Bulletin 229

Hydrogeology and Geochemistry of Glacial Deposits

in Northeastern Kansas

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Rachel E. Miller, Lawrence R. Hathaway,
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Kansas Geological Survey
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Acknowledgments

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Abstract

Twelve counties (Atchison, Brown, Doniphan, Douglas, Jackson, Jefferson, Johnson, Leavenworth, Nemaha, Shawnee, Wabaunsee, and Wyandotte) in northeastern Kansas were glaciated during the Pleistocene Epoch. The glacial deposits consist of till, fluvial, loess, and lacustrine deposits locally totalling thicknesses of 400 ft (120 m). A major buried valley 3 mi (5 km) wide, 400 ft (120 m) deep, and 75 mi (120 km) long trends eastward across southern Nemaha, northern Jackson, and central Atchison counties. Several smaller tributary valleys can be identified in Atchison, Nemaha, Brown, Jackson, and Jefferson counties. Other buried valleys generally trend southward to the Kansas River valley or northward into Nebraska and Missouri. The glacial deposits filling the buried valleys locally are clayey. However, most valleys contain at least some water-bearing sand and gravel. Wells drilled into the best water-bearing sand and gravel deposits may yield as much as 900 gallons per minute (gpm; 0.06 m^3/s), but less than 500 gpm (0.03 m^3/s) is more common. The alluvial deposits of the Kansas and Missouri river valleys are the major sources of ground water in northeastern Kansas. Wells in these aquifers may have yields of 5,000 gpm (0.3 m^3/s), but yields are more commonly less than 3,000 gpm (0.2 m^3/s). We analyzed data from 80 pump tests using computer programs to find the best fit for transmissivity (*T*) and storage (*S*) values on glacial, alluvial, and bedrock aquifers. Transmissivities in the Missouri River valley alluvium ranged from 200,000 gallons per day per foot (gpd/ft) to 600,000 gpd/ft (2,000–7,000 m^2/d), and storage values were between 0.001 and 0.0004. Tests in the Kansas River valley alluvium indicated transmissivities in the range 50,000–600,000 gpd/ft (600–7,000 m^2/d) and storage values of 0.03. In the main buried valley across northeastern Kansas, the glacial deposits had *T* and *S* values of 2,500–25,600 gpd/ft (31.0–318 m^2/d) and 0.00002–0.002, respectively. In the smaller buried valleys the glacial deposits had *T* values ranging from 1,500 gpd/ft to 100,000 gpd/ft (19–1,200 m^2/d). Because of increasing population size in northeastern Kansas, appropriations of water for public and industrial water supplies have been increasing. Most of the pumpage comes from wells in the Kansas and Missouri river valleys. However, in 1981 the Division of Water Resources reported allocations of 1,466 acre-ft of water from wells tapping glacial aquifers associated with the main buried channel across Nemaha, Jackson, and Atchison counties and an additional 837 acre-ft from tributaries associated with the main buried channel. Nemaha County has the largest appropriation of water from the glacial aquifer (1,549 acre-ft/yr in 1983), and Wyandotte County has the largest appropriation of water from the alluvial aquifers (54,250 acre-ft/yr in 1983). Shawnee County has the largest number of ground-water appropriation rights (217). In 1981, for the 12-county study area, the Division of Water Resources found that 773 wells have ground-water appropriation rights. These 773 wells have appropriation rights for 140,484 acre-ft of water from alluvial aquifers, 5,290 acre-ft from glacial aquifers, and 2,146 acre-ft from Pennsylvanian and Permian rock aquifers. Maps for each county show the depth to bedrock, total thickness of Pleistocene sand and gravel deposits, estimated yield of wells, depth to water in wells and test holes, and the saturated thickness of Pleistocene deposits. A bedrock topographic map for the twelve counties was prepared from outcrop data and information from more than 5,000 water well, oil and gas, and test-hole logs. Ground waters from alluvial deposits are hard calcium bicarbonate waters that may have iron concentrations of several milligrams per liter. Sand and gravel associated with the glacial deposits generally yield hard calcium bicarbonate waters and may contain appreciable amounts of iron, manganese, sulfate, and chloride locally. Nitrate concentrations above 45 mg/L are noted in a number of wells of varying depth and aquifer source.

Introduction

As population increases, so does the demand for water, and thus ground-water supplies are gaining significance in northeastern Kansas. These supplies are especially important during times of low precipitation, when surface-water supplies decline. Although bedrock formations in the area generally contain little, if any, high-quality water (Moore, 1940), large quantities of freshwater can be obtained from deposits in glacial buried valleys. Because the extent and character of many of these deposits were not precisely known, a detailed evaluation was undertaken by the Kansas Geological Survey in cooperation with the U.S. Geological Survey.

The general study area (fig. 1) covers 12 counties in northeastern Kansas that were entirely or partially glaciated during pre-Illinoian (classical Kansan and Nebraskan) time. Quaternary deposits exposed in the area include glacial drift (till, outwash, and lacustrine deposits), loess, and alluvium. Pennsylvanian and Permian shale, limestone, and sandstone bedrock formations occur near the land surface in other areas.

The general location of preglacial drainageways is shown in fig. 2. The buried valleys may be up to 3 mi (5 km) wide, 400 ft (120 m) deep, and more than 75 mi (120 km) long. Deposits filling these valleys range from clayey sediments to sand and gravel. Many of the buried-valley aquifers are confined; others are unconfined. Aquifer yields can reach 900 gallons per minute (gpm; 0.06 m^3/s) but are generally less than 500 gpm (0.03 m^3/s). Water levels are commonly 5–50 ft (2–15 m) below the land surface, but locally they may exceed 100 ft (30 m). However, measurements are complicated by the composite water levels obtained from single wells developed in multiple-aquifer systems using standard gravel-pack procedures. Well-construction methods also complicate analyses of water quality from the various aquifers. Although ground water from the buried valleys is generally of good quality, concentrations of nitrate, sulfate, chloride, iron, and manganese in excess of drinking water standards occur within the region.

To define the buried valleys, we compiled data from drillers' logs, engineering firms, and previous hydrogeologic studies. We drilled additional test holes and used geophysical (seismic, resistivity, temperature, gravity, and remote sensing) techniques to evaluate the channel locations and deposits. We used historical (late 1930's to 1973) and more recent (Spruill and Kenny, 1981) water-quality data for more than 1,200 wells in northeastern Kansas to evaluate the general quality of ground water in the area. In 1981, we collected 148 new samples (taken under controlled conditions of sampling, handling, and analysis) from wells with geologic logs and known construction characteristics.

Using a series of computer programs, we transformed the hydrogeologic data from the "free-formatted" county files (see Denne et al., 1990a) to a form that could be used with the KGS SURFACE II graphics system (Sampson, 1978). SURFACE II was used to plot data on county maps, and these maps were used to make interpretations and to hand-contour the bedrock surface elevations.

The five maps included for each of the 12 counties in this report were also plotted using the SURFACE II graphics system. Numerical data from the county files (see Denne et al., 1990a) were separated into selected ranges of values and plotted with certain symbols. The five map types are depth to bedrock, depth to water, total sand and gravel thickness, estimated well yield, and saturated thickness.

Regional Studies

Structural Geology

Northeastern Kansas is located in a structurally stable region of the North American continent characterized by sedimentary rocks of a shallow-marine shelf environment (Merriam, 1963). These sedimentary units are thinly layered with gentle structural features. The Permian and Pennsylvanian beds that crop out in northeastern Kansas have a generally westward dip of 25 ft/mi (4.7 m/km; Merriam, 1963), although the direction of the regional dip varies locally. This outcrop has been called the Prairie Plains homocline, and it originated during post-Permian time as a result of the Ozark area uplift. The Nemaha anticline interrupts and locally reverses the dip of these outcropping strata. The present eastward slope of the land surface formed in late Tertiary time during the deposition of a vast sheet of rock debris over eastern Colorado and western Kansas (Merriam, 1963).

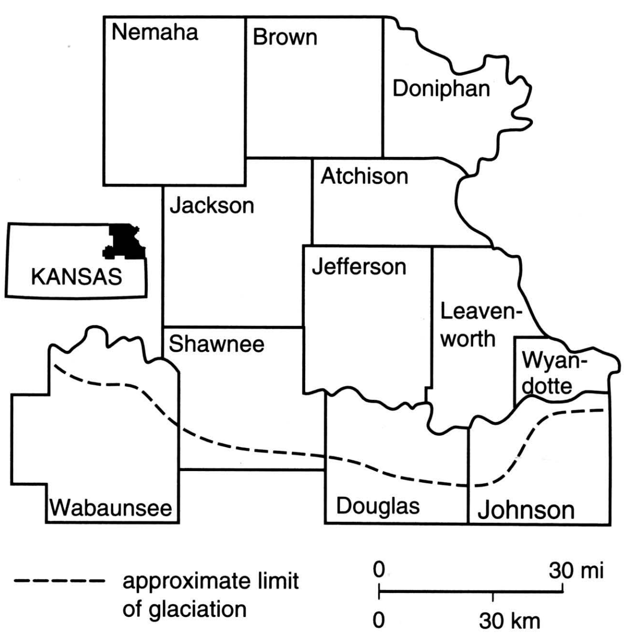

FIGURE 1—BURIED-VALLEY STUDY AREA.

The pre-Mississippian structure in northeastern Kansas is a downwarped area north of the Chautauqua arch and east of the ancestral Central Kansas uplift, called the North Kansas basin (fig. 3). The formation of the Nemaha anticline in post-Mississippian time divided the North Kansas basin into the Salina basin and the Forest City basin (Merriam, 1963). The area of northeast Kansas lies mostly in the Forest City basin and includes part of the Nemaha anticline (fig. 3). The Brownville syncline, the axis of the Forest City basin, lies to the east of the axis of the Nemaha anticline and runs parallel to it. This structural proximity gives the Brownville syncline a relatively steep west flank and a gentle east flank (Merriam, 1963).

The Nemaha anticline is a buried Precambrian uplift of mostly cataclastically deformed granitic rocks (Bickford et al., 1979). The crest of the Nemaha anticline runs in a north-south direction through Nemaha and Pottawatomie counties and near the western edge of Wabaunsee County (Merriam, 1963). The Precambrian granite along the crest of the uplift lies within 600 ft (180 m) of the surface in Nemaha County but plunges southward so that its depth is 4,000 ft (1,200 m) below the land surface at the Oklahoma border (Zeller, 1968).

The Nemaha anticline is a major structural feature of the midcontinent area. Seismic-reflection data (Steeples, 1981) suggest that uplift along the Nemaha anticline occurred at the same time as Pennsylvanian deposition or uplift and that peneplanation occurred between the deposition of Mississippian and Pennsylvanian sediments. During the Early Pennsylvanian, the granite crest of the anticline was exposed as a low ridge of hills, which shed arkosic sediments into the adjoining basins (Merriam, 1963). Consequently, there are many Paleozoic systems absent along the structure's crest, including the Cambrian, Ordovician, Silurian, and Permian (missing throughout the length of this structure but present elsewhere in Nemaha County) and the Upper Devonian, Mississippian, and Early Pennsylvanian (missing along the Nemaha anticline in Nemaha and Wabaunsee counties) (Zeller, 1968). Pennsylvanian rocks immediately overlie Precambrian rocks along the Nemaha anticline in Nemaha and Wabaunsee counties. The erosional periods at or near the end of the Mississippian and during the Pennsylvanian reduced the Mississippian surface to a peneplain as crests of the anticline were truncated, leaving a greater thickness of Mississippian deposits preserved in synclines (Merriam, 1963). The land surface was deeply weathered during this period, and solution features developed locally (Merriam, 1963).

The basement rock core of the anticline is characterized by a series of knobs along the crest of the structure. Along its eastern side the lower Paleozoic strata have been ruptured, truncated, and overstepped by Pennsylvanian sediments, and the Precambrian rocks that underlie these sediments include a large amount of metamorphic rocks (Merriam, 1963). The generally northwestward dip of the Paleozoic beds is reversed along the eastern side of the Nemaha anticline because of uplift. Permian rocks crop out on both sides of the Nemaha crest in Nemaha County and are also present in the subsurface immediately on the east and west sides of the anticline. The Permian rocks have presumably been eroded from the structure's crest throughout Nemaha County and into the edge of Wabaunsee County.

The Humboldt fault borders the eastern flank of the Nemaha anticline in its northern part, and on the surface its displacement may be up to 100 ft (30 m). The Humboldt fault and its associated faults are known to cut Precambrian and lower Paleozoic rocks discontinuously along the eastern flank of the Nemaha anticline for the entire length of the state (Merriam, 1963).

Steeples (1981) carried out seismic-reflection studies on sections a few miles wide and 2,500–5,000 ft (760–1,500 m) deep. The profiles show that Pennsylvanian sediments are draped rather than faulted over the Nemaha Ridge. Four profiles examined in Nemaha County show one or more faults. One profile shows lower Paleozoic (pre-Pennsylvanian) sediments truncating abruptly against the Nemaha anticline. According to Steeples (1981), the western part of the Forest City basin is characterized by grabens, horsts, monoclines, and normal and possibly reverse faulting, and the case is made for a complex zone of faulting. DuBois (1978) studied the surface lineaments detected on remote-sensing imagery in Nemaha County. Field investigations indicated that faulting occurs at and near the land surface immediately south of the Nebraska border.

Faulting of Permian strata in Nemaha County indicates that post-Permian movement has occurred in the Humboldt fault zone, although the displacement is minor compared with the displacement that occurred between Late Mississippian and Early Pennsylvanian time (Steeples, 1981). The glacial-till deposits of Kansan age were also shown to be faulted (DuBois, 1978). While studying the stream-drainage patterns and surface geomorphic features, DuBois found a strong relationship to the underlying Precambrian basement. Many of the

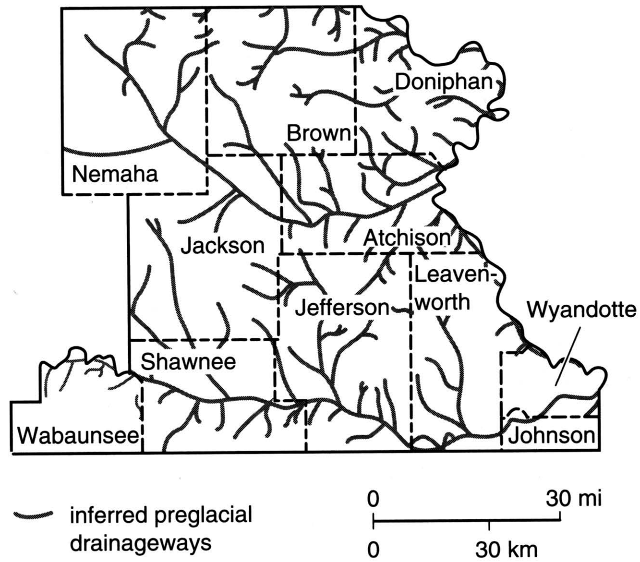

FIGURE 2—Location of preglacial drainageways in northeastern Kansas; after Dreeszen and Burchett (1971).

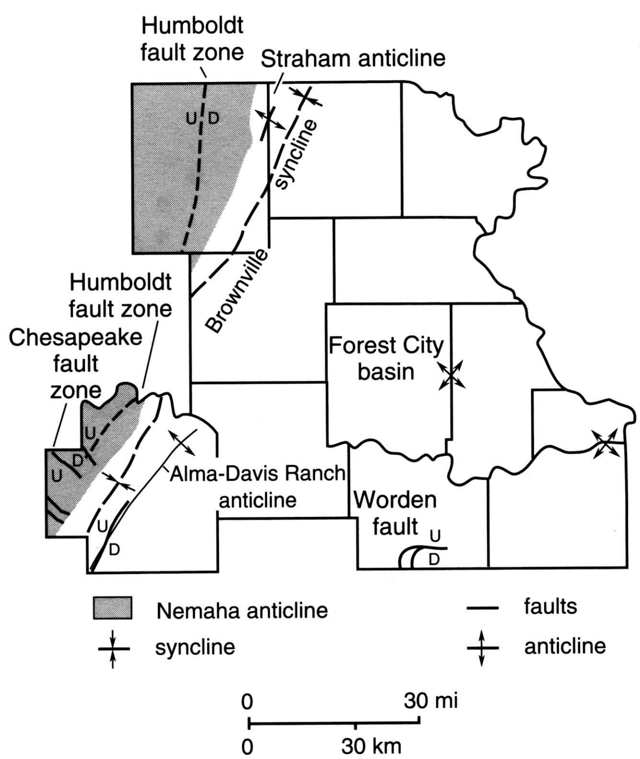

FIGURE 3—Structural features of northeastern Kansas; data compiled from Merriam (1963).

present streams in Nemaha County, especially the Black Vermillion River and Negro Creek, display prominent angular or rectangular drainage patterns. Also, several circular drainage patterns are thought to reflect certain geophysical anomalies (DuBois, 1978). No surficial faulting has been detected south of Nemaha County along the Nemaha Ridge in Kansas (Wilson, 1979).

In Wabaunsee County, the Nemaha anticline is cut by a northwest-trending disturbed zone called the Chesapeake fault zone (Merriam, 1963). This zone can be traced for 600 mi (960 km) through Missouri, Kansas, and Nebraska. The structure is essentially a buried or subsurface graben 6–10 mi (10–16 km) wide with the floor dropped by as much as 1,000 ft (300 m) (Merriam, 1963).

There is a northeast-trending disturbed zone extending for at least 50 mi (80 km) in Douglas County called the Worden fault. This fault is the longest fault recognized on the surface of eastern Kansas (Merriam, 1963), and it developed principally in Early Pennsylvanian time (O'Connor, 1960).

There are many minor structures in northeastern Kansas, and they have been discovered mainly as a result of oil and gas exploration. The Alma–Davis Ranch anticline runs through Wabaunsee County from the southwest to the northeast. The Brownville syncline, which runs parallel to the Nemaha uplift along its eastern side, cuts through Wabaunsee County on the west side of the Alma–Davis Ranch anticline and extends northward to northwestern Brown County (see fig. 3). The McLouth dome is located near the city of McLouth in Jefferson County. The Morris anticline is located in south-central Wyandotte County. The Strahm anticline is in northeast Nemaha County between the east ridge of the Nemaha anticline and west of the Brownville syncline (Merriam, 1963). Located along the crest of the Nemaha anticline are many locally closed anticlinal structures (with local faulting on their steeper eastern flanks), some of which are sizable (Merriam, 1963).

Microearthquakes in northeastern Kansas have been recorded by a network of stations established in eastern Kansas and Nebraska by the Kansas Geological Survey in 1977, and continuously monitored to 1989 (Hildebrand et al., 1988; Steeples et al., 1990), yielding 12 years of record. The pattern of historical earthquakes (last 125 years) reported for the region by Dubois and Wilson (1978) and Steeples et al. (1990) corresponds closely to the pattern of microearthquakes sensed during the monitoring program. Although the Humboldt fault was represented as a singular, long trace on the basement by Cole (1976), Steeples (1982, 1989) has subsequently recognized a zone of faulting tens of kilometers wide along both sides of the Nemaha Ridge after examining the distribution of historical and microearthquake observations and other geological information. The 12-year monitoring program indicated a large number of events on the Nemaha Ridge and low levels of seismic activity bounding it (fig. 4). The diverse pattern of microearthquakes located on the ridge by the

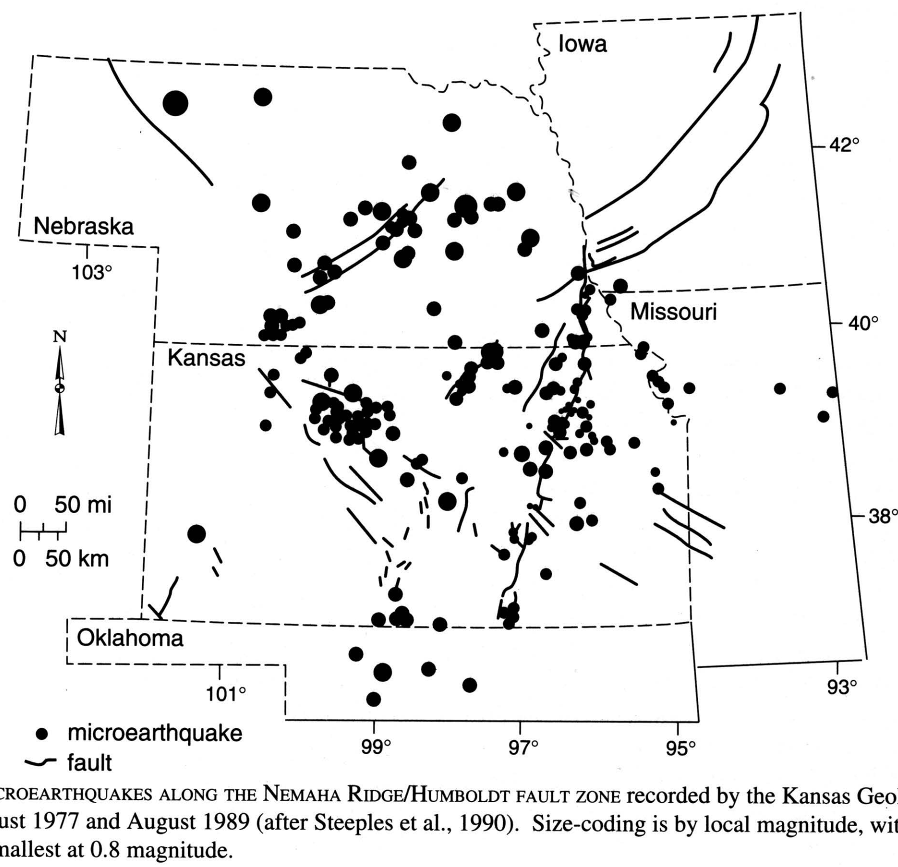

FIGURE 4—MICROEARTHQUAKES ALONG THE NEMAHA RIDGE/HUMBOLDT FAULT ZONE recorded by the Kansas Geological Survey between August 1977 and August 1989 (after Steeples et al., 1990). Size-coding is by local magnitude, with largest event at 4.0 and the smallest at 0.8 magnitude.

seismic network indicates that several faults are sufficiently active to generate small to moderate earthquakes. A myriad of faulting was recognized along the flanks of the Nemaha Ridge via seismic-reflection surveys. Correspondence exists between the gravity and aeromagnetic data and the subsurface faults. Using these data, lineaments detectable on LANDSAT images, and cuttings from hundreds of well cores obtained from both sides of the ridge, Berendsen and Blair (1986) hypothesized faulting between basement crustal blocks. Generally, it is thought that the quakes are the result of reverse faulting in the deep-seated Precambrian rocks (Merriam, 1963). Wilson (1979) speculated that some of the minor seismicity in eastern Kansas and Nebraska may be due to isostatic adjustments resulting from glacial rebound, a hypothesis difficult to prove and unlikely due to the several hundred thousand years (600,000 yrs?) since glaciation. The earthquake risk for the Nemaha Ridge/Humboldt fault zone have been recognized for several years (e.g. Algermissen, 1969; Algermissen and Perkins, 1976).

Pre-Pleistocene Stratigraphy

Northeastern Kansas is characterized by dissected till plains. Glacial sediments of Pleistocene age overlie the older Paleozoic rocks, which are also of sedimentary origin (fig. 5). The Pleistocene deposits are quite thick in some areas, such as Nemaha County (where they range up to 400 ft [120 m] in thickness), but are thin or entirely absent in many other areas. Outcropping rocks of Paleozoic age, including the Pennsylvanian and Permian systems, are present in northeastern Kansas (fig. 6). Where these outcrops are not overlain by glacial drift, they form the Osage cuestas and the Flint Hills physiographic region. Rocks of Mesozoic age are not present in northeastern Kansas.

Rocks of Middle and Late Pennsylvanian age are characterized by cycles of sedimentation that correspond to deposits of marine shales and limestones alternating with nonmarine beds of sandstone and coal (Zeller, 1968). Lower and Middle Pennsylvanian rocks (Morrowan, Atokan, and Desmoinesian stages) do not crop out in northeastern Kansas. Missourian Stage rocks crop out in a belt 20–40 mi (30–60 km) wide extending from Wyandotte and Leavenworth counties in the north to Johnson County and part of eastern Douglas County in the south.

The Missourian Stage consists of the Pleasanton, Kansas City, and Lansing Groups. The Pleasanton Group does not crop out in northeastern Kansas but is exposed farther south. The Kansas City Group includes three subgroups and is 325 ft (99 m) thick (Zeller, 1968). The lower unit (Bronson Subgroup) is 175 ft (53 m) thick and contains thick gray limestones that form prominent escarpments and gray, brown, and black shales, brown sandstones, and local coal beds. The middle subgroup (Linn) consists of two limestone and two shale formations. The shales are bluish gray, greenish gray, and dark gray and locally contain much sandstone and thin coal beds. The limestones are generally gray, cherty, and oolitic. The upper part of the Kansas City Group (Zarah Subgroup) is 100 ft (30 m) thick and contains two shale formations and one limestone formation. The rocks are generally dark gray, and the limestone members contain abundant fossils. The Kansas City Group crops out in parts of Johnson, Wyandotte, and Leavenworth counties. The Lansing Group has an average thickness of 85 ft (25 m) and forms escarpments in Wyandotte and Johnson counties and in parts of Douglas and Leavenworth counties. Two limestone formations and one shale formation make up the Lansing Group. The upper limestone formation (Stanton Limestone) is generally gray and fossiliferous and is 25 ft (8 m) thick. It is separated from the lower limestone formation by the shale formation (Vilas Shale), which consists of gray, sandy, silty, carbonaceous shales that are 35 ft (11 m) thick. The lower formation (Plattsburg Limestone) is commonly 30–50 ft (9–15 m) thick in northern Kansas and consists of gray fossiliferous limestones and gray shales that are locally sandy and that contain some sandstones.

Rocks of the Virgilian Stage are 1,200 ft (365 m) thick and comprise most of the Upper Pennsylvanian section cropping out in northeastern Kansas. These rocks are exposed over large areas of Leavenworth, Jefferson, Shawnee, and Douglas counties and are present in parts of Wabaunsee and Johnson counties. Scattered outcrops are present in Doniphan, Jackson, Brown, and Atchison counties where glacial drift covers much of the bedrock. Three groups make up the Virgilian Stage, the Douglas, Shawnee, and Wabaunsee Groups.

The Douglas Group consists mainly of clastic rocks with a few thin limestones and is 240–400 ft (73–120 m) thick. It is divided into two formations, the Lawrence Formation and the Stranger Formation. Coal beds occur locally in both formations along with buff to brown sandstones (Ireland and Tonganoxie Sandstone Members) that are up to 120 ft (37 m) thick where they fill former valleys.

The Shawnee Group is 325 ft (100 m) thick and includes four limestone and three shale formations. The basal limestone formation (Oread Limestone) is 52 ft (16 m) thick and consists of gray, sometimes massive, fossiliferous limestones and black, gray, or yellow shales. One limestone member (Plattsmouth) contains abundant chert. The limestones are less massive in the middle formations but continue to have abundant fossils, as do the shales. Gray sandstones and sandy shales occur locally in the two upper shale formations. The uppermost limestone formation (Topeka) consists of gray, white, and bluish limestones and shales.

The Wabaunsee Group is composed chiefly of shale, is divided into three subgroups, and is 500 ft (150 m) thick. The lower subgroup (Sacfox) contains two shale formations and a limestone formation. The lower shale formation (Severy Shale) is bluish gray and 70–80 ft (20–24 m) thick. The limestone formation (Howard Limestone) is gray, 8–40 ft (2–12 m) thick, and contains sandy portions and a coal bed. The upper shale formation (Scranton Shale) is 125 ft (38 m) thick and consists of gray shale with local sandstone and a thin coal bed. The middle subgroup (Nemaha) contains two limestone and two shale formations and is 150 ft (46 m) thick. The

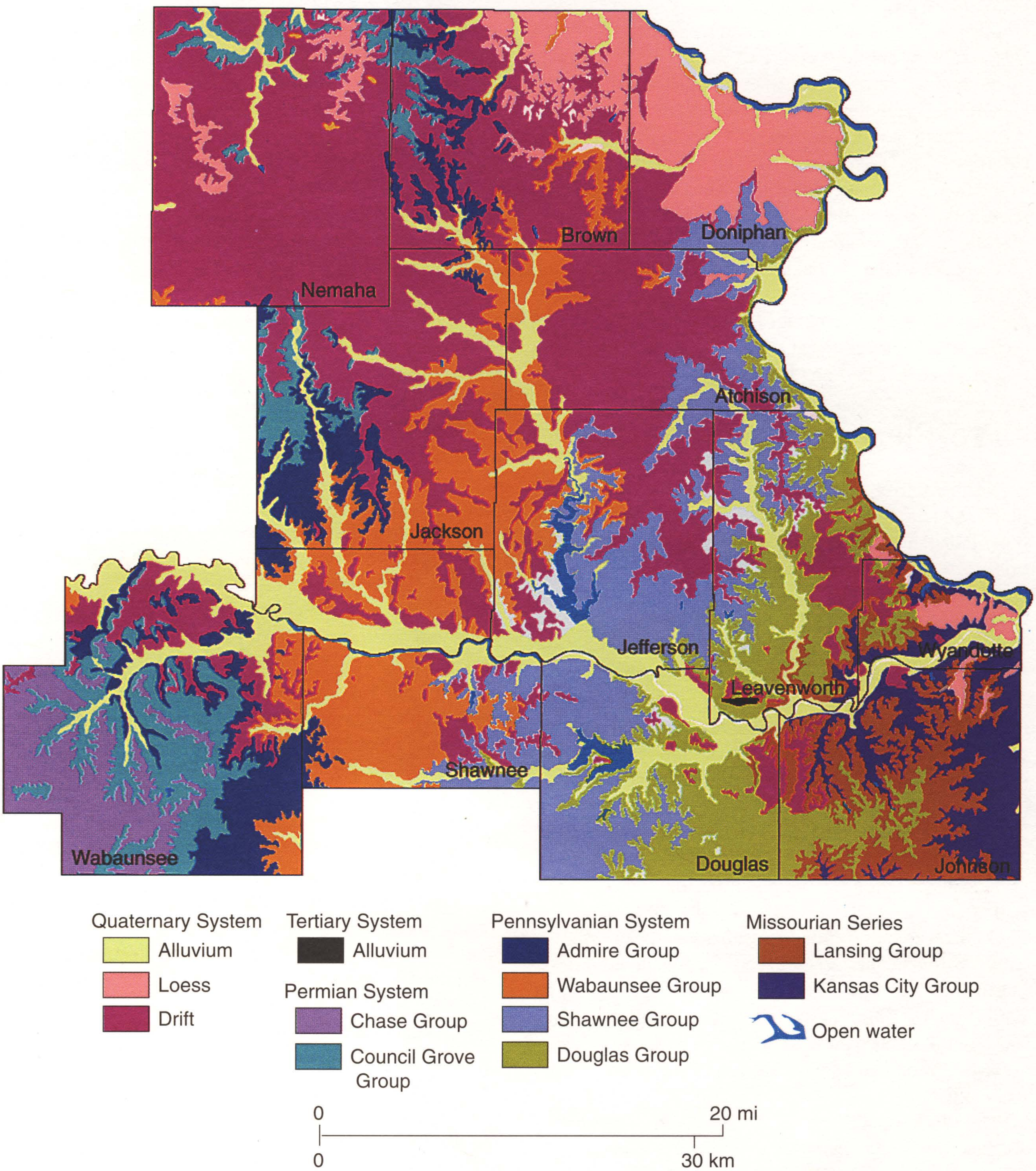

FIGURE 5—Geologic map of northeastern Kansas. Adapted from Kansas Geological Survey, Geologic Map of Kansas (Map Series M–1, 1964, scale 1:500,000).

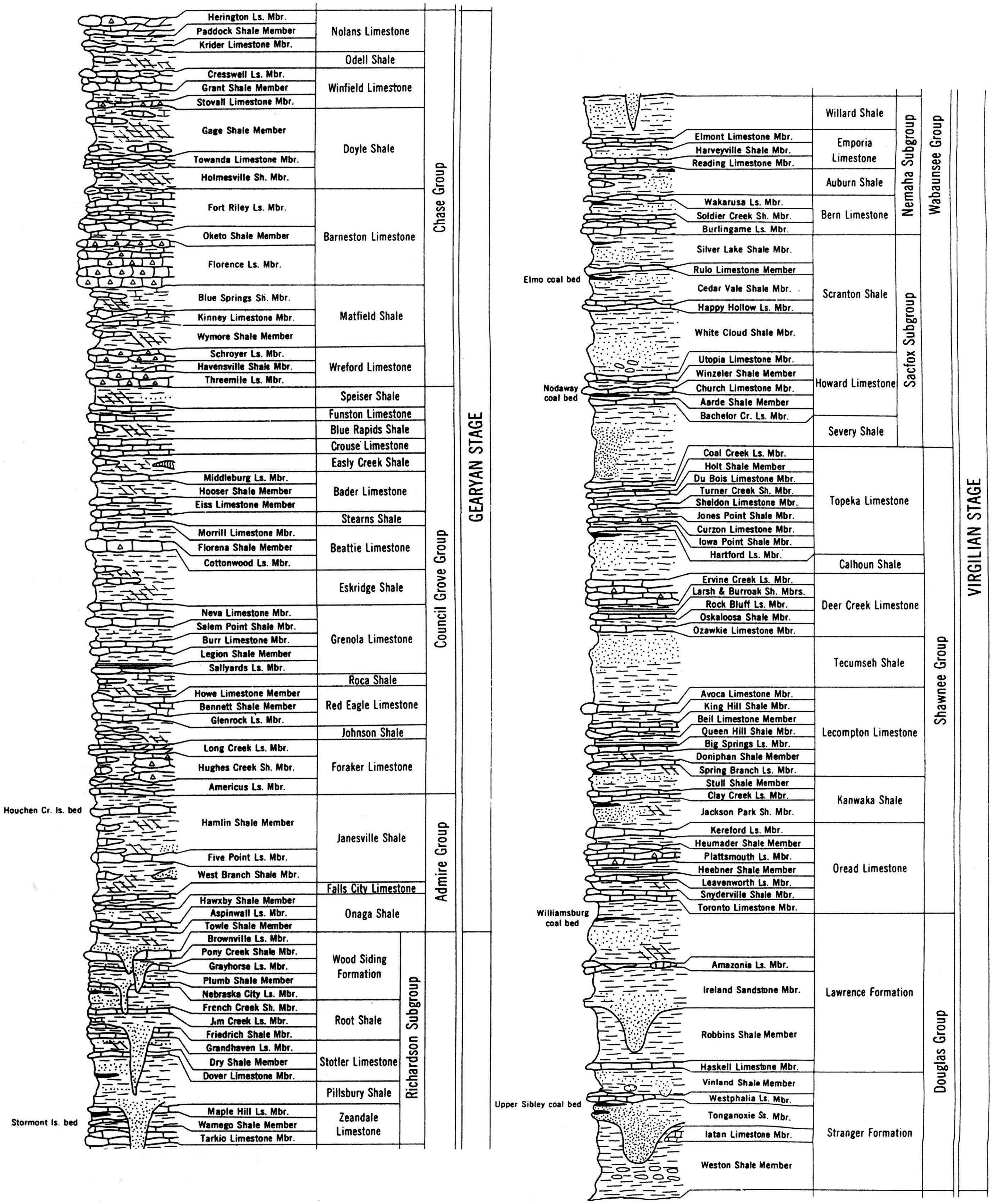

FIGURE 6—STRATIGRAPHIC SECTION OF UPPER PENNSYLVANIAN (VIRGILIAN STAGE) AND LOWER PERMIAN (GEARYAN STAGE) SERIES IN NORTHEASTERN KANSAS (Zeller, 1968).

limestones are generally fossiliferous and brown. The shales are generally dark gray or blue and weather gray or light tan; they are usually clayey and contain calcareous layers just below the limestones. The upper subgroup (Richardson) can be distinguished only in northeastern Kansas; it has a thickness of 150 ft (46 m). The Richardson subgroup consists of five formations, mainly shales and limestones with locally occurring channel sandstones. This subgroup is composed predominantly of clayey and sandy blue-gray shale with some red and green shales. The sandy beds are sometimes micaceous, yellow or brown, and loosely cemented. The limestone formations are blue-gray to gray and weather tan or brown; they generally contain one or two members and may weather into platy limestones (Zeller, 1968).

The Lower Permian Series is partly marine and partly nonmarine in origin. It is composed of 1,900 ft (580 m) of evaporite-bearing siltstones, sandstones, and shales and 800 ft (240 m) of alternating limestone and shale with minor amounts of gypsum. The Gearyan Stage, consisting of the Admire, Council Grove, and Chase Groups, forms an exposed belt in Wabaunsee and Jackson counties and along river valleys in Brown and Nemaha counties.

Permian outcrops are present on both sides of the Nemaha anticline in the northeastern corner and along the extreme western border of Nemaha County and include the Admire, Council Grove, and Chase Groups. The lower section of the Permian also crops out in western Brown County and in western Jackson County. Upper Pennsylvanian rocks are also exposed in Jackson, Nemaha, and Brown counties. Wabaunsee County, in the Flint Hills geographic province, has Permian outcrops, including the Council Grove, Chase, and Admire Groups. The Wabaunsee Group of the Pennsylvanian Series is also present along the eastern edge of Wabaunsee County. Shawnee County has some Permian rock exposed on the western edge; otherwise it contains outcrops from the Wabaunsee and Shawnee Groups of Pennsylvanian age. The Wabaunsee, Shawnee, and Douglas Groups are exposed in Jefferson, Atchison, and Doniphan counties. Douglas County outcrops include the Shawnee, Douglas, and Lansing Groups. In Leavenworth County the Shawnee, Douglas, Lansing, and Kansas City Groups are exposed. The Douglas, Lansing, and Kansas City Groups are exposed in Wyandotte and Johnson counties.

The Admire Group consists chiefly of clastic deposits but contains some thin limestone and coal beds. The group's thickness is 130 ft (40 m), with two shale formations and one limestone formation. The shales of the Admire Group are chiefly clayey, but some are silty, calcareous, or sandy. Most of the shales are very thin bedded to almost fissile. They are dark blue-gray and weather light gray or tan. The limestones are generally gray or light brown and weather tan or buff; they are generally massive but weather to thin bedded or platy.

The Council Grove Group is composed of 310–330 ft (94–100 m) of limestones and shales in 14 formations. Limestones in the lower formation (Foraker) are generally gray, massive, and dense. The exception is the Long Creek Limestone Member, which is argillaceous, porous, and thin bedded. It contains many nodules and geodes of celestite and quartz, indicative of subsurface water action (Zeller, 1968). Shales in the lower formations of the Council Grove Group are generally dark-gray to green clayey shales and contain lenses of fossiliferous argillaceous limestone. The middle formations are predominantly clayey shales, described as variegated green, red, and tan, and weather to a blocky form. The limestones of the middle and upper formations are generally massive, dense, and tan and form prominent rock terraces.

The Chase Group is made up of 335 ft (102 m) of escarpment-forming limestones alternating with shales. The shale formations are red and green. The thick chert-bearing limestones are a prominent topographic feature of the Flint Hills. Generally, only the lower part of the Chase Group is present in the northeastern Kansas outcrops, except in Wabaunsee County, where it is well represented.

The Cambrian through Permian systems are represented in the subsurface of northeastern Kansas, although many series are absent or not well developed and much geologic time is not represented. Generally, the series not represented in northeastern Kansas include Lower and Middle Cambrian, Upper Silurian, Upper Permian, Lower and Middle Triassic, and Lower and Middle Jurassic. The Paleocene, Oligocene, and Eocene series are not present in the Tertiary System deposits in northeastern Kansas (Merriam, 1963). These missing series are shown in the stratigraphic section as unconformities.

The major unconformities in the Paleozoic section are between the Mesozoic and Paleozoic erathems, the Pennsylvanian and Mississippian systems, the Devonian and Silurian systems, and the Paleozoic and Precambrian erathems. There are disconformities, marked by channel sandstones, in the Permian and Pennsylvanian deposits. The end of the Paleozoic is marked by a complete change in depositional and structural conditions, generally characterized by nonmarine sediments and erosional geologic processes (Merriam, 1963).

The sedimentary rocks of the Paleozoic erathem are underlain by Precambrian basement rocks, which form the stable interior of the United States and are an extension of the Canadian Shield. The shallowest known Precambrian rocks encountered in Kansas test wells are in Nemaha County, where the surface of the Precambrian rises to 588 ft (179 m) above sea level and 580 ft (177 m) below land surface. The greatest penetration of

TABLE 1—STRATIGRAPHIC UNITS OF THE PLEISTOCENE AND HOLOCENE SERIES, NORTHEASTERN KANSAS.

