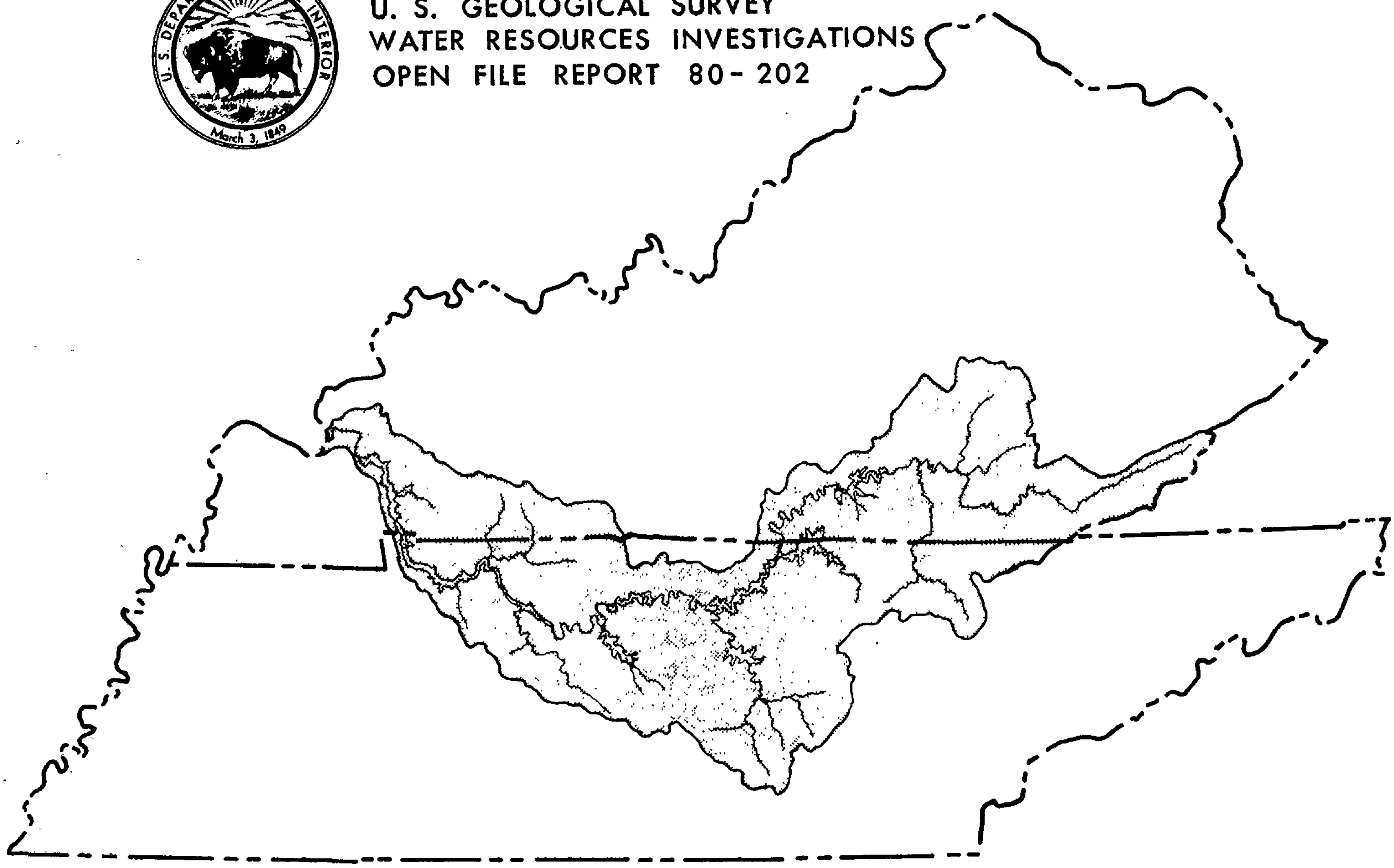
GROUND-WATER RESOURCES IN THE CUMBERLAND RIVER BASIN, KENTUCKY-TENNESSEE

U. S. GEOLOGICAL SURVEY
WATER RESOURCES INVESTIGATIONS
OPEN FILE REPORT 80-202



Prepared by the U.S. Geological Survey
for the Ohio River Basin Commission's
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UNITED STATES DEPARTMENT OF THE INTERIOR

