves from 6 days after each peak were projected back to the day of the peak. An arbitrary line was then drawn from the peak to the point where the stream began to rise. For the minimum, each recession curve was extended to the day of the following peak, then joined by a straight line to the point 6 days after that peak. This method is a modification of that described by Busby and Armentrout (1965) and Moore, Burchett and Bingham (1969).

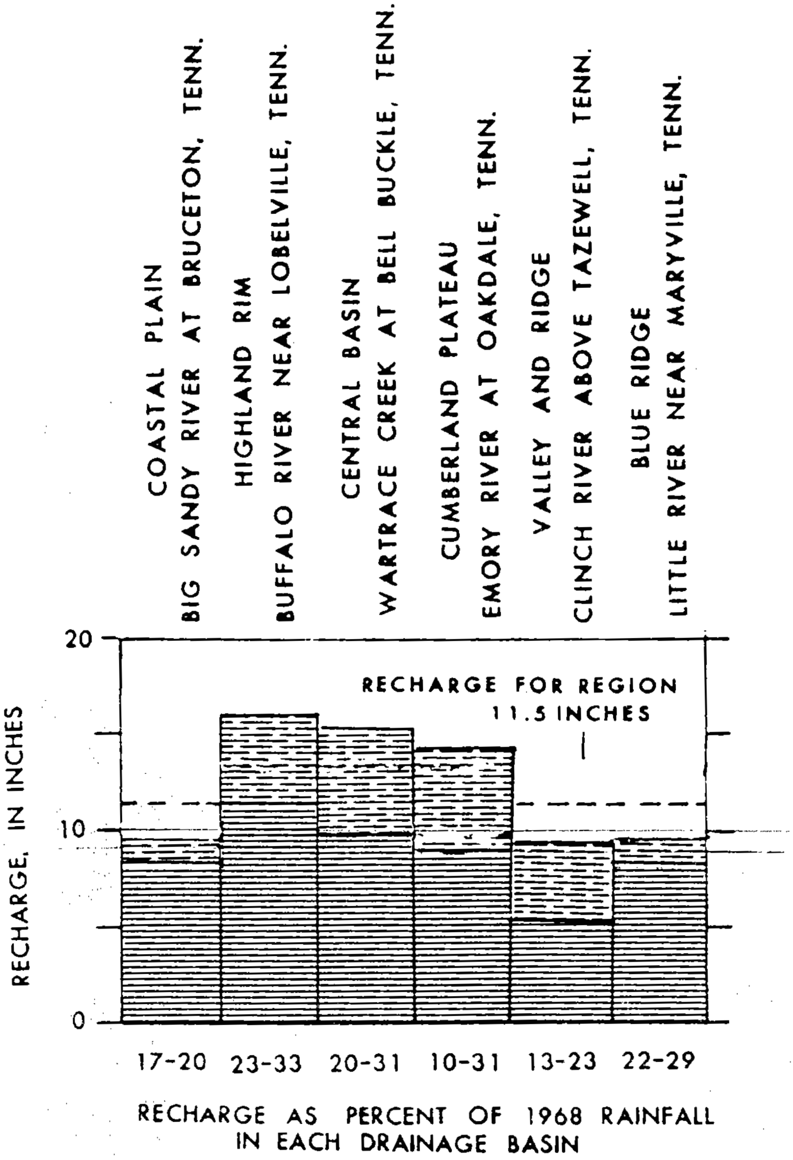


Figure 7.--Ground-water recharge (not including ground-water evapotranspiration) in 1968 in six drainage basins in the Tennessee region, and recharge for the region. This value is the average of the maximum and minimum values for the six basins.

Table 1.--Comparison of water budget of a typical stream in the Tennessee Region with water budgets for Pomperaug River and Beaverdam Creek basins. Values are given as percent of precipitation.

	Pomperaug Basin	Beaverdam Creek Basin	Tennessee Region
Evapotranspiration	52.2	60.7	57.2
Total runoff (streamflow)	46.4	36.1	42.8
Ground water runoff (base flow)	19.6	25.9	22.9 53.5%
Change in storage	1.4	2.1	Not calculated

Flow-duration curves of streams are, in part, indicators of the water-storing properties of aquifers. A flow-duration curve is constructed by plotting specified streamflows against the percentage of time they are equalled or exceeded at a gaging station. The streamflow at any time depends on the climate, drainage area, topography, overburden, and geology of the basin. Variations in these factors from one basin to another result in a variety of shapes of flow-duration curves (Burchett and Moore, 1971). The shape of the low-flow portions of duration curves is controlled chiefly by the geology of the basin (Searcy, 1959) and is indicative of the interaction of ground water and surface water in the basin.

Flow-duration curves of six long-term gaging stations on unregulated streams in the Tennessee Region are shown in figure 8. Each curve is representative of the flow characteristics of streams in a particular physiographic province. The effects of the difference in size of drainage areas have been minimized by plotting the streamflow in cubic feet per second per square mile.

The decreasing slope of four of the duration curves shows that those streams have well-sustained base flow indicating the ability of unconsolidated aquifer material to store and release water slowly. Big Sandy River at Bruceton, Tenn. traverses unconsolidated sand. Buffalo River near Lobelville, Tenn., Clinch River above Tazewell, Tenn., and Little River near Maryville, Tenn. are in areas with thick regolith.

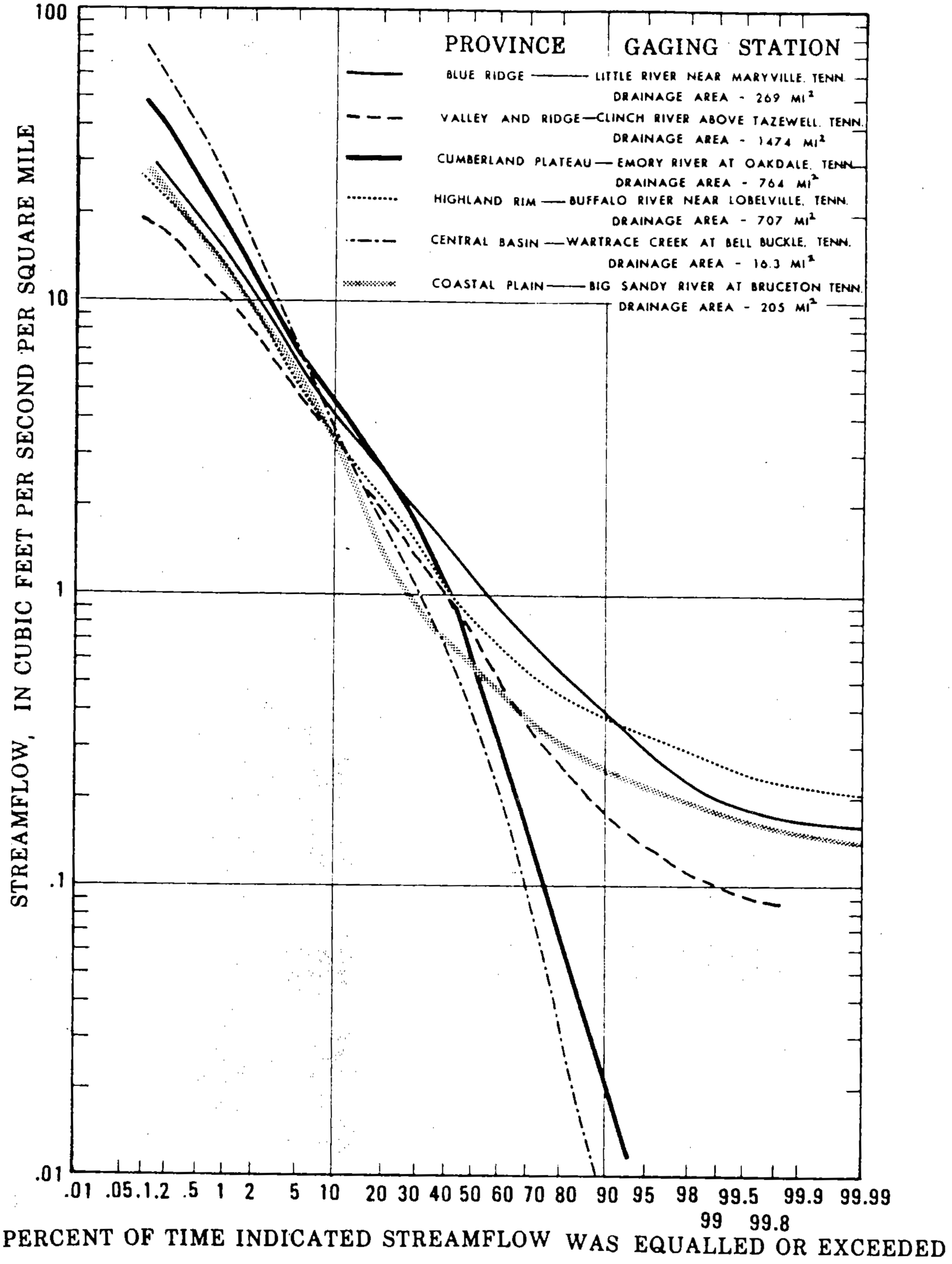


Figure 8.--Streamflow-duration curves for six gaging stations in the Tennessee Region.

The curves for Wartrace Creek at Bell Buckle, Tenn. and Emory River at Oakdale, Tenn. are markedly different from the other curves, indicating the low water-storing properties of the rock underlying the basins and the very poorly-sustained low flows. The curve for Emory River at Oakdale shows the low storage capacity of the fractured rocks capping the the Cumberland Plateau. The curve for Wartrace Creek shows the low storage and rapid release of ground water in flat-lying limestone aquifers of the Central Basin. Interconnected solution openings in the limestone rapidly discharge the water that is temporarily stored above stream level. Low-flow frequency analyses for these gaging stations also show that base flow of Emory River and Wartrace Creek is much more poorly-sustained than that of the other four streams (table 2).

Table 2.--3 day 20-year low flows at six gaging stations in the Tennessee Region

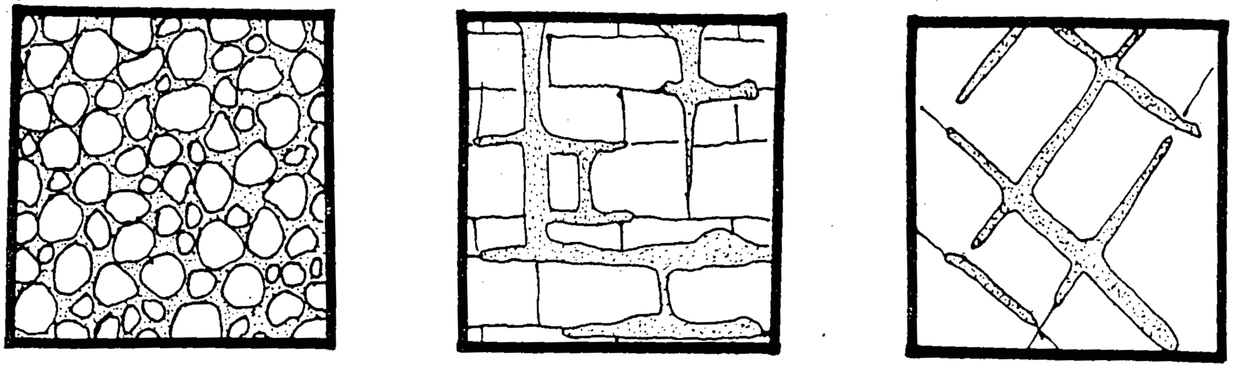
Province	Station	3-day 20-year low flow in cubic feet per second per square mile
Blue Ridge	Little River at Maryville, Tenn.	0.17
Valley and Ridge	Clinch River above Tazewell, Tenn.	0.08
Cumberland Plateau	Emory River at Oakdale, Tenn.	0.0005
Highland Rim	Buffalo River near Lobelville, Tenn.	0.22
Central Basin	Wartrace Creek at Bell Buckle, Tenn.	0.0014
Coastal Plain	Big Sandy River at Bruceton, Tenn.	0.16

Major Aquifers

Three types of aquifers occur in the Tennessee Region: unconsolidated material with intergranular porosity, carbonate rocks with solution openings, and noncarbonate rocks with fractures (fig. 9). One or more of these aquifers is characteristic of each physiographic province (fig. 10).

Unconsolidated Aquifers

Unconsolidated materials are significant aquifers in about half of ? the Tennessee Region (fig. 10). In the Coastal Plain, an area of 4000 mi^2 on the western edge of the region, the important aquifers are sand formations which dip to the west. These formations are the most uniformly productive aquifers of the region, commonly yielding 200 to 600 gal/min to single wells. Parts of another 18,000 mi^2 are covered by unconsolidated material, referred to as regolith, which is a mantle of disintegrated rock that has accumulated over the bedrock. Grain size ranges from clay to coarse gravel and is a major factor in determining the regolith's water-bearing properties. The regolith is hydrologically significant in areas where it is thick and permeable, especially in the Highland Rim and parts of the Blue Ridge and Valley and Ridge. In these areas it acts as a sponge in absorbing and storing large amounts of ground water. Where saturated, the regolith yields dependable domestic supplies, but larger supplies can be obtained where fractures or solution openings in the underlying bedrock are hydraulically connected with the regolith.



UNCONSOLIDATED AQUIFER

CARBONATE ROCK AQUIFER

NON-CARBONATE ROCK AQUIFER

Figure 9.--The three major types of aquifers in the Tennessee Region, distinguished by the kind of water-bearing openings they contain (after Meinzer, 1923).

