Occurrence of Fresh Water in The Lee Formation in Parts of Elliott, Johnson, Lawrence, Magoffin, and Morgan Counties, Eastern Coal Field Region, Kentucky

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1867

Prepared in cooperation with the Commonwealth of Kentucky, University of Kentucky, Kentucky Geological Survey

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By HERBERT T. HOPKINS

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OCCURRENCE OF FRESH WATER IN THE LEE FORMATION IN PARTS OF ELLIOTT, JOHNSON, LAWRENCE, MAGOFFIN, AND MORGAN COUNTIES, EASTERN COAL FIELD REGION, KENTUCKY

By Herbert T. Hopkins

ABSTRACT

This report describes the occurrence of fresh water and its relationship to saline water in the Lee Formation of Pennsylvanian age underlying parts of Elliott, Johnson, Lawrence, Magoffin, and Morgan Counties in the north-central part of the Eastern Coal Field region of Kentucky.

The study is the second in a series of saline-water investigations in Kentucky, and is the result of the initial study in this series, a statewide reconnaissance investigation of the fresh-saline water interface, which showed the presence of fresh water at depth in the study area.

The presence of fresh water at depth is the result of flushing by fresh water (precipitation) over the past 270 million years. Precipitation entered the Lee Formation through a series of outcrops on structural highs, and discharged through a series of outcrops in the valleys of Paint Creek, Blaine Creek, and Little Sandy River and their tributaries. The outcrops resulted from erosion on the flanks and crest of structural highs such as the Laurel Creek, Mine Fork, and Mudlick domes, and the Irvine-Paint Creek, Blaine Creek, and Little Sandy River faults.

The configuration of the piezometric surface shows the relation between ground-water flow and the geologic features in the study area. A flow-net analysis made for the Paint Creek drainage area, which covers approximately one-third of the study area, indicates that ground-water discharge into Paint Creek from the Lee Formation is about 600,000 gallons per day.

Yields that may be expected from the Lee Formation are 10 to 15 gallons per minute from shallow wells in outcrop areas to 25 gallons per minute or more from fully penetrating wells away from the outcrop areas.

The development of the cone of influence for one well, using a transmissibility of 2,000 gallons per day per foot, and the cumulative effect of the cone of influence of another well 2,000 feet away are simulated. The analysis indicates that a cone of influence around a pumping well penetrating the Lee will spread rapidly and widely in the aquifer.

The quality of water in the Lee Formation is excellent, except for iron which frequently exceeds 0.3 milligrams per liter. Contamination by brines occurs in two distinct ways: by the upward movement of brine through abandoned oil- and gas-test holes drilled to the underlying Mississippian and Devonian rocks, and from above by the downward movement of high chloride water from contaminated surface streams.

The fresh-saline water interface is presented in more detail than in the earlier reconnaissance report, "Fresh-saline water interface map of Kentucky." The presence of the interface within the Lee Formation southeast of the study area is a natural condition, but near the Keaton section of Johnson County and Falcon in Magoffin County it is the result of contamination.

The two important conclusions to be drawn from this study are: (1) Contamination will continue to occur through abandoned oil-test wells, not because present regulations are inadequate, but because they followed by some 30 years the period in which contamination was first introduced into this area, and (2) the Lee Formation, if developed with proper application of its hydrologic properties, will sustain yields of 25 gallons per minute or more of fresh water to individual wells throughout the study area.

INTRODUCTION

This report is the second in a series of reports on saline-water investigations in Kentucky prepared by the U.S. Geological Survey in cooperation with the Kentucky Geological Survey. It describes the occurrence of fresh water and its relation to saline water in the Lee Formation underlying parts of Elliott, Johnson, Lawrence, Magoffin, and Morgan Counties in the north-central part of the Eastern Coal Field region.

The initial study, a reconnaissance investigation of the fresh-saline water interface in Kentucky (Hopkins, 1966), showed that the Lee Formation in this area contained fresh water at depths greater than 600 feet below land surface. The occurrence of fresh water at depth suggests that the potential of the Lee Formation as a fresh-water aquifer is greater than had been realized. In this study the fresh-saline water interface in the Lee Formation is defined in more detail than by Hopkins (1966), with emphasis on the availability, potential yield, and quality of water for future use. These data and the study are especially significant in that the area is part of Appalachia. The study is intended to supplement efforts of State and Federal agencies in redeveloping the area's economy.

Data for this report were taken from the files of the office of the U.S. Geological Survey, Water Resources Division, in Louisville, the office of the Kentucky Geological Survey, in Lexington, and files of drillers and oil and gas companies operating in the study area.

GEOGRAPHY AND ECONOMY

The area of study (fig. 1) covers approximately 490 square miles in the Eastern Coal Field region of Kentucky, and includes parts of Elliott, Johnson, Lawrence, Magoffin, and Morgan Counties.

The topography is characteristic of the Kanawha section of the Appalachian plateau region, with narrow winding ridges and steep

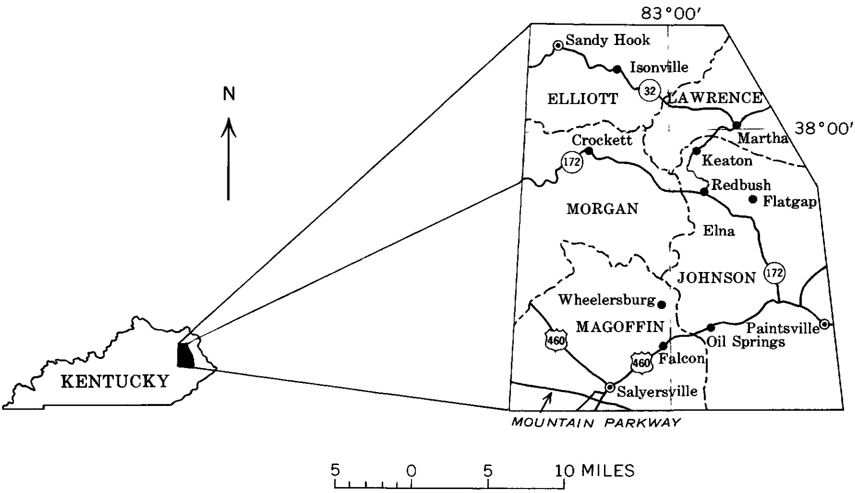

FIGURE 1.—Location of the study area.

valley walls. Ridgetops range from 300 to 600 feet above local valley bottoms.

Flood plains of moderate size have been developed only by the major streams—the Licking River flowing northwest and draining the southern part of the area, the Little Sandy River flowing northeast and draining the northwestern part of the area, Paint Creek flowing southeast and draining the central part of the area, and Levisa Fork flowing due north along the southeastern border and draining the southeastern part of the area.

The economy of the area is based on the production of coal, oil, natural gas, timber, limestone, and water. Farming is done on a subsistence basis with tobacco as the main cash crop. Hillsides formerly cleared and used for grazing are now covered with second growth timber.

In the period 1940–60, U.S. Census figures show a decline in population of 20,500, or 29 percent. This population decline is the result of migration to industrial areas for jobs not available in this area.

In 1963 the Mountain Parkway, a limited-access toll road, was opened from Interstate Highway 64 near Winchester in Clark County, 77 miles west of the study area, to Salyersville in Magoffin County. This road gave the area an accessibility it did not previously have. Proposed improvement of existing highways as part of the Federal Appalachian Regional Development Program will further increase accessibility and enhance the present modest industrial growth. As industrial growth occurs, the need for water for public, industrial, and commercial use will increase.

WATER USE

The major water use in the study area is for municipal supplies, secondary recovery of oil by waterflooding, and domestic supplies.

Salyersville, county seat of Magoffin County, and Sandy Hook, county seat of Elliott County, obtain their municipal supplies from ground water. Paintsville, county seat of Johnson County, and West Liberty, county seat of Morgan County, use surface water for municipal supplies.

Table 1 gives the source of water and the annual pumpage, in gallons per year, for the major water users in the study area.

TABLE 1.—*Annual pumpage, in gallons per year, and source of withdrawals for major water users in the area*

User	Gallons per year	Source	
		Surface water	Ground water
Waterflooding:			
Amax Petroleum	10, 400, 000		Sand of Lee Formation.
Ashland Oil & Refining Co	17, 500, 000		Do.
Cumberland Petroleum	2, 070, 000		Do.
Lobol Oil & Gas Co	6, 600, 000		Do.
Wiser Petroleum Co	11, 400, 000		Do.
Municipal supplies:			
Paintsville	25, 300, 000	Levisa Fork	
Salyersville	19, 800, 000		Sand of Lee Formation.
Sandy Hook	11, 000, 000		Do.
West Liberty	47, 450, 000	Licking River	

At present, 160 million gallons of water are withdrawn annually for public, industrial, and commercial needs within the area. This water, excluding rural and farm supplies, is drawn about equally from surface- and ground-water sources. Rural and farm supplies are drawn primarily from wells and are estimated to be about 40 million gallons per year.

To insure the availability of water supplies for all future needs, an understanding of how water moves in the study area and a knowledge of the geology that controls the availability of the water are necessary.

GENERAL GEOLOGY

Rocks outcropping on and lying near the surface within the study area are predominantly sandstone and shale, with beds of coal, underclay, and some thin limestone. These rocks belong to the Lee and Breathitt Formations of Pennsylvanian age. Alluvial deposits of Quaternary age are present in the major valleys. A brief description of the rocks of the Lee and Breathitt Formations and the Quaternary sediments is given in figure 2.

SYSTEM	SERIES	FORMATION	THICKNESS (FEET)	DESCRIPTION
QUATERNARY			0–20	Alluvium, gravel, sand, and silt; in unconsolidated flood-plain deposits at present drainage. Include large slump blocks of sandstone.
PENNSYLVANIAN	Lower and Middle Pennsylvanian	Breathitt Formation	300–400	Sandstone and shale with coal and underclay. The sandstone is light gray, and weathers to a light yellowish gray; fine to coarse grained, generally crossbedded, and in units a few feet to 80 feet thick. Fine-grained channel-fill sandstone occurs locally in the western part of the area. The shale is light to dark gray and occasionally fossiliferous; locally interlaminated with very fine grained sandstone and siltstone. Numerous coal beds are present and range in thickness from less than 1 foot to more than 6 feet, but generally are less than 3 feet thick. The underclay is light to dark gray and commonly silty or sandy. Limestone, (Magoffin Beds of Morse, 1931), medium-dark-gray, silty; contains marine fossils; less than a foot thick. Generally overlain by gray to black fossiliferous shale.
			200–240	Sandstone, siltstone, shale, coal, and underclay. Sandstone is light gray and weathers to a yellowish gray, to yellowish orange; medium to fine-grained. Siltstone and shale is medium to dark gray, and laminated. Numerous coal beds range in thickness from 6 inches to 4 feet. Underclay is light to dark gray, and commonly silty or sandy.
			50–130	Sandstone, conglomerate, shale, coal, and underclay. Sandstone is light gray, weathers yellowish gray to yellowish brown, fine to coarse grained, and generally crossbedded; lowest 10–15 feet of unit may contain asphalt. Conglomerate concentrated mainly near base of unit in lenticular bodies and at base of crossbeds.
	Lower Pennsylvanian	Lee Formation	110–200	Shale, light- to dark-gray; occurs interbedded with sandstone at top of unit and locally as roof rock above coal beds. Mine Fork coal bed forms lower boundary of unit, locally may be missing. Underclay same as above.
			80+	Shale, siltstone, and sandstone; predominantly shale, medium- to dark-gray; contains marine fossils; in thick units separated by lenses of interbedded shale, siltstone, and ripple-marked sandstone.

Figure 2.—Description of Pennsylvanian rocks and Quaternary alluvium in parts of Elliott, Johnson, Lawrence, Magoffin, and Morgan Counties, Ky.

Earth movements during the Paint Creek uplift at the close of the Pennsylvanian Period folded and faulted the relatively uniformly dipping rocks to produce a series of domes (structural highs) and basins (structural lows).

Erosion by streams from the close of the Pennsylvanian Period to the present time carved the slowly rising rock surface and produced the deep valleys characteristic of the area today. Initially the downcutting by streams exposed only the Breathitt Formation, but with time the underlying Lee Formation was exposed on the flanks of the domes and in the immediate vicinity of the faults.

The exposures of the Lee Formation and thin overburden of the Breathitt Formation on the flanks of the domes are areas of ground-water recharge to the Lee Formation, and the exposures of the Lee Formation at lower altitudes in the vicinity of the faults are areas of ground-water discharge from the Lee Formation. The exposure pattern of the Lee Formation is explained in more detail in the following section.

The rocks of the Lee and Breathitt Formations were deposited as deltaic and flood-plain deposits in a low, swampy, coastal plain. Marine invasions recorded by the presence of marine fossils in limestone, silt, shale, and clay units indicate that the coastal plain had an oscillating shoreline due to rising and falling sea level or land surface, never far removed from the sea. Bateman (1950, p. 640–641) states, "The fresh-water swamps necessary for the growth of the plant species found in coal may be separated from the sea by only a sandbar or barrier of vegetation, since marine beds commonly alternate with or rest unconformably upon coal."

