Reconnaissance of Ground-Water Resources in the Blue Grass Region Kentucky

By W. N. PALMQUIST, JR., *and* F. R. HALL

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By W. N. Palmquist, Jr., and F. R. Hall

ABSTRACT

In the Blue Grass region probably less than half of the attempts to obtain adequate domestic water supplies from wells drilled in bedrock have been successful. The most favorable areas for obtaining ground water in the bedrock are those where thick limestone beds containing little or no shale occur at and below stream level. Areas underlain by shale or interbedded shale and limestone generally are less favorable. In general, more of the wells drilled in valleys are successful than those drilled on ridgetops. Large supplies of ground water can be obtained in many places from the alluvium along the Ohio River, but the alluvium along tributary streams generally is too fine-grained to yield large quantities of water. The water from wells in the Blue Grass region generally is of the calcium bicarbonate type and is hard to very hard. About one-eighth of the wells are reported to yield water containing undesirable amounts of common salt, and about one-fifth of the wells yield water containing noticeable amounts of hydrogen sulfide.

INTRODUCTION

PURPOSE AND SCOPE OF INVESTIGATION

Ground-water investigations in Kentucky are made by the United States Geological Survey in cooperation with the Commonwealth of Kentucky, Department of Economic Development and the Kentucky Geological Survey, University of Kentucky. Investigations under way are of three general types:

1. Detailed investigation of ground-water resources of small areas.
2. Statewide inventory of public and industrial water supplies.
3. Statewide reconnaissance of ground-water resources.

This investigation is of the third type. The chief purpose of this report is to provide general information on the availability of ground water for all uses in the Blue Grass region of Kentucky. The report will serve also to point out areas where further detailed studies are most needed.

Ground-water investigations of the U.S. Geological Survey in Kentucky are under the supervision of G. E. Hendrickson, district geologist.

LOCATION AND EXTENT OF AREA

For convenience in making the ground-water reconnaissances, the State of Kentucky has been divided into five regions of more or less distinctive geology and physiography. These regions are as follows: Eastern Coal Field, Blue Grass region, Mississippian Plateau, Western Coal Field, and Jackson Purchase. The boundaries of the regions are drawn on county lines which approximate but do not coincide exactly with geologic and physiographic boundaries.

The Blue Grass region (fig. 1) comprises 43 counties in the north-

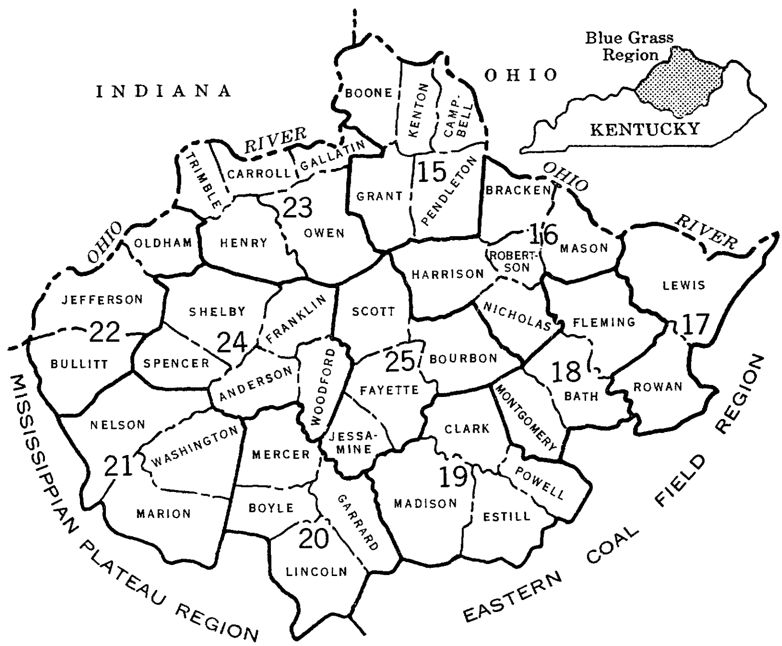

FIGURE 1.—Index map of the Blue Grass region showing counties and county groups.

central part of the State and covers an area of approximately 11,300 square miles. It is bounded on the northeast by the Ohio River and the State of Ohio, on the southeast by the Eastern Coal Field, on the southwest by the Mississippian Plateau, and on the northwest by the Ohio River and the State of Indiana. The population of the 43 counties in 1950 was 1,273,576.

PREVIOUS INVESTIGATIONS

The geology of the Blue Grass region has been described by many authors in publications too numerous to list in this report. "Geology of Kentucky," by A. C. McFarlan (1943), contains a summary of the stratigraphy, structure, physiography, and natural resources of the region, plus an extensive bibliography. A list of references cited in the present report appears at the end of the text.

The first systematic study of the occurrence of ground water in Kentucky was made by G. C. Matson (1909), who briefly described the geology and occurrence of ground water in 30 counties of the Blue Grass region. Since 1944, a number of detailed reports dealing with ground-water conditions in the Louisville area have been published. D. K. Hamilton (1950) described the areas and principles of occurrence of ground water in Bourbon, Fayette, Jessamine, and Scott Counties. A reconnaissance of the ground-water resources of the Covington-Newport alluvial area was described by E. H. Walker (1953). W. N. Palmquist, Jr., and F. R. Hall (1953) described public and industrial ground-water supplies of the region. Ground-water conditions in Jefferson County were described by L. M. MacCary (1956) in a report which includes a map showing ground-water availability.

METHOD OF INVESTIGATION

The fieldwork for this report was done by the writers during the period January 1953 to March 1954. Specific-capacity tests on representative wells were made by W. H. Walker from August through October 1954. Fieldwork consisted chiefly of inventorying wells and springs and studying by direct and indirect means the characteristics of the rocks that affect the storage and movement of ground water.

An average of about 35 representative wells and springs was inventoried in each county. An attempt was made to obtain complete information on each such well and spring. Depth of well and depth to water were measured where possible, and the aquifer supplying each well and spring was determined. A report on the permanence and adequacy of the supply was obtained, generally from the owner. Samples of water from representative wells and springs were collected for chemical analysis. Some well logs and samples of drill cuttings were collected, but no attempt was made to obtain all the available logs. Information obtained in the well and spring inventory is summarized by means of well symbols and explanations on availability maps which are published separately in U.S. Geological Survey Hydrologic Investigations Atlases HA 15–25 (see Palmquist and Hall, 1960a–f; and Hall and Palmquist, 1960a–e).

Selected wells in the more important aquifers were pumped to determine their specific capacity. Some of the larger springs were gaged to determine their flow. The resulting data are presented in tables 1 and 2.

Geologic mapping was restricted largely to part of Rowan County, where no geologic map was available. There the geologic boundaries were drawn on the basis of available well logs and a reconnaissance field study. Additional geologic mapping was done in several counties where the existing maps did not distinguish some of the more important water-bearing strata. Most of the geology shown on the maps, however, has been adapted from existing county geologic maps prepared by the Kentucky Geological Survey. The geologic maps are included in U.S. Geological Survey Hydrologic Investigations Atlases HA 15–25 (see Palmquist and Hall, 1960a–f; and Hall and Palmquist, 1960a–e). References to the original county maps appear in the atlases.

ACKNOWLEDGMENTS

The reconnaissance was aided greatly by the cooperation and interest of well owners, well drillers, county agents, and United States Soil Conservation Service employees in the region.

Dr. A. C. McFarlan, former director of the Kentucky Geological Survey, aided materially in the compilation of the stratigraphic correlation chart of the region.

GEOGRAPHY

The Blue Grass region proper consists of the Inner Blue Grass, Eden shale belt, and Outer Blue Grass physiographic subdivisions. However, for the purpose of this report it is defined to include also the Knobs and small parts of the Eastern Coal Field and Mississippian Plateau. Most of the region lies in the Lexington Plain section of the Interior Low Plateaus physiographic province (Fenneman, 1938). Figure 2 shows physiographic subdivisions and the outer limits of the area of this report as determined by county boundaries.

TOPOGRAPHY AND DRAINAGE

The central part of the Blue Grass region as shown in figure 2 coincides, for the most part, with what is known as the Inner Blue Grass and consists of the outcrop areas of the Cynthiana formation (Ordovician) and older Ordovician strata. The area is a gently rolling upland in which the Kentucky River and some of its tributaries are entrenched as much as 300 feet. Most of the rock underlying the area is limestone that has been subjected to considerable erosion by solution, both on and beneath the surface. As a result, much of the drainage is underground. In places the underground drainage comes to the surface to form springs. The area is dotted with sinkholes as much as 60 feet deep and 1 square mile in area.

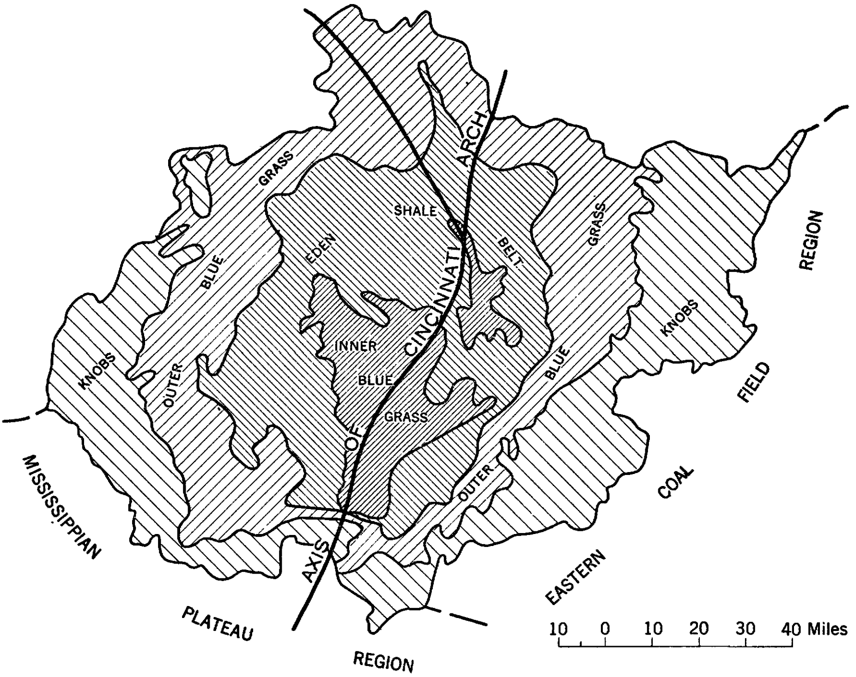

FIGURE 2.—Physiographic subdivisions of the Blue Grass region, Kentucky, and location of the Cincinnati arch.