Series	Stage	Rock Unit	Thickness (ft)	Physical Characteristics	Distribution
HOLOCENE		fluvial deposits, minor terraces	60 (avg.)	silt, sand, and gravel composed of limestone, chert, and igneous and metamorphic fragments	all major valleys and many minor valleys
		Bignell Formation	10 (avg.)	eolian silt	on uplands and terraces, especially thick along Missouri River bluffs
PLEISTOCENE	1. Wisconsinan	Fluvial deposits	0–50	clay, silt, sand, and gravel derived in part from glacial material	underlies low terraces in major river valleys
		Brady Soil	14 (max.)	geosol; leached gray silt grading downward into a more compact faint reddish-buff silt	recognized along Missouri River bluffs
		Peoria Formation	30 (avg.)	eolian silt, buff, massive, generally fossiliferous and calcareous, coarse- to fine-grained	generally on uplands and terraces
		Gilman Canyon Formation	2–4	eolian (silt) and alluvial facies; lower part is light-gray to nearly white silty clay; upper part is dark-gray silty clay; dominated by a well developed geosol	between the Sangamon soil and Peoria loess; with alluvium and low terraces
		fluvial deposits	0–50	silt, sand, and gravel	not exposed; overlain by deposits of late Wisconsinan and Holocene ages
	2. Sangamonian	Sangamon Soil	24 (max.)	A horizon is dark-gray to grayish brown; B horizon is reddish-brown with some caliche	especially thick along the Missouri River valley; becomes thin and discontinuous westward
	3. Illinoian	Loveland loess	15 (avg.)	reddish-brown or yellowish-brown eolian silt (loess)	especially thick along the Missouri River valley; thin and discontinuous elsewhere
	4. Yarmouthian	Yarmouth soil	10 (avg.)	eroded remnants of a paleosol composed of deeply oxidized till with caliche at the base	
		volcanic ash (pearlette O?); loess, glaciofluvial, and lacustrine deposits	20–60	clay, silt, sand, and gravel; locally contains the ash bed and Nortonville Clay	adjacent to major stream valleys; Nortonville Clay present at top of Cedar Bluffs Till in upland areas of Atchison and Jefferson counties
	5. Kansan	Nortonville Clay; Cedar Bluffs Till	0–100	heterogeneous mixture of brown to reddish-brown clay, yellowish-brown or light-gray clay, silt, sand, and gravel; erratics are common; local lenses of sand and gravel	blankets northeastern Kansas
		glaciofluvial deposits	0–50	outwash materials (silt, sand, gravel, and boulders)	

TABLE 1 (continued)

Series	Stage	Rock Unit	Thickness (ft)	Physical Characteristics	Distribution
PLEISTOCENE		Nickerson Till	0–40	heterogeneous mixture of dark-gray to bluish-gray clay with some reddish-brown clay, silt, sand, and gravel. Contains fewer erratics than Cedar Bluffs Till; locally contains lenses of sand and gravel	present in thick till deposits in northeastern Kansas
		Atchison Formation	0–100	well-graded, finely crossbedded, fine-grained to very fine grained silty sand; thin layers of clay and gravel scattered throughout; gravel common at base	generally confined to buried valleys
	6. Aftonian	Afton soil	0–15	dark-gray in till or fluvial deposits in poorly drained areas and red in loess in well-drained areas	
	7. Nebraskan	loess and glacio-fluvial deposits	0–10	water-deposited silt and clay	
		Iowa Point till	0–30	unsorted clay, silt, sand, gravel cobbles, and boulders	present in extreme northeastern Kansas (Doniphan and perhaps Atchison counties)
		David City Formation	0–15	upper part, gray and brown clay, silt, and sand; lower part, chert and limestone gravel containing some arkosic material	Atchison, Brown, and Doniphan counties

Compiled from Zeller (1968), Frye and Leonard (1952), and Johnson (1993).

Precambrian rocks is 2,551 ft (777.5 m) in a test hole drilled in Nemaha County. In contrast, the deepest occurrence of Precambrian rocks in Kansas is at least 4,595 ft (1,401 m) below sea level in the Hugoton embayment in southwestern Kansas. The main Precambrian rock types in northeastern Kansas are granite and granite gneiss.

Tertiary deposits in northeastern Kansas are generally recognized as chert gravels derived from the Flint Hills region. The most easily recognized sections are accumulations of chert gravel in a brownish-red clay matrix; they are less than 20 ft (6 m) thick. The deposits occur as dissected terrace deposits at elevations 100–200 ft (30–60 m) higher than the present major streams (Zeller, 1968). The exact age of these deposits has been debated by many investigators, who report deposition during the Nebraskan Stage or during the late Pliocene (Mudge and Burton, 1959). In any case, because of the absence of glacial erratics in the gravel deposits, these deposits are preglacial. Thick deposits occur in Wabaunsee County along major streams and along the upper terraces of the Kansas River (Mudge and Burton, 1959).

Quaternary Stratigraphy

Classical Pre-Illinoian Glacial Geology of Northeastern Kansas

Quaternary sediments blanket Permian and Pennsylvanian bedrock throughout much of northeastern Kansas. The thickness of the these deposits varies widely from 0 in areas where these sediments were eroded or deposition did not occur to 400 ft (120 m) in areas where deposits fill pre-Pleistocene bedrock valleys. The Pleistocene geology of Kansas has classically been divided into eight stages in the time-stratigraphic classification [see table 3, Zeller (1968)]. Four major glaciations were recognized and are represented by the Nebraskan, Kansan, Illinoian, and Wisconsinan stages. Glaciers of the Nebraskan and Kansas stages were presumed to be the glaciers which actually reached northeastern Kansas. Three associated interglacial stages, the Aftonian, Yarmouthian, and Sangamonian, were characterized by warmer climates and stable land surfaces on which regionally extensive, isochronous soils, or geosols (North American Commission on Stratigraphic Nomenclature), formed (Frye and Leonard, 1952; Zeller, 1968).

Glaciation in northeastern Kansas has received a large amount of attention during the last 85 years. Several aspects of glaciation in Kansas were first studied by Chamberlin (1886, 1895) and Todd (1909, 1911, 1923). Detailed mapping of the glacial limit in Kansas has been conducted by several investigators, including Todd (1918b), Schoewe (1941), Jewett (1964), Dort (1985, 1987a), and Aber (1988a). Frye and Leonard (1952) were the first to conduct detailed studies, in a systematic fashion, of the glacial stratigraphy in the state. They identified two tills, an upper one (Kansas till) and a lower one (Nebraska till), which are frequently separated by a sandy glaciofluvial or lacustrine deposit called the Atchison Formation. Notably, these investigators used the term "Nebraska," although it could not be correlated with the type till. Hallberg (1986) and Aber (1991) observed that by the 1950's glacial stratigraphy of Kansas had evolved to the point that the type area for Kansan glaciation, northeastern Kansas, had a stratigraphy defined from accepted stratigraphy for Iowa and Nebraska, without a viable basis for correlation. The importation to Kansas of such lithostratigraphic terms from Iowa and Nebraska was subsequently criticized by Jewett (1963), however. Another difficulty arose from the indiscriminant use of the Pearlette volcanic ash as a regional stratigraphic marker throughout Kansas and Nebraska (e.g., Read, 1948; Frye and Leonard, 1952), despite the fact that mineralogical differences among the ashes had been documented (Swineford and Frye, 1946).

Given the obvious stratigraphic difficulties, a glacial stratigraphy for the state developed within the context of the classical glacial chronology (table 1). The Nebraskan Stage was the first major cycle of Pleistocene glaciation, and deposits are generally restricted to the northeastern corner of Doniphan, Atchison, and Brown counties in Kansas. Large exposures that include the David City Formation (Lugn, 1935), water-laid proglacial deposits, and the Iowa Point till (Reed and Dreeszen, 1965) are present along the Missouri River bluffs in Doniphan County. The Iowa Point section (NE SE sec. 6, T. 2 S., R. 20 E.), located along the bluffs, is the type section for the Iowa Point till. The David City Formation, first described from well records near David City, Nebraska (Frye and Leonard, 1952), is also present in the Iowa Point section, where it rests on Pennsylvanian limestone. It is composed of beds of gravel and cobbles and sand and silt in which laminations and crossbedding are evident. Fossil shells, including small clams and aquatic snails, have been found in sand lenses. Localized calcium carbonate cementation has occurred, rendering the entire unit calcareous.

Presence of the Nebraskan till (Iowa Point) in parts of Doniphan, Atchison, and Brown counties, and perhaps along part of the Kansas River in southwestern Leavenworth County (Schoewe, 1930b), represents the earliest glacial deposits in Kansas. The Iowa Point Till consists of a clay-sand-silt matrix with boulders and cobbles and exhibits lenses and zones of well-sorted sand. The boulders and cobbles are predominantly limestone, but commonly consist of pink quartzite, conglomeratic quartzite, igneous rocks, and metamorphic rocks. The upper part of the till is dakened by organic matter (Afton Soil) and is leached of carbonates to 2.5 ft (0.8 m) where the soil is present; the lower part of the till is gray-tan.

The Aftonian Stage represents a weathering period, as demonstrated by the absence of limestone and granitic pebbles and by the presence of resistent quartzite pebbles. The Aftonian is represented by a Humic Gley soil and is sometimes referred to as a gumbotil (Frye and Leonard, 1952). The Afton Soil is well-developed and recognized in Nebraska and Iowa, where it overlies the Iowa Point Till. It tends to be dark gray to black and developed on a poorly drained surface (Reed and Dreeszen, 1965), thereby being classified as an Aquoll (Soil Survey Staff, 1992), or Weisenboden in the old soil taxonomy.

Kansan Stage deposits include the Atchison Formation (Frye and Leonard, 1952), NickersonTill (Reed and Dreeszen, 1965), and the Cedar Bluffs Till (Reed and Dreeszen, 1965), interrupted by deposits of loess, glaciofluvial sediments, and lacustrine deposits. The Nickerson and Cedar Bluff Tills have been commonly referred to jointly as the Kansas Till. Overall, the volume of Kansan deposits exceeds that of any other Pleistocene stage deposits in northeastern Kansas.

The Atchison Formation is a pro-Kansan outwash of early Kansan age with a maximum thickness of 100 ft (30 m). The type section, located along a creek bank exposure in Atchison County (SE SW sec. 2, T. 6 S., R. 20 E.), is 70 ft (20 m) thick (Frye and Leonard, 1952). The upper part consists of silt and fine-grained sand (sometimes called "quicksand"), while the basal section is made up of coarser sand and gravel, which occur locally. Similar deposits occur locally between the Cedar Bluffs and Nickerson Tills. The Atchison Formation may have originated as outwash and lacustrine deposits in proglacial lakes produced by the advancing Kansan glacier (Frye and Leonard, 1952). The major buried-valley system, extending across southern Nemaha County and through Atchison County, contains large thicknesses of these deposits. Test drilling has shown that the Kansas till is composed of 50-60 ft (15-18 m) of oxidized till in the upper part, which grades downward into blue-gray unoxidized calcareous till. Color has been explained by the varying degrees of weathering and leaching of the originally deposited till. Three intergradational zones have been described by Frye and Leonard (1952). Frye and Walters (1950) reported well-developed joint systems in some till exposures; the joints may have oxidized rinds or calcium carbonate accumulations along joint planes.

Most till layers are less than 40 ft (12 m) thick and consist of brown or yellowish- to reddish-brown clay. Some lenses of sand and gravel are present locally. Both till units are, however, distinct and differ appreciably from one another. The Nickerson Till, as the most extensive till sheet in Kansas, occurs mainly north of the Kansas River and east of the Little Blue River, with the thickest accumulations in Nemaha, Jackson, and Atchison counties. It is predominantly a dark-gray or blue-gray calcareous till containing local lenses of sand and gravel. The till is mostly unstratified and unsorted and includes sediments that were probably deposited directly from glacial ice, i.e., ice-contact deposits (Frye and Leonard, 1952). Boulders and weakly developed soil zones are present locally. In contrast, the Cedar Bluffs Till is generally more deeply weathered and contains more erratics than the Nickerson Till.

A light-gray massive, plastic clay layer named the Nortonville Clay occurs locally above the Cedar Bluffs Till on upland areas of southwestern Atchison, northern Shawnee, Jefferson, and Jackson counties (Frye and Leonard, 1952). This layer was believed to result from lacustrine deposition in depressions on the newly formed Kansas Till plain. Where present, the Nortonville Clay generally rests upon oxidized and calcareous till with nodules of caliche and is overlain by a few feet of leached Peoria loess. The thickness of the Nortonville clay can reach 40 ft (12 m).

Glaciofluvial sediments deposited as the Kansan glacier(s) retreated were formerly called the Meade formation in northeastern Kansas. Deposits rest above the Cedar Bluffs Till adjacent to major stream valleys. Along the Kansas River these deposits are identified as fill beneath the Menoken terrace (Davis, 1951), and they lie 80 ft (24 m) above the present floodplain (Frye and Leonard, 1952). A few exposures occur in Nemaha County in road cuts and a gravel pit (NW sec. 31, T. 2 S., R. 13 E.). Some glaciofluvial deposits interfinger with underlying till, confirming the relative age of these deposits. Few exposures of glaciofluvial sediments are present in areas thickly mantled by Kansas Till. Deposits dated through their association with a volcanic ash identified as Pearlette by Frye and Leonard (1952) generally rest uncomformably on Kansas Till in Nemaha County.

Recent Changes in the Pre-Illinoian Glacial Stratigraphy

The recognition of several tills indicated that more than two glacial advances into Kansas and Nebraska had occurred, leading many investigators to conclude that the Kansan glaciation was more complex than earlier thought (e.g., Reed and Dreeszen, 1965; Dort, 1966; Bayne, 1968; Boellstorff, 1978). Dort (1969, 1972a), upon examining Pleistocene sections in Doniphan County, suggested that perhaps six or seven separate ice advances were recorded. Dort (1969) also suggested that there might be more than four Pleistocene glacial episodes affecting Kansas, possibly including a pre-Nebraskan glaciation. Bayne et al. (1971) found evidence to support two Kansan tills separated by an interstadial paleosol and proposed dividing the Nebraskan Stage into two substages on the basis of a pre-Aftonian paleosol. Reed and Dreeszen (1965) revised the classification of the Pleistocene deposits in Nebraska because of evidence of multiple glacial pulsations within the Kansan and Nebraskan stages. Consequently, the two-stage model of regional glaciation was modified to accommodate the increased complexity recognized in the glacial stratigraphy (Frye, 1973).

Widespread use of the Pearlette ash bed as a marker bed separating the Yarmouthian and Kansan stages and as an indicator of deposits of late Kansan age was brought into question by the work of Naeser et al. (1973) and Boellstorff (1976, 1977). Research involving the dating of volcanic ashes has shown that the Pearlette ash actually comprised three separate ashes having multiple names: ages include 2.01 ma (Pearlette B, Huckleberry Ridge, Borchers), 1.27 ma (Pearlette S, Coleridge, Mesa Falls), and 610 ka (Pearlette O, Pearlette Restricted, Lava Creek B, Cudahy, Hartford). As a result, Boellstorff (1977) advocated discontinuance of the classic stage terms "Nebraskan," "Aftonian," and "Kansan" and recommended the redefinition of some tills and nonglacial units.

It has become apparent, particularly in recent years, that northeast Kansas was glaciated by two major advances (Schoewe, 1931; Dellwig and Baldwin, 1965; Aber, 1985, 1988a). However, some debate has occurred over the proposed two-ice-lobe model for Kansan glaciation (Aber, 1982, 1985). Aber developed a model that incorporates two confluent ice streams, the Dakota and the Minnesota ice. This model was based on evidence of a resistant topographic barrier, striations, ice-push structures, distribution of Sioux quartzite erratics, and lithologic differences in till layers. Conversely, Dort (1965) believed that the lithologic differences in the till layers are due to climatic influences that caused local ice formation at the glacial front, which contained locally derived sediment only. At a later time, ice that carried cystalline rock debris from distant northern sources arrived.

Aber (1985, 1988b) and Aber and Wayne (1986) proposed redefining Kansan and Nebraskan stratigraphy and the stratotype for the Kansas drift plains west of Atchison, e.g. "At the proposed stratotype, the Kansas drift contains three formations: Lower Kansas Till, Atchison Formation, and Upper Kansas Till. The Lower Kansas Till was deposited by the Minnesota ice lobe coming from the northeast, whereas the Upper Kansas till was laid down by the Dakota ice lobe advancing from the northwest" (Aber, 1985, p. 53). Aber and Wayne thought that the Upper Kansas Till could be the Nickerson Till and that the Lower Kansas Till was equivalent to the Fremont till in Nebraska. In their classification, the Nebraskan was considered the first substage of the Kansan or was deleted and older tills, such as the Geary School till were assigned to the upper Pliocene.

Given the failure of attempts to accommodate the complexity of the glacial stratigraphy within the classic pre-Illinoian stage terminology, it has become apparent that the terms "Nebraskan" and "Kansan" should be abandoned in Kansas (Dort, 1985, 1987a; Aber, 1991), as has been done elsewhere in the midcontinent (Hallberg et al., 1980; Hallberg, 1986; Richmond and Fullerton, 1986). Data from test holes assembled for this study certainly document the complexity of the glacial deposits and difficulties involved in tracing specific deposits over a wide area.

The most recent and comprehensive research into the glacial history of northeastern Kansas is that by Aber (1988a; 1991), in which he recognizes two tills and adopts the term *diamicton* (a non-generic term referring to poorly sorted deposits such as till) to decribe them. The lower diamicton had been designated as the Nebraska, Iowa Point, Nickerson, or lower Kansas Till, whereas the upper diamicton has been known as Kansas, upper Kansas, or Cedar Bluffs Till. Weathering zones, paleosols, or stratified sediments separate the two diamictons. Although others observed additional diamictons and associated paleosols (e.g., Bayne et al., 1971; Bayne, 1968; Dort, 1985), Aber (1991) believed the number of diamictons is reducible to two and that, with the abandonment of pre-Illinoian terminology, a new nomenclature should be introduced. To this end, Aber (1991) introduced the Independence Formation to include all diamicton and stratified sediments in northeastern Kansas. He does not formally subdivide it into members but does divide it into upper and lower diamictons on the basis of the exposure at his designated holostratotype near West Atchison, Atchison County (Aber, 1988b).

According to Aber (1991), two distinct glacial advances are represented by the two diamictons. The lower diamicton and overlying stratified sediments are associated primarily with the large buried valley of the study area, and the upper diamicton mantles the surface on the uplands as well as above the buried valleys. On the basis of directional indicators, the lower diamicton advanced from the northeast as the Minnesota lobe, extending into northern Leavenworth, Jefferson, and Jackson counties, and covered most of Nemaha County (fig. 7) to form the early Independence glacial limit. The

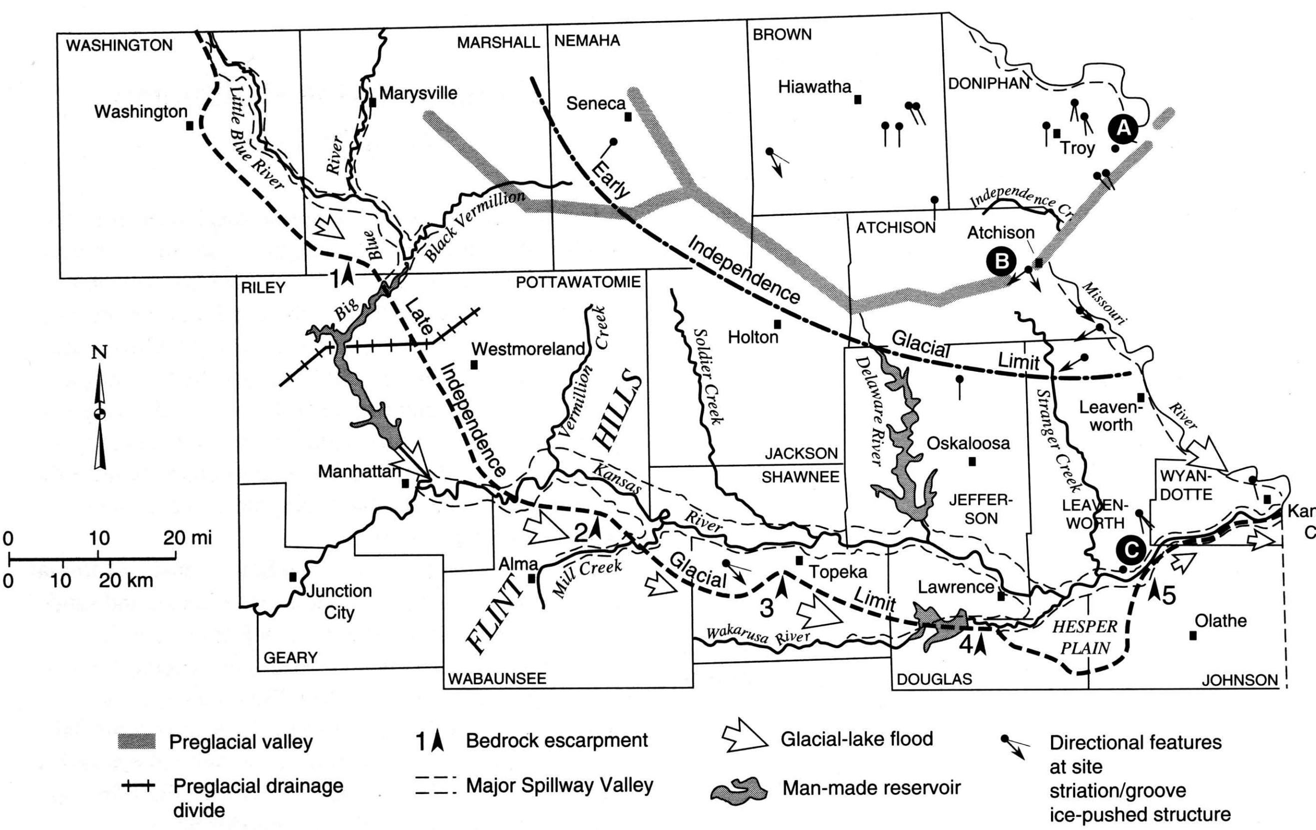

FIGURE 7— PREGLACIAL VALLEY AND GLACIAL LIMIT (after Aber, 1991).

upper diamicton was subsequently deposited from the northwest as the Dakota lobe advanced into Kansas, covering a greater areal extent and reaching south of the Kansas River valley and west of the Little Blue River valley. Aber (1991) proposed that the maximum limit of glaciation was determined by five regional bedrock escarpments: the Fort Riley Limestone Member—southwestern Marshall County, Flint Hills escarpment—north-central Wabaunsee County, Bern Limestone—southwest of Topeka, Oread Limestone—southwest of Lawrence, and Lansing-Kansas City Groups—northern Johnson County. Aber (1991) also speculated that the Independence Formation correlates with the type A2 and A3 tills recognized in the Nebraska and Iowa region (Hallberg, 1986) and with the McCredie Formation of north-central Missouri (Guccione, 1983).

Northeastern Kansas likely experienced numerous drainage blockages and diversions during the course of glaciation. The west-to-east flowing preglacial drainage ways (fig. 2; plate 1) was blocked by the pre-Illinoian glacial advances into Kansas (Early and Late Independence advances), and several ice-marginal drainage systems developed, e.g., the Blue, Kansas, and Wakarusa (Todd, 1911; Aber, 1989). Blockage of this large preglacial system created a large lake, glacial Lake Atchison. Two or more large overflow outlets were identified by Aber (1991), and once established, this spillway system experienced runoff and meltwater discharge from the entire northern Great Plains (Dort, 1987a). Periodic damming also occurred along the ice front, creating proglacial lakes, as evidenced by the existence of glaciolacustrine deposits in the Kansas River valley. Dort (1987a) hypothesized the existence of two such lakes in the Topeka and Manhattan areas, but these lakes and their releases were probably ephemeral and therefore difficult to document and date (Aber, 1991). Although the temporal relationship to the lakes is unclear, outwash accumulated in the Kansas River valley to form fill of the Menoken terrace (Davis and Carlson, 1952), situated about 110 ft (34 m) above the modern floodplain (fig. 8; Dort, 1987b).

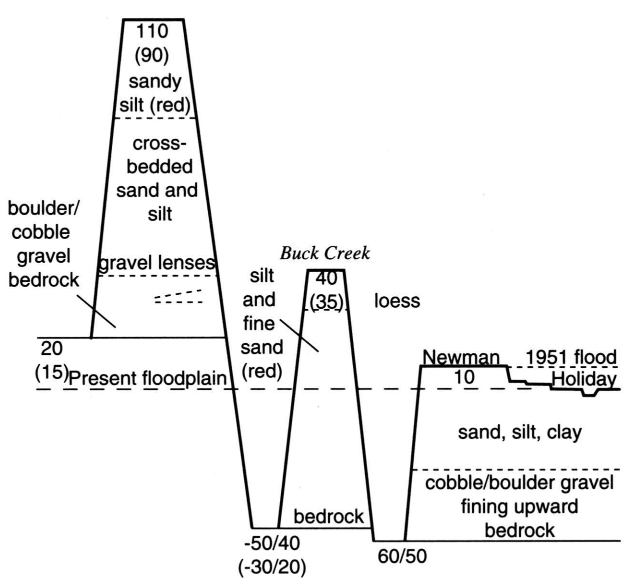

FIGURE 8—MENOKEN TERRACE (Dort, 1987b).

Age of the Independence Formation has been determined by Aber et al. (1988) and Aber (1991) using fission-track dating of volcanic ash, biostratigraphy, and paleomagnetic data. Volcanic ash exposed within alluvium of the Kansas River valley near De Soto, dated to 620 ka (Geil, 1987), provides a minimum age of the Independence Formation: the alluvium is probably postglacial because catastrophic flooding likely removed pre-existing alluvium in such a setting. The Wathena local fauna (Einsohn, 1971) from the Independence Formation parastratotype south of Wathena in Doniphan County (Aber, 1991) is similar to faunas elsewhere in the Great Plains that date to approximately 1.0 ma (Martin and Schultz, 1985), thereby lending a maximum age to the formation. Paleomagnetic data from the lower diamicton indicated no reversals in polarity (Abdel-saheb, 1988), probably placing the event in the early Brunhes chron - 0.7-0.6 ma (Aber et al., 1988). An age of 0.7-0.6 ma for the glacial event corresponds with marine oxygen-isotope stages 18-16 (Shackleton and Opdyke, 1973, 1976), which agrees well with data presented in Richmond and Fullerton (1986) and Ruddiman and Wright (1987).

Illinoian and Post-Illinoian Stratigraphy

Deposits of this period in northeastern Kansas reflect the indirect influence of the glacial environment, rather than the direct influence of glacial ice. Consequently, the deposits are primarily of eolian and alluvial origins, and relatively well-preserved when compared with the older glacial deposits (fig. 9). Stratigraphy for this part of the Pleistocene and for the Holocene is relatively well understood and has been refined in recent years (e.g., Johnson, 1987, 1993). Table 1 reflects changes since the last formal statement of stratigraphic succession in Kansas by Zeller (1968).

The sediments of the Illinoian Stage consist of fluvial gravel, sand, and silt, and eolian silt, or loess, and sand. The Illinoian glaciers did not reach Kansas, and its closest approach has been identified in extreme eastern Iowa (Frye and Leonard, 1952). Illinoian deposits therefore result from the indirect effects of continental glaciation, including the cutting of stream valleys and eolian deposition. In northeastern Kansas, the Illinoian Stage is represented by alluvial deposits and the Loveland loess (Shimek, 1909). The alluvial deposits occur in the Kansas River valley, underlying the Buck Creek terrace (Davis and Carlson, 1952; fig. 8, Dort

1987b), which consists of deposits of basal sand and gravel grading upward into silt and clay. This terrace, topographically lower than the Menoken terrace, is based on the type locality at the Buck Creek school site on the north side of the Kansas River valley in southeastern Jefferson County (Davis and Carlson, 1952). The Loveland loess, the most wide-spread pre-Wisconsin loess in the midcontinent, is a reddish-brown or yellow-brown eolian silt with a maximum thickness of 20 ft (6 m) along the Missouri River valley (Zeller, 1968). Although the constraining ages of the Loveland Loess are unknown, Oviatt et al. (1988) reported thermoluminescence (TL) ages of 136 ka and 130 ka in the upper part of presumed Loveland Loess exposed in an abandoned quarry near Milford in Geary County. Feng et al. (1994) reported similar ages from Barton County, Kansas, as did Forman et al. (1992) for the Loveland paratype section in western Iowa. Also, Maat and

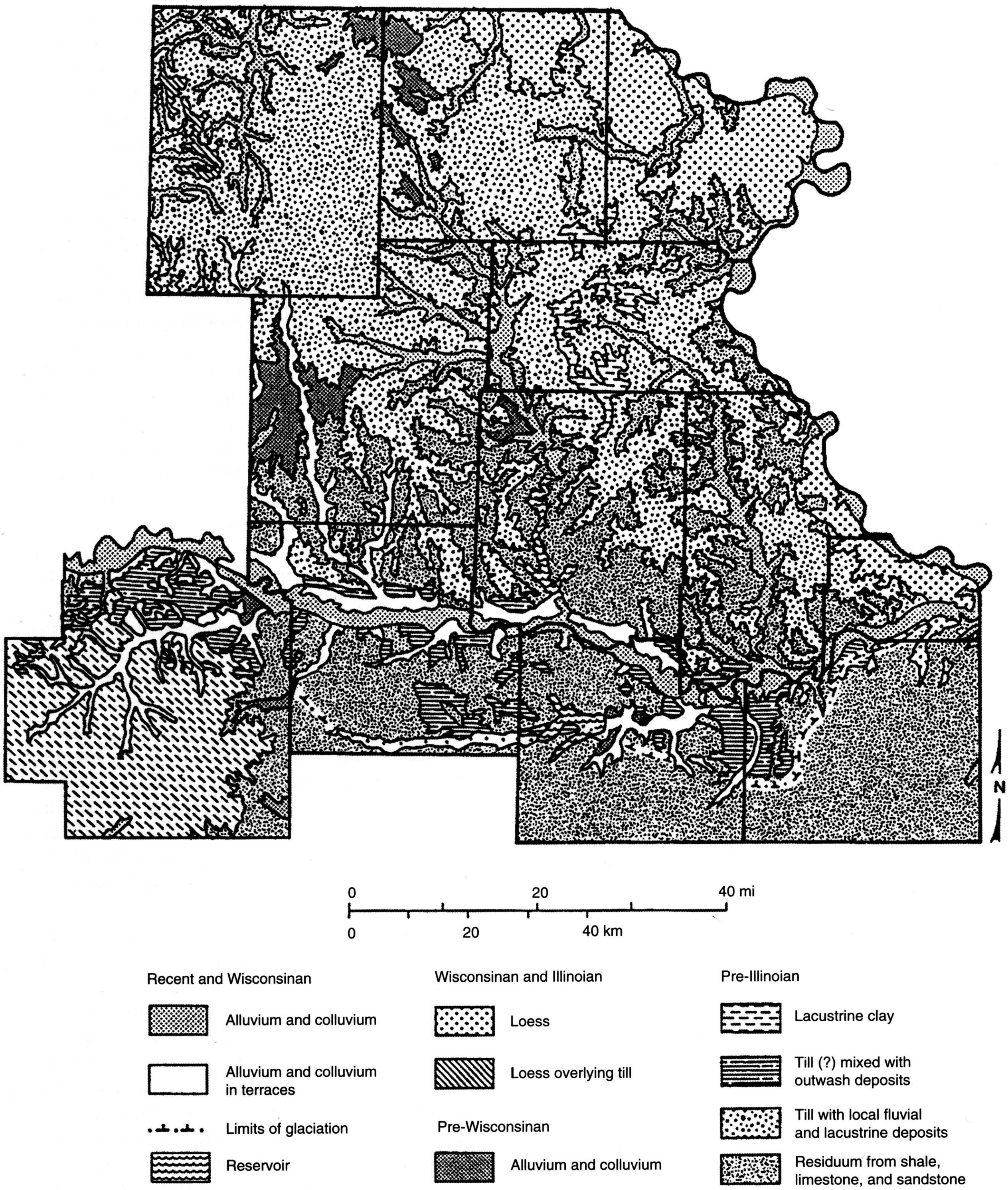

FIGURE 9—QUATERNARY MAP OF NORTHEASTERN KANSAS.

Johnson (in press) reported a TL age of about 164 ka, 1.5 m (4.5 ft) below the Sangamon Soil at a loess exposure in southwestern Nebraska. The little regional environmental data available (fossil pollen; Kapp, 1965, 1970) indicate the loess fall occurred under relatively cool temperatures, high effective moisture, and open coniferous forest in south-central Kansas. The Loveland loess has thus far been recognized in Atchison, Leavenworth, Wyandotte, Doniphan, and Brown counties.

The Sangamon Soil (Leverett, 1899), representing the Sangamon Stage (marine isotope substage 5e), is well expressed throughout the state (Bayne and O'Connor, 1968), but has received considerable attention in the northeastern part (Frye and Leonard, 1949, 1952; Tien, 1968; Caspall, 1970; Bayne et al., 1971; Schaetzl, 1986). This soil zone is exceptionally well preserved and well developed and has been described in exposures along the Missouri River bluffs, including the Iowa Point section (Frye and Leonard, 1949) in Doniphan County. The Sangamon Soil consists of a dark-gray to grayish-brown A horizon and thick reddish-brown Bt horizon containing some caliche in the lower part. In Brown County, the soil has been documented as both a buried and exhumed soil (Schaetzl, 1986). The thickness can reach 24 ft (7.3 m) adjacent to the Missouri River valley (Zeller, 1968). Age of the Sangamon Soil is unknown, and it may be time transgressive in the midcontinent (Folmer, 1983). TL ages reported by Oviatt et al. (1988) and others place a maximum age of about 125 ka on the soil, whereas ages obtained on the overlying loess by Johnson (1993) in Phillips County, Kansas, and by Forman et al. (1992) and Leigh and Knox (1993) elsewhere in the midcontinent provide a minimum age of about 50 ka. Richmond and Fullerton (1986) designate 132-122 ka as Sangamon time, which is similar to the 130 ka derived using the orbital tuning technique (Martinson et al., 1987) and 120-125 ka obtained by the isotopic dating of fossil coral reefs (Edwards et al., 1987; Bard et al., 1990; Ku et al., 1990; Chen et al., 1991). A warm grassland environment is indicated for the Sangamon period from analyses of the opal phytolith morphology (Fredlund et al., 1985) and stable isotope composition (Fredlund, 1993) and from pollen (Kapp, 1965, 1970) records.

The Wisconsinan Stage has traditionally been divided into several substages representing various episodes of glacial advance and retreat (Frye and Leonard, 1952; Wilman and Frye, 1970), but recent data indicate that the names and age limits of these substages should be abandoned here in Kansas (Johnson, 1993). The episodes occurred far to the north of Kansas in association with the near-glacier environment and affected land-surface response in the state mainly through loess deposition and fluvial activity. Two loesses were deposited during this stage: the Gilman Canyon Formation (Reed and Dreeszen, 1965) and Peoria loess (Leverett, 1899). The Gilman Canyon Formation occurs locally above the Sangamon and below the Peoria Loess. The formation is typically dark colored, rich in manganese ped coatings, leached of calcium carbonate, and heavily enriched, particularly in the upper part, with pedogenically derived organic carbon. Thickness of the formation ranges from only 2 to 4 ft (0.6-1.2 m), which, along with evidence of pedogenesis, reflects a relatively low rate of deposition. Radiocarbon ages on the formation range from over 38,000 yrs B.P. near the base to about 20,000 yrs B.P. at the top (May and Souders, 1988; Johnson, 1993). Regional expression and consistency of ages for the Gilman Canyon soil make it a geosol. Paleoenvironmental information emerging for the Gilman Canyon Formation of Kansas and Nebraska define a grassland dominated by warm-season species (Johnson, 1993; Johnson et al., 1993). The Peoria Loess is typically a calcareous, massive, light-yellow-tan to buff silt with scattered molluscan zones. Thickness ranges up to 100 ft (30 m) in the vicinity of the Missouri River, and it is present to a lesser extent on upland areas in a westward direction. Thicknesses of 2 ft (0.6 m) or less are undetectable due to incorporation into the modern surface soil. Deposition of the Peoria began about 20,000 yrs B.P., although the boundary with the Gilman Canyon Formation is transitional, and ended about 10,000 yrs B.P. Presence of spruce (*Picea* cf. *glauca*) remains (Johnson, 1993) and pollen (Gruger, 1973), snail fauna (Leonard, 1952), and evidence of cool-season grasses (Johnson et al., 1993) indicate existence of an open coniferous parkland.

The early Wisconsinan Stage was generally a period of valley deepening, and the fluvial record is recorded in alluvium known only through test drilling, because it is not exposed at the surface in northeastern Kansas (Fent, 1950; Frye and Leonard, 1952). In north-central Kansas, however, an alluvial facies of the Gilman Canyon Formation is preserved within a few feet of the terrace tread (Johnson, 1993). A 10,000-year-old soil buried within alluvial fill of the Kansas River basin indicates that entrenchment occurred sometime during the late Wisconsinan (Johnson and Martin, 1987; Johnson and Logan, 1990), perhaps about 13,000 years ago (Martin, 1990). Alluvium deposited subsequently consists of clay, silt, sand, and gravel derived in part from local glacial deposits.

The last 10,000 years of geologic time, designated the Holocene (Cohee, 1968; Hopkins, 1975), is represented by alluvium, periods of soil development, discontinuous loess deposits and thin colluvium on slopes. Major climatic and environmental change occurred in the early Holocene: a well-developed soil represents landscape stability in the latest Pleistocene/earliest Holocene. This soil (a geosol), the Brady Soil (Schultz and Stout, 1948), typically developed in the uppermost Peoria Loess as deposition dramatically slowed or ceased about 10,500 yrs B.P. (Johnson and May, 1992). Presence of the Brady is defined by existence of the Bignell loess (Schultz and Stout, 1945) above it, and, since the Bignell loess is discontinuous, the Brady soil appears discontinuous as well. An alluvial phase of the Brady soil has been recognized throughout the Kansas River basin (Johnson and Martin, 1987; Martin, 1990; Johnson and Logan; 1990). The Brady soil has been documented in northeast Kansas, particularly Doniphan County (Frye and Leonard, 1951; Caspall, 1970, 1972). Brady pedogenesis ended about 9,000 years ago (Johnson, 1993), where Bignell loess began to accumulate, or as valley-bottom alluviation resumed. Early Holocene valley alluviation created the Newman terrace of the Kansas River valley (Davis and Carlson, 1952; fig.8, Dort 1987b). Subsequent entrenchment and alluviation in the Kansas River valley at 4,400 yrs B.P. or earlier (Johnson and Martin, 1987) resulted in the Holliday terrace fill (McCrae, 1954; fig.8, Dort 1987b). Radiocarbon ages of paleosols developed within Newman and Holliday fill indicate that the former is older than 10,000 years and as young as about 4,400 years, while the latter ranges from before 4,200 years to about 1,200 years ago (Holien, 1982; Johnson and Martin, 1987; Johnson and Logan, 1990). Major entrenchment occurred at about 1,000 yrs B.P. throughout the Kansas River system (Johnson and Logan, 1990). Subsequent alluviation produced a suite of low, ill-defined terraces and the modern floodplain. Changes in Holocene climate have been less dramatic than those of the Pleistocene, but yet a remarkable, extended dry period (the Altithermal: Antevs, 1955) developed and lasted from about 8,000 to 4,000 years ago. Unfortunately, very little climatic proxy data exist for the region and that which does is from the periphery of the prairie (Baker and Waln, 1985; Fredlund and Jaumann, 1987).

Previous Regional Studies Relative to the Quaternary

Early investigations of Quaternary deposits in northeastern Kansas were done by Smyth (1898), Todd (1909, 1911, 1923), and Schoewe (1930a, b, 1931, 1932, 1933, 1939, 1941). Todd mapped the glaciated area of Kansas (including boulder fields and possible moraines) and discussed the formation of Kaw Lake, which resulted from ice blockage of the Kansas River during the Pleistocene. Smyth studied deposits along Shunganunga Creek in Shawnee County. Schoewe studied numerous glacial sections and found evidence that the glacial drift border was located farther south in Kansas than thought by earlier investigators.

Pleistocene stratigraphic studies include reports by Bayne and O'Connor (1968), Bayne (1968), Bayne et al. (1971), and Frye and Leonard (1949, 1952). Frye and Leonard (1952) co-authored the KGS bulletin *Pleistocene Geology of Kansas*. Aber (1981, 1982) presented lithologic data on glacial erratics and discussed a two-ice-lobe model for Kansan glaciation, and has most recently (Aber, 1991), proposed the Independence Formation as a new lithostratigraphic unit to include all diamicton and associated stratified sediment in northeastern Kansas. Bayne (1968) and Dort (1966, 1972b) presented evidence of multiple stades. Davis (1951) reported on gravels in northeastern Kansas, and Hanna and Bidwell (1955) investigated loessal soils in northeastern Kansas. Osterkamp and Wiseman (1980) discussed particle-size analyses of Missouri River basin alluvial materials. Chelikowsky (1976) found evidence of drainage reversal during the Pleistocene in the upper Tuttle Creek Reservoir. Schoewe (1931, 1932, 1933, 1941) and Jewett (1934) described glacial-striae locations in Kansas. Dellwig and Baldwin (1965) discussed evidence of ice-push deformation. Mudge (1955) wrote about the early Pleistocene geomorphic history in the southwestern glaciated area of northeastern Kansas. Heim and Howe (1963) described the Pleistocene drainage and depositional history of northwestern Missouri.

Other studies related to the Quaternary focus on buried valleys, structural characteristics, climatic factors, and ground-water quality. Beck (1961) studied a buried valley northwest of Manhattan, Kansas. Denne et al. (1982, 1984) described multiple approaches to locating glacial buried valleys. Structural characteristics of Nemaha County were investigated by DuBois (1978) and Steeples et al. (1979). Climatic factors during the Pleistocene were discussed by Dorf (1959), Dort (1965, 1970), and Fredlund and Jaumann (1987). Denneet al. (1984) and Denne et al (1987) investigated northeastern Kansas ground waters and the relation of their quality to aquifer materials.

Kansas Geological Survey and U.S. Geological Survey publications and maps focusing on the glaciated counties of Kansas include those by Bayne and Schoewe (1967) for Brown County, Bayne (1973) for Doniphan County, Jewett and Newell (1935) for Wyandotte County, Johnson and Wagner (1967) and Johnson and Adkison (1967) for Shawnee County, Mudge and Burton (1959) for Wabaunsee County; O'Connor (1960) for Douglas County, O'Connor (1971) for Johnson County, Scott et al. (1959) for Pottawatomie County, Walters (1953) for Jackson County, Walters (1954) for Marshall County, Ward (1973) for Atchison County, Ward (1974) for Nemaha County, and Winslow (1972) for Jefferson County.

Regional studies associated with the Kansas River valley include studies by Beck (1959), Davis and Carlson (1952), Dufford (1958), and Fader (1974). Bayne et al. (1971), Dort (1972a), Dreeszen and Burchett (1971), Emmett and Jeffery (1969), and LaRocque (1966) have published studies associated with the Missouri River valley. Other publications and maps that include general information on Quaternary geology for the Kansas City area and regions of northeastern Kansas are those by Davis and Carlson (1952), Fishel (1948), Fishel et al. (1953), and Ward and O'Connor (1983).

