GEOHYDROLOGY OF PARTS OF MUHLENBERG, OHIO, BUTLER, MCLEAN, TODD, AND LOGAN COUNTIES, KENTUCKY

By J. Jeffrey Starn, Robert W. Forbes, Charles J. Taylor, and Martin F. Rose

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Multiply	By	To obtain
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
gallons per minute (gal/min)	0.06309	liters per second
gallons per day (gal/d)	90.8496	liters per second
feet per day (ft/d)	0.3048	meters per day
foot squared per day (ft^2/d)	0.09290	meter squared per day

Degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) by use of the following equation:

$$°F = (9/5)(°C) + 32$$

Sea Level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Abbreviated water-quality units used in this report: Chemical concentrations and water temperature are given in metric units. Chemical concentration is given in milligrams per liter (mg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

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ABSTRACT

Water-level, water-use, water-quality, and aquifer-yield data were collected during a well inventory in 1991 in part of western Kentucky. The data were overlain on digital maps by means of a Geographic Information System to interpret the geohydrologic conditions within the study area. Most wells are less than 300 feet deep and produce water from the uppermost geologic formation. The discontinuous lithology of rocks in the area results in aquifers of limited areal extent in which local ground-water flow systems are developed; however, the regional ground-water flow generally is toward the broad alluvial areas along the Green and Rough Rivers. Fewer wells were in use in 1991 than in the 1960's when a similar well inventory was conducted; this decrease is probably due to expansion of the service areas of several public water-supply systems. The quality of ground water is generally suitable for domestic use, except for a few wells that produce water with low pH and high concentrations of metals. The bacteriological quality of the water is variable and somewhat dependent on the quality of well construction. The specific capacity of wells was found to range from 0.08 to 0.3 gallons per minute per foot of drawdown. This range is somewhat less than values previously reported.

INTRODUCTION

The Kentucky Natural Resources and Environmental Protection Cabinet (KNREPC), Kentucky Division of Water (KDOW), is developing a system for the classification of aquifers in Kentucky. As a preliminary step, the KDOW and the U.S. Geological Survey (USGS) undertook a cooperative project to update the information contained in the USGS Hydrologic Atlas (HA) map series for Kentucky. The HA's describe the availability of ground water in Kentucky, but do not provide data on the movement, use, and quality of ground water, or on the yield of water-producing formations. In order to develop a system for the classification of aquifers in Kentucky, the information that is lacking in the HA's must be addressed. This study is intended to be a pilot study to supplement the data contained in the HA's.

During the 1960's and 1970's, a cooperative mapping program existed between the USGS and the Kentucky Geological Survey (KGS). The result of this program was a series of 1:24,000 Geologic Quadrangle (GQ) maps for the entire State. At the same time, another cooperative effort between the USGS and the KGS was aimed at producing a series of HA's for the State. Each HA encompassed several counties and was based on the results of well inventories. The information published in the HA's included the location and depth of each well, the depth to water in the well, the formation from which water was obtained, the general quality of the water (whether salty, highly mineralized, or sulfurous), and the type of pump used in the well.

Purpose and Scope

This report presents the results of a geohydrologic study of a selected area in western Kentucky. The study, conducted in 1991, provides an overview of the geohydrology of the area that will assist the KDOW in classifying aquifers, making regulatory decisions, and planning future studies. The study will also assist the University of Louisville in its effort to train students in the use of computers in geography. The first objective of the study was to compile and analyze existing spatial data through the use of geographic information system (GIS) technology. The second objective was to collect and analyze new data to supplement the existing data. These new data, collected in 1991, describe ground-water use, the depth to ground water, the quality of ground water, and the yield of water-producing formations. These data are discussed in relation to the geohydrologic framework presented in earlier reports. The results of this study are to be used to design future studies; therefore, the methods used and the results obtained by each method are discussed in detail.

Description of Study Area

The study area (fig. 1) encompasses 949 mi^2, mainly within the Western Coal Field physiographic region of Kentucky (Fenneman, 1938). A small area of the Mississippian Plateau region is represented in Logan and Todd Counties. The area is defined as the area shown on the following 1:24,000 topographic quadrangle maps: Livermore, Equality, Hartford, Horton, Central City West, Central City East, Paradise, Cromwell, Greenville, Drakesboro, Rochester, South Hill, Kirkmansville, Rosewood, Dunmor, and Quality. The selected quadrangles lie in parts of Muhlenberg, Ohio, Butler, McLean, Todd, and Logan Counties (fig. 2).

The northern part of the area is characterized by rolling hills and flat-topped ridges. The Mud, Rough, and Green Rivers traverse the area in broad, flat-bottomed alluvial valleys (McGrain and Currens, 1978). These rivers have a low gradient and tend to meander within their valleys. The northwestern part of the area, in McLean County, is characterized by patches of low hills that protrude like islands through broad, flat alluvial river bottoms. The southern part of the area is a well-dissected upland plateau. Valleys in this area tend to be narrow and steep-sided.

Previous Studies

The study area comprises an area that has been mapped on 16 geologic quadrangle maps (Gourdarzi, 1968, 1969; Guildersleeve, 1968, 1975; Hansen, 1972, 1974; Hansen and Smith, 1978; Johnson, 1971; Kehn, 1971, 1974, 1977, 1978; Miller, 1964; Moore, 1974; Palmer, 1969, 1972). (See fig. 2.) The availability of ground water in McLean and Muhlenberg Counties (Devaul and Maxwell, 1962) and Ohio and Butler Counties (Maxwell and Devaul, 1962a) has been reported in the HA map series, and a report that describes the ground-water resources of the Western Coal Field, based on the HA's, has been published (Maxwell and Devaul, 1962b). Two reports that discuss the occurrence and movement of ground water in the study area have been published since the HA's were completed. Davis and others (1974) investigated aquifers in channel-fill sandstones of Pennsylvanian age. This report includes maps of the extent and thickness of the aquifers and water levels in several channel-fill sandstones. The results of an aquifer test in one of the rock units is also presented. Ryder (1974) studied the alluvial valley-fill aquifer along the Green River. This report describes the lithology and hydraulic properties of the alluvial aquifer.

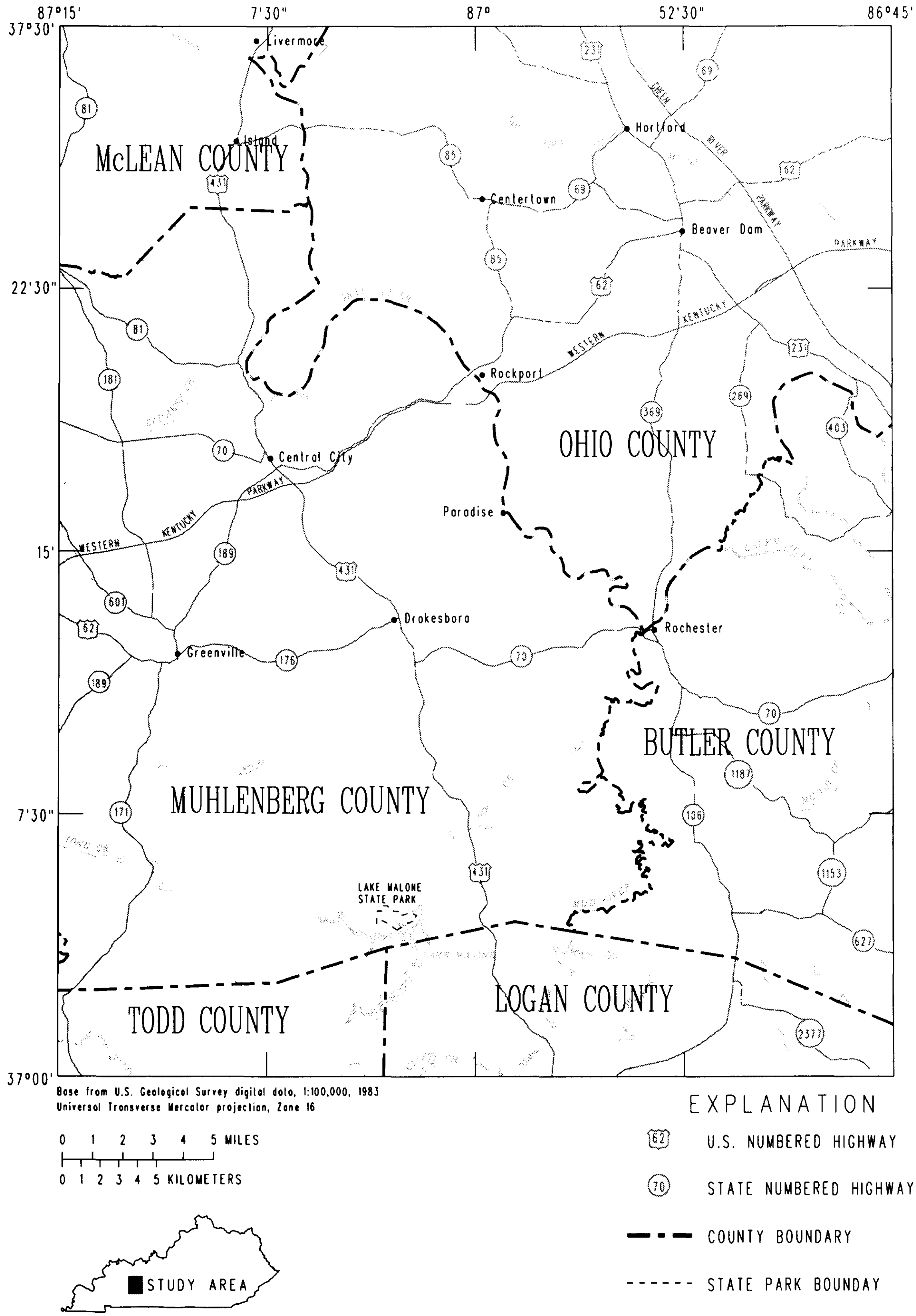

Figure 1.--The study area.

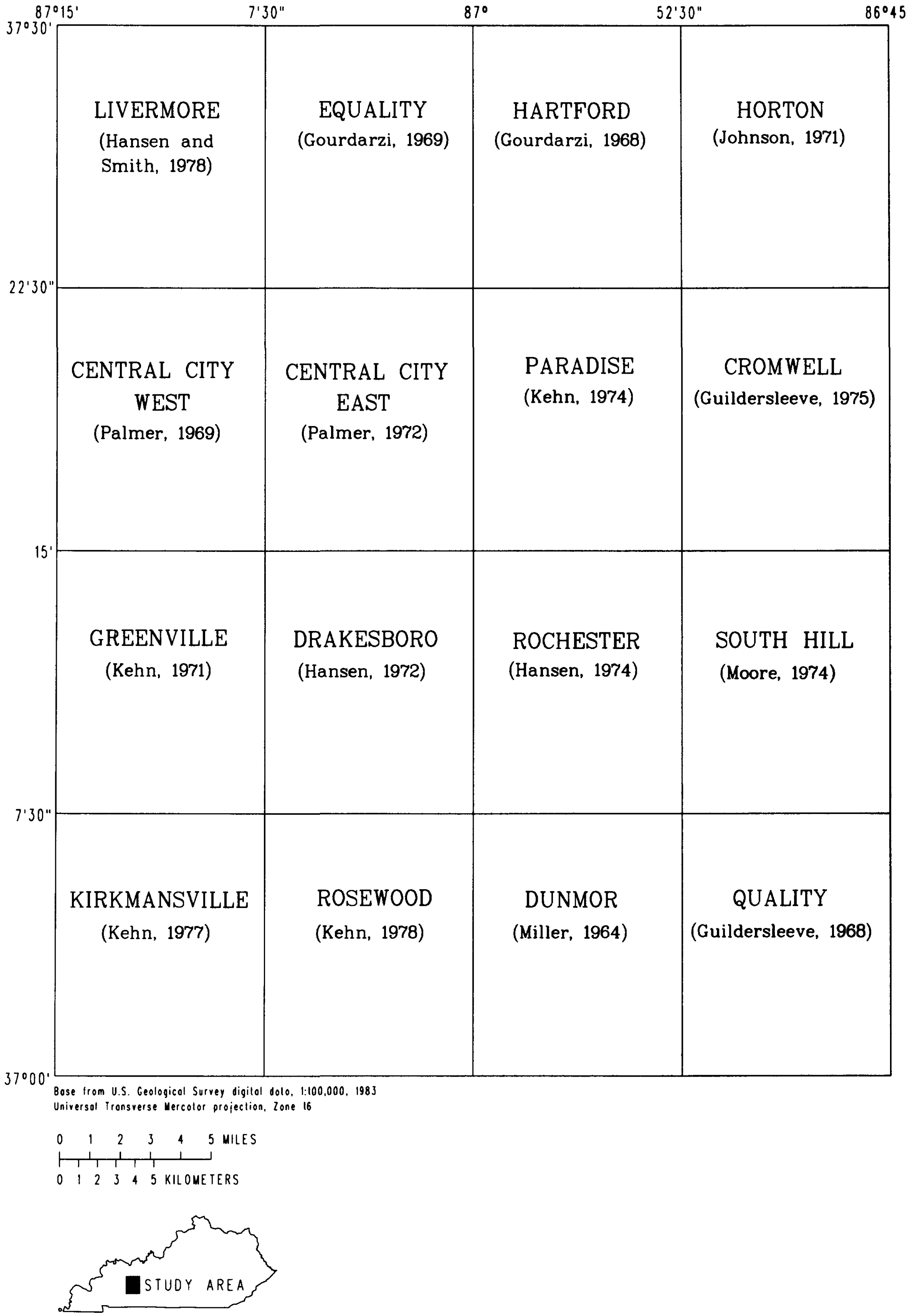

Figure 2.--Geologic quadrangles used in the study.

Acknowledgments

The authors wish to thank the many people who assisted in the collection of data during the study. Billy Mason and J. Mark Boggs of the Tennessee Valley Authority (TVA) provided information on ground water at the Paradise Coal Plant. County Environmentalists Mark Wilkerson of Muhlenberg County and David Miller of Ohio County provided much useful information on ground-water wells in their respective counties. Numerous local water companies provided information on their service areas. Of particular help were Mickey Morris of the Island Water District and Buddy Spencer of the Beaver Dam Municipal Water and Sewer System. The authors would also like to thank all of the homeowners who provided access to their wells for the inventory.