The Inner Blue Grass is surrounded by a band of dissected, hilly country known as the Eden shale belt. The Eden shale belt consists of the outcrop area of the Eden group of Ordovician age, which is made up mainly of shale and interbedded thin layers of limestone and is characterized by sharp, irregular ridges and narrow valleys. Because of the steep slopes, runoff is rapid, and few perennial streams originate in the Eden shale belt.

The Outer Blue Grass surrounds the Eden shale belt. The Outer Blue Grass consists of the outcrop areas of the Richmond and Maysville groups of Ordovician age and part of the outcrop area of rocks of Silurian age. These rocks are chiefly limestone but include considerable interbedded shale. The topography is gently rolling except near major streams, where it is dissected and rugged. There has been some subsurface solution, and small sinkholes are fairly common, but most of the drainage is on the surface.

Bordering the Outer Blue Grass on the east, south, and west is a belt, known as the Knobs, which is underlain by rocks of Silurian, Devonian, and Early Mississippian ages. The outcrop of Silurian and Devonian rocks west of the Cincinnati arch is gently rolling and more or less continuous with the Outer Blue Grass. East of the arch, rocks of Silurian and Middle Devonian age underlie long, wide valleys extending into the Knobs. Upper Devonian and Lower Mississippian rocks make up the hillsides and most of the hilltops of the rough, hilly belt of the Knobs proper.

Rocks of Late Mississippian age crop out in the Knobs along the west and south edges of the area. These rocks are outliers of the Mississippian Plateau. Rocks of Early Pennsylvanian age crop out in the Knobs along the east edge of the area, mainly on the tops of hills and ridges. These rocks are outliers of the Eastern Coal Field.

The alluvial terraces of the Ohio River valley lie along the entire north border of the Blue Grass region. The valley is cut about 350 feet below the general level of the adjacent area. The part of the Ohio River valley to be considered in the present report consists of the alluvial terraces on the Kentucky side of the Ohio River. The width of the terraces ranges from zero, where the river impinges on the valley walls, to a maximum of about 5 miles, near Louisville.

The entire Blue Grass region lies within the drainage basin of the Ohio River. The important tributaries of the Ohio that drain the region are the Kentucky, Licking, Salt, Cumberland, and Green Rivers. The Kentucky River drains an area of about 3,700 square miles, or 33 percent of the Blue Grass region as defined. It enters the region in the southeast in Estill County, flows westward to Jessamine County, and then northward to the Ohio River at Carrollton. The Kentucky River is incised as much as 300 feet below the general upland level and has cut a steep, narrow gorge where it crosses the Cincinnati arch. The Licking River enters the area in the east in Rowan County and flows northwestward to the Ohio River at Covington and Newport. It drains 2,900 square miles, or 25 percent of the Blue Grass region. It has cut a valley as much as 300 feet below the upland level, but it has a wider valley and flood plain than the Kentucky River and nowhere is entrenched in a steep, narrow valley. The Salt River heads in Boyle County, flows northward to Anderson County, and thence westward to the Ohio River at West Point, south of Louisville. The Salt River drains about 2,670 square miles, or 24 percent of the area. About 160 square miles in Lincoln County in the extreme southern part of the region is drained by the Cumberland and Green Rivers, which join the Ohio River in western Kentucky. A narrow strip of land along the Ohio River is drained by small directly tributary streams.

The subsurface drainage pattern is composed of many small independent units much like the surface drainage, which is made up of many small watersheds. In areas underlain by limestone, subsurface drainage courses may deviate locally from the surface drainage. Such deviations usually are evident from discontinuities in the surface drainage pattern.

CLIMATE

The climate of the Blue Grass region is of the humid continental type, with sharp contrasts between the winter and summer. The mean annual temperature ranges from 53° to 57° F., 55° F. being about average for the region. The mean January temperature ranges from 32° to 37° F. and averages about 34° F. The mean July temperature ranges from 75° to 78° F. and averages about 76° F. The growing season is about 180 days. The mean annual precipitation ranges from 39 to 47 inches and averages about 43 inches. Precipitation is rather evenly distributed throughout the year, there being sufficient rain during the growing season in most years to cause crops to mature. The spring months sometimes have enough rain to produce floods; yet, in contrast, drought conditions occasionally prevail for several weeks during the summer.

Figure 3 consists of two graphs showing the monthly temperature and precipitation averaged for 10 stations in the Blue Grass region.

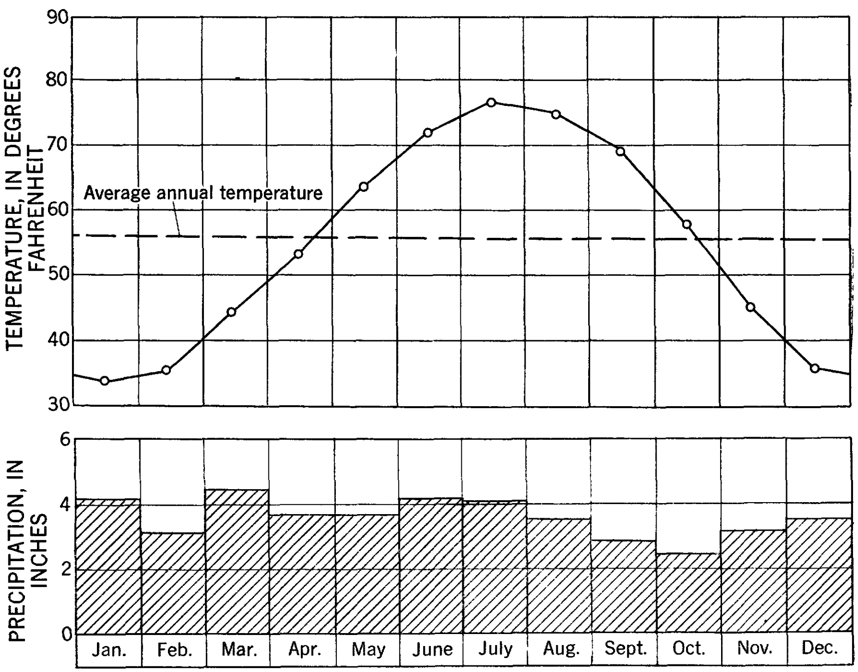

FIGURE 3.—Monthly temperature and precipitation averaged from normals for 10 stations in the Blue Grass region.

For a period of about 2 years, from the summer of 1952 to the fall of 1954, Kentucky had prolonged dry spells accompanied by higher than average temperatures. The effect was not appreciable until 1953, when a dry winter was followed by a very dry summer. United States Weather Bureau records for the Blue Grass region show a precipitation deficiency ranging from about 6 to 13 inches in 1953, and average temperatures about 2° F. above normal. During the summer and fall of 1953 many wells, springs, and streams went dry, some for the first time in the memory of local residents, others for the first time since the dry spells of the early 1930's. The early part of the summer of 1954 was nearly as dry as 1953, but above-average rainfall in the late summer and early fall brought the drought to an end.

ECONOMY AND RESOURCES

The economy of the Blue Grass region is predominantly agricultural; tobacco is the major crop. Most large industrial plants are in the cities along the Ohio River, although small factories are located in many of the towns throughout the region.

The chief mineral resource is limestone, which is used for cement, roadbuilding, and agricultural products. Sand and gravel are obtained in the Ohio Valley. McFarlan (1943) includes a discussion of the mineral resources of the State. Many reports describing clay, limestone, sand, brine, oil and gas, and other resources have been published by the Kentucky Geological Survey.

GEOLOGY

GENERALIZED STRATIGRAPHY

The rocks (pl. 1) that crop out in the Blue Grass region are of sedimentary origin and range in age from Ordovician to Quaternary. About 90 percent of the region is underlain by rocks of Ordovician age. The oldest rocks exposed are of lowermost Middle Ordovician (Chazy) age and form the lower part of the High Bridge group. Overlying these are rocks of later Ordovician and Silurian, Devonian, Mississippian, and Pennsylvanian age. The youngest consolidated rocks are of Pennsylvanian age. There are no rocks of Mesozoic age in the region. Unconsolidated deposits of clay, silt, sand, and gravel of Pliocene or Pleistocene and of Recent age make up the rocks of Cenozoic age in the Blue Grass region.

The areal extent and geologic characteristics of the rocks of the region can be found on the generalized geologic maps and columnar sections which are included in U.S. Geological Survey Hydrologic Investigations Atlases HA 15–25 (see Palmquist and Hall, 1960a–f; and Hall and Palmquist, 1960a–e).

A series of Cambrian and Ordovician limestone, dolomite, and sandstone units lies between the lower part of the High Bridge group and the Precambrian basement rocks. Although this series is not exposed, the rocks have a total thickness of about 5,000 feet so far as is known from logs of wells. The lower part of the High Bridge group is not exposed but extends 200 to 300 feet beneath its lowest exposed part. The St. Peter sandstone of Ordovician age, represented by sandstone, sandy dolomite, and dolomite, underlies the High Bridge. Dolomite of Cambrian and Ordovician age extends down to a basal sandstone unit that lies on the rhyolite porphyry of the Precambrian basement (Freeman, 1953, p. 209).

STRUCTURE

The Cincinnati arch (figs. 2, 4) is the major structural feature of the Blue Grass region. The axis of the arch enters the region from the south in Boyle County and trends north-northeastward to the central part of the region, where it branches. One branch continues northwestward to Boone County, where it then leaves the region. The other branch crosses Pendleton County northward to the point where it leaves the region. Two domes and a sag have been developed along the axis of the arch. These features are, from south to north, the Nashville dome of central Tennessee, the sag, centered over Cumberland County south of the Blue Grass region, and the Jessamine dome, centered over Jessamine County in central Kentucky. The Jessamine dome is a high point on the arch in the county, and the rocks have a dip of 20 to 40 feet per mile on the east and west and about 10 feet per mile on the north and south (McFarlan, 1943, p. 132). Figure 2 shows that, since the arching, erosion has removed the top of the dome, leaving older rocks exposed in the center and concentric belts of progressively younger rocks outward.