County studies

Atchison County

Geology

Westward-dipping Pennsylvanian bedrock underlies Atchison County (fig. 5), and some exposures occur along streams and near the Missouri River (Frye, 1941; Ward, 1973). Along the eastern edge of the county, the upper Douglas Group (especially sandstone and shale) crops out. Limestones and shales of the Shawnee Group occur in the eastern and central parts of the county, and shales and limestones of the lower Wabaunsee Group are found in or under the western two-thirds.

The geologic map of Atchison County (Ward, 1973) suggests glacial buried valleys in areas where bedrock exposures are absent along modern streams and/or where the alluvial deposits widen (e.g., the Delaware River in T. 6 S., R. 17 E.; Stranger Creek in T. 6 S., R. 19 E.; Clear Creek in sec. 6, T. 5 S., R. 18 E.; and Grasshopper Creek in secs. 29 and 30, T. 5 S., R. 18 E., and sec. 3, T. 6 S., R. 17 E.). A map of the bedrock topography (plate 1), prepared using data from 353 well logs (Denne et al., 1990a) and the county geologic map with surface topographic contours (Ward, 1973), indicates a major buried valley trending from the west to the east for 25 mi (40 km) across the middle of the county. The width of the main channel ranges from 0.5 to 2.5 mi (0.8–4.0 km), and many smaller tributaries enter from the north and south. Modern stream drainage in Atchison County is predominantly to the south and southeast. Bedrock exposed at or near the land surface controls the drainage (and contours) evident in the northwestern, southwestern, and eastern parts of the county. Near these areas differentiation of the modern and buried drainage systems is complex (e.g., near the border between T. 5 S., R. 17 E., and T. 5 S., R. 18 E.).

The depth to bedrock is greatest over the buried valleys (fig. 10), and exceeds 250 ft (76 m) in some places. The unconsolidated deposits in Atchison County include a basal limestone and chert gravel, a fine-grained silty sand of the Atchison Formation, at least two different tills (with a locally occurring layer of outwash between them), the Nortonville Clay, loess, terrace deposits, and alluvium (Ward, 1973). The total thickness of sand and gravel (fig. 11) ranges up to 155 ft (47 m). In the buried valleys the Atchison Formation generally makes up the bulk of these sediments (up to 105 ft [32 m]); basal gravels account for as much as 36 ft (11 m) but usually less than 10 ft (3 m); and lenses of sand and/or gravel within or between the tills make up the balance (Denne et al., 1990a). Alluvium in the Missouri River valley is commonly 100 ft (30 m) thick, with sand and gravel predominating. In smaller stream valleys the clayey alluvium and terrace deposits are 15–50 ft (5–15 m) thick and generally contain less than 5 ft (2 m) of basal sand and gravel fill, but locally have a thickness up to 25 ft (7.6 m). The log for an oil well in the Delaware River valley (NWSWSW sec. 21, T. 7 S., R. 17 E.) indicates that bedrock occurs at 130 ft (40 m), providing a bedrock elevation of 795 ft (242 m) at this site; thus either a narrow, deep buried channel underlies the more recent alluvial deposits, or the well log or location is in error. The Nortonville Clay and loess deposits, each of which is less than 50 ft (15 m) thick, do not contain sand and gravel.

Frye (1941; fig. 5) prepared a map of areas in Atchison County where wells obtain water from Pleistocene sands. It shows a lobate pattern connecting parts of the main buried valley and its tributaries as presently mapped (plate 1) and as mapped by Ward (1973). Frye (1941) observed that the lower of two tills (which he considered Nebraskan) was present from southern Doniphan County only to Cummings in southern Atchison County and that, although the unit may have covered the entire county, only the eastern two-thirds now has such deposits. The presence of a continuous buried channel was recognized by 1950, when Frye and Walters indicated a "filled early Pleistocene valley" extending from Marshall County into T. 6 S., R. 17 E., of Atchison County. In 1952, Frye and Leonard mapped this drainage, which extends eastward across the entire county and is partially coincident with the limit of Nebraskan ice (cf., early Independence glacial limit; fig 7). In the future detailed stratigraphic and geomorphic studies should be done to evaluate potential relations between the buried valleys and to find the best sand and gravel deposits and better define the position of the ice margin. Such investigations should provide excellent strategies for obtaining good ground-water supplies.

Ground Water

Ground-water yields to wells with various diameters and other construction characteristics in Atchison County show a large range (fig. 12). The bedrock units commonly yield less than 1 gpm (0.00006 m^3/s), although sandstones, fractured limestones, and weathered zones may provide somewhat greater quantities locally (Ward, 1973). In contrast, the glacial aquifers yield 5–200 gpm (0.0003–0.01 m^3/s). The basal gravel, other glaciofluvial deposits, and the Atchison Formation yield the largest amounts of water, but wells completed in the last unit must be constructed and developed carefully so that they do not pump the fine-grained silty sand. Sand and gravel lenses within the tills are frequently small and discontinuous; thus recharge may be inadequate for sustained pumpage. Alluvial aquifers are also important sources of ground water in Atchison County. Well yields of up to 3,000 gpm (0.2 m^3/s) are available from the Missouri River valley, and the smaller tributary valleys commonly provide up to 5 gpm (0.0003 m^3/s) and locally may yield 35 gpm (0.0022 m^3/s).

Ground-water recharge to the buried-valley aquifers is predominantly from precipitation, although leakage from bedrock units contributes to the amount. Discharge is to streams, seeps, springs, and wells, some of which flow (Ward, 1973; Frye, 1941). Four areas with artesian flow were mapped by Ward (1973, sheet 2); the main one is on the eastern side of the Delaware River valley in T. 6 S., R. 17 E., where the sand and gravel aquifer is confined between relatively impermeable till and alluvium above and bedrock below.

Ward (1973) mapped potentiometric contours only in the major stream valleys because he recognized the discontinuous nature of the potentiometric surface in other areas. A map of water elevations calculated from Denne et al. (1990a) also indicates that discontinuities and other problems (e.g., composite water levels from wells penetrating multiple aquifers) limit the usefulness of these data to construct contours and to determine ground-water-flow directions.

The depth to water and saturated thickness of unconsolidated deposits are shown in figs. 13 and 14, respectively, but the same limitations apply to these values. In general, the depth to water is less than 30 ft (9 m) in alluvial deposits and considerably less than the deepest reported value of 180 ft (55 m) in glacial aquifers. Water levels greater than 50 ft (15 m) deep commonly are associated with parts of the deep buried valleys (e.g., in T. 6 S., R. 18 E.) and bedrock wells. The saturated thickness of alluvial deposits approaches 100 ft (30 m) in the Missouri River valley and is 0–40 ft (0–12

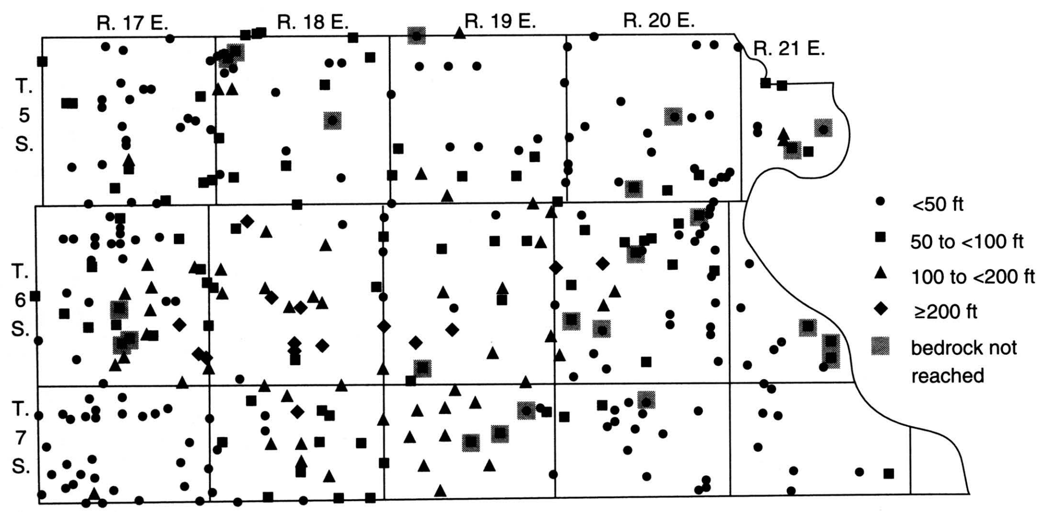

FIGURE 10—Depth to bedrock, Atchison County.

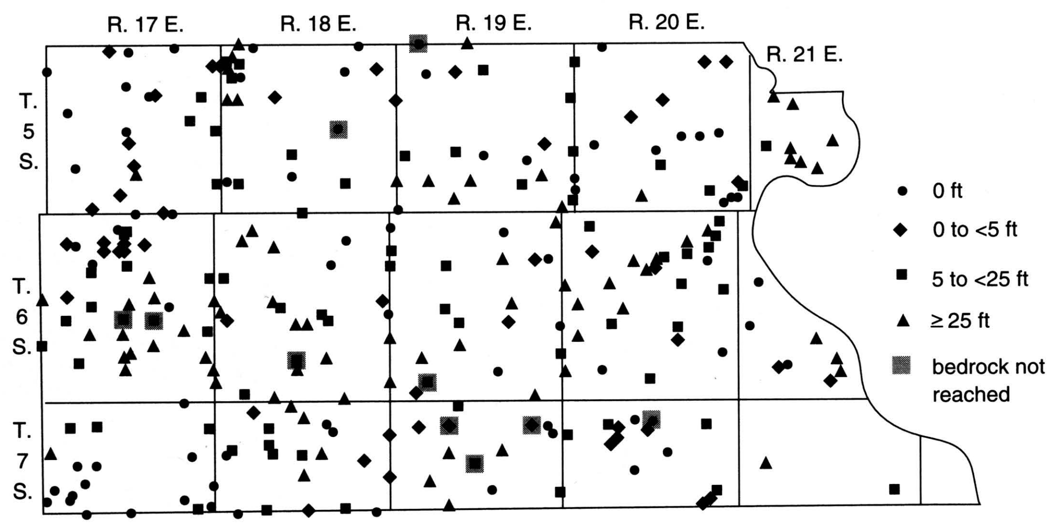

FIGURE 11—Total Pleistocene sand and gravel thickness, Atchison County.

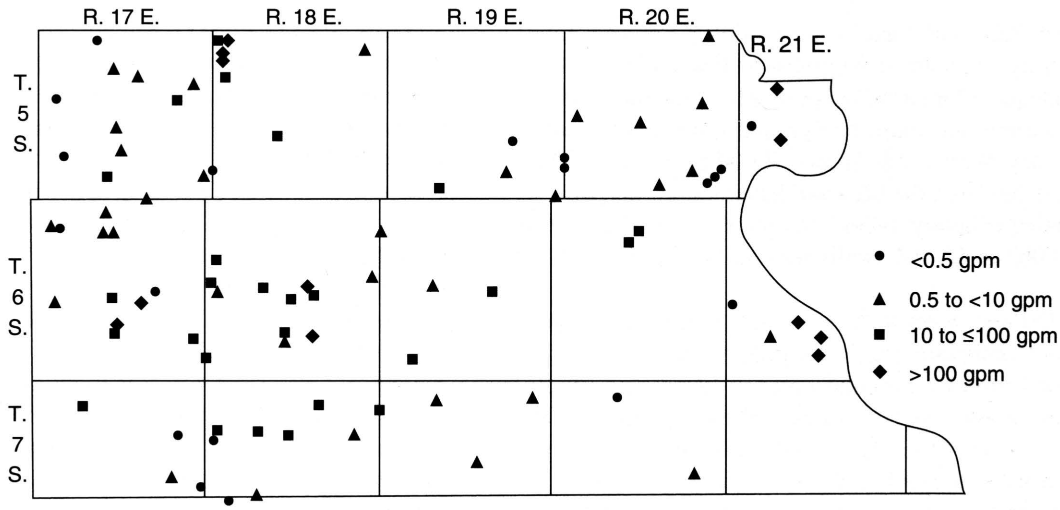

FIGURE 12—Estimated well yields, Atchison County.

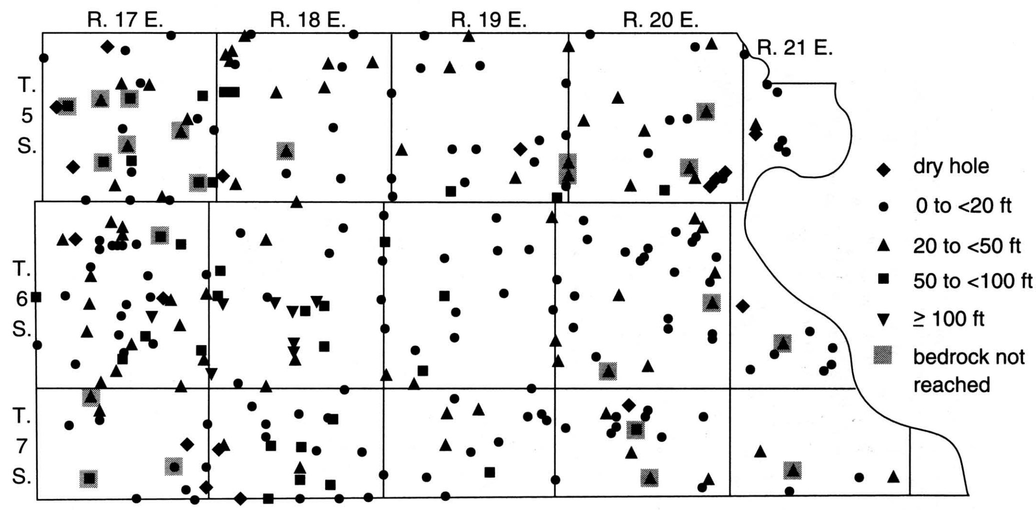

FIGURE 13—Depth to water in wells and test wells, Atchison County.

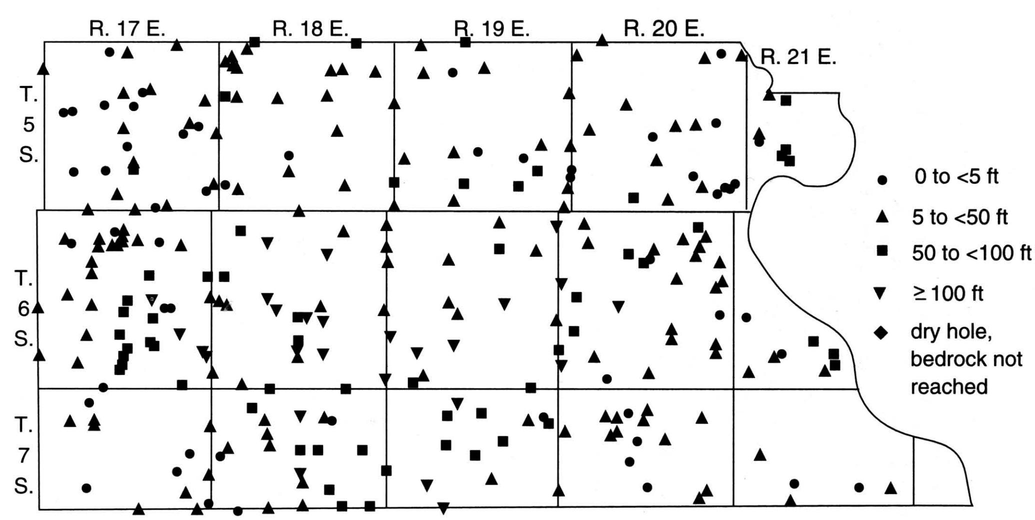

FIGURE 14—Saturated thickness of Pleistocene deposits, Atchison County.

m) in the smaller stream valleys. Saturated-thickness values in the rest of the county range up to 225 ft (68.6 m), with the greatest saturated thicknesses occurring in the buried valleys. However, if the bulk of the saturated material is of low permeability (e.g., glacial till or Nortonville Clay), even large thicknesses may not yield a significant quantity of water. On the other hand, where sand and gravel layers are present, saturated thicknesses as small as 5–15 ft (2–5 m) have been reported to yield at least 3 gpm (0.0002 m^3/s).

Geologic Sections

Geologic cross section A–A′ (fig. 15) represents part of the main buried valley that starts in southwestern Atchison County and continues into northwestern Jefferson County (fig. 2). A bedrock surface high can be seen in SWNWNW sec. 10, T. 6 S., R. 17 E., corresponding to the bedrock island shown on the map view. This bedrock high is reported from a measured section that indicates boulders and chert gravel near the shale bedrock contact. The Layne–Western Co. drilled five test holes for the city of Muscotah in 1956, all of which are located in the northern part of the cross section. These test holes all fall north of the bedrock high and probably indicate a tributary (plate 1). A public supply well constructed for Muscotah in this area has a yield of 10–15 gpm (0.00063–0.00094 m^3/s). Farther south in the main buried valley, well yields increase: 50 gpm (0.003 m^3/s) in SWSWNW sec. 22, T. 6 S., R. 17 E.; 100 gpm (0.006 m^3/s) in NENWSW sec. 27, T. 6 S., R. 17 E.; and 60 gpm (0.004 m^3/s) in SWNWSW sec. 27, T. 6 S., R. 17 E. In the main part of the buried valley, these wells penetrate as much as 50 ft (15 m) of fine-grained sand and 10 ft (3 m) of gravel. The three southernmost test wells in the cross section are from U.S. Geological Survey data and define the bedrock surface but do not give detailed information concerning the glacial formations.

Geologic cross section B–B′ (fig. 15) cuts through an extensive tributary to the main buried valley. Two domestic wells and two test holes supply the data. The western well along the valley wall has a yield of 3 gpm (0.0002 m^3/s), and the well located in the valley has a yield of 20 gpm (0.001 m^3/s). Gravel layers are located just above the bedrock contacts in the tributary valley and in the upper clay layer on the eastern bedrock high. Surface elevations are slightly higher in the valley regions but do not vary much over the geologic cross section region.

Geologic cross section C–C′ (fig. 15) cuts through a tributary valley containing as much as 30 ft (9 m) of fine-grained sand, and well yields are as high as 170 gpm (0.011 m^3/s). Data obtained for the geologic section are all from test drilling done by the Layne–Western Co. in 1978 for the city of Horton (Brown County). The city of Everest has also done test drilling in this area. Two Horton public supply wells, located close to Atchison County Lake in sec. 6, T. 5 S., R. 18 E., yield 110 gpm (0.0069 m^3/s) and 170 gpm (0.011 m^3/s). These wells are close to Atchison County Lake. A domestic well slightly north of the western part of the geologic section has a higher bedrock elevation than any of the wells shown, but it still reports 16 ft (4.9 m) of fine-grained sand and a yield of 15 gpm (0.00095 m^3/s).

Brown County

Geology

The cover of glacial deposits in Brown County is generally thinner than in the neighboring counties (fig. 9). Nevertheless, outcrops of Permian and Pennsylvanian bedrock occur primarily along modern stream valleys (fig. 5). Bedrock units in Brown County have been described by Bayne and Schoewe (1967). The Wabaunsee Group of Late Pennsylvanian age is exposed in the eastern half of the county and underlies all of it. This group is 400 ft (120 m) thick and consists primarily of limestones and shales with some sandstone and coal. Permian rocks of the Admire and Council Grove Groups are exposed in the western half of Brown County. The total thickness of these limestones (some of which are cherty) and shales ranges up to 350 ft (110 m).

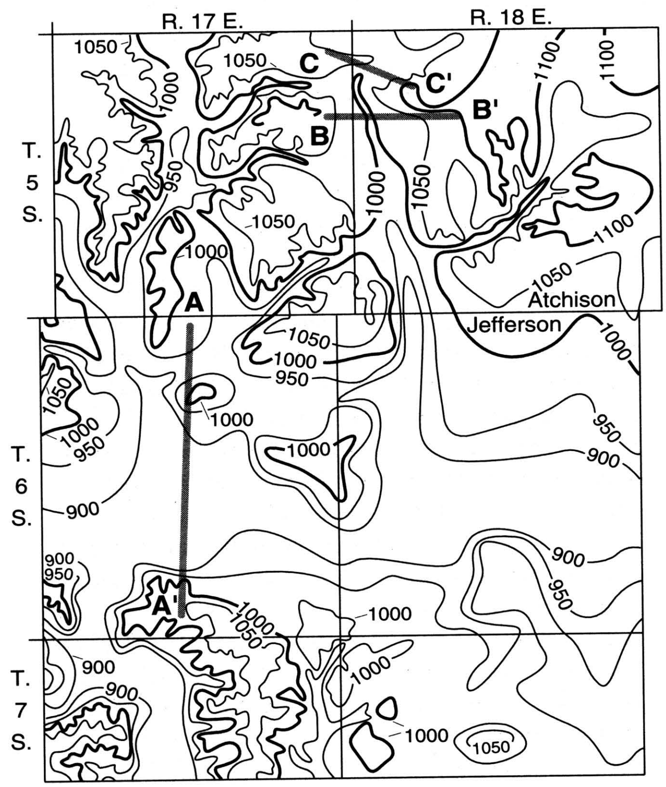

FIGURE 15—Geologic cross sections and bedrock surface in western Atchison County.

In addition to geologic (Bayne and Schoewe, 1967) and generalized surface topographic maps (U.S. Geological Survey, 1986) modified locally from corresponding topographic bedrock maps, we used records from 509 drill holes (Denne et al., 1990a) to construct the bedrock topographic map shown in plate 1. Where bedrock is exposed or near the land surface (e.g., in western Brown County), the contours reflect the modern surface topography. In other areas buried valleys dominate, although some of these appear to coincide with or connect to modern streams. The lobate shape of many of the modern streams (e.g., Pony, Terrapin, Mulberry, and Spring creeks with Walnut Creek in the northwest quarter of Brown County; Roy Creek in the northeast; Gregg, Plum, and Delaware creeks in the southwest; and the Wolf River and its fork tributaries in the southeast) and the distribution of (upland) gravel and/or sand deposits near and especially south of these drainages suggest that the ice margin was near these locations. Glacial striations and ice-push deformation of bedrock units found in SENE sec. 28, T. 3 S., R. 15 E., are oriented from 124° to 150° (Dellwig and Baldwin, 1965) and indicate ice movement from the northwest (Dakota lobe?), consistent with the direction of lobate streams in the southwest part of the county. Farther east in Brown County, beyond the bedrock high that could have funneled ice lobes, glacial striations (plate 1) indicate ice flow generally to the south or southeast (Schoewe, 1931, 1932, 1941). Although classical moraines are not apparent, the modern streams could have developed at the ice margin or they could have formed later in response to differential rebound of the land surface.

The main buried valley in Brown County extends eastward, just south of the border between T. 1 S. and T. 2 S. (plate 1). The buried channel intersects Walnut Creek at the boundary between R. 16 E. and R. 17 E. and could have drained ice blocking the Walnut Creek valley. A similar connection may have existed between the Spring and Walnut creeks and the Wolf River along the southern edge of T. 2 S., R. 16 E. North-south tributaries through the middle of R. 17 E. and R. 18 E. also may have connected the main buried valley to the Wolf River on the south and drained into the main channel from the north. Additional test drilling should be done to define the possible northern tributaries. For example, a broad area of alluvial deposits along the northwestern edge of T. 1 S., R. 18 E., in Brown County and an associated wide bedrock low extending 2 mi (3 km) toward the Missouri River in Richardson County, Nebraska (Emery, 1964), should be investigated for a southern connection. In addition, several logs in the northern part of T. 1 S., R. 17 E. (e.g., SWSW sec. 3, SWSW sec. 4, and SESWSE sec. 4), indicate buried drainageways with considerable thicknesses of sand, but their orientations are poorly defined.

Other buried-valley deposits in Brown County occur in the southern part of the county. The northern edge of the major northeastern Kansas buried valley crosses the southwest corner of the county, and a tributary of unknown length extends at least into SESESW sec. 35, T. 4 S., R. 15 E. Another channel, heading toward the area south of the Wolf River, leaves Brown County along the eastern side of the border between R. 17 E. and R. 18 E. Several of the modern streams in T. 4 S. also seem to be near to or to coincide with small buried channels. For example, the great length of the South Fork Wolf River, the eastward curve at its southern end, the bedrock topography, and the sand and gravel deposits in SESESE sec. 24, T. 4 S., R. 18 E., suggest that all or part of the river may have once flowed southward into the southeastern part of T. 4 S., R. 18 E.

In Brown County the greatest thicknesses of glacial deposits occur in the buried valley that extends eastward from near the border between T. 1 S. and T. 2 S. (fig. 16). The maximum known depth to bedrock there is 177 ft (53.9 m) (NENENW sec. 11, T. 2 S., R. 18 E.). Other significant thicknesses of glacial deposits occur in the buried valleys in the southwestern corner of the county, in T. 1 S., R. 17 E., and in relatively isolated locations along the northern border of the county (e.g., NESWSW sec. 3, T. 1 S., R. 15 E. and SWNW sec. 4, T. 1 S., R. 16 E.). An oil log for NENW sec. 7, T. 2 S., R. 16 E., indicates that the depth to bedrock there is 150 ft (46 m), which suggests the presence of a buried tributary to Walnut Creek between and roughly parallel to Terrapin and Mulberry creeks.

As described by Bayne and Schoewe (1967), the unconsolidated deposits in Brown County include chert gravels, glaciolacustrine silt and fine-grained sand, till, outwash, loess, and alluvium. Pre-Kansan chert gravel deposits, ranging up to 20 ft (6 m) thick but generally less than 10 ft (3 m) thick, are exposed in the uplands near Pony Creek in northwestern Brown County and occur locally at the base of the deep buried valley in northeastern Brown County. Bayne and Schoewe (1967) suggested that the Nebraskan glacier may have entered the county, although they did not identify any deposits associated with it. Up to 50 ft (15 m) of silt and fine-grained sand of the Atchison Formation occur near the base of the northeastern Brown County buried valley. Bayne and Schoewe (1967) believed that these deposits originated in quiet water, such as in a lake formed by ice blockage of drainageways. Glacial-till deposits are heterogeneous mixtures dominated by clay, but they also contain silt, sand, and gravel. Sand and gravel lenses and layers of outwash occur locally within the till. Wisconsinan loess [generally less than 85 ft (26 m) thick] mantles the uplands, especially in the northeastern part of the county, as are the pre-Wisconsinan loess and associated Sangamon Soil (Schoetze, 1986). Alluvial deposits are generally poorly sorted and consist of clay, silt, sand, and gravel. They range up to 55 ft (17 m) thick in the major river valleys.

The total thickness of all sand and gravel layers in Brown County is greatest in and near the buried valleys (fig. 17). The maximum value is 90 ft (27 m) (in NENENW sec. 11, T. 2 S., R. 18 E.) in the main channel just south of T. 1 S. Sand thicknesses up to 88 ft (27 m) also occur in the drainage system in the northern part of T. 1 S., R. 17 E. Gravel was reported at 30–110 ft (9–34 m) in an oil log for SWNW sec. 4, T. 1 S., R. 16 E., at the western edge of the modern Pony Creek valley. Many of the buried valleys contain a basal sand and/or gravel deposit that is less than about 30 ft (9 m) thick and underlies other sand or sand and gravel layers. Some of the modern alluvial valleys contain several feet [generally less than 10 ft (3 m) but locally up to 20 ft (6 m) along the major rivers] of sand and gravel near the underlying bedrock surface. These

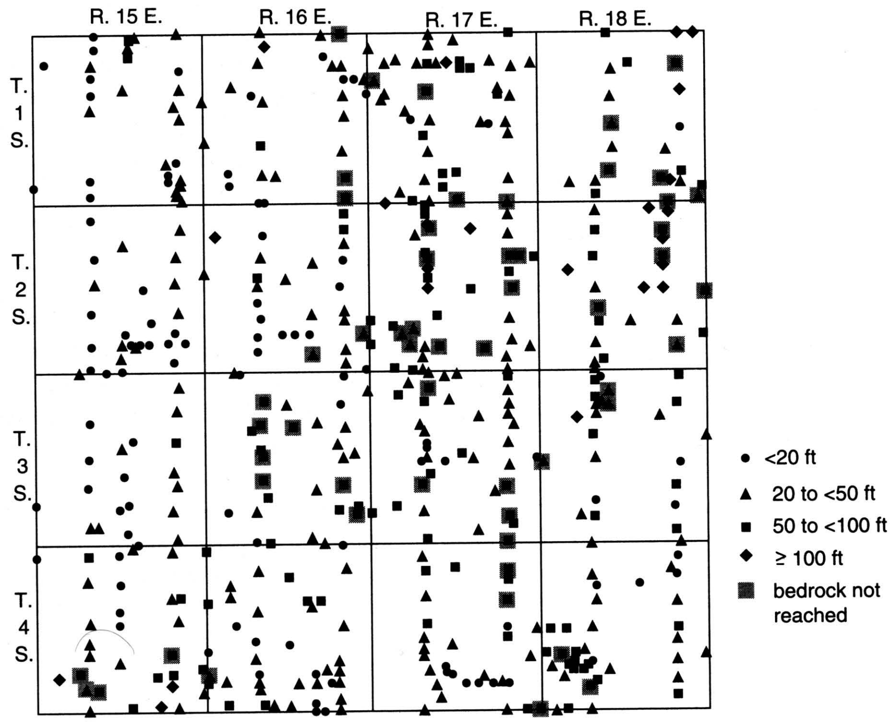

FIGURE 16—Depth to bedrock, Brown County.

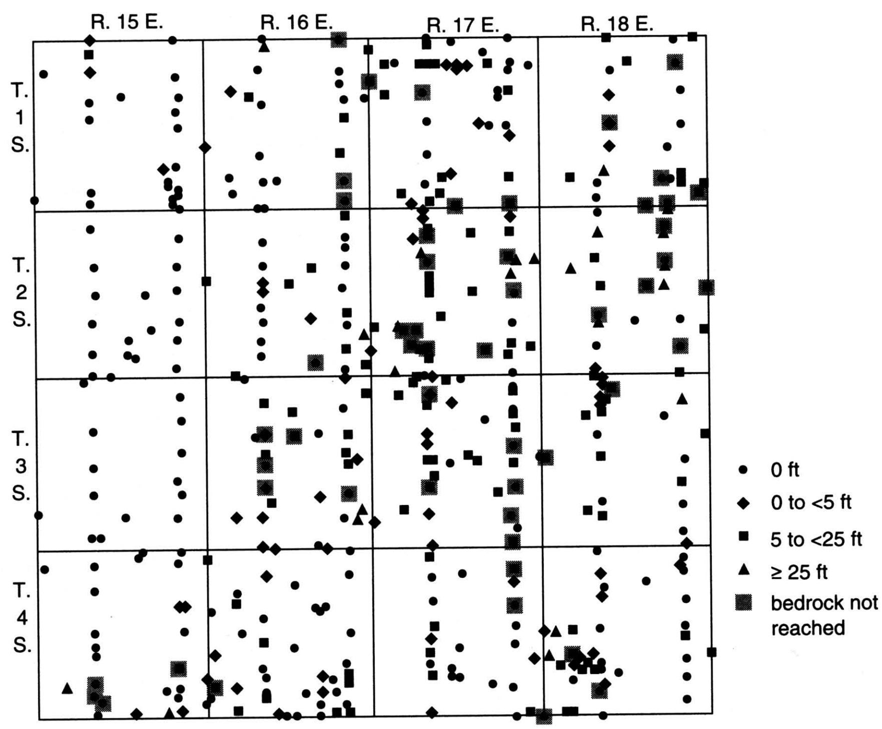

FIGURE 17—Total Pleistocene sand and gravel thickness, Brown County.

coarse-grained deposits, where they are saturated, generally yield 50–100 gpm (0.003–0.006 m^3/s) of water to wells.

Ground Water

Although no correction factor has been applied to control for wells of different diameters or other characteristics, yields vary considerably in Brown County (fig. 18). Many drill holes yield no water, whereas others have been reported to produce 300 gpm (0.2 m^3/s). The largest yield is found in sand and gravel deposits in the main buried valley near its junction with Walnut Creek (sec. 5, T. 2 S., R. 17 E.). Bedrock formations in the Council Grove Group (Permian), especially the Grenola Limestone, Roca Shale, and Foraker Limestone in northwestern Brown County (Bayne and Schoewe, 1967), also yield large quantities of water. The values reported for bedrock wells are as high as 235 gpm (0.0148 m^3/s) in NENWNE sec. 35, T. 1 S., R. 15 E. However, the water becomes more mineralized with depth, and sulfate problems in water from the Foraker Limestone are common.

Although the yields from some bedrock units are high, other formations yield no water. Even the same Council Grove Group rock aquifers that yield a large quantity of water in northwestern Brown County are less permeable south of T. 2 S. and generally yield only a few gallons per minute (Bayne and Schoewe, 1967). In eastern Brown County, the Pennsylvanian sandstones provide a small quantity of water to wells, and springs are associated with limestones of the Wabaunsee Group (Bayne and Schoewe, 1967).

Glacial and alluvial aquifers provide additional ground-water supplies where these deposits are saturated. Alluvial deposits in Brown County yield up to 40 gpm (0.003 m^3/s) along the major rivers, but most produce only 1–20 gpm (0.00006–0.001 m^3/s). Glacial sand and gravel associated with the buried valleys commonly yield 10–150 gpm (0.0006–0.0095 m^3/s), although yields as high as 300 gpm (0.2 m^3/s) have been obtained. Even where no channel deposits are evident, yields of several gallons per minute can be obtained from some glacial deposits. If fine-grained sands of the Atchison Formation are used for water supplies, wells must be carefully constructed and developed to prevent pumpage of sand.

Although many drill holes encounter no water at all, the greatest depth to water reported to date in Brown County is 130 ft (40 m) in NENENE sec. 15, T. 4 S., R. 16 E. (fig. 19). Only three other wells, also in bedrock aquifers in T. 4 S., had water depths greater than or equal to 100 ft (30 m). Most water levels in bedrock wells range from 20 ft to 80 ft (6–24 m). Wells penetrating alluvial aquifers commonly have water at depths less than 20 ft (6 m). Water levels in wells constructed in glacial deposits are generally less than 50 ft (15 m), although the range is 5–90 ft (2–27 m).

Water-elevation values calculated from data given by Denne et al. (1990a) were not contoured because they

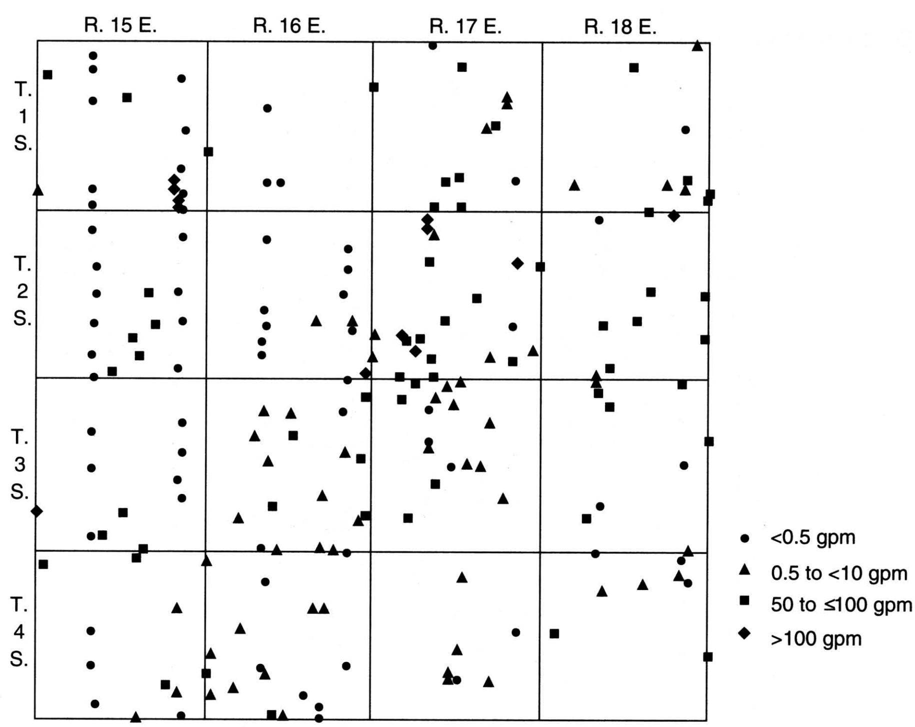

FIGURE 18—Estimated well yields, Brown County.

were not separated into confined and unconfined aquifers and because they represent only composite values where wells penetrate multiple aquifers. Also, as found by Bayne and Schoewe (1967), the water table is discontinuous. Water-table contours for part of the county indicated that the shape of the water table is similar to the shape of the surface topography and that ground water moves toward and into almost every stream.

The saturated thickness of unconsolidated deposits in Brown County is greatest over the buried valleys in the northeastern and southwestern parts of the county (fig.

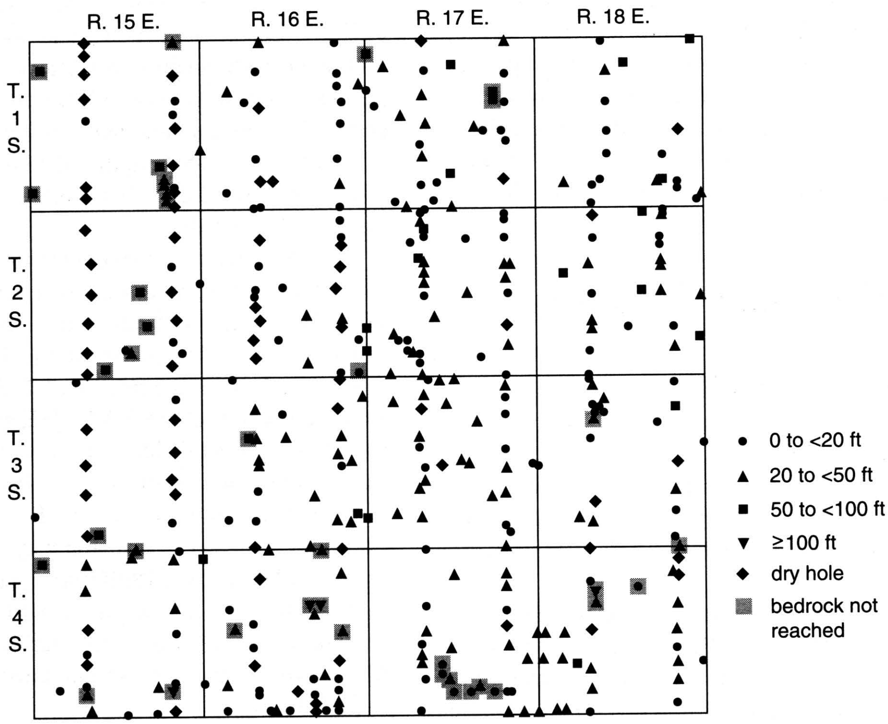

FIGURE 19—Depth to water in wells and test wells, Brown County.

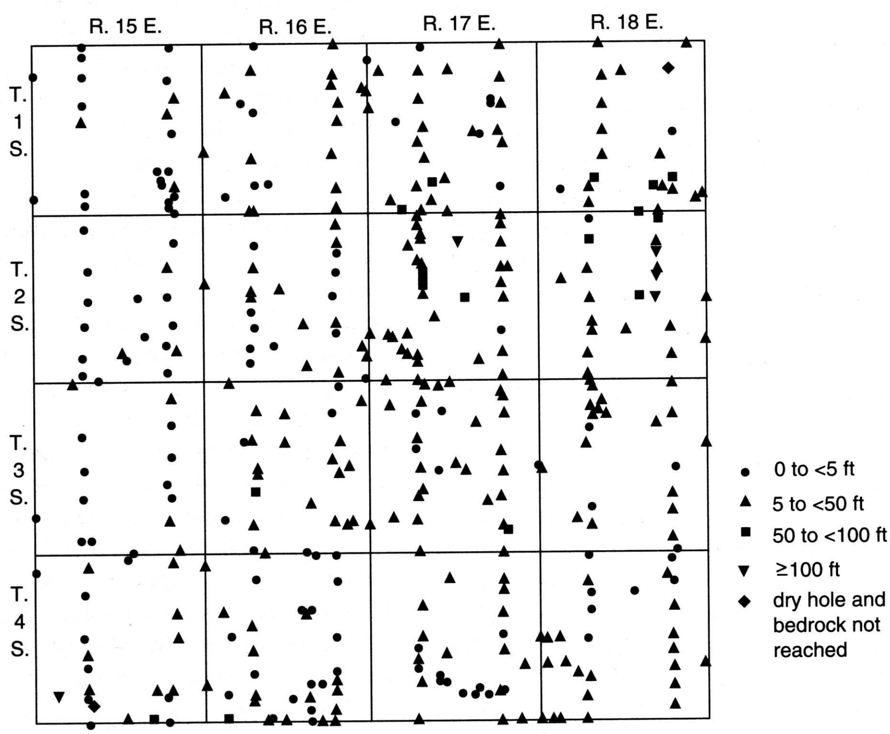

FIGURE 20—Saturated thickness of Pleistocene deposits, Brown County.

20). The values range up to 161 ft (49.1 m) (NENENW sec. 11, T. 2 S., R. 18 E.). Most glacial deposits, however, have saturated thicknesses of less than 50 ft (15 m). In the major river valleys the saturated thickness of alluvial deposits may be nearly 50 ft (15 m), but values less than 25 ft (8 m) are more common near most streams.

In Brown County ground-water discharge is to wells, springs, and streams or through evapotranspiration. Recharge is predominantly from precipitation. Bayne and Schoewe (1967) constructed four hydrographs for wells in the county. Three wells in glacial deposits showed similar trends in water-level fluctuations in response to climate. One well in bedrock also showed a similar but more subdued trend in water-level fluctuations.

Doniphan County

Geology

The geology of Doniphan County was mapped by Bayne (1973). Most of the county is covered with alluvial, eolian, and glacial deposits (fig. 9). Bedrock exposures occur along some of the major streams, especially in the south.