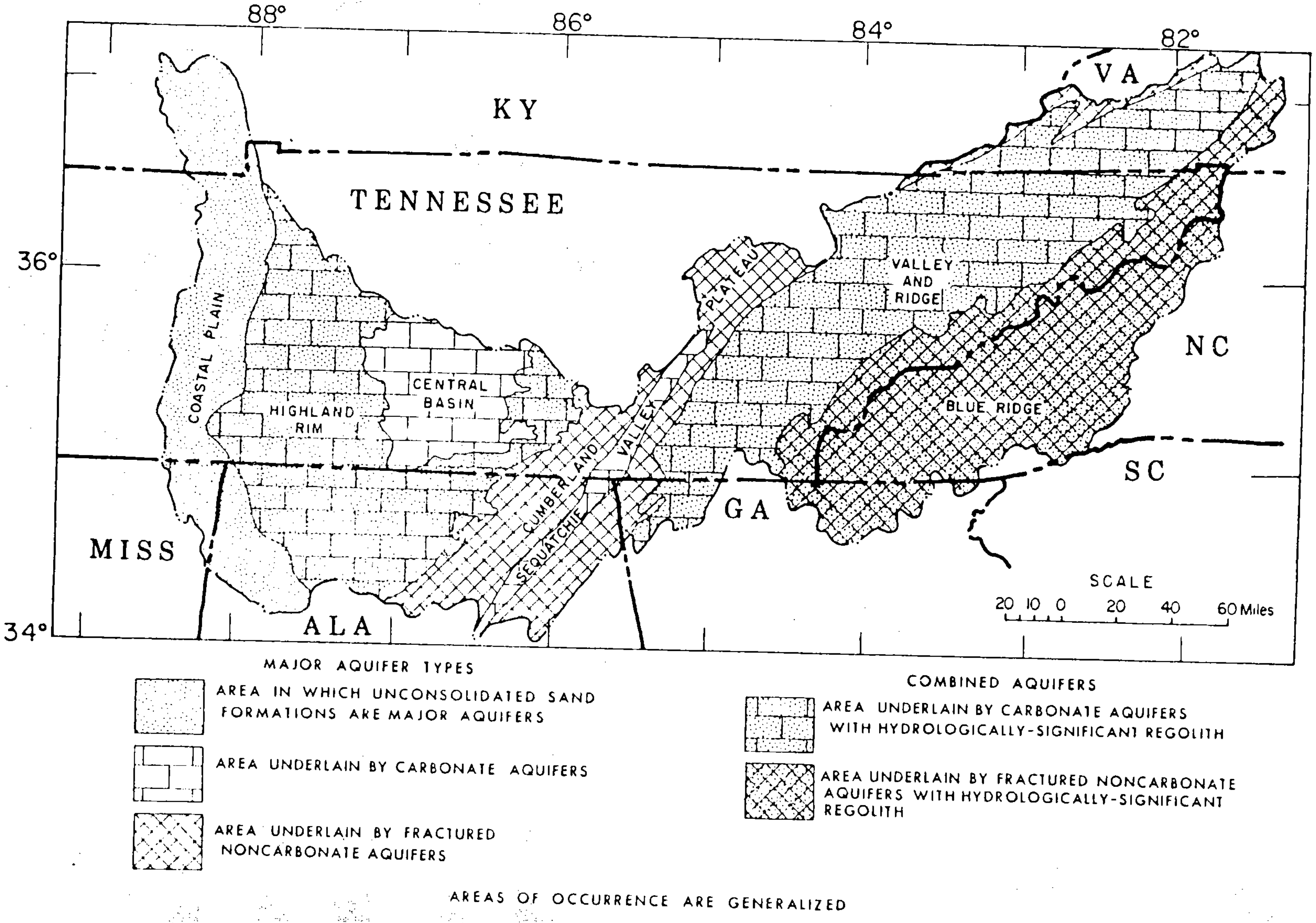


Figure 10.--Distribution of major aquifer types in the Tennessee Region.

Figure 11.--Deleted.

Carbonate Aquifers

Carbonate aquifers underlie about half of the Tennessee Region (fig. 10). The rocks in the Valley and Ridge section of the region are steeply tilted and west of the Valley and Ridge are essentially flat-lying. Water occurs in openings along fractures, faults, and bedding planes which have become enlarged by circulating ground water. Solution openings occupy a small volume in the rock and generally occur within about 300 ft of land surface. Individual openings range from a fraction of an inch to several feet in height and can be laterally extensive. Wells that penetrate large openings may be able to produce several thousand gallons per minute, but such openings occupy a small proportion of the rock. As a result, well yields vary widely in carbonate terrane. For example, at Franklin, Tenn., in the Central Basin just north of the Tennessee Region, two test wells 100 ft apart produced 18 and about 180 gal/min respectively. Variability of solution openings makes well placement critical in obtaining large amounts of ground water from carbonate rocks.

Figure 12.--Deleted.

Fractured Noncarbonate Aquifers

Slightly more than a third of the Tennessee Region is underlain by noncarbonate rocks which, unlike the Coastal Plain deposits, have very little porosity aside from fractures (fig. 10).

These rocks range from sedimentary rocks such as shale and sandstone underlying the Cumberland Plateau to rocks that have been subjected to metamorphism and deformation in the Blue Ridge. Weathering along fractures and faults has created avenues for water movement. These fracture openings probably comprise less than one percent of the rock volume, and water-bearing fractures are uncommon at depths over 300 ft (McMaster and Hubbard, 1970). The fractures at greater depths are likely to be unweathered and closed. Fractures are commonly more abundant near faults. Well production is determined by the depth, size, and degree of interconnection of fractures penetrated and by the thickness of overburden hydraulically connected to the fractures.

Fractured rocks are generally considered to be poor aquifers, but they have generally not been adequately tested to determine their water-yielding potential. Newcome and Smith (1958) report that wells producing 50 gal/min or more are rare on the Cumberland Plateau. However, the town of Wartburg, Tenn. has three wells which, at the time they were drilled, were reported to produce more than 100 gal/min each. Test drilling in the Great Smoky Mountains National Park (McMaster and Hubbard, 1970) showed that where fractured rock is hydraulically connected to thick regolith, properly located wells can produce 100 gal/min or more.

Figure 13.--Deleted.

Aquifer Productivity

Aquifer productivity as used in this report refers to the rate at which ground water can be withdrawn from an aquifer at a particular locality on a continuing basis by means of a well or group of wells. Well yields are determined by the hydraulic properties of the aquifer. In the Tennessee Region, however, the areal variability in properties of the aquifers, combined with lack of data for many areas make the definition of aquifer productivity difficult. Several approaches can be used to quantify aquifer productivity.

The basic hydraulic properties of an aquifer are transmissivity (the rate at which water can be transmitted through the aquifer) and storage (related to the amount of water that is released by draining part of a water-table aquifer or lowering the pressure in an artesian aquifer). The more nearly an aquifer approaches uniformity in its water-bearing properties, the more applicable are these measures of hydraulic characteristics.

In the Tennessee Region, the unconsolidated aquifers of the Coastal Plain section, on the western margin of the region, are the least variable in their hydraulic properties. Two aquifer tests indicate transmissivity of 3300 and 4300 ft^2/d and coefficients of storage of 0.0008 and 0.0001 for the McNairy Sand, a confined unconsolidated aquifer (Boswell, Moore and MacCary 1965). However, nine tenths of the region is underlain by carbonate or fractured noncarbonate aquifers which are far from uniform in their hydraulic properties. Five aquifer tests in Madison County, Alabama, indicate transmissivity ranging from 650 to 130,000 ft^2/d and storage of 0.04 to 0.0004 for the Fort Payne Chert (Malmberg and Downing, 1957). This extreme variability is evident in the results of aquifer tests made elsewhere in the Tennessee Region and is typical of carbonate aquifers.

Another indicator of aquifer productivity is the specific capacity of wells, the rate of yield per foot of drawdown. Although it is a characteristic influenced in part by conditions in and around the well, specific capacity data reflect the properties of the aquifer. The ranges of specific capacities shown in figure 14 illustrate the high degree of variability in the aquifers of the Tennessee Region, although some of the low values may be the result of poor well design rather than aquifer properties. This variability is of critical importance in developing a ground-water supply because the more variable the aquifer productivity, the greater the risk of failure to obtain the desired amount of ground-water at a particular site. In the Tennessee Region, the least variability of yields is from wells that tap unconsolidated aquifers. The most variability is in carbonate-rock aquifers not associated with a thick, saturated mantle of regolith. In economic terms, greater variability in yields means that more preliminary study, more test wells, and more leeway in well location will probably be needed to obtain a desired amount of ground water.

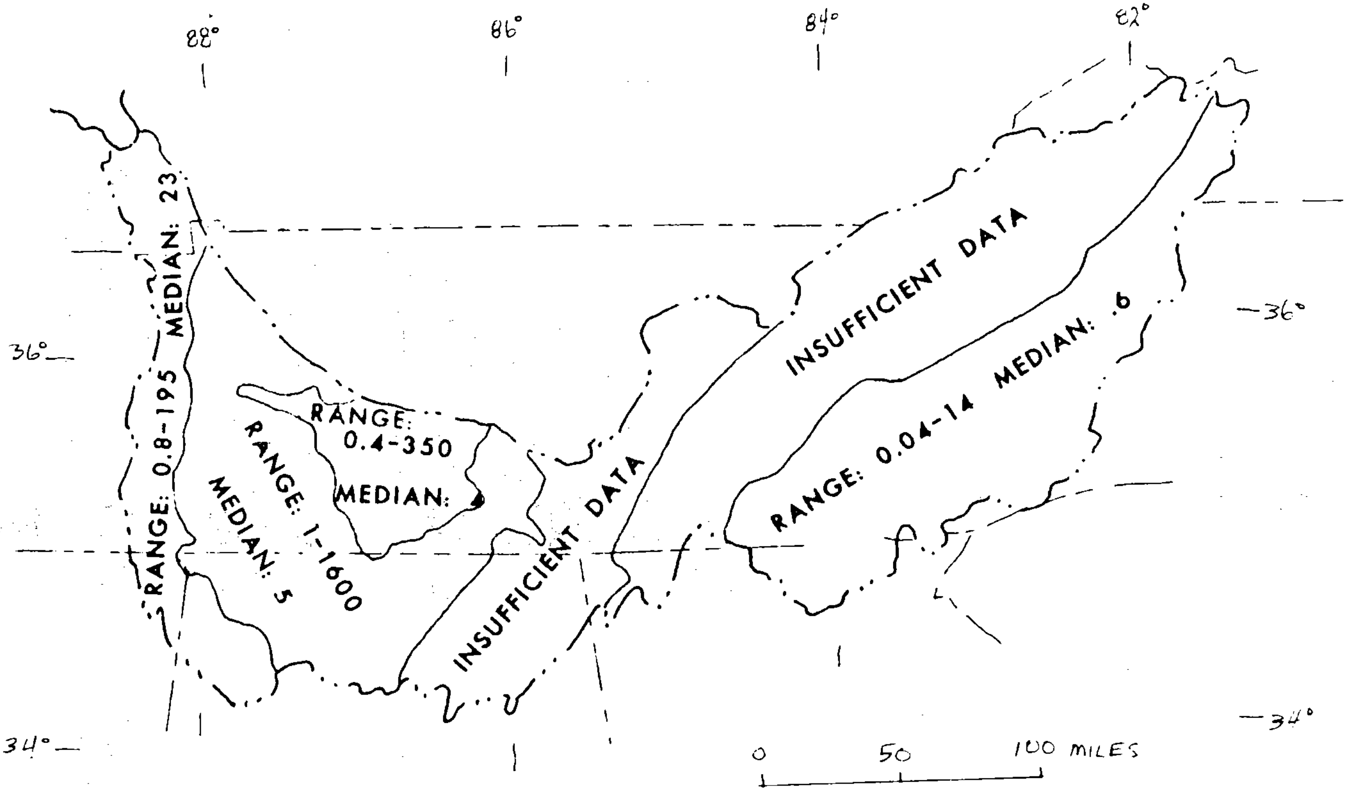


Figure 14.--Ranges and median values of specific capacities of selected wells in the Tennessee Region, in (gal/min)/ft.

Another approach to quantifying aquifer productivity is to estimate probable yields that could be obtained from wells located on the basin of geologic and hydrologic information. Table 3 gives yields that might be expected from different types of aquifers in the Tennessee Region. These yields are for single wells constructed to obtain maximum yield having at least 50 ft of available drawdown. The numbers are based on figures given by Cederstrom (1973) for areas with geology similar to that of the Tennessee Region and on inferences drawn from records of well production in the region. Ground-water withdrawals are ultimately limited by the rate of recharge to the aquifer. In the Tennessee region, maximum withdrawals on a continuing basis are about 0.5 Mgal/d per square mile of area contributing recharge to the system.

Table 3.--Probable yields from the major aquifer types of the Tennessee Region.

Type of aquifer	Yield per well, in gallons per minute
Unconsolidated Sand	500-100
Carbonate rocks with regolith	100-300
Carbonate rocks without regolith	0-300
Noncarbonate rocks with regolith	25-100
Noncarbonate rocks without regolith	Unknown

Efficient and economical development of the ground-water resources of the Tennessee Region are strongly influenced by the variability of aquifer productivity. Predictability of well yields and the availability of ground-water supplies at particular sites is greatest in the Coastal Plain sand aquifers and the regolith-mantled carbonate rocks. Hence, it is probable that ground-water development will proceed most efficiently in these areas. The risk of not obtaining a ground-water supply is greatest in the noncarbonate rocks and the carbonates that have no regolith cover. In these areas, development will be less efficient until methods are developed to locate ground water and predict well yields with greater accuracy.

Occurrence of Ground Water

The distribution of ground water in the Tennessee Region is influenced by the difference in topography, geology, and hydrology among the six physiographic provinces (fig. 2). Though large amounts of ground water exist in each physiographic area, less preliminary study and exploratory drilling are usually needed to obtain a specified supply in areas where the ground water occurs in the intergranular pore spaces of unconsolidated aquifers, than in areas where water occurs in discrete fractures or openings. The following section describe for each physiographic area the topographic, geologic, and hydrologic controls on the distribution of ground water.

Blue Ridge

The part of the Tennessee Region in the Blue Ridge province is composed of the remants of an ancient mountain chain. The topography is rugged and relief is greater than in any part of the region. In most places, the dense, massive bedrock contains little water except where faulted or fractured. Overlying the bedrock on all but the steeper slopes is a mantle of regolith that is more than 100 ft thick on the lower slopes of the mountains. The regolith is composed of sand, clay and rock fragments (McMaster and Hubbard, 1970). It stores large amounts of water, releasing it slowly to the underlying fractures and to springs and streams. The fractures store only limited amounts of water but acts as collectors, transmitting water from the overlying regolith to points of discharge (fig. 15). Most of the bedrock in the Blue Ridge is noncarbonate, but a few areas underlain by carbonate rocks, such as Cades Cove, contain the largest amounts of ground water in solution openings and in porous zones in the intensity weathered rock.

In the Blue Ridge province, McMaster and Hubbard (1970) and LeGrand (1967) determined that the chances of drilling high-producing wells are increased at sites in relatively low topographic position within a few hundred feet of a fault zone, and in areas having thick regolith. The broad valleys underlain by carbonate rocks, such as Cades Cove, may be favorable sites for locating ground-water supplies. However, these occur only in a few small areas of the Blue Ridge.