Methods of Study

Available data, in published reports and publicly accessible data bases, were merged and displayed using GIS technology. Existing wells then were inventoried in the field and records made of selected well characteristics. These records were added to the project data base. A subset of newly inventoried wells was selected for the investigation of aquifer yield and water quality.

The Ground-Water Site Inventory (GWSI) data base, a data base maintained by the USGS as part of the National Water Information System (NWIS), was used to store and manage the data for this study. Before 1991, GWSI contained records of about 240 wells in the study area (fig. 3). To supplement these data, records of about 70 additional wells in the study area were added to GWSI from the Assembled Kentucky Groundwater Data Base (AKGWA), a data base maintained by the KDOW.

Use of Geographic Information System Technology

New digital-data coverages were created for the study area, including a point coverage of well locations and polygon and line coverages of geologic features. The well-location coverage was generated from the latitude and longitude stored in GWSI. The information in GWSI is linked to the points in this data layer, so that the data can be analyzed based on the geographic location of the wells.

Three geologic coverages were created from each of the 16 geologic quadrangle maps--one depicting the uppermost geologic formation, one depicting faults, and one depicting structure contours. These coverages were edge matched to produce new coverages of the formation, faults, and structure for the entire study area. A second coverage depicting the uppermost geologic formation was created from the 1:250,000 Geologic Map of Kentucky (McDowell and others, 1981).

The two coverages depicting the uppermost formation (one at the 1:24,000 scale and one at the 1:250,000 scale) were overlaid in some areas to determine formation boundaries. For example, the Tradewater and Caseyville Formations are mapped as a single unit on the geologic quadrangle map of the Dunmor quadrangle. These formations are mapped as separate units on the Geologic Map of Kentucky based on information that was not available at the time the geologic quadrangle map was produced. The geologic map in this report (pl. 1) follows the geologic quadrangle maps except where the Geologic Map of Kentucky was needed to delineate formations.

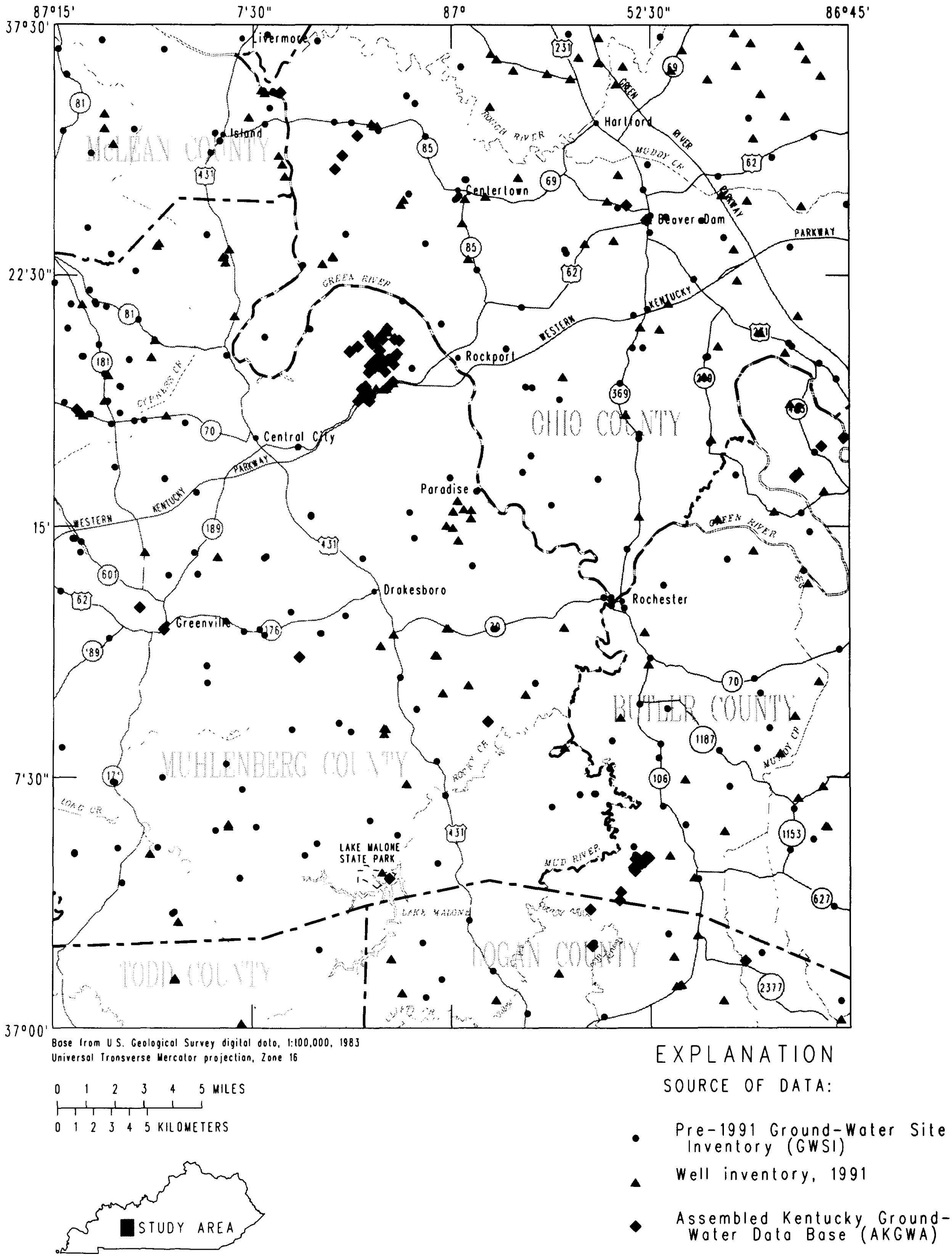

Figure 3.--Wells used in the study.

Well Inventory

The well inventory was conducted in late summer and early fall of 1991. Approximately 160 wells were inventoried during this period (fig. 3), including domestic, public water-supply, monitoring, and abandoned wells. Parts of the study area have been extensively strip mined for coal. Little or no new information was available in these areas. Information that was collected included the location, elevation, depth, and construction details of the well, the depth to water in the well, and the use of the water. The formation from which water is obtained was determined from the appropriate geologic quadrangle map, the depth of the well, and its stratigraphic position with regard to mapped coal and limestone marker beds and geologic contacts.

Many wells in the area are shallow hand-dug domestic wells. Such wells rarely penetrate rock units of regional interest and were generally excluded from the inventory. In areas where deeper wells were not present, hand-dug wells were inventoried. Also, hand-dug wells that are still in use were inventoried.

The Tennessee Valley Authority (TVA) maintains a network of monitoring wells at the Paradise Electrical Generation Plant. The coal-fired generation plant is located near Drakesboro in eastern Muhlenberg County. Water-level measurements, made by TVA personnel, were obtained for these wells. Also, driller's logs and historical water-level data were obtained from TVA.

Specific-Capacity Testing

Most water wells in the study area are completed as open holes in bedrock. Although wells are generally drilled until a rock unit is penetrated that yields sufficient water, the wells can be recharged by overlying water-bearing zones. Specific-capacity tests were conducted on selected water wells to obtain data on the quantity of ground water available in typical domestic wells. During the tests, wells were pumped with a submersible pump while the drop in water level in the well was monitored with an electric water-level tape at fixed time intervals. The pumping rate was monitored and regulated during each test to hold the discharge of water from the well approximately constant for the duration of the test. Typically, tests lasted 1 to 2 hours.

Quality of Water Analyses

Samples of ground water were collected from 12 wells in the study area. Wells were selected to achieve as even a distribution of wells among geologic formations as possible. It was not possible to sample ground water at many locations because the wellbores had collapsed or were plugged with rocks, debris, or pump equipment, or were located in inaccessible sheds or pits or swampy terrain.

To obtain a sample that was representative of the ground water and not affected by conditions within the borehole, all wells were pumped until either the borehole until was dry, or, as in most cases, successive measurements of the temperature of the water changed by less than 2° C, specific conductance changed by less than 10 percent, and pH changed by less than 0.2 units. The water sample was collected when one of the above conditions was met, depending on the yield of the well. If a borehole was purged until dry, the sample was not collected until the following day.

Wells with open boreholes were sampled using a submersible pump. Water samples were collected by filling the sample bottles directly from the pump's discharge line. Several wells selected for sampling were outfitted with pumps by the well owner. Samples from these wells were collected at a tap within the dwelling, provided that no in-line water treatment systems (carbon filters, water softeners, etc.) were being used.

Measurements were made in the field of pH, specific conductance, and temperature. Samples were analyzed in the laboratory for two groups of constituents, trace metals, and major ions. The trace metals were done for comparison with the U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Levels (MCL's). The major ions were selected to allow the construction of Stiff diagrams which give a visual indication of water type.

GEOHYDROLOGY

Ground-water movement in the study area is controlled by the geology of rocks of Mississippian, Pennsylvanian, and Quaternary age. The rock units that transmit and store most of the ground water in the study area are the channel-fill sandstones of Pennsylvanian age and the unconsolidated alluvial deposits along the Green River.

Geology

The rocks in the study area were formed from sediments that were deposited near the edge of the Illinois Basin. The rocks consist of beds of shale, sandstone, limestone, and coal that crop out in concentric bands around the center of the of the basin (pl. 1). The rocks dip inward toward the center of the basin so that the youngest rocks crop out in the center of the basin.

Structure

The Illinois Basin is a major sedimentary basin in the eastern interior of the continent. Sedimentary rocks in the basin have a maximum thickness of about 4,000 ft in Kentucky (Rice, 1986). The study area includes parts of the Rough Creek Fault system in the north and the Pennyrile Fault system in the south (fig. 4). The Rough Creek Fault system is composed of numerous subvertical faults that generally displace Pennsylvanian strata about 300 ft; however, local displacement is as much as 3,000 ft. The Pennyrile Fault system is roughly parallel to the Rough Creek system, forming a downdropped block (a graben) between the two fault systems (fig. 5). Rocks within the graben form a concave-upward structure known as the Moorman syncline.

Stratigraphy

Rocks of Mississippian age that crop out in the study area consist of clastic and interbedded carbonate and detrital strata of the upper Chesterian Series (fig. 6). Carbonate units predominantly consist of limestone with minor amounts of dolomite and interbedded shale and sandstone. Karst features (sinkholes and springs) are sparsely developed in the area, owing to the thin bedding and argillaceous nature of the carbonates (Grabowski, 1986). Clastic rocks, representing channel fill, deltaic, and near-shore barrier deposits, constitute 25 to 50 percent of the upper Chesterian stratigraphic section (Sable and Dever, 1990). The sandstone units are fine to coarse grained with interbedded carbonaceous and silty shale. Minor amounts of limestone are also present.

Rocks of Pennsylvanian age generally consist of alternating sequences of shale, sandstone, limestone, and coal. The deposition of sediments occurred mainly in stream channel and deltaic complexes; therefore, most lithologic units are laterally discontinuous and not traceable for more than several miles (Quinones and others, 1983). The boundaries of formations in the Pennsylvanian System are assigned on the basis of a few laterally

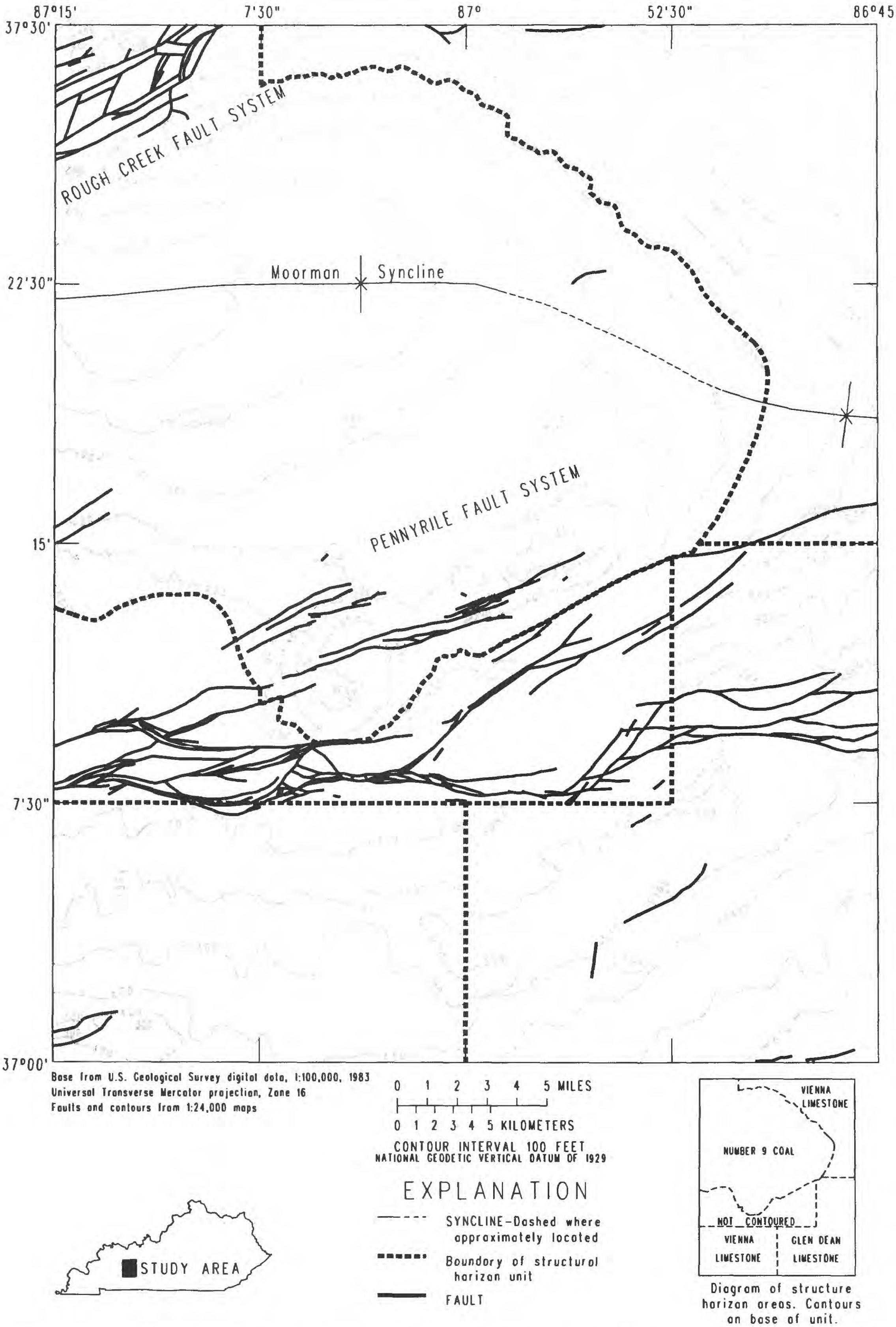

Figure 4.--Geologic structure of a portion of the Illinois Basin compiled from 1:24,000 geologic quadrangle maps.