Their proximity to the sea and numerous marine invasions imply that the sediments making up the Lee and Breathitt Formations were deposited in fresh to very saline water. Consequently, these types of water were entrapped initially in the Lee and Breathitt Formations. Oil and gas formed later by complex changes in the remains of plant and animal organisms entrapped in the silts, shales, and clays of marine origin. Outerbridge (1966) reports that in the Oil Springs 7½-minute quadrangle, "The base of the sandstone member of the Lee Formation locally is saturated with oil to a thickness of as much as 15 feet. Locally on hot days fresh cuts in the sandstone will 'bleed' oil." The Oil Springs quadrangle covers approximately 57 square miles in the south-central part of the area. The town of Oil Springs is about the geographic center of the quadrangle.

STRUCTURAL GEOLOGY AND RELATED LANDFORMS

The present series of folds and faults in the study area are the result of the earth movements associated with the Irvine-Paint Creek fault and anticline and the Paint Creek uplift.

The Paint Creek uplift, a large upwarp with a north-south axis, commenced prior to Pennsylvanian time. Subsequent movement at the close of the Pennsylvanian Period produced a series of symmetrical folds, domes, and basins with a maximum vertical distance between adjacent highs and lows (closure) in the rocks of Pennsylvanian age of about 200 feet. In the Mississippian and older formations underlying the Pennsylvanian rocks closure greater than 200 feet is indicated.

The Irvine-Paint Creek fault and anticline system is an east-west trending anticline accompanied by normal faulting (McFarlan, 1943). Displacement along these faults is generally between 80 and 160 feet, but exceeds 200 feet in places, with the upthrown side to the north. The Little Sandy fault in the north and the Irvine-Paint Creek fault in the center of the study area cross from east to west. The Blaine Creek fault in the northeast and the Johnson Creek fault in the southwest have but short lateral extent within the study area.

The combination of folding and faulting did not change the land surface abruptly; instead, changes took place at a very slow rate. As a result, streams were able to maintain their courses by eroding and downcutting the slowly rising surface. In this manner, streams cut through the rocks of the Breathitt Formation and exposed the sandstones of the Lee Formation in the valleys of Paint Creek and its tributaries flowing across the Irvine-Paint Creek fault and the Mine Fork dome; Blaine Creek and its tributaries flowing down the north flank of the Laurel Creek dome just south of the Blaine Creek fault; and the Little Sandy River and its tributaries flowing across the Little Sandy fault, the Sandy Hook anticline, Burke dome, and Briar Fork basin. The Lee Formation is not exposed along the Johnson Creek fault in the southwestern part of the study area.

Plate 1 shows the major structural features and the outcrop areas of the Lee Formation within the study area. It is this pattern of exposures, requiring about 270 million years to reach its present stage of development, that is responsible for the hydraulic system as it exists today.

HYDROGEOLOGY

DEFINITION OF SELECTED HYDROLOGIC TERMS

In this and the following sections a number of terms are used frequently in discussing the occurrence of water. These terms are defined below for ready reference.

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

Aquifer, confined. Aquifer which is overlain and underlain by confining beds and which contains water that is under sufficient pressure to rise above the top of the aquifer. Also called artesian aquifer.

Drawdown and recovery. Drawdown is the lowering of the water level as a result of withdrawal of water. Recovery is the rise of the water level after withdrawal of water has ceased. Both are generally measured in feet.

Equipotential line. A line connecting all water levels of equal altitude. Each point on the line has the same hydrostatic head.

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

Flow lines. Lines representing the path followed by a particle of water as it moves through the aquifer in the direction of decreasing head.

Hydrostatic head. The height of a vertical column of water above a datum.

Hydrostatic pressure. The pressure exerted by the water at a given point in a body of water at rest.

Hydraulic gradient. The change of water level per unit distance of flow at a given point in a given direction.

Permeability, coefficient of. The amount of water, in gallons per day, that will flow through a cross-sectional area of 1 square foot of an aquifer under a hydraulic gradient of 100 percent (loss of 1 foot in head for each foot the water travels) at a temperature of 60°F. In laboratory determinations the standard temperature requirement of 60°F temperature is met; however, in field determinations the prevailing water temperature is used. (See fig. 3.)

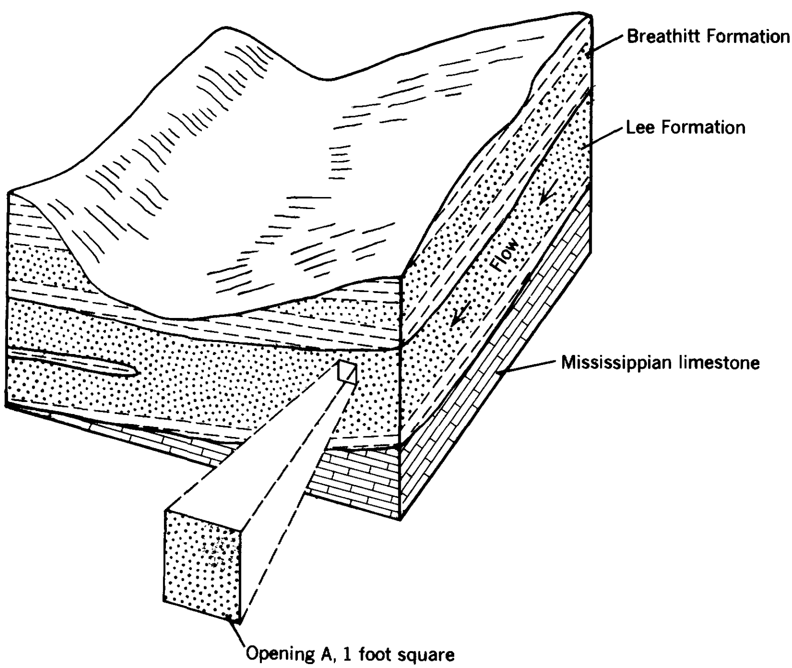

FIGURE 3.—Cross-sectional area of 1 square foot. The rate of flow of water, in gallons per day, through this opening under a hydraulic gradient of 100 percent is the coefficient of permeability.

Piezometric surface. The imaginary surface defined by the level to which water will rise in wells tapping an aquifer. Its shape and slope are indicative of the direction and relative rate of movement of water in the aquifer. For unconfined aquifers, it is the water table.

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. It is an approximate indication of how much water a well can yield.

Static water level. The water level measured in a well when the water level is unaffected by withdrawals or recharge through the well or nearby wells.

Storage, coefficient of. The volume of water released from, or taken into, storage in each vertical column of the aquifer having a base 1 foot square when the water level changes 1 foot.

Transmissibility, coefficient of. The rate of flow of water at the prevailing water temperature, in gallons per day, through a vertical strip of an aquifer 1 foot wide extending the full saturated thickness of the aquifer under a hydraulic gradient of 100 percent. The field coefficient of permeability is the coefficient of transmissibility divided by the saturated thickness of the aquifer. (See fig. 4.)

PERMEABILITY OF THE LEE FORMATION

The Lee Formation is an artesian or confined aquifer throughout most of the study area. It is overlain by the interbedded shale and siltstone unit at the base of the Breathitt Formation, and is underlain by the series of laminated shale and siltstone at the base of the Lee Formation.

Water occurs in the openings between the sand, silt, and clay particles (interstitial or primary openings), and in fractures or joints (secondary openings) formed after the rocks were partly or wholly consolidated. The rate at which a formation will transmit, or yield, water to a well is governed by its permeability and depends on the size and shape of the openings and the size, shape, and extent of the interconnections between them.

Laboratory analyses for permeability were made of eight core samples collected from the Lee Formation in the Eastern Coal Field region, none of which was collected from within the study area. Five samples taken at right angles to the bedding had permeability coefficients ranging from 0.0003 to 0.02 gpd per sq ft (gallons per day per square foot), and three samples taken parallel to the bedding had permeability coefficients ranging from 0.003 to 0.03 gpd per sq ft.

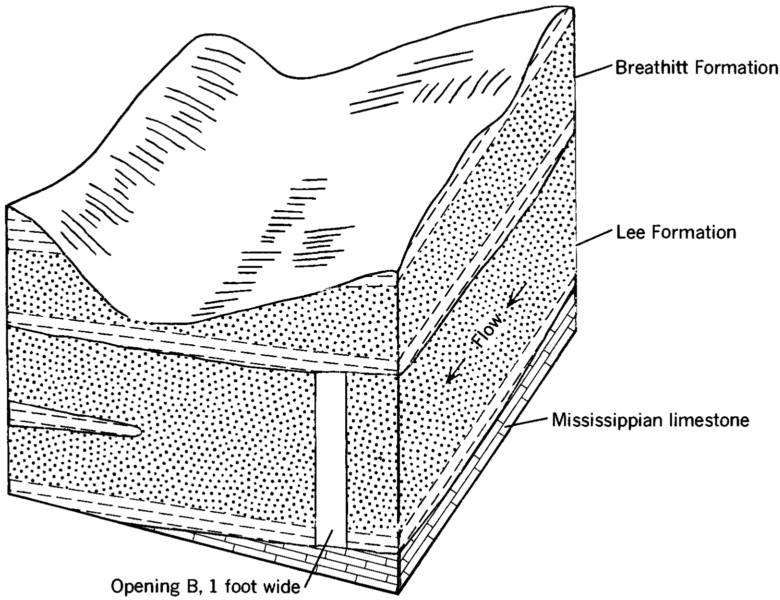

FIGURE 4.—Vertical strip 1 foot wide extending through the saturated thickness of the aquifer. The rate of flow of water, in gallons per day, through this opening under a hydraulic gradient of 100 percent is the coefficient of transmissibility.

Field permeabilities determined from two pumping tests within the study area give an average permeability of 12.0 gpd per sq ft. This is substantially higher than the laboratory permeabilities, but still relatively low when compared with permeability coefficients as large as 70 gpd per sq ft for the alluvial deposits along the Big Sandy River northeast of the study area.

The difference in results of laboratory and field determination of permeability is due primarily to the extent of area sampled. The core sample used in a laboratory determination is a solid waferlike unit less than 2 inches in diameter, generally less than 0.5 of an inch thick, and containing none of the secondary openings; therefore, it is a measure only of the interstitial flow at a single point. A field permeability determination, on the other hand, is an average of the interstitial flow and flow through the secondary openings within a volume of a formation approximating a cone that may be more than 1 mile in diameter and greater than 150 feet deep.

Although field permeability determination is a better index of the capacity of the Lee Formation to transmit water, the laboratory determination of permeability, in distinguishing between horizontal and vertical flow, suggests that the maximum flow may be parallel to the bedding in the flat-lying sediments. However, this would not be true for the crossbedded parts of the Lee Formation, which compose a major part of this aquifer.

POTENTIAL YIELDS FROM THE LEE FORMATION

Yields of individual wells from the Lee Formation range from 10 gpm (gallons per minute) for the rural domestic and farm supply to more than 25 gpm for industrial, commercial, municipal, and institutional supplies. The yields of wells for this latter group of supplies are most representative of the potential yield of the Lee Formation.

Industrial water-supply wells finished in the Lee Formation and used to supply water for the secondary recovery of oil by the water-flood method yield 25 gpm or more throughout the study area. Yields of less than 25 gpm are attributed to improper well spacing which results from concentration of wells in the immediate vicinity of the waterplant.

In Magoffin County a water-supply well open in the lower 120 feet of the Lee Formation and used for waterflood operations near Falcon was pumped at an average rate of 50 gpm for 47 hours. The specific capacity was 0.4 gpm per foot of drawdown. Near Wheelersburg a reported specific capacity of 0.70 gpm per foot of drawdown was obtained for a fully penetrating water-supply well for waterflood operations. The test was reported to be of several hours duration with an average discharge of 30 gpm. In Johnson County a fully penetrating well pumped at an average rate of 34 gpm for 36 hours had a specific capacity of 0.3 gpm per foot of drawdown.

Water-supply wells for waterflood operations in the vicinity of Keaton in Johnson County and Martha in Lawrence County have reported yields ranging from 25 to 40 gpm. On the basis of reported pumping levels and pump-intake settings, it is estimated that specific capacities range between 0.5 and 1.0 gpm per foot of drawdown for wells in the Martha and Keaton sections. Water-supply wells with only partial penetration of the Lee Formation furnish water for approximately 600 students at the high school in Oil Springs and at the grade school in Flat Gap. To meet maximum demands at each school the wells are estimated to pump between 15 and 25 gpm, intermittently rather than continuously. No drawdown records are available to determine the specific capacity of either well.

In Elliott County the municipal-supply well for Sandy Hook, which fully penetrates the Lee Formation, was tested at 100 gpm and two wells at the school in Sandy Hook, with only partial penetration, have reported yields of 20 gpm. No drawdown data are available to determine the specific capacities of these wells.

From the above it is evident that potential yields to individual wells drilled into and fully penetrating the Lee Formation will equal or exceed 25 gpm. Wells finished in the upper 100 feet of the Lee Formation and shallow wells (less than 100 feet deep) in and near outcrop areas may yield less than 25 gpm, but will generally be sufficient for domestic and farm supplies.

Where geologic and hydrologic data are sufficient the coefficient of transmissibility is a more explicit expression of an aquifer's ability to yield water than is the specific capacity of a single well. The two tests within the study area for which sufficient data are available show that the transmissibility ranges from about 1,000 to 2,000 gpd per ft (gallons per day per foot).

THE CONE OF INFLUENCE OF A PUMPING WELL

The effect of a single well withdrawing water from an aquifer is not limited to the immediate vicinity of the pumping well, but is transmitted over a large part of the formation. The extent to which the pumping effect is transmitted within the formation is referred to as the *cone of influence.*

The extent and shape of the cone of influence is outlined by the drawdowns in observation wells at any time after pumping has started and recovery at an equivalent time after pumping has stopped. As long as the pumping well is withdrawing water from storage, the cone of influence will continue to spread out until an area of recharge or natural discharge is reached which is capable of making up the amount of water being pumped from storage by either an increased inflow at the recharge area or a decreased outflow at the discharge area, or a combination of these, and a balanced hydraulic system with a lowered piezometric surface is reestablished.