Several fault systems also are important structural features, and they have had a marked effect on the present topography. The Kentucky River "fault" is actually a zone of echelon normal faults extending from Lincoln County northeastward to Mount Sterling, in Montgomery County. A monocline in Bath County represents a continuation of the fault system. Westward-trending faults southeast of Danville, in Boyle County, terminate near Lebanon, in Marion County. One of the faults trends along the base of the Knobs and forms a faultline scarp. The relation of the Kentucky River to the Kentucky River fault is shown along the Clark County-Madison County line, where the river abruptly changes its northwestward course to southwestward as it intersects the fault zone, then follows

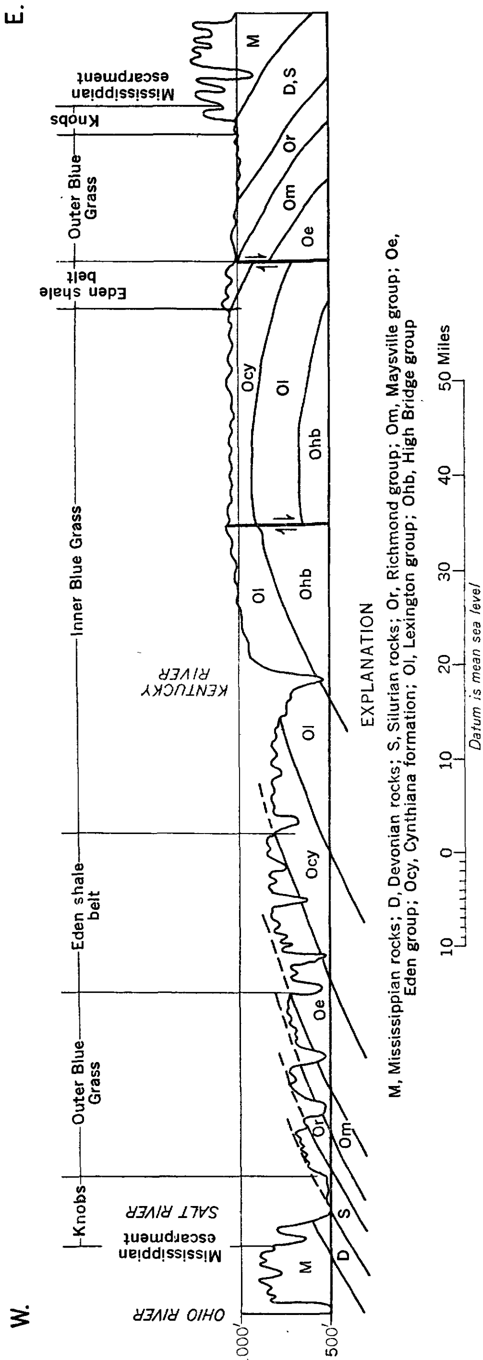

FIGURE 4.—Generalized cross section of the Blue Grass region, Kentucky.

the fault zone southwestward for about 15 miles before resuming its northwestward course. Another effect of this fault zone is shown at Burdette Knob in Garrard County, where the Ohio shale and Lower Mississippian rocks are preserved in a downdropped fault block. Erosion since the faulting has left the Devonian and Mississippian rocks in a knob rising above surrounding Ordovician rocks.

The West Hickman fault terminates against the Kentucky River fault in Jessamine County and trends northeastward to Maysville in Mason County (McFarlan, 1943, p. 145–150). One effect of this fault can be seen in the Inner Blue Grass, where the Eden group is preserved in a downdropped fault block.

Some faults in the eastern part of the Blue Grass region are not part of the Kentucky River or West Hickman fault systems; most of these are small and unimportant. The Irvine-Paint Creek fault extends from Estill and Powell Counties into the Eastern Coal Field.

A domelike structure in the midst of flat-lying, relatively undisturbed sedimentary rocks is found at Jeptha Knob in Shelby County. The dome apparently originated in Early Silurian time, as it is capped by flat-lying Middle Silurian rocks (McFarlan, 1943, p. 152–153). The origin of this structure is unknown, but it has been postulated that it was caused by deep-seated igneous activity (Bucher, 1925).

The major structural feature of the region, the domed Cincinnati arch, has resulted in a circular outcrop pattern, bringing rocks of differing lithology to the surface in concentric bands. The occurrence of ground water, which is determined in part by the lithology of the rocks, naturally is related to the circular geologic outcrop pattern.

Hamilton (1950) indicated that saline water was found along faults in the Inner Blue Grass. It is possible that some of the highly mineralized water in the rest of the region may be connate, reaching the surface along the numerous faults.

GEOLOGIC HISTORY

Middle Cambrian sedimentary rocks rest on the Precambrian basement in central Kentucky (Freeman, 1953, fig. 1). Nearly continuous deposition took place from the Middle Cambrian epoch to the Pennsylvanian period. The rocks are marine in origin from the Middle Cambrian through the deposition of the Ohio shale in Late Devonian time. Upper Mississippian and Pennsylvanian rocks, however, are in large part continental in origin. The Jessamine-dome part of the Cincinnati arch underwent two main periods of arching; namely, before Onondaga and after early Lexington time, and during Late Mississippian and Early Pennsylvanian time (McFarlan, 1943, p.

155). Most of the earth movement that formed the Kentucky River and West Hickman fault systems took place during late Paleozoic time, but the faulting may have started earlier and continued later (McFarlan, 1943, p. 155).

Erosion and peneplanation throughout the Mesozoic era removed any rocks of Mesozoic age that might have been deposited. Uplift and erosion in early Tertiary time formed the Lexington Plain. The Irvine formation represents old stream deposits below the level of the Lexington Plain and is considered to be Pliocene or Pleistocene in age. A late Tertiary uplift caused dissection of the Lexington Plain and entrenchment of major streams.

Glaciation during Pleistocene time resulted in deposition of pre-Illinoian and Illinoian glacial material on the hills along the Ohio River in northern Kentucky and thick outwash deposits of the Wisconsin stage that form the alluvial terraces along the Ohio River. In Recent time, alluvium has been deposited along present-day streams.

GENERAL HYDROLOGY

The primary purpose of this report is to provide information on ground water for the residents of the region. Therefore, the use of technical terms is restricted to those which are considered essential to an understanding of the occurrence of ground water. The following definitions are based largely on those given by Meinzer (1923a, 1923b). A few terms not given in the following list are defined where they are used in the text.

DEFINITION OF TERMS

Aquifer.—A formation, group of formations, or part of a formation that is water yielding.

Aquifer, confined.—An aquifer, which is overlain by a confining bed and which contains water that is under sufficient pressure to rise above the bottom of the confining bed.

Aquifer, semiconfined.—An aquifer overlain by a confining bed which itself is somewhat permeable and may act as an aquifer and through which water may move either into or out of the lower aquifer.

Aquifer, unconfined.—An aquifer which is not overlain by a confining bed and in which, therefore, the water table is free to rise and fall. Also called "water-table aquifer."

Discharge, ground-water.—Discharge of water from an aquifer, either by natural means such as evapotranspiration and flow from seeps and springs or by artificial means such as pumping from wells.

Drawdown.—Lowering of the water level in a well as a result of withdrawal of water.

Evapotranspiration.—Total discharge of water to the air by direct evaporation and plant transpiration.

Permeability.—The capacity of earth materials to transmit water under pressure. In general, the larger the connected pore spaces or other openings in the material the greater the permeability.

Piezometric surface.—The imaginary surface defined by the level to which water will rise in wells tapping a confined aquifer. It is analogous to the water table in that its shape and slope are indicative of the direction and relative rate of movement of water in the aquifer.

Porosity.—The ratio of the volume of the openings to the total volume of a rock or soil. A high porosity does not necessarily indicate a high permeability.

Recharge, ground-water.—Addition of water to an aquifer by infiltration of precipitation through the soil, by flow from streams or other bodies of surface water, by flow of surface water through sinkholes, or by flow of ground water from another aquifer.

Saline water.—Water having a substantially higher concentration of dissolved solids than water considered fresh in the same locality. It has been defined in some reports as water containing more than 1,000 ppm of dissolved solids. In some areas, however, no better water is available and water containing more than 1,000 ppm is not considered saline; on the other hand, some water containing less than 1,000 ppm but having a high sodium and chloride content has a salty taste and is considered saline.

Semiperched ground water.—Ground water which has a greater pressure head than an underlying body of ground water, from which it is, however, not separated by any unsaturated rock.

Specific capacity.—The rate of yield of a well per unit of drawdown, generally expressed in gallons per minute per foot of drawdown at the end of a specified period of discharge. Not an exact quantity, as drawdown increases with time. Gives an approximate indication of how much water a well can yield.

Water table.—The upper surface of the zone of saturation except where that surface is formed by impermeable material.

Zone of saturation.—The zone in which the openings in the rocks are filled with water under hydrostatic pressure.

THE HYDROLOGIC CYCLE

The hydrologic cycle may be defined as the cycle through which water passes, commencing as atmospheric water vapor, passing into liquid and solid form as precipitation, thence along or into the ground surface (streamflow and underground flow), and finally again returning to the form of atmospheric water by means of evapotranspiration.

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The hydrologic cycle is complex and in any specific area is controlled mainly by such factors as amount and rate of precipitation, temperature, type of soil and vegetation, topography, and geology. This report is concerned primarily with the recovery of water that is underground.

Most water of economic importance in the Blue Grass region comes from local precipitation. The precipitation falling on the ground evaporates, runs off in streams, or soaks into the soil. Part of the water that seeps downward into the soil is evaporated directly or is intercepted by plant roots and transpired. Part continues downward to the water table and becomes a part of the zone of saturation, moving slowly in that zone to points of lower elevation. Eventually, this water discharges through springs or seeps into surface-water bodies or is discharged by evapotranspiration. In dry weather the discharge of ground water is the principal source of streamflow (base flow).

The Blue Grass region is a self-contained (ground-water) hydrologic unit composed of many smaller self-contained units, each very much like the individual watersheds that comprise the surface drainage system; with few exceptions, each coincides with a watershed. The source of ground water at any point in the region is the precipitation that has fallen on the area upgradient. Very little water moves underground from one watershed to another.

If no net change occurs in the amount of water stored on the surface or in the soil and rocks under an area in a given period of time, the amount of stream runoff from the area plus the amount of water discharged by evapotranspiration will be equal to the amount of precipitation on the area in the same period of time. In the Blue Grass region, the average annual precipitation is about 43 inches, and the average annual runoff as measured at stream-gaging stations is about 15 inches. Therefore, the discharge of water by evapotranspiration for an average year is about 28 inches. This means that under present conditions only about a third of the water that falls on the area is even potentially available for development; only a part of that can be developed practicably, of course.

FLUCTUATION OF WATER LEVELS

In the preceding section, it was assumed that the amount of water stored underground remained constant, to permit estimating evapotranspiration on the basis of precipitation and runoff. In areas in the Blue Grass region where little water is withdrawn by pumping from wells, the amount of ground-water storage generally does not change greatly from year to year, but the seasonal variation in storage may be considerable. The amount of water stored underground is affected by the same variables that influence the hydrologic cycle and, therefore, is constantly increasing or decreasing.

The position of the water table is related directly to the amount of water in underground storage. Therefore, fluctuations of water levels in wells are a measure of changes in ground-water storage. The more common and easily observed causes of fluctuations of ground-water levels in the Blue Grass region are recharge from precipitation, reduction or cessation of such recharge as a result of soil-moisture deficiency during the growing season, atmospheric-pressure changes, changes in river stage, and pumping. Continuous records of the water levels in certain wells illustrate these influences.

Single measurements of water level were made in most of the wells tabulated in the present report. In a few wells, periodic water-level measurements were made at arbitrary intervals of time, and in 17 wells continuous measurements were made for extended periods by means of automatic water-level recorders. A graph showing fluctuations in the level of water in a well for a period of time is termed a hydrograph.