The bedrock units at or near the land surface in Doniphan County are Upper Pennsylvanian (fig. 5). Shales and limestone of the Lawrence Formation of the Douglas Group occur in the east. Overlying the Douglas Group is the Shawnee Group, which includes 300 ft (90 m) of shales, limestones, and some sandstones. Up to 100 ft (30 m) of shale with some limestone, coal, and sandstone from the Wabaunsee Group occurs in the western part of the county. The eastern limits of sandstone aquifers in the White Cloud and Stull Shale Members of the Shawnee and Wabaunsee Groups, respectively, are shown in Bayne's (1973) report.

By utilizing data from 189 drill holes (Denne et al., 1990a) and Bayne's (1973) map of geology with surface topography, we have constructed a bedrock topographic map for Doniphan County (plate 1). Where bedrock occurs near the land surface, the contours reflect the surface topography and therefore appear more detailed than in other areas. Several buried valleys are evident on the bedrock topographic map; modern streams suggest other areas where drainage may have been modified during the Quaternary.

Wolf River is a rather small stream for its broad alluvial valley, i.e., an underfed stream. This alone suggests that more water flowed in the channel at an earlier time, but deposits of coarse-grained material (sometimes described by drillers as plate-size; see, for example, the logs for wells in NENESE sec. 29, T. 2 S., R. 20 E., and NENENE sec. 3, T. 3 S., R. 20 E.) near the river and its tributaries also support the idea of more water flowing with greater tractive force than at present. The lobate shape of the Wolf River system in Brown County has already been discussed; there is a bedrock high on the south and east side of the Wolf River in Doniphan County, and thus the drainage here also may have developed marginal to the ice.

The major buried valley of northeastern Brown County enters Doniphan County just south of the border of T. 1 S. It then appears to bend northward through the middle of the township, where an eastward-flowing tributary joins it. Bedrock elevations and sand and gravel deposits also indicate another tributary that flowed from the south in the eastern parts of T. 1 S. and T. 2 S. and joined the other drainage in the modern Missouri River valley.

Although not conclusive, data from several test holes and the absence of bedrock along certain reaches of the Wolf River valley indicate that a significant amount of water may have flowed toward the Wolf River at some time [e.g., through the middle of T. 2 and 3 S.; a log of an oil test reportedly in SWNWSE sec. 6, T. 3 S., R. 20 E., also supports this idea, but it was not used for this study because its 155-ft (47.2-m) depth to bedrock gives a bedrock elevation of only 759 ft (231 m), which is extremely low for the area and may fit better in T. 2 S., R. 20 E.]. Wolf River itself may even have flowed southwesterly for a time; this would explain the peculiar entrance angles of several tributaries, such as the Rittenhouse Branch and an unnamed pair in sec. 27, T. 2 S., R. 20 E.

Drainage may also have flowed southward from the modern Wolf River at several locations. To the northeast of secs. 23 and 26, T. 3 S., R. 19 E., the alluvial plain broadens considerably. Perhaps this area was the headwater for the now-buried valley that flowed south out of Doniphan County near the middle of T. 4 S., R. 19 E. Other such connections across the bedrock high may exist along the western side, near the center, and in the eastern part of T. 3 and 4 S., R. 20 E. To complement or complicate these possibilities, the modern Independence Creek drainage reflects some radical changes over time. For example, the angle at which Jordan Creek joins the system suggests that the drainage should be reversed from its present flow direction. Perhaps Jordan Creek originally flowed northward into the North Branch Independence Creek, or maybe it flowed southwestward into Independence Creek or the smaller tributary directly opposite the Jordan and from there into the major buried valley in Atchison County.

Several additional buried valleys occur in eastern Doniphan County. Apparently there was a connection between Rock Creek and a small Missouri River tributary to its east. The 76-ft (23-m) depth to bedrock and the layers of sand and gravel in a borehole in SWNWNW sec. 5, T. 5 S., R. 21 E., and the wide topographic low in the area suggest a former channel just north of the constriction (which may be the result of the adjacent bedrock knob) in the modern Rock Creek where it joins Independence Creek. Buried valleys also seem to drain generally southward toward the Missouri River valley in the eastern part of T. 4 S., R. 21 E. Drilling data near and especially north of Peter Creek also suggest buried drainage now connected to this valley.

Even the Missouri River did not originate as a south-flowing stream at its present location (Bayne, 1973; Dreeszen and Burchett, 1971). Before Illinoian time the major northeastern Kansas buried valley left the state at Atchison and flowed northeastward along the present Missouri River to St. Joseph (roughly T. 4 S., R. 23 E., in Kansas). Another tributary to the ancestral Grand River in Missouri flowed along the northern border of Doniphan County through T. 2 S., R. 22 E.

The depth to bedrock in Doniphan County (fig 21) ranges up to 256 ft (78.0 m). The largest values are associated with the buried valleys in the northern part of the county, but there and elsewhere along the Missouri River loess deposits are also thick. For example, 195 ft (59.4 m) of loess overlies 61 ft (19 m) of glacial and fluvial deposits in SENENW sec. 22, T. 1 S., R. 19 E. Based on data from 189 test holes and wells (Denne et al., 1990a), unconsolidated deposits in Doniphan County are most commonly between 20 ft (6 m) and 100 ft (30 m) thick. Values greater than 100 ft (30 m) and less than 20 ft (6 m) were reported at 26 and 22 sites, respectively. Alluvial deposits along small streams range from 15 ft to 50 ft (5–15 m) thick. In the larger valleys deposits are generally thicker, with the greatest depths to bedrock in the Missouri River valley [117 ft (35.7 m)] and along the Wolf River [88 ft (27 m)] .

The unconsolidated deposits in Doniphan County were described by Bayne (1973). The oldest are pre-Illinoian and commonly include a basal limestone and chert gravel below silty clay and fine-grained sand. As many as three glacial tills overlie the older fluvial deposits, and lacustrine and outwash deposits locally separate the upper two (Kansan) tills. These deposits range up to 110 ft (34 m) in total thickness.

Glacial striations on bedrock below till in Doniphan County (see fig. 22) are oriented at various angles from south 144° to 189°, with two sites having cross striations (Schoewe, 1931, 1933, 1941). This indicated to Schoewe (1931) a range of possibilities, including two ice sheets, two advances of one ice sheet, advances of two lobes of one ice sheet, and minor cross-movements near the glacier margin. Two different glacial tills in Doniphan County (considered to be Nebraskan and Kansan in age) were documented near Iowa Point by Frye and Leonard (1949, 1952) and near Wathena by Aber (1988a). Excellent descriptions of several different exposures in the county, including two Kansan tills (Cedar Bluffs and Nickerson) are given by Bayne et al. (1971). Dort (1965, 1966, 1972b) also stressed the complexity of pre-Illinoian glaciations, citing his interpretation of five or more stadial advances based on exposures in Doniphan County.

Bayne (1973) reported the presence of one Illinoian and two Wisconsin loesses locally overlying the older

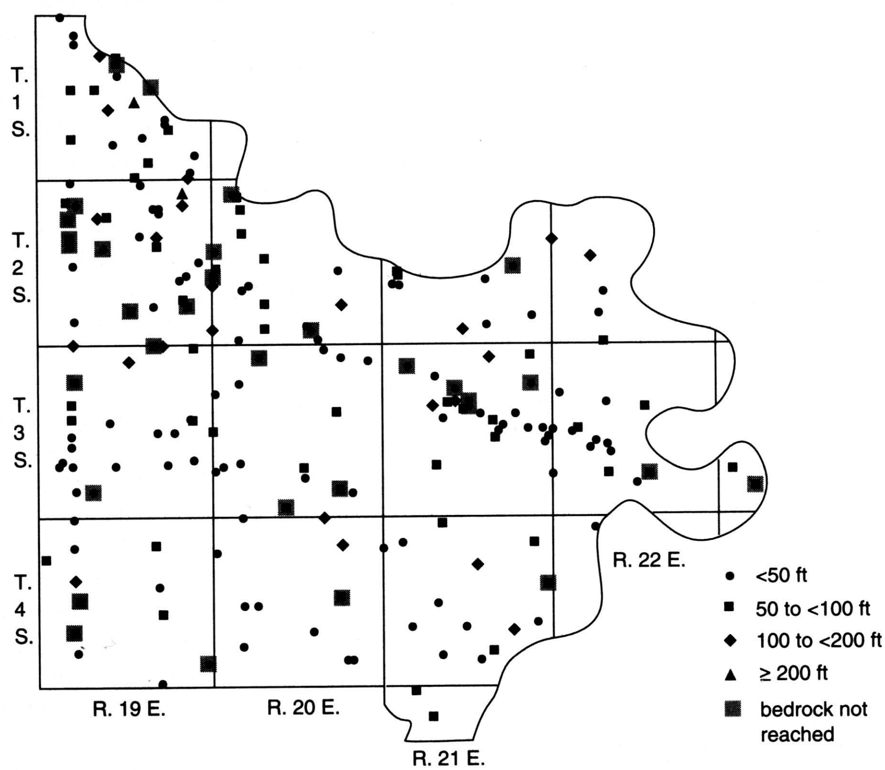

FIGURE 21—Depth to bedrock, Doniphan County.

deposits in Doniphan County. The loess is primarily silt with some clay. Ten to 30 ft (3–9 m) of loess commonly mantles the uplands, and the deposits are thickest [sometimes more than 100 ft (30 m)] near the Missouri River.

Aber (1988a, 1991) designated an exposure located south of Wathena (SE sec. 32, T. 3 S., R. 22 E.) as the parastratotype for the Independence Formation, his complex including two distinct diamictons. The lower of the two diamictons is thick, gray, and contains wood fragments, limestone blocks, and bodies of stratified sand and silt. The upper diamicton is brown, relatively thin, and overlain by loess. The preglacial alluvium which underlies the Independence Formation contains the Wathena local fauna (Einsohn, 1971). This section, like the holostratotype located in Atchison County (Aber, 1988b), is situated within the buried valley that crosses the study area.

Alluvial and terrace deposits also can be as old as Illinoian. At the western edge of the county, Illinoian terraces were mapped along the Wolf River (Bayne, 1973); these deposits are less than 20 ft (6 m) thick and consist of silt, clay, sand, and gravel. More recent alluvial deposits occur along most streams in the county. In the Missouri River valley, the deposits are coarse grained and range up to 120 ft (37 m) in thickness. Finer-grained material dominates along most of the smaller streams.

The total thickness of sand and gravel deposits in Doniphan County is illustrated in fig. 23. The two largest values [122 ft (37.2 m) and 121 ft (36.9 m)] occur at the sites with the fourth and third largest depths to bedrock [150 ft (45.7 m) and 163 ft (49.7 m)]. Both of these wells (SESENE sec. 8, T. 2 S., R. 19 E., and NWNWNW sec. 14, T. 2 S., R. 19 E.) contain sand from a depth of less than 50 ft (15 m) to the bedrock surface. These wells and others in the area with large thicknesses of sand and gravel are part of the buried-valley system in northern Doniphan County. Other significant thicknesses of sand and gravel occur in the Missouri River valley, where values are known to exceed 90 ft (27 m) (e.g., NWSWSE sec. 17, T. 2 S., R. 22 E., and NWSWNW sec. 18, T. 2 S., R. 22 E.) and commonly are more than 40 ft (12 m). Most of the modern and buried valleys in Doniphan County contain at least some sand and gravel deposits, often near the bedrock surface and sometimes in overlying layers.

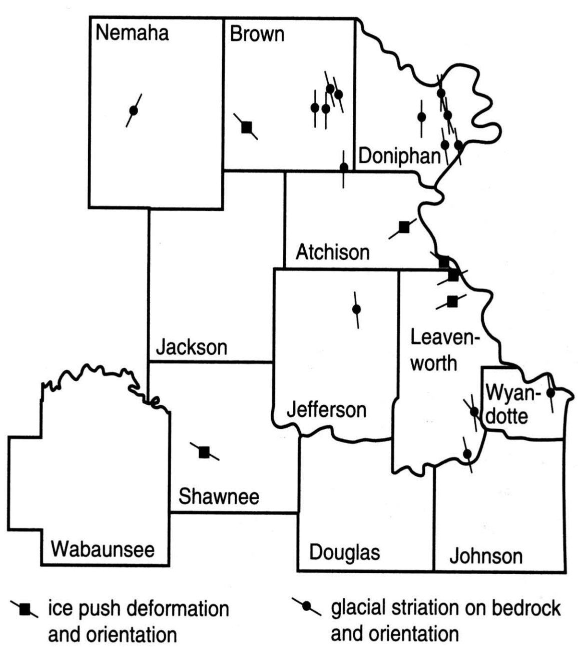

FIGURE 22—MAP OF NORTHEASTERN KANSAS SHOWING WHERE ICE-PUSH DEFORMATION OF BEDROCK OF GLACIAL STRIATIONS ON BED-ROCK HAVE BEEN OBSERVED BELOW GLACIAL TILL.

Ground Water

In Doniphan County the three largest well yields (uncorrected for well diameter, etc.) were reported from alluvium in the Missouri River valley (fig. 24). The yields range from 150 gpm to 250 gpm (0.0095–0.016 m^3/s), but values closer to 3,000 gpm (0.2 m^3/s), as found in Atchison County, could be expected from coarse-grained sediments in the alluvium. Other moderate well yields [20–100 gpm (0.001–0.006 m^3/s)] can be obtained from sand and gravel in the buried valleys, such as those in the northwestern part of the county. Along the Wolf River well yields of 5–50 gpm (0.0003–0.003 m^3/s) are common. In the smaller stream valleys and in some other glacial deposits, yields of a few gallons per minute can be obtained.

The Pennsylvanian bedrock in Doniphan County may yield a few gallons per hour from the weathered upper zones of the limestone or up to 5 gpm (0.0003 m^3/s) from sandstones in the Stull and White Cloud Shale Members (Bayne, 1973). However, because the water from the sandstones declines in quality or becomes more mineralized with depth and because the rock units dip 25 ft/mi (5 m/km) to the northwest, water from the sandstones is probably not potable more than 5 mi (8 km) west of the sandstone outcrops.

The water-level elevations can be calculated from data reported by Denne et al. (1990a), but for reasons previously discussed, we did not attempt to contour these values. Bayne (1973) contoured the water table in the large stream valleys of Doniphan County, and the contours indicate that ground water flows toward the streams. Bayne noted that the water table is discontinuous from the valleys to the adjacent bedrock and that seeps and springs occur along many valley walls. He also recognized that the rugged topography in the county makes collection of a large amount of water-level data necessary before a county water-table map can be contoured.

Where water was reported in drill holes in Doniphan County, it was less than 100 ft (30 m) deep (fig. 25). The

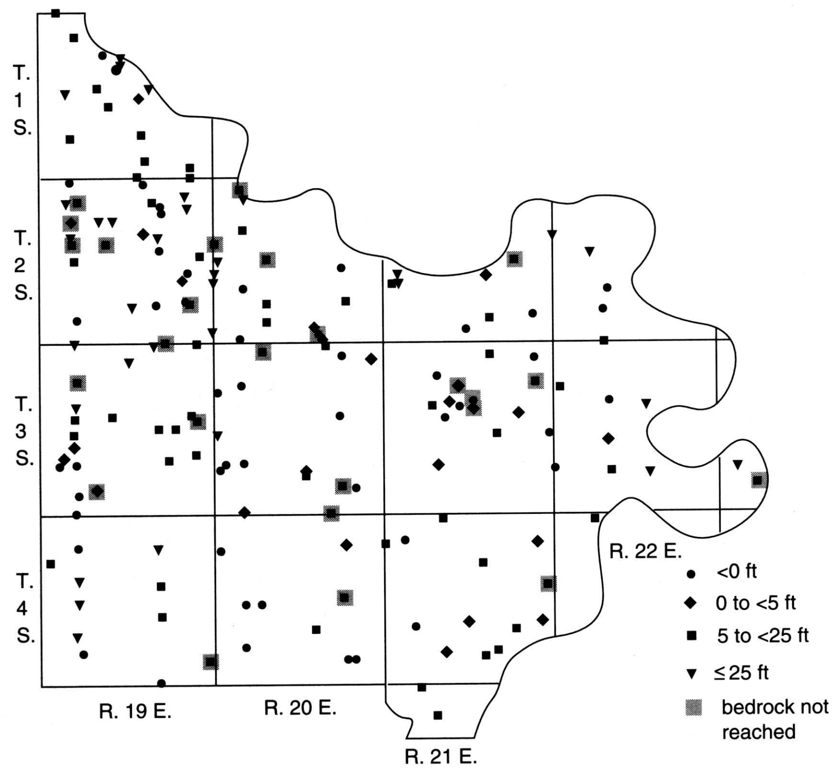

FIGURE 23—Total Pleistocene sand and gravel thickness, Doniphan County.

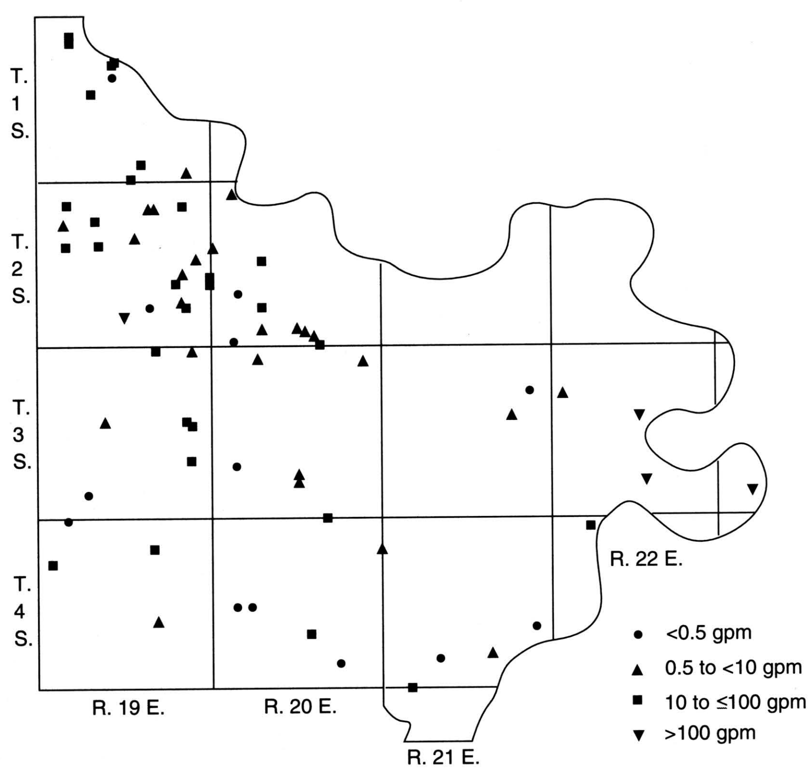

FIGURE 24—Estimated well yields, Doniphan County.

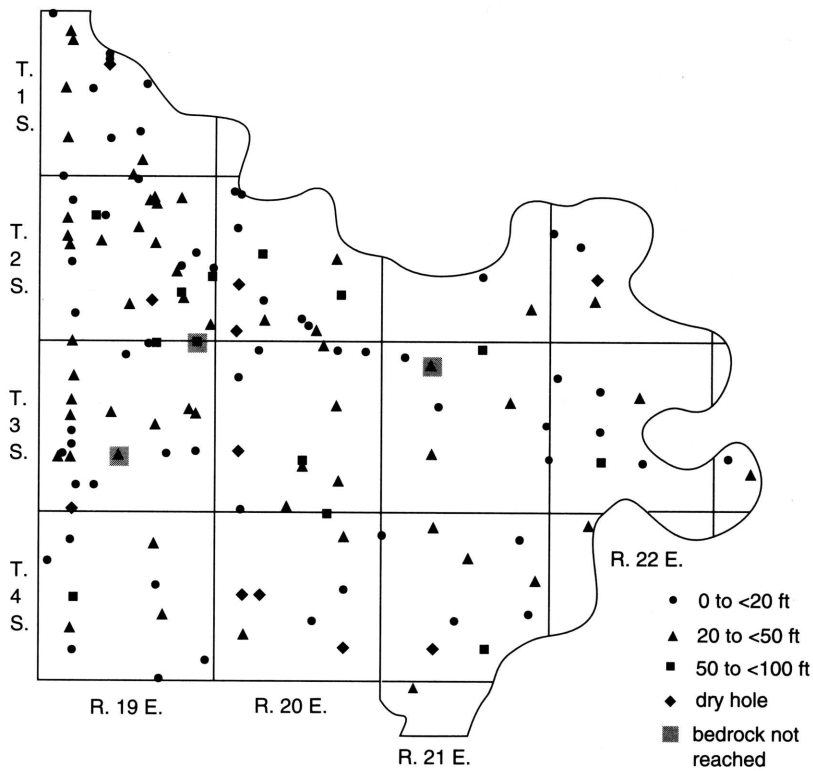

FIGURE 25—Depth to water in wells and test wells, Doniphan County.

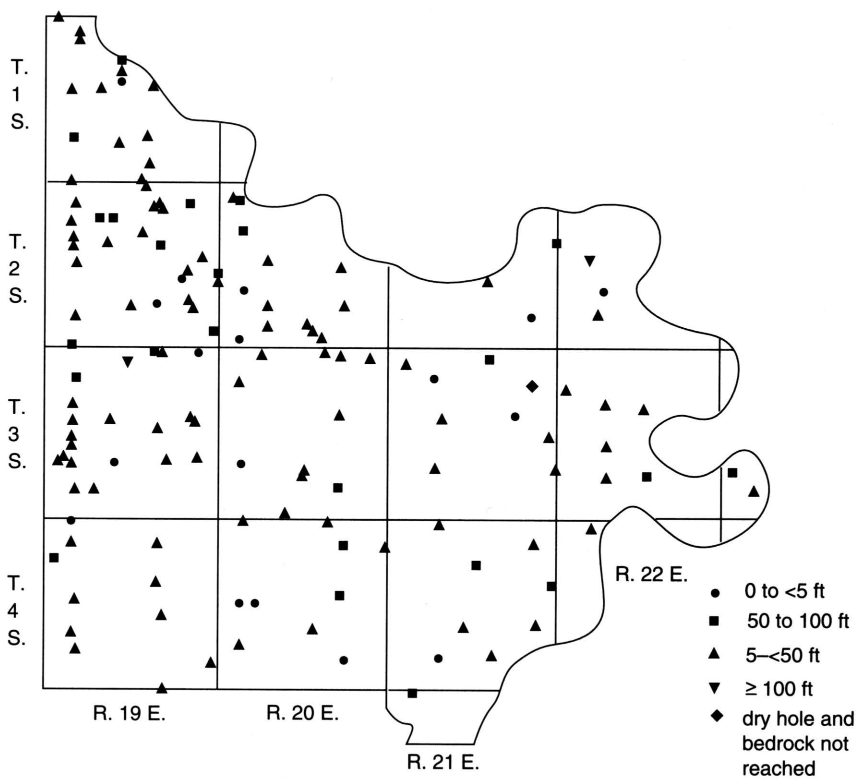

FIGURE 26—Saturated thickness of Pleistocene deposits, Doniphan County.

four greatest water depths [75–95 ft (23–29 m)] were found in upland areas where the depth to bedrock is more than 100 ft (30 m). However, water levels under apparently similar conditions may be as shallow as 10 ft (3 m). For all the glacial deposits the depth to water was 3–95 ft (0.9–29 m), and more than half of the values were greater than 30 ft (9 m). The depth to water in alluvial deposits was generally shallower, with most values between 5 ft (2 m) and 25 ft (7.6 m).

The saturated thickness of unconsolidated deposits in Doniphan County (fig. 26) is greatest in the buried drainageway along the border between T. 2 S., R. 19 E., and T. 3 S., R. 19 E., where it is 133 ft (40.5 m), and in the Missouri River valley, where it is 107 ft (32.6 m). In the Wolf River saturated alluvial deposits generally range from 30 ft to 60 ft (9–18 m) in thickness. In the smaller stream valleys, thicknesses less than 20 ft (6 m) are common. The thickness of saturated glacial deposits is generally greater than 15 ft (5 m), and most values from borehole data are more than 30 ft (9 m).

As Bayne (1973) observed, almost any area in Doniphan County with 30–40 ft (9–12 m) of saturated Pleistocene deposits will provide sufficient water for domestic and stock supplies to a well obtaining water from at least one thin saturated sand or gravel layer. He also noted that in the uplands the most productive aquifers do not necessarily coincide with the greatest saturated thicknesses. The buried valleys or other areas with saturated sand and gravel deposits are capable of supplying the largest quantities of ground water.

Douglas County

Geology

The geology of Douglas County has been well described and mapped by O'Connor (1960, 1992). The regional structure is dominated by the Prairie Plains homocline, and post-Permian rocks dip northwestward at 20 ft/mi (4 m/km). The homocline has many smaller synclinal and anticlinal structures superimposed on it. Several faults have been mapped in the southern part of the county. Oil and gas fields have been developed in the eastern part of the county, primarily from the Cherokee and Pleasanton Groups, at depths between 340 ft (100 m) and 800 ft (240 m).

As described by O'Connor (1960), the bedrock units exposed in Douglas County range from the Lansing Group (oldest) to the Shawnee Group (youngest). Sixty-five to 100 ft (20–30 m) of rocks of the Lansing Group, including limestone, shale, sandstone, and some coal, are exposed along drainageways in the northeastern part of the county (fig. 5). The total thickness of the sandstone, shale, limestone, and coal of the overlying Douglas Group ranges from about 150 ft to 450 ft (46–140 m). Locally the group contains two major channel sandstones. The valley in which the Tonganoxie Sandstone Member was deposited extends from the northeast corner to the southwest corner of the county, and the Ireland Sandstone Member fills a former valley located in the southern part of the county. The two sandstones may be 120 ft (37 m) and 150 ft (46 m) thick, respectively. The youngest bedrock units exposed in Douglas County include 300–375 ft (90–114 m) of Shawnee Group limestones and shales with some sandstone, siltstone, and coal.

The total thickness of exposed Pennsylvanian and Quaternary units in Douglas County is 1,000 ft (300 m) (O'Connor, 1960). The southern limit of glaciation in Kansas apparently crossed the county (figs. 7 and 9). Surficial deposits include till, glaciofluvial and glaciolacustrine sediments, loess, and alluvium (fig. 9).

Pre-Illinoian glacier-related deposits occur primarily in the northern half of Douglas County, especially in the northeastern Hesper plain area (O'Connor, 1960). The oldest Quaternary sediments are leached and oxidized gravels (composed primarily of chert but including up to 40% erratics locally) in a reddish sandy clay matrix. The chert gravels are probably preglacial stream deposits, and the gravels with both chert and erratics may reflect reworking by ice or glacial meltwater.

Glacial till in Douglas County has been described and mapped by O'Connor (1960). The till is generally unstratified and unsorted, but stratified sand and gravel occurs locally within till in uplands or grades into till in other areas. Between the Kansas and Wakarusa rivers, most of the till is clay, and O'Connor (1960, p. 50–52) suggested that it "probably accumulated by lodgement from the base of the ice. . . . Other till deposits accumulated by dumping or being let down by slow wastage of the ice (superglacial ablation moraine)," and the latter deposits have relatively less clay and silt and more sand and gravel because of washing by meltwater.

Glaciofluvial and glaciolacustrine deposits occur in all topographic positions in northern Douglas County, as described and mapped by O'Connor (1960), who assigned these deposits to the Kansan Atchison, Grand Island, and Sappa formations. Some of the stratified materials originally may have been till that was reworked by meltwater. O'Connor (1960, p. 52) concluded that "the predominance of stratified deposits rather than till in the terminal area of the glacier indicates that the Kansan glacier at its climax may have been a slowly flowing, rapidly melting ice mass." The ice probably extended at least as far south as the Wakarusa River valley (O'Connor, 1960; Todd, 1909; Schoewe, 1930a, b; Aber, 1991).

South of the Wakarusa River, stratified gravel deposits, 2–30 ft (0.6–9 m) thick, occur on some topographic highs (O'Connor, 1960). The deposits consist of poorly sorted sand and gravel. Where thin, the material is leached and includes primarily chert, quartz, and igneous and metamorphic rocks from the northern

United States and southern Canada. Where thick, the deposits are leached only in the upper part and are dominated by limestone and other local rock types. The areal distribution and the character of the sediments indicate that the material was deposited at the ice margin, probably by streams flowing on bedrock along the glacier front or on or within the ice in marginal crevasses (O'Connor, 1960).

Just north of the present Wakarusa River valley (which probably developed before its direct glaciation) and extending for several miles from the western border of Douglas County are deposits of an east-flowing stream that may have been englacial or subglacial (O'Connor, 1960). The deposits consist of up to 40 ft (12 m) of gravel, sand, and silt that now form a ridge where they have not been eroded. Continuing eastward, the deposits underlie the town of Clinton and fill an abandoned valley. South of Lawrence, the deposits again form a ridge, with boulders, gravel, and sand in the lower and middle parts and finer-grained material in the upper zone. At least locally, till overlies the stratified deposits south of Lawrence. The history of the Wakarusa River valley is undoubtedly complex, with episodes of entrenchment, coverage by ice, and alluviation. As the ice receded, the Kansas River valley probably developed further and captured much of the Wakarusa drainage.

Glaciolacustrine silt and sand were deposited in lakes that developed from blockage or derangements of drainage by ice or glacial deposits. O'Connor (1960) has described several such lacustrine deposits, including those in SW sec. 2, T. 13 S., R. 19 E., and SE sec. 8, T. 14 S., R. 21 E., where the sediments range up to 7 ft (2 m) in thickness. These deposits include at least 24 pairs of varves and locally are covered by till. Although O'Connor (1960) believed that many temporary lakes were formed in Douglas County, he suggests that the lacustrine deposits are now rare, probably because they were thin, destroyed by glaciation, and/or subsequently eroded where not topped by a protective cover of till or gravel. This perspective was also expressed by Dort (1985) and Aber (1991).

The northeastern part of Douglas County (the Hesper plain area south of the Kansas River and east of Little Wakarusa Creek) contains extensive glacial, glaciofluvial, and glaciolacustrine deposits, except where they have been eroded by streams (O'Connor, 1960). Schoewe (1930a, b) and Hoover (1936) classified the deposits as reworked till, whereas Dufford (1958) considered the material in the northern half of the area to be part of the Menoken terrace (outwash from a retreating "Kansan" glacier; Davis and Carlson, 1952). O'Connor (1960) cited till deposits in sec. 17, T. 14 S., R. 21 E., as evidence that the glacier extended at least this far south. Within the general Hesper plain area the deposits, as described by O'Connor (1960), commonly include a basal layer of gravel or sand that ranges from well sorted to poorly sorted and from clean to clayey. The upper part of the deposits commonly consists of clayey and silty sand or sandy clay with some gravel and cobbles. Locally, however, the entire sequence of material contains only unstratified sandy and gravelly silt and clay.

The preglacial topography of the Hesper plain area was a lowland developed on Douglas Group shales and sandstones, with higher (more resistant) limestones on the east and west sides (O'Connor, 1960). The surface and base of the Quaternary sediments deposited on this lowland rise 100 ft (30 m) over a distance of 7.5 mi (12 km) toward the south from altitudes of 885 ft (270 m) and 855 ft (261 m), respectively, along the south bluff of the Kansas River. The difference between this northeastern area and the remainder of the county is clearly visible on Landsat imagery (e.g., Image ID 246716171, path 29, row 33, May 3, 1976, where the region appears blue-gray on the false-color composite).

The Kansas River valley changed significantly during glaciation. Lohman and Frye (1940) thought that the modern Kansas River originated during the advance of the Kansan glacier and was an ice-marginal drainageway. When the ice crossed and blocked the Kansas River, the Wakarusa River may have served as a spillway for meltwater (Todd, 1911). As the glacier retreated to north of the Kansas River, meltwater carried gravels and later finer-grained sediments into the valley, where locally more than 60 ft (18 m) of leached and oxidized reddish-brown sand, silt, and clay were deposited above 20 ft (6 m) of coarse, poorly sorted gravel (O'Connor, 1960). Most of these deposits were subsequently eroded from the valley, but (Menoken) terrace deposits remain along the southern side of the Kansas River between Baldwin Creek and Lawrence and directly opposite this area on the northern side of the valley.

As described by O'Connor (1960), the Illinoian Stage in Douglas County included erosion of deposits in the Kansas River valley and its tributaries, entrenchment of the river 50–60 ft (15–18 m) below basal Kansan deposits, and then at least 70 ft (21 m) of aggradation. Buck Creek terrace deposits represent late Illinoian time and include coarse-grained basal deposits and reddish or tan silt, sandy silt, and clay in the upper part. The reddish Sangamon soil is well developed on Buck Creek terrace deposits.

Loess deposits are minor in Douglas County. As described by O'Connor (1960), thin [generally less than 5 ft (2 m)] loess of the Loveland loess (Illinoian) occurs locally in bluffs bordering the Kansas River valley, and thin [less than 5 ft (2 m)], discontinuous deposits of the Wisconsinan Peoria formation can be found on uplands. The Peoria loess is thickest [locally 5–10 ft (2–3 m)] along the bluffs of the Kansas River valley.

During early Wisconsinan time, the bedrock floor of the Kansas and Wakarusa River valleys was eroded to

20–50 ft (6–15 m) below the basal Illinoian deposits, and alluviation produced deposits that underlie the Newman terrace, the surface of which is generally 30–40 ft (9–12 m) below the Buck Creek terrace (O'Connor, 1960). In the Kansas River valley the Newman terrace deposits include cobbles and gravel overlain by sand to clayey silt. The basal deposits are coarser than the sediments presently carried by the river, but the upper 40 ft (12 m) of the deposits are similar (Davis and Carlson, 1952). In the Wakarusa River valley, the Newman terrace deposits are dominated by silt and clay.

Within Douglas County the Kansas River floodplain ranges from 2.5 mi to 3 mi (4–5 km) in width, except where it narrows near the Johnson County line. The Wakarusa River valley is generally 1–1.5 mi (2–2.4 km) wide. Most other valleys in the county are less than 0.5 mi (0.8 km) wide, although parts of the Rock and Washington Creek valleys are wider. As noted by O'Connor (1960), slightly less than half of the Kansas River floodplain west of Eudora is Newman terrace, whereas the balance is late Wisconsin and Holocene alluvium. In the Wakarusa River valley and along many other Kansas River tributaries, the Newman terrace forms at least 90% of the floodplain.

In the Kansas River valley the late Wisconsin and Recent alluvium consists primarily of sand and silt. Several investigators have suggested that there may be additional terrace surfaces between the alluvium and the Newman terrace (O'Connor, 1960).

The bedrock topographic map of Douglas County (plate 1) was prepared using data from 370 drill-hole logs (Denne et al., 1990a), geologic maps (O'Connor, 1960; Ward and O'Connor, 1983), and a metric topographic map (U.S. Geological Survey, 1981a). Where bedrock is exposed at the land surface, the surface and bedrock topography are equivalent.

There are no major buried valleys in Douglas County. Till and glaciofluvial deposits occur on the Hesper plain area of T. 13 and 14 S., R. 21 E.; these deposits slope generally northward toward the Kansas River valley. At some time, more of the drainage may have flowed south toward Captain Creek, or Captain Creek may cut glaciofluvial deposits that were once more extensive [note the wide area of stream deposits and thick (7–13 ft; 2–4 m) sand in sec. 15, T. 14 S., R. 21 E.]. The Wakarusa River is currently underfit for the size of its valley (indicating that it once carried more drainage), and the bedrock floor is at approximately the same elevation as in the Kansas River valley to the north. The buried segment of a former subglacial (?) channel, as previously described, underlies the area near the town of Clinton in approximately the center of T. 13 S., R. 18 E.

The depth to bedrock in Douglas County (fig. 27) ranges up to 136 ft (41.5 m). A log for an oil test in SWNENE sec. 21, T. 13 S., R. 19 E., indicates the presence of sand and gravel from 80 ft to 136 ft (24–41.5 m) at this site in the valley where the modern Wakarusa River and Washington Creek join. If the depth and elevation of bedrock at this site are correct, then a narrow, deep channel must underlie the Wakarusa and Kansas River valleys or meltwater near the ice margin created a large local depression. A record for a water well in NESW sec. 13, T. 13 S., R. 19 E., shows that the depth to bedrock elsewhere in the Wakarusa River valley is at least 85 ft (26 m). The other two largest values for depth to bedrock in the county are in the Kansas River valley, where a somewhat ambiguous log

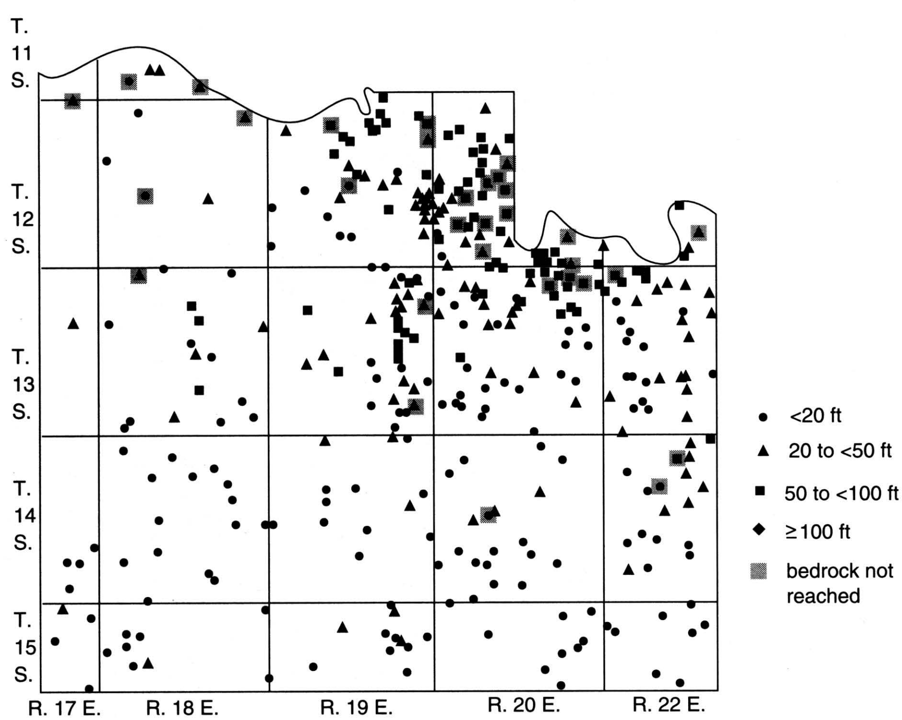

FIGURE 27—Depth to bedrock, Douglas County.

for a borehole in SWSENE sec. 35, T. 12 S., R. 20 E., indicates bedrock between 81 ft (25 m) and 101 ft (30.8 m), and in a well in NESWNE sec. 8, T. 12 S., R. 20 E., where the bedrock is 90 ft (27 m) deep.

The thickness of deposits in the Kansas River valley below areas mapped by O'Connor (1960) as alluvium is generally 40–75 ft (12–23 m), with the majority of values between 40 ft (12 m) and 60 ft (18 m). Deposits underlying the Newman terrace (Wisconsin–Holocene; Davis and Carlson, 1952) in the Kansas River valley tend to be somewhat thicker, with values commonly ranging from 40 ft to 90 ft (12–27 m) and more than half of the thicknesses being greater than 60 ft (18 m). The thickest stream deposits generally occur near the Kansas River junctions with the Mud Creek and Wakarusa River valleys.

Deposits mapped as the Newman terrace or undifferentiated terrace (O'Connor, 1960) along drainages other than the Kansas River in Douglas County range from 10 ft to 70 ft (3–21 m) in thickness. Along the Wakarusa River and Washington Creek, thicknesses are typically 30–70 ft (9–21 m), although they can reach 136 ft (41.5 m) (SWNENE sec. 21, T. 13 S., R. 19 E., as previously described). Stream deposits range from 20 ft to 50 ft (6–15 m) in thickness along Rock Creek, from 15 ft to 37 ft (5–11 m) along Coal Creek, and from 20 ft to 30 ft (6–9 m) along Captain Creek.

The depth to bedrock is as much as 32 ft (9.8 m) below the Newman terrace deposits along Baldwin Creek, but it ranges from 26 ft to 53 ft (7.9–16 m) below the Buck Creek terrace (Illinoian; Davis and Carlson, 1952) between Baldwin Creek and the Kansas River valley, as mapped by O'Connor (1960). Along the Wakarusa River the Buck Creek terrace is 50–85 ft (15–26 m) thick, and along Washington Creek it is at least 35 ft (11 m) thick.

The depth to bedrock below glacial and glaciofluvial deposits in Douglas County ranges up to 66 ft (20 m), with approximately half of the data points between 10 ft (3 m) and 30 ft (9 m) (fig. 27). The channel deposits in the northern half of T. 13 S., R. 17 E., are up to 48 ft (15 m) in thickness and in the center of T. 13 S., R. 18 E., up to 28 ft (8.5 m) thick. Just south of the Kansas River valley, from Baldwin Creek to Lawrence, outwash deposits (of the Menoken terrace) range from 10 ft to 66 ft (3–20 m) thick; just opposite, to the north of the river, these deposits are 44–62 ft (13–19 m) thick. From the southern side of Lawrence southward to the Wakarusa River valley, outwash deposits range from 24 ft to 50 ft (7.3–15 m) thick.

East of Lawrence, between the Kansas and Wakarusa rivers, glacial till and glaciofluvial deposits generally are between 20 ft (6 m) and 60 ft (18 m) thick. In the Hesper plain area the depth to bedrock ranges up to 58 ft (18 m), although more than half of the values are between 15 ft (5 m) and 35 ft (11 m).

Of the 157 data points in areas mapped as bedrock in Douglas County, 90% (141) indicate that the depth to bedrock is less than 20 ft (6 m). The surficial materials at these sites may include thin glacial, glaciofluvial, or loess deposits or residuum.