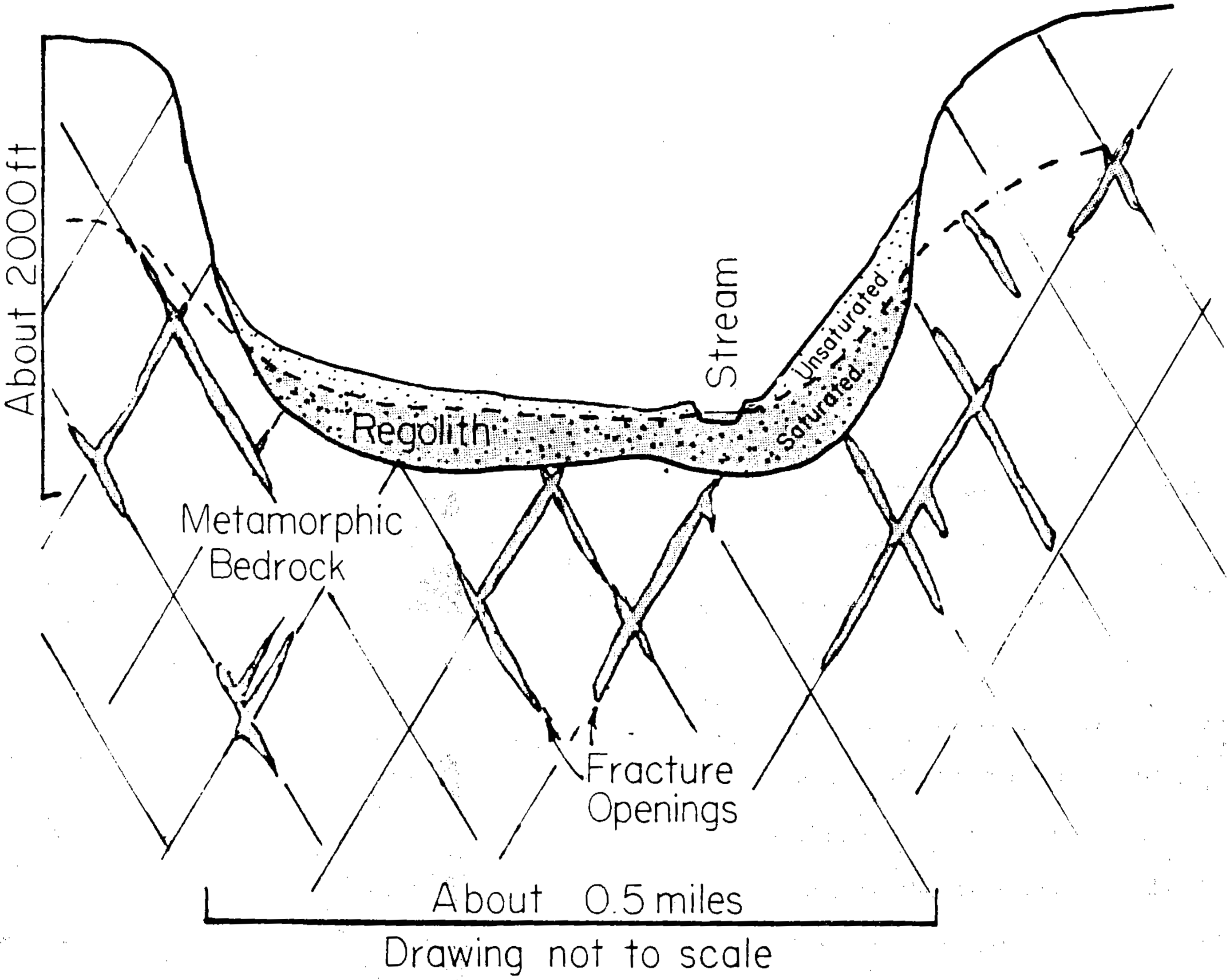


Figure 15.-- Sketch of idealized geologic and hydrologic conditions in the Blue Ridge province.

Valley and Ridge

The Valley and Ridge province is characterized by northeast-trending ridges underlain by resistant rock separated by valleys underlain by less resistant rock. The rock formations crop out in long, narrow belts parallel to the trend of ridges and valleys; some belts are bounded by faults. The linear ridges and valleys channel surface drainage into a "trellis" pattern of long streams flowing along valley floors fed by short lateral streams.

All three major aquifer types occur in the Valley and Ridge. The shale and sandstone formations (fractured noncarbonate rocks) are the poorest aquifers. Limestone and dolomite of varying solubility occur with a cover of regolith ranging in thickness from a few feet to over 100 ft with extreme areal variability (DeBuchananne and Richardson, 1956). The largest ground-water supplies are in the soluble carbonate rocks, especially where they are associated with thick regolith (fig. 16). Water moves through enlarged fractures and solution openings in these carbonate rocks, emerging in places as large springs. Some of these flow at an average rate of 4500 gal/min or more (Sun, Criner, and Poole, 1963). Geologic maps are essential tools for site selection, especially in the Valley and Ridge province. The Knox Dolomite, which underlies about 60 percent of the province, is the most significant water-bearing formation. The most productive wells are located in areas of ground-water discharge such as stream valleys or else they penetrate fracture zones. These fracture zones are sometimes indicated by straight stream segments and aligned tributaries.

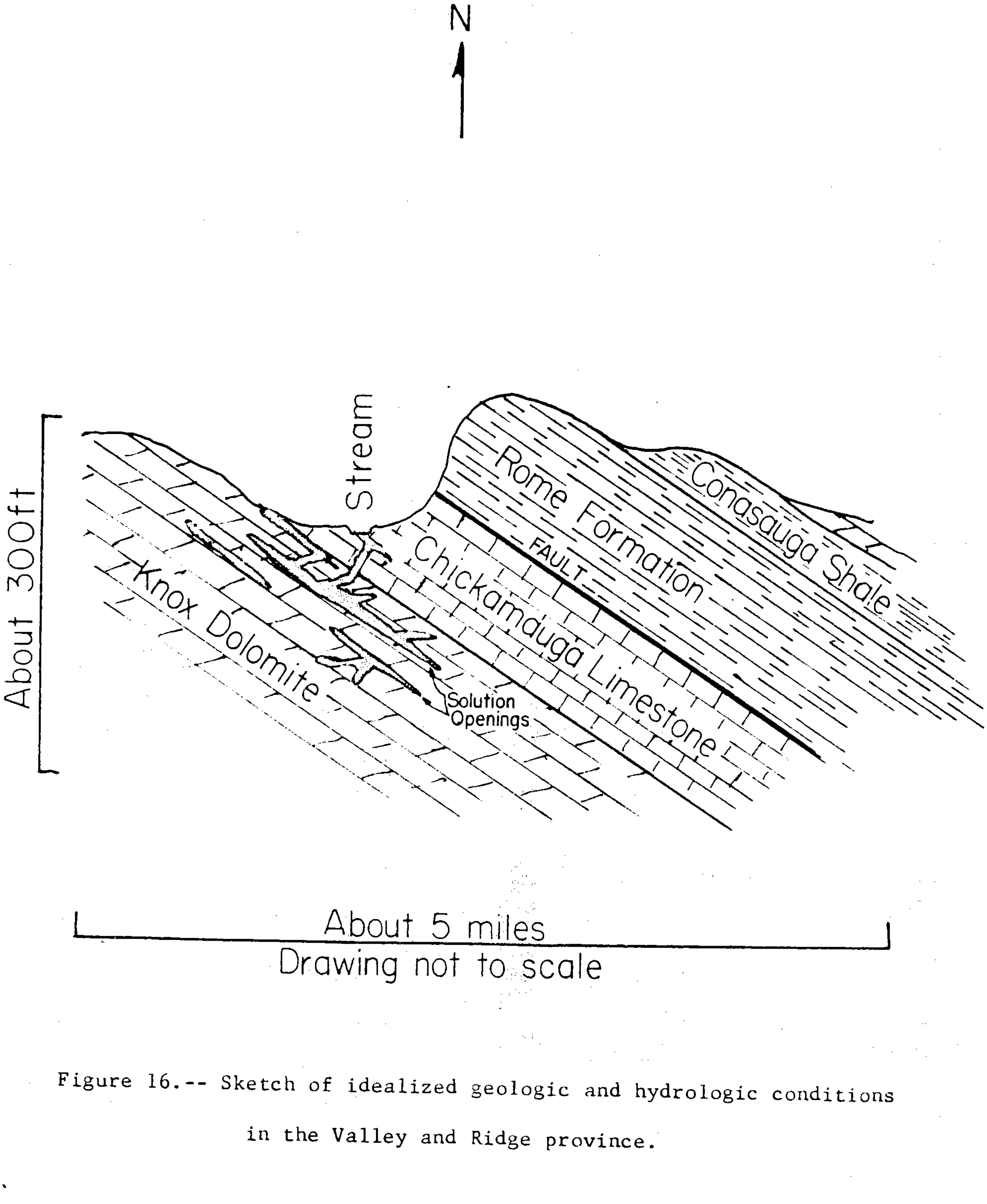


Figure 16.-- Sketch of idealized geologic and hydrologic conditions in the Valley and Ridge province.

Most of the larger water-bearing openings in the Knox occur at a depth of less than 300 ft. Swingle (1959) states that surface faults indicate areas with deep and numerous fractures which allow deep solution activity. Wells tapping water-filled solution openings in low areas are more dependable as a source of water supply than wells on ridges because the seasonal fluctuations of water level are small in the low areas.

Cumberland Plateau

The Cumberland Plateau section of the Appalachian Plateaus province is about 1000 to 1500 ft higher than the adjoining Valley and Ridge province and Highland Rim. It extends about 175 miles northeast-southwest across the Tennessee Region. North from Anderson County, Tennessee, the steep eastern escarpment of the Plateau forms the Tennessee River-Cumberland River divide.

The bedrock is a sequence of mostly horizontal Pennsylvanian sandstone, shale, conglomerate, and coal, underlain by Mississippian and older shale and carbonates. The Mississippian carbonates are exposed where Sequatchie Valley, a 130 mile long, linear valley, cuts deeply into the Plateau. Large springs emerge along the sides of the Plateau and from the Mississippian and older limestones exposed in Sequatchie Valley (fig. 17). An example of these large springs is Blue Spring which is used as a source of water supply by the City of Jasper, Tenn. An average of 172,000 gal/d was used by the City in 1970 (Tennessee Dept. of Public Health, 1975). Newcome and Smith (1958) reported the flow of this spring to be 900 gal/min but the seasonal variation in discharge has not been determined.

1x10-10 ft/s · 3600s/hr x 24hr/dy

The Pennsylvanian rocks have low permeability except where fractured. The regolith is usually thin, providing little ground-water storage (DeBuchananne and Richardson, 1956). As a result of the uneven distribution of fractures, the average of reported well yields is less than 50 gal/min (Newcome and Smith, 1958). Even domestic supplies cannot always be obtained. However, since detailed studies involving test drilling have not been made, the full water-yielding potential of the Plateau is not known. Wilson (1965) states that in Cumberland Co., Tennessee, the Sewanee Conglomerate, 200 to 500 ft below the surface of the Plateau, is a relatively untested aquifer.

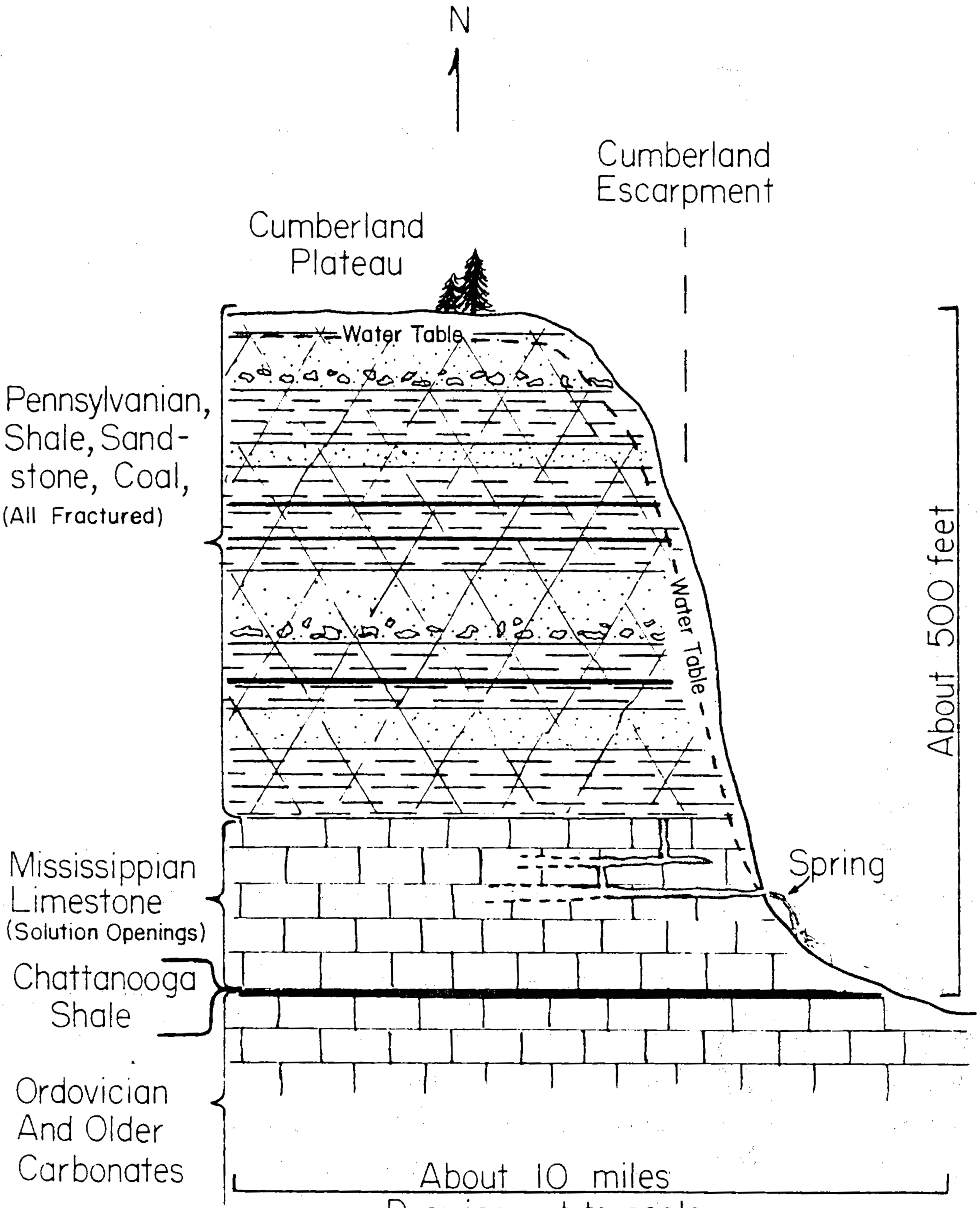


Figure 17.--Sketch showing idealized geologic and hydrologic conditions in the Cumberland Plateau section. The prevalence of solution openings in the limestone underlying the Plateau is unknown.