Within the study area the industrial- and public-supply wells are pumped for periods ranging from 8 to 24 hours. As a result, the cone of influence extending outward from any single well or group of wells will vary. The cone of influence can, however, be simulated for specific conditions as in the following example.

In this example, the cone of influence has been simulated using a coefficient of transmissibility determined from a pumping test on an industrial-supply well finished in the Lee Formation just east of Falcon near the Magoffin-Johnson County line and the coefficient of storage from a pumping test on a municipal-supply well finished in the Lee Formation outside the study area. The coefficient of transmissibility is 2,000 gpd per ft, the coefficient of storage 0.001, and the pumping rate 50 gpm. It was assumed that the Lee Formation in this area is homogeneous and isotropic, and has infinite areal extent.

Using the above assumptions and values for the coefficients of storage and transmissibility, the drawdown as specific times and distances can be determined from the Theis nonequilibrium formula (Ferris and others, 1962, p. 92–98). Figure 5 shows the drawdown in feet versus distance from the pumping well for five specific times in days and years.

The parallelism of these curves shows that the rate of decline of the piezometric surface along the cone of influence is similar and proportional to the amount of water being released from storage for the given conditions and that no areas of recharge or discharge were intercepted within the distance shown.

If the cone of influence intercepts an area of recharge, such as the recharge area along the crest of the Mine Fork Dome to the north or an area of discharge such as along Little Paint Creek to the east, and the induced infiltration or capture of discharge is sufficient to balance the withdrawals from storage by the pumping well, the cone of influence will stabilize with a steeper gradient in the direction of the induced infiltration.

At equal distances in any direction from the pumping well, the drawdown will be the same. For example, the curve representing the drawdown after 30 days pumping shows that the drawdown will be 15 feet at a distance of 320 feet from the pumping well and 30 feet at a distance of 23 feet from the pumping well.

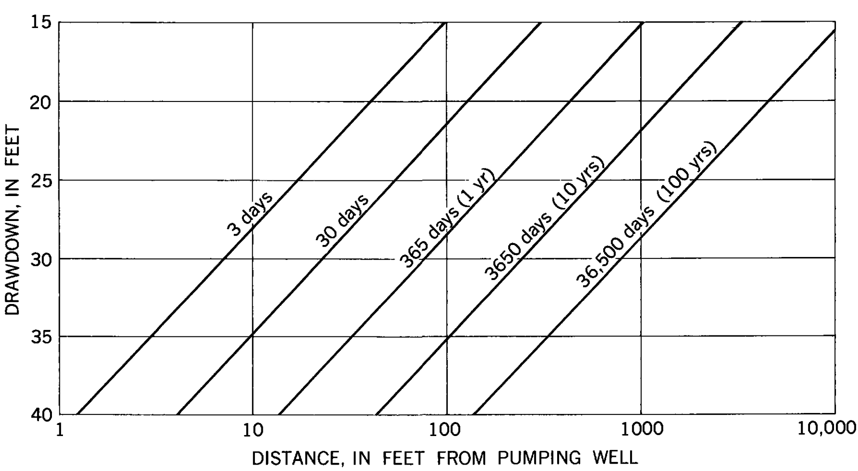

Figure 5.—Relation between drawdown and distance from a well pumping 50 gpm for selected times since pumping began. The coefficient of transmissibility is 2,000 and the coefficient of storage 0.001.

356–410 O—70——3

Figure 6 shows the drawdown at different distances from the pumping well after 30 days pumping as a series of concentric circles. The drawdown along any one circle is equal and decreases by 5 feet at each successive circle away from the pumping well. It should be noted that the spacing between successive circles increases with distance from the pumping well.

Figure 7 shows the cone of influence in cross section along the line *X–Y* in figure 6.

The above discussion was restricted to a cone of influence resulting from one pumping well to show that its effect within the Lee Formation is extensive rather than localized. A practical application of this information is the resultant cone of influence when the cones of influence from two pumping wells overlap. In the following example another pumping well is introduced at a distance of 500 feet to the south of the pumping well in the previous example. The Lee Forma-

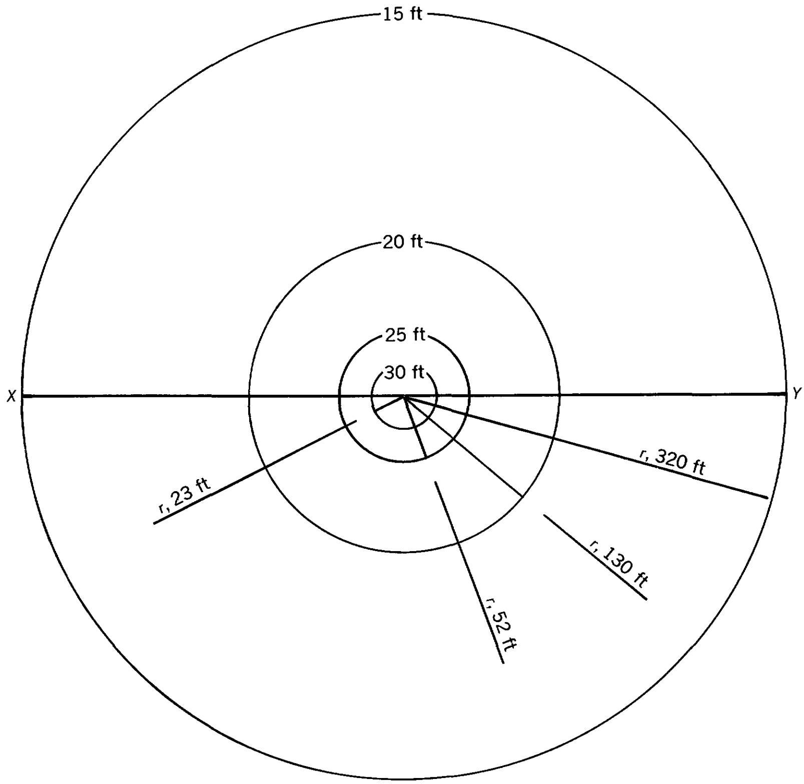

FIGURE 6.—The drawdown at different distances from the pumping well as a series of concentric circles. The drawdown along any one circle is the same.

tion has the same physical characteristics assumed in the previous example, and both pumping wells have the same construction and are discharging at equal rates. Consequently, each cone of influence will be identical.

The simulated drawdown along the cone of influence between the two wells is the sum of the individual drawdowns at any point. Thus, in figure 8, the cone of influence for each well pumped individually is shown by a dashed line and the resultant cone of influence when both wells are pumped simultaneously by a solid line. The drawdown S_r at any point along the resultant cone of influence is the sum of the individual drawdowns S_1 and S_2 at that point.

This method for determining the resultant drawdown is not restricted to two wells, but may be applied to a number of wells when cones of influence overlap. The resultant drawdown would thus be the algebraic sum of the individual drawdowns at the point, whether between or away from the pumping wells.

Here, as for the cone of influence for a single well, the resultant cone of influence will stabilize only after reaching a recharge and (or) discharge area capable of making up the amount of water being withdrawn from storage.

The two examples above show that the effect of withdrawal of water from the Lee Formation is transmitted over a large area rather than being confined to the immediate vicinity of the pumping well or wells. Future development of this aquifer can be greatly enhanced by proper well spacing to minimize interference between pumping wells. Well spacing, taking into account local field conditions, can be determined by using the techniques discussed above.

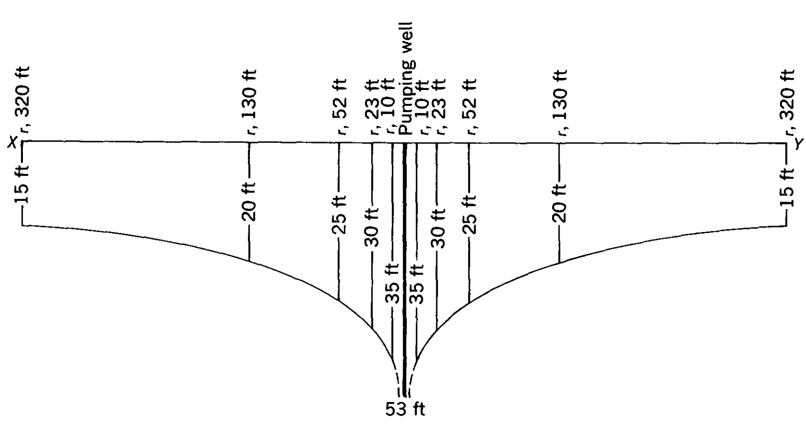

FIGURE 7.—The cone of influence in cross section along the line X–Y in figure 6.

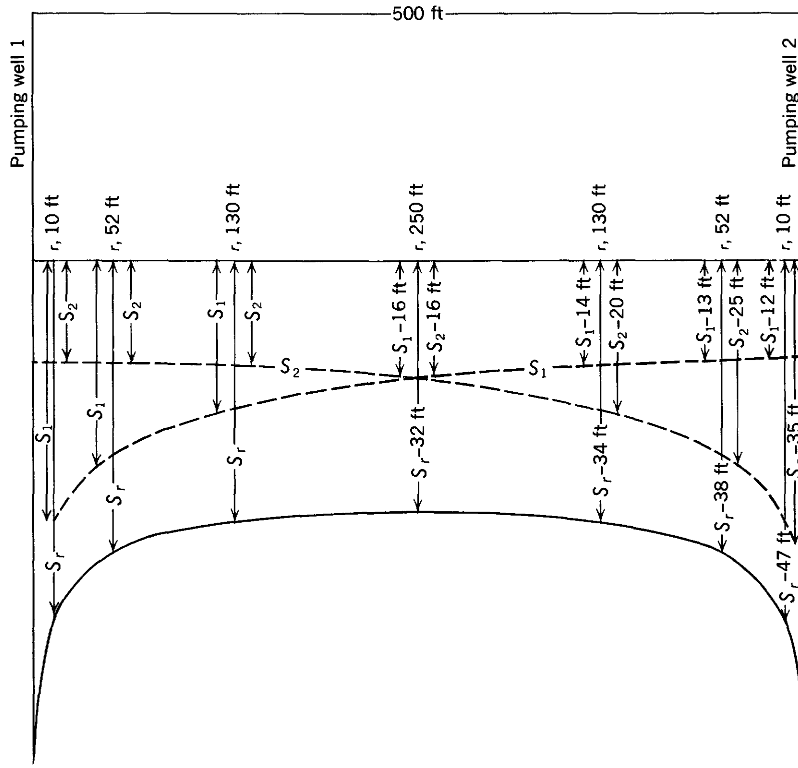

FIGURE 8.—A dashed line shows the cones of influence for wells 1 and 2, which are 500 feet apart, when they are pumping individually, and the resultant cone of influence is shown as a solid line when both wells are pumping simultaneously. The resultant drawdown, S_r at any point is the sum of the individual drawdowns S_1 and S_2.

RECHARGE

Precipitation accounts for all the recharge to the Lee Formation, either directly through outcrops of the Lee Formation or indirectly through the overlying Breathitt Formation.

The average annual precipitation for the study area is 43.53 inches, based on the U.S. Weather Bureau precipitation gage at Paintsville in Johnson County. About 28 inches (62 percent) of this average annual precipitation is returned to the atmosphere by evapotranspiration, and about 15 inches (38 percent) is runoff carried away by streams. Less than 3 inches of the total average annual precipitation that falls in the study area is considered recharge to the Lee Formation. About one-half of this recharge reaches Paint Creek, Blaine Creek, and Little Sandy River to be included as part of the average runoff within the study area. The balance of this recharge eventually becomes part of the average annual runoff to streams outside the study area such as the Licking River to the west and Levisa Fork to the east.

The major areas of recharge in the Blaine Creek drainage basin occurs along the crest and west, north, and east flanks of the Laurel Creek dome and the south and east flanks of the Big Fork dome; in the Paint Creek drainage basin along the east, northeast, and southeast flank of the Mine Fork dome, the south-central flank of the Laurel Creek dome, and the crest and west and south flanks of the Mudlick dome; and in the Little Sandy River drainage basin within the study area along the axis of the Paint Creek anticline including Burke dome and the crest and north flank of the Brack Adkins dome. North and west of the Brack Adkins dome the sequence of shale and interbedded siltstone and shale near the base of the Breathitt Formation thins and is not present near Sandy Hook. Consequently in this area there is substantially more vertical leakage through the Breathitt Formation than anywhere else in the study area.

South and east of Sandy Hook and away from the structural-high areas the sequence of shale and interbedded siltstone and shale near the base of the Breathitt Formation generally exceeds 120 feet. This relatively impermeable unit restricts considerably the downward movement of water.

Ratios of the size of the drainage basins indicate tributaries on the crests and flanks of the structural highs have sustained flows about 70 percent of the year.

RELATION OF GROUND-WATER FLOW TO GEOLOGY

The influence of geologic conditions on the flow of water in the Lee Formation is best exemplified by the configuration of the equipotential lines for this formation in the study area. Plate 2 is a map showing equipotential lines, major structural features, and outcrop areas of the Lee Formation. Wells shown on this map are listed in table 2. The equipotential lines indicate water levels of equal altitude above mean sea level in the Lee Formation. The overall direction of flow is at right angles to the equipotential lines from higher water levels toward the lower water levels.