The total thickness of sand and gravel in Douglas County (fig. 28) is greatest in the Kansas River valley, where it ranges up to 83 ft (25 m). The maximum value occurs in the Newman terrace [as mapped by O'Connor (1960)] in SWSENE sec. 7, T. 12 S., R. 20 E., where

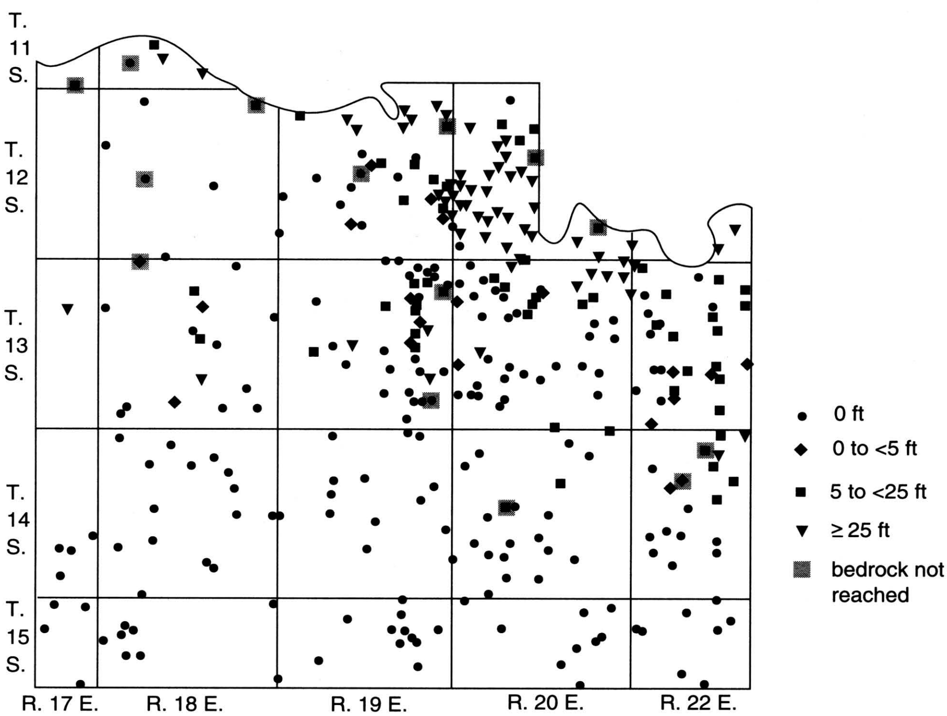

FIGURE 28—Total Pleistocene sand and gravel thickness, Douglas County.

Mud Creek enters the valley, and another large value [64 ft (20 m)] occurs nearby in the alluvium near the edge of the Newman terrace in NENENW sec. 20, T. 12 S., R. 20 E. The questionable log for a borehole in SWSENW sec. 35, T. 12 S., R. 20 E., indicates between 76 ft (23 m) and 82 ft (25 m) of sand and gravel in the alluvium between the junctions of the Kansas River with the Mud Creek and Wakarusa River valleys. A test hole in the alluvium in SESENE sec. 9, T. 12 S., R. 19 E. (near Lakeview), shows 68 ft (21 m) of sand and gravel. Of these four sites, sand and gravel make up the full thickness of unconsolidated sediments at two sites and all but the upper 5–8 ft (2–2.4 m) at the other two sites.

In general, logs for 50 wells in the Kansas River valley alluvium indicate a range in total sand and gravel thickness of 13–82 ft (4.0–25 m), with the majority between 30 ft (9 m) and 50 ft (15 m). Twenty-five drill holes in the Newman terrace of the Kansas River valley suggest a range of 0–83 ft (0–25 m) for total sand and gravel thickness, with the majority again between 30 ft (9 m) and 50 ft (15 m). The alluvial and terrace material typically becomes coarser with depth, with fine- to medium-grained sand near the land surface and gravel or sand and gravel above bedrock. Intermediate layers of coarser sand and/or gravel sometimes "interrupt" the downward progression from fine to coarse grained. The thickness of the basal gravel layer ranges up to 45 ft (14 m) in SENENE sec. 28, T. 12 S., R. 20 E., with other large values [greater than 29 ft (8.8 m)] in NWSESE sec. 17, T. 12 S., R. 20 E.; NWSENE sec. 21, T. 12 S., R. 20 E.; SESW sec. 2, T. 13 S., R. 20 E.; and NWNWNW sec. 7, T. 13 S., R. 21 E.—all of which are between the junctions of the Kansas River with the Mud Creek and Wakarusa River valleys.

In deposits mapped by O'Connor (1960) as the Newman terrace or undifferentiated terrace elsewhere in Douglas County, the total sand and gravel thickness ranges from 0 to 56 ft (17 m). The maximum value from an oil log in SWNENE sec. 21, T. 13 S., R. 19 E., however, is questionable. As previously discussed, the sand and gravel reported from 80 ft to 136 ft (24–41.5 m) (if accurate) may indicate a deep, narrow channel underlying the Washington Creek valley near its junction with the Wakarusa River. In Rock Creek the total thickness of sand and gravel ranges from 2 ft to 45 ft (0.6–14 m), with the largest value consisting of 40 ft (12 m) of sand underlain by 5 ft (2 m) of gravel in SWNE sec. 27, T. 13 S., R. 18 E. Ten logs in the Wakarusa River valley indicate 0–14 ft (0–4.3 m) of sand and gravel, with a mean value of 6 ft (2 m). In both the Coal Creek and Captain Creek drainages, the total sand and gravel thickness ranges from 0 to 13 ft (4.0 m) and has a mean value of 7 ft (2 m).

Six logs for drill holes in the Buck Creek terrace [as mapped by O'Connor (1960)] in the Wakarusa River valley indicate a total sand and gravel thickness of 0–30 ft (0–9 m). In SWNW sec. 20, T. 13 S., R. 20 E., fine-grained sand occurs from 32 ft to 60 ft (9.8–18 m) in depth. South of Lawrence (NESW sec. 13, NENE sec. 14, and SWSWNW sec. 13, T. 13 S., R. 19 E.), sand and gravel make up the lower 4–30 ft (1–9 m) of the unconsolidated deposits. In the Buck Creek terrace between Baldwin Creek and the Kansas River, 1–9 ft (0.3–3 m) of sand and gravel or sand overlie bedrock at two sites.

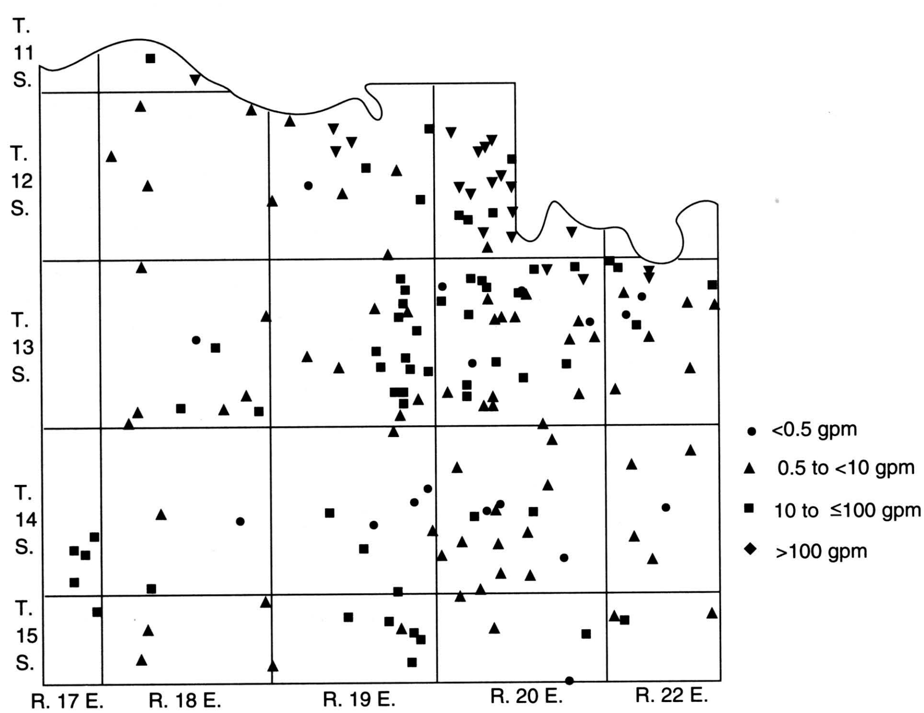

FIGURE 29—Estimated well yields, Douglas County.

The total thickness of sand and gravel in the till and outwash deposits in Douglas County is 0–50 ft (0–15 m). The largest value occurs in the Hesper plain area (NENE sec. 3, T. 14 S., R. 21 E.), where 32 ft (9.8 m) of coarse-grained sand overlies 18 ft (5.5 m) of fine-grained sand above bedrock. The second largest value [38 ft (12 m)] occurs nearby in SWSWSW sec. 3, T. 14 S., R. 21 E. Other sand and gravel thicknesses in the Hesper plain area are less than 25 ft (7.6 m), and the mean for 24 values is 12 ft (3.7 m). Thirteen of the sites have a gravel or sand and gravel layer [ranging from 1 ft to 18 ft (0.3–5.5 m) thick and having a mean of 6 ft (2 m)] overlying bedrock. Layers of sand are commonly fine- to medium-grained.

In the outwash deposit (Menoken terrace) along the northern edge of the Kansas River (T. 12 S., R. 20 E.), four drill holes indicate 10–24 ft (3–7.3 m) of sand or sand and gravel. Directly opposite the Kansas River from these sites (between Baldwin Creek and Lawrence), eight logs show 0–30 ft (0–9 m) of sand and gravel, although seven of the sites have 10 ft (3 m) or less. In the outwash deposits between Lawrence and the Wakarusa River, the total sand and gravel thickness ranges from 0 to 8 ft (2.4 m), whereas in the outwash and till between the Wakarusa and Kansas rivers east of Lawrence, sand and gravel make up 0–15 ft (0–4.6 m) of the deposits. One site (SWSW sec. 12, T. 13 S., R. 17 E.) in the former channel near the western border of the county contains 25 ft (7.6 m) of fine-grained sand. The outwash deposits near Clinton include up to 11 ft (3.4 m) of a basal sand and gravel (NWNWNE sec. 22, T. 13 S., R. 18 E.).

In the southern part of the county and in other areas where bedrock occurs at or near the land surface, there are no sand and gravel deposits.

Ground Water

Ground-water availability in Douglas County varies widely. Reported well yields, uncorrected for such factors as well diameter, are shown in fig. 29, which clearly indicates that the large supplies come from deposits in the Kansas River valley. Of 24 wells in the Kansas River alluvium with reported yields, 14 produce at least 200 gpm (0.01 m^3/s) and six of these yield 1,000–3,000 gpm (0.06–0.2 m^3/s). The remaining 10 wells yield 7–60 gpm (0.0004–0.004 m^3/s). Two wells in the Newman terrace deposits of the Kansas River valley yield 50 gpm (0.003 m^3/s) and 100 gpm (0.006 m^3/s), whereas six others produce 350–2,000 gpm (0.022–0.13 m^3/s). The largest yields in the county [>1,000 gpm (>0.06 m^3/s)] are reported near Lakeview and between the junctions of the Kansas River with the Mud Creek and Wakarusa River valleys (NWNWNE sec. 9 and NENWSW sec. 10, T. 12 S., R. 19 E.; NESW sec. 20, SWSWNW sec. 20, NWSENE sec. 21, NENWNW sec. 21, SENENE sec. 28, and SWNENE sec. 33, T. 12 S., R. 20 E.).

Although a well in NENE sec. 10, T. 13 S., R. 21 E., in the Captain Creek drainage yields 30 gpm (0.002 m^3/s), Newman terrace deposits in other stream valleys generally yield 2–10 gpm (0.0001–0.0006 m^3/s) where the material is saturated. Larger values occur locally where underlying bedrock contributes all or part of the water to the wells (e.g., NE sec. 33, T. 13 S., R. 18 E., and SWSW sec. 21, T. 13 S., R. 20 E.). O'Connor (1960) speculated that yields of 50–100 gpm (0.003–0.006 m^3/s) could be obtained from deposits along the Wakarusa River but that it would be difficult to screen and develop wells to prevent pumpage of sand and silt. In the lower parts of the Little Wakarusa and Captain creeks, where stream deposits are at least 30 ft (9 m) thick and contain a basal sand and gravel layer, O'Connor (1960) also estimated potential yields of 10–50 gpm (0.0006–0.003 m^3/s).

Reported yields from the Buck Creek terrace deposits in Douglas County include 10 gpm (0.0006 m^3/s) near Baldwin Creek and 15 gpm (0.00095 m^3/s) and 40 gpm (0.0025 m^3/s) in the area between Lawrence and the Wakarusa River. However, the first and third of these values also include contributions from underlying sandstone bedrock. Although the basal sand and gravel is generally poorly sorted and contains silt and clay, O'Connor (1960) suggested that 25–50 gpm (0.0016–0.003 m^3/s) could be produced from properly constructed and developed wells in the Buck Creek terrace.

Most of the wells completed in till or outwash deposits that have reported yields also obtain water from underlying bedrock units. It is therefore difficult to estimate the quantity of water available from the pre-Illinoian Pleistocene sediments. In the Hesper plain area, several wells yield 0–20 gpm (0–0.001 m^3/s), with three values in the range 2–4 gpm (0.0001–0.0003 m^3/s). The 20-gpm (0.001-m^3/s) yield was reported from fine-grained, dirty sand in NWNWSW sec. 17, T. 13 S., R. 21 E. O'Connor (1960) stated that saturated sand and gravel in the Hesper plain area probably could yield 50 gpm (0.003 m^3/s) locally. Areas with undissected outwash of adequate areal extent (e.g., the Menoken terrace between Baldwin Creek and Lawrence and the deposits between the Kansas and Wakarusa rivers to the south and east of Lawrence) may yield up to several gallons per minute.

Based on data from 87 drill holes in areas mapped as bedrock (not including wells penetrating multiple aquifers), seven were reportedly dry and 10 have yields of less than 1 gpm (0.00006 m^3/s). Another 33 wells have yields of 1–5 gpm (0.00006–0.0003 m^3/s), and 30 others have yields of 6–25 gpm (0.0004–0.0016 m^3/s). Yields from the other seven sites have values in the range 30–50 gpm (0.002–0.003 m^3/s). The larger values are associated with the Tonganoxie and Ireland Sandstone Members.

O'Connor (1960) described the bedrock aquifers in Douglas County. When near-surface limestones and shales are weathered so that joints, fractures, and bedding planes are enlarged, these units locally provide small supplies of water to shallow wells. Water levels in these wells may fluctuate greatly over time, however, and in dry years the wells may go dry. Thin [5–30 ft (2–9 m) locally] fine-grained sandstones of the Calhoun, Tecumseh, and Kanwaka Shales may yield up to 2 gpm (0.0001 m^3/s). The Ireland Sandstone Member of the Lawrence Formation is an important aquifer in southern Douglas County; it commonly yields 5–50 gpm (0.0003–0.003 m^3/s) and could possibly produce 100 gpm (0.006 m^3/s) where conditions are favorable. Locally, the Ireland Sandstone Member is more than 115 ft (35 m) thick and as much as 100 ft (30 m) of the unit may be saturated. The Tonganoxie Sandstone Member of the Stranger Formation is the other major bedrock aquifer in the county, and it extends from the northeast border to the southwest border. The sandstone is locally

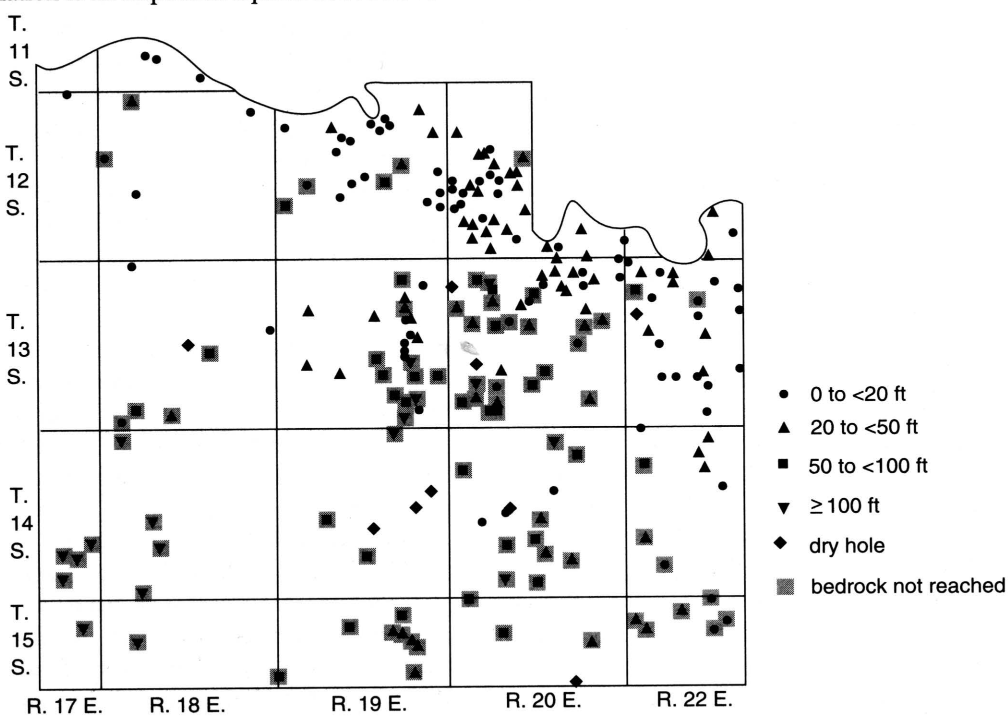

FIGURE 30—Depth to water in wells and test wells, Douglas County.

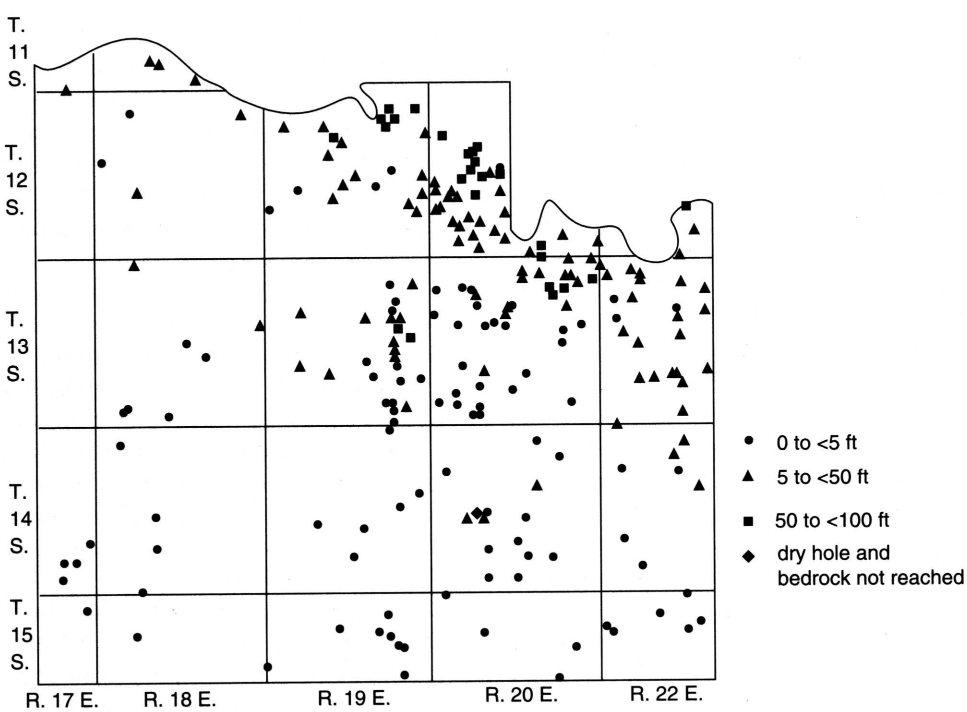

FIGURE 31—Saturated thickness of Pleistocene deposits, Douglas County.

as thick as 70 ft (21 m) and generally yields 5–50 gpm (0.0003–0.003 m^3/s), although where most permeable, it could produce 50–100 gpm (0.003–0.006 m^3/s). The Vinland Shale Member, also of the Stranger Formation, locally contains a thin, calcareous sandstone that yields small amounts of water to some wells. Both the Rock Lake Shale Member of the Stanton Limestone and the Bonner Springs Shale locally contain thin [less than 16 ft (4.9 m)] sandstone that yields 1–10 gpm (0.00006–0.0006 m^3/s). The quality of water from bedrock aquifers in Douglas County varies considerably, from good to unusable.

Figure 30 illustrates the depth to water in wells in Douglas County. When analyzing these data, it is important to remember that they represent values from many different seasons and years and that some indicate the water table, some the piezometric surface of various confined aquifers, and others the composite level from multiple aquifers. Nevertheless, some generalizations can be made. The greatest depths to water occur in bedrock units, especially those in the southwestern and central parts of the county. For example, values between 200 ft (60 m) and 360 ft (110 m) are found in SENESE sec. 35, T. 13 S., R. 19 E.; SESE sec. 24, SWSENE sec. 25, and SENE sec. 35, T. 14 S., R. 17 E.; SWSE sec. 32, T. 14 S., R. 18 E.; and SWNE sec. 1, T. 15 S., R. 17 E. Water levels in other bedrock wells, however, cover nearly the full range of depths to a minimum of 4 ft (1 m). Where saturated, water levels in the pre-Illinoian till and outwash range from 3 ft to 109 ft (0.9–33.2 m), although most values over 40 ft (12 m) reflect water levels combined with underlying bedrock units. In the Buck Creek terrace, the depth to water in a well near Baldwin Creek is 14 ft (4.3 m), and it is between 10 ft (3 m) and 44 ft (13 m) in four wells in the Wakarusa River valley. The depth to water in Newman terrace deposits in the Kansas River valley may be as shallow as 6 ft (2 m), but almost all other values are between 20 ft (6 m) and 30 ft (9 m). Along tributaries, water levels in Newman or undifferentiated terrace deposits are generally between 5 ft (2 m) and 25 ft (7.6 m). The depth to water in 57 wells in the Kansas River valley alluvium ranges from 3 ft to 40 ft (0.9–12 m), with 80% (46) of the values between 10 ft (3 m) and 30 ft (9 m). The greater depths occur in areas where many wells pump water from the alluvial aquifer (e.g., near Lawrence).

The same factors that limit the usefulness of the depth to water data must also be considered in calculating the saturated thicknesses of unconsolidated deposits. The saturated thickness of Pleistocene deposits in Douglas County is shown in fig. 31. The largest values [up to 63 ft (19 m) in SESESE sec. 8, T. 12 S., R. 20 E.] occur in Newman terrace deposits and alluvium in the Kansas River valley, particularly near Lakeview and in the area where Mud Creek enters the valley. The saturated thickness of alluvium in the Kansas River valley ranges from 20 ft to 60 ft (6–18 m), with 19 of 57 values between 30 ft (9 m) and 40 ft (12 m). The Newman terrace in the Kansas River valley appears to have a slightly greater saturated thickness, with 11 (60%) of 18 values between 50 ft (15 m) and 63 ft (19 m) and most others between 30 ft (9 m) and 40 ft (12 m). Although the saturated thickness of some Newman terrace deposits in the Wakarusa River valley ranges from 0 to 10 ft (3 m), most values are between 35 ft (11 m) and 50 ft (15 m). One value in the Washington Creek valley is 44 ft (13 m), and saturated thicknesses along three other Wakarusa River tributaries range up to 27 ft (8.2 m) in two tributaries and 15 ft (4.6 m) in the third.

Three saturated thickness values of 15 ft (4.6 m) occur in the Captain Creek terrace deposits. In Baldwin Creek the values are as great as 22 ft (6.7 m). In other stream valleys throughout the county the saturated thickness of Newman and undifferentiated terrace deposits is generally 0–10 ft (0–3 m). Saturated thickness values for the Buck Creek terrace include 6 ft (2 m), 44 ft (13 m), 54 ft (16 m), and 55 ft (17 m) along the Wakarusa River and 12 ft (3.7 m) near Baldwin Creek. Glacial till and outwash deposits in the Hesper plain area have saturated thicknesses ranging from 0 to 42 ft (13 m). Except for two large values [25 ft (7.6 m) and 42 ft (13 m)] in SWSWNW sec. 27, T. 13 S., R. 21 E., and SWSESE sec. 4, T. 14 S., R. 21 E., data points generally show 5–15 ft (2–5 m) of saturated thickness. Between the Kansas and Wakarusa rivers, to the south and east of Lawrence, the saturated thickness of the till and outwash deposits is 15 ft (5 m) or less, with many of the sediments here and elsewhere in the county being dry or having no permeable saturated zones.

Because of the problems with depth to water measurements previously described, water-level data must be used with some caution. However, it is clear that ground water flows with an average hydraulic gradient of 2–3 ft/mi (0.4–0.6 m/km) from northwest to southeast along the Kansas River valley. The general flow pattern and gradient are interrupted locally by the dam at Lawrence and by areas with heavy ground-water pumpage.

O'Connor (1960) estimated that the average hydraulic gradient of the water table in the alluvium and terrace deposits of the Wakarusa River valley is 4 ft/mi (0.8 m/km). O'Connor (1960) also estimated that the average hydraulic gradient in a portion of the artesian part of the Tonganoxie Sandstone Member is 7 ft/mi (1.3 m/km) and that water moves from the southwestern part of the county northeastward toward Lawrence, where it discharges into the stream deposits of the Wakarusa and Kansas River valleys.

Characteristics for some of the major aquifers in Douglas County have been described by O'Connor (1960). In the alluvium and Newman terrace deposits of the Kansas River valley, the coefficient of permeability is generally more than 1,000 gpd/ft^2 (40 m/d) and is

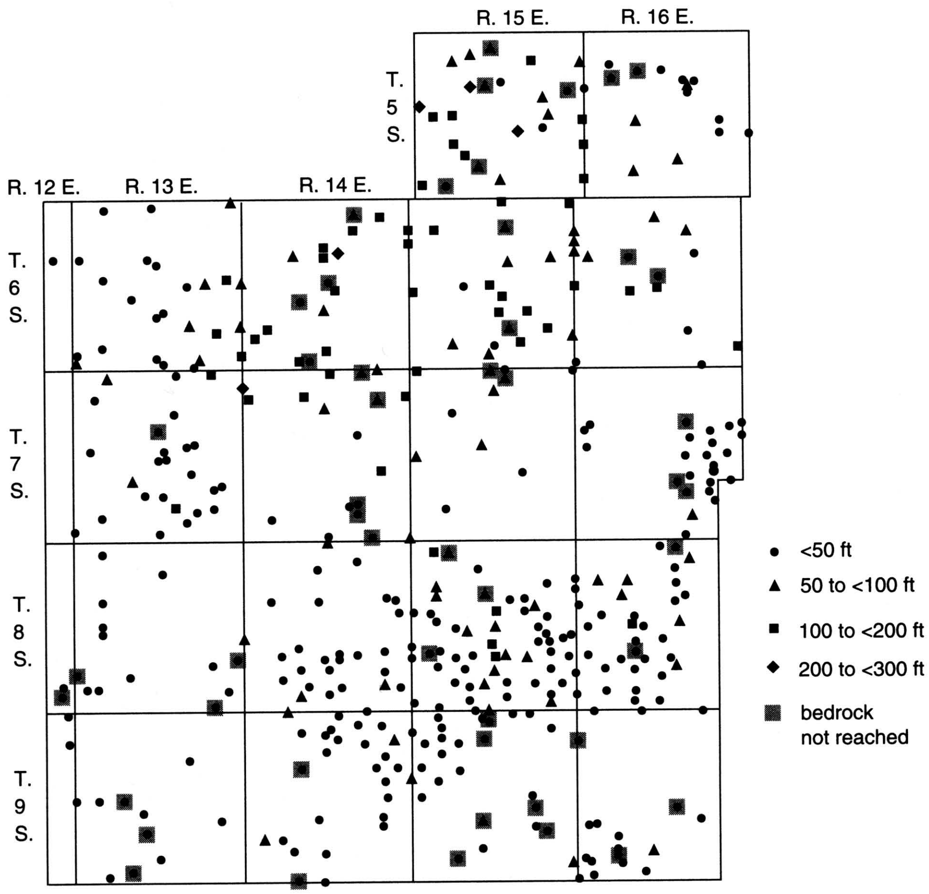

FIGURE 32—Depth to bedrock, Jackson County.

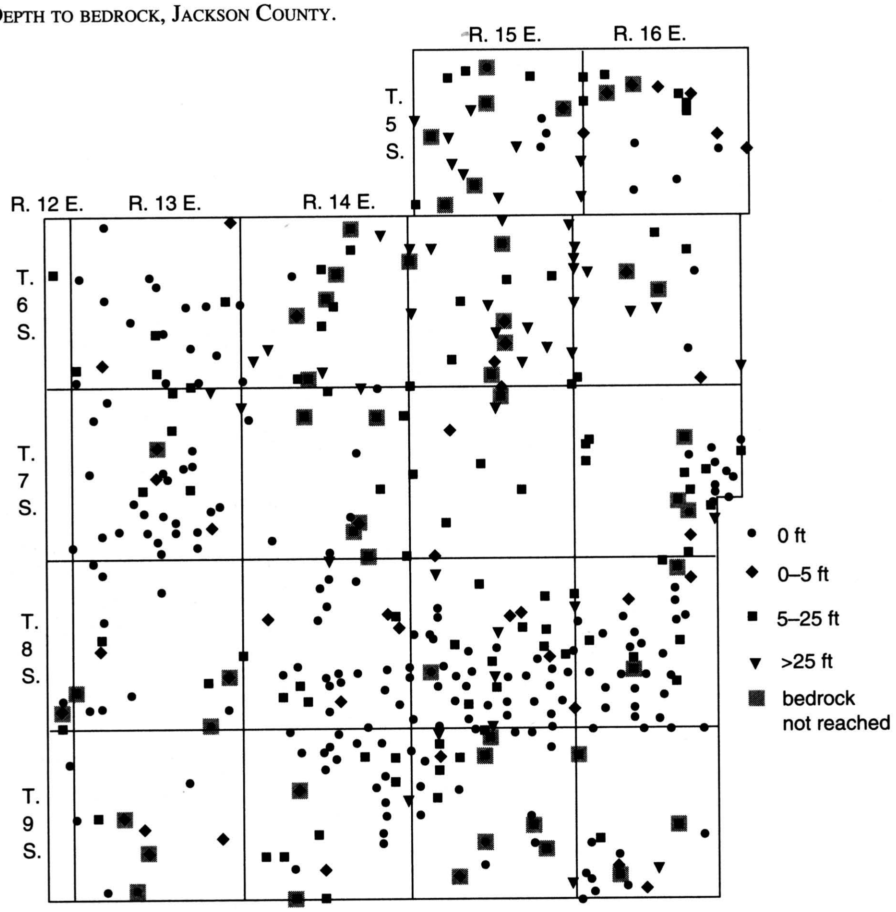

FIGURE 33—Total Pleistocene sand and gravel thickness, Jackson County.

locally more than 12,000 gpd/ft^2 (490 m/d). Transmissivity values range up to 354,000 gpd/ft (4400 m^2/d) (as reported for a well in SESE sec. 1, T. 12 S., R. 19 E.). Specific capacities range from 14 gpm/ft to 175 gpm/ft (0.0029–0.0362 m^2/s) of drawdown. In the well-sorted massive portions of the Ireland Sandstone Member, the coefficient of permeability ranges from 100 gpd/ft^2 to 350 gpd/ft^2 (4–14 m/d), but elsewhere it is commonly 25–150 gpd/ft^2 (1.0–6.1 m/d). The specific capacities for two wells are 1 gpm/ft (0.0002 m^2/s) and 7.6 gpm/ft (0.0016 m^2/s) of drawdown. The coefficient of permeability for the Tonganoxie Sandstone Member generally ranges from 15 gpd/ft^2 to 150 gpd/ft^2 (0.61–6.1 m/d).

In Douglas County the largest quantities of water can be obtained from the Kansas River valley alluvium and terrace deposits and from the Ireland and Tonganoxie

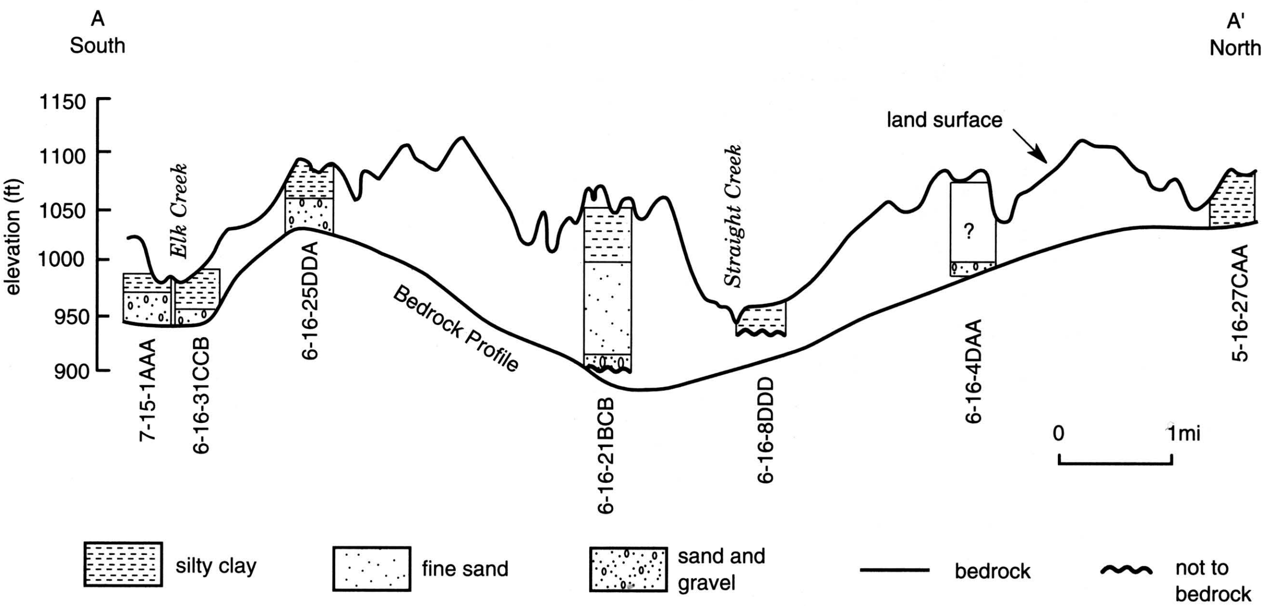

FIGURE 34—Cross section A–A′ showing surface topography and drill-hole data. Location of section shown in plate 1.

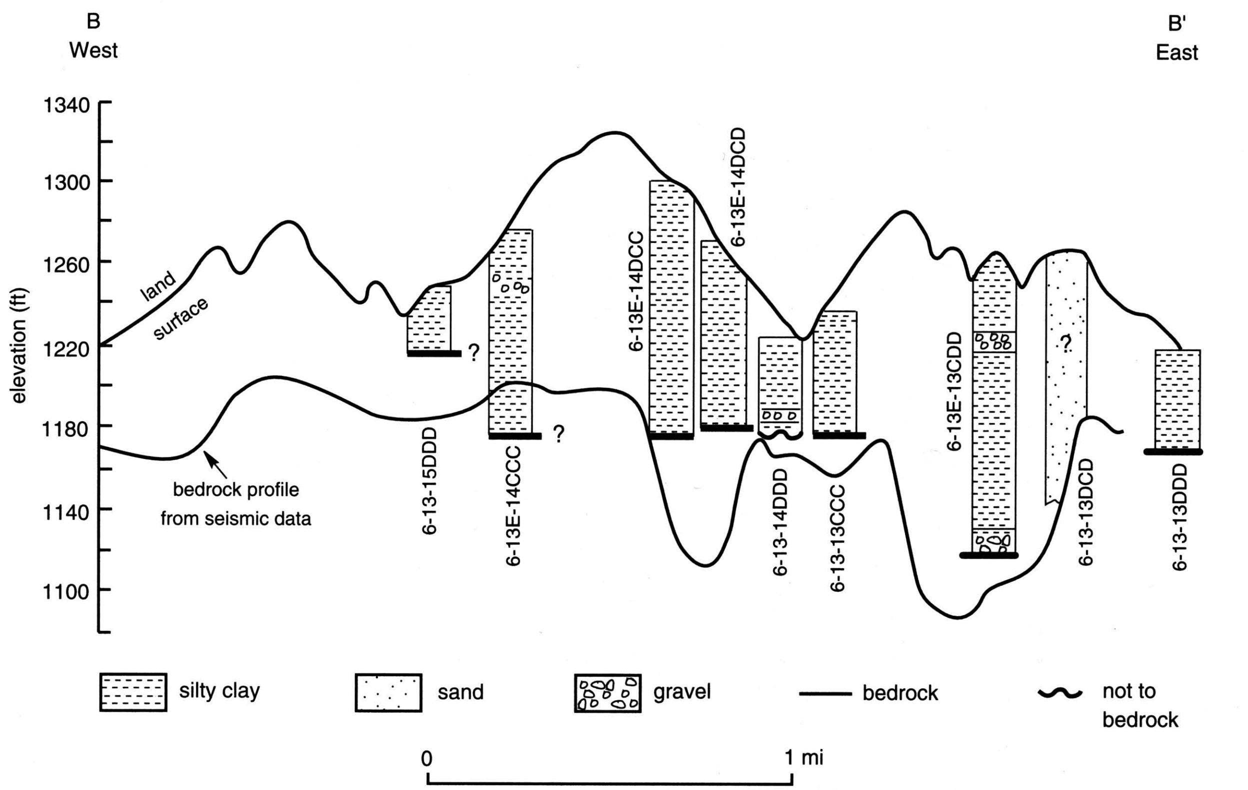

FIGURE 35—Cross section B–B′ showing surface topography, drill-hole data, and bedrock topography as interpreted from a seismic profile. Location of section shown in plate 1

Sandstone Members. However, the quality of water, especially from the bedrock units, must be evaluated before a supply is developed.

Ground-water discharge in Douglas County is to streams, wells, evapotranspiration, and springs, whereas recharge is primarily from precipitation, influent seepage from surface water, and subsurface inflow (O'Connor, 1960). Lohman (1941) estimated that the annual recharge in the Kansas River valley is 64 million gal/mi^2 (94 million L/km^2) based on 10% precipitation.

Jackson County

Geology

The surface geology of Jackson County was mapped by Walters (1953). Pennsylvanian bedrock is exposed locally in the eastern part of the county, and Permian limestones and shales occur in the west and northeast (fig. 5). Thick glacial deposits cover the northern and east-central areas of the county, and alluvium overlies the older deposits where they have been crossed by modern streams (fig. 9).

A map of the bedrock topography (plate 1) was contoured using data from 530 well logs (Denne et al., 1990a), the county maps of the geology (Walters, 1953), and surface topography (U.S. Geological Survey, 1981b). Drainage on the bedrock surface, as indicated in R. 12 E. and R. 13 E. and in the southern half of the county, is primarily a reflection of modern streams. Buried valleys dominate the bedrock topography in the north. The major buried channel extends from northwest to southeast in T. 5 S., R. 15 E., and T. 6 S., R. 16 E. Several buried tributaries enter the main valley from the west in T. 6 S., and Elk Creek (at the border of T. 6 S. and T. 7 S.) appears to overlie older drainage. Several bedrock highs in T. 5 S. and T. 6 S. may have influenced the position of the ice margin and its drainage. Referring to the buried valley mapped in Jackson and Nemaha counties in 1950, Frye and Walters (1950, p. 157) "judged that this bedrock 'sag' probably represents a . . . valley eroded in marginal position to the . . . ice front." They specified that the valley developed along the Nebraskan ice front and was overridden by the Kansan glacier, but the age terminology is now in question.

The depth to bedrock in Jackson County (fig. 32) is as great as 226 ft (68.9 m) beneath the main buried valley. Deposits filling the channels generally include a basal gravel [less than 20 ft (6 m) thick] overlain by layers of fine-grained sand and silty clay till with local sand and gravel lenses. The total thickness of sand and gravel deposits can exceed 100 ft (30 m) (fig. 33). A cross section roughly perpendicular to the main channel (A–A′ on fig. 34 and plate 1) illustrates the range of sediment types and thicknesses.

Seismic profiles were made across three small buried valleys in Jackson County to evaluate the channel widths and orientations. A test hole drilled in 1950 in SESESW sec. 13, T. 6 S., R. 13 E., had 12 ft (3.7 m) of gravel below 138 ft (42.1 m) of glacial deposits, suggesting the presence of a buried valley despite bedrock exposures 0.5 mi (0.8 km) to the north. The land-surface topography and the bedrock surface, as interpreted from seismic data for the line B–B′ are shown in fig. 35, and the location of the profile is shown on plate 1. Although it is probably not quite perpendicu-

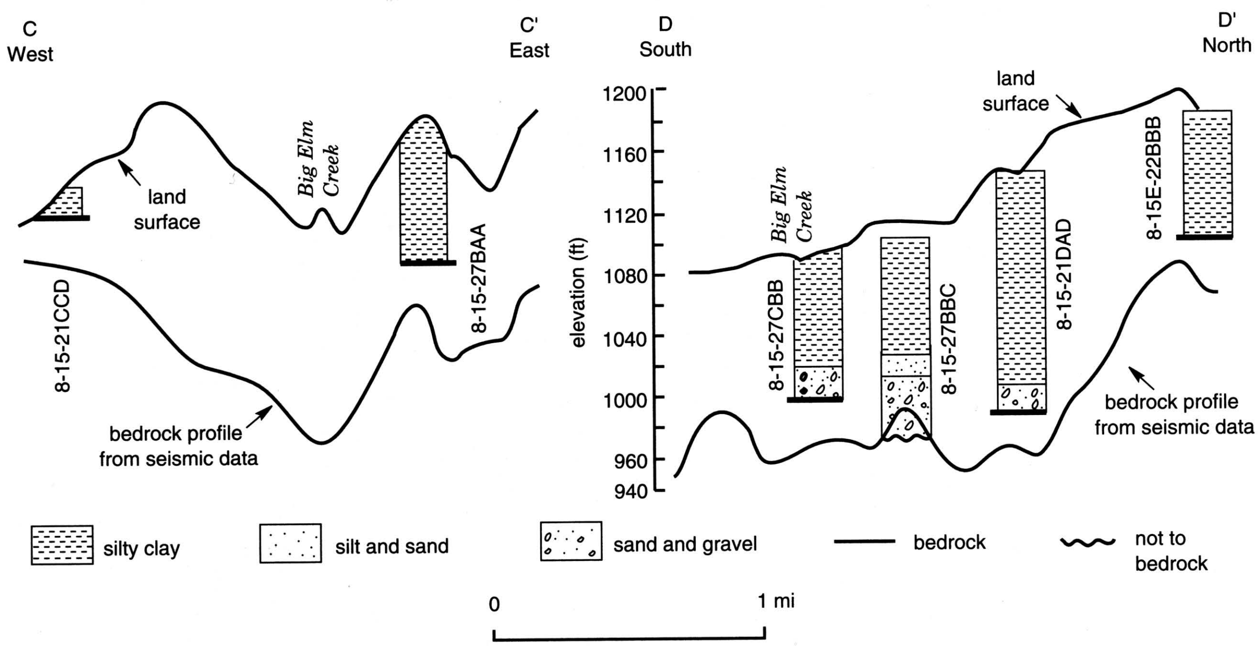

FIGURE 36—Surface topography and bedrock topography as interpreted from seismic profiles for cross sections C–C′ and D–D′. Location of sections shown in plate 1.