Highland Rim

The Highland Rim section of the Interior Low Plateaus province is a gently rolling plateau which occupies a large part of the center of the Tennessee Region. It is extensively dissected where it adjoins the Central Basin and Coastal Plain lowlands. The bedrock of the Highland Rim is flat-lying Mississippian carbonates. These formations, principally the Fort Payne Chert, a cherty dolomite, and the Tuscumbia Limestone (with its equivalents, the Warsaw Limestone and St. Louis Limestone), constitute the most areally extensive aquifer in the Tennessee Region.

These Mississippian formations weather to form a deep chert regolith typically having a "rubble zone" at the base. The residual chert grades from gravel-sized fragments at the base to a layer of clay-sized chert particles which partially seals the top of the aquifer creating artesian conditions in some areas. The regolith in places may rest directly on the Chattanooga Shale which retards downward movement of the water, but in most places it rests on unweathered Fort Payne bedrock. In many places the carbonate bedrock contains solution openings which can transmit water rapidly. For example, in areas adjacent to the Highland Rim escarpment, water drains out of the bedrock openings as springs and seeps. These springs provide the well-sustained low flow of streams that dissect the edge of the Highland Rim. However, in the broad undissected areas of the Highland Rim streams barely cut into the regolith and, therefore, have little effect on the discharge of water from the regolith and solution openings in this area. The solution openings that supply water to wells in the undissected areas are hydraulically connected to water stored in the regolith (fig. 18).

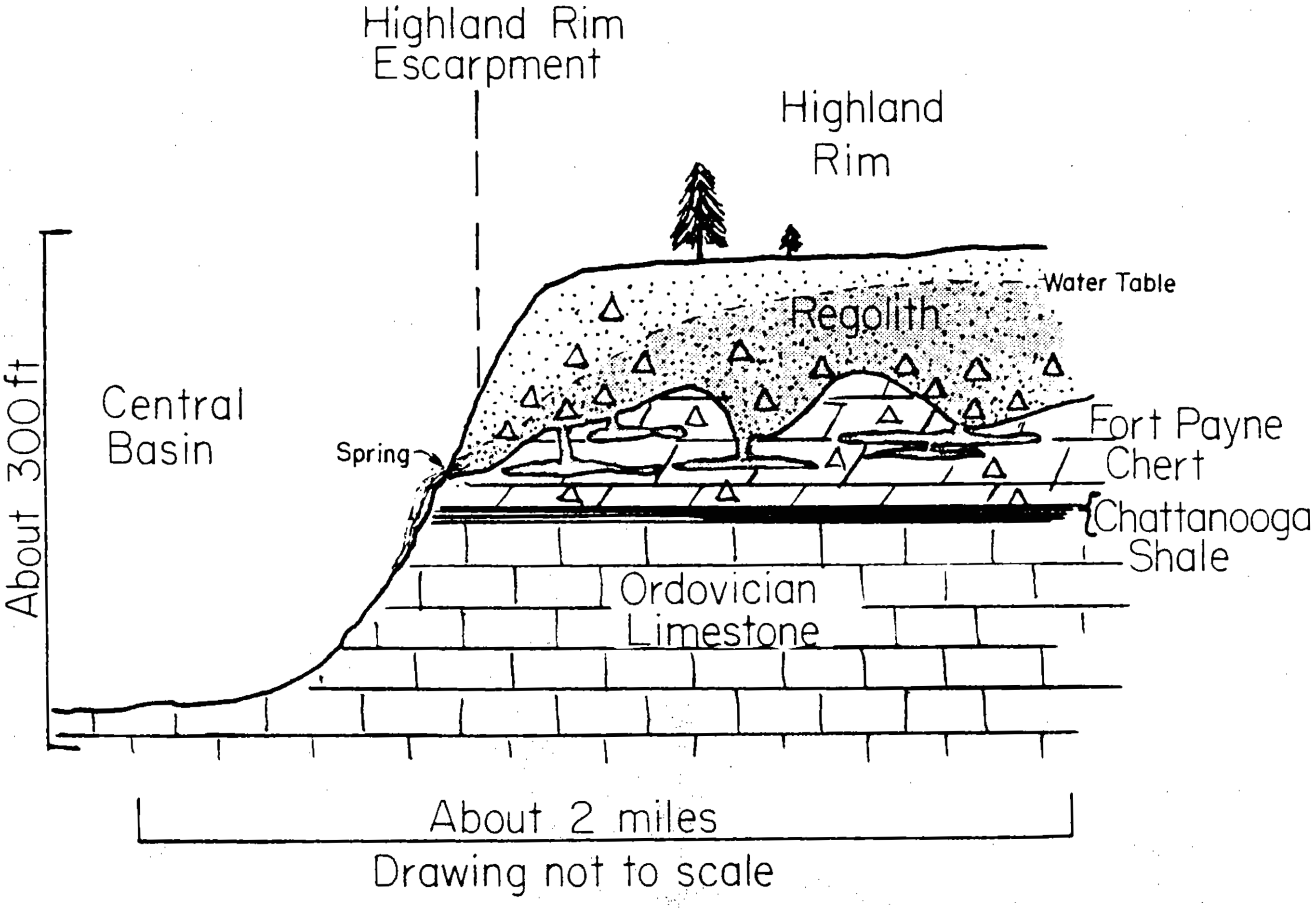


Figure 18.-- Sketch of idealized geologic and hydrologic conditions in the Highland Rim section of the Interior Low Plateaus province.

The aquifer formed by the bedrock and regolith of the Fort Payne Chert has been named the "Manchester aquifer" (Burchett and Hollyday, 1974). Its areal extent has not been determined, especially on the western Highland Rim. This is basically the same aquifer that is present in the Tuscumbia Limestone and Fort Payne Chert in parts of northern Alabama. In places where the regolith is thin and little or no bedrock remains overlying the Chattanooga Shale only small amounts of ground water are available. In areas where sections of Mississippian carbonate rocks remain beneath a thick regolith, however, extensive solution networks may develop that yield large quantities of water to wells and springs. For example, discharge measurements at Water Cress Spring in Madison County, Alabama, indicate a sustained flow of about 5000 gal/min (7-1/2 Mgal/d) (Geol. Survey of Ala., 1975). The Williams well, southwest of Huntsville, Alabama, has been pumped continuously at 3000 gal/min for three days with a maximum drawdown in water level of 2.5 ft. It was also noted during the period of pumping that water levels 0.8 mile away were unaffected (W. J. Powell, U.S. Geological Survey, oral commum. 1975).

Criteria that are important in selecting well sites on the Highland Rim are as follows: an area with at least 40 ft of regolith overlying the Fort Payne Chert, amplitude of water level fluctuation less than 10 ft. (W. J. Powell, oral comm. 1975), and at least 1/2 to 1 mile from the Highland Rim escarpment in a topographic low area such as a long shallow depression (swale) parallel to the escarpment and other linear feature (C. R. Burchett and E. F. Hollyday, U.S. Geological Survey, oral commun. 1975). Seismic surveys, which indicate the depth to bedrock, may be a useful exploration tool in determining the thickness of overburden (Joiner and Scarbrough, 1969).

Central Basin

The Tennessee Region includes the southern portion of the Central Basin (Nashville Basin). The Central Basin, a section of the Interior Low Plateaus province, is an oval area in middle Tennessee lying about 200 ft lower than the surrounding Highland Rim. The bedrock is carbonate rocks that are generally flat-lying but locally are folded. Ground water moves through solution-enlarged vertical joints and horizontal bedding-plane openings (fig. 19). Soil cover is usually thin and surface streams are cut into bedrock. The lack of regolith, along with open joints in the rock, allow rapid runoff and infiltration of precipitation. Water is relatively briefly stored above stream level and is rapidly discharged to streams through solution openings. As a result, small streams respond quickly to precipitation and have poorly-sustained base flows.

Deeper solution openings commonly range from 0.005 to 0.2 in in height and about 100 to 2,500 ft in width (Moore, 1973). Most solution openings are within 300 feet of the surface. Burchett (1977) states that in Upper Duck River Basin, "46 percent of the water produced from wells in the Central Basin comes from a depth of 60 to 100 feet below land surface. Less than 1 percent ... comes from a depth greater than 300 feet."

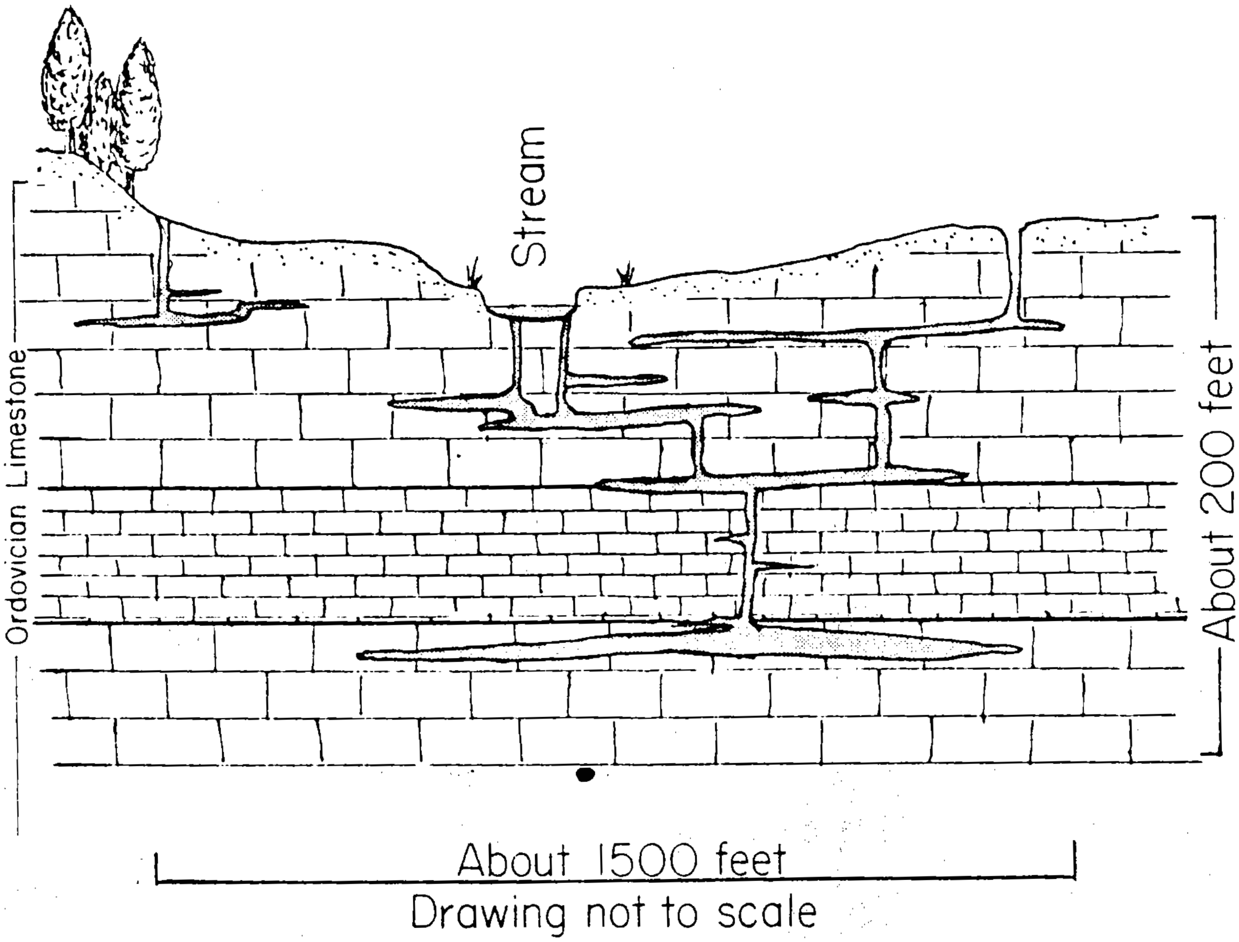


Figure 19.--Sketch showing idealized geologic and hydrologic conditions in the Central Basin (Nashville Basin section of the Interior Low Plateaus province).

The distribution of ground water in the Central Basin is highly variable. Except for the secondary openings most of the limestone has extremely low porosity. Most wells produce at least some water from bedding-plane cracks as large solution openings are relatively uncommon. Of the wells reported by drillers near Center Hill Lake in Tennessee (north of the Tennessee Region), 46 percent of those in the Central Basin produced less than 4 gal/min and 89 percent (produced less than 20 gal/min. Only 3 out of 74 wells produced over 50 gal/min (Moore and Wilson, 1972). In spite of the low reported well production, it is possible in many areas to drill wells capable of producing over 70 gal/min or 0.1 Mgal/d. In some areas it is possible to drill wells capable of producing several hundred gallons per minute. About 15 ft of solution openings were penetrated by a test well at Franklin, Tennessee, (about 10 mi north of the Tennessee Region). The well was pumped at 200 gal/min for 8 hours with a drawdown in water level of 0.58 ft. Another test well about half a mile away penetrated a 5 ft opening. These drilling sites were selected on the basis of stratigraphic criteria, an investigation of streamflow gains and losses, and surficial evidence of solution activity. It appears that the use of hydrologic and geologic studies in selecting drilling sites in the Central Basin greatly increases the chances of wells penetrating high-yielding solution openings.

The Knox Dolomite, at depths of 350 to 1500 ft below the surface, comprises an areally extensive artesian aquifer throughout the Central Basin. It is a dependable source of domestic water supplies (usually 10 gal/min or less) of variable quality (Newcome and Smith, 1962). The largest known production from a well finished in the Knox in the Central Basin is 50 gal/min (Kernie Cothran, driller, oral comm.). However, in eastern Tennessee, production from single wells in the Knox can exceed 1000 gal/min. The potential of the Knox to yield large amounts of ground water in the central part of the region is unknown.

Coastal Plain

A narrow strip of the Coastal Plain province extends along the western edge of the Tennessee Region. Its eastern boundary is approximately the edge of the Paleozoic rock outcrop and its western edge is the Tennessee River - Mississippi River drainage divide. The Tennessee River flows along the eastern boundary against the edge of the Highland Rim. The topography west of the river valley is of moderate relief, less than that of the dissected edge of the Highland Rim. The major aquifers in the Coastal Plain section of the Tennessee Region are two unconsolidated Cretaceous formations, the Coffee Sand and McNairy Formation (fig. 20).

According to Boswell and others (1965), both the McNairy Formation and the Coffee Sand are capable of yielding municipal and industrial supplies nearly everywhere to the west of the outcrop. The Coffee Sand yields up to about 300 gal/min to wells and is used as a source of water in the westernmost counties in the Tennessee Region as far north as Carroll County, Tennessee. The McNairy Formation, however, is capable of much greater production, and good wells produce 500 to 1000 gal/min. The McNairy Formation is used as a source of water in the Tennessee Region counties north of Carroll County, Tennessee. The amount of water that can be withdrawn from these formations depends, in part, on the thickness of saturated sand layers and the construction of the wells that penetrate them.