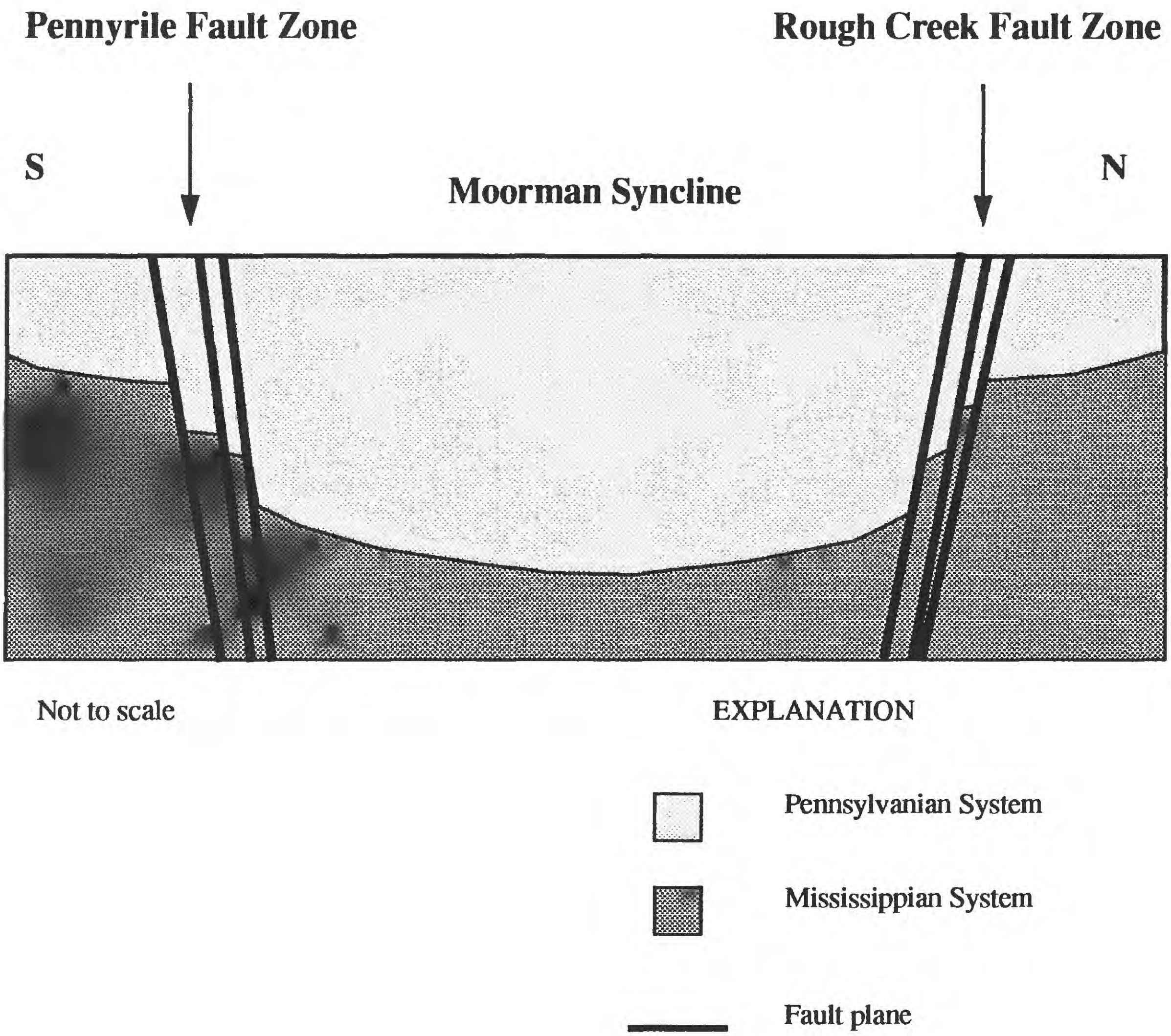

Figure 5.--Generalized geologic section from Kirkmansville to Livermore.

System	Series	Formation	Thickness, in feet	Description
Quaternary	Pleistocene		10 - 170	Clay and silt.
				Fine sand to gravel.
Pennsylvanian		Sturgis	100 - 990	Fine- to coarse-grained channel-fill sandstone; friable; in places conglomeratic.
		Carbondale	80 - 340	Shale, sandstone, and coal; upward coarsening; laterally persistent coal beds.
		Tradewater	40 - 1,005	Transitional formation; lower portion similar to Caseyville, upper portion similar to Carbondale.
		Caseyville	320 - 650	Sandstone, siltstone, shale, coal, and limestone in cyclic depositional sequences; lower portion channel-fill sandstone and conglomerate in fine- to coarse-grained sandstone matrix; friable.
Mississippia	Chesterian			Limestone, sandstone, and shale; limestone interbedded with sandstone and shale; sandstone, fine to coarse grained, interbedded with shale.

Figure 6.--Generalized stratigraphic column for the study area.

persistent coal and limestone beds rather than on large-scale vertical changes in lithology. The thickness of the rocks between these beds is generally constant because subsidence of the basin at the time the rocks were deposited occurred at a constant rate (Rice, 1986).

Sandstones of Pennsylvanian age generally occur in two phases, the sheet phase and the channel-fill phase (Rose, 1963). The sheet phase was deposited in broad alluvial plains and tends to be more fine grained than the channel-fill phase. The channel-fill phase was deposited in channels that were incised on an existing bedrock surface. Paleochannels exist at the base of the Pennsylvanian System and less prominently throughout formations of Pennsylvanian age. Coarse-grained and conglomeratic sandstones are common in paleochannels.

The Pennsylvanian System in the study area comprises four formations--the Caseyville, the Tradewater, the Carbondale, and the Sturgis (fig. 6). Paleochannel conglomerates in the Caseyville Formation have been studied and mapped by Davis and others (1974), Rose (1963), Wilson and Van Couvering (1965), and BeMent and others (1978). The channel-fill phase of the Caseyville Formation is a thick-bedded, friable quartz-pebble conglomerate and conglomeratic sandstone in a fine- to coarse-grained sandstone matrix. This conglomerate is 120 ft thick where it crops out in the Dunmor quadrangle (Miller, 1964). These deposits grade upward into the sheet phase of the Caseyville Formation, which consists of alternating beds of sandstone, siltstone, shale, coal, and limestone. The Tradewater Formation represents a transition between the Caseyville and the Carbondale; its lower half is similar to the sheet phase of the Caseyville Formation, and its upper half is similar to the Carbondale Formation (Whaley and others, 1979). In interchannel areas, dominated by the sheet phase of the Caseyville formation, the lower boundary of the Tradewater Formation is not easily differentiated from the underlying Caseyville Formation.

The Carbondale Formation is characterized by upward-coarsening beds of shale, sandstone, and coal. These sequences are more laterally persistent and of more uniform lithology than adjacent formations (Whaley and others, 1979). The Sturgis Formation is thin and patchy away from the axis of the Moorman Syncline and lacks the widespread, thick coals of the Carbondale Formation. The Sturgis Formation contains several friable, fine- to coarse-grained channel-fill sandstones that, in places, are conglomeratic. The same spatial variability is noted for the Sturgis Formation as for the Caseyville Formation. One hydrologically important unit in the Sturgis Formation, the Anvil Rock Sandstone Member, is a coarse-grained sandstone that is 110 ft thick.

The Green River occupies a relatively flat-bottomed, alluvium-filled valley formed by the erosion of weak Pennsylvanian shales (Ryder, 1974). During Pleistocene time, the Green River was filled with coarse-grained deposits (fine sand to gravel) derived from the glaciers to the north and transported to the area by the Ohio River. Eventually, the Green River drainage basin became choked with sediment, causing impoundment of the north-flowing streams and deposition of finer-grained sediments (clay and silt) overlying the coarse deposits.

Hydrology

The sources of ground water in aquifers in the study area include precipitation on outcrop areas of aquifers, inflow from losing streams (Maxwell and Devaul, 1962b), and water trapped in sediments at the time of their deposition (Davis and others, 1974). Ground water occurs in consolidated bedrock formations throughout the study area and in unconsolidated sand and gravel along the Green River and its tributaries. The availability of ground water seems to be unrelated to topography (Quinones and others, 1983). The movement of ground water is through the pore spaces in poorly cemented sandstone and unconsolidated sand and gravel, and through fractures in fine-grained, shaly, or well-cemented sandstone, limestone, and coal. In limestone, the fractures can be enlarged by the dissolution of carbonate minerals.

Aquifers

Wells drilled into rocks of the Pennsylvanian System generally yield more than 500 gal/d at depths of less than 300 ft (Maxwell and Devaul, 1962a; Devaul and Maxwell, 1962). Wells drilled into formations of Mississippian age yield 100 to 500 gal/d. The yield of wells drilled near faults is unpredictable. Wells completed in channel-phase sandstones at the base of the Caseyville Formation and the Anvil Rock Sandstone Member of the Sturgis Formation potentially yield above-average quantities of water (Maxwell and Devaul, 1962b).

Unconsolidated

Sources of ground water in the alluvial deposits include precipitation that falls directly on the alluvial surface, flow that enters the alluvium in the subsurface from the surrounding bedrock, and inflow from the Green River in some locations. Direct recharge from precipitation is limited because of the overlying sediments with low permeability. Recharge from the bedrock is also limited because of the low permeability of most of the formations of Pennsylvanian age in the area. The lithology of the bedrock is variable, however, and at one site where the bedrock is more permeable than at most locations, recharge to the alluvium from the bedrock is estimated to be 0.016 ft/d (Ryder, 1974). The source of most of the recharge to the alluvium is water from the Green River that is induced to infiltrate by pumping. The area of hydraulic connection between the aquifer and the river increases in locations where the river fully penetrates the alluvium.

Bedrock

Davis and others (1974) grouped sandstone aquifers in the Pennsylvanian System in western Kentucky into four categories. Group I is composed of poorly cemented channel-phase sandstone and conglomeratic sandstone at the base of the Caseyville Formation. Many of these sandstone aquifers are deep, on the order of 1,000 ft below land surface. Groups II and III are composed of deltaic, barrier-bar, or channel-fill sandstones deposited within the Pennsylvanian system. Group II aquifers overlie Group I aquifers and can receive recharge from them by upward leakage. Group III aquifers are channel-fill sandstones several hundred feet above the contact between the Mississippian and Pennsylvanian Systems and probably do not receive significant recharge from adjacent rocks (Davis and others, 1974). Group IV aquifers are shallow sandstones (less than 300 ft deep) in any part of the Pennsylvanian System that are recharged in their outcrop area and contain fresh water for varying distances downdip.

All wells in the study area, with few exceptions, obtain water from aquifers in Group IV. Individual aquifers in Group IV have not been mapped in the study area because their lithology is variable over short distances. The aquifer in the Anvil Rock Sandstone Member is one aquifer in this group. Yields up to 100 gal/min have been obtained from the Anvil Rock Sandstone Member.

Davis and others (1974) mapped one aquifer of Group I which they refer to as the "Rochester Valley" aquifer. This aquifer is a western extension of the Brownsville paleochannel of the Caseyville Formation mapped by BeMent and others (1978). According to Davis and others (1974), it "may be the largest potential source of potable ground water from Pennsylvanian deposits in western Kentucky." Yields up to 300 gal/min are possible at depths from 700 to 940 ft. The aquifer was mapped to its recharge area in eastern Butler and Edmonson counties and could receive recharge from precipitation, unlike most channel-fill sandstones of the Caseyville Formation.

Other Group I aquifers have been reported in the study area. Wilson and Van Couvering (1965) investigated a "fresh-water" aquifer (where the water contains less than 1,000 ppm total dissolved solids (TDS)) at a depth of 1,100 ft near Greenville, Kentucky. They reported that this aquifer was receiving recharge in its outcrop area north of the Pennyrile Fault System.

Ground Water

This section presents an interpretation of the ground-water resources of the study area. A GIS was used to analyze how the basin-like geologic structure of the study area affects the occurrence, movement, and use of ground water. In a ground-water basin, water enters the aquifers in their outcrop area and moves downdip to a point of discharge. In the study area, the discharge from an aquifer can be to a water well, to an oil or gas well, to a surface stream or wetland, to an underground mine, or to other aquifers through vertical leakage. The amount of water used decreases downdip because: (1) the water in the formation becomes more mineralized due to long residence time, (2) the yield of the aquifer is less due to the smaller number and aperture of fractures with depth, and (3) the cost of drilling increases with depth.

Occurrence

Rocks of the Mississippian System crop out in the southeastern, southwestern, and northeastern corners of the study area (fig. 7). The areal extent of the outcrop is 93 mi^2, which is about 10 percent of the study area. The project data base contains records of 63 wells that penetrate rocks of Mississippian age. Thirty-nine of these are located in the outcrop area and probably receive ground water along shallow, local flow systems. Wells outside the outcrop area are as far as 13 mi from the nearest outcrop. The use of most of these wells is unknown; the wells are probably related to the exploration for hydrocarbons in the area.