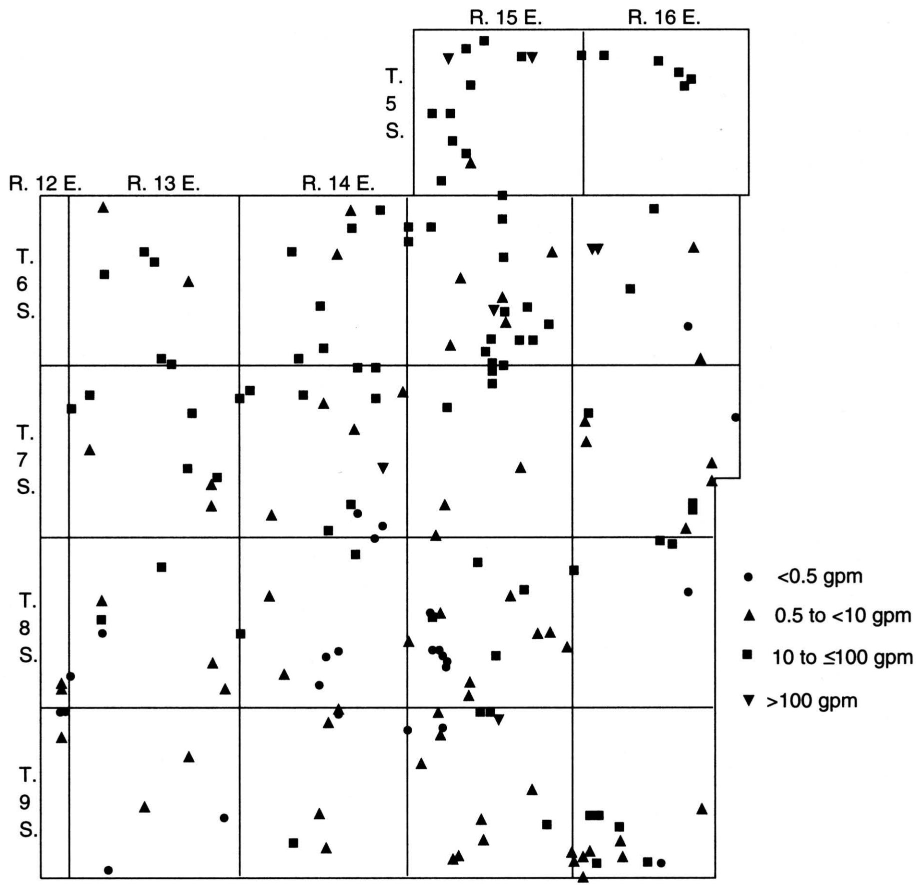

FIGURE 37—Estimated well yields, Jackson County.

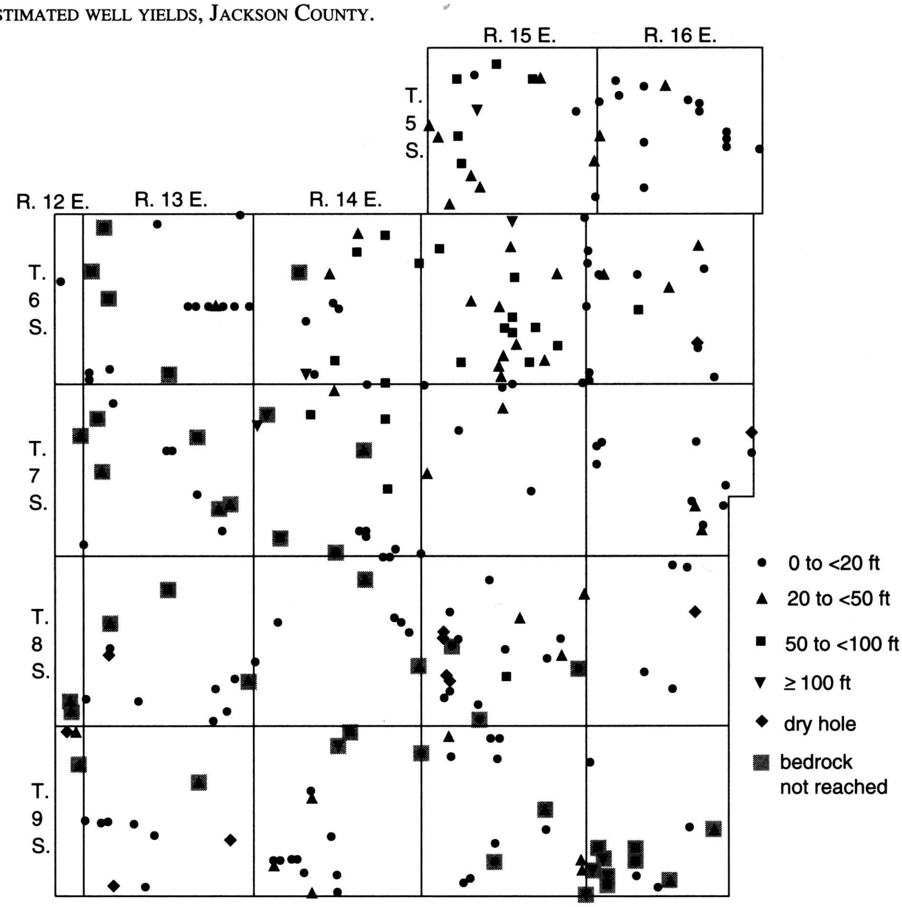

FIGURE 38—Depth to water in wells and test wells, Jackson County.

lar to the buried valley, the seismic profile indicates that the channel (near B′) is 180 ft (55 m) deep and 0.5 mi (0.8 km) wide. The seismic data suggest a second buried valley near the center of the profile, but drilling did not confirm this (fig. 35). The contour map of bedrock elevations (plate 1) indicates that the test hole in sec. 13, T. 6 S., R. 13 E., is near the beginning of a tributary that flowed southeastward and then either into the Elk Creek drainage or northeastward to the main channel.

Well logs from oil exploration near the northeastern corner of T. 7 S., R. 13 E., suggest the presence of a bedrock low with significant thicknesses of sand and gravel. A north-south seismic profile from SENENE sec. 25, T. 6 S., R. 13 E., to SESENE sec. 1, T. 7 S., R. 13 E., shows a south-sloping bedrock surface, with the lowest point at the southern end. A test hole in NWNWSW sec. 6, T. 7 S., R. 14 E., and area bedrock elevations confirm the presence of a buried tributary that apparently flowed eastward.

A bedrock low near the town of Mayetta in the center of T. 8 S., R. 15 E., is indicated by a 1978 water-well record from SWNWNW sec. 27, and a 1947 letter about two wells near town. Based on two perpendicular seismic lines (C–C′ and D–D′, as shown in plate 1 and in fig. 36), the long axis of the buried valley is oriented in a generally north-south direction, and the channel is 0.5 mi (0.8 km) wide. Several Phillips (oil) core logs obtained after the field study are also illustrated in fig. 36. Although the modern drainage complicates evaluation of this buried valley, bedrock-elevation data (in addition to sand and gravel thickness and well yield) suggest that the channel flowed southeastward into the northwest part of T. 8 S., R. 15 E., and then southward from near Mayetta, where it apparently coincides with Big Elm Creek (plate 1). This long, narrow buried valley may have drained ice that covered the northern townships of Jackson County.

The location and orientation of some of the buried valleys as now mapped may change as new drillers' logs are obtained. Small buried valleys that are masked by modern drainage may also become evident from additional logs that show thick sand and gravel deposits.

Ground Water

Although the bedrock formations in Jackson County generally do not yield significant amounts of water, moderate quantities can be obtained from the Dry and Friedrich shale members of Pennsylvanian age and from the Foraker, Red Eagle, Grenola, and Beattie Limestones of Permian age (Walters, 1953). Water-well records for wells completed in bedrock indicate that the better aquifers yield 5–30 gpm (0.0003–0.002 m^3/s), whereas many formations provide less than 1 gpm (0.00006 m^3/s) to wells. The quality of water from

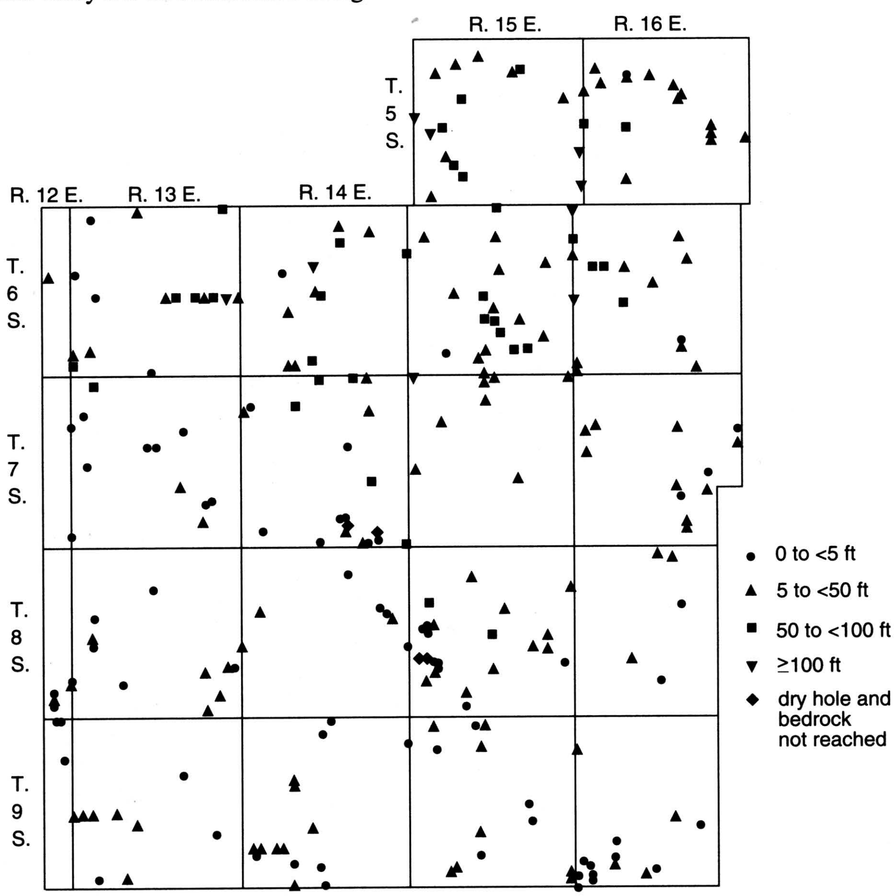

FIGURE 39—Saturated thickness of Pleistocene deposits, Jackson County.

bedrock units is variable, but the water is commonly highly mineralized.

Figure 37 shows reported yields from wells of various diameters and other construction characteristics in Jackson County. The unconsolidated deposits generally yield a larger quantity of water than the bedrock units. Wells in alluvial aquifers commonly yield 5–25 gpm (0.0003–0.0016 m^3/s), and yields from glacial aquifers range up to 600 gpm (0.04 m^3/s). The major buried valley in the northeastern part of the county yields the largest quantity of water, but the water quality is variable, as discussed later. The buried tributaries commonly yield 10–50 gpm (0.0006–0.003 m^3/s) to wells, but locally yields may exceed 100 gpm (0.006 m^3/s).

As previously discussed, reported water depths and calculated water elevations are not necessarily representative of a single aquifer and should not be used as an unsorted group to determine ground-water-flow directions. In general, however, the water elevations in Jackson County do appear to decline along the downgradient slope of the major buried valley toward the southeast. The data also tend to support Walters' (1953) conclusion that in the northern area of the county with thick glacial deposits, ground-water movement is generally eastward, with northeastward flow south of Straight Creek (which drains eastward in the northern part of T. 6 S., R. 15 E.) and southeast flow north of the creek.

Caution is again advised in analysis of the water-level data as shown in fig. 38. Nevertheless, the data suggest that the depth to water in Jackson County is generally less than 50 ft (15 m), and in modern stream valleys often less than 15 ft (5 m). Water levels between 50 ft (15 m) and 100 ft (30 m) are not uncommon in some of the thick glacial deposits and the bedrock aquifers. Several wells penetrating bedrock have water levels as deep as 180 ft (55 m).

Because the water levels reported for wells may be composites from multiple aquifers or may have other problems, as previously described, saturated thicknesses of unconsolidated deposits (fig. 39) calculated using this data also may be erroneous. As would be expected, however, the greatest thicknesses [ranging up to 200 ft (60 m)] occur over the major buried valley and its tributaries. Modern stream valleys commonly contain 5–40 ft (2–12 m) of saturated deposits.

Jefferson County

Geology

The geology of Jefferson County has been mapped and described by Winslow (1972). Rock formations exposed within the county range from the Lawrence Formation (oldest) in the southeast to the Willard Shale (youngest) in the northwest. In outcrops the Douglas Group is represented only by the Lawrence Formation, which consists of 60 ft (18 m) of shale to fine-grained silty sandstone. The Shawnee Group, exposed in the southern, central, and eastern parts of the county, includes 300–400 ft (90–120 m) of shale (several layers of which are carbonaceous), limestone, and local sandstone. Shales, limestones, local sandstones, and two coals compose up to 330 ft (100 m) of the Wabaunsee Group, which is exposed in central and western Jefferson County. These Late Pennsylvanian bedrock units dip generally west-northwestward at 15 ft/mi (2.8 m/km), and they are exposed in ridges, bluffs, and valley walls (fig. 5).

Unconsolidated deposits in the county include glacial drift, lacustrine clay, loess, and alluvium (fig. 9). Except in the uplands of the northeast, they are generally less than 50 ft (15 m) thick (Winslow, 1972). Pre-Illinoian tills range up to 100 ft (30 m) thick; they consist of clay, silt, sand, gravel, and boulders and occur primarily on the uplands. Winslow (1972) thought that a dense, pebble-bearing clay near the bedrock surface in deep test holes in the vicinity of Nortonville was a Nebraskan till. Another till, which he termed Kansan, overlies bedrock or the "Nebraskan (?)" till in the uplands. Near Nortonville this till consists of two or more zones of pebble-bearing clay interbedded with fine- to medium-grained glaciofluvial deposits. Winslow's (1972) geologic map is conservative in its representation of glacial deposits, which are generally more extensive than shown. In the Kansas River area, for example, Davis and Carlson (1952) include better detail of the drift on their geologic map.

In the uplands of north-central Jefferson County the Nortonville Clay covers the glacial deposits. The Nortonville is a silty clay (which locally has a few pebbles and layers of silty sand) and is 0–70 ft (0–21 m) thick (Winslow, 1972). The deposits may have formed in depressions on the till plain (Frye and Leonard, 1952). The designated type location (Thorp and O'Connor, 1966) is 3 mi (5 km) north of Jefferson County (NENENW sec. 12, T. 7 S., R. 18 E., in Atchison County).

Loess deposits in Jefferson County occur primarily over bedrock or glacial sediments in the uplands, and they are 0–20 ft (0–6 m) thick (Winslow, 1972). The deposits are thickest in the north and become thin and discontinuous toward the south. The material is predominantly silt with some clay and fine-grained sand. Most of the loess is Wisconsinan, but some is Illinoian (Winslow, 1972; Thorp and Bayne, 1966).

Dissected and weathered terraces of Kansan (pre-Illinoian), Illinoian, and Wisconsinan age occur locally in the Kansas and Delaware River valleys and generally are less than 50 ft (15 m) thick (Winslow, 1972). Davis and Carlson (1952) specifically mapped and described the Menoken ("Kansan") and Buck Creek (Illinoian) terraces along the Kansas River. The Menoken terrace, which is at least 80 ft (24 m) above the floodplain, includes silt, sand, and gravel and minor amounts of glacial till. The Buck Creek terrace is dominated by silt and sandy silt and has local lenses of coarser material (ranging up to fine gravel) in the basal part. The Buck Creek terrace, which is at least 35 ft (11 m) above the the Kansas River floodplain, has generally been removed by erosion except in tributary valleys. It was named for its well-developed surface along Buck Creek in sec. 27, T. 11 S., R. 19 E. A test hole in SWNW sec. 27 penetrated 90 ft (27 m) of silt and clay, and a well in SESENE sec. 28 showed bedrock at greater than 97 ft (30 m) deep.

The undissected Newman terrace was also named for its expression in Jefferson County, near the town of Newman. This terrace has been mapped and described by Winslow (1972) and Davis and Carlson (1952). Its surface is commonly 25–30 ft (7.6–9.1 m) above the Kansas River, and the sediments generally include 10–25 ft (3.0–7.6 m) of clay and silt grading downward into sand and gravel.

Kansas River alluvium consists of silt and fine- to medium-grained sand over coarse-grained sand and gravel (Davis and Carlson, 1952), but locally clay fills abandoned meanders. Alluvial deposits in the Delaware River valley are similar (perhaps with clay and silt at the surface), but material in the smaller tributaries is generally finer grained (Winslow, 1972). The total thickness of alluvial and Newman terrace deposits ranges from 0 to 90 ft (27 m), with the largest values in the Kansas River valley.

As can be seen from the geologic map by Davis and Carlson (1952), the floodplain of the Kansas River on the southern side of Jefferson County is generally 2–3 mi (3–5 km) wide. The width is greatest near the mouths of Buck Creek, the Delaware River, and Muddy Creek. The Kansas River itself generally flows along and cuts the southern side of its valley. Davis and Carlson (1952) believed that this results from the Wakarusa River intercepting most of the runoff south of the Kansas River and from the larger and more numerous tributaries to the north of the Kansas River, which provide more sediments and thus produce a delta effect that forces the river to the south. As Davis and Carlson observed, the Kansas River channel shifts north only opposite major north-flowing tributaries (e.g., the Shunganunga Creek at the Shawnee–Jefferson county border). Winslow (1972, p. 3) believed that the present drainage system in Jefferson County "generally has developed along courses coincident with those of a previous drainage system or systems." The Kansas River provides an interesting example. Terraces (e.g., the Menoken and Buck Creek) indicate several earlier episodes of cut and fill. Furthermore, Davis and Carlson (1952, p. 211) state: "North of the Kansas River valley the till-mantled bedrock surface has a slope of about 90 to 100 feet in a distance of from 1 to 2 miles toward the present axis of the valley. The proximity of the glacial margin suggests that this slope was not caused by glacial scour and that a valley existed here prior to Kansan time."

Although undoubtedly modified by glaciofluvial action, the Kansas River and the major northeastern Kansas buried valley (which trends west to east just a few miles north of Jefferson County) probably developed before the advance of ice. Tributaries to these systems in Jefferson County would then have flowed north to the buried valley and south to the Kansas River with a drainage divide between them. As glaciers covered and blocked the rivers, flow directions and paths would have changed. Ice margins also have strongly influenced drainage development, as discussed in other parts of this report.

The bedrock topographic map of Jefferson County (plate 1) was prepared using data from 509 drill holes and measured sections (Denne et al., 1990a) and Winslow's (1972) geologic map with surface topography shown by contours at 50-ft intervals. Where bedrock is at or near the land surface, the surface and bedrock topographic maps are equivalent.

Davis and Carlson (1952) cited evidence [including the position of the former Kansas River at least 15 ft (4.6 m) above the modern floodplain and the thickness of glacial drift to the north] that the topography in the area was more subdued than at present. If true, then the bedrock topographic map (plate 1) reflects this less-dissected surface (especially in the northeast) and not just areas of inadequate data where thick glacial deposits cover bedrock.

There are numerous buried valleys in Jefferson County, many of which are at least partly related to modern drainages. The most striking channel (with definitely nonsubdued topography) occurs in an area that was formerly mapped by Winslow (1972) as bedrock. This narrow buried valley between exposures of bedrock less than 0.5 mi (0.8 km) apart was discovered when a commercial driller put in wells on several 10-acre parcels of land that had been subdivided in connection with the development of Perry Lake (formed in 1970 when the Delaware River was dammed). Although shallow bedrock and low yields were found on most lots, more than 100 ft (30 m) of glaciofluvial sands and gravels were found on one lot (NWNENE sec. 3, T. 10 S., R. 17 E.). A rural water district subsequently drilled test holes and a well [which was test pumped at 500 gpm (0.0315 m^3/s)] close to the private well. Additional test drilling and geophysical investigations in the area (fig.40) by the Kansas Geological Survey (Denne et al., 1982, 1984) have shown that the channel is locally 500 ft (150 m) wide and up to 200 ft (60 m) deep (figs. 41 and 42) and extends northeast-southwest for at least 1.5 mi (2.4 km) (from SWSWSW sec. 35, T. 9 S., R. 17 E., to SESENE sec. 9, T. 10 S., R. 17 E.).

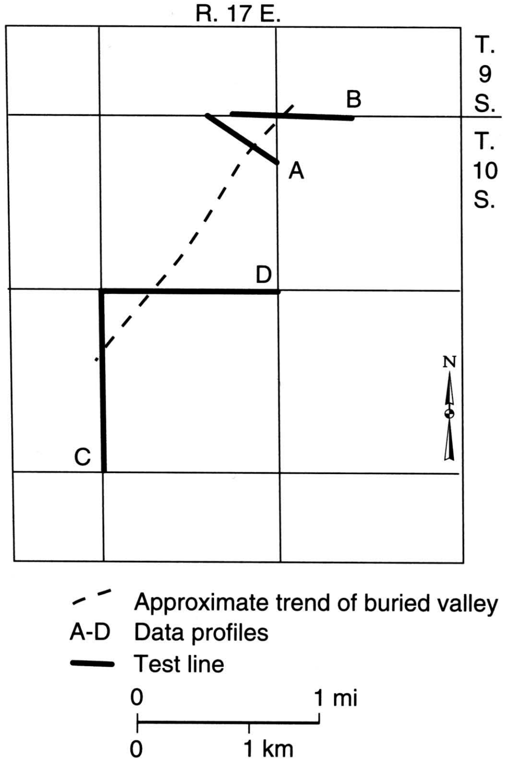

FIGURE 40—Sites of test drilling and geophysical investigations in the study area by Denne et al. (1982, 1984).

Contouring the short segment of this buried valley into the regional framework is extremely difficult. Not all contours for this buried valley are shown in plate 1 because the channel is extremely narrow and steep-walled. To the north the buried valley probably connects with the modern Delaware River system. It may extend as far as the tributary in NW sec. 25, T. 9 S., R. 17 E. Its peculiar entrance angle to the Delaware River suggests that previously the Delaware may have flowed north or the tributary may have flowed south. If the tributary flowed south, it may have flowed just west of the bedrock high [on which the town of (New) Ozawkie was constructed] toward the wide area of alluvial deposits in central sec. 36, T. 9 S., R. 17 E., and/or to the buried channel.

The observed elevation of the bedrock surface below the buried valley is as low as 783 ft (239 m) (SWNENE sec. 3, T. 10 S., R. 17 E.), and that value is comparable to the floor of the Delaware and Kansas River valleys as known more than 7 mi (11 km) to the south. A connection to the wide area of Rock Creek alluvium (SW sec. 16, T. 10 S., R. 17 E.) would fit the southwest trend of the buried valley, but information from test drilling in SESWNE sec. 16 was ambiguous at best. An auger hole at this site indicated sand and gravel from 25 ft to 112 ft (7.6–34.1 m) and a bedrock elevation of less than 833 ft (254 m), but mechanical difficulties make the validity of these data questionable. A rotary hole at this site and within a few feet of the auger hole showed bedrock at a depth of 39 ft (12 m) and an elevation of 906 ft (276 m).

The deep, narrow character of the channel and the coarse-grained material that fills it suggest that the valley was cut and buried quickly by water flowing at a high velocity and/or under a steep gradient, possibly along a preexisting zone of weakness. Field investigations on opposite sides of the buried valley near sec. 3, T. 10 S., R. 17 E., provided no evidence of faulting at the land surface, although a fault could exist at depth. Joints in the bedrock of northeastern Kansas are commonly oriented northeast or northwest (Frank W. Wilson, personal communication, 1986; DuBois, 1978), and the rock layers in Jefferson County strike northeast. Meltwater from an advancing or adjacent glacier could have followed such weak zones. Alternatively, the stream could have developed under high pressure below ice that covered the area.

Other important buried valleys are located in north-central and northeastern Jefferson County. The channel in T. 7 S., R. 19 E., trends northeastward into Atchison County, where it joins the main buried valley. Several public water supplies (e.g., Nortonville and Jefferson County Rural Water District 12 in secs. 29 and 32, T. 7 S., R. 19 E.) obtain up to 600 gpm (0.04 m^3/s) of water from the sand and gravel in the channel. The buried valleys seem to go around a bedrock high in the southwestern corner of T. 7 S., R. 19 E. In this area it also appears that the channels connect southwestward to modern drainages (e.g., Walnut, Brush, and Rock creeks). Perhaps the flow directions changed as the ice advanced and blocked the northern drainageways. Because of limited data and the apparent interrelations of old and modern drainage, the orientations of the buried valleys are difficult to determine.

Upstream from Valley Falls (NE sec. 24, T. 8 S., R. 17 E.), the alluvial deposits of the Delaware River widen from 0.5 mi to 2.5 mi (0.8–4.0 km). The tributary Cedar Creek valley is also wide [0.5–1 mi (0.8–1.6 km)]. In this area the two streams cross the Scranton Shale and the Howard Limestone and locally the Severy Shale and the Topeka Limestone [map units of Winslow (1972)]. Although the bedrock may be at least partly responsible for the increased upstream valley widths, earlier drainage also may have influenced the size and orientation. The Delaware River and Cedar Creek together with either the North Cedar Creek or the South Cedar Creek form a lobate shape that may reflect ice-marginal drainage. Drill holes in NENENW sec. 1, T. 8 S., R. 16 E.; NWNESW sec. 6, T. 8 S., R. 17 E.; SESWNW sec. 12, T. 8 S., R. 16 E.; and NWSWSE sec. 19, T. 8 S., R. 17 E., show relatively deep bedrock overlain by a thick basal gravel that probably was not deposited by the modern streams. Extensive terraces in the Delaware River and Cedar Creek valleys also represent earlier drainage.

The wide valleys of Peter and Walnut creeks overlie the same bedrock units as do those of the Delaware River and Cedar Creek. Peter Creek valley (west of

Valley Falls) also contains a large terrace and enters the Delaware River valley at a peculiar angle (similar to that for the tributary northwest of Ozawkie) for its flow direction. Perhaps Peter Creek formerly flowed south toward Duck Creek, possibly through SWSWSE sec. 3, T. 8 S., R. 17 E., an area mapped as bedrock but where an 80-ft-deep (24-m-deep) well described by Winslow (1972) obtained water from glacial drift. Alternatively, the Delaware River and Peter Creek may have flowed northward to the major buried valley in Atchison County, whereas Walnut Creek and the Delaware River below Valley Falls may have flowed southward to the Kansas River. It is interesting to note that between Valley Falls and Ozawkie, the Delaware River includes several horseshoe meanders. In this region the river cuts the Calhoun Shale and the Deer Creek Limestone, and the bedrock may be largely responsible for the meanders. However, the bends may indicate an older segment of the river or may be a result of a change in discharge, such as would occur if ice blocked the upstream drainage and large amounts of meltwater flowed south.

Several isolated locations in Jefferson County suggest the possibility of additional deep, narrow buried channels similar to the one in T. 10 S., R. 17 E. A drill hole for oil in SWSESW sec. 16, T. 9 S., R. 17 E. (a low area between two bedrock highs), showed sand and gravel at a depth of 60–70 ft (18–21 m). The channel deposits may connect to the southeast with the modern French Creek or to the west with Rock and Tick creeks (which together form a lobate shape). Another drill hole for oil (NWSESE sec. 29, T. 8 S., R. 17 E.) had sand from 54 ft to 75 ft (16–23 m); if this material is not sandstone, then it may be a buried channel deposit connected to the Cedar Creek system. A water well in NESWNE sec. 13, T. 11 S., R. 17 E., indicates a buried valley in an area mapped by Winslow (1972) as bedrock, slightly east of a short [1.5 mi (2.4 km) long], wide [0.25 mi (0.4 km)] modern tributary to the Kansas River. In the southeastern part of the county other seemingly isolated sites (e.g., NENE sec. 3, NENE sec. 12, and SENESE sec. 18, T. 10 S., R. 19 E.; SESENW sec. 19, T. 10 S., R. 20 E.; and NESE sec. 14, T. 9 S., R. 19 E.)

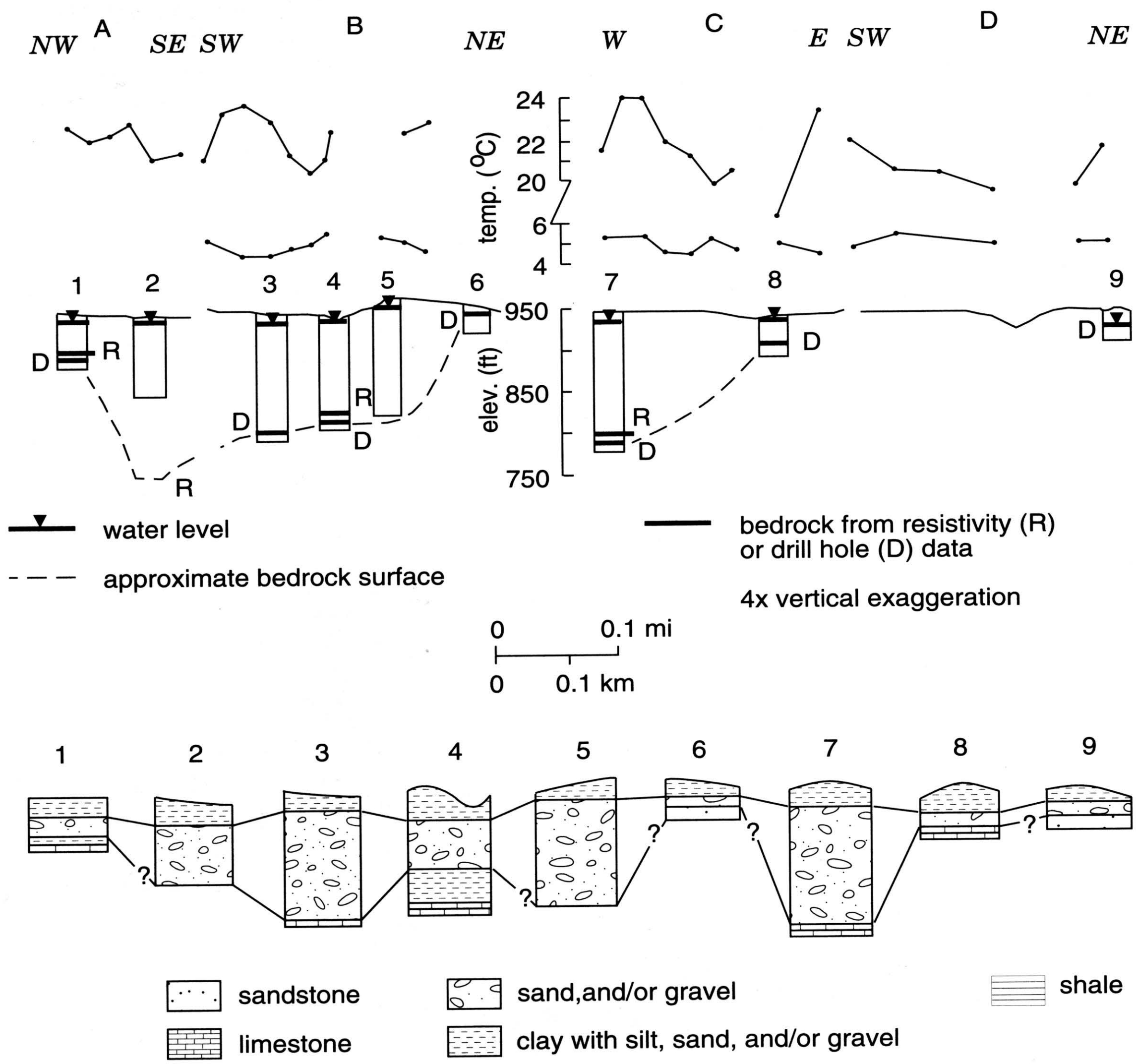

FIGURE 41—Data profiles A, B, C, and D for Jefferson County test lines. Number above profile indicates test site. Highest temperatures measured in August 1980; lower temperatures measured in March 1980.

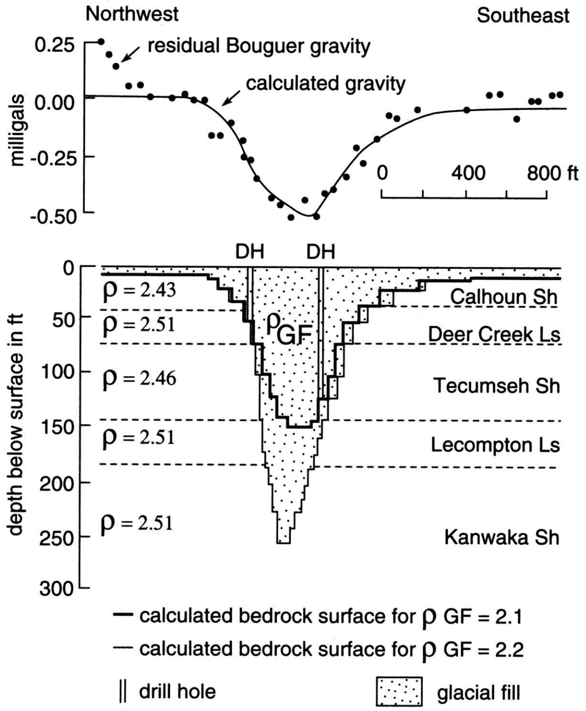

FIGURE 42—Calculated fill and surface of buried valley.

indicate buried drainages that may be at least marginally related to modern streams. In any case, it is difficult to determine whether the general flow direction was northward or southward. In T. 9 S., R. 20 E., numerous drill holes from oil and gas field development near McLouth indicate a north-trending buried valley that appears to underlie the upstream portion of the modern Fall Creek and then cross the divide to follow Prairie Creek. With additional drilling in Jefferson County, many other buried valleys will undoubtedly be located and the orientations of others will become more evident.

The depth to bedrock in Jefferson County (fig. 43) is greatest in two of the buried valleys, where values range up to 179 ft (54.6 m) (SENWNW sec. 29, T. 7 S., R. 19 E.) in the north-central channel and 175 ft (53.3 m) (SESENE sec. 9, T. 10 S., R. 17 E.) in the valley west of Perry Lake. Other great depths to bedrock, several in excess of 100 ft (30 m), occur in the smaller buried valleys (e.g., NENE sec. 12 and SENESE sec. 18, T. 10 S., R. 19 E.; NENW sec. 8, T. 10 S., R. 20 E.; NWNW sec. 29, T. 9 S., R. 20 E.; and NESE sec. 14, T. 9 S., R. 19 E.). Typically, however, the glacial deposits throughout the county are between 15 ft (4.6 m) and 65 ft (20 m) thick (which equals the depth to bedrock).

The alluvium that fills many stream valleys in Jefferson County contains glaciofluvial deposits at

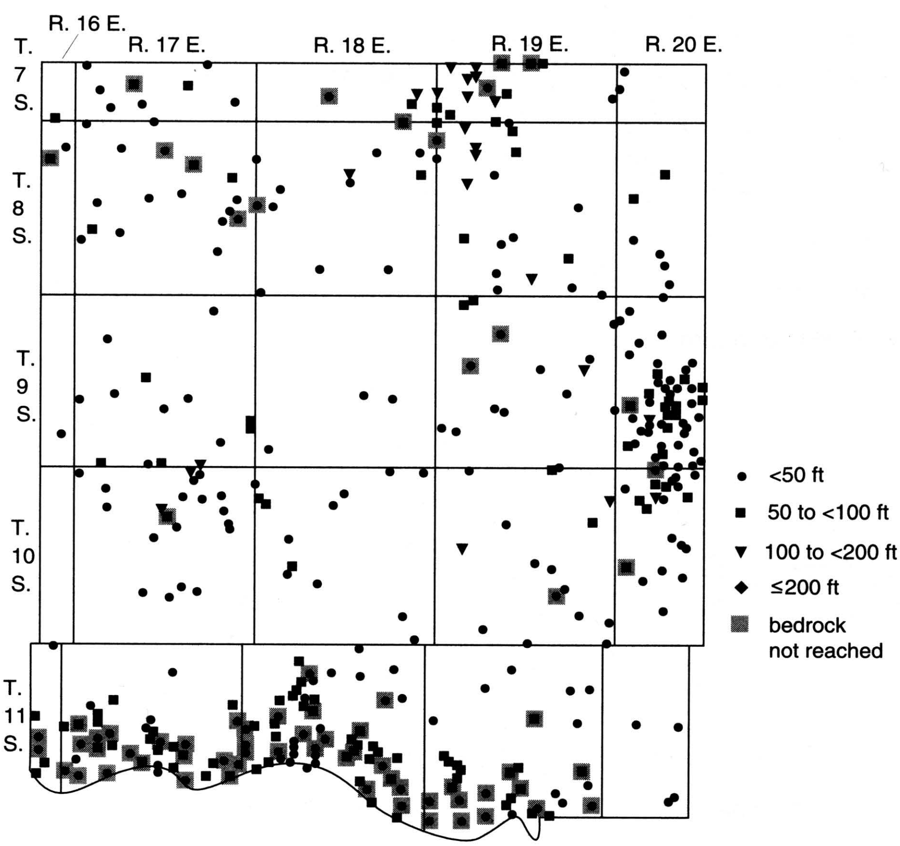

FIGURE 43—Depth to bedrock, Jefferson County.

depth. However, considering both units as one, these deposits range up to 97 ft (30 m) thick (SESENE sec. 28, T. 11 S., R. 19 E.). In the Kansas River valley, many drill holes do not reach bedrock, but most of the alluvial deposits (as indicated by 90% of the data points) are between 40 ft (12 m) and 80 ft (24 m) thick. The greatest values [over 80 ft (24 m)] occur near the junctions with Little Muddy Creek, the Delaware River, and Buck Creek. Perhaps these drainages carried the major portion of the glacial meltwater with associated sediments. Deposits in the upper reaches of Buck Creek are as thin as 23 ft (7.0 m), whereas they are as thick as 97 ft (30 m) in the Buck Creek terrace at the junction with the Kansas River valley. Upstream from the Kansas River, alluvium in the Delaware River valley most commonly ranges from 35 ft to 55 ft (11–17 m) in thickness. Alluvial deposits along other tributaries in Jefferson County are generally between 15 ft (4.6 m) and 50 ft (15 m) thick.

Bedrock is at or near the land surface, especially in western and southern Jefferson County and along the major streams. Locally, thin [generally less than 20 ft (6 m)] colluvium, residuum, or loess deposits overlie shallow bedrock.

The total thickness of sand and gravel in Jefferson County (fig. 44) ranges from 0 to 141 ft (43.0 m). The values are greatest [commonly more than 90 ft (27 m)] in the deep, narrow buried channel west of Perry Lake, where the maximum value occurs in SWNENE sec. 3, T. 10 S., R. 17 E. The fill of this channel is dominated by coarse-grained sand and gravel. Other significant thicknesses [commonly more than 20 ft (6 m)] of sand and/or gravel occur in the buried-valley system in the north-central part of the county, where at least 73 ft (22 m) of sand was reported in an 87-ft (27-m) drill hole that did not reach bedrock in NWNWNW sec. 27, T. 7 S., R. 19 E., and where 67 ft (20 m) of sand and gravel was encountered in the lower part of a well in SENWNW sec. 29, T. 7 S., R. 19 E. In a buried channel that appears to trend southward but could instead be connected to the north-central channel, an oil-well log for SESWNW sec. 34, T. 8 S., R. 19 E., indicates 62 ft (19 m) of sand overlying bedrock at 134 ft (40.8 m). In T. 9 and 10 S., R. 20 E., 5–20-ft (2–6-m) thicknesses of sand and gravel are common in the small buried valleys, although thicknesses range up to 42 ft (13 m) in SWSE sec. 20, T. 9 S., R. 20 E. The buried tributary to the Kansas River in NESWNE sec. 13, T. 11 S., R. 17 E., has a total thickness of 52 ft (16 m) of sand and gravel with fine-grained sand from 30 ft to 65 ft (9–20 m) deep and a 17-ft (5.2-m) basal sand and gravel layer to a depth of 88 ft (27 m). Other buried valleys, as previously described, typically have 5–25 ft (2–7.6 m) of sand and gravel deposits.