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by

D. R. Rima and D. S. Mull

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The Cumberland River basin has a significant supply of potable ground water which could play a major role in satisfying the future water needs of the region. The potential for development of large ground-water supplies in the basin has previously been described as minimal due to the relatively small yields reported for most wells. However, the presence of some high-yielding wells indicates that large supplies (100 to 300 gallons per minute) can be obtained from aquifers heretofore considered to have only a limited or marginal capacity to yield water.

Most of the ground water occurs in consolidated rock aquifers which characteristically exhibit a wide range in their water-bearing properties. Thus, the availability of supplies differs widely from place to place depending upon topography, thickness of regolith, and the occurrence and distribution of fractures and solution openings in the bedrock.

Although large ground-water supplies can be developed in most parts of the Cumberland River basin, the search for these supplies will require extensive study and test drilling to locate the most productive well sites. The best areas to explore are those where the geologic and topographic features occur in a favorable combination.

The major sources of ground water and their areas of occurrence listed in order of geologic age are:

(1) Unconsolidated deposits of sand and gravel in the alluvium along the main stem and major tributaries of the Cumberland River,

(2) Sandstone and conglomerate formations of Pennsylvanian age beneath the Cumberland Plateau, and

(3) Carbonate rocks and overlying regolith (weathered rock overburden) of Mississippian age in the Highland Rim,

(4) Limestones of Ordovician age in the Nashville basin.

On the basis of present knowledge, the areas or parts of the basin having the highest potential for future development of large ground water supplies include the Highland Rim (both the eastern and western sections) and the area between Pine and Cumberland Mountains at the eastern end of the basin. By comparison the area having the lowest potential for development is the Nashville basin which lies in the heart of the Cumberland basin between the eastern and western sections of the Highland Rim.

The amount of water produced from wells will be accompanied by a corresponding reduction in the amount of water being discharged naturally to springs and streams. In this regard the natural rate of recharge and discharge as calculated in the water budget for the basin ranges from 300,000 to 400,000 gallons per day per square mile.

Much of the ground water in the upper Cumberland River basin is of suitable chemical character for drinking water according to the standards recommended by the U.S. Environmental Protection Agency (National Academy of Sciences and National Academy of Engineering, 1973). Specialized use may require treatment for the removal of selected constituents.

Introduction

This report presents a broad generalized appraisal of the ground-water resources in the Cumberland River basin. It is intended for use as a guide by planners and action agencies in the identification of possible alternatives for the development of water supplies to meet future needs. Hence, emphasis has been placed on the potential for development of large ground-water supplies.

The information presented in this report is based largely on the results of previous investigations covering all or parts of the basin. Most of these reports are listed in the selected references at the end of this report. They describe the results of ground-water investigations made by the U.S. Geological Survey in cooperation with state and local governmental agencies. For the most part, these investigations were aimed at inventorying a large number of wells, sampling selected supplies and evaluating these records in terms of location, yield, and chemical quality of ground-water supplies.

This traditional approach to appraising ground-water resources by examining the records of existing wells can be misleading as to the potential for maximum development of ground-water supplies. The problem is that most wells were drilled to obtain a minimum supply of ground water. Hence, the drilling was stopped for economic reasons as soon as satisfactory supply was obtained. Thus, the reported yields of existing wells reflect more correctly the need for water supplies rather than the potential for development of supplies.

In view of this limitation of reported well-yield data, a different approach to the appraisal problem has been used in the preparation of this report. Attention is focused primarily on the highest-yielding wells and the particular combination of hydrologic features which are represented by these wells. Although the highest yielding wells might comprise as little as one precent of the wells in a particular region the rationale is that the highest yielding wells more accurately reflect the potential for development of ground water than the average or mean of all wells for which records are available.

Based on this approach, the Cumberland River basin has a sizeable and significant potential for development of ground-water supplies.