The highest equipotential lines are coincident with structural-high areas and generally approximate their geometric form.

The lowest equipotential lines are coincident with exposures of the Lee Formation in the valley bottoms along Paint Creek and its tributaries near the Irvine-Paint Creek fault from the Morgan-Magoffin-Johnson County line to Paintsville in Johnson County; Keaton Creek and Lower Laurel Creek, tributaries to Blaine Creek, near the Blaine Creek fault; and Little Sandy River and its tributaries near the Little Sandy fault in Elliott County. These are the areas in which discharge from the Lee Formation occurs.

TABLE 2.—*List of wells used to construct equipotential lines shown on plate 2*

Reference number used in illustrations	Latitude and longitude	Depth of well, in feet below land surface	Depth of water level, in feet below measuring point	Altitude of water level above mean sea level
3	[1] 374501N0830434. 1	660	140	720
5	374727N0825934. 1	679	140	700
[2] 8	374808N0824629. 1	[3] 520	60	615
9	374812N0825912. 1	608	[4] 280	710
10	374822N0824833. 1	280	[5] 0	610
[2] 11	374839N0825639. 1	385	[4] 130	710
13	374903N0830144. 1	513	225	730
15	374906N0824706. 1	145. 2	35	585
16	374818N0830033. 1	440	180	760
17	374941N0825043. 1	92	[4] 40	590
18	374946N0824905. 1	800	600	600
19	375018N0830146. 1	205	135	780
20	375052N0824844. 1	585	115	635
21	375129N0825139. 1	345	30	610
22	375135N0825144. 1	51	30	610
23	375146N0825415. 1	91	85	645
24	375205N0825305. 1	245	85	665
25	375323N0825624. 1	151	143	665
27	375406N0825751. 1	380	154	690
28	375423N0825741. 1	290	[4] 190	690
29	375522N0825501. 1	135	41	727
30	375601N0825957.1	76	45	705
31	375606N0825331.1	142	95	740
32	375609N0825315.1	330	[4] 80	740
33	375633N0825818.1	239	150	730
34	375719N0825405.1	125	[4] 110	740
35	375721N0830906.1	295	[4] 120	700
36	375804N0830137.1	216	55	700
38	375847N0825805.1	132	[4] 90	690
39	375955N0825654.1	540	232	683
41	380032N0830420.1	584	294	716
43	380116N0825543.1	325	[4] 34	650
44	380128N0825532.1	615	[4] 240	645
45	380233N0830336.1	290	[4] 50	680
46	380253N0830220.1	235	[4] 85	685
47	380409N0830315.1	146	18	670
48	380408N0830314.1	241	[4] 18	670
49	380506N0830745.1	242	90	700
52	380615N0831022.1	160	[4] 100	740
53	380625N0830228.1	90	55	675
54	380625N0830710.1	161	140	660

[1] The first six digits represent degrees, minutes, and seconds of latitude; "N" refers to north latitude and is used to break up the string of numbers; the next seven digits are degrees, minutes, and seconds of west longitude; and the number after the decimal point is a sequential number assigned in the order in which the wells are located in a 1-second quadrangle.
[2] Shown on figure 12, not on plate 2.
[3] Originally drilled to 1825 ft.
[4] Reported.
[5] Flowing well.

The dominant direction of ground-water flow in the study area is from the thin overburden of the Breathitt Formation on Laurel Creek and Mine Fork domes toward the outcrops of the Lee Formation in the valley of Paint Creek.

In the lower areas where water discharges from outcrops of the Lee Formation in the stream valleys, the equipotential lines outline the valleys with a series of parallel lines on either side. These lines close upstream and open downstream, except along Paint Creek at Paintsville in Johnson County where the equipotential lines are closed at the point of the lowest known hydraulic head in the system within the study area. This hydraulic low is the result of ground-water discharge from the Lee Formation into Paint Creek. The upward movement occurs mainly through a series of "deeps" in the bed of Paint Creek from just north of Staffordsville to just west of Paintsville.

In the vicinity of the faults the configuration of the equipotential lines vary; for example, along the Irvine-Paint Creek fault, just north and west of the Mine Fork dome, and west of Big Mine Fork, the lines do not cross the fault because of poor hydraulic connection. In this area the vertical displacement along the Irvine-Paint Creek fault is about 200 feet, the approximate thickness of the Lee Formation in the area. As a result the hydraulic connection across the fault between the displaced blocks of the Lee Formation is poor. There is, however, flow from the Lee Formation across the fault. On the south, or downthrown, side of the fault the Lee Formation is opposite the Mississippian limestone, and water flows northward across the fault into the Mississippian limestone. To the east of the Mine Fork dome and southwest of the Laurel Creek dome the equipotential lines cross the Irvine-Paint Creek fault with no apparent deviation. In this area the displacement along the fault ranges from 110 to 160 feet and is substantially less than the 350-foot thickness of the Lee Formation in the area; therefore, a relatively good hydraulic connection exists.

The gradient of the equipotential lines on the north flank of the Laurel Creek dome indicate a ground-water discharge through exposures of the Lee Formation in the valleys of Upper and Lower Laurel Creeks just south of the Blaine Creek fault. The pattern of the equipotential lines in the immediate vicinity of the Blaine Creek fault shows the hydraulic connection across the fault to be poor, even though displacement along this fault is only about 50 feet near Martha. However, the displacement is sufficient to move the basal shale unit of the Lee Formation on the north, or upthrown, side against the sand unit and the basal shale unit of the Breathitt Formation on the south, or downthrown, side, resulting in a poor hydraulic connection.

In the northern part of the area near Sandy Hook, the fact that equipotential lines outline the Little Sandy River and its tributaries indicates ground-water discharge from the Lee Formation to the Little Sandy River. There is no apparent change in hydraulic gradient as a result of displacement along the Little Sandy fault.

GROUND-WATER FLOW IN THE PAINT CREEK DRAINAGE BASIN

In the Paint Creek drainage area the configuration of the equipotential lines shows that the flow is from the hydraulic highs toward the outcrops in the valley. Plate 3 is a flow-net diagram showing the movement of water in the Lee Formation from the recharge areas on Mine Fork, Laurel Creek, and Mudlick domes to discharge areas in the valleys of Paint Creek and its tributaries. This area exemplifies the interrelation of ground-water flow and geologic features within the study area.

The two sets of lines composing the flow-net diagram are the equipotential lines and the flow lines. The flow lines are essentially a trace of the path of water as it moves toward the discharge area.

The equipotential lines are drawn so that the change in head between adjacent lines is equivalent to 20 feet; the flow lines are drawn so that the total quantity of flow is divided evenly between the adjacent pairs of flow lines. The resulting orthogonal pattern, or "squares," formed by these lines can be used to evaluate the ground-water flow in the area, assuming laminar flow, with the following variation of Darcy's law:

$$q = Th,$$

q=flow through the area between adjacent flow lines in gallons per day,
T=coefficient of transmissibility in gallons per day per foot, and
h=potential drop between adjacent equipotential lines in feet.

Using $T=1{,}000$ gpd/per ft and $h=20$ ft, the flow through any segment of the net is 20,000 gpd. The total ground-water discharge from the Lee Formation for the 30 segments of this net terminating in the valley of Paint Creek and its tributaries is 600,000 gpd. The coefficient of transmissibility used above in computing the ground-water discharge by the flow-net method is based on test data in the immediate discharge area.

There is a close relation between this value for ground-water discharge from the Lee Formation and the low flows in Paint Creek. Ground-water discharge from the Lee Formation is significant during the periods of low flow.

The flow-net diagram (pl. 3) shows that 20 segments of the net terminate in the valley of Paint Creek and its tributaries above the gaging station and 10 segments of the net terminate in this valley below the gaging station. The ground-water discharge from the Lee Formation above the gaging station is equal to 400,000 gpd and below the gaging station 200,000 gpd, the latter being ungaged flow. Gaged flows of less than the ground-water discharge above the gaging station at Staffordsville do occcur and are attributed to losses by evapotranspiration. The frequency of occurrence of flow less than the ground-water discharge and relation between precipitation and water losses, streamflow, and evapotranspiration are given below.

Low-flow frequency curves (fig. 9) based on 9 years of record for the Paint Creek gaging station show that the recurrence of flows of

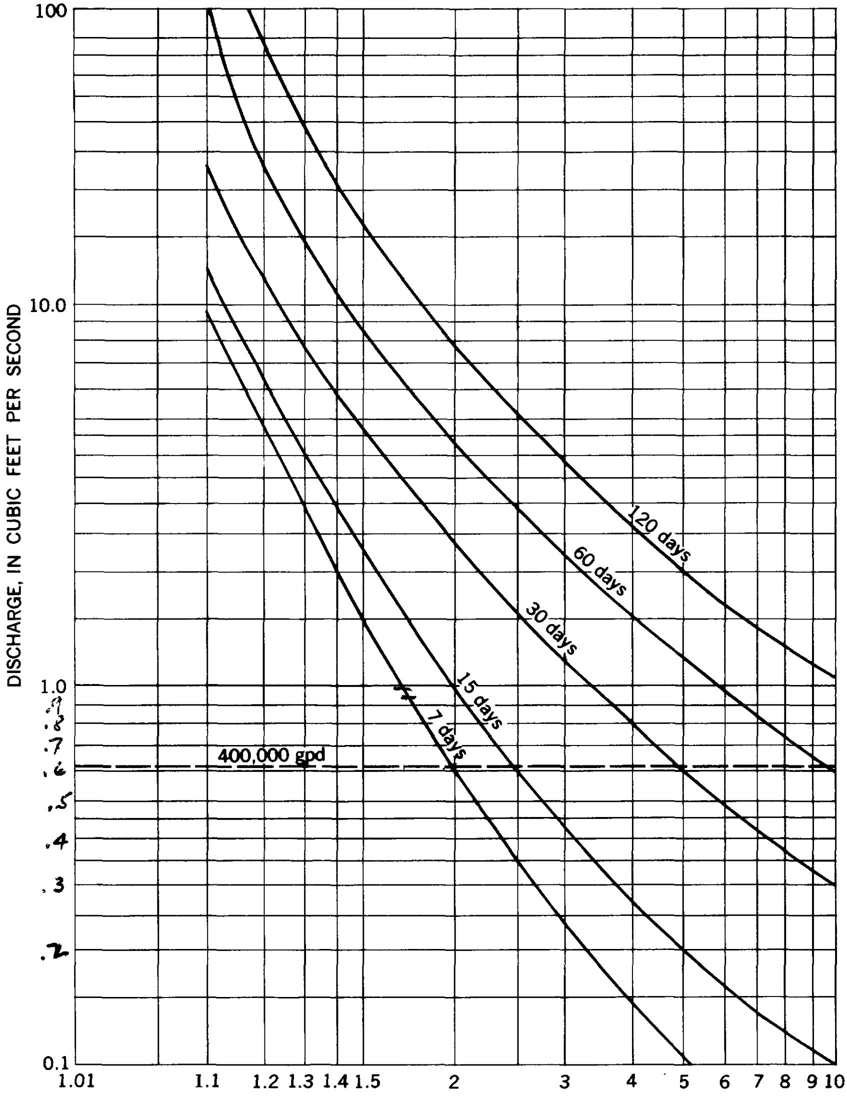

FIGURE 9.—Low-flow frequency curves, Paint Creek at Staffordsville, Ky. Based on period of record 1950–58 (climatic year April 1–March 31).

less than 400,000 gpd for 7 days and 15 days duration will occur once every 2.0 and 2.5 years, respectively. For the period of record, March 1950 to December 1967, no flow was recorded at this station on October 3, 5, and 6, 1952, September 18, 1955, and September 1–8, 1957.

Figure 10 shows the relation between evapotranspiration, streamflow, and precipitation in inches for the water year October 1 through September 30. The losses to evapotranspiration and streamflow are in balance with precipitation for the water year. Changes in basin storage (surface-water storage, ground-water storage, and soil moisture) have not been included. The monthly evapotranspiration was adjusted for the Paint Creek drainage area from the potential evapotranspiration compiled by the Penman method for Lexington, Ky. The monthly averages for precipitation and runoff are based on the period of record 1950 through 1966. Runoff was adjusted by removing an exceptionally high flow and a low flow for the same month for the period of record. For example, the monthly runoff for July 1961 exceeded the cumulative runoff in July for 13 of the above 16 years of record. This high runoff, July 1961, and the lowest runoff, July

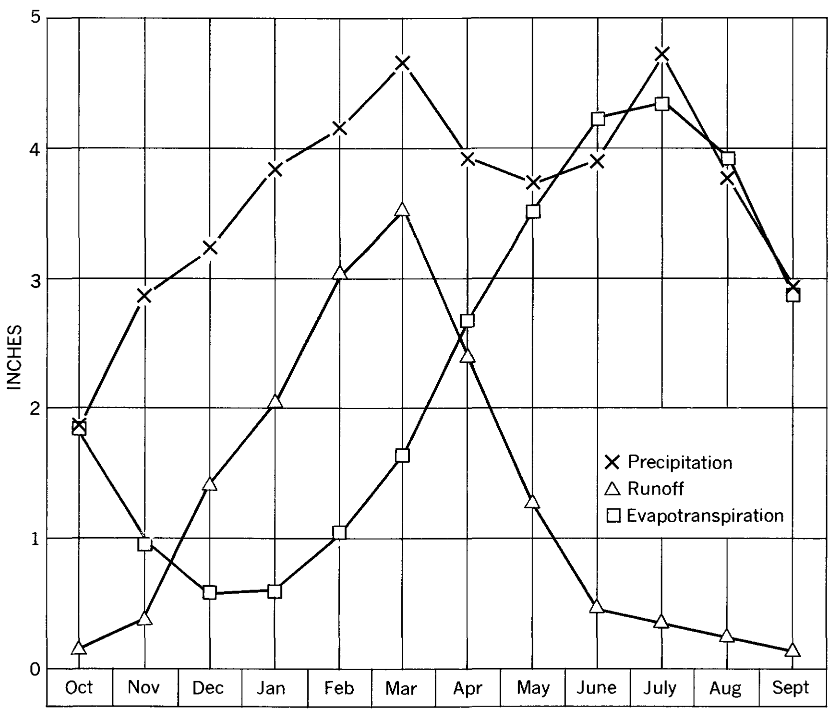

FIGURE 10.—Monthly average precipitation, runoff, and evapotranspiration for the Paint Creek drainage area, (water year October 1 to September 30).