Figure 5 includes graphs showing water levels in the Ohio River and in a nearby well in the alluvium of the Ohio River at Covington, Ky. The observation well is about 300 feet from the river and within about 400 feet of 3 pumped wells. The rise and fall of the water level in the well is similar to, but not as pronounced as, that of the river stage. Pumping from nearby wells began in late June and lowered the water level in the observation well at an increased rate. When pumping of large quantities of water from the underground reservoir stopped in mid-September, there was a definite reversal of the downward trend of the water level in the well.

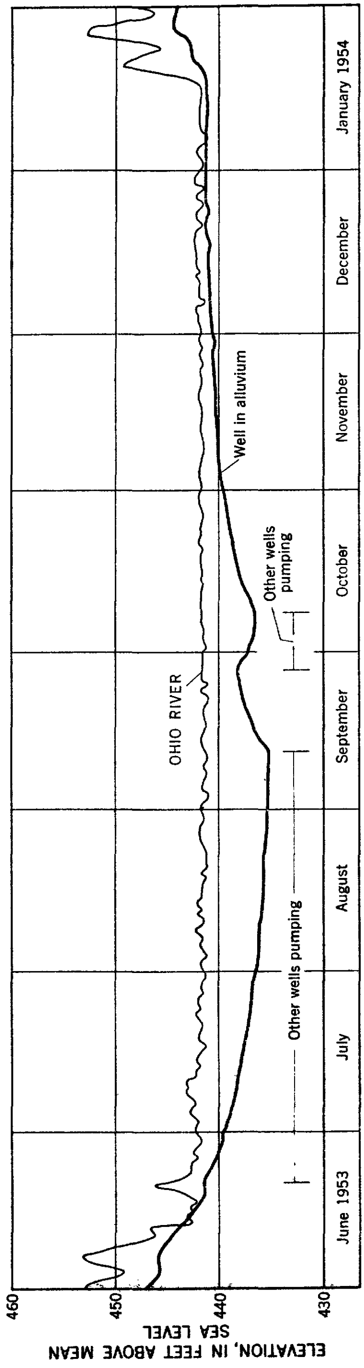

FIGURE 5.—Graph showing relation between stage of Ohio River and water level in a well at Covington, Ky.

Figure 6 is a 1-week hydrograph of a well in a semiconfined aquifer and a graph of atmospheric pressure. Fluctuation of atmospheric pressure causes a corresponding but smaller fluctuation of the water level in the well.

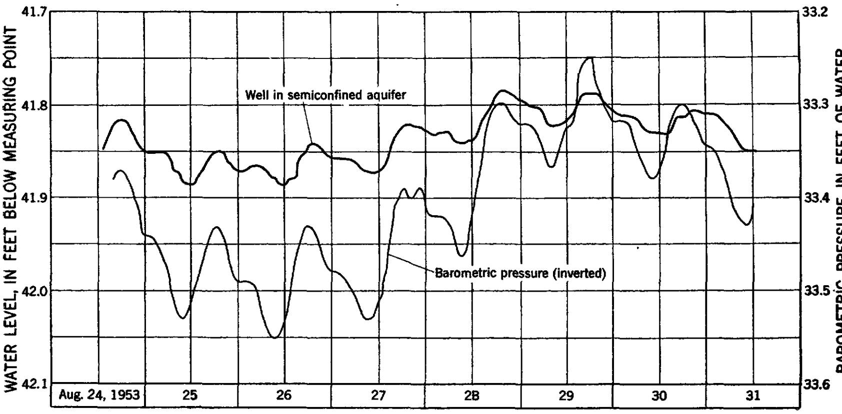

FIGURE 6.—Graph showing relation between water level in a well and barometric pressure at Covington, Ky.

Figure 7 is an 8-month hydrograph of an unused dug well on a hilltop underlain by rocks of the Maysville group, with a diagram showing local precipitation. During the growing season, the water level in the well rose abruptly and fell less abruptly after each rain. The end and beginning of the growing season are indicated respectively by the abrupt and sustained rise or recovery of the water level in the fall and gradual lowering or decline of the water level during the growing season.

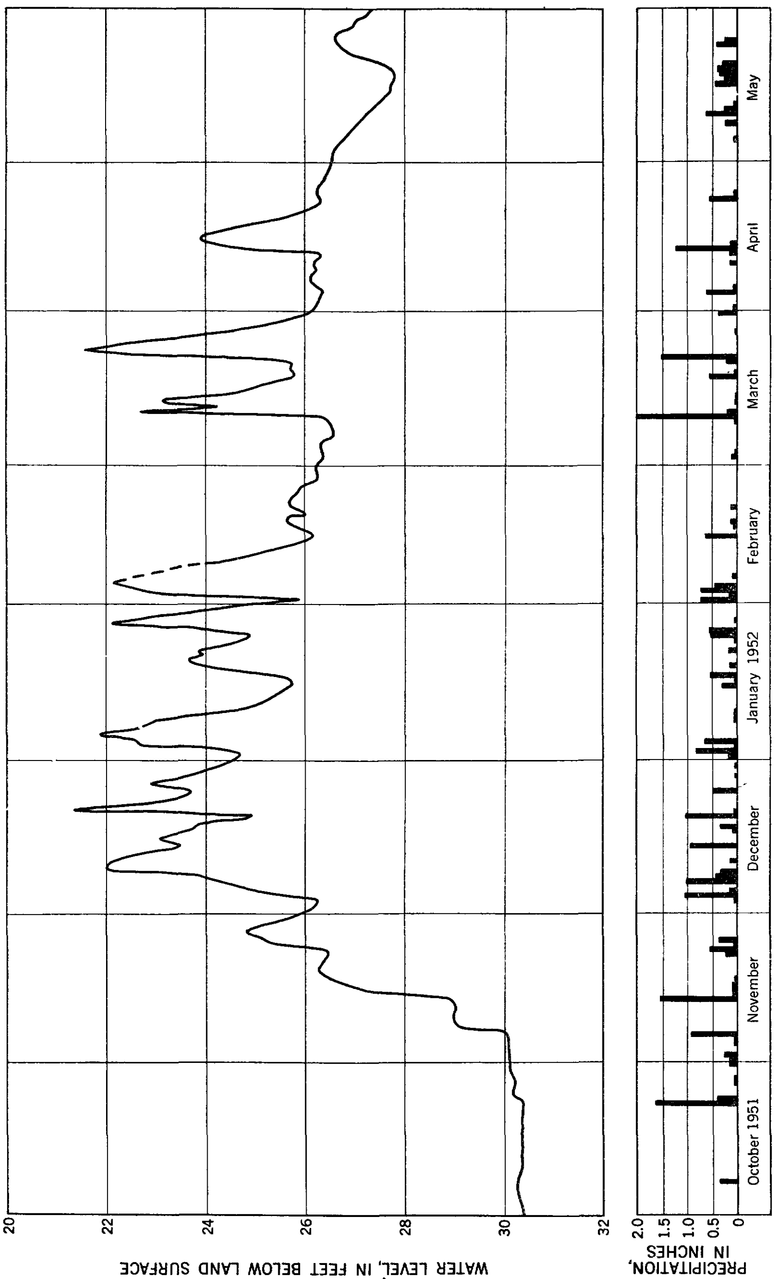

FIGURE 7.—Graph showing relation between water level in a well and precipitation near Covington, Ky.

Figure 8 is a hydrograph of a well in a semiconfined aquifer in Lower Mississippian shale and siltstone. The trace shows short-term drawdown and recovery resulting from intermittent pumping of a nearby well. The large recovery from the 16th to the 19th day was due to recharge from rainfall. The small upward fluctuations were caused by the weight of trains that passed the well about 300 feet away and temporarily compressed the aquifer, causing water to rise in the well.

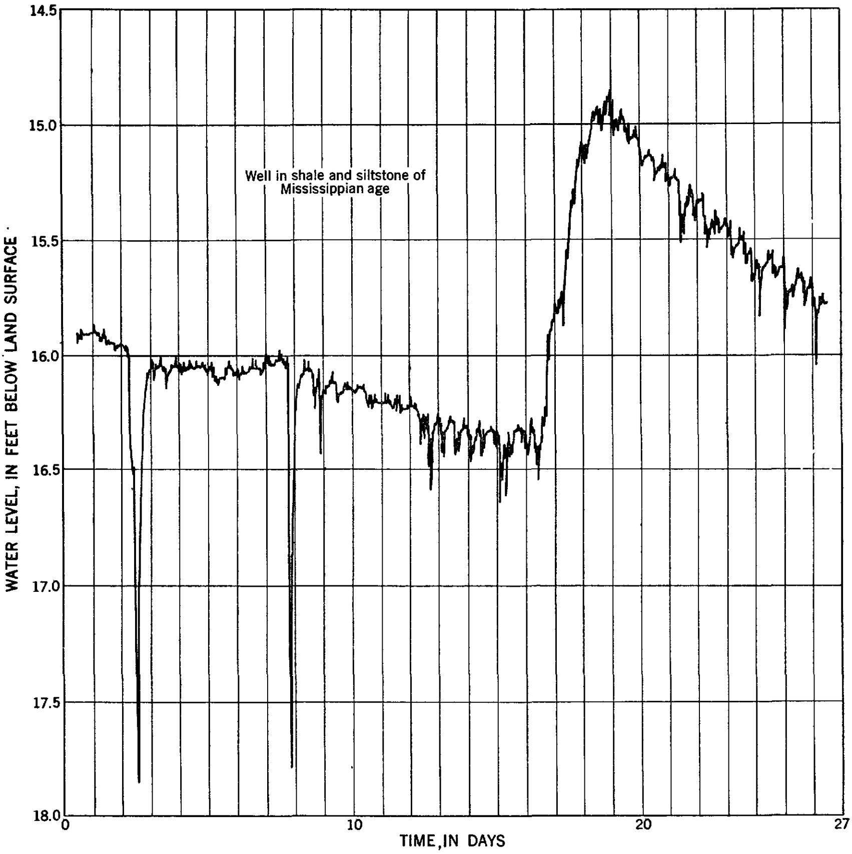

FIGURE 8.—Graph showing water level in a well near Morehead, Ky.