The Caseyville Formation crops out in the study area south of the Pennyrile Fault System and along the northern boundary (fig. 8). The areal extent of the outcrop is 150 mi^2, which is about 16 percent of the study area (fig. 8). The project data base contains records of 40 wells that produce water from the Caseyville Formation. Of these 40 wells, only 4 lie more than a mile from the outcrop area; the most distant well is about 7.5 mi from the nearest outcrop.

The Tradewater Formation crops out in the study area along the northeastern boundary and north of the Pennyrile Fault System (fig. 9). The areal extent of the outcrop is 152 mi^2, which is about 16 percent of the study area. The project data base contains records of 81 wells that produce water from the Tradewater Formation. Of these 81 wells, all but 3 lie within a mile of the outcrop area; the 3 exceptions lie about 3 to 4 mi from the nearest outcrop. Many of the wells along the northeastern boundary are unused (fig. 9).

The Carbondale Formation is highly dissected by streams; the pattern of its outcrop in the center of the study area is patchy and broken (figs. 10, 11, and 12). The areal extent of the outcrop is 141 mi^2, which is 15 percent of the study area. The project data base contains records of 81 wells that produce water from the Carbondale Formation and about 20 wells lie outside the outcrop area in the center of the Moorman Syncline. Two other wells in southern Ohio County lie in an area where the outcrop of the Carbondale Formation is broken by faults.

The Sturgis Formation crops out along the axis of the Moorman Syncline. The areal extent of the outcrop is 137 mi^2, which is 14 percent of the study area (fig. 13). The project data base contains records of 105 wells that produce water from the Sturgis Formation. The Sturgis Formation is the youngest consolidated rock formation in the study area; therefore, there are no wells that obtain water from the Sturgis outside the outcrop.

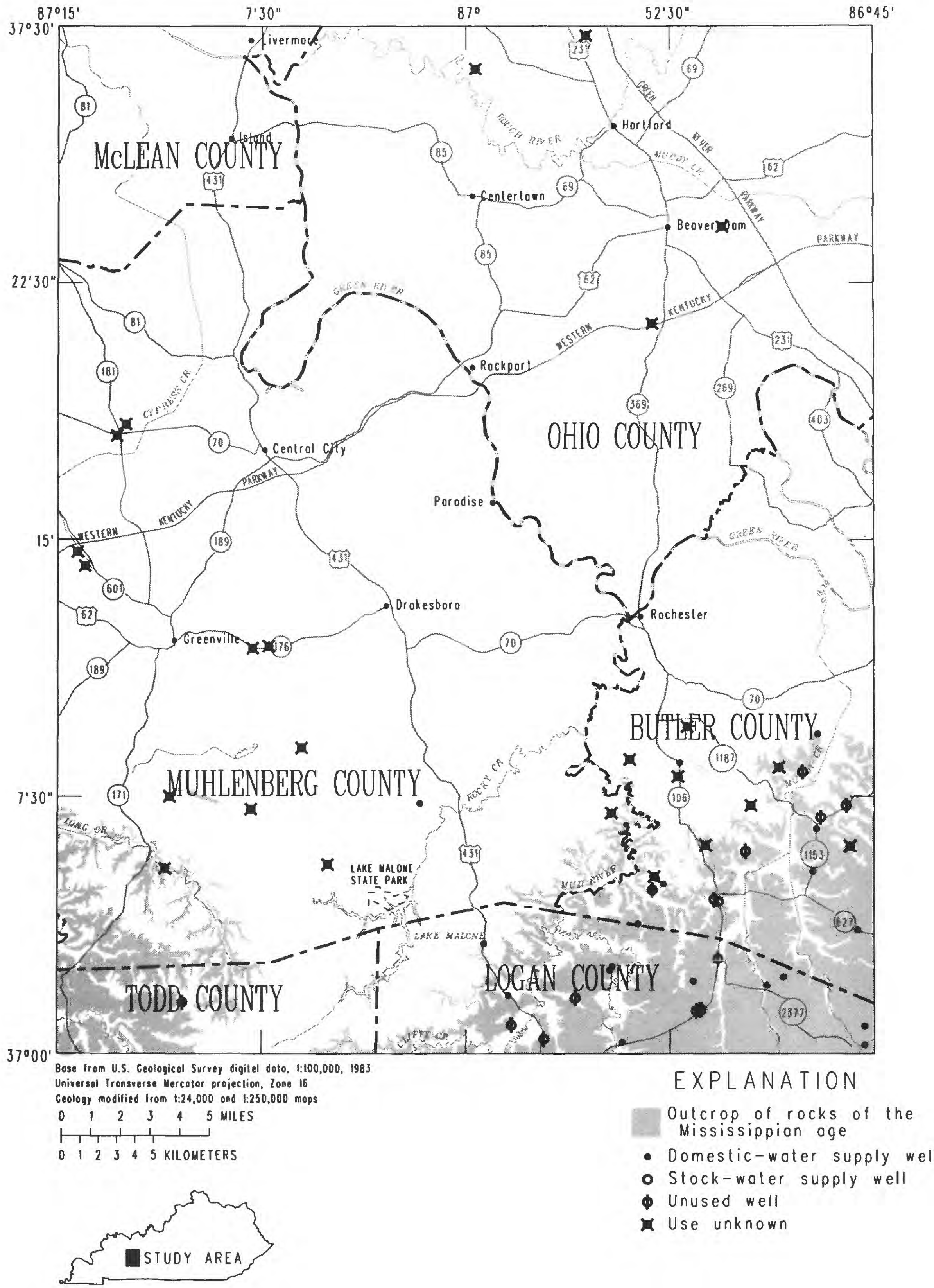

Figure 7.--Wells completed in rocks of the Mississippian age.

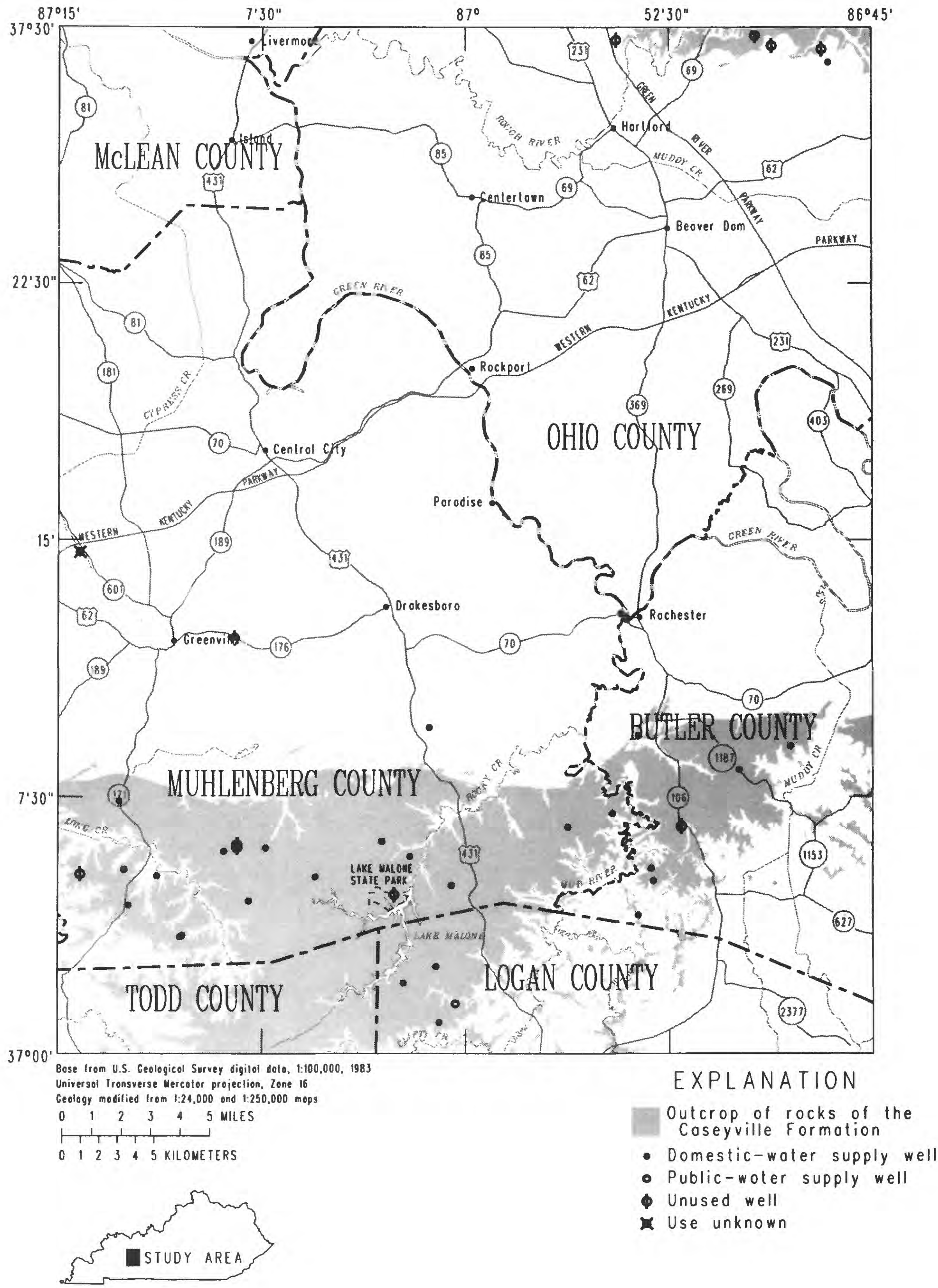

Figure 8.--Wells completed in rocks of the Caseyville Formation.

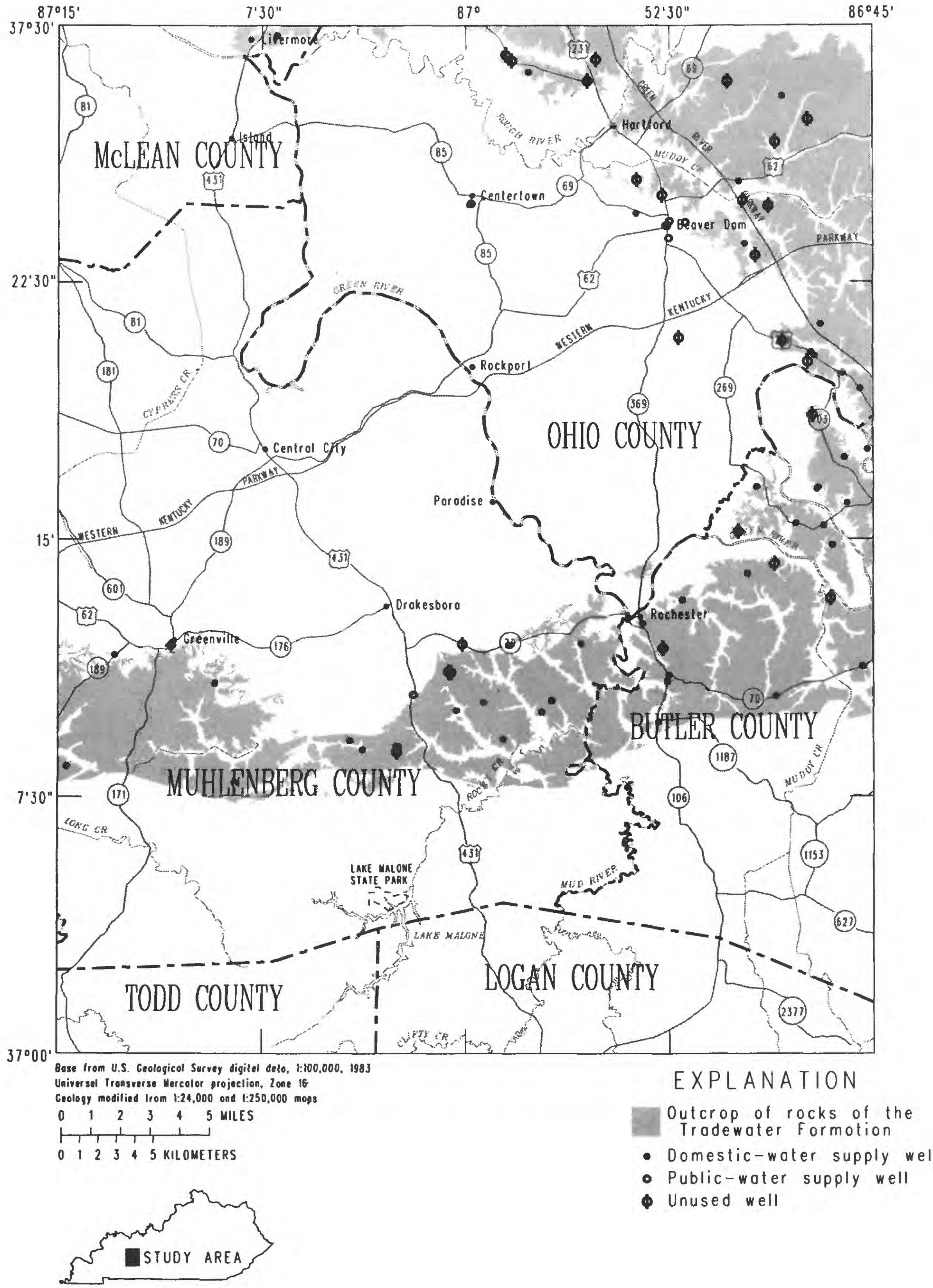

Figure 9.--Wells completed in rocks of the Tradewater Formation.