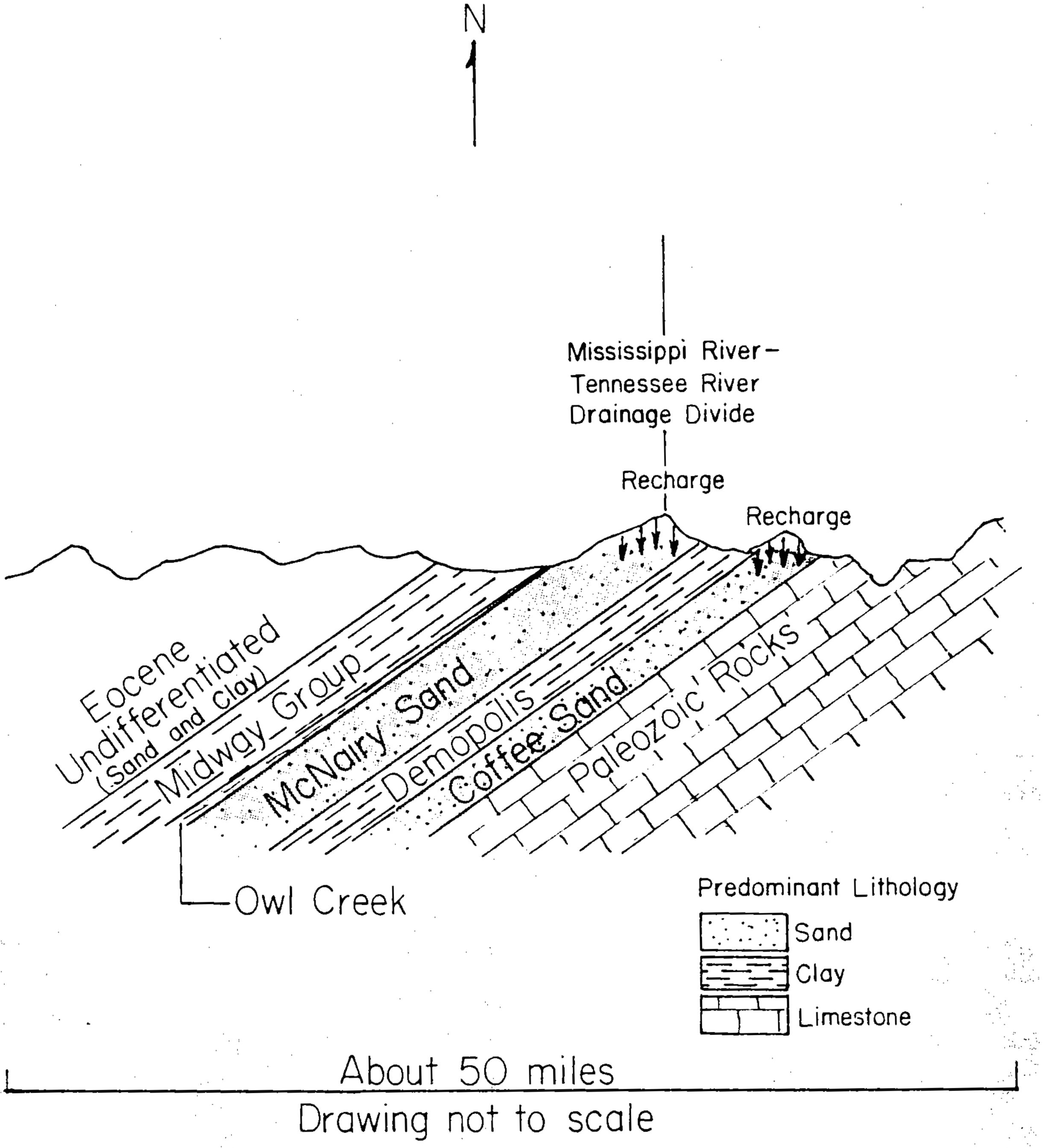


Figure 20.--Sketch showing idealized geologic and hydrologic conditions in the Coastal Plain province. The cross section extends east and west approximately at a latitude of 35°N.

In northern Mississippi, test wells in a shattered Paleozoic chert aquifer produced up to 550 gal/min with a specific capacity of 5 (gal/min)/ft. (Newcome and Callahan, 1964). The Camden Chert and Fort Payne Chert comprise this fractured chert aquifer in Tennessee (Wells, 1933).

Quality of Ground Water

The natural quality of ground water in the Tennessee Region depends on many factors, but mainly upon the composition of the rock in which the water occurs. When water from precipitation enters the aquifer as recharge it is generally low in dissolved solids, soft, and slightly acidic. As the water moves through the aquifer it acquires a greater concentration of dissolved constituents which change its chemical and physical properties.

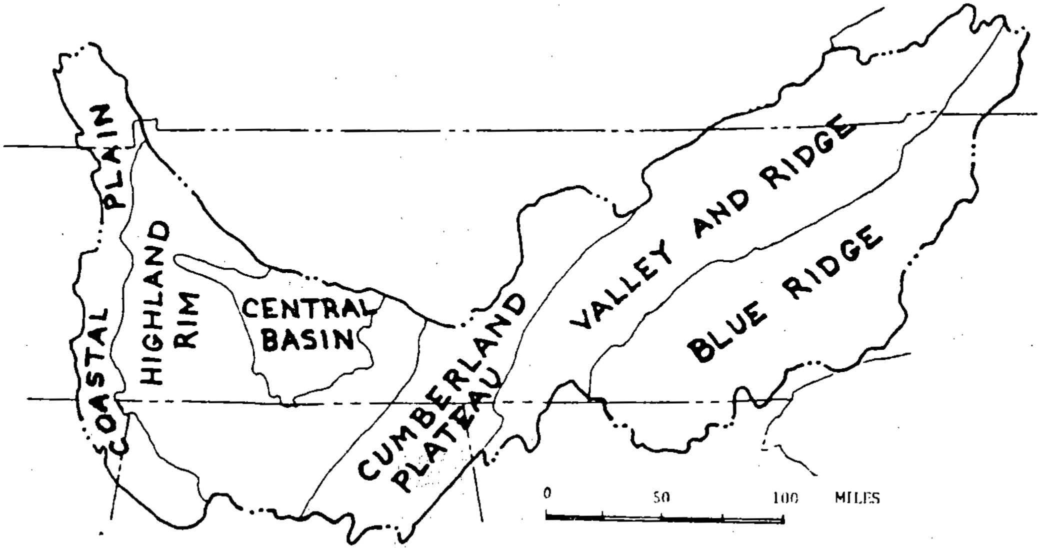
Several changes in the chemical composition and physical properties of ground water take place in the aquifers of the Tennessee Region, depending on the type of rock composing the aquifer. The least change occurs in the aquifers composed of regolith. The ground water in the regolith remains slightly acidic and low in dissolved solids. This type of ground water is common in the regolith of the Blue Ridge and Highland Rim. Water in the outcrop belt (recharge area) of the unconsolidated aquifers of the Coastal Plain is also fairly close to rainwater in composition, but becomes harder and higher in dissolved solids as it moves deeper below land surface.

Ground water that comes in contact with sandstone and shale containing pyrite remains soft but may become acidic and high in iron and hydrogen sulfide. This type of water occurs in some noncarbonate formations of the Valley and Ridge, in the Pennsylvanian shale and sandstone of the Cumberland Plateau, and immediately below the Chattanooga Shale of the Highland Rim.

A third kind of change occurs in water that contacts carbonate rocks. Because rainwater that has passed through the soil is somewhat acidic, it can dissolve limestone and dolomite, becoming enriched in bicarbonate, calcium, and magnesium. As the dissolved solids content increases, the water becomes harder and slightly alkaline. This type of chemical change occurs in the carbonate aquifers such as those in the Valley and Ridge, in the Highland Rim, in the Central Basin, in Sequatchie Valley of the Cumberland Plateau, and those underlying limestone coves of the Blue Ridge.

The analyses shown in figure 21 are representative of the chemical quality of the ground water from the six physiographic areas of Tennessee. Dissolved constituents, consisting mainly of calcium and bicarbonate ions, are highest in the ground water of the Central Basin, with somewhat lower concentrations in the Highland Rim and Valley and Ridge. Unlike aquifers of the Central Basin, aquifers in the latter two areas to not consist entirely of carbonate rocks, and the influence of the regolith and other noncarbonate rocks is seen in the lower amounts of dissolved constituents, including calcium and bicarbonate.

Physiographic Province	Values are medians, in milligrams per liter										
	Silica	Iron	Calcium	Magnesium	Sodium	Potassium	Bicarbonate	Sulfate	Chloride	Fluoride	Nitrate
1) Blue Ridge	16	0.05	4.6	0.5	3.3	0.8	29	1.6	0.9	0.1	0.1
2) Valley and Ridge	10	0.09	38	12	3.5 ~~4.5~~	1.0	178	5	3.5	0.0	3.9
3) Cumberland Plateau	6.4	1.0	16	3.5	3.9	1.2	60	10	2.8	0.1	0.8
4) Highland Rim	11.5	0.00	39	3.8	2.7 ~~3.4~~	.7	146	4.2	4.0	0.1	1.9
5) Central Basin	7.3	0.08	79	9.7	4.4	1.5	256	26	5.0	0.3	0.5
6) Coastal Plain	14	0.5	16	4.6	22	3.4	95	12	4.7	0.2	0.7



3.9 : 1.2

Source of analyses: 1) McMaster and Hubbard, 1970, 23 samples; 2) DeBuchananne and Richardson, 1950, 235 samples; 3) Newcome and Smith, 1958, 13 samples; 4) Geol. Survey of Alabama bulletins, 125 samples; 5) U.S.G.S. test wells at Columbia, Normandy, and Franklin, Tenn., 22 samples; 6) Boswell, Moore, MacCary, and others, 1965, median for Ripley Fm. (McNairy Sand), number of samples unknown.

Figure 21.--Results of chemical analyses of ground-water samples from each physiographic subdivision of the Tennessee Region.

The analyses for the Blue Ridge, Cumberland Plateau and Coastal Plain, all areas with mainly non-carbonate aquifers, indicate considerably lower dissolved solids in the ground water of these areas than in carbonate terranes. In the Blue Ridge, where most of the ground water occurs in the highly-weathered regolith, dissolved solids are lowest.

Ground-water quality is reflected in the chemical character of stream water during periods of base flow. To some extent, streams can be used to obtain an integrated sample of discharge from the aquifers underlying the watershed. Betson and McMaster (1975) have developed, for the Tennessee River basin, a model to simulate mineral constituent concentrations in streamflow for watersheds underlain by different types of rock. Concentration values generated using their regression coefficients and a streamflow of 1 $(ft^3/s)/mi^2$ agree fairly closely with the analyses in figure 21 when the coefficients used are those for rock types most commonly found in each physiographic province.

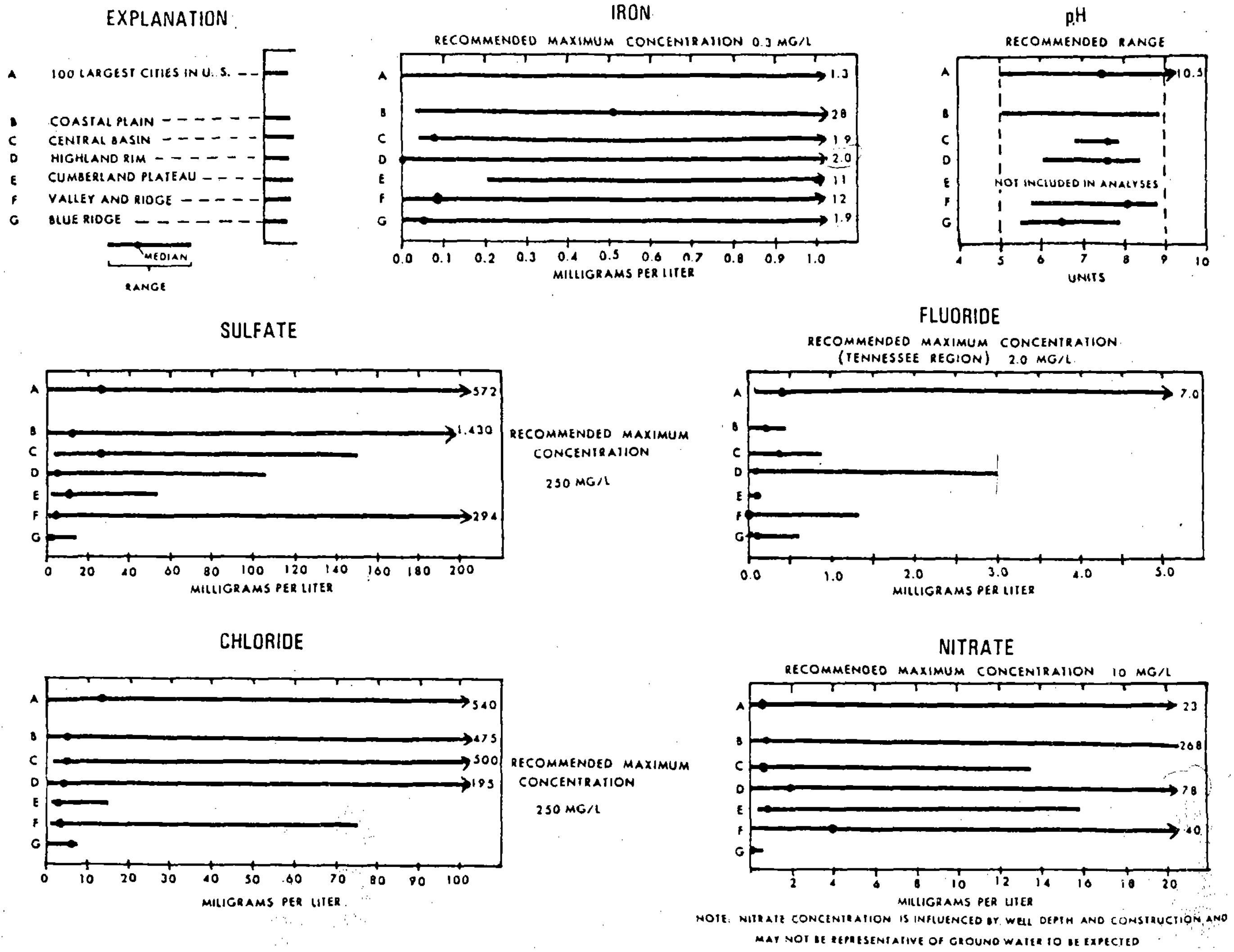
In the Tennessee Region, ground water is usually in contact with the aquifer material for a sufficient time to reach chemical equilibrium, but rate of circulation within the aquifer has an important effect on ground-water quality. Where circulation has been rapid, aquifers can be flushed of readily dissolved substances. Where the regolith is hydraulically connected to well-developed openings in the underlying bedrock, water from the regolith, low in dissolved solids, can circulate rapidly through the openings without great increases in hardness. As a result of situations like these, water from wells that tap very permeable formations or highly-developed solution or fracture systems tends to be lower in dissolved solids than water from poorly interconnected openings.