GROUND-WATER OCCURRENCE

Ground water occurs in openings in both consolidated and unconsolidated rocks. The nature of the openings controls the amount of water that can be stored in the rocks and the rates at which it can be replenished, or given up, to wells and springs. In unconsolidated material, such as gravel, sand, and silt, the openings consist of spaces (pores) between individual particles or grains. The amount of open space (porosity) and the size and interconnection of the openings, which together determine permeability, are determined by the size, shape, and arrangement of the grains. In consolidated clastic rocks, such as sandstone, siltstone, or shale, openings also occur between the grains, but the porosity and permeability are reduced to a greater or lesser extent by cementing material. The amount of cementing material may range from almost nothing to enough to fill the openings completely. In carbonate rocks, such as limestone, the principal openings are usually secondary and exist as a result of solution along joints and bedding planes. These openings generally are larger and more numerous near the surface and decrease in size and number with depth. The size of the openings and the depth to which they extend are determined essentially by the relative solubility of the rock and by the amount of water that has been in contact with the rock. Solution openings are largest and extend to greatest depths in thick, relatively pure limestone; they are confined to shallower depths where layers of shale, bentonite, or impure limestone serve as effective barriers below which the process of solution is ineffective. Types of limestone that are relatively insoluble include those which contain significant amounts of impurities such as clay (argillaceous limestone), magnesium carbonate (dolomitic limestone), or silica (siliceous limestone).

In the Blue Grass region ground water occurs in two distinct environments. One includes unconsolidated sand and gravel in the valleys of the Ohio River and the larger tributaries; the other consists of the consolidated bedrock that underlies the entire region.

Although the unconsolidated alluvial deposits cover only a small part of the region (Walker, 1957), they are not only the source of much of the ground water presently pumped, but they also are the greatest potential source of ground water for future municipal and industrial development. Almost everywhere the alluvium of the Ohio Valley will yield sufficient water for domestic and farm use, and in many places it will yield several hundred to 1,000 gpm (gallons per minute) and in a few places more than 1,000 gpm. The largest known yield is 1,400 gpm to a well near Louisville. Specially designed wells or collectors may be able to produce several thousand gallons per minute from the alluvium. One such collector, downriver from the Blue Grass region, has been pumped at a rate of 9,000 gpm (Maxwell, 1954). Such large quantities are replenished largely by induced infiltration from the river. Alluvium in the valleys of the larger tributaries yields, in some places, several hundred gallons of water per minute, as well as adequate supplies for domestic needs in most places. Alluvium in the smaller tributaries is generally thin and mostly silt and clay. Small amounts of water may be obtained from the thin deposits of alluvium, but few wells are known that obtain water from this source.

The only wells in bedrock that produce more than 100 gpm are those that penetrate rocks of Middle Ordovician age in the Inner Blue Grass area and a few that penetrate younger rocks in the Ohio River valley. Otherwise in younger rocks, only 2 wells produce more than 50 gpm and only 7 more than 25 gpm.

Of the 608 inventoried wells drilled in bedrock, 238 are known to produce enough water for modern domestic use with a power-pump and pressure system. About half the 284 wells equipped with hand pumps might furnish enough water for a power-pump and pressure system. Therefore, roughly 375, or three-fifths, of the wells in bedrock that were inventoried are thought to be capable of providing a modern domestic supply. The writers were told of many "dry holes" but did not inventory these, and no doubt many more have been abandoned and forgotten. Less than a quarter of the wells in bedrock that were inventoried are reported to go dry on occasion or are of such small yield as to be inadequate for any purpose. Nevertheless, considering the dry holes that were not inventoried, it is estimated that less than half the attempts to obtain adequate domestic water supplies from wells drilled in bedrock have been successful.

Locally, as much as 300 gpm is obtained from a few wells in bedrock. The specific capacity of 17 wells in alluvium and 23 wells in bedrock was determined and is shown in table 1. Table 2 shows the measured discharge of 13 springs.

Thick beds of pure limestone underlie parts of the Blue Grass region at depths greater than about 100 feet below the land surface. However, they are covered by essentially impermeable rock in most places. As a result, circulation of ground water in those areas has been restricted to a zone above the impermeable rock units, extending little more than 100 feet beneath the land surface. Solution openings at greater depths are so small that they have little or no effect on the occurrence of ground water.

The availability of ground water in a part of the Inner Blue Grass is closely related to topography and drainage (Hamilton, 1950). Other things being equal, more water is available from rocks beneath valleys than from rocks beneath hills. This relation is apparent not only in the remainder of the Inner Blue Grass where similar topographic and geologic conditions exist, but also in the entire Blue Grass under a wide range of geologic and topographic conditions.

TABLE 1.—*Specific capacity of drilled wells in the Blue Grass region, Kentucky*

[Aquifer: Ol, Lexington group; Ocy, Cynthiana formation; Om, Maysville group; S, Silurian system; Qal, Quaternary alluvium]

County	Date	Aquifer	Average pumping rate (gpm)	Specific capacity (gallons per minute per foot for indicated length of test)								
				1 hour	2 hours	3 hours	4 hours	6 hours	8 hours	12 hours	24 hours	48 hours
Boone		Qal	210								38	
Bourbon	May 26, 1954	Ocy	41	23								
Boyle		Ol	50									[1] 8.3
Campbell	Oct. 19, 1951	Qal	505				[2] 35					
Do	June 13, 1952	Qal	525				[2] 31					
Do	July 13, 1954	Qal	310				19					
Do	Aug. 3, 1951	Qal	498				[2] 87					
Do	Sept. 4, 1952	Qal	475				77					
Do	Nov. 25, 1953	Qal	348				[2] 64					
Do	Sept. 10, 1954	Qal	310	57	56							
Carroll	1945	Qal	600							[3] 27		
Do	Sept. 9, 1954	Qal	520		26							
Fayette	June 3, 1954	Ocy	65				7.3		6.0	5.2	3.7	3.0
Do	June 8, 1954	Ocy	280				3.9			3.8		
Do	Sept. 29, 1954	Ocy	150		1.9		1.7	1.6				
Do	Sept. 30, 1954	Ocy	213	1.8	1.4		1.3					
Do	June 17, 1954	Ocy	24		.4		.4		.4	.4	.4	
Do	June 6, 1954	Ocy	310		9.0		7.6		6.7			
Do	June 13, 1954	Ocy	67		8.8		7.4		6.2	5.6	[4] 5.2	
Do	Sept. 28, 1954	Ocy	213	21	20							
Do	Sept. 30, 1954	Ocy	213	14	13		11	11				
Do	Oct. 7, 1954	Ocy	82	7.8	6.8							
Do	Aug. 9, 1953	Ol	15		6.9							
Gallatin	Sept. 9, 1954	Qal	250	[5] 21								
Garrard	Oct. 12, 1954	Om	22		17							
Harrison	Oct. 15, 1954	Ol	25	1.3	1.3	1.3						
Do	1950	Ol	150							[6] 21		
Jefferson	Oct. 22, 1946	Qal	1,110	38	38	38	38	38	38	38	38	[7] 38
Do	Aug. 10, 1953	Qal	609			38	38	38		37	36	[8] 32
Jessamine	Oct. 13, 1954	Ol	60	4.7	4.2							
Kenton	Aug. 20, 1954	Qal	32	7.1	7.0	6.9	6.8	6.9	6.9	6.9	6.6	
Lewis	Sept. 14, 1954	Qal	83	[9] 26								
Mason		Qal	125				8.3					
Nelson	June 24, 1939	Om	30	2.3	2.3	2.1	2.0	2.0	1.8	1.6	.9	
Do	Oct. 12, 1954	Om	20	2.1								
Do	June 24, 1939	Om	25	2.5	2.0	1.8	1.7	1.6	1.5	1.7	.9	
Do	do	Om	8	1.1	.9	.7	.6	.5	.5	.4	.3	
Do	do	Om	25	5.2	4.5	4.4	3.3	3.2	2.9	2.4	.7	
Do	do	S	5		.1							
Powell	1934	Qal	50							[4] 1.7		
Robertson	May 25, 1954	Ol	35	[9] 19								
Woodford	Oct. 1, 1954	Ol	75	20	14							

[1] 54 hr.
[2] 5 hr.
[3] 13 hr.
[4] 14 hr.
[5] 1.5 hr.
[6] 16 hr.
[7] 240 hr.
[8] 234 hr.
[9] 0.5 hr.

TABLE 2.—*Spring-discharge measurements, in gallons per minute*

[Aquifer: Ot, Tyrone limestone; Ob, Benson limestone; Ol, Lexington group; Sb, Brassfield limestone; Sla, Laurel dolomite]

County	Aquifer	Spring 1947	Fall 1953	Spring 1954	Fall 1954	Fall 1955
Bath	Sb				2	2
Fayette	Ol	3, 460	95		924	40
Do	Ol	185	24		50	48
Do	Ol	804	82		145	57
Jessamine	Ot			428	105	43
Do	Ot			125		4
Do	Ob			46		
Nelson	Sla				4	
Do	Sla				1	
Scott	Ol	1, 350	8		23	20
Do	Ol			73		
Woodford	Ol				457	359
Do	Ol				12	1

Exceptions to this relation are found: (1) In areas where the original subsurface drainage pattern has been altered by piracy or ponding. Such areas constitute a small part of the Blue Grass region; they are generally underlain by rocks of relatively uniform high solubility; (2) In areas where topographic highs are underlain by rocks that are significantly more soluble than the rocks beneath adjacent topographic lows. Such areas normally have springs on hillsides near the contact of rocks of different solubilities. The water held up in the soluble zone may be discharged so rapidly through the springs that during dry periods this zone may contain little water.

In most places, solution openings are more extensively developed beneath the valleys than beneath the ridges. Therefore, more of the wells drilled in valleys are successful than those drilled on the ridgetops. Plate 2 shows the relation of items of well data gathered in the inventory. For example: Of 250 wells in bedrock in valley bottoms, only 16, or 6 percent, were inadequate for domestic use, whereas 19, or 35 percent, of 54 wells on hilltops were inadequate for domestic use.

In most of the Blue Grass region, the area of recharge for any well is confined to the surface area that drains to the site of the well. Exceptions are found in a small part of the region underlain by thick limestone where large solution channels may conduct water in directions other than the direction of the surface drainage. In those areas, where underground drainage does not accord with surface drainage, it may be difficult to determine the course and direction of movement of ground water. However, in most places alinement of sinkholes or depressions on the surface indicates the alinement of underground watercourses, but not the direction of flow.

FAVORABLE AND UNFAVORABLE CONDITIONS FOR OBTAINING GROUND WATER

Large supplies of ground water can be obtained in many places from thick deposits of alluvium in the Ohio River valley. For the largest yield, wells should be located near the river, as much of the recharge to the alluvial aquifer is from the river and because highly mineralized water has been found in some wells drilled near the valley walls.

The alluvium of the Kentucky River and Licking River valleys, although generally finer grained than that of the Ohio River valley, contains some lenses of coarse sand and gravel. Adequate domestic supplies can be obtained generally in the lower reaches of these valleys. Coarse sand or gravel may yield as much as several hundred gallons per minute in places.