Geologic Setting

The Cumberland River basin is underlain by a variety of sedimentary rocks ranging in age from Ordovician to Quaternary. The principal types of rock and their areal distribution are shown in plate 1, a generalized geologic map of basin. The oldest rocks--those of Ordovician, Silurian, and Devonian age--crop out in the Nashville basin, a low-lying, oval-shaped limestone plain that includes and surrounds the city of Nashville, Tenn. The rocks of Mississippian age underlie the Highland Rim, a gently undulating partially dissected upland that surrounds the Nashville Basin and exhibits many karst features. Rocks of Pennsylvanian age underlie the Cumberland Plateau, an elevated region of fairly rugged terrain that lies along the eastern border of the Highland Rim and rises nearly 1000 ft above it.

The youngest formations consist of unconsolidated sediments of Cretaceous and Quaternary age. The Cretaceous sediments cap the upland between Barkley and Kentucky Lakes. The Quaternary sediments underlie the flood plain of the Cumberland River and its major tributaries.

Throughout most of the Cumberland River basin the structure of the rocks is relatively simple. For the most part, the exposed formations slope gently away from the center of the Nashville Basin which is situated on the axis of a broad regional anticline. Superimposed on this regional pattern are local undulations or flexures having dips (slope inclinations) from 2 to 8 degrees. These local flexures, which tend to obscure the regional dip of the formations form a series of alternating synclincal valleys or depressions and anticlinal hills or mounds. As a result, the configuration of the bedding plane surfaces of the rock formations exhibit some relief from place to place.

In addition to minor folding, the rocks are locally displaced by faults. Several of these are shown on large-scale geolgoic maps published by the Tennessee Division of Geology and the U.S. Geological Survey. In general, the vertical displacement along most of the mapped faults is limited to a few tens of feet. Horizontal displacement along these faults is unknown.

A more complex structure occurs along a narrow belt that includes the eastern tip fo the basin and extends southwesterly from Harlan County, Ky., into Campbell County, Tenn. Along this belt the rocks have been tilted and elevated by overthrust faulting into a pair of parallel mountain ridges.

Another feature that is visible in many bedrock exposures in the basin is jointing or vertical rock fractures. Moore and others (1969) report that there are two prominent directions of rock jointing; one trending northwest-southeast and the other trending northeast-southwest.

Major Aquifers and their Water-Bearing Properties

Although each of the mapped units shown in plate 1 contain some permeable zones from which ground water can be obtained, the major aquifers or sources of ground water, those capable of yielding sizeable supplies of ground water, are contained within four of the mapped units. These are from youngest to oldest, the alluvium in the main valley of the Cumberland River; the Pennsylvanian rocks in the Cumberland Plateau; the Mississippi rocks in the Highland Rim; and the Ordovician rocks in the Nashville Basin. The hydrologic features of these aquifer systems are summarized in table 1 and are discussed briefly in succeeding sections of this report.

Table 1 - Generalized hydrologic properties of the major aquifers and chemical character of the ground water in the Cumberland River Basin.

(Numerical ranges represent typical values and do not include unusually high or low values)

Geologic unit and area	Aquifer type	Thickness (ft)	Yields of high capacity wells (gal/min)	Depth of high capacity wells (ft)	Depths to water (ft)	Hardness (mg/L)	Iron 1/ (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Total dissolved solids (mg/L)	pH (units)
Alluvium in the main valley.	Sand and gravel	30-120	50-500	50-120	10-30	150-300	10-30	0.2-5.0	3-10	200-350	7.0-7.8
Pennsylvanian rocks (und.) in the Cumberland Plateau.	Fractured sandstones and conglomerates	200-900	50-200	150-300	10-100	40-120	0.4-6.0	5-60	5-50	250-400	6.4-7.2
Mississippian rocks (und.) in the Highland Rim.	Carbonate rocks	100-2000	100-300	100-300	30-100	100-300	0.1-1.0	1-100	1-20	150-400	6.8-7.8
Ordovician rocks (und.) in the Nashville Basin.	Limestone	Not determined	50-500	100-300	20-50	200-400	0.1-2.0	5-50	2-50	250-500	6.8-8.0