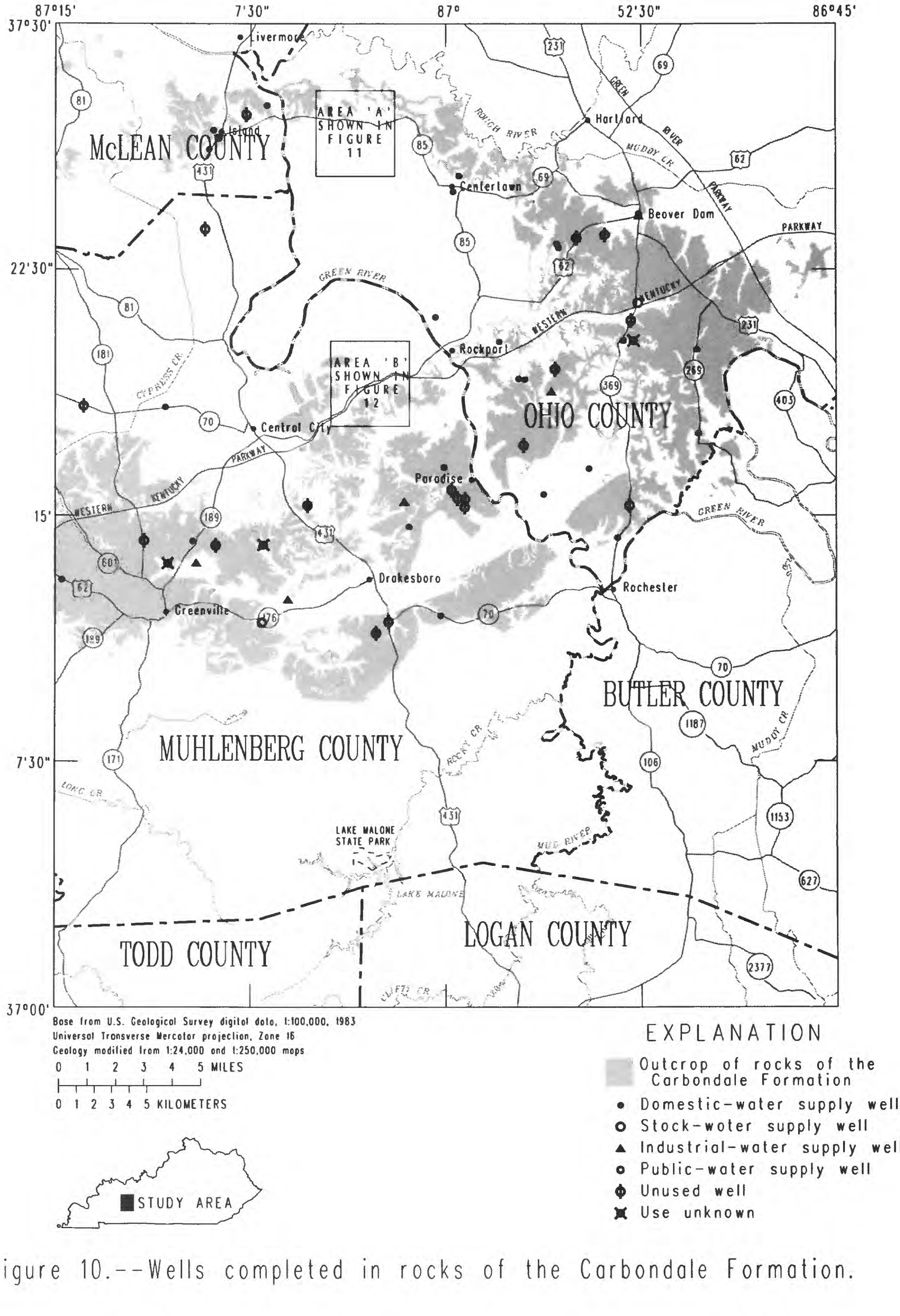

Figure 10.--Wells completed in rocks of the Carbondale Formation.

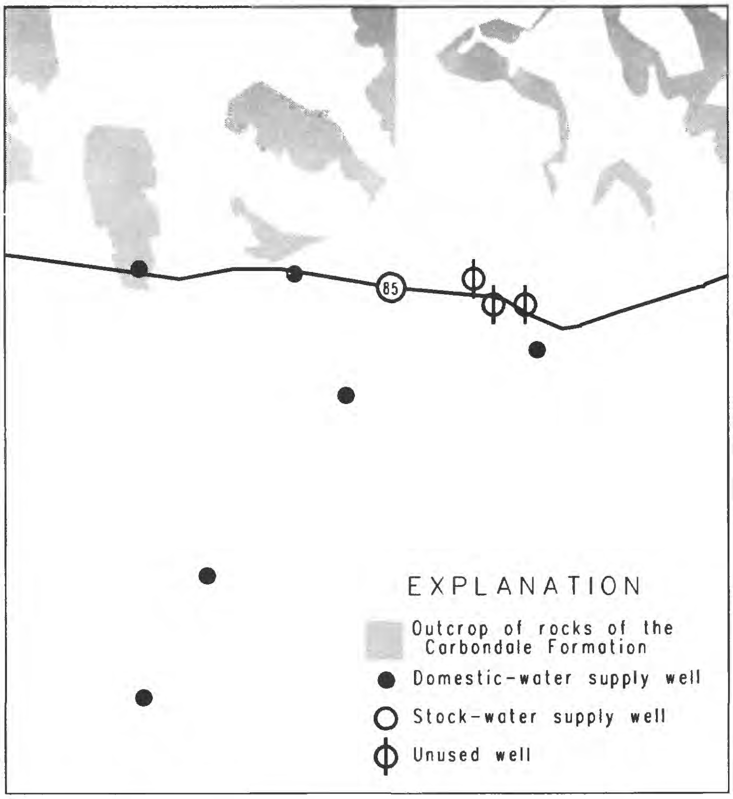

Figure 11.--Inset A shown on figure 10.

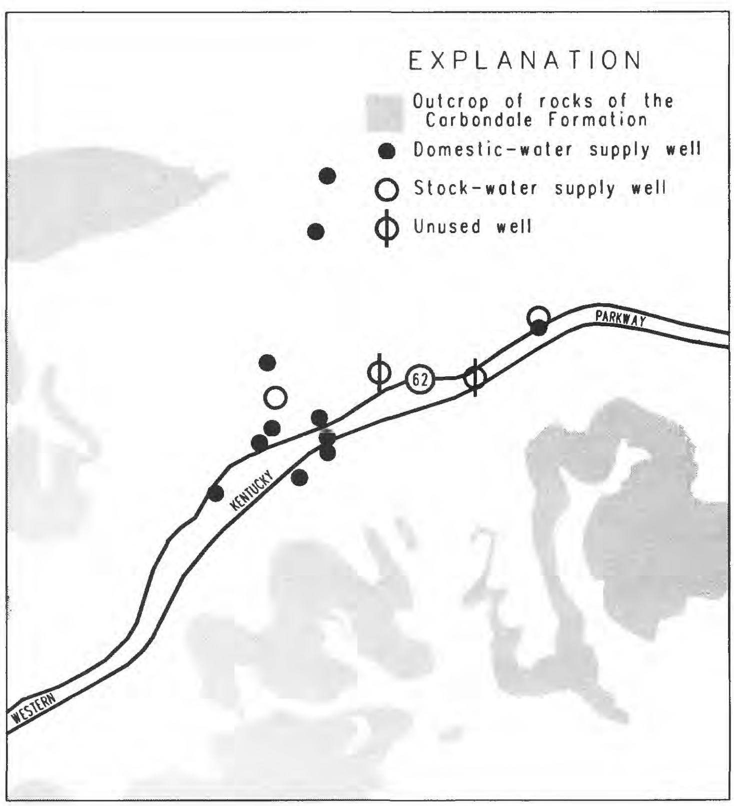

Figure 12.--Inset B shown on figure 10.

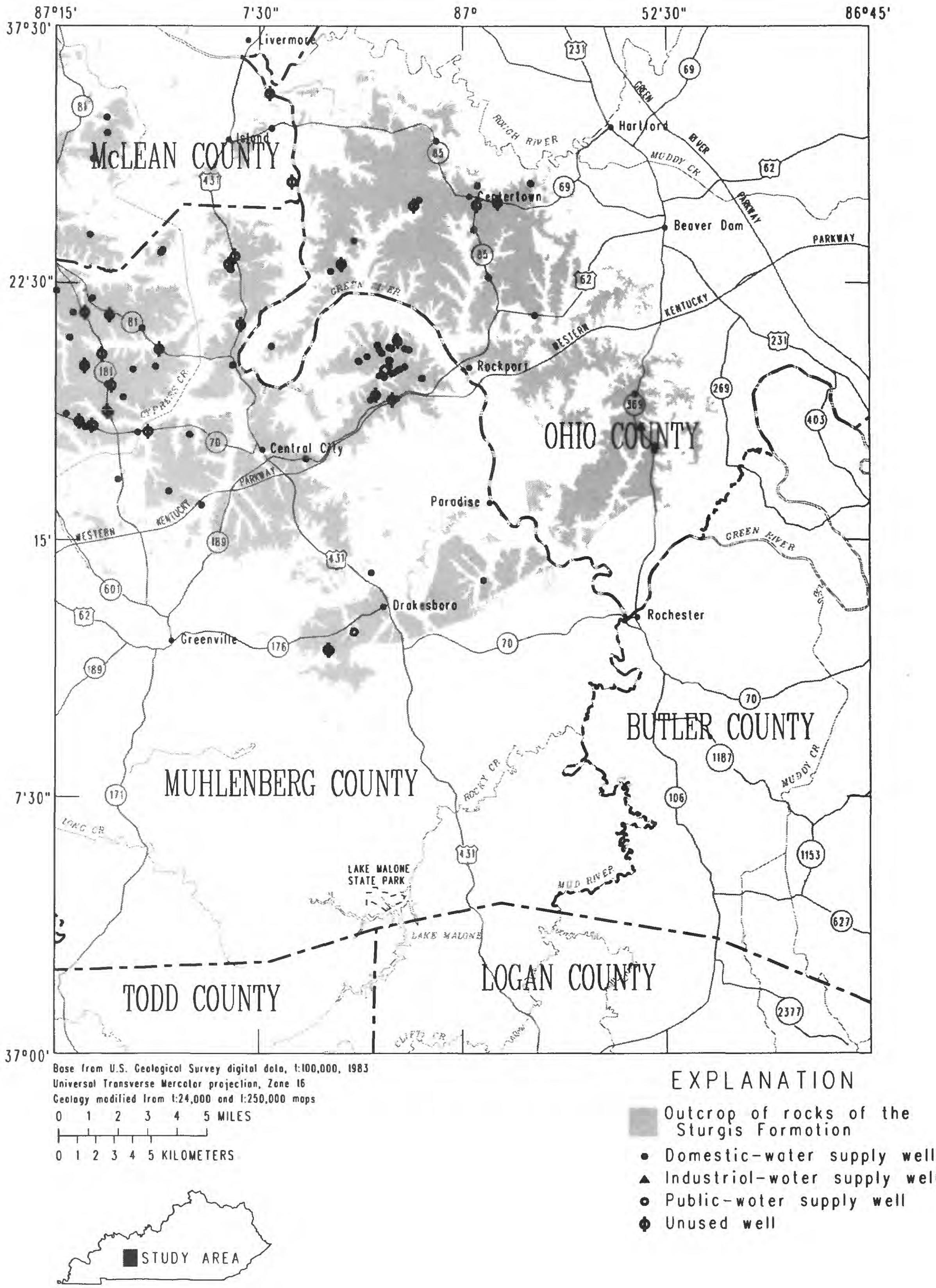

Figure 13.--Wells completed in rocks of the Sturgis Formation.

Unconsolidated alluvium of Quaternary age underlies 276 mi^2, which is 29 percent of the study area (fig.14), making it the aquifer with the largest outcrop in the study area. In many places, however, the alluvium is thin and would not yield much water to wells. The project data base contains records of 33 wells that produce water from the alluvium. Most of these wells are located in the broad alluvial area along the Green and Rough Rivers in the northwestern part of the study area. Although the alluvium along the Green River is expected to be the most productive alluvial aquifer in the study area, several wells also obtain water from the alluvium along the Rough River and smaller tributaries to the Green and Rough Rivers.

It was not possible to distinguish among the Caseyville, Tradewater, and Carbondale Formations in parts of the study area; this is because the formations here are very similar in lithology. Nineteen wells fell into this category.

Water Levels

Selected statistics are presented in table 1 to describe water-level conditions within the study area. The median depth to water, total depth of well, and altitude of water level indicate the conditions that generally might be anticipated when drilling a water well. Wells drilled for oil and gas exploration were excluded from this analysis because they are not drilled to obtain ground water. The available data do not lend themselves to the rigorous use of statistics. The number of wells in each formation is different, the amount of variation in the data among the formations is different, and so on; however, the distribution of these data about the median can be used in a general sense to determine if some differences in the median might be significant. The Tukey Multiple Range Comparison Test (MCT; Statware, 1990) was used to determine significant differences (at the alpha = 0.05 level) among formations based on depth of well, depth of water below land surface, and altitude of the water level. In this study, if the MCT identifies differences between formations, the differences are probably significant; however, the MCT may not identify all differences that actually exist.

Table 1 indicates several differences among formations. Wells in the Caseyville Formation and the alluvium are shallower than wells in the other formations. The depth to water is least in the alluvium and greatest in the Tradewater Formation. The altitude of the water level reflects the correlation between land-surface altitude and altitude of the water level (fig. 15). The altitude of the water level is highest in the Caseyville Formation. It is lower in the rocks of Chesterian age than in the Caseyville Formation and is lowest in the alluvium. The altitudes of the water levels in the remaining formations are about equal, are lower than in the rocks of Chesterian age, and are greater than in the alluvium.

Water-level data were published for 1953-78, and 1980 for an observation well in Beaver Dam (U.S. Geological Survey, 1956a, 1956b, 1957, 1962, 1965, 1971, 1975, 1976-79, and 1981). The water levels ranged from 158.93 to 77.99 ft below land surface. Remarks published with the data indicate that the well was influenced by changes in atmospheric pressure until 1953 and then by atmospheric pressure and nearby pumpage. Data collection was discontinued in 1980. Water levels in an observation well in Drakesboro were published for 1952-55 (U.S. Geological Survey, 1955, 1956a, 1956b, and 1957). Until 1955, the depth to water from land surface ranged from about 2 to 12 ft. In 1955, the depth to water increased abruptly to 47 ft below land surface, probably in response to nearby pumpage.