In the Kansas River valley, sand and gravel thicknesses range from 0 to 77 ft (23 m). The smaller values are commonly associated with the Newman and Buck Creek terraces. The larger values [greater than 40 ft (12 m)] occur primarily near the Kansas River junctions

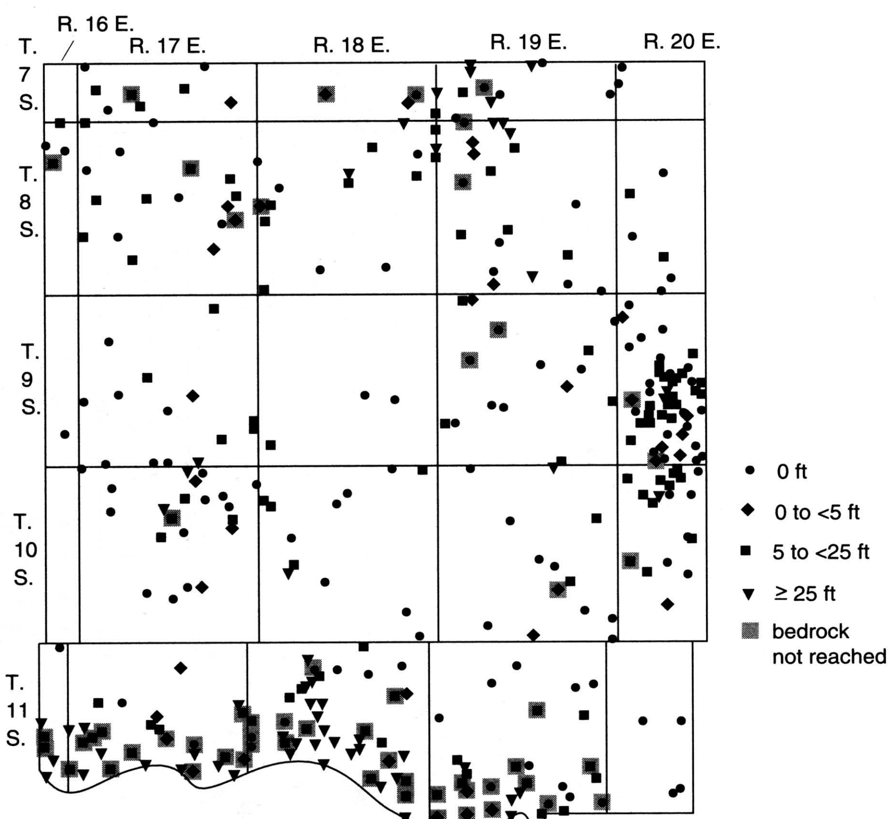

FIGURE 44—Total Pleistocene sand and gravel thickness, Jefferson County.

with Little Muddy Creek, the Delaware River, Little Wild Horse Creek, and Stone House Creek and along the southern side of the Kansas River valley (especially where tributaries such as Shunganunga Creek enter from the south).

The Delaware River valley contains sand and gravel layers that are 0–57 ft (0–17 m) thick, with the largest values occurring near the Kansas River valley junction. Upstream along the Delaware, the sand and gravel deposits range in thickness up to 25 ft (7.6 m). It appears that the greater sand and gravel thicknesses occur upstream from Valley Falls and downstream from Ozawkie, although this observation may be due to the distribution of data (which is influenced largely by Perry Lake).

Other tributaries in Jefferson County generally have 0–10 ft (0–3 m) of sand and gravel, although larger values occur where recent valleys apparently overlie buried drainages (e.g., in SESWNW sec. 12, T. 8 S., R. 16 E., and in SWSWSW sec. 35, T. 9 S., R. 19 E.). Values of 10 ft (3 m) can be found in the valleys of Plum Creek, Mud Creek, Buck Creek, and Little Wild Horse Creek. Near the junction of Muddy Creek and the Kansas River valley (SENENE sec. 18, T. 11 S., R. 17 E.), 17 ft (5.2 m) of coarse-grained sand and gravel overlie bedrock. These small tributaries must have been close to the ice margin, with its supply of coarse-grained sediments, and/or carried water of large volume or at high velocity.

Ground Water

Bedrock is generally not a good water source in Jefferson County; it commonly yields a few gallons per hour or less (Winslow, 1972). Locally, however, small quantities of water may be obtained from the upper weathered zones (especially of limestones), from sandy layers (e.g., in the Auburn, Scranton, Severy, Calhoun, Tecumseh, or Kanwaka Shales and the Lawrence Formation), or from the Howard Limestone. Many wells inventoried by Winslow (1972) were large-diameter dug wells that obtain water slowly from the weathered bedrock (or glacial till) and provide storage space. Many bedrock wells in the area reportedly obtain brackish water at depths of less than 150 ft (46 m) (Davis and Carlson, 1952).

Estimated yields (uncorrected for well construction and other variables) are shown in fig.45. The largest values are from the Kansas River valley, where yields of 2,000 gpm (0.1 m^3/s) have been reported at the junction with the Delaware River (NENWSW sec. 16, T. 11 S., R. 18 E.). Values in the range 1,322–1,350 gpm (0.08340–0.08516 m^3/s) have been obtained near the junction with Muddy Creek, which is also near the mouth of Shunganunga Creek (e.g., SESWSW sec. 17, SWNWSE sec. 20, and SENWNW sec. 20, T. 11 S., R. 17 E.). In these same general areas, eight other wells provide 1,000–1,300 gpm (0.06–0.082 m^3/s). In contrast

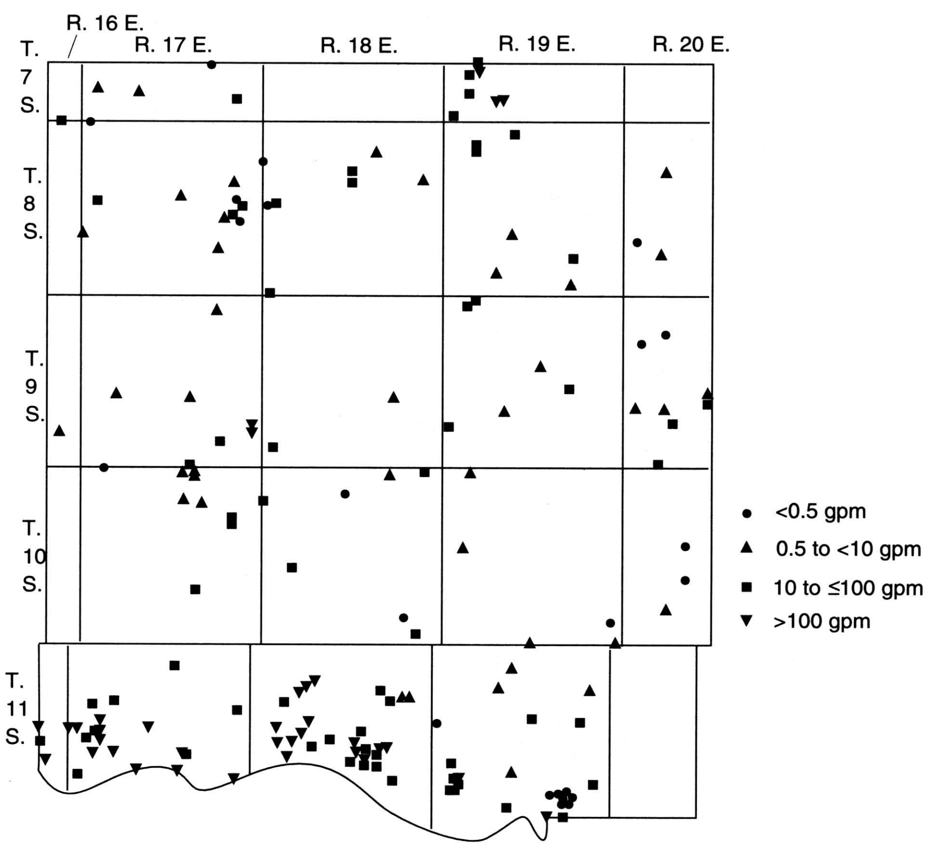

FIGURE 45—Estimated well yields, Jefferson County.

to these large values, more than half (31) of the 59 reported well yields from the Kansas River valley are between only 7 gpm (0.0004 m^3/s) and 60 gpm (0.004 m^3/s). These wells probably have small diameters, do not penetrate deep enough to reach the basal gravel, and/or are located in an area with only fine-grained material (e.g., abandoned meanders or some terraces). Between the low and high extremes, eight wells had yields between 100 gpm (0.006 m^3/s) and 300 gpm (0.02 m^3/s) and eight others were between 500 gpm (0.03 m^3/s) and 940 gpm (0.059 m^3/s).

Yields have been reported for 18 wells in the Delaware River valley. The six largest values [100–300 gpm (0.006–0.02 m^3/s)] occur near the junction with the Kansas River valley and near the town of Ozawkie. Ten other wells provide 8–60 gpm (0.0005–0.004 m^3/s), with values of 8–40 gpm (0.0005–0.003 m^3/s) reported at and above Valley Falls and 15–60 gpm (0.00095–0.004 m^3/s) downstream from Ozawkie. Two drill holes in NENWSW sec. 13, T. 8 S., R. 17 E., and SWSWSW sec. 18, T. 8 S., R. 18 E., were reportedly dry; the first had thin, fine-grained alluvial deposits on an apparent bedrock high, and the second may not have reached bedrock below fine-grained sand at 25–27 ft (7.6–8.2 m). Poor road access and the presence of Perry Lake are not the only reasons for the lack of well yield and other data between Valley Falls and Ozawkie; the narrow alluvial aquifer in this area may not be particularly productive.

Other tributaries in Jefferson County generally yield 0–20 gpm (0–0.001 m^3/s). One exception is in SWNWNE sec. 1, T. 10 S., R. 18 E., in Slough Creek, where 50 gpm (0.003 m^3/s) is reported for a well with 7 ft (2 m) of basal gravel. The yield and thickness of gravel here tend to support the connection of Slough Creek to the buried channel deposits to the northeast (e.g., in NENWSW sec. 30, T. 9 S., R. 19 E., and in SESWNW sec. 34, T. 8 S., R. 19 E.). Well yields of 10–20 gpm (0.0006–0.001 m^3/s) are fairly common from several tributaries that drain directly into the Kansas River valley, including Mud, Buck, Little Wild Horse, Prairie, and Muddy creeks. A drill hole in SWNWNW sec. 26, T. 10 S., R. 17 E., suggested a yield of 15 gpm (0.00095 m^3/s) from Rock Creek alluvium, and other Delaware River tributaries (e.g., Coal and Cedar creeks) may yield 10 gpm (0.0006 m^3/s). Deposits along the smaller streams in the county commonly yield less than 5 gpm (0.0003 m^3/s), with some deposits yielding less than 1 gpm (0.00006 m^3/s).

In addition to alluvium, glaciofluvial deposits also provide a significant quantity of water in Jefferson County. The buried valley in the north-central part of the county may yield at least 300–600 gpm (0.02–0.04 m^3/s) (e.g., NWSENE sec. 32, NESENE sec. 32, and SENWNW sec. 29, T. 7 S., R. 19 E.), but more typical values are in the range of 10–60 gpm (0.0006–0.004 m^3/s). Although the driller reported an estimated 400-gpm

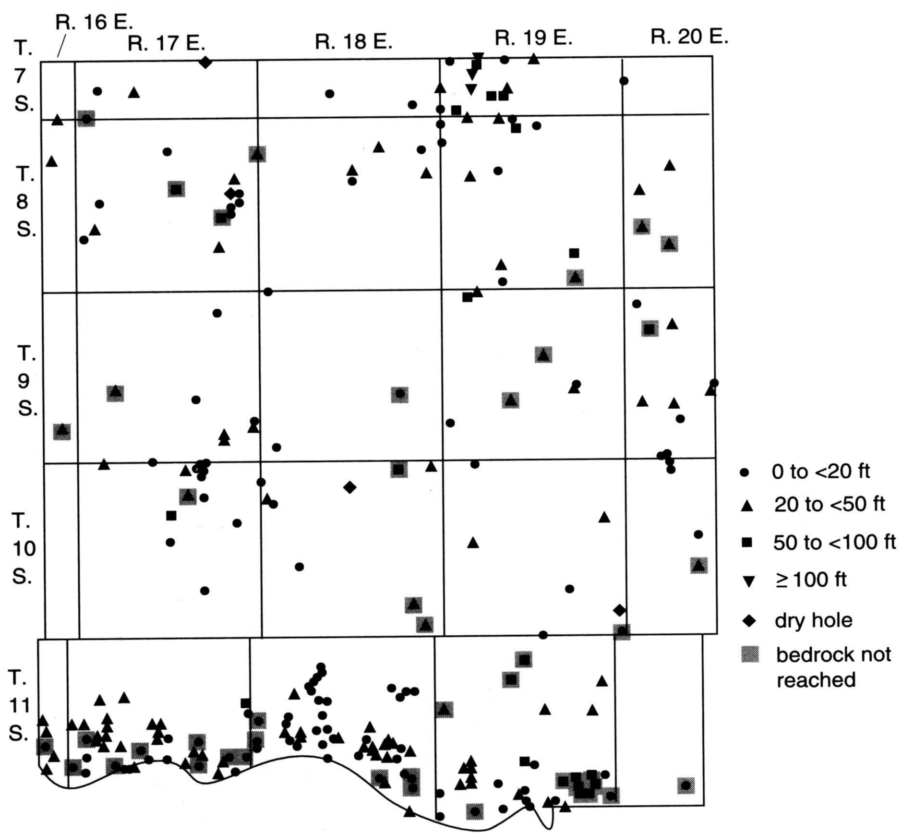

FIGURE 46—Depth to water in wells and test wells, Jefferson County.

(0.03-m^3/s) yield, the rural water district well (SWNENE sec. 3, T. 10 S., R. 17 E.) in the deep, narrow buried valley west of Perry Lake was test pumped at 500 gpm (0.032 m^3/s) for 25 hours. The water level in the well declined from 2 ft (0.6 m) to 40 ft (12 m), with stabilization occurring only after 8 hours. Other wells in the area that obtain water from the buried-channel deposits reportedly yield 20–100 gpm (0.001–0.006 m^3/s). A well either in the buried valley near McLouth or in sandstone bedrock produces 60 gpm (0.004 m^3/s). Other small buried valleys in Jefferson County, as previously described, yield 10–25 gpm (0.0006–0.0016 m^3/s). In other areas where glacial deposits are sufficiently thick, especially where they contain sand and gravel lenses, yields of up to several gallons per minute of water can be obtained.

Although most bedrock units provide little [<1 gpm (<0.00006 m^3/s)] or no water in Jefferson County, there are several wells that reportedly yield 2–10 gpm (0.0001–0.0006 m^3/s) from rock (e.g., in SWNESW sec. 36, T. 10 S., R. 18 E.; SWSESE sec. 36, T. 10 S., R. 19 E.; NESESE sec. 4, T. 11 S., R. 19 E.; and SWSENE sec. 23, T. 8 S., R. 17 E.). These wells generally obtain water from "loose" limestone (in drillers' terms), sandstone, and/or shale in the Shawnee Group.

Because of the generally discontinuous character of the water table, the presence of multiple aquifers, the methods of well construction that connect the aquifers, and water-level measurements made at different times by different people, available ground-water-level data are of limited usefulness. Ground-water elevations in Jefferson County suggest that ground-water flow is from the uplands toward the major streams and in the downstream direction in the Delaware and Kansas River valleys. The average hydraulic gradient along the Kansas River valley in the southern part of the county is 2 ft/mi (0.4 m/km). Locally, depressions in ground-water-level elevations may reflect heavy pumpage. Although it is difficult to determine flow directions in and near the major buried valleys, it appears that water moves from the west toward the narrow, deep channel in T. 10 S., R. 17 E., and from a high area in T. 8 S., R. 19 E., toward the north-central channel in T. 7 S., R. 18 and 19 E., and T. 8 S., R. 18 E.

The depth to water in Jefferson County (fig. 46) ranges from 1 ft to 109 ft (0.3–33.2 m). In the Kansas River valley, 90% of the water-level measurements are between 10 ft (3 m) and 32 ft (9.8 m) in depth. A few other values ranged as shallow as 3 ft (0.9 m) and as high as 47 ft (14 m). In the Delaware River valley, about one-half of the depth to water values are between 10 ft (3 m) and 20 ft (6 m). Several drill holes in thin alluvial deposits near Valley Falls are dry. The maximum depths to water [46 ft and 47 ft (14 m)] are reported upstream from Valley Falls in NENWNW sec. 13, T. 8 S., R. 17 E. Values as small as 2 ft (0.6 m) have been measured

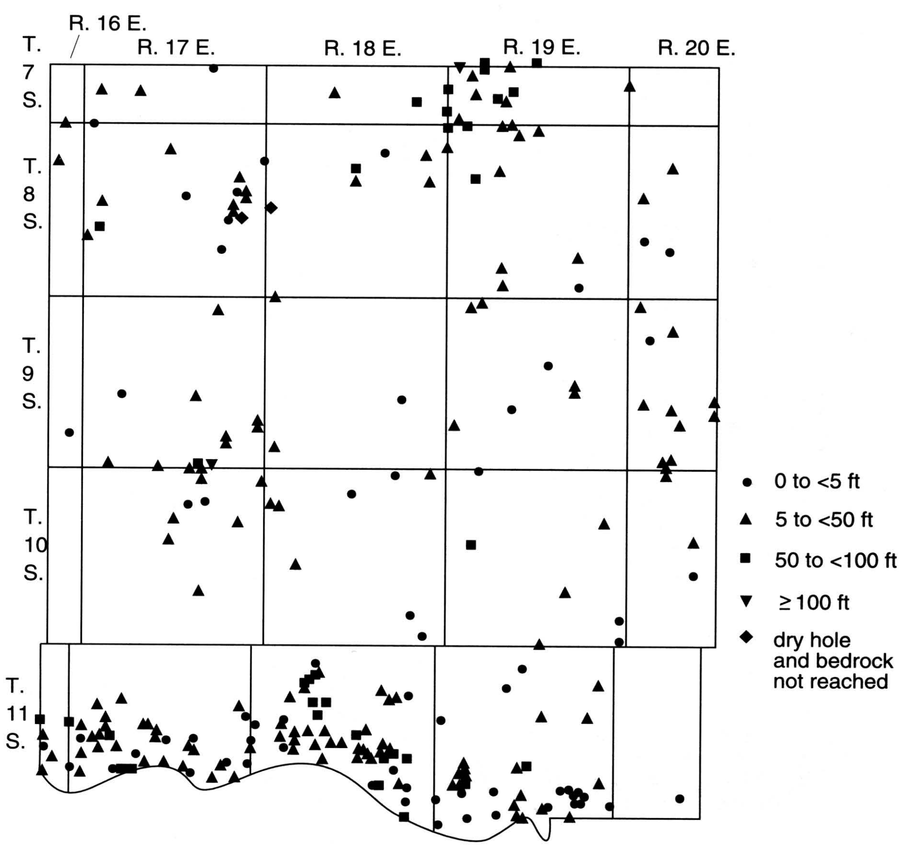

FIGURE 47—SATURATED THICKNESS OF PLEISTOCENE DEPOSITS, JEFFERSON COUNTY.

near the junction of the Delaware and Kansas River valleys. In other Jefferson County stream valleys where the alluvium is saturated, ground water is generally between l ft (0.3 m) and 25 ft (7.6 m) deep, with all other reported values less than 36 ft (11 m), except for one 68-ft (21-m) value in the Buck Creek terrace (SESENE sec. 28, T. 11 S., R. 19 E).

In the glacial deposits, water-level measurements show greater variation. In the north-central buried valley the maximum water-level depth [109 ft (33.2 m)] for the county occurs in SESENE sec. 30 and NENENE sec. 31, T. 7 S., R. 19 E., whereas the second and fourth largest depths [106 ft (32.3 m) and 86 ft (26 m)] occur nearby in sec. 29. In contrast, the depth to water in test holes in NWNENW sec. 30, T. 7 S., R. 19 E., and SWSWNW sec. 36, T. 7 S., R. 18 E., is 3 ft (0.9 m). In the deep, narrow buried valley west of Perry Lake, the ground water is shallow, with values typically between 2 ft (0.6 m) and 12 ft (3.7 m). Elsewhere in the county, the depth to water in the glacial deposits is generally less than 50 ft (15 m) and most commonly less than 30 ft (9 m).

The third largest depth to water [95 ft (29 m)] in Jefferson County is from a landfill sampling or monitoring well completed in bedrock (probably the Oread Limestone and Lawrence Formation) in NENENW sec. 35, T. 11 S., R. 19 E. Several other sampling wells in the same section had water levels between 60 ft (18 m) and 84 ft (26 m) deep. Each of these wells has a reported yield of 0 gpm, and the reported water level is equal to the total depth of the well. In other areas of the county, bedrock water-level depths range from 10 ft to 78 ft (3–24 m), but most commonly they are less than 31 ft (9.4 m). It should be noted again, however, that many wells drilled into bedrock in the county yield no ground water and are considered dry.

The saturated thickness of unconsolidated deposits in Jefferson County (fig. 47) is greatest in the two major buried valleys [164 ft (50.0 m) in NWNENW sec. 30, T. 7 S., R. 19 E., and 148 ft (45.1 m) in SWNENE sec. 3, T. 10 S., R. 17 E.]. Values between 30 ft (9 m) and 80 ft (24 m) are common in the north-central buried-valley system, whereas saturated thicknesses greater than 90 ft (27 m) occur frequently in the deep, narrow channel west of Perry Lake. In the buried valleys near McLouth (especially in T. 9 S., R. 20 E.), saturated unconsolidated deposits range from 15 ft to 45 ft (4.6–14 m) in thickness. In SENESE sec. 18, T. 10 S., R. 19 E., the saturated thickness is at least 76 ft (23 m). Elsewhere in the county the saturated thickness of glacial deposits generally is 0–45 ft (0–14 m). More than a dozen drill holes for which the depth to bedrock is up to 30 ft (9 m) have no free water in the unconsolidated sediments. As O'Connor et al. (1979) observed, glacial deposits in the upland areas are often highly dissected by erosion and may be at least partly drained of their water. The larger saturated thicknesses generally occur in buried drainages, some of which underlie recent streams.

In the Kansas River valley at least 80% of the saturated thickness values for the alluvial deposits are between 25 ft (7.6 m) and 65 ft (20 m). The largest thicknesses [e.g., 50–76 ft (15–23 m)] occur near the junction of the Kansas River with the Delaware River and close to the mouths of Little Muddy Creek and Little Wild Horse Creek. The Buck Creek terrace has up

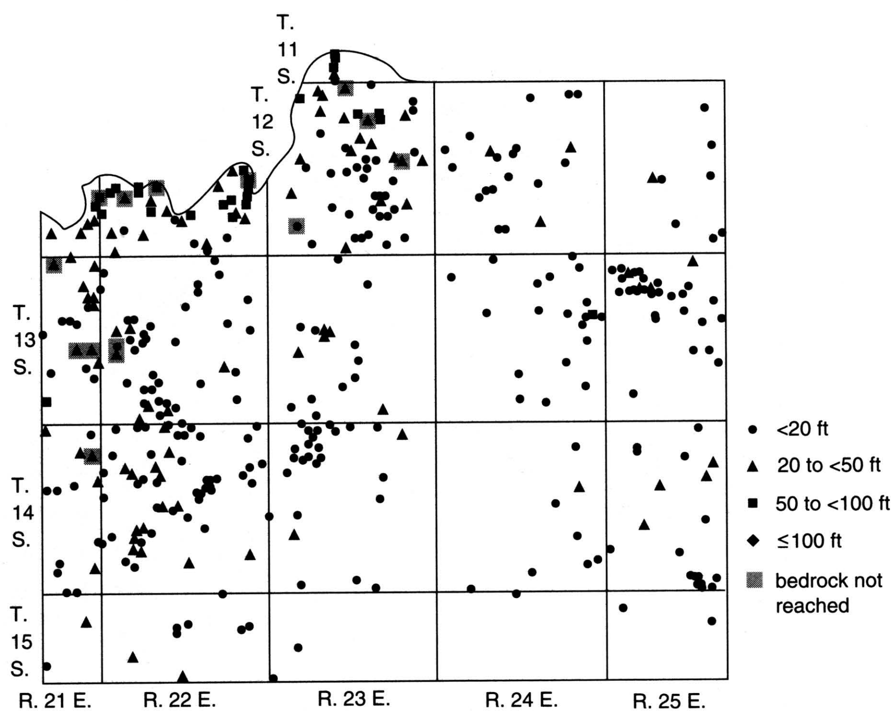

FIGURE 48—Depth to bedrock, Johnson County.

to 74 ft (23 m) of saturated unconsolidated deposits (SWNW sec. 27, T. 11 S., R. 19 E.). In the Delaware River valley, saturated alluvial deposits are 0–64 ft (0–20 m) thick, with the largest thicknesses occurring near the junction with the Kansas River valley. From Ozawkie to 6 mi (10 km) downstream, the saturated thickness is commonly between 15 ft (4.6 m) and 45 ft (14 m). Near Valley Falls several drill holes encountered no saturated unconsolidated deposits that would yield free water, but further upstream values ranged to 37 ft (11 m) (NWNESW sec. 13, T. 8 S., R. 17 E.). The saturated thickness of alluvial deposits along other streams in Jefferson County is most commonly less than 25 ft (7.6 m). Several larger thicknesses occur along Mud, Rock, and Buck creeks and in areas where modern streams are underlain by buried valleys (e.g., NENENW sec. 1 and SESWNW sec. 12, T. 8 S., R. 16 E.).

In Jefferson County most ground-water discharge is to streams, wells, and evapotranspiration. Recharge is primarily from precipitation, but it may also be from Perry Lake and from the major rivers during floods or induced by pumping. Within the county a large amount of water can be obtained from Perry reservoir and the Kansas River and from the alluvial deposits along modern drainageways and in buried valleys.

Johnson County

Geology

Bedrock is exposed throughout much of Johnson County, and the units include formations of the Kansas City, Lansing, and Douglas Groups of Pennsylvanian age (O'Connor, 1971). Shales, limestones, and some sandstone are included in the total outcrop sequence, which is 500 ft (150 m) thick (fig. 5). The oldest units (the Swope and Dennis Limestones) are exposed in the eastern part of the county, and the youngest unit (the Ireland Sandstone Member of the Lawrence Formation) is in the southwest. The average dip of the rocks is northwestward at 12 ft/mi (2.3 m/km) in this area of the Prairie Plains homocline. Locally the dip is modified by the northeast-trending Gardner anticline, the parallel depression to its east, and several faults, as mapped and described by O'Connor (1971). An upland gravel deposit in NWSE sec. 30, T. 14 S., R. 23 E., consists of quartz, quartzite, chert, and sandstone and was considered a possible remnant of the Dakota Formation (?) (Cretaceous) by O'Connor (1971).

The oldest Quaternary deposits in Johnson County (fig. 9) are pre-Illinoian and include the Atchison Formation (outwash), at least one glacial till, and undifferentiated fluvial and lacustrine deposits. These

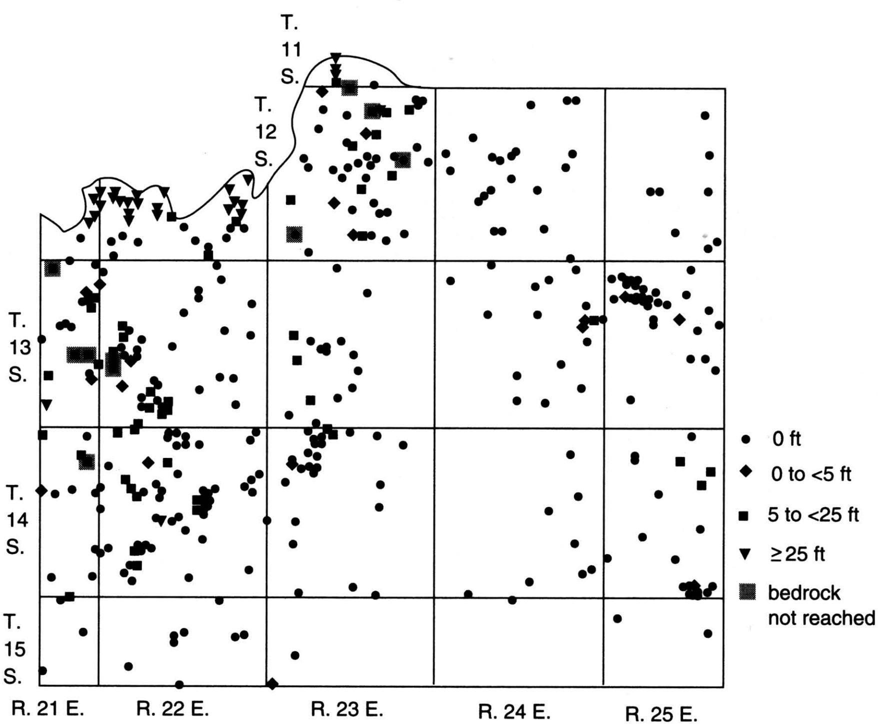

FIGURE 49—Total Pleistocene sand and gravel thickness, Johnson County.

sediments and their depositional environments have been described by O'Connor (1971), and we give a brief summary in what follows.

A glacial lobe crossed the Kansas River valley and extended southward for 10 mi (16 km) in northeastern Douglas and northwestern Johnson counties. Meltwater from the ice deposited sand and gravel in low areas and on the uplands south of the river [which are 150–200 ft (45–60 m) higher]. Outwash gravel that caps hills in Douglas County has been interpreted to represent deposits made along or in contact with the ice at its maximum southern extent (O'Connor, 1960), and these gravel-capped hills trend northeastward into Johnson County in secs. 26 and 35, T. 13 S., R. 21 E., and sec. 2, T. 14 S., R. 21 E. (O'Connor, 1971). The northwestern part of Johnson County (especially west of Kill Creek) contains much outwash material in addition to sandy till. Some sand deposits may also be from lakes formed when ice blocked the Kansas River and its north-flowing tributaries. The total thickness of these deposits is commonly 30–60 ft (9–18 m) where they have not been removed by erosion.

Second to the northwestern part of Johnson County for extent of pre-Illinoian deposits is the Holliday area in T. 12 S., R. 23 E., as described by O'Connor (1971). Deposits include glacial till, outwash, and sandy silts that may be lacustrine. Buried valleys cross the area, including one that is interpreted to have been cut by an ice-marginal stream that formed when ice blocked the Kansas River valley in secs. 34 and 35, T. 11 S., R. 23 E. An exposure in SESW sec. 16, T. 12 S., R. 23 E., shows cobble and boulder gravel filling a narrow channel on a hill. In the gravel pit in sec. 11, T. 12 S., R. 23 E., steeply dipping beds of pebble, cobble, and boulder gravel overlie flat layers of sand and gravel, and some zones are cemented with calcium carbonate. A 71-ft (22-m) measured section of sand and gravel from NE sec. 11 at this pit has been described by Newell (1935).

Illinoian deposits in Johnson County include alluvium in the Buck Creek terrace along tributaries of the Kansas River and the Loveland loess (O'Connor, 1971). The Buck Creek terrace is 25 ft (7.6 m) above the younger Newman terrace in the area of sec. 25, T. 12 S., R. 22 E., and includes sand and gravel overlain by locally sandy clay and silt. The silty loess deposits are generally less than 8 ft (2 m) thick and occur on some uplands near the Kansas River and in northeastern Johnson County.

The youngest deposits (Wisconsin and Holocene) also include alluvium and loess and have been described by O'Connor (1971). The Peoria loess is thickest [up to 15 ft (4.6 m)] in the northeastern part of the county, but it is commonly 2–6 ft (0.6–2 m) thick on uplands throughout the area. The Newman terrace occurs in the Kansas River tributaries as deposits of silt and clay overlying sand, gravel, and silt up to 70 ft (21 m) thick. Alluvial deposits in the Kansas River and its tributaries are 3–20 ft (0.9–6 m) below the Newman terrace, and they are generally coarse grained. Very fine grained to medium-grained sand with some thin lenses of silt and clay overlies medium-grained sand to gravel which is above a basal layer of gravel to boulders. The floodplains of the Kansas River and the main tributary streams (of the Kansas, Missouri, and Marais des Cygnes rivers) are 1–2 mi (1.6–3 km) wide and 0.2–0.5 mi (0.3–0.8 km) wide, respectively.

A bedrock topographic map of Johnson County (plate 1) was constructed using data from 401 drill holes (Denne et al., 1990a) and O'Connor's (1971) geologic map (surface topography contours at 50-ft intervals). Because bedrock is exposed in much of the area, the bedrock topography is similar to that of the present surface, with the exceptions of modern stream valleys, the northwestern part of the county, and the area near Holliday.

As previously discussed, buried valleys are evident in exposures in T. 12 S., R. 23 E. The bedrock map and drill-hole data suggest that a now-buried channel to the south of the bedrock knob at the border between T. 11 S., R. 23 E., and T. 12 S., R. 23 E., may have connected the Kansas River valley to the mouth of Mill Creek. In any case, a broad buried drainage is indicated to the north of Clear Creek. The area west of Kill Creek (portions of T. 12–14 S., R. 21 and 22 E.) is part of the Hesper plain area of Douglas County, which has a gentle northward slope to the Kansas River. A test hole in SESWSW sec. 26, T. 13 S., R. 21 E. (almost directly south of Captain Creek in Douglas County and west of its curve into Johnson County), showed the best buried-channel deposits in this area on the western edge of Johnson County.

There is a severe constriction in the width of the alluvial deposits as mapped (O'Connor, 1971) along Indian Creek in NE sec. 12, T. 13 S., R. 24 E., an area near the beginning of exposures of the Chanute Shale and Drum Limestone. An oil log from 1 mi (1.6 km) upstream (SWNWNE sec. 13, T. 13 S., R. 24 E.) indicates sand and gravel from 44 ft (13 m) to bedrock at 50 ft (15 m), but site investigations do not support the presence of Pleistocene deposits on this slope.

To the east in Missouri, Turkey Creek valley (which heads toward the northeastern part of Johnson County, Kansas) is known to have as much as 242 ft (73.8 m) of Pleistocene (primarily pre-Illinoian outwash) deposits in an abandoned segment (O'Connor and Fowler, 1963). It is believed that the deep channel there formed when ice blocked the extension of the Kansas River (the modern Missouri River) in Missouri and meltwater drained into the Turkey Creek valley, where it eroded the resistant Kansas City Group limestones and shales and the softer underlying Pleasanton Group.

As might be expected for an area near the maximum limit of glaciation, the depth to bedrock in Johnson County (fig. 48) is generally much less than it is to the north. The maximum known depth is 76 ft (23 m), occurring in the Newman terrace at the mouth of Cedar Creek (NWNESE sec. 26, T. 12 S., R. 22 E.). Three other large values [63–65 ft (19–20 m)] have been found in the Kansas River valley alluvium nearby (NENWNW, NWNWNW, and SENWNW sec. 25, T. 12 S., R. 22 E.). The glaciofluvial deposits near Holliday may include the thickest in the county; they exceed 71 ft (22 m) at the exposure (NE sec. 11, T. 12 S., R. 23 E.) previously discussed, and the depth to bedrock in a well in SESESW sec. 3, T. 12 S., R. 23 E., is 65 ft (20 m).

In northwestern Johnson County and in the Holliday area, the depth to bedrock is commonly between 10 ft (3 m) and 50 ft (15 m). Alluvial deposits in the Kansas River valley range from 40 ft to 65 ft (12–20 m) in thickness. In the smaller valleys (tributaries of the Kansas, Missouri, and Marais de Cygnes rivers), the depth to bedrock may be as great as 76 ft (23 m), but it is generally less than 40 ft (12 m). Throughout most of the rest of the county, thin deposits of loess or colluvium overlie bedrock that is near the land surface.

The total thickness of sand and gravel in Johnson County (fig. 49) is greatest in the Kansas River valley alluvium. Values in SWNWSW and SENESE sec. 19, NENWNW sec. 25, NENESW sec. 20, and SESWNW sec. 21, T. 12 S., R. 22 E., range from 50 to 58 ft (15–18 m). The deposits generally include fine-grained sand near the surface and, with the exception of local intermediate layers of clay, become coarser with depth. The sand and gravel layers in the Kansas River valley may only be as thick as 15 ft (4.6 m), but they are more commonly greater than 30 ft (9 m) thick. In the smaller valleys of Johnson County sand and gravel generally make up less than 15 ft (4.6 m) and most frequently less than 8 ft (2 m) of the alluvial deposits. Relatively thick, coarse-grained deposits may be found locally in the Blue River, Cedar Creek, and Mill Creek valleys.

The sand and gravel layers in pre-Illinoian deposits in northwestern Johnson County generally total less than 15 ft (4.6 m), but the channel in SESWSW sec. 26, T. 13 S., R. 21 E., contains 45 ft (14 m). On the divide between Kill and Spoon creeks, several oil logs indicate up to 18 ft (5.5 m) of boulders (e.g., SENE sec. 32, T. 13 S., R. 22 E.); these boulders may represent weathered bedrock, moraine deposits, or narrow boulder-till-filled channels. Near Holliday, sand and gravel make up the entire 71-ft (22-m) measured section (as previously discussed), but the thickest sequence known from a drill hole in that area (NWNWNW sec. 11, T. 12 S., R. 23 E.) is only 25 ft (7.6 m).

Ground Water

The ground-water yields in Johnson County (uncorrected for well diameter and other variables, as previously described) are shown in fig. 50. Yields are largest in the Kansas River valley alluvium; the maximum value reported is 1,200 gpm (0.076 m^3/s) in SENWNW sec. 25, T. 12 S., R. 22 E., near the mouth of Cedar Creek. Other wells in the Kansas River valley generally yield at least 100 gpm (0.006 m^3/s), with most exceeding 400 gpm (0.03 m^3/s).

In the tributary valleys yields range up to 100 gpm (0.006 m^3/s) (e.g., SWSWSW sec. 1, T. 12 S., R. 23 E., in Mill Creek). Although the data are sparse for other

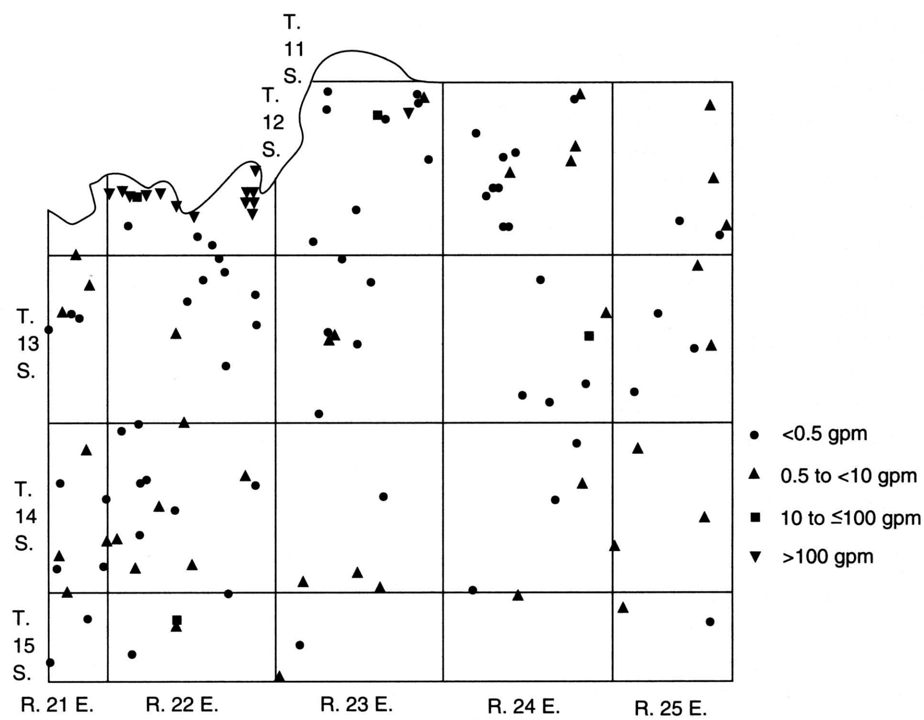

FIGURE 50—Estimated well yields, Johnson County.

alluvial deposits, O'Connor (1971) reported yields of 25–100 gpm (0.0016–0.006 m^3/s) in large tributaries and 1–10 gpm (0.00006–0.0006 m^3/s) in small tributaries.

Yields from glaciofluvial deposits in northwestern Johnson County and in the area near Holliday have been reported to be 1–12 gpm (0.00006–0.00076 m^3/s). Because many drill holes that provide no yield data indicate large thicknesses of sand and gravel in these areas, yields much greater than 10 gpm (0.0006 m^3/s) could be expected locally. For reference, a spring in SW sec. 2, T. 12 S., R. 23 E., was reported to yield 60 gpm (0.004 m^3/s) from the lower part of the Quaternary aquifer, even during the 1934 drought (Jewett and Williams, 1935; O'Connor, 1971). In some areas along outcrop margins, little or no water can be obtained because it has been drained. Where the aquifer is dominated by fine-grained sand, yields are also relatively small, and wells must be carefully constructed to avoid pumping fine-grained sand.

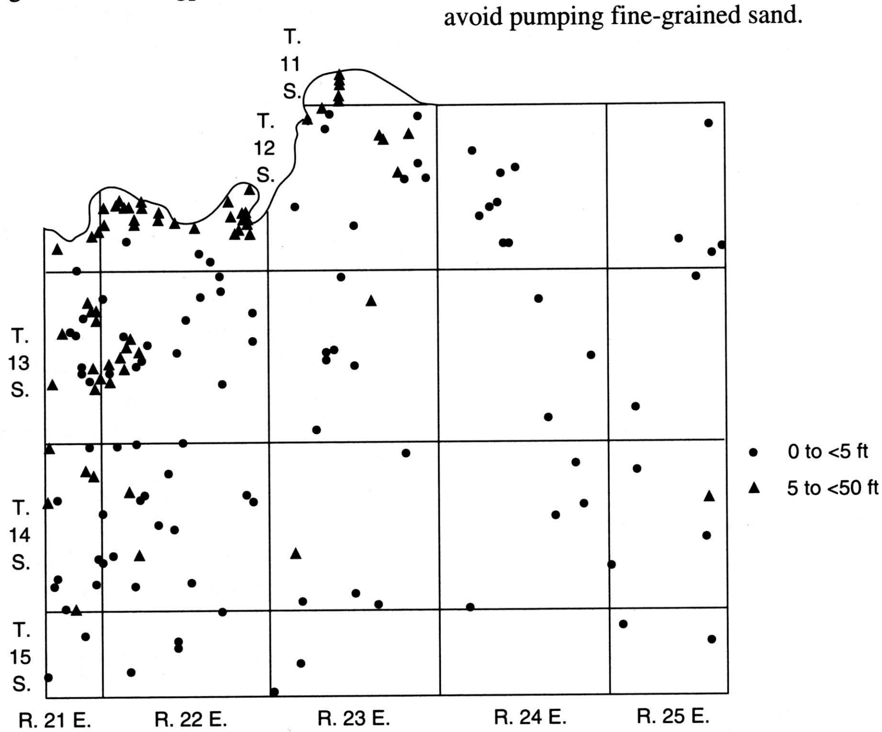

FIGURE 51—Saturated thickness of Pleistocene deposits, Johnson County.