1/ Includes manganese

Aquifers in the Alluvium

The alluvium underlies the flood plains of the main stem and major tributaries of the Cumberland River. It is composed of interfingering beds and lenses of gravel, sand, silt and clay. Characteristically, the beds and lenses of sand and gravel occur most commonly in the lower part of the alluvium; the upper part consists predominately of silt and clay. The thickness of the alluvium, according to boring and seismic data from the Corps of Engineers, is greatest in the downstream reaches of the Cumberland River and thins gradually in an upstream direction. At Barkley Dam in Kentucky the thickness is about 100 ft; at Old Hickory Dam near Nashville, Tenn., it is about 50 ft; and upstream at Carthage, Tennessee, it is only about 30 ft.

Aquifers in the alluvium along the main valley of the Cumberland River are little used as a source of water supply even though they comprise some of the most productive water-bearing materials in the basin. This may be due to their restricted area of occurrence and the abundance of good quality water from the nearby river. In addition, impoundments have inundated large segments of the flood plain beneath which the alluvium occurs. Nevertheless, the aquifers in the alluvium are capable of yielding sizeable quantities of ground water to wells.

The most productive zones in the alluvium are the beds of coarse sand and gravel that make up somewhat less than half of the total thickness of the otherwise fine-textured sediments. The coarse-textured deposits act as arteries or "pipelines" which transmit ground water readily. Hence, the ability of the alluvium to yield ground water to wells is proportional to the vertical thickness and areal extent of the sand and gravel deposits penetrated by the wells. According to Ryder (1975) these aquifer materials are about 40 ft thick in the alluvium below Barkley Dam and they have the potential to furnish about 500 gal/min to individual wells.

Upstream the thickness of the alluvium and the productive beds within it diminishes causing a similar reduction in the capacity of the alluvial aquifer to yield ground water. For example, at Nashville the maximum thickness of the alluvium is about 60 ft or half that below Barkley Dam, individual wells may yield 200 to 300 gal/min instead of 500 gal/min. Similarly, at Carthage where the alluvium is about 30 ft thick potential yields from the alluvial aquifer might be 50 gal/min or less.

The water in the alluvium is characteristically a calcium bicarbonate type. It is notably hard and moderately mineralized. The most objectionable features are the excessive concentrations of iron and manganese which combined range from 10 to 30 mg/L. These substances, however, can be removed by treatment.

Aquifers in the Pennsylvanian Rocks

The rocks of Pennsylvanian age crop out in the Cumberland Plateau section, a partially dissected upland which occupies the easternmost third of the basin. Sandstone and shale are the predominant rock types with siltstone, conglomerate, and coal making up the remainder of the sequence of formations. The maximum thickness of the exposed strata is about 900 ft. The coarse-textured rocks (sandstones and conglomerates) are more abundant in the lower or oldest part of the sequence, whereas the fine-textured rocks (shale, siltstone, and coal) are more abundant in the upper part. Characteristically, the sandstones and conglomerates are firmly cemented and highly resistant to erosion.

The principal aquifers in the Pennsylvanian rocks are the sandstone and conglomerates which occur throughout the sequence but are more abundant in the lower or oldest part. Although the permeability of some of the sandstones is known to result from intergranular porosity, most of these rocks are made permeable by openings in the form of fractures, joints, and bedding plane separations. The number and size of these openings determines the capacity of the rocks to store and transmit ground water.

Throughout the area underlain by Pennsylvanian rocks, wells generally yield ample water supplies for domestic use. However, the sandstone and conglomerate aquifers are capable of yielding moderate to large supplies of ground water under favorable conditions. The conditions most favorable for the development of high-yielding wells are a broad valley underlain by several hundred feet of sandstone. In addition wells located on fracture traces or fault zones typically yield more than wells drilled in nonfaulted areas. The potential for obtaining large yields is illustrated by two wells near Barbourville, Ky., that are located in a broad valley. These wells penetrate the upper part of a thick sandstone. They are 220 ft deep and are reported to yield 100 gal/min. Another example is a well 158 ft deep near Corbin, Ky., that is located in a broad valley and yields 200 gal/min.