1963, were excluded from determinations for the average July runoff. Similar exclusions of one high and one low were made in determining the average runoff for the months of August and November.

Figure 10 shows that for the period October through March when losses to evapotranspiration are low the curves for precipitation and streamflow are similar in shape, as precipitation increases streamflow increases. For the remainder of the water year when evapotranspiration losses are high the curve for streamflow is in recession even though the average precipitation during this 6-month period is higher than during the previous 6 months. The highest average monthly precipitation for this area occurs in July. The high losses to evapotranspiration, reflected as decreasing streamflow, remove water from storage in the Lee Formation which would eventually discharge into Paint Creek.

In the reach of Paint Creek from near the gaging station at Staffordsville to just west of Paintsville, depressions in the streambed are conspicuous. These depressions are the result of solution of the cementing material in the sandstone by discharging ground water from the Lee Formation and removal of the loose sand grains by streamflow.

QUALITY OF WATER

Fresh water as used in this report is water with 1,000 mg/l (milligrams per liter) or less of total dissolved solids, and saline water is water having more than 1,000 mg/l of dissolved solids. The U.S. Public Health Service (1962) in "Drinking Water Standards" recommends that water for public supplies should not contain more than 500 mg/l total dissolved solids; however, if water of suitable quality is not available, water containing up to 1,000 mg/l total dissolved solids is permissible. Other limitations by the Public Health Service for chemical constituents commonly found in water for human use are: iron and manganese combined, 0.3 mg/l;[1] nitrate, 45 mg/l; sulfate, 250 mg/l; and chloride, 250 mg/l.

McKee and Wolf (1963, p. 113) state, "Water safe for human consumption may be used by stock; indeed it has been recommended that stock, for their highest production should have such water. On the other hand, it appears that animals can tolerate higher salinity than men and it is conceivable also that they differ in their tolerances of specific substances."

[1] Drinking water standards recommended by the U.S. Public Health Service in 1946 set a limit of 0.3 mg/l for iron and manganese combined; however, in the revised 1962 standards it is recommended that a limit be established for each and that the concentration of iron be limited to 0.3 mg/l and manganese to a maximum of 0.05 mg/l.

TABLE 3.—*Chemical analyses of water from wells and streams in parts of*

[Chemical constituents are given in milligrams per liter]

Reference No. used on illustrations or in text	Location [1]	Depth of well, in feet below land surface	Date of collection	Temperature (°F)	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)
			Lee Formation						
[2,3] 1	374308N0830043.1		May 12, 1965			0.3		13	
2	374408N0830137.1	421	Aug. 18, 1966	59		.09	0.54		
3	374501N0830434.1	660	Mar. 27, 1958			.04			
3a			Nov. 18, 1966	60		0.5	.00	4.6	1.6
4	374509N0830329.1	506	Aug. 19, 1966	59		5.3	1.6		
[5] 5	374727N0825934.1	679		60	4.5	.37	.0	17.0	6.0
6	374803N0825901.1	500	July 8, 1958	57	11	53	.01	902	214
7	374806N0825906.1	384	do		13	.82	.05	51	17
8	374808N0824629.1	520	Sept. 5, 1950	60	9.2	4.6		1,362	424
10	374812N0824833.1	280	July 20, 1950	57	17	1.2		29	8.0
11	374839N0825639.1	385	Jan. 19, 1967			8.6	.09		
[2,3] 12	374852N0825901.1		May 3, 1966	60		1.9	.0	11	5
14	374917N0830122.1	247	Sept. 21, 1966			0.3	.62		
20	375052N0824844.1	585	Apr. 21, 1966	59		.99			
21	375129N0825139.1	345	Sept. 22, 1966			.34	.00		
24	375205N0825305.1	245	Nov. 18, 1966			.24	.00		
26	375343N0825731.1		do	59		.02	.05		
31	375606N0825331.1	142	Jan. 18, 1967			5.1	2.8		
32	375609N0825315.1	330	Jan. 19, 1967			.34	.00		
[2,3] 39	375955N0825654.1		Apr. 4, 1967	52		17.0	3.1	344	84
40	380009N0825515.1	100	Oct. 22, 1954	57		16			
[2,3] 42	380120N0825547.1		Apr. 25, 1967	56		.20	.00	30	10
49	380506N0830745.1	242	Feb. 21, 1955	57					
51	380519N0830746.2	232	Apr. 17, 1959			5.5	0		
51a			Apr. 21, 1965			32.0	.20	50.0	18.21
			Breathitt Formation						
56	374533N0830347.1	325	Aug. 16, 1966						
57	374804N0825753.1	75	Apr. 26, 1961			21			
58	374804N0825753.2	16.7	do	58		.22			
59	374818N0825706.1	85	do	57		90			
			Surface water						
60	Paint Creek at gaging station on U.S. Highway 460, Johnson County.		Apr. 29, 1960	66					
61	Paint Creek, 1,000 feet north of gaging station on U.S. Highway 460, Johnson County.		Nov. 18, 1966			.12	.23		
62	Above confluence of Low Gap Branch and Paint Creek near Morgan-Johnson County line.		do			.18	.13		
63	Licking River at gaging station on State Highway 30 near Salyersville, Magoffin County.		Apr. 29, 1960	62					
64	Mash Fork near Salyersville, Magoffin County.		Apr. 26, 1961						
65	State Road Fork at Dewey Hilton Farm near Johnson-Magoffin County line.		do			1.5			
66	Overflow from oil separator discharging into local drainage, Magoffin County.		do			30			
[7] 67	Burning Fork at confluence with Licking River at Salyersville, Magoffin County.		Nov. 6, 1961						

See footnotes at end of table.

Elliott, Johnson, Lawrence, Magoffin, and Morgan Counties, Ky.

[Chemical constituents are given in milligrams per liter]

Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids: Calculated	Dissolved solids: Residue at 180° C	Hardness as $CaCO_3$: Ca, Mg	Hardness as $CaCO_3$: Noncarbonate	Specific conductance (micromhos at 25° C)	pH	Color	Carbon dioxide (CO_2)
Lee Formation—Continued															
------	------	------	----	------	716	----	------	--------	-------	--------	13	-------	7.1	----	----
------	------	178	16	17	144	----	0.4	--------	462	28	0	830	8.9	----	----
------	------	348	11	4	192	0.2	.9	[4] 678	-------	14	0	1,130	8.6	----	----
268	2.0	372	0	1.2	205	.5	.7	685	648	18	0	1,200	8.0	3	----
------	------	240	0	5.2	380	----	.1	--------	878	238	42	1,620	6.9	----	----
------	------	248	----	10.5	124	----	------	[6] 400	-------	70.0	------	-------	7.7	----	9.0
2,880	27	229	0	.0	6,360	----	34	10,590	11,090	3,130	2,950	18,000	6.3	5	----
111	2.6	300	0	4.8	137	.2	.0	485	481	197	0	884	7.2	3	----
13,410	162	370	0	0 2	3,980	----	------	39,810	39,830	--------	------	53,290	7.2	2	----
38		198	0	2.6	9.0	.4	11	214	210	105	0	344	7.3	7	----
------	------	141	0	.4	18	----	.0	--------	168	122	6	253	6.9	----	----
------	------	30	0	------	57	----	------	[6] 260	-------	48	------	-------	7.1	----	7.0
------	------	100	0	22	9.0	.1	.1	--------	145	114	32	223	7.5	----	----
------	------	246	0	5.2	6.0	.2	.1	[4] 229	-------	105	0	394	7.6	5	----
------	------	262	0	2.8	10	.1	.1	--------	238	142	0	405	7.1	----	----
------	------	294	0	2.4	3.0	.1	.1	--------	261	78	0	430	7.2	----	----
------	------	164	0	3.6	7.0	.2	.1	--------	157	40	0	261	7.2	----	----
------	------	174	0	17	.5	----	5.6	--------	188	148	6	308	7.7	----	----
------	------	249	0	.4	2.0	----	1.8	--------	231	162	0	392	7.0	----	----
------	------	39	0	9	2,950	----	------	[6] 4,050	-------	--------	------	1,280	6.6	----	8.0
------	------	126	0	.8	169	.1	.2	[7] 449	-------	175	------	748	6.5	----	----
------	------	106	0	3	103	----	------	[6] 400	-------	118	------	-------	6.9	----	26.0
------	------	------	----	------	16	----	------	--------	-------	--------	------	-------	----	----	----
------	------	------	----	10	2.8	0	0	--------	324	191	5	-------	7.3	10	----
------	------	------	----	19	23.0	.4	.65	--------	322	145	55	-------	7.2	----	----
Breathitt Formation—Continued															
------	------	482	0	23	1,200	----	1.2	--------	2,480	202	0	4,530	7.7	----	----
------	------	125	0	------	2,450	.0	------	[4] 4,592	-------	2,190	2,090	7,620	6.3	----	----
------	------	26	0	68	18	.0	12	--------	-------	104	82	287	6.8	----	----
------	------	------	----	------	5,400	.0	------	[4] 9,180	-------	3,560	------	15,300	4.6	----	----
Surface water—Continued															
------	------	28	0	25	580	----	------	--------	1,195	276	253	1,880	6.5	----	----
------	------	38	0	22	354	.1	2.6	--------	761	190	159	1,260	7.0	----	----
------	------	38	0	20	220	.1	1.7	--------	520	134	103	825	6.9	----	----
------	------	32	0	18	141	----	------	--------	314	94	68	584	6.3	----	----
------	------	------	----	------	775	----	------	--------	-------	--------	------	2,650	----	----	----
------	------	------	----	------	1,850	----	------	--------	-------	--------	------	5,760	----	----	----
------	------	141	0	------	44,600	----	------	--------	-------	19,200	19,100	92,800	6.0	----	----
------	------	------	----	------	1,375	----	------	--------	-------	--------	------	-------	----	----	----

TABLE 3.—*Chemical analyses of water from wells and streams in parts of*

Reference No. used on illustrations or in text	Location [1]	Depth of well, in feet below land surface	Date of collection	Temperature (° F)	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Mangesium (Mg)
Surface water									
[7]67A			Aug. 8, 1963						
[7]68	State Road Fork of confluence with Licking River at Salyersville, Magoffin County.		Nov. 6, 1961						
[7]68A			Aug. 8, 1963						
[7]69	Licking River at gaging station on State Highway 30 near Salyersville, Magoffin County.		Nov. 6, 1961						
[7]69A			Aug. 8, 1963						

[1] The first six digits represent degrees, minutes, and seconds of latitude; "N" refers to north latitude and is used to break up the string of numbers; the next seven digits are degrees, minutes, and seconds of west longitude; and the number after the decimal point is a sequential number assigned in the order in which the wells are located in a 1-second square quadrangle.
[2] Composite analysis for more than one well
[3] Analysis supplied by the Ashland Oil and Rfining Co.

The degree of salinity of water is classified as follows:

Description	*Dissolved solids in milligrams per liter*
Slightly saline	1,000–3,000
Moderately saline	3,000–10,000
Very saline	10,000–35,000
Brine	>35,000

Slightly saline water is found in many of the surface- and ground-water supplies within the area. The upper limit for very saline water was set as that of ocean water. Concentrations of dissolved solids exceeding that of ocean water are grouped arbitrarily as brines (Krieger and others, 1957).

The quality of water varies throughout the Lee Formation, with total dissolved solids ranging from about 150 mg/l to more than 1,000 mg/l. A generalization of the quality of water is presented on plate 4 drawn on the basis of 26 of the chemical analyses shown in table 3.

In this report, fresh water is subdivided into two categories; (1) water that contains 0–400 mg/l dissolved solids and (2) water that contains 400–1,000 mg/l dissolved solids. The division is based on the ratio of chloride to dissolved solids. The curve of a plot of chloride versus dissolved solids (fig. 11) shows a distinct change in slope at 400 mg/l dissolved solids. Above this point the ratio of chloride to dissolved solids is decreasing; below this point the ratio of chloride to dissolved solids is increasing.