Several wells have been reported to flow at the ground surface under natural conditions; these wells produce water from the Caseyville Formation. One well in Muhlenberg County, measured in 1967, flowed at 1 gal/min. Another well, in Ohio County, flowed at 5 gal/min when measured in 1945. A well at Horse Branch, just outside the study area east of Horton, was reported to flow at about 9 gal/min. Two wells near Graham, just outside the study area west of Greenville, reportedly produced water under natural pressure from a depth of 1,000 to 1,200 ft.

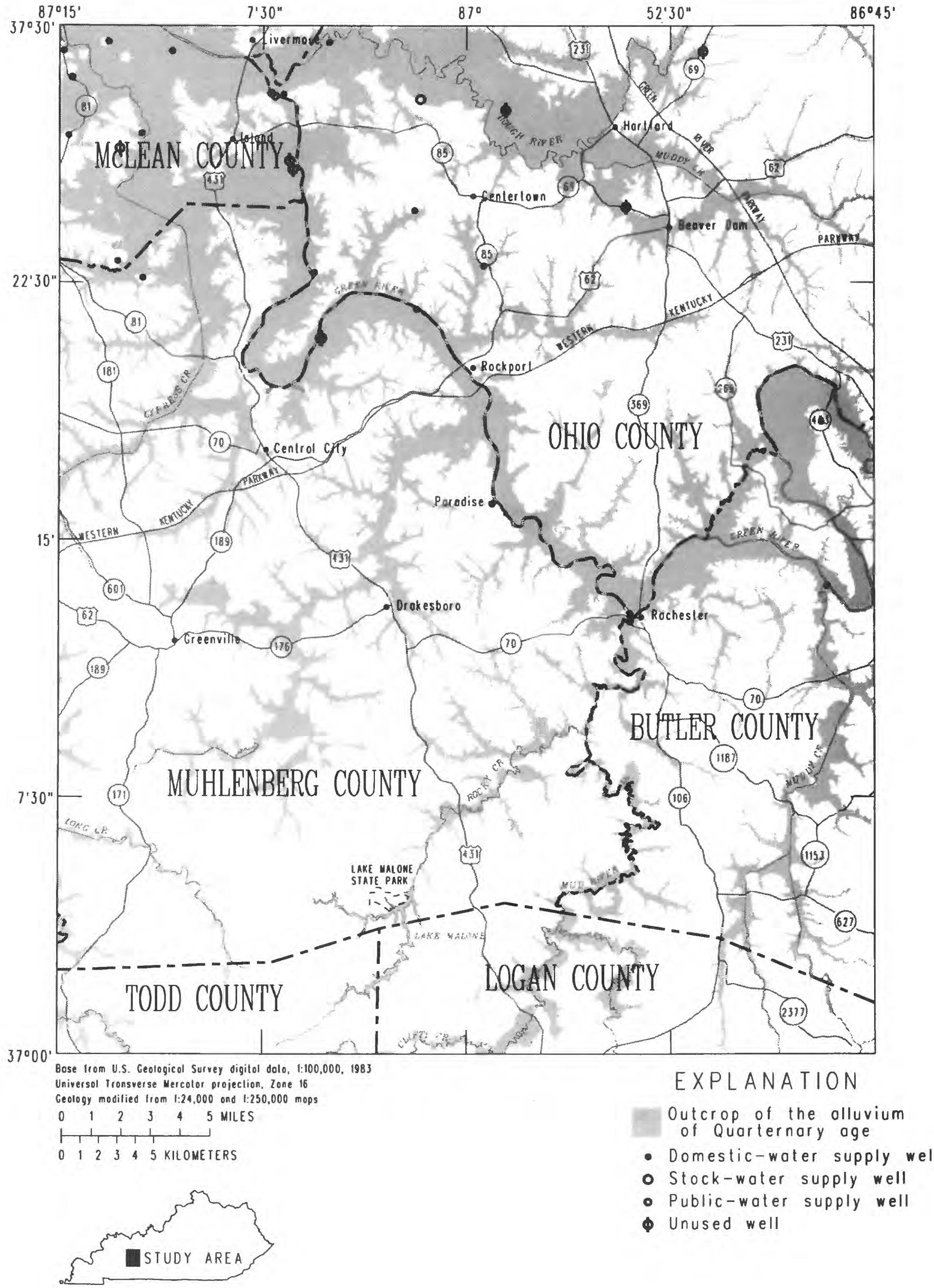

Figure 14.--Wells completed in alluvium of Quaternary age.

Table 1. Summary of well data by formation for selected quadrangles in western Kentucky

[CSTR, Chesterian Series; CSVL, Caseyville Formation; TRDR, Tradewater Formation; CBDL, Carbondale Formation; STRG, Sturgis Formation; QAL, Quaternary alluvium; significant differences between formations is determined from the Tukey Multiple Range Test (Statware, 1990); the probability of not recognizing real differences between groups is 1 chance in 20 (alpha=0.05)]

	Group number and geologic unit					
	1	2	3	4	5	6
Well data	CSTR	CSVL	TRDR	CBDL	STRG	QAL
Median depth of well, in feet	79.0	38.4	74.0	70.2	63.0	20.0
Groups with which there are significant differences	6	3	2,5,6	6	3,6	1,3,4,5
Median depth to water level, in feet	21.3	18.2	34.4	18.7	26.1	11.2
Groups with which there are significant differences	--	--	5,6	6	3,6	3,4,5
Median altitude of water level, in feet	462.3	561.7	422.8	425	431.3	388.7
Groups with which there are significant differences	2,3,4,5,6	1,3,4,5,6	1,2	1,2,6	1,2,6	1,2,4,5

Flow

Ground-water flow systems occur on a range of scales in the study area. The scale of a ground-water flow system is the length of the flow path from the recharge area to the discharge area. Local flow systems, where the length of the flow path is short, can be superimposed on deeper, more regional flow systems. Topography and geology influence the length of the flow path. Large differences in land-surface elevation tend to produce local flow systems with relatively short flow paths. Regional aquifers that have high permeability tend to produce regional flow systems.

Direction

Water-level altitude data were collected as part of the well inventory during the late summer and early fall of 1991. There is an apparent randomness in the data that is probably a result of the discontinuous lithology that has produced local-scale ground-water flow systems. There are too few data points to define ground-water flow at the local scale; however, filtering the data can reveal regional patterns not otherwise obvious, much the same as a linear regression can determine the best-fit straight line through data that have a random component.

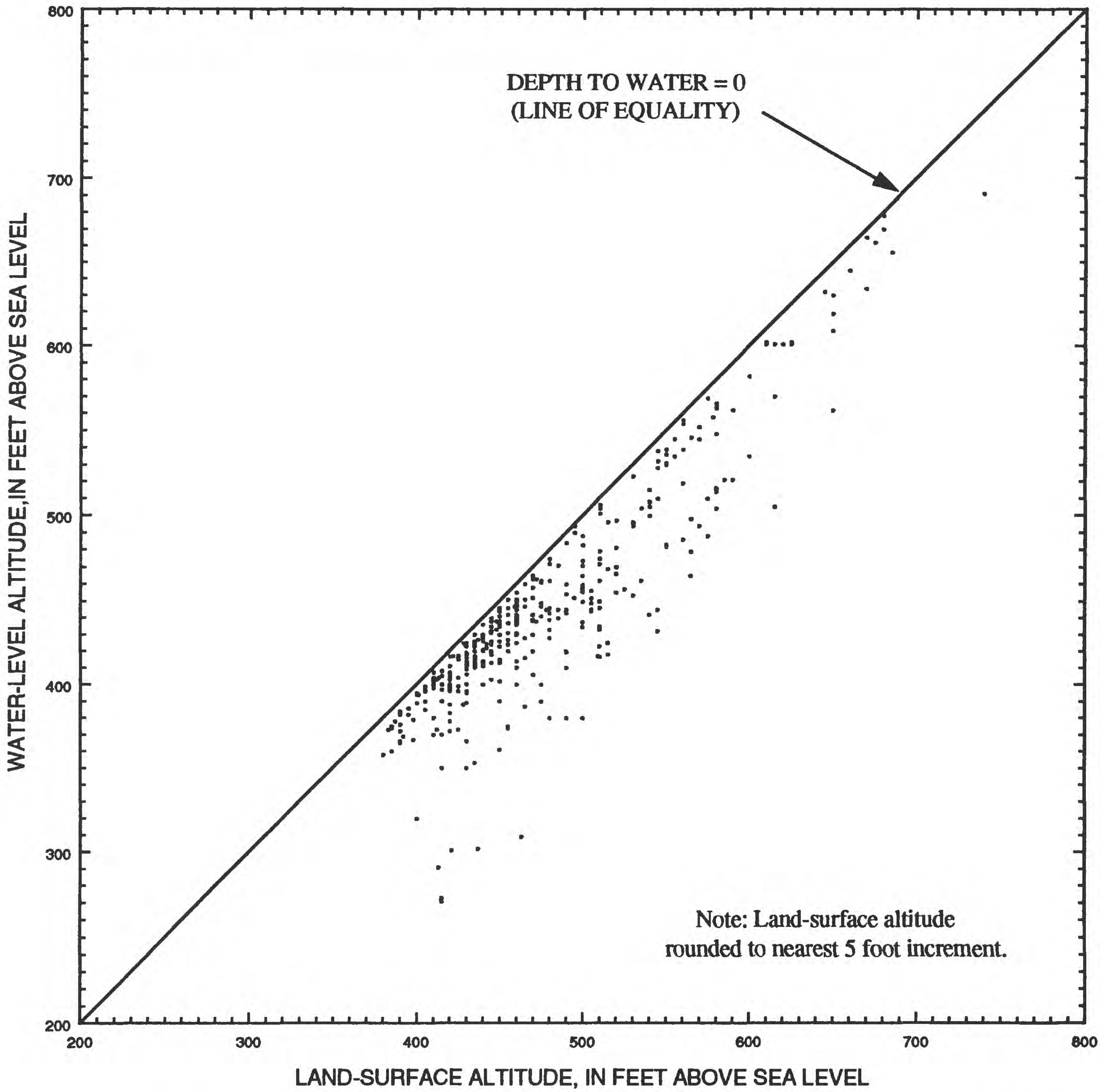

Figure 15.--Relation of altitude of the water level in open boreholes to land-surface altitude in selected quadrangles in western Kentucky.

Kriging--a linear, unbiased estimator of data values at specified locations--was used to filter the randomness from the water-level altitude data in this study. The subject of kriging is complex and is not discussed in detail in this report, but a thorough introductory discussion of kriging is provided by the American Society of Civil Engineers (1990). In this study, ordinary point kriging was performed using an exponential variogram model (Englund and Sparks, 1991).

The map of kriged water-level altitudes (fig. 16) indicates a steep hydraulic gradient at the Pennyrile Fault System. This is probably due to the contrast in permeability associated with the fault system. A broad area of high water-level altitude corresponds to the outcrop area of the Carbondale Formation. Low water-level altitudes are present in the alluvial areas adjacent to the Carbondale Formation. The map indicates that regional flow is toward the broad alluvial area along the Green River in the northwest.

Effects of Faults

Aquifers can be hydraulically isolated from some recharge areas by faulting. The movement of rocks along faults, particularly those with vertical displacement, can place strata of different water-transmitting properties laterally adjacent to each other, interrupting the continuity of aquifers between recharge areas and downdip portions of the aquifer. Also, where shales are present in the fault zone, they are often smeared along the fault plane, producing a low-permeability barrier to ground-water flow. The rapid decline in water levels in some deep aquifers when pumped, and the large differences between water levels in wells on different sides of faults (Davis and others, 1974) are evidence that faults affect ground-water flow.

Faults in the study area have had an effect on the development of pre-Pennsylvanian stream channels, the distribution of sediment during the Pennsylvanian Period, and on the present-day movement of ground water. Rose (1963) mapped the channels of incised pre-Pennsylvanian streams in Muhlenberg County (fig. 17). Faults tend to be coincident with the pre-Pennsylvanian streams; thus, some faulting probably occurred before the Pennsylvanian Period. Davis and others (1974) mapped the thickness of one aquifer that was formed in a pre-Pennsylvanian stream channel (fig. 18). This aquifer is thinner and less areally extensive near the Pennyrile Fault System (fig. 18), indicating movement along the faults and differential deposition in the Pennsylvanian Period. Hopkins (1966) mapped the altitude of the boundary between fresh and saline water (defined as water having greater than 1,000 ppm TDS) (fig. 19). The difference in the altitude of this water-quality zone from one side of the Pennyrile Fault System to the other is over 700 ft. The surface of this zone forms a closed depression that seems generally coincident with the Moorman Syncline. Two possible explanations for the basin-like character of this zone are presented below.

The first hypothesis is that renewed vertical movement along existing faults resulted in a graben containing ground water with a low TDS concentration relative to the surrounding ground water. For example, if the light-colored rock units on figure 6 represent ground water with a relatively low TDS concentration, the resulting pattern in a map view is similar to that presented on figure 19. The second hypothesis is that the aquifer is continually flushed with water from precipitation having a low TDS concentration. In this scenario, precipitation enters the aquifer in the outcrop area. The resulting difference in water level causes water to flow toward areas of lower water level where it discharges from the aquifer. Aquifers discharge to overlying aquifers, into surface streams, and to pumping centers. Although ground water has not been used extensively for water supply in this area, the production of oil and gas has resulted in large quantities of high TDS ground water being pumped.