The most favorable localities for obtaining ground water in the bedrock are those where thick limestone beds containing little or no shale occur at and below stream level. Parts of the High Bridge and Lexington groups and the Cynthiana formation of the Inner Blue Grass and the limestone of Silurian and Devonian age of the western part of the Outer Blue Grass meet these conditions. Wells are less successful where shale, bentonite, or relatively insoluble limestone occurs at shallow depths. Most wells are successful where thick pure limestone underlies broad ridges or uplands.

Where bedrock consists of alternating relatively thin limestone and shale beds, the chance of obtaining an adequate ground-water supply is considerably decreased. Parts of the Cynthiana formation and Eden group and the Maysville and Richmond groups are characterized by rocks of this type.

In areas where limestone is underlain by relatively impermeable rocks that inhibit deeper percolation of water, solution has been concentrated at the base of the limestone, resulting in lateral extension and enlargement of solution channels above the impermeable rock. Most wells that penetrate thick pure limestone beds before reaching shale will be successful, except near valleys where the limestone is drained. Many of the large springs of the region issue at such horizons. In areas where limestone is overlain by shale, little recharge is available to the limestone, and there has been little or no solutional enlargement of existing openings. Very few wells will obtain an adequate or dependable water supply beneath a layer of shale.

In areas underlain by shale, water reaching the water table moves at shallow depths in weathered shale to points of lower elevation. The resistance of the shale to disintegration by water is relatively uniform, and the water is directed by the form of the surface on which it flows, thus being concentrated beneath valleys or other topographic depressions. Some wells drilled in valleys underlain by shale will be successful. Most wells on hillsides and ridgetops underlain by shale will be failures.

Rocks of Mississippian and Pennsylvanian age, composed of limestone, siltstone, shale, and sandstone, form many of the knobs and most of the escarpment surrounding the Blue Grass region. Little water is available to wells in rocks of those types where they occur on the sides or tops of the knobs or where they are exposed on the face and steep hillsides of the escarpment. Where they underlie broad ridges, uplands, or broad stream valleys, they may yield adequate domestic supplies.

The occurrence of ground water in geologic units is described on the generalized columnar sections that accompany the geologic and ground-water-availability maps in U.S. Geological Survey Hydrologic Investigations Atlases HA 15–25 (see Palmquist and Hall, 1960a–f; and Hall and Palmquist, 1960a–e).

METHODS OF OBTAINING GROUND WATER

SPRINGS

Springs have played an important role in the development of the Blue Grass region. Many towns, distilleries, and farm homes were located to be near perennial springs. In recent years the yield of many of the springs has become inadequate for current needs, owing to excessive demand, improper development, or lack of maintenance.

Although springs still are used by a few distilleries and some towns, the most widespread use is for stock and domestic water supply. Many springs throughout the region are not utilized. With proper development they would provide additional and, in many places, much needed supplies of water.

Springs can be developed by a number of methods, and each spring requires a unique installation to suit the local environment. The most important factor in development is that the flow of water from the mouth of the spring must be unimpeded. Damming or ponding of the water to a level higher than the mouth will allow sediment to collect and may clog the spring. To prevent clogging, the outlet of any pool or basin must be lower than the lowest point of the natural outlet.

An undeveloped spring should be cleaned of all debris and sediment around the mouth to insure a free flow of water. Surface drainage should be diverted from the spring to avoid contamination and turbidity. The collecting basin or sump should be cleaned periodically to remove sediment. The installation should be housed in a weather- and animal-proof structure. In spite of precautions taken at the mouths of springs, the water may become polluted. All spring water used for human consumption, therefore, should be examined periodically for evidence of organic pollution.

Although the minimum flow of many small springs is less than the pumping rate of most small domestic power pumps and often has been considered as inadequate for a perennial water supply, a spring that flows at the rate of only half a gallon per minute will yield 720 gpd, which is adequate for a household. However, in order to permit utilizing such a small spring, the storage of water should be increased to equal the daily water demand.

DUG WELLS

Dug wells have been an important source of ground water in many areas, but many now are abandoned or used as cisterns.

Dug wells have certain advantages over drilled wells where ground water is difficult to obtain in quantity and where the water table is not much more than 30 feet below the surface. Their relatively large diameter, 2 to 4 feet, offers a relatively large storage capacity and a large infiltration area. On ridgetops where the ground water occurs mainly in the soil and in the underlying weathered-rock zone on top of relatively impermeable bedrock, water is yielded more readily to dug wells than to drilled wells. However, dug wells are likely to go dry in dry weather because they commonly extend only a short distance below the water table, and they are particularly susceptible to pollution.

Most dug wells have been excavated by hand to bedrock. Some extend into bedrock a few feet to provide additional storage capacity. Wells usually are lined with masonry, tile, or concrete pipe to prevent caving. To prevent contamination from the surface, the land should slope in all directions from the well, and the well should be watertight from above the land surface to the water level.

Few of the dug wells inventoried yield more than several hundred gallons per day, and many go dry, or nearly so, in dry weather. Many dug wells are used as cisterns by adding water from eaves troughs or water hauled by truck. Much of this water is lost by seepage. Only when a well is sealed on sides and bottom will it serve as a cistern, and then, of course, it cannot function as a well.

DRILLED WELLS

Drilled wells are the most common type in most of the Blue Grass region. All those inventoried were drilled by the cable-tool method, which consists principally of repeatedly raising and dropping a cutting tool or bit suspended from a tripod or derrick.

Wells in bedrock are usually cased to rock with metal pipe 6 or 8 inches in diameter. Seepage and pollution are minimized by firmly sealing the casing in the bedrock. Cable-tool drilling in rock produces a mud or slurry of pulverized rock mixed with water which is bailed out of the well repeatedly as drilling progresses. The action of the bit forces some of the mud into the openings in the wall of the well and may partially seal the sides. This material should be removed to allow water to enter freely; development may be by brushing, surging, or bailing. Yields from properly developed wells are greater than from undeveloped wells. The use of chemicals, dry ice, or blasting may further increase the yield of some wells.

Wells ending in unconsolidated material are usually finished with a screen extending below the casing and are developed by pumping, surging, and backwashing to remove fine-grained materials from around the screen. Large-capacity tubular wells in the alluvium of the Ohio River valley are as much as 18 inches in diameter. Many are constructed with a gravel envelope around the screen, and one is reported to yield 1,400 gpm. Installations of multiple horizontal wells yield as much as 3,500 gpm from a single caisson in the Blue Grass region. Elsewhere, as stated previously, yields as high as 9,000 gpm have been reported.

Multistage electric-turbine pumps are used in most large-capacity wells. Most small-diameter domestic-supply wells are equipped with electric jet pumps. Centrifugal or other suction pumps are used on wells in which the water level rarely drops below the limit of suction.

Jetted and driven wells are not common in the Blue Grass region. They are used in areas of unconsolidated material where the water is at relatively shallow depths.

QUALITY OF WATER

The quality of ground water in the Blue Grass region varies considerably from place to place and is determined by its geologic source. Because drilled wells generally are deeper, water from drilled wells is generally more highly mineralized than that from dug wells. Water from springs is generally less mineralized than that from dug wells.

The range in concentration of various constituents, in parts per million (ppm), is given in table 3. A series of bar diagrams based on median values of the chemical analyses, in equivalents per million, by aquifers as defined in the present report is presented in plate 3. Equivalents per million, an expression of concentration in terms of the combining or reacting capacity of the ions, is the number of unit equivalent weights of an ion contained in 1 million unit weights of water. One equivalent of sodium (22.997 ppm) for example, will combine exactly with one equivalent of chloride (35.457 ppm) to form the compound sodium chloride (common salt). Median values were used in plate 3 in preference to averages because a few of the samples have a very high dissolved-solids content and are not representative of the majority of samples. The amount of magnesium plus calcium, in equivalents per million, was calculated from the hardness as calcium carbonate in the partial analyses. Sodium plus potassium was obtained by subtracting the amount of magnesium plus calcium from the total anions, because in natural water the sum of cations (principally calcium, magnesium, sodium, and potassium) in equivalents per million is equal to the sum of the anions (principally bicarbonate, sulfate, and chloride) in equivalents per million.

Water from most drilled wells is of the calcium bicarbonate type and has a hardness of 250 to 350 ppm. The principal exception is water from drilled wells in rocks of the Lower Ordovician series, which is predominantly sodium chloride water. Water of the calcium bicarbonate type is characterized by a predominance of calcium cations and bicarbonate anions; water of the sodium chloride type is characterized by a predominance of sodium cations and chloride anions. The analyses of water from dug wells typically show calcium bicarbonate water having a hardness of 250 to 350 ppm but much less sodium chloride than the drilled wells. Spring water is also of the calcium bicarbonate type and has a hardness ranging from about 200 to 250 ppm, and a lower dissolved-solids content than water from wells. Spring water from the Eden group is harder (median, 380 ppm) than the rest and contains more sodium. Water from Devonian rocks has a rather high sodium sulfate content. Nitrate is of consequence only in dug wells and springs, and only in water from dug wells in areas underlain by rocks of the Maysville group does the median approach 45 ppm. However, several analyses show a nitrate content in excess of 45 ppm, above which the nitrate concentration may be regarded as making the water unsafe for infant feeding (Comly, 1945).

The content of silica, iron, and manganese is not shown on the bar diagrams. Median values of silica range from 6 to 17 ppm. Manganese determinations were not made in most of the analyses, and manganese was detected in only some of the samples tested. The iron or iron-plus-manganese content has a median value of about 0.3 ppm in most of the drilled and dug wells, and more than half the analyses show undesirable amounts of iron or manganese or both. Less than half the analyses of spring water show undesirable amounts of iron or manganese.

The pH was determined in about a third of the analyses. Most of the samples had a pH greater than 7, indicating neutral to mildly alkaline water.

Fluoride is combined with chloride in the bar diagrams. Water from rocks of the Lower Ordovician series has a median fluoride content of 3.2 ppm and a range of from 1.8 to 4.0 ppm. The median content of fluoride in water from all other aquifers is less than 1.5 ppm; however, many individual analyses show more than 1.5 ppm of fluoride, and water from one spring in the Lexington group contained 15 ppm of fluoride. It has been shown (Maier, 1950) that about 1 ppm of fluoride in water is sufficient to decrease the incidence of dental caries (decay of teeth) when the water is consumed by children whose teeth are developing. Fluorosis, or mottling of the tooth enamel, may become evident if, during the period of tooth development, the water consumed contains more than about 1.5 ppm of fluoride.

The two most common constituents that make water in the Blue Grass region objectionable for domestic use are common salt and hydrogen sulfide. Both salt and hydrogen sulfide occur in water from some wells in the alluvium, but they are present more commonly in water from wells and springs in the bedrock. Hydrogen sulfide was detected by its odor at the time the wells were inventoried in about a fifth of the drilled wells, and salt in undesirable amounts in about an eighth.

Table 3 gives maximum, minimum, and average values of chemical analyses of 276 samples of water. Table 4 shows the significance of dissolved mineral constituents and physical properties of natural waters.