Elliott, Johnson, Lawrence, Magoffin, and Morgan Counties, Ky. (Continued)

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 (micromhos at 25° C)	pH	Color	Carbon dioxide (CO_2)
								Calculated	Residue at 180° C	Ca, Mg	Noncarbonate				
Surface water—Continued															
----	----	----	----	----	500	----	----	----	----	----	----	----	----	----	----
----	----	----	----	----	6,860	----	----	----	----	----	----	----	----	----	----
----	----	----	----	----	7,500	----	----	----	----	----	----	----	----	----	----
----	----	----	----	----	1,510	----	----	----	----	----	----	----	----	----	----
----	----	----	----	----	400	----	----	----	----	----	----	----	----	----	----

[4] Computed from specific conductance.
[5] Analysis supplied by Amox Petroleum Co.
[6] Taken from graph figure.
[7] Analysis suppled by Kentucky Water Pollution Control Commission.
[8] Analysis supplied by Kentucky State Department of Health.

The water in most of the Lee Formation contains less than 400 mg/l total dissolved solids (pl. 4). The presence of saline water at Keaton in Johnson County and Falcon in Magoffin County is the result of contamination and is discussed on page 33.

Water having total dissolved solids ranging from 400 to 1,000 mg/l is found at the base of the Lee Formation in the shale and siltstone unit. This unit is generally about 80 feet thick but thins toward the west to less than 20 feet, and may not be present in the northwest near Sandy Hook in Elliott County. Fresh water, in some places sulfurous, is present in the Mississippian limestone underlying the Lee Formation just west and northwest of the study area, and may be present near Sandy Hook.

The contact of fresh and saline water is not as abrupt as shown on plate 4; instead, it is a zone of diffusion ranging from less than 40 feet to more than 100 feet thick. To the southeast of Paintsville in Johnson County and Burning Fork in Magoffin County the interface is within the Lee Formation. The position of the interface is discussed more fully in the section "The fresh-saline water interface."

The chemical difference between saline water and the two types of fresh water is represented by the three curves shown in figure 12. These curves were plotted using equivalent milligrams per liter of chloride, bicarbonate, and sulfate for three ranges of total dissolved solids (0–400 mg/l, 400–1,000 mg/l, and greater than 1,000 mg/l). The concen-

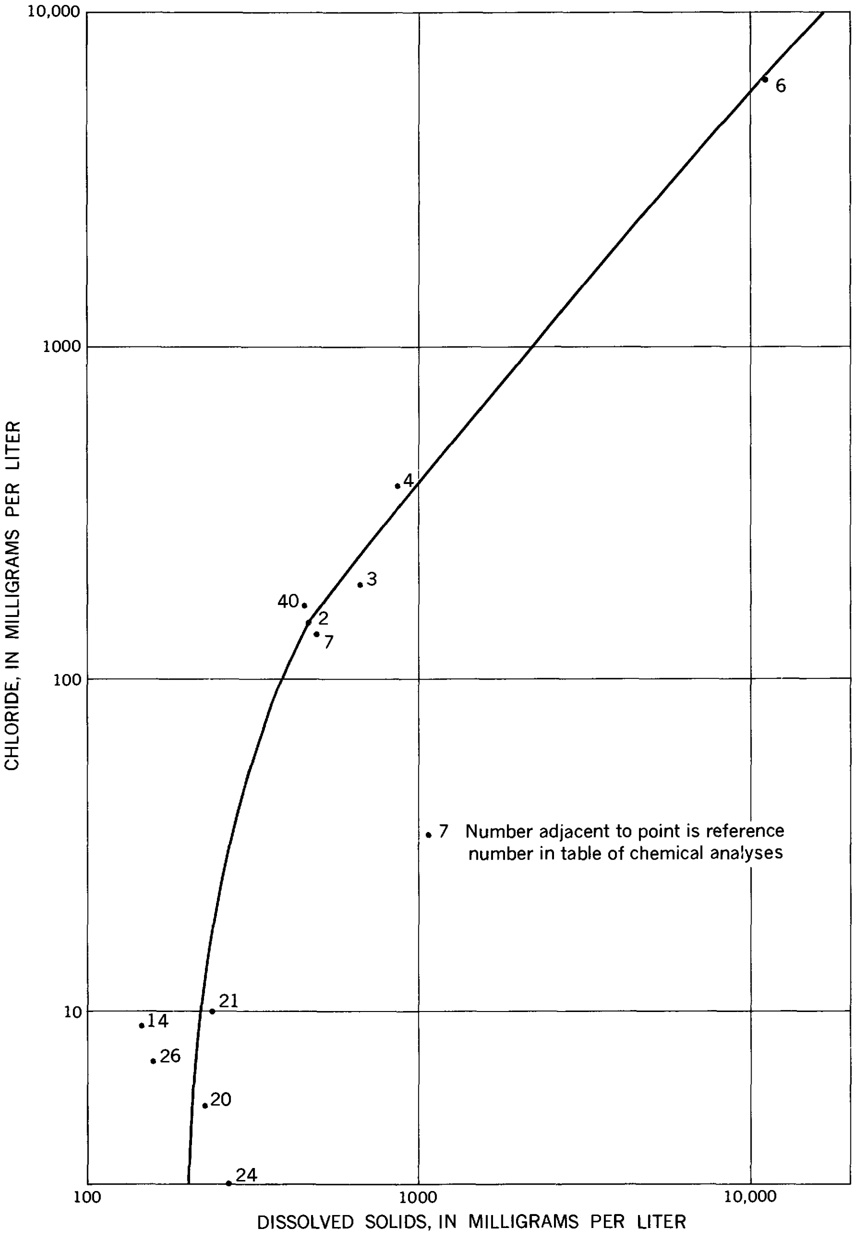

FIGURE 11.—Dissolved solids versus chloride concentrations.

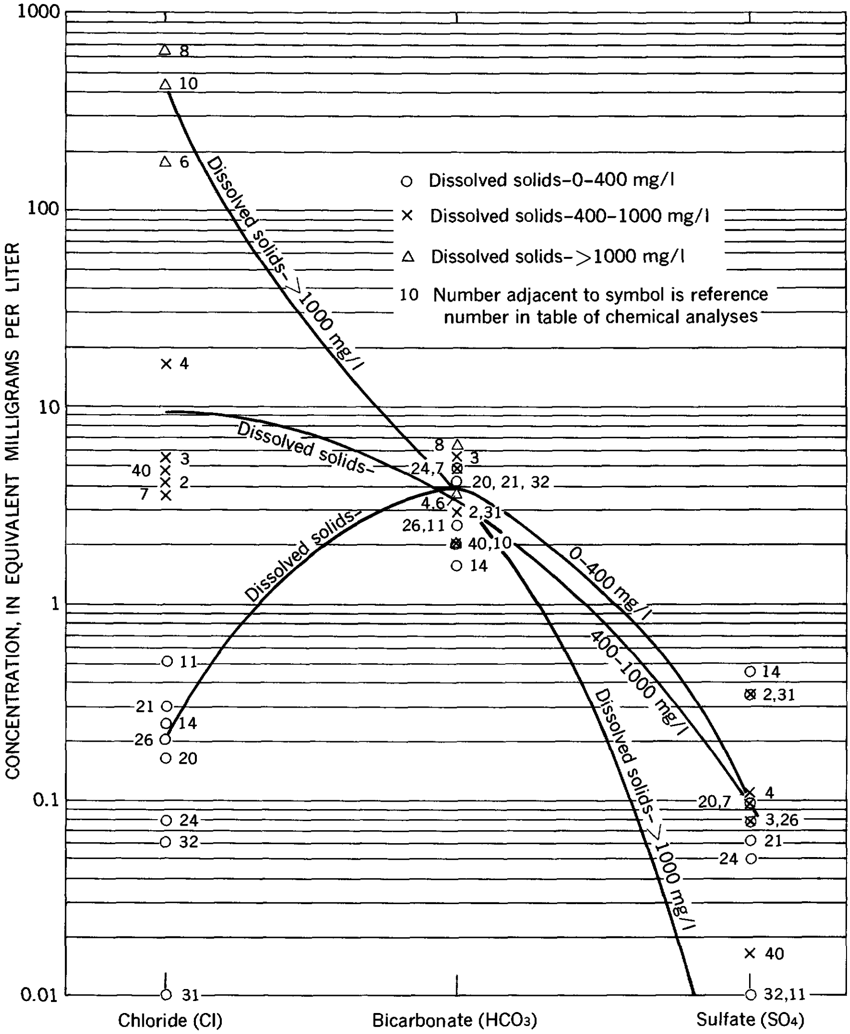

FIGURE 12.—Characteristic curves for three ranges of dissolved solids (0–400 mg/l, 400–1,000 mg/l, and greater than 1,000 mg/l) based on chloride, bicarbonate, and sulfate concentrations.

tration in equivalent milligrams per liter is plotted on the logarithmic scale. The range of total dissolved solids is represented by a symbol for each plotting.

The bell-shaped curve representing water with less than 400 mg/l of dissolved solids (pl. 4) shows the water to be a bicarbonate type, low in chlorides and sulfates. This is the type of water to be anticipated in drilling the Lee Formation, uncontaminated and of excellent quality except for iron and manganese. Iron and manganese combined exceed the U.S. Public Health Service (1962) recommendation of 0.3 mg/l in all but four wells sampled in the study area. The main objection to iron and manganese in domestic or farm supplies is that it discolors laundry and household and farm facilities, and gives an objectionable taste to beverages, especially the morning coffee. Industrial water users, mainly waterflood operators, reduce the iron concentration to below 0.3 mg/l where practical to prevent plugging of injection wells and the interstitial spaces in the oil sands.

The curve representing total dissolved solids ranging from 400 mg/l to 1,000 mg/l shows an increase in chlorides with bicarbonate and sulfate remaining basically the same as that for water with less than 400 mg/l total dissolved solids. The water is a sodium chloride bicarbonate type. The increase in chloride is accompanied by an increase in hardness as calcium carbonate. Hardness generally ranges between 175 and 250 mg/l (the U.S. Geological Survey classifies water with 121–180 mg/l calcium carbonate as hard and with more than 180 mg/l calcium carbonate as very hard). Hardness is a detriment to domestic, farm, and industrial supplies in that it forms scale in boilers, water heaters, and water pipes, and drastically reduces the efficiency of household soaps. For example, by reducing hardness of a municipal water supply from 400 mg/l to 85 mg/l, approximately 140 pounds of soap per year can be saved by an average family of five persons (Betz, 1953, p. 205).

The curve representing dissolved solids greater than 1,000 mg/l shows a sharp increase in chlorides while the sulfates, owing to sulfate reduction, approach zero. The bicarbonate remains basically the same as for each of the other two curves. The water is a sodium chloride bicarbonate type. Chlorides in water having more than 1,000 mg/l dissolved solids generally exceed the U.S. Public Health Service recommended limit of 250 mg/l, and give a salty taste to the water that makes it undesirable for drinking or use in beverages. Hardness as calcium carbonate may be greater than 300 mg/l, well above the lower limit for very hard water. The presence of water of this quality in the Lee Formation is the result of contamination.

THE FRESH-SALINE WATER INTERFACE

The fresh-saline water interface as shown on plate 4 generally coincides with the contact of the Mississippian and Pennsylvanian rocks, except near Paintsville in Johnson County and Burning Fork in Magoffin County where it is within the Lee Formation, and near Sandy Hook in Elliott County where it is within the Newman Limestone of Mississippian age.

The silt and shale unit at the base of the Lee Formation is relatively impermeable when compared with the overlying fine- to coarse-grained crossbedded sandstone and the underlying fine- to medium-grained dolomitic limestone with well-formed solution openings. This relatively impermeable unit restricts the upward movement of saline water from the Mississippian and older rocks, and the downward movement of fresh water from the Lee Formation.

Toward the northwestern part of the study area the silt and shale unit at the base of the Lee Formation thins, and is absent near Sandy Hook in Elliott County; therefore, the flow of water between the Lee Formation and the underlying Mississippian rocks is not restricted. In the vicinity of Sandy Hook the fresh-saline water interface is about 100 feet below the Mississippian-Pennsylvanian contact, based on records for oil- and gas-test wells drilled in the area. The records of oil- and gas-test wells indicate shows of oil and (or) gas at 130 to 200 feet below the Mississippian-Pennsylvanian contact. Brine is associated with oil and gas in the Mississipian rocks and is probably present although not reported with the oil and gas shows in these test wells. The position of the brine serves to place the top of the interface at a point above the shallowest reported show of oil, 130 feet below the Mississippian-Pennsylvanian contact. The base of the interface would be the point at which the brine was intercepted. No water wells of sufficient depth are available for establishing the exact position of the interface in this area.

The municipal water-supply well for Sandy Hook is finished open hole in the Lee Formation to a point just above the Newman Limestone of Mississippian age. The flow of ground water toward this well during periods of withdrawal is from both the Lee Formation and underlying Newman Limestone, as shown in figure 13.

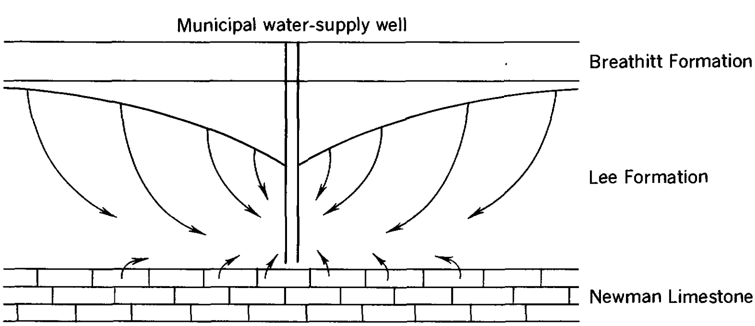

FIGURE 13.—Ground-water flow toward the municipal water-supply well finished open hole in the Lee Formation to a point just above the Newman Limestone of Mississippian age at Sandy Hook in Elliott County.