The quality of ground-water from a particular aquifer at any one place tends to be relatively constant with time. This property is most evident where the regolith filters the water that replenishes the aquifer. In aquifers having direct connections with land surface (via sinkholes, for example) marked changes in quality may occur as storm runoff enters the system.

Well-developed openings and highly-porous material, when less than about 100 ft below land surface are very susceptible to pollution, and strong protective measures are needed to ensure that the ground-water quality will remain unimpaired.

A study sponsored by the U.S. Public Health Service identified a high incidence of contamination of rural domestic water supplies in three counties in Tennessee, as shown by the presence of coliform and fecal coliform bacteria in water samples (Bureau of Water Hygiene, 1971). Fifty-nine percent of the water supplies examined failed to meet bacteriological standards. However, according to the report, nearly every one of the rural, individual systems examined had one or more facility deficiencies. Very few of these systems were constructed to prevent entrance of contamination. It is entirely probable that they represent contamination at the well site and not of the aquifers that furnish water to the wells. Water obtained from relatively deep aquifers penetrated by test wells has usually contained very few, if any, coliform bacteria, and it is not unusual for the water to be entirely free of any indications of contamination.

Most of the ground water in the Tennessee Region is of suitable chemical character for public drinking-water supplies. Figure 22 shows the medians and ranges of some of the chemical parameters for which maximum concentrations have been recommended by the Environmental Protection Agency (National Academy of Science and National Academy of Engineering, 1972; EPA, 1975). In two areas the median values for iron exceed the recommended maximum concentration, but most of the samples are well within the recommendations.



NOTE: NITRATE CONCENTRATION IS INFLUENCED BY WELL DEPTH AND CONSTRUCTION AND MAY NOT BE REPRESENTATIVE OF GROUND WATER TO BE EXPECTED

RECOMMENDATIONS FROM ENVIRONMENTAL PROTECTION AGENCY, 1975, AND ENVIRONMENTAL STUDIES BOARD, NAT. ACAD. SCI., NAT. ACAD. ENG., 1973.
VALUES FOR 100 LARGEST CITIES FROM DURFOR AND BECKER, 1965.
ANALYSES USED ARE THE SAME AS THOSE IN FIGURE 21.

Figure 22.--Medians and ranges of six chemical constituents in untreated ground water of the Tennessee Region and in the treated, finished water of the 100 largest cities in the United States. Also given are the recommended maximum or minimum values for these constituents in drinking water.

The Tennessee Region has no known significant bodies of saline ground water. Of about 1000 analyses (mostly published) of water from wells and springs throughout the region, only 40 indicate water with over 1000 mg/L total dissolved solids. The high dissolved solids content is usually associated with stagnant ground water in poorly-developed solution openings in flat-lying carbonate rocks. Most of the wells and springs with high dissolved solids are in the Central Basin or Highland Rim, and 17 of the wells tap the Knox Dolomite of central Tennessee. In almost every case they reportedly produce less than 20 gal/min (.03 Mgal/d).

DEVELOPMENT OF THE GROUND WATER RESOURCES

Ground Water Use

In 1970, the use of ground water in the Tennessee Region totaled 173 Mgal/d (Murray and Reeves, 1972). This is less than one percent of the estimated 22,000 Mgal/d of ground water that is discharged annually to the streams of the Tennessee Region, which is an indication of the large amounts available for development. The ground water that is used amounts to slightly less than eight percent of the total water use in the Region excluding that used for electric power generation (table 4). However, the percent of the population served by ground water is much larger than the total-use figures would indicate.

According to the 1970 census, the population of the Tennessee Region was about 3,300,000. One third of the people were living in towns or cities with populations of 2500 or more. The rest lived in small towns or rural areas (Delury, 1973).

At present, most of the large towns and cities in the Tennessee Region use surface water. A notable exception is Huntsville, Alabama, a city of 138,000, which obtained all its water from Big Spring until 1950. Now it draws half its supply from five wells and one spring and the other half from the Tennessee River (Geol. Survey of Ala., 1975). In that part of the State of Tennessee within the Tennessee River basin, the largest towns supplied entirely with ground water are Tullahoma, population 15,000, and Elizabethton, population 12,000. Both draw their water from springs (Tennessee Div. Water Resources, written comm., 1976).

Table 3.--Water use in the Tennessee Region in 1970 (from Murray and Reeves, 1972)

		Water withdrawn (in Mgal/d)		
Use of water		Ground water	Surface water	
Public supplies		64 (21%)	240 (79%)	
Rural domestic use		51 (98)	.9 (2)	
Livestock and irrigation	32% 128	13 (34)	25	266
Self-supplied industrial use		45 (3)	1,300	
(excluding power generation)		Σ (10%)	(90%)	
Power generation (thermoelectric)		0	6,100	
Power generation (hydroelectric		0	12,000	
Total		173	19,700	

Many of the smaller towns in the Tennessee Region use ground water. Seventy-nine percent of the small water-distribution systems (serving fewer than 2500 people) use ground water for at least half their supply. As these towns and others that withdraw water from small streams grow, the present surface source may become inadequate and ground water could play a major role in supplementing these supplies.

The rural population of the Tennessee Region obtains most of its water supply from wells and springs. Approximately 50 Mgal/d was used for rural domestic purposes in 1970. In contrast, only a third of water used for livestock and irrigation was ground water (Murray and Reeves, 1972).

Industries in the Tennessee Region that have their own source of water used 45 Mgal/d of ground water in 1970. This was only 3 percent of the water used by self-supplied industries other than power-generating plants.

In addition to industrial use, ground water supplies many businesses in isolated areas such as service stations and motels. Springs are used for raising fish because of the constant temperature and low turbidity of the ground water.

Potential for Development

Ground water is generally overlooked as a water supply in the Tennessee Region because of the abundance of surface water. Only a small part of the available ground-water supply, about 0.8 percent of the average annual recharge, is being used. The advantages in using ground water as a water supply are as follows: 1) its widespread availability, 2) its general dependability, particularly at depth, 3) the minimal amount of treatment required, 4) the relatively low cost of developing a ground-water supply, and 5) its uniform temperature and chemical character. Ground water can be used very efficiently for small-scale developments such as water supplies for rural communities, industries and small towns. In addition, ground water has potential for supplemental and conjunctive use with surface water supplies.

There is growing interest in the feasibility and advisability of injecting fresh water into aquifers for storage. The use of underground space for storage of liquids has been practiced on only a limited scale in the region.

Availability

In many parts of the Tennessee Region, ground water is available in amounts comparable to those that might be obtained from surface-water impoundments. The ground-water reservoir stores water with minimal evaporation, insulated to some degree from pollutants and available at diverse points, as opposed to surface impoundments for which sites are limited. In addition, ground-water supplies can be developed more quickly and at lower cost compared to the time and cost of creating surface-water storage.

Dependability

It is a common belief that ground-water levels are continually declining in all parts of the country. However, this is true only in places where pumpage of ground water greatly exceeds natural recharge. In the Tennessee Region, ground-water levels show only normal seasonal trends. Water levels usually decline during the growing season (April - November) and rise during the remainder of the year when most ground-water systems are being recharged from precipitation (fig. 23). Shallow dug wells are not dependable sources of supply during periods of prolonged drought as they are generally not dug deep enough to allow for any extreme decline in water level. However, production from drilled wells that penetrate deeper solution cavities or water-bearing formations is generally not seriously reduced by drought.

In areas where ground water is developed, local lowering of water levels can occur as a result of pumping. However, if pumpage is within the capacity of the aquifer to supply water, the rate of water-level decline will gradually diminish and the water level will stabilize. The response of the water level to various rates of pumping is shown in figure 24. Nowhere in the region has ground-water development caused significant depression of water levels, although there are instances where inadequate spacing between wells has caused excessive water-level drawdown in a localized area.

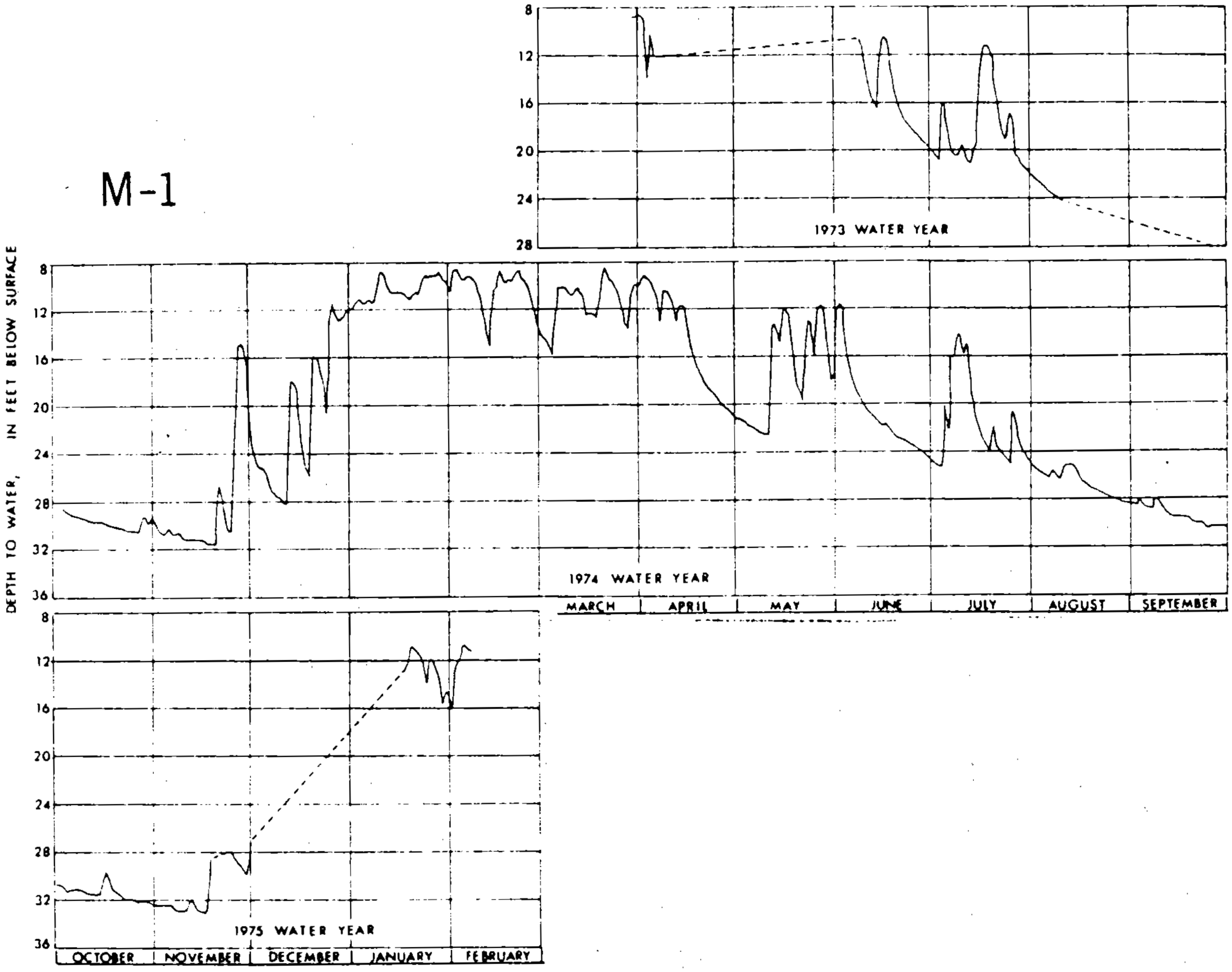


Figure 23.--Water-level fluctuations in test well M-1, Manchester, Tennessee, showing seasonal trends (from Burchett, 1977).

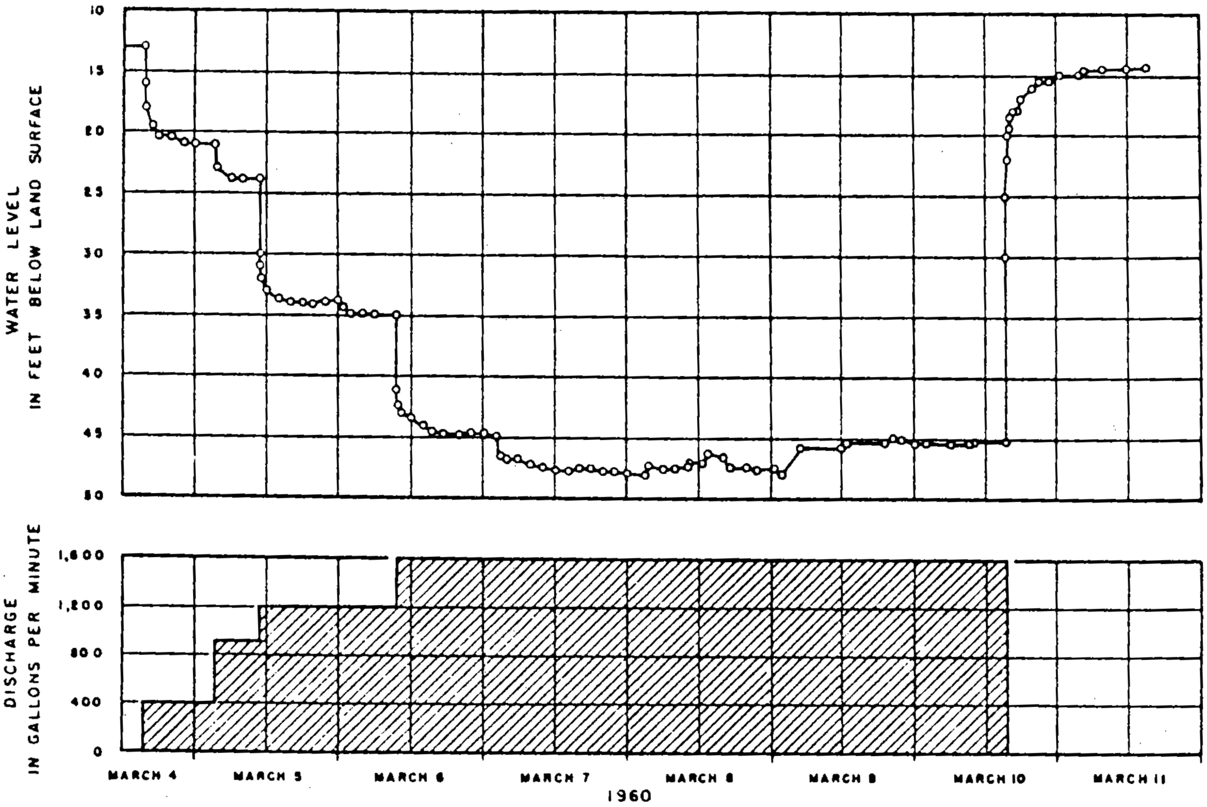


Figure 24.--Pumping rate and water levels in well M-157, Colbert County, Alabama, during pumping test (from Harris and others, 1963).