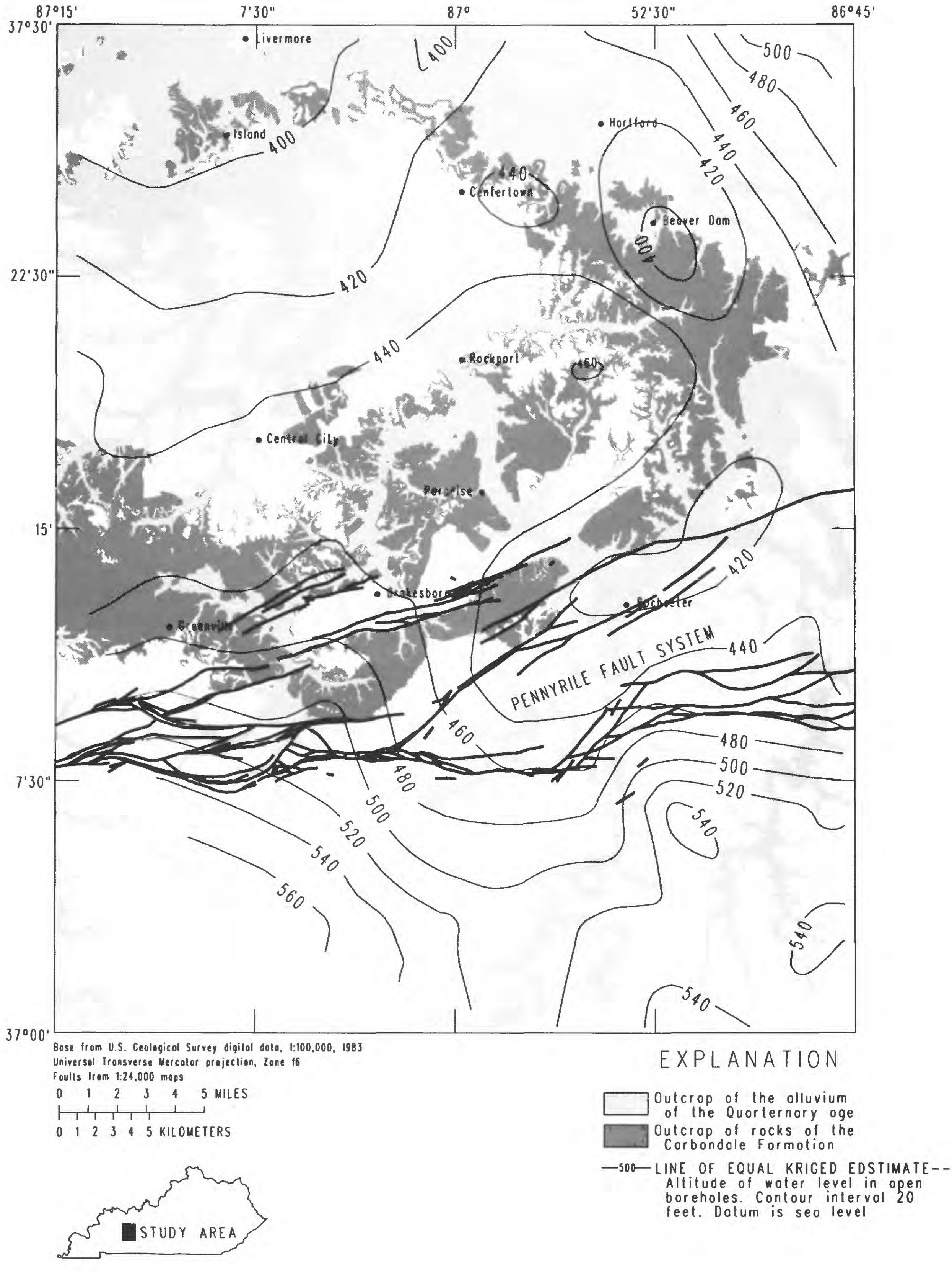

Figure 16.--Kriged estimates of altitude of water level.

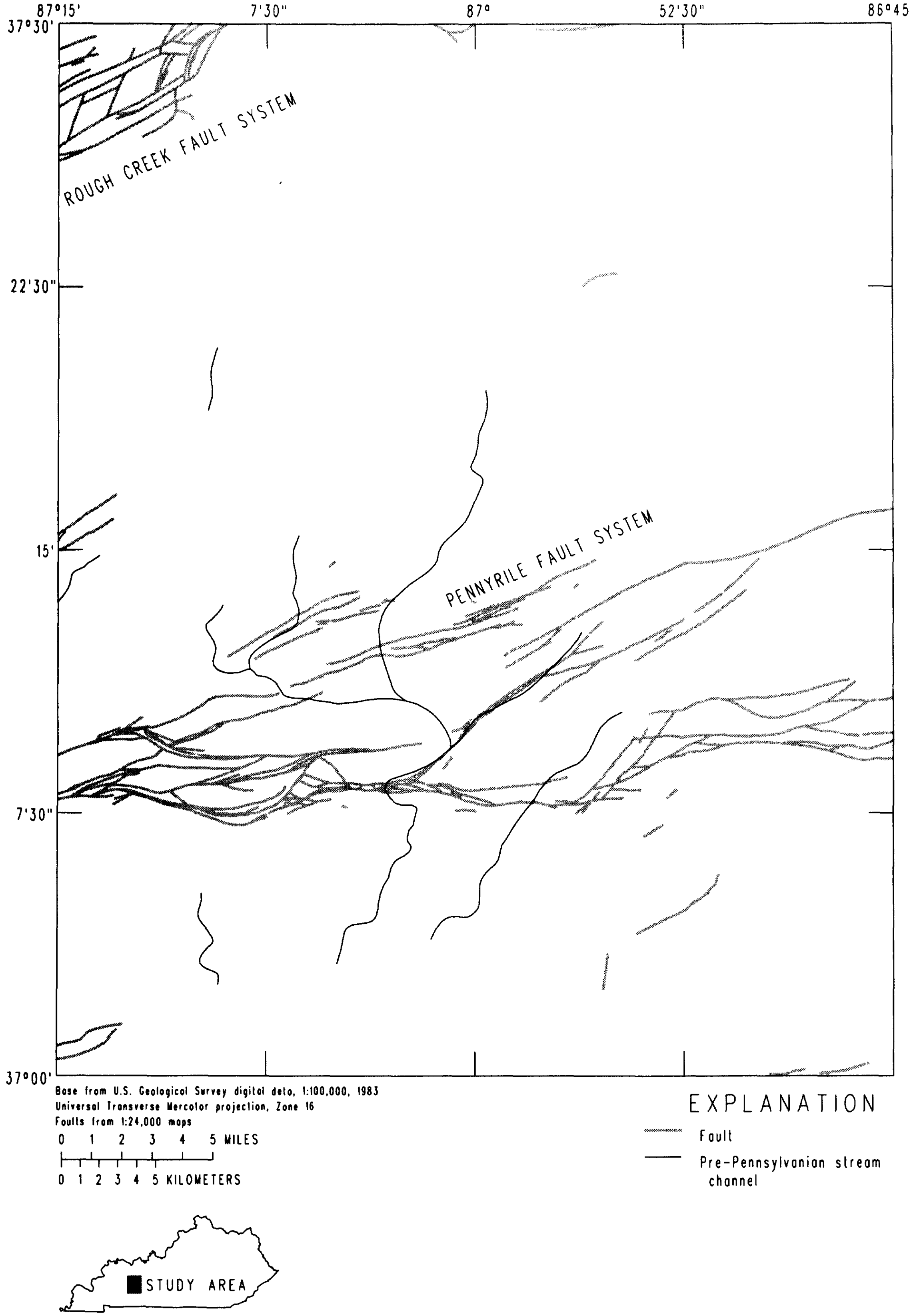

Figure 17.--Pre-Pennsylvanian stream channels in Muhlenberg County, [modified from Rose, 1963].

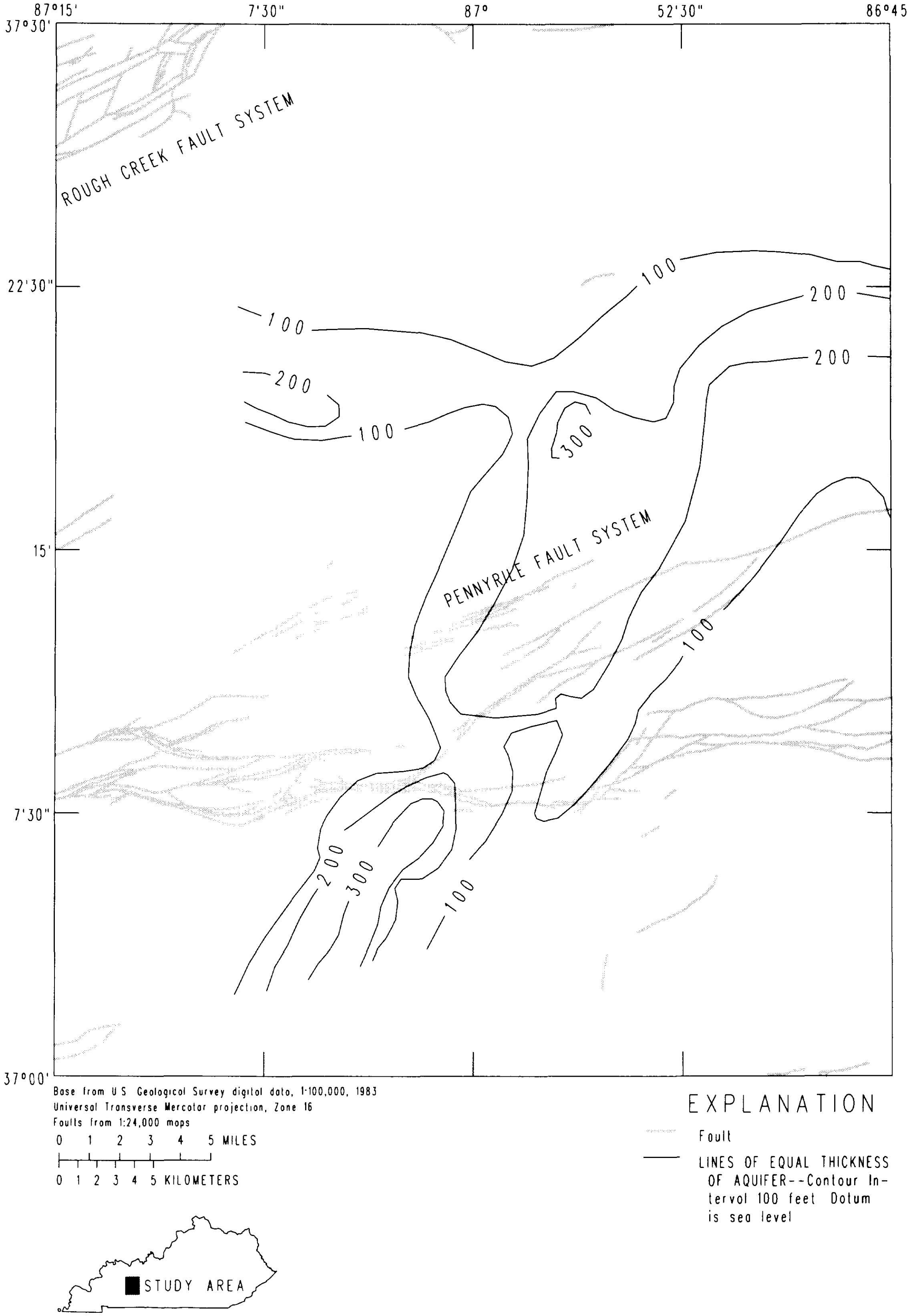

Figure 18.--Thickness of an aquifer at the base of the Pennsylvanian System, [modified from Davis, 1974].

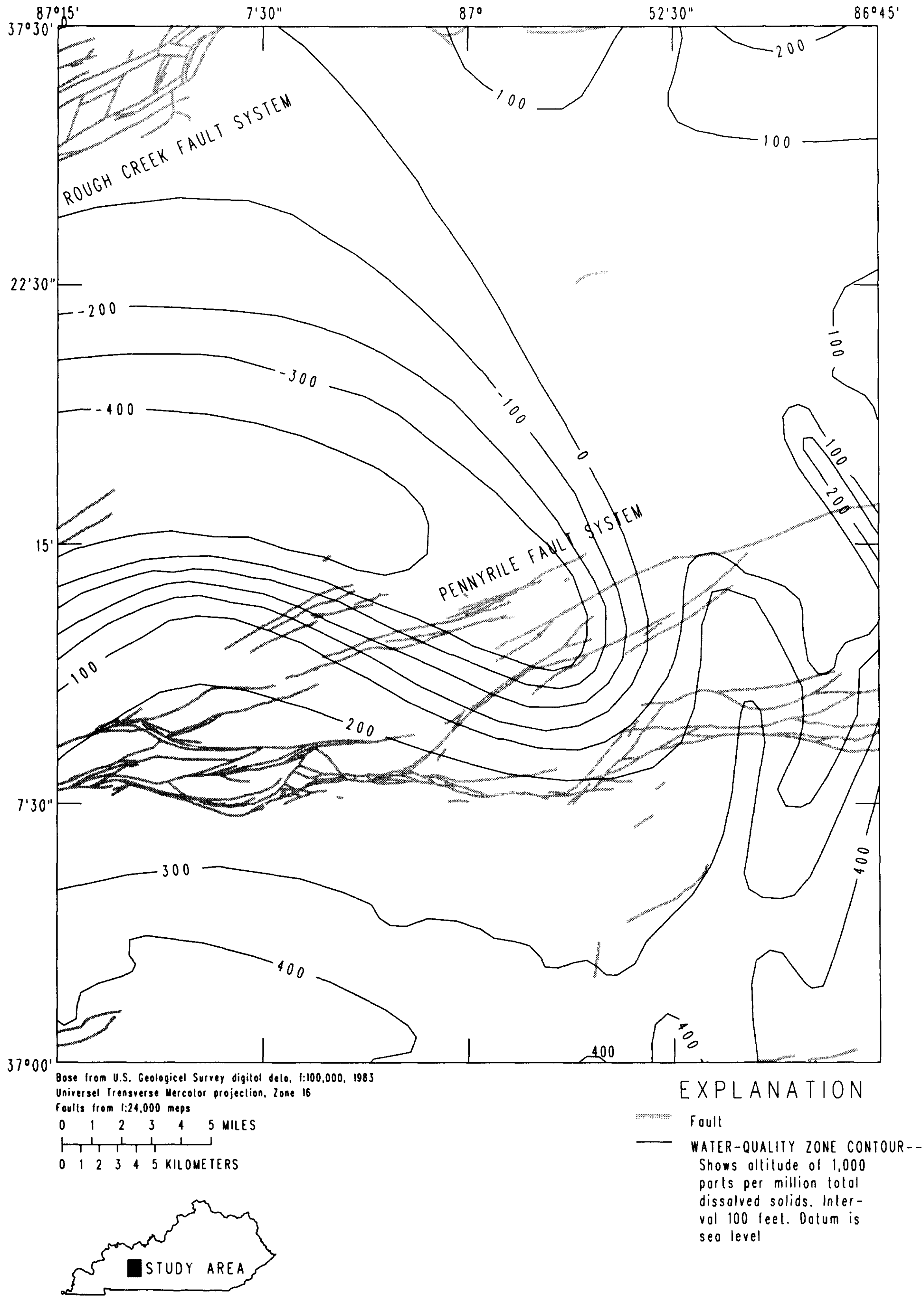

Figure 19.--Altitude of 1,000 parts per million total dissolved solids interface [modified from Hopkins, 1966].