Comparison of chemical analyses of water samples 51 and 51a, table 3, collected at this well in 1959 and 1965, respectively, shows a sharp increase in iron, manganese, and sulfate with a decrease in bicarbonate. These changes in chemical quality indicate that the aquifer environment has been transformed from a chemical equilibristic environment to an iron-reducing environment. The chemical changes suggest that the iron is derived from solution of an iron sulfide mineral, such as pyrite, present in the Lee Formation. There is no indication that the change in chemical quality was brought about by water with higher mineral content moving upward from below as there is no appreciable change in the dissolved-solids concentration.

Southeast of Paintsville in Johnson County, the interface is within the Lee Formation. This is a natural condition and reflects two different hydrologic environments. Within the study area northwest of Paintsville, recharge and discharge areas are exposed at land surface and flushing by fresh water (precipitation) has replaced most of the brine, oil, and gas, accordingly, the Lee Formation is a fresh-water aquifer. Southeast of Paintsville the Lee Formation passes beneath the surface as it continues the regional dip to the southeast and does not crop out again until it is brought to the surface along the Pine Mountain thrust fault, approximately 44 miles to the southeast near the Kentucky-Virginia State line. The limited recharge and discharge areas southeast of Paintsville have restricted any major flushing activity such as occurred to the northwest, and the Lee Formation contains brine. The Lee Formation is a commercial gas sand in Floyd County adjoining Johnson County to the south.

The present position of the interface southeast of Paintsville is static; the hydrostatic pressures on the fresh and saline sides are in balance. Any change in the hydrostatic pressure as the result of withdrawals from the Lee Formation will cause the interface to move toward the center of withdrawal. Consequently, large withdrawals in the vicinity of Paintsville would cause the interface to move toward the discharging well, although very slowly.

Southeast of Burning Fork in Magoffin County the natural interface is similarly within the Lee Formation. Analysis 1, table 3, is of a composite sample of water from two or more wells finished in the Lee Formation in this area, and shows that the water in the Lee Formation is saline. Just southeast of this area, fluids in the Lee Formation are reported to be brine, however, no analyses are available to substantiate this.

Here, again, the position of the interface reflects two different hydrologic environments. South and east of Burning Fork the Lee Formation continues its regional dip to the southeast beneath the

Breathitt Formation, and outcrop areas through which recharge and discharge may occur are limited. However, in the immediate area of Burning Fork, dilution has occurred from fresh water flowing southeastward from recharge areas to the northwest (analyses 2–4, table 3).

SOURCES OF CONTAMINATION

The presence of saline water in the Lee Formation to the southeast and east of the study area is a natural condition; however saline water in the Lee Formation within the study area is the result of contamination. Contamination of fresh water in the Lee Formation occurs in two ways; the upward movement of brine through abandoned oil and gas wells drilled to pay zones in the Mississippian and older rocks, and the downward movement of saline waste water from oil separators through water wells drilled "open hole" in the Breathitt Formation and finished in the Lee Formation. Of these two methods, the upward movement of brines has produced the most apparent effect at specific locations such as Keaton in Johnson County and Falcon in Magoffin County, whereas the downward movement of water from above has been less apparent, but more widespread.

There is no evidence that either brine or saline water is presently moving upward or that fresh water is moving downward along any of the faults in the study area. However, there is indirect evidence that brine may have moved upward with oil from the Weir sand of Mississippian age in the past. McFarlan (1943, p. 357) states that I. B. Browning attributes the lack of oil production from the Weir sand on the northwestern flank of the Mine Fork dome to the loss by seepage along the Irving-Paint Creek fault.

In the Keaton section of Johnson County the presence of saline water in the Lee Formation on the south side of the Blaine Creek fault (fig. 14) is the result of contamination from below. Contamination also occurs on the north side of the fault but is not as apparent. The brine causing the contamination has moved upward through old and abandoned oil- and gas-test wells under pressures created by the secondary recovery of oil in the area. Two curves representing the chloride, sulfate, and bicarbonate concentrations in equivalent milligrams per liter for water on the north and south sides of the fault are shown in figure 15. These curves, when compared with the curves in figure 12, show that the curve for water on the south side of the fault has a similar shape as that for saline water, and the curve for water on the north side of the fault has the same shape as that for fresh water having dissolved solids of 400 to 1,000 mg/l. In both places the ratio of chloride to dissolved solids is decreasing, a characteristic of brine invasion of fresh water. The sulfate in the saline water on the

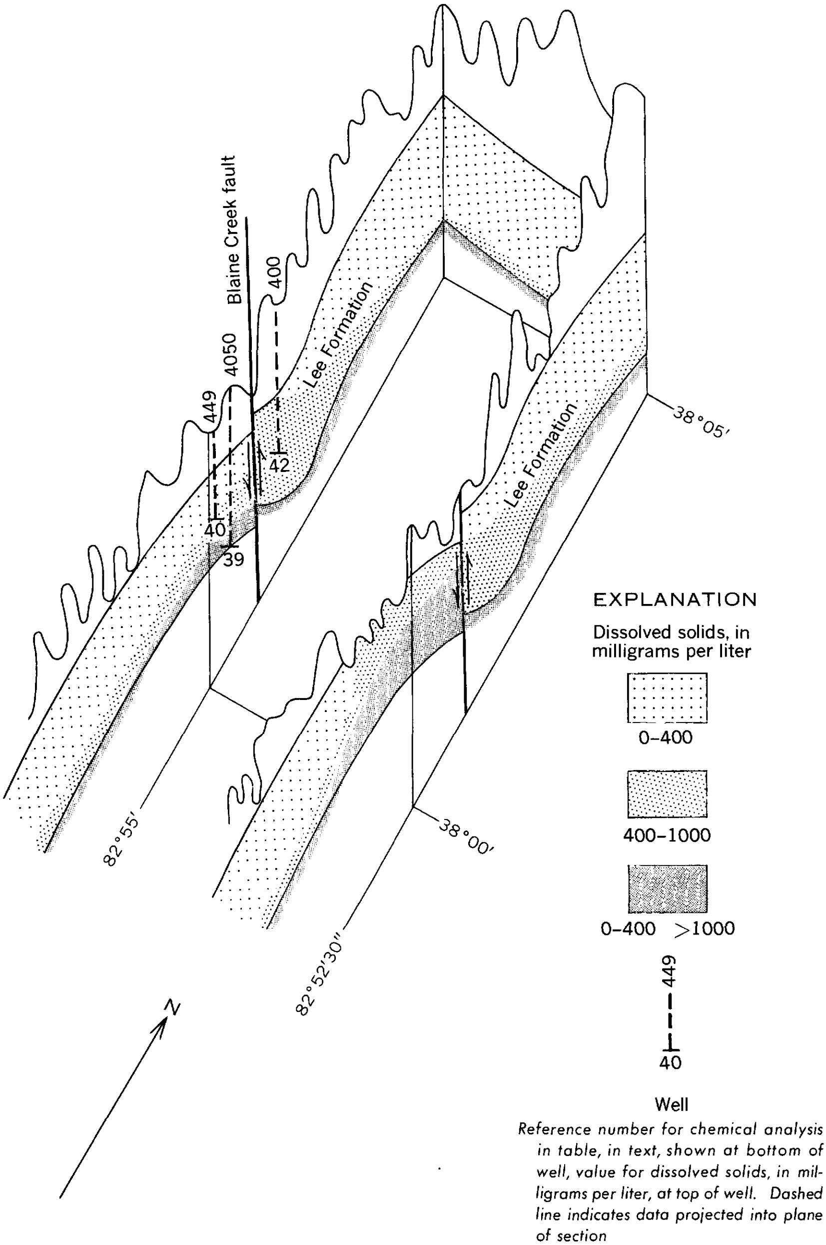

Figure 14.—Quality of water in the Lee Formation on the north and south sides of Blaine Creek fault in the Keaton section of Johnson County.

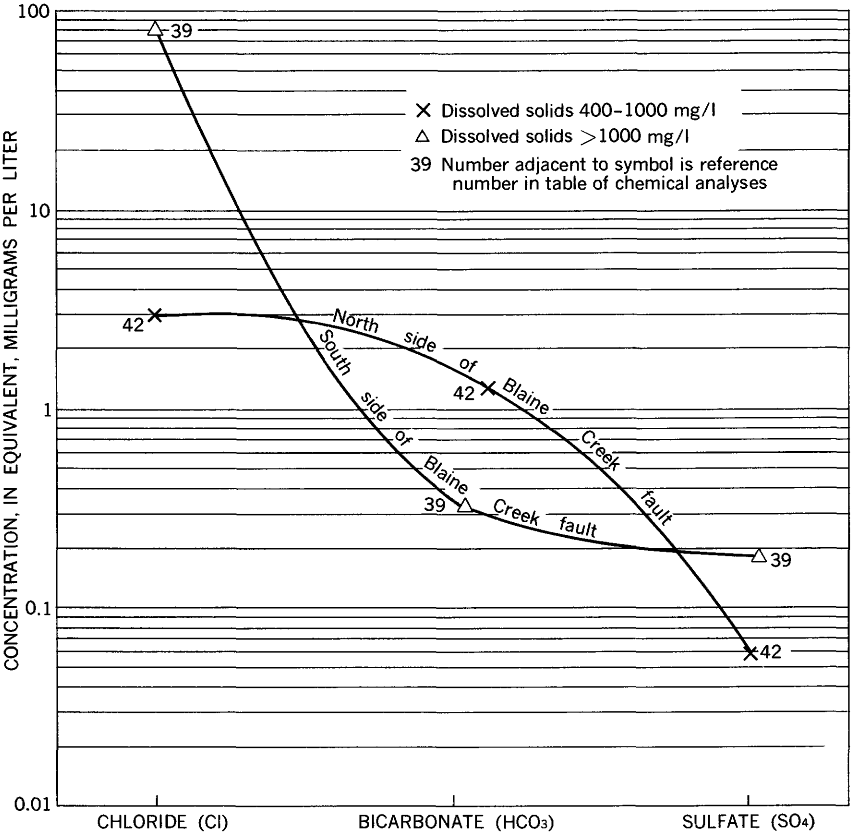

FIGURE 15.—Characteristic curves for water on the north and south sides of Blaine Creek fault.

south side of the fault probably is due to the presence of gypsum and (or) the more readily soluble sodium, potassium, and magnesium sulfates in the source rock (limestones of Mississippian and Devonian ages) containing the brine.

This high iron concentration, 17.0 mg/l, reported in the analysis of a composite sample of untreated water from the south side of the fault as compared with the 0.2 mg/l of iron reported in a similar analysis of untreated water from the north side of the fault may be due to a reducing environment enhanced by the introduction of brines from below. Data are insufficient to state specifically that this is the cause of the high iron concentration. However, the problem is significant and warrants further study. There is some indication of contamination from above, but it is inconclusive and masked by the contamination from below in the area.

A list of other chemical constituents is shown in table 3; analysis 39 for water on the south side of the fault and analysis 42 for water on the north side of the fault were made of composite samples of untreated water from two or more wells in each area.

The upward movement of brine occurs through unrecorded wildcat oil- and gas-test wells and initial production wells drilled prior to the present organized production methods employed in this field. These old wells drilled in the early 1920's and 30's were in many places simply backfilled with or without a near-surface plug, or plugged at one or more places to protect the fresh water and oil and gas sand or sand beds; the old plugging methods were inadequate compared to modern plugging methods now used in this oilfield. Present production-well construction and plugging methods are designed to prevent any interflow among oil and gas sand beds and fresh-water aquifers and saline-water aquifers.

Prior to waterflooding, which began about 1960, fluid levels in the Weir sand of Early Mississippian age were at about 600 feet above mean sea level, and in the Lee Formation about 700 feet above mean sea level at Keaton. Under pressure from waterflood, fluid levels in the Weir sand may equal 700 feet above mean sea level near Keaton. The base of the Lee Formation is at about 450 feet above mean sea level here. The fluid levels under natural conditions and under pressure by waterflood are, therefore, of sufficient magnitude to rise above the base of the Lee Formation in this area. Under natural conditions, flow would be from the Lee Formation into the Weir sand through the old wells, but sufficient lowering of the fluid levels by withdrawals from the Lee Formation would cause brine to move from the old wells into the Lee Formation.

The present static level in the Lee Formation is about 680 feet above mean sea level at Keaton and decreases to about 660 feet above mean sea level near the Blaine Creek fault. The effect of pumping the Lee Formation and the path of brine movement from the old abandoned hole down the hydraulic gradient toward the water-supply well, resulting in contamination of the fresh water, are shown diagrammatically in figure 16. The exact amount of brine entering the Lee Formation in this area is not known; however, dilution in the composite water sample (analysis 39, table 3) is about 22 gallons of fresh water for each gallon of brine. The brine in the Weir sand of Mississippian age contains approximately 65,000 mg/l of chloride in the immediate area.