Although coal beds are not considered major aquifers, underground coal mines, which are common in the upper Cumberland River Basin, form collection galleries that, in places, furnish sufficient water for a municipal or industrial supply.

The chemical quality of the ground water from the aquifers in the Pennsylvanian rocks varies within relatively wide limits, but the water is generally satisfactory for most uses or can be made so with minor treatment. Typically, the water is moderately mineralized, slightly acidic, and moderately soft.

Iron and Chloride are the two most common objectionable constituents in the ground water from these sandstone aquifers (Price and others, 1962). High iron is most likely to occur where water drains through beds of black shale or coal. Iron contents in excess of 0.3 mg/L are generally present in the water from most wells and springs. Thus, iron removal is usually desirable for most uses.

High concentrations of chloride are known to occur at depths of less than 300 ft throughout much of the Cumberland Plateau region (Price and others, 1962). In general, the concentration of chloride increases as the depth below drainage increases. However, the chloride content is usually negligible in high-yielding wells.

Aquifers in the Mississippian Rocks

The Mississippian rocks crop out in the Highland Rim, an upland plain that surrounds the Nashville Basin. They are also exposed in a narrow band along the north slope of Pine Mountain in the extreme eastern part of the basin. These rocks are composed of limestone, chert, dolomite and siltstone with minor beds of shale and sandstone. These formations have a combined thickness in the basin of about 2000 ft.

Throughout most of the Highland Rim section, the Mississippian rocks are deeply weathered forming a relatively thick mantle of insoluble cherty regolith (disintegrated rock material) overlying the fresh unweathered bedrock. The regolith generally ranges in thickness from about 30 to 200 ft. It is best developed beneath the upland surface. The upper part is composed chiefly of clay and silt-sized fragments. The lower part, however, generally contains a large percentage of gravel-sized particles.

Both the regolith and the underlying bedrock are water bearing in the sense that they contain openings for the storage and movement of ground water. However, their hydrologic properties are strikingly different. The regolith contains openings in the form of intergranular spaces much like those in a deposit of sand or gravel.

In constrast, the underlying bedrock contains openings in the form of solution-enlarged cavities created by the solvent action of ground water. These cavities had their origin along fractures, joints and bedding planes which provided the initial pathways for ground water to enter and circulate through the otherwise impenetrable rock mass.

Unlike intergranular openings which tend to be uniformly distributed, the solution-enlarged openings are randomly and irregularly distributed in carbonate bedrock. They also vary considerably in size. As a rule, these cavities tend to be larger and more numerous within 200 ft of the land surface, but wells in some areas have penetrated relatively large water-bearing openings at depths in excess of 500 ft.

Although their hydrologic properties are widely different, the regolith and the solution-riddled bedrock combine to form one of the most productive aquifer systems in the Cumberland River basin. In essence, the intergranular openings in the mantle of regolith provide the reservoir space to store large volumes of ground water, and the solution-enlarged cavities in the underlying bedrock provide the arteries or pipelines through which ground water can be readily transmitted to points of withdrawal.

The capacity of this two-phased aquifer system to yield ground water to wells is dependent upon the saturated thickness of the regolith and the size and number of solution-enlarged openings in the bedrock. Although most wells produce small amounts of ground water, a significant number have reported yields ranging from 100 to 300 gal/min. Many of these high-yielding wells obtain their supply from openings in the bedrock beneath a thick mantle of saturated regolith (Rima and Goddard, 1979). These favorable conditions are fairly widespread throughout the Highland Rim sections of the Cumberland basin.

The Mississippian rocks along Pine Mountain are virtually untested for high-yield wells. However, the potential for high yield is suggested by two wells 110 ft deep at Pineville that are reported to yield 500 gal/min. These wells are located near the Cumberland River and penetrate abundant fractures associated with the Pine Mountain thrust fault.