Water Use

Selected data fields in the GWSI data base were cross-tabulated to summarize the use of ground water and the type of well construction (tables 2 and 3). The data were grouped by source. The wells shown on the HA's, along with a small number of additional wells, were entered into GWSI before 1991. This group reflects water use during the 1950's, 1960's, and 1970's. Those inventoried by the USGS as part of this project were entered into GWSI in 1991. This group reflects current water use. Data obtained from the KDOW represent wells that are located primarily in two small areas--near Nelson in Muhlenberg County, and in southwestern Butler County. This group of data also includes some springs in the Mississippian Plateau region.

Table 2. Use of ground water in selected quadrangles in western Kentucky

[GWSI, Ground-Water Site Inventory; AKGWA, Assembled Kentucky Ground Water Data Base]

Data base	Approximate total number of wells	Use of water, in percent of total: Domestic	Use of water, in percent of total: Unused	Other uses
pre-1991 GWSI	200	80	8	Industrial, public water supply, livestock, and other uses
Well inventory, 1991	150	34	63	Public water supply
AKGWA	70	80	4	Commercial, irrigation, mining, industrial, public water supply and livestock

Table 3. Construction of wells in selected quadrangles in western Kentucky

[GWSI, Ground-Water Site Inventory; AKGWA, Assembled Kentucky Ground Water Data Base]

Date of inventory	Approximate total number of wells	Well construction, in percent of total: Drilled	Well construction, in percent of total: Hand-dug
pre-1991 GWSI	200	49	51
Well inventory, 1991	150	82	18
AKGWA	70	91	9

Two public water-supply systems depend on ground water in the study area. The City of Island, in McLean County, operates 2 wells adjacent to the Green River that serve approximately 1,500 customers. The wells are pumped on alternate days at a rate of 180 gal/min for about 10 hours. Two wells at Beaver Dam, Ohio County, produce water for public supply from a sandstone aquifer in the Tradewater Formation that is 230 to 285 ft below land surface. These wells supplement water obtained from the Green River. The system serves about 4,300 customers. The average pumpage from these two wells was reported to be 47 gal/min (Buddy Spencer, Beaver Dam Municipal Water and Sewer System, oral commun., 1991).

Quality of Water

The majority of wells sampled during the study exhibit water quality that indicate infiltration of surface and near-surface waters, and surface-mining disturbance. Most of the wells sampled produced turbid water containing concentrations of dissolved manganese above the Secondary MCL of 0.05 mg/L (U.S. Environmental Protection Agency, 1990). Except for well H12A0037 (fig. 20), the wells located in Ohio County in the two northernmost quadrangles of the study area produced acidic water, as indicated by pH values ranging from 4.2 to 5.8. Water from three of the wells contained concentrations of dissolved iron above the Secondary MCL of 0.3 mg/L. The sample from well H12A0033 (fig. 20) contained concentrations of dissolved aluminum, cadmium, nickel, and total dissolved solids at or above the MCL or Secondary MCL for these constituents (U.S. Environmental Protection Agency, 1990, 1991, and 1992). This sample also had the lowest pH value of any sample (4.2), and contained high concentrations of the following constituents: dissolved manganese, 3.3 mg/L; nitrate plus nitrite nitrogen, 7.7 mg/L; cobalt, 0.18 mg/L; lithium, 0.12 mg/L; and strontium, 0.11 mg/L. The sample from well H12B0021 (fig. 20) contained a concentration of total dissolved solids above the Secondary MCL, the highest concentration of dissolved iron (9.9 mg/L), and high concentrations of dissolved ammonia nitrogen (0.37 mg/L), lithium (0.10 mg/L), manganese (2.8 mg/L), and strontium (1.1 mg/L). The high concentrations of trace metals in this and other wells with low pH values reflect the leaching effects of acidic waters generated by surface-mining disturbance.

The quality of ground water differs greatly throughout the study area. Stiff diagrams, which indicate the relative major-ion composition water (Hem, 1989), were constructed to illustrate the differences in water composition. Stiff diagrams of waters with similar chemical compositions will exhibit similar shapes regardless of the effects of dilution. The dissimilar shapes of the Stiff diagrams (fig. 20) indicate that the ground-water samples are from different aquifers and/or are influenced differently by interaction with the rock matrix and that there is a lack of mixing among waters in different locations. The chemistry of the ground water is also influenced by the infiltration of surface waters into poorly sealed wells, occurrence of natural brines, and acidic shallow ground water from surface-mining disturbance.

County Health Departments in Kentucky are routinely requested to collect ground-water samples from wells for bacteriological analysis. The Health Departments report that roughly 70 percent of the wells tested in the study area indicate the presence of coliform bacteria. This is usually the result of shallow or faulty well construction or poor well maintenance. The wells may not be adequately sealed to prevent the entry of surface runoff, which may be contaminated by human and animal waste into the well. This can result in coliform contamination of the well water. State regulations, enacted in 1985, specify proper well construction practices that have reduced this problem in newer wells.

Yield of Water-Producing Formations

One measure of the ability of an aquifer to transmit water is the transmissivity, or the rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient. The storage coefficient is the volume of water an aquifer releases from or takes into storage, per unit surface area of the aquifer, per unit

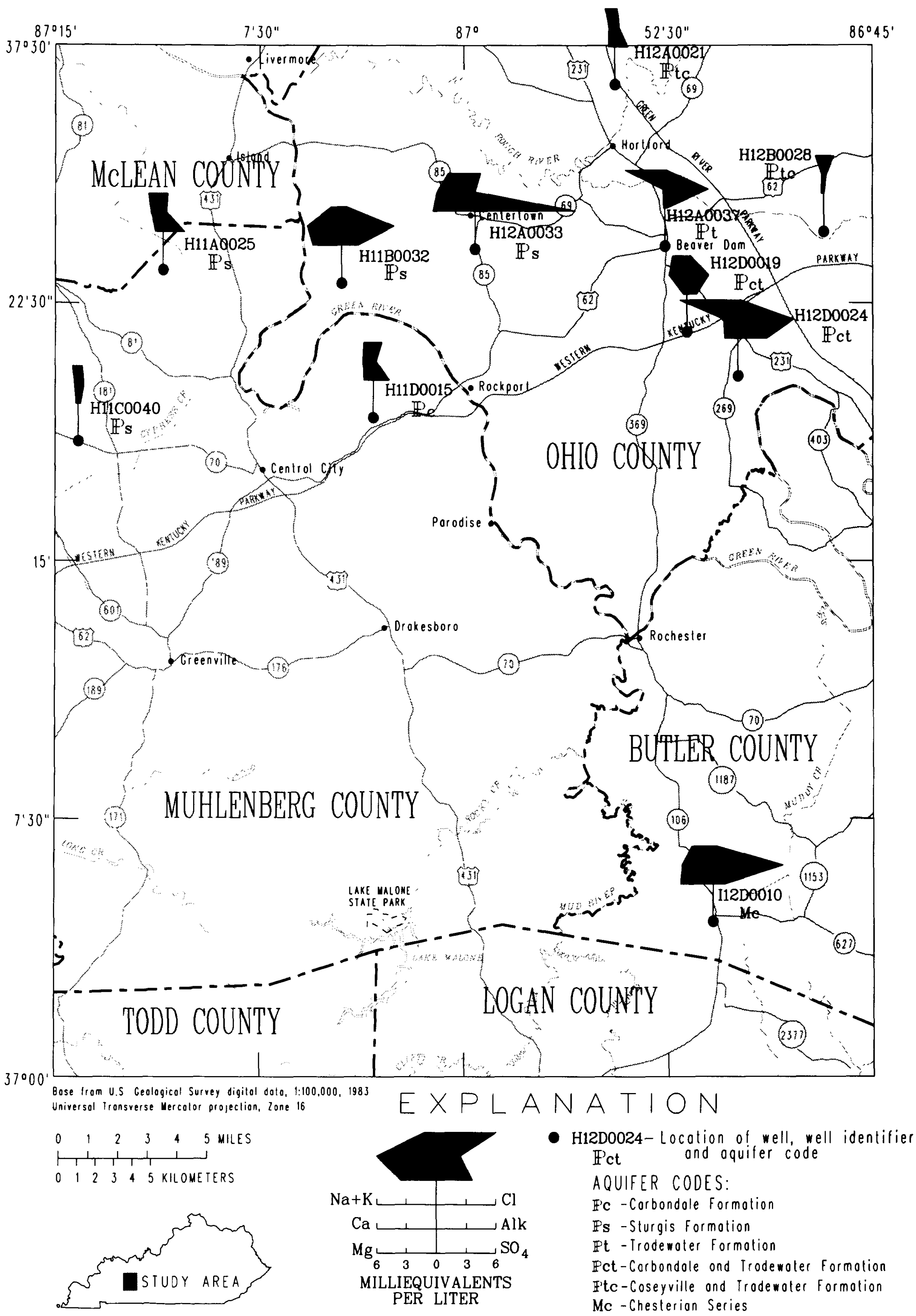

Figure 20.--Quality of ground water at selected sites.

change in head. In an unconfined aquifer, it represents the volume of water that can be drained by gravity from a volume of the aquifer. In a confined aquifer, it mainly represents the volume of water that is produced by the compaction of the aquifer when pressure in the aquifer is reduced, as when pumping occurs.

The hydraulic properties of the aquifer at two sites in the alluvial area adjacent to the Green River were determined by Ryder (1974). At both sites the aquifer was about 30 ft thick and composed of fine- to medium-grained sand. The transmissivities were estimated to be 1,000 to 1,600 ft^2/d and the storage coefficients to be $3x10^{-5}$ to $8x10^{-5}$. Davis and others (1974) reported that the transmissivities of aquifers in the Pennsylvanian System range from 100 to 350 ft^2/d and the storage coefficients range from 4×10^{-5} to 9×10^{-4}. The transmissivity of the Number Nine Coal, in the Carbondale Formation, ranges at one site from 1,000 to 2,000 ft^2/d (Duncan Coal Company, written commun., 1952).

Maxwell and Devaul (1962b) and Whitesides (1971) reported specific capacities for several wells in the area. Specific capacity is the rate of discharge from a well divided by the drawdown of the water level within the well. It is a less exact measure of the yield of an aquifer than is transmissivity, but it is more often available because it is less expensive to obtain. The mean specific capacity of nine wells that obtain water from the Tradewater, Carbondale, and Sturgis Formations is 0.5 gal/min/ft, of five wells that obtain water from the alluvium is 0.8 gal/min/ft, and of six wells that obtain water from the Caseyville Formation is 1.4 gal/min/ft.

The specific capacity of 16 wells tested in this study (pl. 1) ranged from 0.08 to 0.3 gal/min/ft. Specific capacities could not be determined for several wells because the wells dewatered rapidly upon pumping at rates as low as 7 gal/min. The rate of water-level recovery in the dewatered wells was monitored for up to 1 hour after pumping ceased, and the rate of recovery in most of these wells was estimated to range between 0.5 to 3.0 ft of recharge to the well bore, per hour.

CONCLUSIONS

Although some geologic units in the study area reportedly yield more water to wells than do others, the data collected in this study indicate that local well drillers do not specifically target these units when drilling new wells. The reasons for this are as follows: (1) no areally extensive lithologic units produce quantities of water sufficient for other than a single-dwelling domestic water supply, (2) the potential for developing a water supply in deep aquifers has not been fully explored, and (3) local aquifers have not been mapped. The need for ground water is not great and has not justified the cost to obtain the data necessary to address the second and third reasons listed above. Most ground water is used for single-dwelling domestic water supply. In most cases, the water is produced from the uppermost geologic formation at depths less than 300 ft. Given the variable nature of the lithology in this area, it is likely that, at a minimum, a marginally suitable aquifer or aquifers will be penetrated at a depth of less than 300 ft. Fractures are very important in the ground-water flow system and probably transmit water from the surface to aquifers and between aquifers that are separated by changes in lithology.

Although ground water flows primarily in shallow, local flow systems, there is evidence of a regional component to ground-water flow. The map of kriged water-level altitudes (fig. 16) indicates that, in the absence of any major pumping centers, regional ground-water flow is toward broad alluvial areas near the confluence of the Green and Rough Rivers in the northwest part of the study area. Water flows at land surface from wells that are completed in aquifers 1,000 ft below land surface; thus, there is the potential for ground water to migrate upward by vertical leakage into overlying formations.

The Pennyrile Fault System affects the flow of ground water. The level of water in open boreholes generally occurs at higher altitudes in the area south of the faults than elsewhere in the study area. The faults seem to have been present at the time the first Pennsylvanian rocks were deposited; they have affected the location, thickness, and recharge to water-bearing rocks.

Ground-water use in the study area has decreased since the HA's were produced in the 1950's and 1960's. As a result of the expansion of public water-supply systems, few residents in the study area rely solely on ground water as their domestic supply. Some residents use wells to supplement their public supply--most commonly to water crops or livestock, or to wash cars. A few homes have cisterns, and a small number of residents haul water to their homes. Many wells that were once used for single-dwelling, domestic water supply are now destroyed or abandoned.

The yield of most wells in the study area is not sufficient for more than single-family dwellings, except for deep aquifers in the Pennsylvanian System, which could supply up to 300 gal/min to a well. The quality of the water is generally acceptable for domestic use except for a few wells that produce water having low pH and high metals content. The quality of ground water can be adversely affected by local sources of contamination.

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