Treatment Needs

Ground water in the Tennessee Region usually needs less treatment than surface water to make it acceptable for most uses. It can often be used untreated for cooling and process water in industrial plants. Chlorination is the basic treatment needed for drinking-water supplies. In some cases aeration is needed to dissipate dissolved gases such as hydrogen sulfide or to precipitate dissolved iron. Buffering may be needed, especially for water systems where low-pH ground water is to be mixed with slightly alkaline surface water. Ground water usually has low turbidity and does not generally require filtration to meet turbidity standards for drinking water. Ground water has the additional advantage of being uniform in chemical quality, and would therefore require less monitoring than a surface-water supply. For example, the turbidity of surface water is increased by storm runoff, but ground-water turbidity is usually constant, except in shallow carbonate aquifers that have direct connections with land surface such as sinkholes.

As a result of the minimal treatment needed by most ground-water supplies, low-cost treatment facilities can be installed at the well field. This makes it possible to have multiple self-contained units located at points of use of the water rather than a single treatment plant with an extensive distribution system.

Cost of Development

Another potential benefit of ground-water development is its relatively low cost. Cederstrom (1973) estimated that in the North Atlantic states the cost of large supplies of ground water at the wellhead, taking into account the costs of locating and developing a well or well field, ranged from 1.5 to 5 cents per thousand gallons in 1970 depending on the aquifer material. Many of the aquifer materials in this study area are similar to those of the Tennessee Region, ranging from Coastal Plain sediments from which ground water can be obtained most cheaply to carbonate rocks in which ground-water development is most costly. The investment required to construct and operate a ground-water distribution facility is further reduced at places where the water requires little treatment.

A study of the alternatives for water supply may reveal an economic incentive to use ground water. An example is a small utilities district in central Hamilton County, Tennessee. Owing to the proximity of the surface-water intake for this system to the site of a nuclear power plant on the Tennessee River, a study of alternative sources of water was made. The results of the investigation indicated that the use of ground water from the Knox Dolomite would lower the cost of providing finished water to the consumers by as much as 50 percent, and the utility is now using wells.

Temperature Stability

A relatively constant annual temperature, about the same as the average annual air temperature of the area where it occurs, is characteristic of ground water. This characteristic makes it extremely useful for cooling and for industrial processes where constant temperature is required. In the Tennessee Region ground-water temperatures normally range from 50 to 65°F.

A growing use of ground water is as a heat exchange medium for heat pumps. Heating and cooling of buildings is much more efficient with a ground water to air rather than air to air interface, because of its constant temperature and the high specific heat of water.

Efficiency for Small-Scale Development

Owing to the scale of ground-water developments, ground water in the Tennessee Region has great potential as a sole water source for small communities and industries that are remote from large reservoirs.

In sparsely populated areas and small rural communities a multifamily well may be a more efficient water supply than a connecting pipeline to a large centralized water distribution system (Lehr, 1976). Cederstrom concluded in his cost analysis of ground-water supplies in North Atlantic states (1973) that "where large water requirements consist of many small to moderate demands at distinctly separate points ground-water supplies may serve admirably from a cost point of view." This approach is being taken in Lincoln County, Tennessee, where the U.S. Geological Survey has undertaken a cooperative study with the Lincoln County Public Utilities Commission to investigate the occurrence and availability of ground water as an aid in developing ground-water supplies for small communities throughout the county.

For industrial use, the cost of installing a well or developing a well field may compare favorably with the cost of a long pipeline connecting to a municipal system. Also, the initial cost would be defrayed by the low operation and maintenance cost of the ground-water facility. Where sufficient ground water cannot be obtained on-site, water can be piped from wells at more favorable sites, as is being comtemplated in Chattanooga, Tenn. (D. R. Rima, U.S. Geological Survey, oral comm. 1976).

Supplemental and Conjunctive Use

In areas where ground water alone is inadequate to supply a needed amount of water, it can play a supplemental role. There are several situations in which use of ground water would be an attractive alternative source of supply. For example, when a town grows gradually to the point where demand for water occasionally exceeds the supply available from ground water-sources, a surface-water impoundment might be needed. However, until the need was such that a major construction of this nature could be justified, ground water, even in relatively small amounts, could supply the peak water demand. In areas where surface water is not available, municipalities are faced with the alternatives of building a pipeline to connect to another water system or of developing ground-water supplies. In this situation, a thorough investigation of available ground-water resources is warranted because of the high cost of constructing a pipeline. Ground water can also play a role in urban development as the water supply for outlying areas of growth.

Conjunctive use of ground water and surface water has received little attention in the Tennessee Region. The following examples illustrate how knowledge of ground water - surface water interaction could increase the efficiency with which both are used. In Chattanooga, Tennessee, there is a plan to modify a water system that normally uses water from a stream which is subjected to occasional chemical pollution. The stream will be monitored and, when pollution occurs, the system will draw water from nearby wells until the surface water is again useable. Ground water could also be used to augment the low flows of streams, both to supply water systems and to maintain sufficient flow to assimilate waste.

When a large surface-water impoundment is made, it could benefit ground-water users by reducing the ground-water level fluctuations in the vicinity of the lake. Surface water can be stored without the use of an impoundment where a suitable aquifer is available. Such an aquifer can be recharged with surface water during times of high flow for withdrawal during dry periods. Well fields can also be used to capture subsurface flow in stream beds by inducing flow from the stream toward the wells.

In an alluvial aquifer, of which there are few in the Tennessee Region that are not covered by reservoirs, there is a fluctuation of temperature in the aquifer caused by infiltration of river water. The ground water temperature lags about six months behind the river temperature. It is warmest in winter and coolest in summer. This property could be useful for heating and cooling purposes.

Underground Storage

Deep wells are being used in the Tennessee Region for disposal of liquid waste. Two industries, in New Johnsonville, Tennessee and Mt. Pleasant, Tennessee, use wells for disposal of chemical waste. At Oak Ridge, Tennessee, medium level liquid radioactive wastes are injected into a shale formation in cement grout so that once they solidify they cannot move from the point of injection (de Laguna, 1968).

No aquifer in the Tennessee Region is capable of completely isolating injected liquid substances. Therefore, the possibility exists that injected liquids would displace poor-quality water and migrate upward into aquifers used for sources of water supplies.

The use of aquifers for storage of fresh water has not been strongly considered in the region. The inadequacy of information on local groundwater movement currently makes it difficult to evaluate the feasibility and environmental impact of injecting fresh water into a deep aquifer for later withdrawal.

Locating a Ground-Water Supply

Ground water is not necessarily available in adequate quantities precisely where it is needed, especially in carbonate rocks. The chances of finding adequate supplies of ground water are greatly increased if drilling of production wells is preceeded by a hydrologic study of the area to determine the most favorable areas for high-producing wells and by test drilling to verify these areas. In many areas the drilling and test pumping of more than one test well might be required before a satisfactory supply can be obtained.

In his cost analysis of ground-water supplies in the North Atlantic Region, Cederstrom (1973) states that the "average yield" of wells in any one area, as commonly given in the literature, is no guide to what might be obtained because most wells were constructed to supply water for domestic use and the potential yield of the aquifer was not determined. The "average yield", therefore, represents something a little greater than the average need and is not a measure of the full potential of wells in the rock type being studied.

In the Tennessee Region the generally low production from wells reported by drilling contractors has tended to discourage exploration for large ground-water supplies in almost all areas except the Coastal Plain. For example, in the part of the Upper Duck River Basin of Tennessee that is on the Highland Rim, 86 percent of wells reported to the Tennessee Division of Water Resources produced 20 gal/min or less. However, of 19 test holes drilled in the same area, only 16 percent produced 20 gal/min or less and 74 percent produced 100 gal/min or more (Burchett, 1977). The reason for this success in test drilling was the use of site-selection criteria based on hydrologic concepts of the occurrence and availability of water in the Fort Payne regolith and bedrock.

Site-selection criteria are the practical application of an understanding of the hydrologic system in an area. In some parts of the Tennessee Region the controls on ground water occurrence are well-defined. Two such areas are the Coastal Plain and northern Alabama. Test drilling in the Great Smoky Mountains National Park (McMaster and Hubbard, 1970) has helped to identify criteria for the Blue Ridge. However, in other parts of the region, criteria are either nonexistent or incomplete. The Cumberland Plateau is the only area where very little test drilling for water has been done. Considering the unreliability of the flow of surface streams on the Plateau and the reported difficulty in obtaining even domestic ground-water supplies in some areas, an intensive study of the Plateau's water resources would contribute information needed to fill the biggest gap in knowledge of Tennessee Region's ground-water hydrology.

In the Central Basin, Highland Rim and Valley and Ridge Provinces, ongoing studies by the U.S. Geological Survey, including test drilling, are leading to development of site selection criteria which can greatly improve chances of obtaining large ground-water supplies in carbonate-rock terranes. These criteria are continually being tested and refined.

Some of the hydrologic controls in each province of the Tennessee Region have been discussed in the section on "Occurrence of Ground Water." Site selection criteria vary from one area to another depending on which factors have the greatest influence on ground-water distribution. Use of the criteria does not guarantee that large ground-water supplies will be located; it merely increases the chances of drilling successful wells, especially when a site is chosen on the basis of several different criteria. For example, test drilling, test pumping, definition of surface geology and subsurface structure, mapping of soil thickness, and correlation of the withdrawal of ground water with piezometric maps prepared during periods of high and low water levels were the basis for locating and developing a well field in a limestone terrane near Huntsville, Alabama, capable of producing 14,000,000 gal/d at a fraction of the cost of a proposed surface-water supply (Lamoreaux and Powell, 1963). Figure 25 illustrates the kinds of information used in selecting drilling sites in central Tennessee. It should also be noted that in areas of great variability in ground-water occurrence, especially where carbonate rocks are the aquifers, a single test hole is not adequate to determine the maximum amount of ground water available at a particular site.

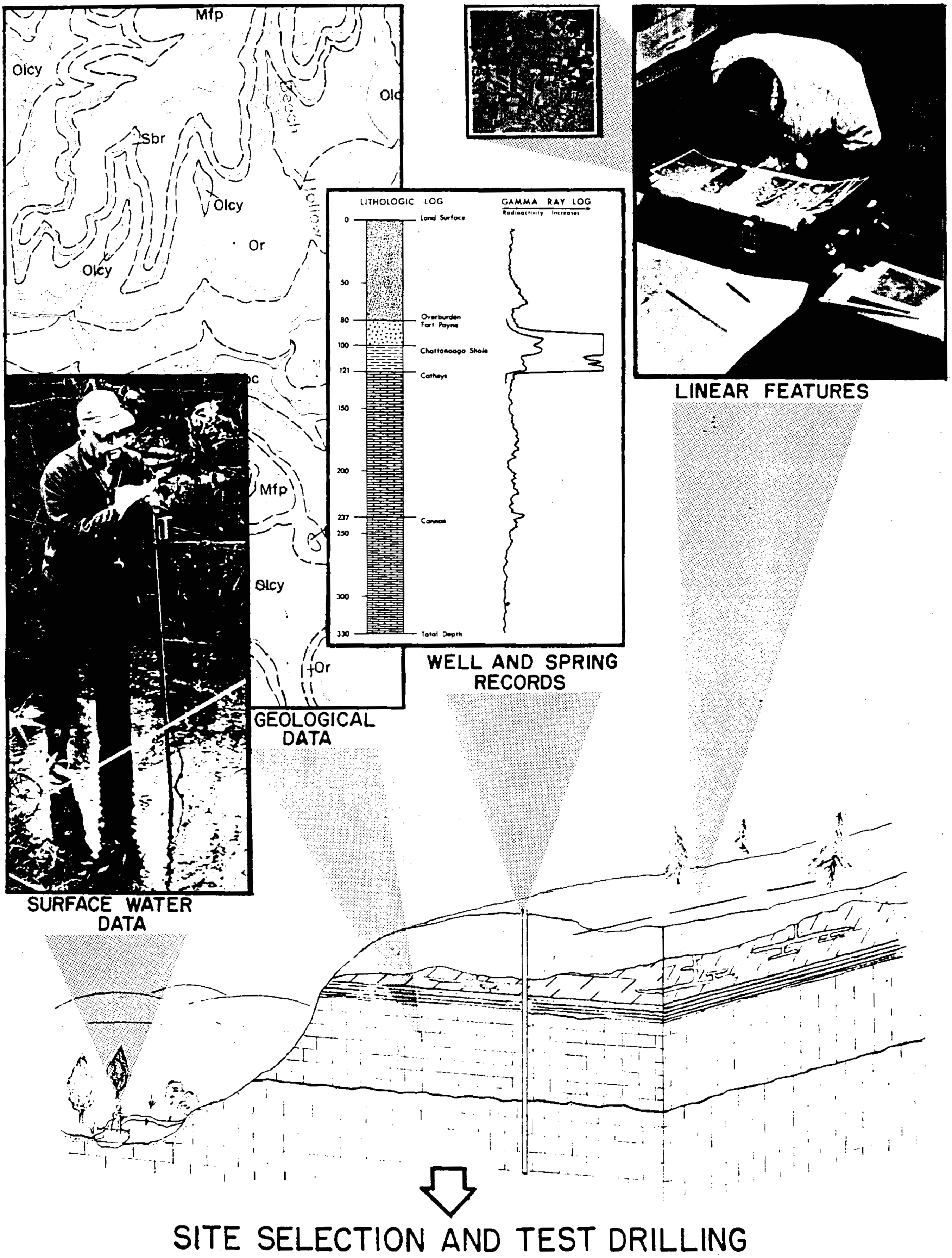


Figure 25.--Types of data used to derive criteria for locating test well sites.