The chemical quality of the water from the Mississipian rock aquifers is generally good. Characteristically, the water is a calcium bicarbonate type and is slightly alkaline. Most of the reported values for dissolved solids range from 150 to 500 mg/L, those for hardness range from 50 to 400 mg/L, and those for iron and manganese range from 0.1 to 1.0 mg/L. As a rule, the water in the regolith is less mineralized and softer than that in the underlying bedrock. Thus, except for local occurrences of hydrogen sulfide gas in the water from some wells, the water from the Mississippian rock aquifers has no objectionable chemical constituent.

Aquifers in the Ordovician Rocks

The rocks of Ordovician age crop out mainly in the Nashville basin, a low-lying, oval-shaped area that includes and surrounds the city of Nashville, Tenn. They are also exposed in the main valley of the Cumberland River as far upstream as southern Russell County, Ky. The formations are composed almost exclusively of limestones with a combined thickness in excess of 1000 ft. The composition of the limestone formations ranges from 75 to 98 percent soluble carbonate material (Moore and others, 1969, p.11). Non-carbonate material is scattered throughout the rocks but is concentrated mainly in thin layers of shaly or sandy limestone interbedded with relatively pure limestone.

Owing to the low concentrations of insoluble material within the limestones, only small amounts of regolith or residual soil material accumulate on the land surface from weathering. Thus, soil development is minimal; the average thickness is about 4 ft.

Like the carbonate rocks of Mississippian age, the limestones of Ordovician age contain ground water in solution-enlarged cavities. But the storage capacity of the Ordivician rocks is greatly reduced because of the absence of a thick mantle of regolith. Thus, the occurrence and movement of ground water in tne Ordovician rocks is entirely dependent on the presence of solution cavities.

These cavities occur in a wide variety of types and sizes. Some are oriented perpendicular to the bedding planes in the rock while others are parallel to the bedding. The latter are the most common type penetrated by water wells (Burchett and Moore, 1971). Both types of openings are probably most abundant at depths of 50 ft or less but some openings have been penetrated at depths of 1000 ft or more.

The distribution of these openings does not appear to be restricted to any particular formation (Rima and Goddard, 1979). However, the size of the openings and hence their capacity to transmit water to wells appears to be related to bed thickness. Although the thin-bedded limestones tend to have more bedding plane openings, these openings are very thin in comparison with the height of solution openings in the massive bedded formations.

The total volume of solution cavities in the Ordovician limestones comprises less than one-half of one percent of the rock volume (Moore and others, 1969). To put this in perspective, a volume of rock 1 mile square and 100 ft thick could store 100 million gallons of water, enough to maintain a flow of about 200 gal/min from a well for a period of one year.

The capacity of the Ordovician limestones to furnish ground water to wells is documented in the records of some 8000 wells filed with the Tennessee Division of Water Resources. More than 90 percent of these wells were successful in obtaining some amount of ground water. About 70 percent of the wells were reported to yield in excess of 3 gal/min, 8 percent were reported to yield 25 gal/min or more, and slightly less than 1 percent had reported yields of 50 gal/min or more. The highest-yielding well was reported to yield 600 gal/min.

The foregoing suggests that ground-water supplies, however small, are generally obtainable from the aquifers in the Ordovician rocks. It also suggests that large supplies (50 gal/min or more) can be obtained under favorable conditions. In an effort to learn what conditions favor the occurrence of these large supplies Rima and Goddard (1979) determined that 92 percent of the large-yielding wells in the Nashville Basin are located in flat-bottomed valleys underlain by depressions in the bedrock structure. This combination of topographic and geologic features is fairly common in the outcrop area of the Ordovician rocks.

The water from the Ordovician rock aquifers is characteristically very hard, moderately mineralized, and moderately alkaline. Most of the supplies are free of any objectionable chemical constituents, but there are some exceptions. Somewhat less than half of the supplies sampled contained small but detectable quantities of hydrogen sulfide gas, about one-third contained excessive concentrations of fluoride, and less than 10 percent contained objectionable concentrations of iron.