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TABLE 3.—*Summary of chemical analyses of ground waters, by aquifers*

[Dissolved constituents in parts per million. Source: Dr, drilled wells; Du, dug wells; Sp, spring. (Analyses by U.S. Geological Survey)]

Geologic unit	Source		Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Hardness as $CaCO_3$		Specific conductance at 25° C (micromhos)	pH
																	Total	Noncarbonate		
Lower Ordovician rocks.	Dr	Number of analyses.	2	4	1	2	2	2	2	4	......	4	4	3	3	2	4	......	4	2
		Maximum	7	2.5		308	75	1,400	32	424	......	820	5,800	4.0	0.8	4,346	1,088	......	7,280	7.6
		Average	6	1.31	0.50	223	69	707	17.7	318	......	318	2,034	2.7	0.3	2,883	745	......	6,775	----
		Minimum	5	0.29		138	64	15	3.4	256	......	0.4	10	1.8	0.1	1,421	205	......	1,130	7.6
High Bridge group.	Dr	Number of analyses.	1	4	1	1	1	1	1	4	......	4	4	2	4	1	4	1	4	1
		Maximum	......	11						306	......	30	12	0.2	16		264		526	
		Average	11	2.92	0.36	86	12	8.5	2.2	272	......	20	5.4	0.1	11.7	307	252	13	489	7.4
		Minimum	......	0.13						240	......	12	3.0	0.1	5.0		250		466	
	Sp	Number of analyses.	......	2	......	......	......	......	......	2	......	2	2	......	2	......	2	......	2	----
		Maximum	......	0.40	......	......	......	......	......	284	......	21	6.2	......	19	......	261	......	488	----
		Average	......	0.35	......	......	......	......	......	228	......	16	4.6	......	18	......	222	......	421	----
		Minimum	......	0.31	......	......	......	......	......	172	......	12	3.0	......	17	......	184	......	354	----
Lexington group	Dr	Number of analyses.	12	25	4	12	12	12	12	25	......	25	25	23	23	12	25	11	25	12
		Maximum	10	10	0.48	117	38	176	9.6	438	......	364	14,000	1.8	55	795	4,180	80	34,390	8.1
		Average	7.6	0.85	0.39	79	15.5	25.9	3.1	278	......	62	619	0.5	6.2	354	422	46	2,012	----
		Minimum	4.4	0.03	0.28	46	7.3	3.5	0.7	82	......	17	5	0.1	0.1	183	124	29	173	7.0
	Du	Number of analyses.	1	2	1	1	1	1	1	2	1	2	2	2	2	1	2	1	2	1
		Maximum		1.0						264		48	7.5	0.2	15		266		497	
		Average	6.8	0.63	0.00	94	7.8	5.0	3.1	262	0	34	4.4	0.1	13.5	310	253	50	477	7.2
		Minimum		0.27						260		21	1.4	0.1	12		240		458	
	Sp	Number of analyses.	6	14	......	7	7	6	6	14	1	14	14	13	14	6	14	6	14	7
		Maximum	9.1	1.4	......	90	8.7	4.9	1.6	280	......	50	21	15	43	302	276	60	620	8.0
		Average	7.2	0.33	......	79	6	3.1	1.0	232	......	26	7.9	1.3	15	259	231	36	460	----
		Minimum	4.1	0.01	......	65	2.4	1.6	0.5	152	......	7	2.2	0.1	4	208	172	27	315	7.2

Cynthiana formation.	Dr	Number of analyses.	5	20	2	5	5	5	5	20	----	20	20	17	18	5	20	2	20	5
		Maximum	13	25	0.98	100	31	60	4.2	716	----	1,290	1,186	2.8	41	565	1,470	19	4,550	7.9
		Average	9.7	2.7	0.59	75	28	36	3.4	385	----	126.3	214	0.8	5.8	429	385	19	1,435	----
		Minimum	7.8	0.06	0.21	58	22	21	2.5	200	----	7.2	13	0.1	0.1	325	140	19	510	6.7
	Du	Number of analyses.	----	8	----	----	----	----	----	8	----	8	8	7	8	----	8	----	8	----
		Maximum	----	2.4	----	----	----	----	----	458	----	190	187	0.7	102	----	442	----	1,380	----
		Average	----	1.08	----	----	----	----	----	294	----	91	59	0.3	47.1	----	322	----	886	----
		Minimum	----	0.07	----	----	----	----	----	212	----	26	7	0.1	0.2	----	108	----	457	----
	Sp	Number of analyses.	2	6	1	2	2	2	2	6	----	6	6	3	4	2	6	2	6	2
		Maximum	8.3	0.55		67	11	8.0	2.2	468	----	670	6,500	1.6	38	255	2,240	47	18,800	8.0
		Average	6.9	0.30	0.04	62	7.4	5.0	1.6	234	----	101	1,095.6	1.1	18	228	524	45	3,150	----
		Minimum	5.6	0.08		58	3.9	2.0	1.0	143	----	9.1	1.6	.2	4	201	138	44	283	8.0
Eden group	Dr	Number of analyses.	----	6	----	----	----	----	----	6	----	6	6	3	6	----	6	----	6	----
		Maximum	----	2.7	----	----	----	----	----	446	----	351	1,895	0.8	18	----	621	----	6,028	----
		Average	----	1.2	----	----	----	----	----	314	----	145	607	0.5	5.3	----	342	----	2,658	----
		Minimum	----	0.2	----	----	----	----	----	258	----	1	91	0.1	0.1	----	22	----	1,480	----
	Du	Number of analyses.	1	13	1	1	1	1	1	13	1	13	13	11	13	1	13	1	13	1
		Maximum		2.1						504		522	385	0.5	42		980		2,200	
		Average	10	0.63	0.38	131	31	34	3.7	305	0	131	62	0.4	18.1	638	330	122	893	7.7
		Minimum		0.02						92		25	3	0.1	3.9		110		251	
	Sp	Number of analyses.	----	3	----	----	----	----	----	3	----	3	3	3	2	----	3	----	3	----
		Maximum	----	3	----	----	----	----	----	474	----	157	56	0.4	9.8	----	470	----	885	----
		Average	----	1.49	----	----	----	----	----	374	----	635	23.3	0.3	4	----	365	----	741	----
		Minimum	----	0.09	----	----	----	----	----	238	----	4.5	5.5	0.2	2.3	----	239	----	479	----
Garrard sandstone of Eden group.	Du	(1)	----	0.64	----	----	----	----	----	355	0	144	55	0.0	56	----	----	----	1,050	----
Maysville group	Dr	Number of analyses.	4	16	2	4	4	3	3	16	----	16	16	9	14	4	16	3	16	4
		Maximum	9.4	8.9	0.26	97	35	230	15	428	----	1,086	8,900	1.8	55	761	2,810	117	23.500	7.7
		Average	6.5	1.4	0.17	77	23	124	10.2	275	----	173	900	0.5	19.1	576	506	56	3.081	----
		Minimum	2.4	0.14	0.09	31	12	16	7.4	132	----	3.3	7	0.1	1.2	364	164	8	476	7.2
	Du	Number of analyses.	----	11	----	----	----	----	----	11	----	11	11	8	11	----	11	----	11	----
		Maximum	----	2.1	----	----	----	----	----	346	----	164	73	0.4	209	----	489	----	1,160	----
		Average	----	0.41	----	----	----	----	----	241	----	79	222	0.2	587	----	354	----	688	----
		Minimum	----	0.01	----	----	----	----	----	168	----	12	1.8	0.1	4.6	----	157	----	295	----

See footnote at end of table.

TABLE 3.—*Summary of chemical analyses of ground waters by aquifers*—Continued

[Dissolved constituents in parts per million. Source: Dr, drilled wells; Du, dug wells; Sp, spring. (Analyses by U.S. Geological Survey)]

Geologic unit	Source		Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Hardness as $CaCO_3$: Total	Hardness as $CaCO_3$: Noncarbonate	Specific conductance at 25° C (micromhos)	pH
Maysville group	Sp	Number of analyses.	----	9	----	----	----	----	----	9	----	9	9	5	----	----	9	----	9	----
		Maximum	----	1.44	----	----	----	----	----	396	----	56	24	0.2	----	----	344	----	678	----
		Average	----	0.64	----	----	----	----	----	260	----	27	7	0.1	----	----	234	----	461	----
		Minimum	----	0.06	----	----	----	----	----	102	----	10	2.4	0.1	----	----	10	----	287	----
Richmond group	Dr	Number of analyses.	1	10	1	1	1	1	1	10	1	10	10	9	9	1	10	1	10	1
		Maximum		9.5						435		110	2,225	1.4	51		430		8,050	
		Average	8.7	2.35	0.00	61	31	3.6	0.9	313	0	48.4	337	0.5	8.5	290	307	43	1,662	7.9
		Minimum		0.15						158		1.4	1.8	0.1	0.1		140		272	
	Du	Number of analysis	----	8	----	----	----	----	----	8	----	8	8	6	8	----	8	----	8	----
		Maximum	----	3.9	----	----	----	----	----	410	----	87	47	0.3	110	----	472	----	866	----
		Average	----	0.96	----	----	----	----	----	276	----	58	247	0.1	30	----	318	----	650	----
		Minimum	----	0.13	----	----	----	----	----	158	----	28	6.5	0.1	0.6	----	173	----	357	----
	Sp	Number of analyses.	2	5	----	2	2	2	2	5	----	5	5	4	5	2	5	----	5	2
		Maximum	12	0.88	----	58	38	6.5	2.4	324	----	49	12	0.1	36	335	336	8	634	7.9
		Average	8.3	0.36	----	44	26	6.2	1.6	214	----	20	8.7	0.1	12.3	244	219	8	422	----
		Minimum	4.6	0.16	----	30	14	5.9	0.8	136	----	1.7	3	0.1	1.6	153	134	8	267	7.6
Silurian rocks	Dr	Number of analyses.	1	10	1	1	1	1	1	10	1	10	10	6	9	1	10	1	10	1
		Maximum		3.3						460		215	890	0.7	16		485		3,240	
		Average	7.5	1.27	0.00	37	30	1.2	0.6	295	0	69	99.6	0.3	5.8	216	309	32	883	7.9
		Minimum		0.11						134		9.5	1.6	0.1	0.3		157		393	
	Sp	Number of analyses.	4	11	1	4	4	4	4	12	----	12	12	9	12	4	12	4	12	4
		Maximum	11	2.5		61	34	5.2	1.2	366	----	215	11	0.2	43	312	418	52	772	7.9
		Average	10.2	0.53	0.24	41	23	2.0	8.5	23	----	35	42.5	0.1	15.6	210	219	29	451	----
		Minimum	7.5	0.08		29	16	1.4	0.3	9	----	1.5	1.2	0.1	0.3	140	9	3	180	7.3