On the north side of the Blaine Creek fault, water in the Lee Formation shows evidence of contamination, but it is not so apparent as on the south side. Analysis 42, table 3, shows the chloride concentration

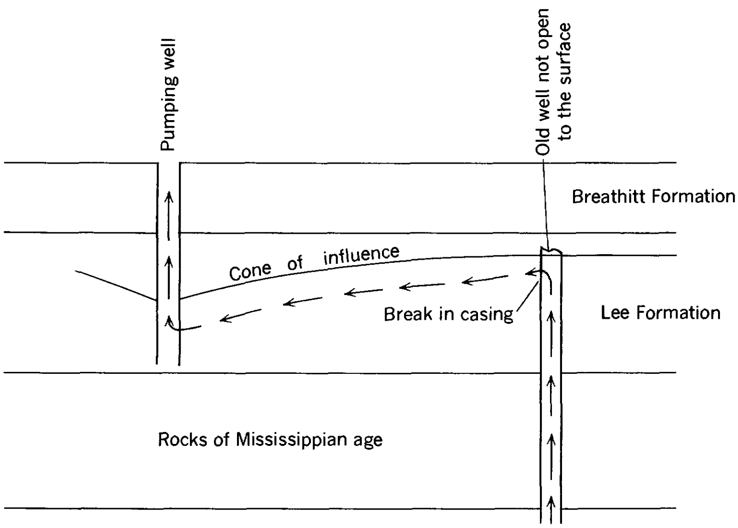

FIGURE 16.—Movement of brine from oil pay upward through an abandoned well drilled to oil- or gas-pay zones toward a pumping water-supply well in the Lee Formation.

to be 103 mg/l, higher than the 10 mg/l chloride or less for natural water in the Lee Formation; carbon dioxide is high at 26 mg/l and is an indication of contamination by oil-field water; however, the analyses show none of the hydrogen sulfide generally associated with carbon dioxide through sulfate reduction. The contamination on the north side of the fault occurs in the same manner as that described for the south side.

Contamination in the Falcon area of Magoffin County occurs by brine moving up abandoned oil- and gas-test and production wells drilled in the early 1920's and 30's in the same manner as that described for the method of contamination on the south side of the Blaine Creek fault in the Keaton area of Johnson County.

The maximum contamination occurs at the base of the Lee Formation where most of the water-supply wells for waterflood operations are finished. The brine moves from the old and abandoned holes toward these water-supply wells during periods of pumping. Analyses 6 and 7, table 3, are for two wells at Falcon about 0.1 mile apart. The shallower of the two wells has a chloride concentration of 137 mg/l and dissolved solids of 485 mg/l; the deeper well open in both the lower and upper parts of the Lee Formation has a chloride concentration of 6,360 mg/l and dissolved solids of 11,090 mg/l. The considerable amounts of oil recorded in the remarks column for the latter sample moved up with the brine from the pressured oil sand below through one or more old abandoned holes. Analysis 5, table 3, for a water-supply well 0.7 mile due east of these wells and open only in the lower 114 feet of the Lee Formation has a chloride concentration of 124 mg/l and dissolved solids estimated to be 420 mg/l.

The relatively high chloride concentration present in the water-supply well at Falcon, open to the entire thickness of the Lee Formation, is not reflected in the well 0.1 mile to the northwest, finished in the upper part of the Lee Formation, nor the well 0.7 mile to the east, finished in the lower part of the Lee Formation. The old well(s) through which the brine and oil is moving up from the pressured formations is probably within the immediate vicinity of the water-supply well at Falcon.

At Salyersville and in the Burning Folk area about 2.5 miles southeast of Saleyrsville, analyses show that water from the Lee Formation has dissolved solids in the range of 400 to 1,000 mg/l. The high chloride concentration of 716 mg/l (analysis 1, table 3) shown for the Burning Fork area is the result of its proximity to the Fresh-saline water interface which is entirely within the Lee Formation just southeast of the area.

Contamination of the Lee Formation and the Breathitt Formation from above results from disposal of brine from oil separators into surface streams. (See analysis 6b, table 3). The brine with minimum dilution during the periods of low flow (mid-June through November) move downward by natural infiltration, primarily along joint systems, from the streams to the shallow aquifer in the Breathitt Formation, and by induced infiltration from pumping wells near the stream throughout the year. The downward route from the shallow aquifers in the Breathitt Formation to the deeper confined aquifers in the Lee Formation is through wells that are drilled to the Lee Formation but are open to the Breathitt Formation because shallow surface casing is used. If the static water level in the Lee Formation is lower than the static water level in the shallow aquifers, as frequently true, contaminated water with high chloride concentration will flow by gravity from the shallow aquifer into the deeper well finished in the Lee Formation. This flow contaminates the water in the well. With time the contamination will spread to that part of the Lee Formation adjacent to the well. If the static water level in the Lee Formation is higher than that in the shallow aquifer, water with high chloride content is brought into the deeper well when the water level is lowered during successive periods of pumping. During repeated periods of pumping, the rising and falling of the water level mixes the fresh water from the Lee Formation with the high chloride water from the shallower aquifer in the well, eventually contaminating the aquifer.

Excellent examples of this condition are noted at two wells on a farm adjacent to State Road Fork in the Paint Creek drainage area at the Johnson-Magoffin County line. The dug well on this farm is 17 feet deep and has a chloride concentration of 18.0 mg/l (analysis 58, table 3), and a drilled well in the Breathitt Formation, 75 feet deep, has a chloride concentration of 2,450 mg/l (analysis 57, table 3). State Road Fork [2], which drains the area, is less than 200 feet from both wells and had a chloride concentration of 1,850 mg/l when sampled (analysis 65, table 3). The bottom of the dug well is approximately 5 feet higher than the bed of State Road Fork at this point and, therefore, is not contaminated by brines from the stream.

The substantially lower chloride concentration in State Road Fork as compared with water from the 75-foot well results from dilution of the brine in State Road Fork at the time the sample was collected. The higher chloride concentration in the well reflects contamination at this point in the Breathitt Formation by natural and induced infiltration from State Road Fork prior to sampling. A drilled well, 85 feet deep, finished in the Breathitt Formation about 0.75 mile downstream at Oil Springs had a chloride concentration of 5,400 mg/l on April 26, 1961 (analysis 59, table 3). It was necessary to deepen the well at Oil Springs High School, just east of these wells, as a result of contamination from above.

A similar pattern of contamination occurs at Salyersville. Samples of river water collected in 1960 and 1963 showed chloride concentrations of 1,510 mg/l at the gaging station on Licking River just west of Salyersville, 1,375 mg/l in Mash Fork just east of Salyersville, and 6,860 mg/l in State Road Fork [3] at Salyersville. Other chloride concentrations for these streams are given in table 3.

An abandoned domestic-supply well, finished in the Breathitt Formation below the level of the local drainage just north and east of Saylersville, has a chloride concentration of 1,200 mg/l (analysis 56, table 3). An unused recreational-supply well, finished in the upper part of the Lee Formation about 0.5 mile southwest of the abandoned domestic-supply well, has a chloride concentration of 380 mg/l. The municipal-supply well at Salyersville, finished in the Lee Formation about 3,000 feet west of the unused recreational well, has a chloride concentration of 192 mg/l.

The above statements indicate that the chloride concentration is decreasing downward from the shallow aquifers in the Breathitt For-

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[2] State Road Fork in the Oil Springs area, Johnson County, flows due east to Barnetts Creek, a tributary of Paint Creek, and drains areas of oil production using waterflood for oil recovery.

[3] State Road Fork in Magoffin County flows due west to the Licking River and drains areas of oil production using waterflood for oil recovery.

mation immediately below the level of the local drainage to the base of the Lee Formation. Chemical analyses for the Salyersville municipal-supply well listed below show that the concentrations of chloride and dissolved solids are increasing with time.

Date sampled	*Dissolved solids (mg/l)*	*Chloride (mg/l)*
July 30, 1952	582	160
Mar. 27, 1958	655	192
Nov. 18, 1966	685	205

The rate at which downward movement of saline water occurs is accelerated in the Salyersville area by pumping of the municipal-supply well, as evidenced by the decline in water level in the unused recreational well during periods of pumping. For example, in September 1966, the municipal-supply well pumped continuously for about 6 days; during this period a decline of about 9 feet in water levels in the unused recreational well resulted in an increase in the hydraulic gradient toward the municipal-supply well for a distance of more than 3,000 feet. The increased hydraulic gradient increased the rate of ground-water flow toward the pumping well.

Recent termination of several small waterflood operations because of declining oil production and successive cutbacks at some continuing operations should reduce the chloride concentrations in these streams. Although chloride concentrations in these streams will be reduced almost immediately, flushing of the shallow aquifers will require years before any noticeable change occurs.

Samples 61 and 62, table 3, collected on the same day from Paint Creek 1,000 feet north of the gaging station at Staffordsville and from Paint Creek near Elna, show chloride concentrations of 354 and 220 mg/l, respectively. The Lee Formation outcrops in this reach of Paint Creek and ground-water discharge from this formation prevents inflow of high chloride water. There is little pumping in this reach of Paint Creek to lower the head and induce infiltration from Paint Creek into the Lee Formation.

It is evident from the preceding examples that contamination from above can be more extensive, but less apparent, than contamination from below.

In the preceding discussion the presence of water with relatively high chloride concentration in the shallow aquifers under natural conditions was excluded because there is no evidence that this condition exists. Instead, the pattern of high chloride water locally in the shallow aquifers and streams results from contamination.

NATURAL FLUSHING OF THE LEE FORMATION

The fresh water in the Lee Formation is the result of a natural flushing activity that commenced approximately 270 million years ago at the close of the Paleozoic Era.

At the close of the Pennsylvanian Period the interstitial and secondary openings in the Lee Formation were filled with brine, oil, and gas. The brine was entrapped during deposition, and the oil and gas were derived from organic material within the source rocks after deposition. The initial phases of flushing were essentially dilution of the brine near the recharge areas on the Laurel Creek and Mine Fork domes with only a slight loss of brine, oil, and gas at limited discharge areas in the valley of Paint Creek in the immediate vicinity of the Irvine-Paint Creek fault, and the valleys of Upper and Lower Laurel Creeks on the south side of the Blaine Creek fault. Base leveling of the land surface at the close of the Cretaceous Period, about 100 million years later, enlarged both the recharge and discharge areas substantially, but to less than their present extent. After the period of base leveling the present flow system was initiated. As the recharge and discharge areas were enlarged, the extent of the flushing activity increased. As this process continued the water changed from saline to fresh with total dissolved solids of less than 400 mg/l.

The flushing process is still in progress. The brine has been replaced by fresh water, but residual oil and gas are still found in drilling some domestic- and industrial-supply wells. Of the two, gas from the sand near the base of the Lee Formation is most frequently found and may be sufficient for individual supplies, especially in the area just north of Salyersville in Magoffin County to near Crockett in Morgan County. Oil is seldom present except where trapped in quantities sufficient to produce more than a rainbow or oil slick on the water surface. In the area just east of the Morgan-Magoffin-Johnson County line the base of the sandstone overlying the basal shale section is reported to "bleed" oil locally in fresh cuts. Some oil production has been reported from the lower part of the Lee Formation at Royalton in Magoffin County, about 5 miles south of Salyersville. This oil production from the lower part of the Lee Formation could not be verified, however.

Asphalt has been reported to occur in the upper section of the Lee Formation in the area bounded by Flat Gap, Redbush, and Keaton in northwest Johnson County.

Petroleum residues or high chloride water need not be an obstacle to withdrawing fresh water from the Lee Formation as these zones can be sealed off by proper well construction. Residual gas may be a problem, but proper venting and (or) aeration will allow most of the gas to escape.

CONCLUSIONS

The Lee Formation contains sufficient fresh water for present industrial, public, rural domestic, and farm supplies, but there is some contamination. Maximum development of this aquifer to provide water supplies needed for redeveloping the economy of the study area is of major importance. Available data are insufficient to predict potential yields from the Lee Formation in specific locations, nor is it practical to do so. Instead, future development of this formation for the withdrawal of water should require proper testing of the aquifer to determine its hydrologic characteristics at the proposed drilling site. These data can be used to determine the extent of the cone of influence whereby proper well spacing for optimum development of the Lee Formation as a fresh-water aquifer may be ascertained.

Future water-supply wells drilled near areas of contamination or near the natural position of the fresh-saline water interface within the Lee Formation will cause saline water to move toward the pumping well as the cone of influence extends outward from the well with time and intercepts an area of contamination. The time at which the cone of influence will intercept an area of contamination and the rate of movement of saline water toward the pumping well can be ascertained from the hydrologic properties of the aquifer and by flow-net analysis of the Lee Formation in the immediate area.

On plate 4 all areas where the fresh-saline water interface is within the Lee Formation, other than the areas southeast of Paintsville in Johnson County and Burning Fork in Magoffin County, are the result of contamination from below or above or a composite of both. No decrease in the extent of contamination can be expected in the immediate future; not because present regulations are inadequate, but because there were no regulations in effect when the oil and gas fields were initially developed in the early 1900's. It was then that the present sources and methods of contamination were unknowingly introduced into the area. Contamination is not restricted to the Lee Formation, but also has occurred in the overlying Breathitt Formation and in the streams draining the area.

Water withdrawn from the Lee Formation used for cooling or in a process that does not contaminate it or expose it to the atmosphere may be returned to the formation through a recharge well. The recharge well can be located so as to reduce or stop the movement of saline water toward the pumping well. Returning water to the aquifer should be practiced throughout the study area, especially where large quantities of water are involved and only reduction of temperature or limited treatment is required.

Should future development of the Lee Formation incorporate aquifer testing and water-conservation practices it probably will sustain yields of 10–15 gpm from shallow wells near outcrop areas, and 25 gpm or more from fully penetrating wells throughout most of the study area.

As demands for water in the area increase, further studies will be needed of additional problems such as the iron content of the water, sources and methods of contamination, well spacing in specific areas, and availability and quality of surface water and water in the Breathitt Formation.

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