Potential for Development

The foregoing discussion of the water-bearing properties of the major aquifers in the Cumberland River basin suggests that under favorable conditions sizeable ground-water supplies can be developed in most parts of the basin. The development of ground-water supplies, however, involves the recovery of ground water from the intricate network of water-bearing openings in the rock formations. As these openings are irregularly distributed and hidden from view, it is rarely possible to predict prior to the drilling of a well at what depths such openings will be found or how much water they will produce. Nonetheless, the chances of successfully obtaining large ground-water supplies can be significantly increased if drilling sites are chosen where geologic and topographic conditions favor the occurrence of water-bearing openings in the subsurface.

The relative potential for the development of large ground-water supplies in the Cumberland River basin is shown on the map in plate 2. This map delineates high, moderate and low potential areas based on the prevalence of geologic and topographic conditions that are most favorable for obtaining large ground-water supplies. As previously noted the potential for development of ground-water supplies is based on an evaluation of the records of the highest yielding wells in the region. As these wells constitute about one percent of the total number of wells, the implication is that random drilling will produce one high-yielding well for every 100 wells drilled. This ratio can be vastly improved in favor of the high yielding wells provided the selection of drilling sites is based on scientific knowledge and reasoning rather than convenience. For example, 3 of the 12 test wells that were drilled in the Franklin, Tennessee, area produced in excess of 100 gal/min.

It should be noted that the degrees of potential shown on the map (plate 2) do not reflect or relate to the quantity of water that might be developed from any one well. To be sure, more successful wells will probably be developed within the high or moderate-potential areas than in the low-potential areas, but it is incorrect to assume that the successful wells in the high-potential areas would produce more water than those in either the moderate-potential or low-potential areas. It is correct, however, to assume that the conditions favoring the development of large ground-water supplies are more widespread in the high-potential areas than is the case in the other parts of the basin.

It should also be noted that the development of ground-water supplies from wells does not constitute an overall increase in the total water supply. Instead, whatever amount of water is withdrawn from wells will, in time, be offset by a corresponding reduction in the amount of water being discharged by springs and streams. In effect, the water produced from wells is diverted from its natural flow path toward points of withdrawal.

Overall, there is a finite limit to the quantity of water that can be withdrawn perennially from wells. The amount will, of course, vary from place to place, but it cannot exceed the long-term average rate of ground-water recharge and discharge. As indicated by the water budgets derived from streamflow hydrographs (Rima and Goddard, 1979; Moore and Wilson, 1972), the long-term average rate of ground-water discharge ranges from about 6 in/yr in the Nashville Basin to about 8 in/yr in the Highland Rim. This is equivalent to 300,000 to 400,000 $(gal/d)/mi^2$. However, all discharge cannot feasibly be captured by wells. The actual amount that can be captured is a function of the hydraulic character of the aquifer,the hydraulic gradient that can be imposed at points of withdrawl,and the number and distribution of pumping centers. Thus, the quantity of water that could be produced from a given well or well field, for all practical purposes,is limited to some fraction of the total ground-water discharge from the area that contributes ground water to the well(s).

The amount of water that can be obtained from individual wells depends upon the hydraulic properties of the aquifer systems tapped by the wells. As evidenced by the range in yields of high-capacity wells reported in table 1, production rates in excess of 100 gal/min can be obtained from all the major systems in the basin. In fact, about 10 percent of the highest reported well yields equal or exceed 150 gal/min while five percent equal or exceed 200 gal/min. In all probability, the frequency of obtaining well yields of 150 gal/min or more could be increased if an adequate test drilling program preceded the selection of sites for production wells.

Where more than one production well is required to satisfy a particular need for water, consideration should be given to the installation of a well field with proper spacing between adjacent production wells. This value can usually be determined for a given site from aquifer tests in which water levels are monitored in observation wells at various radial distances from the pumped well. The results of such tests in the Nashville Basin indicate that adjacent production wells should be spaced about 1000 ft apart to avoid significant interference between wells and consequent loss of production. Similar tests in the Highland Rim indicate that 500 ft is generally adequate spacing for production wells in that physiographic setting. Available data are insufficient, however, to suggest a spacing for production wells in the Cumberland Plateau section.

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