Devonian rocks	Dr	Number of analyses.	----	7	----	----	----	----	----	7	----	7	7	7	6	----	7	----	7	----
		Maximum	----	28	----	----	----	----	----	806	----	293	1,087	1.1	24	----	302	----	4,490	----
		Average	----	5.12	----	----	----	----	----	344	----	79	195.3	0.3	5.3	----	168	----	1.270	----
		Minimum	----	0.01	----	----	----	----	----	2	----	1.4	6.4	0.1	0.1	----	66	----	252	----
	Du	Number of analyses.	----	5	----	----	----	----	----	5	1	5	5	2	5	----	5	----	5	----
		Maximum	----	1.9	----	----	----	----	----	376	----	84	32	0.1	22	----	376	----	787	----
		Average	----	0.92	----	----	----	----	----	236	14	53	17	0.1	8	----	267	----	503	----
		Minimum	----	0.23	----	----	----	----	----	28	----	24	2	0.1	0.2	----	116	----	106	----
	Sp	Number of analyses.	1	3	----	1	1	1	1	2	1	3	3	3	3	1	3	1	3	1
		Maximum	----	0.5	----	----	----	----	----	442	----	157	20	0.2	26	----	286	----	594	----
		Average	11	0.3	----	66	31	19	3.8	363	0	94	109	0.2	10	356	228	59	511	7.3
		Minimum	----	0.05	----	----	----	----	----	284	----	47	5.8	0.1	1.6	----	106	----	389	----
Mississippian rocks.	Dr	Number of analyses.	----	6	----	----	----	----	----	6	----	6	6	6	6	----	6	----	6	----
		Maximum	----	30	----	----	----	----	----	500	----	838	1.120	0.5	7.2	----	1,212	----	4,040	----
		Average	----	6.16	----	----	----	----	----	243	----	157	354	0.3	1.4	----	311	----	1,691	----
		Minimum	----	0.25	----	----	----	----	----	91	----	4.7	10	0.1	0.1	----	97	----	277	----
	Du	Number of analyse.	----	7	----	----	----	----	----	7	----	7	7	2	7	----	7	----	7	----
		Maximum	----	0.52	----	----	----	----	----	306	----	30	87	0.1	44	----	262	----	617	----
		Average	----	0.28	----	----	----	----	----	101	----	223	191	0.1	124	----	101	----	2,743	----
		Minimum	----	0.07	----	----	----	----	----	8	----	9.2	3.5	0.1	0.2	----	20	----	68.7	----
	Sp	Number of analyses.	2	7	----	2	2	2	2	6	----	7	7	2	7	2	7	1	7	2
		Maximum	7.6	13	----	40	3.4	1.0	1.2	232	----	180	9.5	0.2	5	126	197		379	7.3
		Average	7	2.04	----	27	2.2	0.8	0.7	124	----	35	3.9	0.2	2.3	89	111	1	252	----
		Minimum	6.5	0.09	----	14	1.0	0.5	0.2	11	----	2	1.0	0.1	0.2	52	15		76.2	6.5
Glacial sand	Sp	(1)	17	0.23	0.00	11	2.4	9.9	2.6	30	0	11	3.5	1.8	24	98	38	13	144	6.7
Quaternay alluvium (other than Ohio River).	Dr	Number of analyses.	6	12	4	6	6	5	5	12	----	12	12	10	10	6	12	3	12	6
		Maximum	19	10	1.1	136	54	64	1.9	742	----	146	1,575	3.9	199	1,520	570	59	5,190	7.7
		Average	12.2	7.9	0.41	87	27.6	30	1.4	397	----	36	229.5	0.8	26.8	627	335	41	1,277	----
		Minimum	2	0.25	0.04	19	2.9	3	0.7	164	----	2.1	5.5	0.1	0.1	246	60	18	422	7.3
	Dr	Number of analyses.	24	39	9	28	28	18	18	39	1	39	39	24	32	23	38	22	35	29
		Maximum	20	11	1.4	246	91	236	21	683		336	720	1.4	61	1,740	940	581	3.080	8.1
		Average	13.4	2.97	0.63	129	41.2	32.7	3.84	417	9	101.1	76.2	0.3	10.8	393	433	107	926	----
		Minimum	8.2	0.05	0.36	68	11	2.5	0.9	209		6.6	2.2	0.1	0.2	240	202	26	404	6.8

[1] 1 sample.

TABLE 4.—*Significance of dissolved mineral constituents and physical properties of natural waters*

Constituent or physical property	Source or cause	Significance
Silica (SiO_2)	Dissolved from practically all rocks and soils, usually in small amounts from 1 to 30 ppm. High concentrations, as much as 100 ppm, generally occur in highly alkaline waters.	Forms hard scale in pipes and boilers. Carried over in steam of high-pressure boilers to form deposits on blades of steam turbines. Inhibits deterioration of zeolite-type water softeners.
Iron (Fe)	Dissolved from practically all rocks and soils. May be derived also from iron pipes, pumps, and other equipment. More than 1 or 2 ppm of soluble iron in surface water usually indicates acid wastes from mine drainage or other sources.	On exposure to air, iron in ground water oxidizes to reddish-brown sediment. More than about 0.3 ppm stains laundry and utensils reddish-brown. Objectionable for food processing, beverages, dyeing, bleaching, ice manufacture, brewing, and other processes. Public Health Service drinking-water standards recommend that iron and manganese together should not exceed 0.3 ppm. Larger quantities cause unpleasant taste and favor growth of iron bacteria.
Manganese (Mn)	Dissolved from some rocks and soils. Not so common as iron. Large quantities often associated with high iron content and with acid waters.	Same objectionable features as iron. Causes dark-brown or black stain. Public Health Service drinking-water standards recommend that iron and manganese together should not exceed 0.3 ppm.
Calcium (Ca) and magnesium (Mg).	Dissolved from practically all soils and rocks, but especially from limestone, dolomite, and gypsum. Calcium and magnesium are found in large quantities in some brines. Magnesium is present in large quantities in sea water.	Cause most of the hardness and scale-forming properties of water; soap consuming. (See "Hardness as $CaCO_3$.") Waters low in calcium and magnesium desired in electroplating, tanning, dyeing, and textile manufacturing.
Sodium (Na) and potassium (K).	Dissolved from practically all rocks and soils. Found also in ancient brines, sea water, some industrial brines, and sewage.	Large amounts, in combination with chloride, give a salty taste. Moderate quantities have little effect on the usefulness of water for most purposes. Sodium salts may cause foaming in steam boilers and a high sodium ratio may limit the use of water for irrigation.
Bicarbonate (HCO_3) and carbonate (CO_3).	Action of carbon dioxide in water on carbonate rocks such as limestone and dolomite.	Bicarbonate and carbonate produce alkalinity. Bicarbonates of calcium and magnesium decompose in steam boilers and hot-water facilities to form scale and release corrosive carbon-dioxide gas. In combination with calcium and magnesium cause carbonate hardness.

Sulfate (SO_4)	Dissolved from rocks and soils containing gypsum, iron sulfides, and other sulfur compounds. Usually present in mine waters and in some industrial wastes.	Sulfate in water containing calcium forms hard scale in steam boilers. In large amounts, sulfate in combination with other ions gives bitter taste to water. Some calcium sulfate is considered beneficial in the brewing process. Public Health Service drinking-water standards recommend that the sulfate content should not exceed 250 ppm.
Chloride (Cl)	Dissolved from rocks and soils. Present in sewage and found in large amounts in ancient brines, sea water, and industrial brines.	In large amounts in combination with sodium gives salty taste to drinking water. In large quantities increases the corrosiveness of water. Public Health Service drinking-water standards recommend that the chloride content should not exceed 250 ppm.
Fluoride (F)	Dissolved in small to minute quantities from most rocks and soils.	Fluoride in drinking water reduces the incidence of tooth decay when the water is consumed during the period of enamel calcification. However, it may cause mottling of the enamel, depending on the concentration of fluoride, age and susceptibility of the individual child, and amount of drinking water consumed. Public Health Service drinking-water standards set a limit of 1.5 ppm.
Nitrate (NO_3)	Decaying organic matter, sewage, and nitrates in soil.	Concentrations much greater than the local average may suggest pollution. There is evidence that more than about 45 ppm of nitrate (NO_3) may cause a type of infant cyanosis, sometimes fatal. Water of high nitrate content should not be used in baby feeding. Nitrate has been shown to be helpful in reducing intercrystalline cracking of boiler steel. It encourages growth of algae and other organisms which produce undesirable tastes and odors.
Dissolved solids	Chiefly mineral constituents dissolved from rocks and soils. Includes any organic matter and some water of crystallization.	Public Health Service drinking-water standards recommend that the dissolved solids should not exceed 500 ppm. Waters containing more than 1,000 ppm of dissolved solids are unsuitable for many purposes.
Hardness as $CaCO_3$	In most waters nearly all the hardness is due to calcium and magnesium. Free acid and all the metallic cations other than the alkali metals also cause hardness.	Causes consumption of soap before a lather will form. Causes deposition of soap curd on bathtubs. Hard water forms scale in boilers, water heaters, and pipes. Hardness equivalent to the bicarbonate and carbonate is called carbonate hardness. Any hardness in excess of this is called noncarbonate hardness. Waters having a hardness up to 60 ppm are considered soft; 61 to 120 ppm, moderately hard; 121 to 200 ppm, hard; more than 200 ppm, very hard.

TABLE 4.—*Significance of dissolved mineral constituents and physical properties of natural waters*—Continued

Constituent or physical property	Source or cause	Significance
Specific conductance (micromhos at 25° C).	Ionization of dissolved mineral matter.	Specific conductance is a measure of the capacity of the water to conduct an electric current; varies with concentration and degree of ionization of the constituents. Varies with temperature; reported at 25° C.
Hydrogen-ion concentration (expressed as *p*H).	Acids, acid-generating salts, and free carbon dioxide lower the pH. Carbonates, bicarbonates, hydroxides, phosphates, silicates, and borates raise the pH.	A pH of 7.0 indicates neutrality of a solution. Values higher than 7.0 denote increasing alkalinity; values lower than 7.0 indicate increasing acidity. The pH is a measure of the activity of the hydrogen ions. Corrosiveness of water generally increases with decreasing pH. However, excessively alkaline waters also may attack metals.
Temperature		Affects usefulness of water for many purposes. For most uses, a water of uniformly low temperature is desired. Shallow wells show some seasonal fluctuation in water temperature. Ground waters from moderate depths usually are nearly constant in temperature, which is near the mean annual air temperature of the area. In very deep wells the water temperature generally increases about 1° F with each 50 to 100 feet of increased depth. Seasonal fluctuations in temperatures of surface waters are comparatively large, depending on the depth of water, but do not reach the extremes of air temperature.

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