Once a ground-water supply has been located, the characteristics of the hydrologic system should be taken into account in designing the pumping facility. The optimum design is a balance of well yield and operating efficiency against undesirable impacts on the hydrologic system (for example, distribution of stream or spring flow, interference with nearby wells, and deterioration of water quality as a result of induced recharge). One of the most frequently neglected principles of well-field design is adequate spacing of wells to avoid interference. For example, in 1960 the town of Waverly, Tennessee was provided with water from two wells less than 500 ft apart, each reportedly producing 300 gal/min. Pumpage from these wells had created a 25 ft cone of depression around the wells (Marcher, Bingham and Lounsbury, 1964). In 1960 a third well was drilled in the same city-owned lot as the other two municipal wells, but it could not supply sufficient water to be used as a production well. In effect, however, the three wells were functioning as a single well, and withdrawals had exceeded the capacity of the aquifer to supply water to that small area. It is likely that had the well been placed sufficiently far away so as not to be influenced by pumping from the other two, it would have produced an adequate amount of water. The necessary spacing between wells could have been calculated from aquifer test data.

Land use can also be affected by ground-water development. For example, sinkhole development is a possible consequence of ground-water utilization in the parts of the Tennessee Region underlain by carbonate rocks. Where considerable lowering of ground-water levels is predicted, the likelihood of accelerated sinkhole formation should be investigated (Newton, Copeland, and Scarbrough, 1973).

Wells withdraw water that would naturally discharge to streams or springs. Pumping wells will inevitably reduce the ground-water supply to these discharge points and may eventually alter the gradient enough to cause surface water to enter the aquifer. While these effects may not be serious or may even be beneficial, plans for ground-water use would ideally include an evaluation of their impact on both ground water and surface water. This is particularly important when ground water and surface water are to be used conjunctively because ground-water withdrawals affect streamflow at times of low flow when the need for sustained surface-water flow is greatest.

Data Needs

Accurate assessment of an area's potential for ground-water development is only possible where adequate data exist or can be acquired to define the ground-water system. Much of the basic data required, even for a small-area study, cannot be obtained in a short period, but must be collected on a continuing basis throughout the Region. Geologic data, well records, water-level and water-quality data, and information on aquifer characteristics are typical of information required as a foundation for hydrogeologic studies.

Large scale general purpose geologic mapping is available nearly everywhere in the Tennessee Region. In addition, mineral exploration has provided subsurface stratigraphic data in many areas. A large volume of unpublished well records are available as a result of state laws requiring drillers to submit information for wells they drill. This information soon will exceed 50 wells per county in each state. Some of this information has been computer-listed by state water resources agencies. Federal and state water-resource agencies also keep well records and logs.

The greatest deficit in ground-water basic data is in records of water-levels, water-quality and aquifer tests. Northern Alabama is unusual in the completeness of its basic records. For example, as shown by figure 26, the number of network observation wells operated by the U.S. Geological Survey in the northern Alabama part of the Tennessee Region is equal to the number in the remainder of the region even though only 17 percent of the region is in Alabama. Outside of Alabama, observation wells are sparse, and they do not give representative information for all the physiographic provinces in the region. Strengthening the observation well network before large-scale ground-water development takes place would provide necessary information on water levels, on baseline ground-water quality, and on aquifer behavior under natural stresses such as drought.

Records of natural ground-water level fluctuations are particularly important, alone or in conjunction with stream seepage investigations, for identifying recharge and discharge areas. Identification of sources of contamination is most critical in recharge areas in order to manage ground-water quality. Large ground-water supplies that are subject to minimal water-level variation can often be located in or near ground-water discharge areas. Hence, the identification of these areas aids in exploration for ground water.

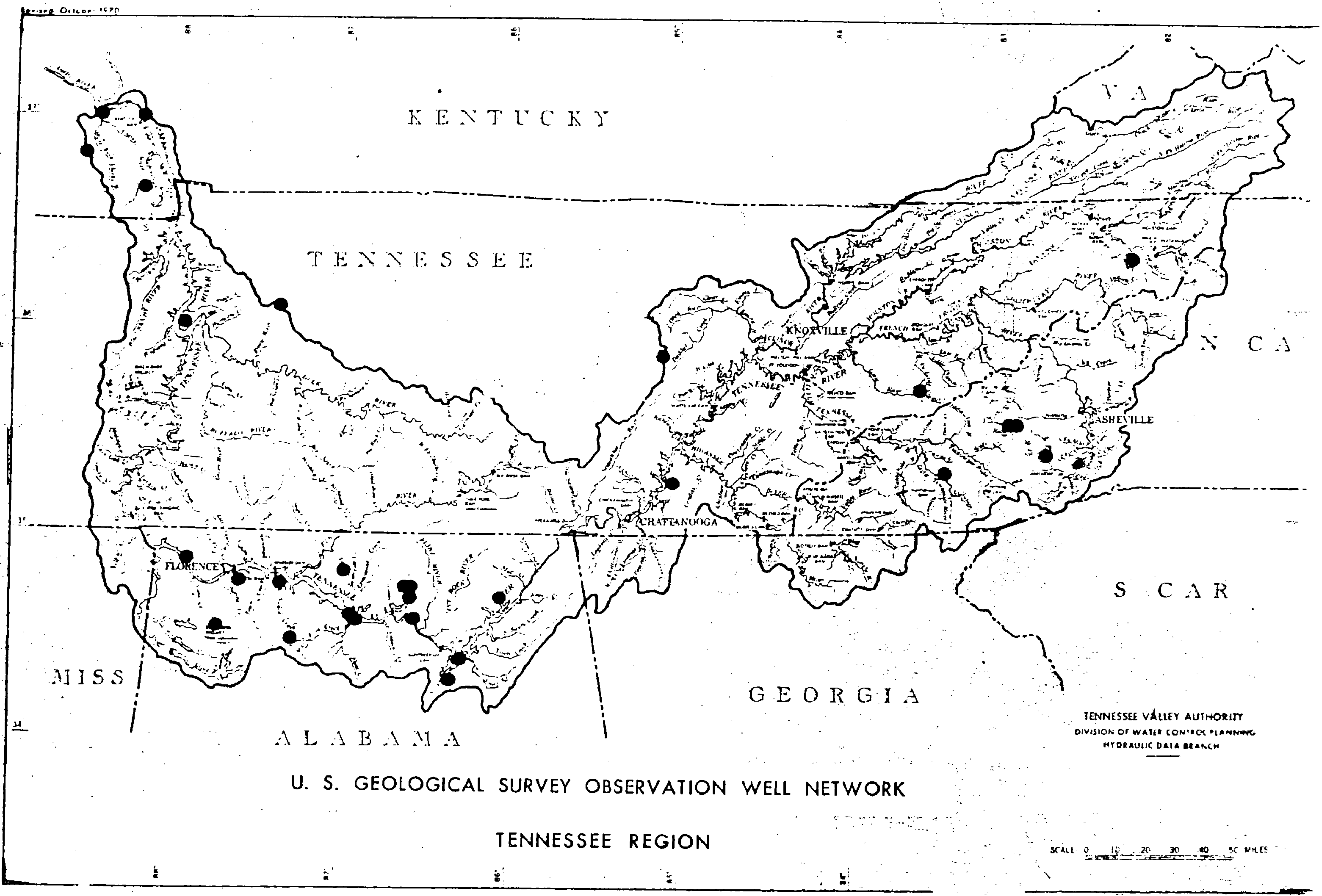


Figure 26.--Locations of wells in the U.S. Geological Survey observation well network.

Aquifer characteristics, as determined by pumping tests, are not known in most of the Region. Many of the pumping tests that have been made served chiefly to test well performance rather than aquifer characteristics. Governmental regulation of public water supplies is increasing and more quantitative information from pumping tests will be required to satisfy the needs anticipated under these regulations. The results of these pumping tests would be useful in defining aquifer characteristics on a regional basis.

According to an assessment of the availability of ground-water data in the Tennessee Valley (W. M. McMaster, Tennessee Valley Authority, written comm. July, 1975) the density, utility, and age of published reports of ground-water information are highly variable. Large-area reconnaissance reports, published between 1932 and 1962, exist for most of the Region. These reports are generally based on rather cursory well inventories and cover large areas. Only the parts of the Tennessee Region in northern Alabama, Kentucky, and North Carolina are adequately covered by reports on smaller areas that are useful for defining well-site selection criteria.

Detailed hydrogeologic studies involving test drilling and aquifer testing, are necessary for an understanding of ground-water hydrology that would allow the development of criteria for locating feasible areas in which to develop high-producing wells. The results of these studies should be considered in regional, metropolitan, and industrial water planning and management programs.

The study of hydrologic systems in the Tennessee Region requires considerable time. However, if present sources of supply are placed under a severe stress resulting from a major drought or population expansion, the degree to which water management can deal with problems will depend, in part, on how much information is available and on how well the hydrologic systems of critical areas are understood. Information required to deal with these problems might include such things as where untapped ground-water supplies can be located, which parts of the region have the lowest ground-water storage, how ground water and surface water can be used conjunctively, and what the effects of utilizing one will be on the other.

Water Resources Management

Effective management of water resources cannot deal with water problems in isolation but as they relate to the hydrologic system as a whole. Stress imposed on one part of a hydrologic system is certain to have repercussions in other parts of the system. This is true whether the stress is applied to ground water or surface water. For example, ground-water withdrawals can reduce the low flow of streams by intercepting ground-water that is naturally discharged to the stream. Impoundment of surface water can increase the quantity of ground water in storage by altering head relationships in an aquifer. Although the surface-water resources in the Tennessee Region are heavily developed, there are no region-wide plans for management of ground water or of the combined ground- and surface-water resources of the region.

The response of a hydrologic system to stress may be experienced at points distant from the place where the stress is applied. For this reason, study and management of water resources can be accomplished most effectively within hydrologic boundaries rather than political boundaries. Yet many of the organizations, including most government agencies, whose function is to study or manage water resources have programs which operate within political boundaries such as state or counties. To deal with the broad implications of hydrologic problems, either of two approaches could be considered: close coordination among the organizations, or the involvement of an organization whose jurisdiction includes the entire hydrologic system.

In the past conflicts as to matters such as funding and the means of implementing management policies have arisen in the course of some attempts to coordinate the efforts of several organizations concerned with water. Notable success at managing water resources of a basin-wide scale has been achieved by agencies such as the Delaware River Basin Commission and the Tennessee Valley Authority. However, because the Tennessee Valley Authority was established primarily to control the Tennessee River, it has not been called upon to direct a major effort toward developing the region's ground-water resources, though it has supported ground-water studies in some parts of the region.

The need for a region-wide ground-water management plan is not yet pressing in the present infancy of ground-water development in the Tennessee Region. In the absence of crisis, a regional ground-water management plan could serve serveral purposes: 1) to coordinate data collection and interpretive studies, 2) to indicate the most efficient and economical use of ground-water resources in the region, 3) to recommend measures to maintain the quality of present and potential ground-water supplies, and 4) to provide support for predicting the enviornmental impact of ground-water diversions by means of digital models which would simulate the conjunctive functioning of both ground-water and surface-water systems. Regardless of how a ground-water management plan would be administered, its formulation and implementation in conjunction with surface-water management plans should recognize the interdependence of ground water and surface water and provide for utilization of both aspects of the region's water resources to their fullest potential.

CONCLUSIONS

Ground water is an abundant resource in the Tennessee Region. As much as one fifth to one third of the precipitation that falls in the region enters the ground-water reservoirs each year. A significant part of the 22,000 Mgal/d contributed annually to the ground water reservoir from precipitation is available for development.

In 1970, less than one percent of the estimated ground-water recharge, amounting to 173 Mgal/d, was used in the Tennessee Region. This was less than eight percent of the total quantity of water used in the region. There is, therefore, a large potential for increased development of ground-water supplies.

At present, ground water is used chiefly in rural areas and small communities and by industries and commercial establishments beyond the limits of municipal water-supply systems. This use of ground water for small-scale developments is practical and economical because in many parts of the region ground water can be obtained at or near the points of use, eliminating the need for water impoundments and extensive distribution systems. The cost is further reduced by the need for only minimal treatment facilities for most ground-water developments.

Ground water can also be used in larger communities to augment existing supplies. Use of ground water to provide for peak demand and as a stand-by or emergency water source is not uncommon in the Tennessee Region, but many more opportunities exist in which ground water could be used along with surface-water supplies to obtain maximum benefit from the water resources. Conjunctive use of ground water and surface water, such as the use of wells to obtain water to maintain a minimum streamflow, has not been given much consideration in the Tennessee Region. This kind of development as well as the use of aquifers for storage of surface water during periods of excess flow require a degree of knowledge of ground-water occurrence and movement which is at present unavailable in most of the region.

The amount of ground water available in the Tennessee Region, if all the recharge to an area were recoverable, would be about 0.5 $(\mathrm{Mgal/d})/\mathrm{mi}^2$. The degree to which this quantity is recoverable depends on the hydraulic properties of the aquifers and their areal variability. A narrow strip along the western edge of the region, in the Coastal Plain province, is underlain by unconsolidated sand aquifers from which a large part of this ground-water recharge could be recovered with proper development. Aquifer yields at a given site are more predictable in the Coastal Plain than anywhere else in the region and wells producing 500 to 1000 gal/min are possible.

However, only a tenth of the Tennessee Region lies in the Coastal Plain. The remainder is underlain by carbonate rocks or fractured noncarbonate rocks. The water-bearing properties of these rocks are variable resulting in high exploration costs in developing ground water. Carbonate rocks with little or no regolith, as they occur in the Central Basin and parts of the Valley and Ridge, are the most variable with well yields ranging from less than 1 gal/min to as much as several thousand gal/min within a short distance.

An important factor in aquifer productivity in the region is the occurrence of the regolith. A thick regolith stores ground water and releases it slowly to openings in the underlying rock. Carbonate aquifers with a thick regolith occur in the Highland Rim and parts of the Valley and Ridge. Because of their great areal extent and relatively uniform distribution of ground water, these areas have the greatest potential for ground-water development.

Chemical constituents and physical properties of ground water in the Tennessee Region are usually within the limits recommended by the Environmental Protection Agency for drinking water. Water in unconsolidated aquifers and regolith tends to be soft, low in dissolved solids, and slightly acidic. In carbonate rocks the water is usually hard and somewhat alkaline. Water in noncarbonate rocks is generally soft and in some parts of the region, may contain certain undesirable amounts of iron and sulfate. Saline water is not known to occur in significant quantities in the region.

Both basic data and interpretation derived from intensive studies are essential tools for managing the ground-water resources, and predicting the results of developmental activities. The information needed for management cannot be obtained immediately when it is needed; it must be the product of a continuing program to understand and evaluate the Tennessee Region's water resources. Because ground-water development has been largely neglected in the region, there is opportunity to establish the data base and management capability before stress on the region's water resources increases to the point that management problems become difficult to solve.

At present the management of the region's water resources is unbalanced. Due to the establishment of the Tennessee Valley Authority, surface water is controlled to a high degree regionwide; however, there has been no comparable attempt to manage the ground water systematically. Any plans for fully developing the water resources should be based on hydrologic principles which recognize the interdependence of ground water and surface water and should provide for utilization of both aspects of the regions' water resources to their fullest potential.

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