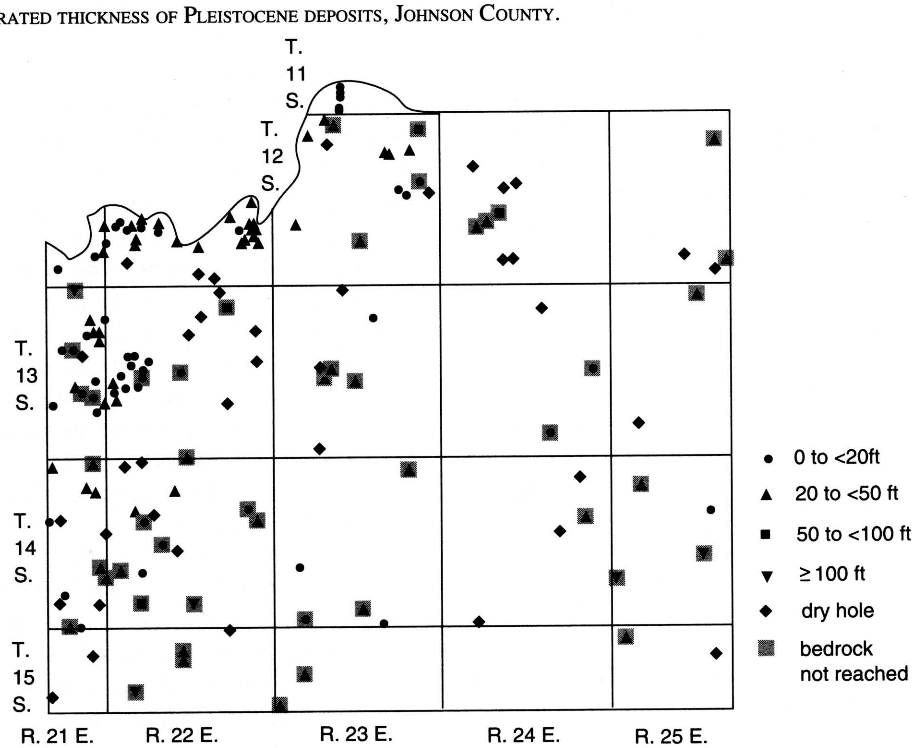

FIGURE 52—Depth to water in wells and test wells, Johnson County.

Pennsylvanian bedrock units that are exposed in Johnson County commonly yield 0–20 gpm (0–0.001 m^3/s), but most are at the low end of the range and many are dry. As described by O'Connor (1971), the major bedrock aquifers include weathered shales or dark shales with vertical fractures of the Hushpuckney, Stark, Muncie Creek, and Eudora Shale Members and the Quivira formation; the Wyandotte Limestone (where it has fractures or solution cavities) and other weathered limestones with open fractures, joints, or bedding planes; and sandstones of the Cherryvale, Chanute, Lane, Bonner Springs, and Vilas Shales, the Lawrence Formation, and the Rock Lake Shale Member of the Stanton Limestone. Except for the permeable areas of the Wyandotte Limestone and the Lawrence Formation, yields from the bedrock units generally range from 0.2 gpm to 5 gpm (0.00001–0.0003 m^3/s). At depths greater than 250 ft (76 m), although sometimes less than 100 ft (30 m), water from the bedrock aquifers is saline. The older, deeper rocks commonly yield a large quantity of saltwater.

The saturated thickness of unconsolidated deposits in Johnson County (fig. 51) ranges up to 46 ft (14 m) in NWNWSE sec. 19 and NWNESE sec. 26, T. 12 S., R. 22 E. These two sites and others with large saturated thicknesses occur in the Kansas River valley alluvium and in the Newman terrace at the mouth of Cedar Creek. Other tributary valleys and the glacial deposits are known to contain 0–20 ft (0–6 m) of saturated material, although the values near Holliday are undoubtedly larger.

Many drill holes in Johnson County are dry or encounter no free water in the drill hole (fig. 52). Of those that encounter water, the maximum reported depth to water is 125 ft (38.1 m) (SWNWNW sec. 17, T. 15 S., R. 22 E.). Bedrock wells have the greatest depth to water, although they also have some of the smallest [e.g., 8 ft (2 m) in NENE sec. 34, T. 13 S., R. 24 E.]. In the glacial and glaciofluvial deposits, the depth to water is generally between 5 ft (2 m) and 30 ft (9 m). Alluvial deposits in the Kansas River valley and along smaller streams commonly have water within 10–30 ft (3–9 m) of the land surface. However, O'Connor (1971, p. 44) observed that "the water table in the Kansas River valley, at distances more than about 0.5 mile from the river and in areas not affected by industrial, irrigation, or municipal pumping, may fluctuate as much as 15 to 20 feet through a cycle of wet and dry years." Hydrographs for four Kansas River valley observation wells measured from 1961 to 1968 are included in O'Connor's report.

The elevations of ground-water levels in Johnson County decline in the downstream direction in the Kansas River valley. Water-table-contour maps of the valley by Dufford (1958) and Fader (1974) indicate that the average hydraulic gradient is 2.5 ft/mi (0.5 m/km) and that ground water generally flows toward the river. However, heavy pumpage at some localities alters the shape of the contours and sometimes induces flow from the river toward a well.

O'Connor (1971) reported values for some aquifer parameters in Johnson County. Hydraulic conductivity of the Lawrence Formation sandstone ranges from 200 gpd/ft^2 to 400 gpd/ft^2 (8–16 m/d), whereas for other sandstones it is generally less than 100 gpd/ft^2 (4 m/d). Specific capacity for one well in the Ireland Sandstone Member of the Lawrence Formation, which was pumped at 12 gpm (0.00076 m^3/s) was 0.8 gpm/ft (0.0002 m^2/s). In the coarse-grained glaciofluvial deposits, permeability is probably greater than 1,000 gpd/ft^2 (40 m/d). For 12 wells pumped between 150 gpm (0.0095 m^3/s) and 1,080 gpm (0.0681 m^3/s) in the Kansas River valley, specific capacity ranged from 14 gpm/ft to 116 gpm/ft (0.0029–0.0240 m^2/s). Fader (1974) reported the results of aquifer tests for two wells in the Kansas River valley in SWSWSW sec. 24 and SWNWNW sec. 25, T. 12 S., R. 22 E.; the former was pumped at 1,000 gpm (0.06 m^3/s) and had a transmissivity of 18,700 ft^2/d [139,000 gpd/ft (1,730 m^2/d)], and the latter was pumped at 1,080 gpm (0.0681 m^3/s) and had a transmissivity of 24,000 ft^2/d [180,000 gpd/ft (2200 m^2/d)] and a storage coefficient of 0.05.

In Johnson County most discharge is to streams or springs, evapotranspiration, and wells. Most recharge is from precipitation with some by seepage from streams and ponds or by subsurface inflow.

Leavenworth County

Geology

The generalized geology of Leavenworth County has been mapped by Ward and O'Connor (1983) on a geologic map of the Topeka to Kansas City corridor (fig. 5). Rock formations exposed within the county range from the Wyandotte Limestone of the Kansas City Group (oldest) in an area adjacent to the Kansas River to the Deer Creek Limestone of the Shawnee Group (youngest) in northwestern Leavenworth County along Stranger Creek. The Wyandotte Limestone is the only formation of the Kansas City Group exposed in the county, and it is only poorly exposed in a few southeastern areas. The Lansing Group, exposed along the Missouri River, its western tributaries, and the eastern part of the Kansas River drainage area, includes 75 ft (23 m) of fossiliferous limestone and black, brown, and gray shales. The Douglas Group is the most widely exposed group in Leavenworth County. It occurs over a large area in the southwestern uplands surrounding Stranger and Ninemile creeks. Exposures are also present along stream valleys in the northeastern region of the county. The Douglas Group [240–400 ft (73–120 m) thick] is divided into two formations (Zeller, 1968): The Stranger Formation contains sandstone, shale, and a minor amount of limestone, coal, and conglomerate; the Lawrence Formation consists chiefly of gray shale and sandstone, which weathers yellowish-gray, and minor amounts of red shale, coal, gray limestone, and conglomerate. Rocks of the Shawnee Group that are exposed in the county include five formations: the Oread Limestone, the Kanwaka Shale, the Lecompton Limestone, the Tecumseh Shale, and the Deer Creek Limestone. The complete Shawnee Group is 325 ft (99 m) thick. It consists of escarpment-forming limestone, gray, tan, black, and red shales, local coal beds, and some cherty limestones. Exposures of the Shawnee Group are chiefly of the Kanwaka Shale and Oread Limestone. The Tecumseh Shale and the Lecompton Limestone are exposed along streams in northwestern Leavenworth County, and the Deer Creek Limestone has a few scattered exposures in extreme northwestern Leavenworth County.

Unconsolidated deposits in the county include glacial drift, loess, and alluvium (fig. 9). Glacial drift generally covers the upland regions of the county and sections along the Kansas River. Loess deposits occur mainly along the Missouri River bluffs and other scattered upland regions. Alluvial deposits are extensive and include alluvium of the bordering Missouri and Kansas rivers and of Stranger Creek, which cuts through the county in a north-south direction, flowing southward into the Kansas River.

The oldest Quaternary deposits in Leavenworth County are of "Kansan" age and include alluvial terraces and glacial drift deposits. Dissected remnants of outwash gravel, sand, and silt deposited during glacial retreat in pre-Illinoian time are preserved as the Menoken terrace along the Kansas River. Menoken terrace deposits are generally 80–100 ft (24–30 m) above the floodplain (Dufford, 1958) and are found along the Kansas River, except in areas where the river alluvium is adjacent to outcropping rock of the Pennsylvanian System. Glacial-drift deposits consist of a heterogeneous mixture of clay, silt, sand, gravel, and boulders deposited by glacial ice and meltwater and are of pre-Illinoian age. Glacial-drift deposits can reach 100 ft (30 m) in thickness in a buried valley area in Leavenworth County, and thicknesses on hilltops can reach 65 ft (20 m) (NE sec. 1, T. 9 S., R. 21 E.).

Illinoian time is represented by a few dissected remnants of the Buck Creek terrace, preserved along the Kansas River predominantly near the mouths of large tributary streams. The Buck Creek terrace consists of sand, sandy silt, and fine gravel grading upward into silt.

North of De Soto, Kansas (NENE sec. 21, T. 12 S., R. 22 E.), there is an exposure of volcanic ash in the lower part of deposits mapped by Dufford (1958) as Menoken terrace deposits. O'Connor (1971) referred to these deposits as late Kansan because of the presence of Pearlette volcanic ash (Swineford, 1963). Geil (1987) has dated the ash as 0.58 ± 0.09 m.y. Given this age, the ash is interpreted by Geil as being the Lava Creek B (Pearlette O) ash K/Ar dated at 0.62 m.y. by Izett and Wilcox (1982). The terrace deposit mapped as Menoken would therefore be pre-Illinoian according to the prevailing Pleistocene glacial chronology (e.g., Hallberg, 1986).

Deposition during the late Wisconsin and the Holocene is represented by fill of the Newman and younger terraces and floodplain alluvium of the Kansas River. The lithology of the alluvium is similar and grades upward from locally derived limestone pebbles and boulders and arkosic sand and gravel to fine-grained sand, silt, and silty clay. The Newman terrace in Leavenworth County occurs mainly in association with streams draining to the Kansas River, including Wolf Creek, Kaw Creek, Stranger Creek, and Ninemile Creek. At the confluence of the Kansas and Wakarusa rivers, the valley width of the Kansas River is 5 mi (8 km), diminishing eastward to 1 mi (1.6 km) close to the Wyandotte County border.

During late Wisconsinan time (ca. 40–ka) and into the Holocene, loess accumulated on hills adjacent to the Missouri River valley and other scattered upland regions mainly in eastern Leavenworth County. Deposits can range from a few feet to 60 ft (18 m) thick and origi-

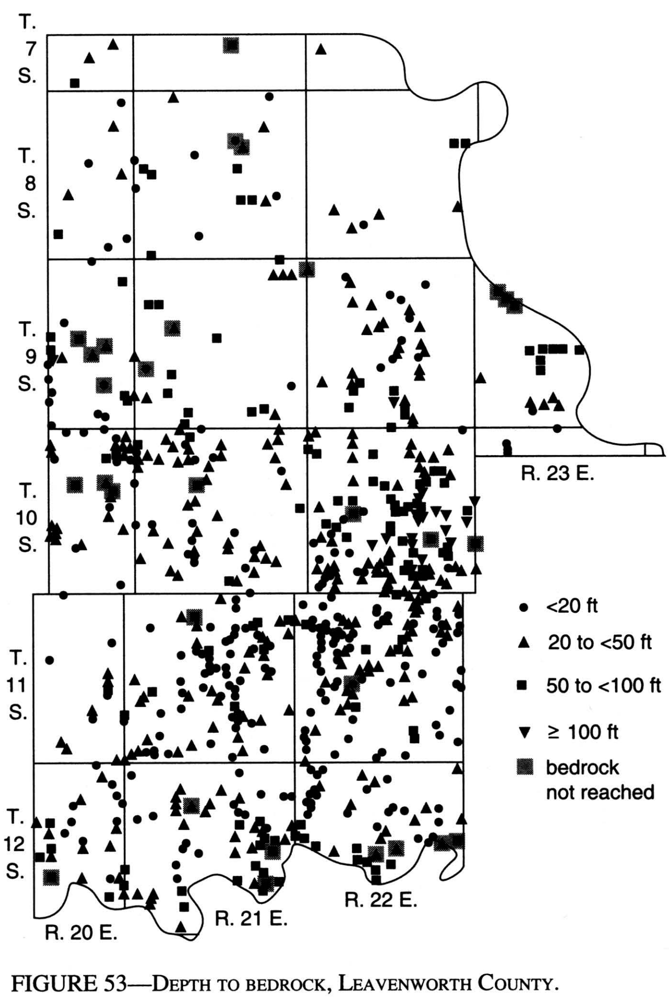

FIGURE 53—Depth to bedrock, Leavenworth County.

nated as windblown particles largely derived from floodplain silts of the Missouri River valley (Dort, 1972a).

The drainage systems of Leavenworth County were greatly influenced by Pleistocene glacial events. Pre-Pleistocene drainage in the county may have been mainly in a southern direction into the Kansas River and probably included Stranger and Ninemile creeks. Dufford (1958) stated that these streams were misfits in their present regime, indicating that their meanders do not fit the size of the valley in which the modern stream flows. A period or periods of incision may have produced these effects. Incision might have resulted from isostatic uplift in front of the ice load, glacial rebound as the glacier retreated, the great amount of meltwater produced by the receding glacier, or intermittent seasonal melting.

The bedrock topographic map of Leavenworth County (plate 1) was prepared using 947 drill logs, as described by Denne et al. (1990a), the geologic map prepared by Ward and O'Connor (1983), and the metric surface topographic map (U.S. Geological Survey, 1981c). The data densities vary greatly in Leavenworth County, with the densest data located in the southeast,

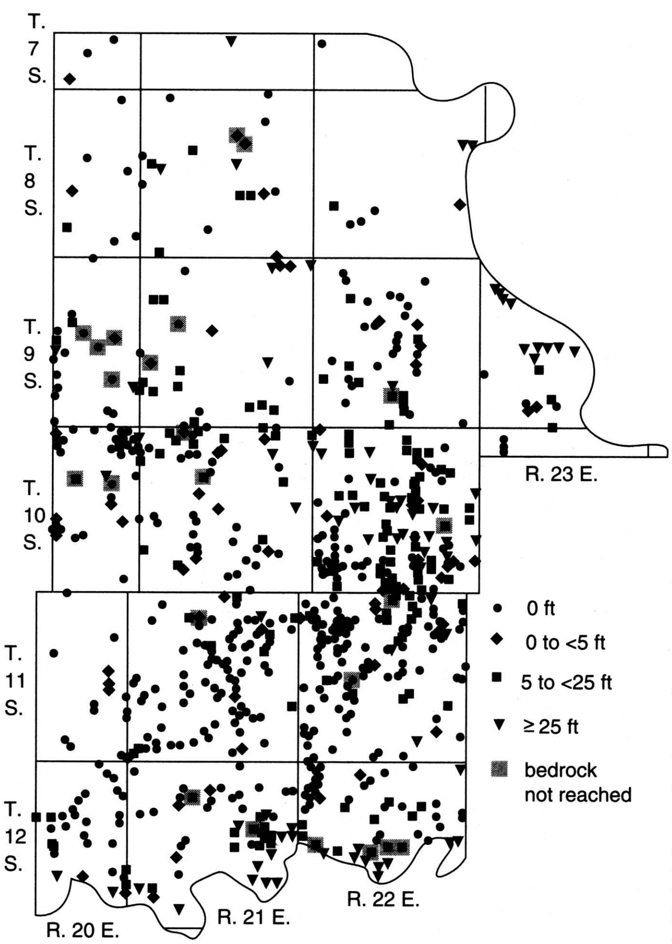

FIGURE 54—Total Pleistocene sand and gravel thickness, Leavenworth County.

adjacent to Wyandotte County. The sources of these data are predominantly old (pre-1974) and new (1974 and later) water-well records for domestic wells.

Steep bedrock surface topography, discernible on the bedrock topographic map, reflects drainage incision processes, and topographically subdued areas are generally overlain by glacial drift. O'Connor and Fowler (1963) believed that this area had a much more subdued topography before glaciation.

A deep buried valley is located in T. 10 S., R. 22 E., and cuts in an east-west direction into Wyandotte County and eventually reaches the Missouri River valley. This buried channel is defined by depth to bedrock values of up to 105 ft (32.0 m) in sec. 15 and a gravel thicknesses of 69 ft (21 m) from a test hole in SWSWSE sec. 14, T. 10 S., R. 22 E. Depth to bedrock values and total sand and gravel thicknesses (figs. 53 and 54, respectively) support the existence of this buried channel.

The relationship of the buried channel to a constriction in the bedrock floor of Stranger Creek (southeast corner of T. 10 S., R. 21 E.) and a shallower buried channel trending north-south in T. 11 S., R. 22 E., may indicate a drainage pattern affected by channeling of meltwater around and away from an ice lobe in this area. The possible blockage of Stranger Creek by ice at this constriction may have caused ponding above the constricted area and subsequent diversion of its waters to the east and south along the buried channels. The greater sinuosity of Stranger Creek south of this constriction supports the location of an ice lobe in this area. The ice caused greater stream incision because of isostatic effects and the large amount of meltwater. The greater meandering south of the constriction also supports this conclusion. Schumm (1963) has suggested that greater meandering results when a large proportion of the load is carried as suspended load (mainly silt and clay).

The bedrock knob located in the southeastern portion of T. 11 S., R. 22 E., is associated with a large amount of sand and gravel [45 ft (14 m)] reported on its eastern side (NWNENW sec. 35, T. 11 S., R. 22 E.) according to test holes drilled by an engineering firm in 1983. This bedrock knob supports the theory that the shallow buried valley to the north was a short-term spillway that flowed around the resistant bedrock into small tributaries north of the Kansas River.

The general trend of the northern tributary to Little Stranger Creek is north-south and may be an extension of the buried channel in T. 11 S., R. 22 E. This drainage system is parallel to the present Stranger Creek drainage and supports the spillway scenario. Four data points, located along the buried northern drainage, have sand and gravel thicknesses of 3–46 ft (0.9–14 m) and depth to bedrock values of 26–70 ft (7.9–21 m).

Another explanation for these drainage systems is the existence of an ice-marginal drainage along Stranger

Creek, ending along the buried valley in T. 10 S., R. 22 E. Meltwaters might have flowed around the ice margin and southward and eastward from its southern extent. A large amount of sand and gravel to the east of Stranger Creek and in relation to the buried valley supports the existence of an ice margin here.

There are many Stranger Creek tributary valleys that contain a large amount of sand and gravel in their upper reaches. The presence of coarse-grained material in these regions probably results from glacial processes. Questionable sand and gravel thicknesses of 7–60 ft (2–18 m) and depth to bedrock values of 61–127 ft (19–38.6 m) in secs. 22 and 25, T. 9 S., R. 20 E., are found in an extension of the bedrock valley of a Fall Creek tributary. Sand and gravel thicknesses of 7–12 ft (2–3.7 m) occur in the region where Fall Creek joins Stranger Creek. These streams cut through thick glacial drift deposits in this area. Three data points along Ninemile Creek report sand and gravel thicknesses between 1 ft (0.3 m) and 17 ft (5.2 m) and depths to bedrock of up to 52 ft (16 m); Tonganoxie Creek has sand and gravel 4–15 ft (1–4.6 m) thick. A small tributary valley on the western side of Stranger Creek (SESWSE sec. 2, T. 11 S., R. 21 E.) has a questionable sand and gravel thickness of 47 ft (14 m) and a depth to bedrock of 82 ft (25 m).

Up to 35 ft (11 m) of sand and gravel overlie an elevated bedrock area (NWSWNW sec. 6, T. 9 S., R. 22 E.; SESWNE sec. 2, T. 9 S., R. 21 E.) that forms a divide between drainage to Stranger Creek on the west and drainage to the Missouri River on the east. Northward along this divide, sand and gravel deposits range from 1 ft to 35 ft (0.3–11 m) thick, and depth to bedrock values can reach 65 ft (20 m) (NENENE sec. 2, T. 9 S., R. 21 E.) along the uplands. A questionable data point (NWNWNW sec. 34, T. 9 S., R. 22 E.) indicates a depth to bedrock value greater than 104 ft (31.7 m) in an upland region at the head of southward drainage into Stranger Creek or into the buried-valley area. Sand and gravel thicknesses in this upland area are 8–25 ft (2–7.6 m).

The largest sand and gravel thicknesses are located in the Missouri and Kansas River alluvium; the thickness can reach 95 ft (29 m) [58 ft (18 m) of sand and 37 ft (11 m) of fine-grained sand] in the Kansas River alluvium (NWNENW sec. 21, T. 12 S., R. 22 E.). The depth to bedrock values reach 99 ft (30 m) in the Missouri River alluvium deposits and 72 ft (22 m) in the Kansas River deposits. The Stranger Creek alluvium has sand and

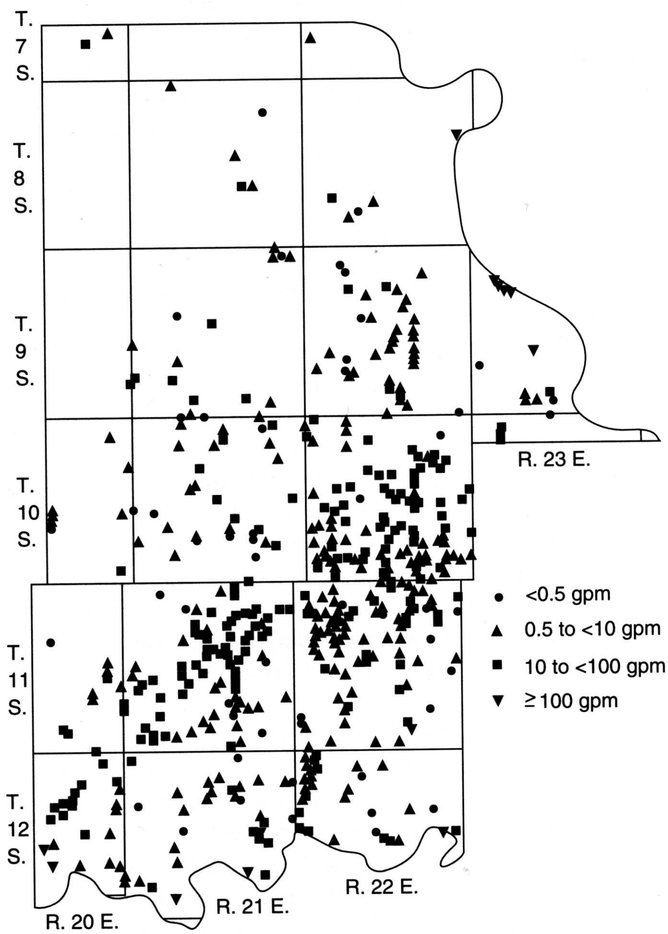

FIGURE 55—Estimated well yields, Leavenworth County.

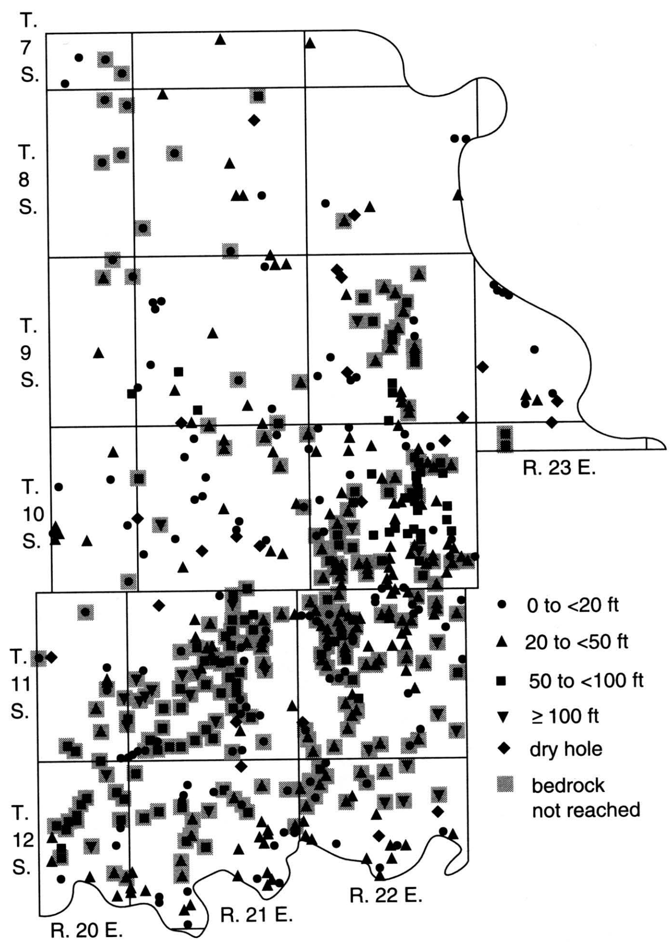

FIGURE 56—Depth to water in wells and test wells, Leavenworth County.

gravel thicknesses ranging from 2 ft to 29 ft (0.6–8.8 m). The depth to bedrock generally increases in a northerly direction from 36 ft to 62 ft (11–19 m) (NWNENE sec. 19, T. 8 S., R. 21 E.) in the Stranger Creek deposits.

Ground Water

The alluvial deposits along the Missouri and Kansas rivers provide the greatest quantity of water to wells in Leavenworth County. Well yields are shown in fig. 55 and are given by Denne et al. (1990a). Wells can yield up to 5,000 gpm (0.3 m^3/s) of water in the Missouri River alluvium (NWNENE sec. 13, T. 8 S., R. 22 E.) and 2,000 gpm (0.1 m^3/s) in the Kansas River alluvium (NWNWNE sec. 27, T. 12 S., R. 20 E.). Fader (1974) reported yields for the Kansas alluvium of 500–1,000 gpm (0.03–0.06 m^3/s), depending on the saturated thickness of the deposits. The city of Leavenworth has seven public supply wells, yielding 2,000 gpm (0.1 m^3/s) each, in the Missouri River alluvium (secs. 7 and 8, T. 9 S., R. 23 E.). Reported yields in the Stranger Creek alluvium where it joins the Kansas River alluvium are 50–150 gpm (0.003–0.0095 m^3/s). Otherwise, the alluvium of Stranger Creek and its tributaries have yields of 10–50 gpm (0.0006–0.003 m^3/s).

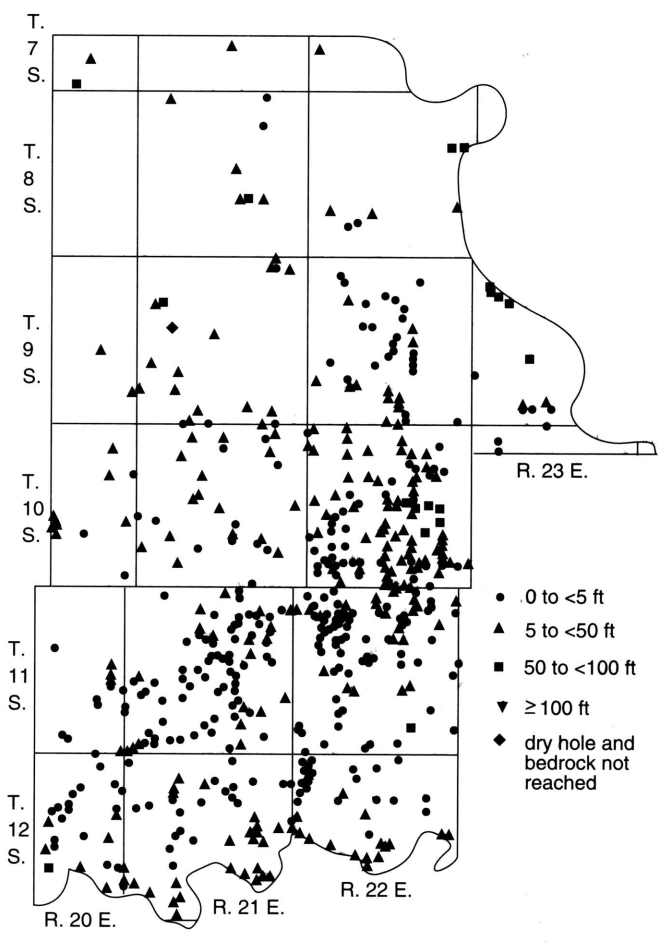

FIGURE 57—Saturated thickness of Pleistocene deposits, Leavenworth County.

The buried-valley area in T. 10 S., R. 22 E., shows yields in the range 10–100 gpm (0.0006–0.006 m^3/s) (fig. 55). Thirty-three domestic wells in this region have yields of 10–36 gpm (0.0006–0.0023 m^3/s). Along the north-south-trending valley on the eastern side of the bedrock knob (NWNENW sec. 35, T. 11 S., R. 22 E.), two engineering test holes were expected to yield 200 gpm (0.01 m^3/s). Hilltop drift deposits generally yield 0–8 gpm (0–0.0005 m^3/s) where they are saturated. In the region where Fall Creek cuts through glacial deposits, reported yields range from 7 gpm to 40 gpm (0.0004–0.003 m^3/s) in 5 wells.

Sandstone bedrock of the Stranger Formation is an important aquifer for domestic wells in Leavenworth County. There are 84 bedrock wells located in T. 11 S., R. 21 and 22 E., and T. 12 S., R. 20 E., that have yields ranging from 10 gpm to 75 gpm (0.0006–0.0047 m^3/s). These wells have a mean yield of 25 gpm (0.0016 m^3/s) and a mean total depth of 130 ft (40 m). The initial bedrock type encountered in these wells is chiefly yellow, brown, or red sandstone or sandstone of undescribed color. There are also many bedrock wells that report yields of less than 1 gpm (0.00006 m^3/s). The great density of wells in these areas of Leavenworth County is largely due to these bedrock wells.

The depth to water in Leavenworth County is greatest in bedrock wells. All depth to water values of 100 ft (30 m) or greater are from bedrock formations, except for one questionable value in sec. 35, T. 10 S., R. 21 E. There were four bedrock wells with water levels of 200 ft (60 m). Figure 56 indicates that most of the bedrock wells have water levels between 50 ft (15 m) and 100 ft (30 m).

Water levels in the Missouri River valley have a mean of 11 ft (3.4 m) below the land surface using eight data points. Water levels in the Kansas River valley have a mean of 22 ft (6.7 m) below the land surface using 33 data points, including five wells in terrace deposits with water levels between 30 ft (9 m) and 48 ft (15 m). There were only five points overlying the deepest part of the bedrock valley of Stranger Creek. Three data points north of the constricted area have depth to water values of 5, 5, and 6 ft (2 m), and two data points south of this area have depth to water values of 16 ft (4.9 m) and 23 ft (7.0 m). This may give clues to the depositional history of the Stranger Creek valley, although data from the Stranger alluvium are sparse at present.

The buried-valley region in T. 10 S., R. 22 E., has depth to water values of 18–90 ft (5.5–27 m) for 29 data points and a mean of 56 ft (17 m). There are four data points north of the deepest section of the buried valley with water levels of 80 ft (24 m) below the land surface, and two data points to the south reporting depth to water values of 90 ft (27 m). The depth to water values in glacial-drift deposits located in other areas of Leavenworth County are generally between 10 ft (3 m) and 30 ft (9 m). Water levels of 30 ft (9 m), 40 ft (12 m), 50 ft (15 m), and 59 ft (18 m) below the land surface (Denne et al., 1990a) are associated with the area where Fall Creek joins Stranger Creek.

Unconsolidated deposits in Leavenworth County have saturated thicknesses (fig. 57) of less than 100 ft (30 m), with a maximum value of 86 ft (26 m) from the Missouri River alluvium (sec. 13, T. 8 S., R. 22 E.). Saturated thicknesses in the Missouri River deposits range from 57 ft to 86 ft (17–26 m) compared to the Kansas River values, which range from 9 ft to 53 ft (3–16 m). The Stranger Creek valley has saturated thickness values of 46 ft (14 m) and 52 ft (16 m) in the vicinity of Wolf Creek.

The buried valley in T. 10 S., R. 22 E., contains saturated glacial materials 13–71 ft (4.0–22 m) in thickness, with 16 values greater than or equal to 30 ft (9 m). Saturated sections of unconsolidated materials are prominent in many areas adjacent to bedrock knobs (sec. 35, T. 11 S., R. 22 E.; sec. 3, T. 11 S., R. 21 E.; and secs. 9, 16, and 17, T. 10 S., R. 21 E.) and can be of the order of 20–30 ft (6–9 m) in thickness along other bedrock highs (e.g., data points in sec. 2, T. 9 S., R. 21 E., and sec. 27, T. 8 S., R. 21 E.).

There are many saturated thickness values for unconsolidated deposits of zero, reflecting the presence of bedrock wells in these areas. Unsaturated (no free water) materials are chiefly located in areas of bedrock highs and to some extent in the upper portions of stream valley bedrock walls.

The water table along the Kansas River generally declines from 791 ft (241 m) to 753 ft (230 m) as the river flows eastward. Water-table values of 744–768 ft (227–234 m) are reported in a 12-mi (19-km) reach of the Missouri River bordering Leavenworth County. Data along the Stranger Creek valley indicate water-table values of 870 ft (265 m) in the upper reaches, declining to 819 ft (250 m), 12 mi (19 km) to the south along its course (SW sec. 6, T. 11 S., R. 22 E.).

Some of the highest water-table values are present in hilltop-drift deposits in northwestern Leavenworth County. They range from 1,065 ft to 1,090 ft (324.6–332.2 m) in elevation. A hilltop area in T. 10 S., R. 20 E., also has many high water elevations in glacial-drift deposits, including nine data points ranging from 1,044 ft to 1,090 ft (318.2–332.2 m). The water table in the buried-valley region is generally at 900 ft (270 m), declining toward Stranger Creek to the west with values in the 800-ft (240-m) range.

Nemaha County

Geology

The geology of Nemaha County has been described by Mudge et al. (1959) and Ward (1974). The development of the Nemaha anticline and the Humboldt fault zone (see fig. 3) significantly influenced the distribution, thickness, and dip of the bedrock units in the county. Although glacial deposits cover most of the surface, some bedrock exposures occur along valleys in the northern half of the county and along the southwestern border. The oldest exposed rocks (from the Shawnee and Wabaunsee Groups of Pennsylvanian age) extend from north-central to southwestern Nemaha County (fig. 5). Permian rocks are exposed on both sides of the anticlinal structure. The total thickness of sedimentary rocks above the Precambrian basement ranges up to 1,000 ft (300 m) on the western flank of the anticline and to 4,000 ft (1200 m) on the eastern flank. Dips of bedrock units vary from 30° eastward in the Permian units on the downthrown (eastern) side of the fault near Bern to horizontal or slightly westward in the Pennsylvanian beds just west of the fault to 15 ft/mi (0.16°) westward in the western part of the county (Ward, 1974).

As described by Ward (1974) and Mudge et al. (1959), the Pennsylvanian rocks exposed in Nemaha County include shales and limestones with some sandstones and coal beds. The Topeka Limestone of the Shawnee Group is 20–30 ft (6–9 m) thick, and the formations in the Wabaunsee Group are 325–450 ft (99.1–137 m) thick. The Admire Group of Permian age contains 100 ft (30 m) of shale, limestone, and sandstone. The Council Grove Group is 239–310 ft (72.8–94.4 m) thick and is dominated by shales and limestones. Some of the limestones are cherty, whereas others contain gypsum or solution channels where gypsum has been dissolved. The cherty Wreford Limestone of the Chase Group is 30–40 ft (9–12 m) thick and is the youngest bedrock unit in the county.

Unconsolidated deposits cover most of Nemaha County. The oldest are pre-Illinoian tills, outwash, and glaciolacustrine sands and silts. In the buried valleys a basal limestone and chert gravel, generally less than 15 ft (4.6 m) thick, is overlain by up to 100 ft (30 m) of fine-grained to very fine grained silty sand (or, locally, sandy silt or clay) of the Atchison Formation (Ward, 1974). The Atchison Formation has been interpreted as glaciolacustrine, and Mudge et al. (1959, p. 211) noted that "bedding is apparent in all [glaciolacustrine] deposits, and iron stains are on the bedding planes." Overlying the older sediments in the buried valleys and occupying other areas in the county are heterogeneous mixtures of clay, silt, sand, and gravel, considered by Ward (1974) to be the Cedar Bluffs and Nickerson tills. The older (Nickerson) till ranges from 0 to 240 ft (73 m) in thickness, is generally gray, and contains fewer erratics than does the Cedar Bluffs Till, which is tan to brown to light gray and less than 100 ft (30 m) thick (Ward, 1974). Lenses of sand and gravel occur locally within each till, and a layer of outwash 0–50 ft (0–15 m) thick occurs between the two tills. Ward (1974, p. 9) believed that the Nickerson till "may not have been deposited on the highest bedrock surfaces" and that the "Cedar Bluffs Till is present throughout the county except along stream valleys where it has been removed by late Pleistocene erosion." Figure 58 shows the distribution of the pre–Cedar Bluffs Pleistocene units as mapped by Ward (1974). One peculiar feature of this map is that, if the buried valleys and basal gravel [shown as Nebraskan (?) deposits] are correctly mapped, then in the tributaries the coarse-grained material occurs only at the downstream ends. This still could be true if erosion removed the gravel upstream or if the gravel was deposited near an ice margin and/or by streams that had reversed drainage for some period of time.

The youngest deposits in Nemaha County are loess and alluvium; they have been described by Ward (1974) and Mudge et al. (1959). The Illinoian and Wisconsin loess deposits generally mantle the uplands with less than 10 ft (3 m) of silt. Terraces and alluvial deposits in stream valleys range from Illinoian to Holocene and generally consist of sandy clay (commonly reworked glacial deposits) with a sand and gravel layer at the base and/or locally within the deposit. The texture varies along different streams, however; for example, the Spring Creek alluvium is mainly fine-grained sand and silt (Mudge et al., 1959). In Nemaha County the older terraces and valley-fill deposits range up to 50 ft (15 m) in thickness, whereas the younger alluvial deposits are generally less than 30 ft (9 m) thick (Ward, 1974).

Using 582 drill-hole logs (Denne et al., 1990a) and maps of the surface topography [with contours at 50-ft intervals generalized from the U.S. Geological Survey (n.d.)] and bedrock geology (Ward, 1974), we constructed a bedrock topographic map of Nemaha County (plate 1). Several data problems (sparse availability of data in some areas, the difficulty in differentiating gray shales from gray glacial clays on some logs and in some boreholes, and the numerous water wells and test holes that did not even reach bedrock) limit the accuracy of the bedrock topographic map. To interpret channel locations between distant data points, we considered several factors: (1) valley width (because Recent stream valleys widen where they cross some buried valleys), (2) "gaps" in bedrock exposures along streams (because now-buried drainages would have eroded bedrock to a lower level), and (3) sand and gravel deposits. We also used total well depth and aquifer information from the U.S. Geological Survey historical water-quality file to estimate bedrock elevations when other data were unavailable.

In Nemaha County the main buried valley, which is a tributary of the ancestral Grand River in Missouri, has been recognized by Frye and Walters (1950), Frye and Leonard (1952), Dreeszen and Burchett (1971), and Ward (1974). In plate 1 the channel is clearly evident, extending from west to east in the southern part of Nemaha County. Data in the area common to T. 3 and 4 S., R. 13 and 14 E., suggest that the valley trends northeastward to the common corner of the townships and then bends to follow a southeastern course. There is a bedrock high to the south of the valley, but the structure may also contribute to the channel orientation.

In T. 4 S., R. 13 E., the buried valley is between faults, as mapped by Cole (1976) and DuBois (1978). The southeast-trending channel in T. 4 S., R. 14 E., is close to part of and coincident with the remainder of the fault that DuBois (1978) mapped in that township. The latter fault also underlies Wolfley Creek near the Jackson County border. In addition to fault control of valley locations, perhaps an ice lobe developed and later blocked a marginal drainage system.

The western part of the main buried valley (from the Marshall County line to the northeast corner of T. 4 S., R. 13 E.) corresponds closely to a LANDSAT tonal pattern, as described by Denne et al. (1982) and Denne, Yarger, et al. (1984). In this area the valley underlies a modern topographic high. The LANDSAT pattern continues along a probable bedrock high and a topographic high to the northwestern corner of T. 3 S., R. 14 E., where the pattern becomes indistinct. The lobate shape of the LANDSAT pattern and the topographic high of the land suggest that the pattern high indicates the remnants of an end moraine. To the north the feature may have been obliterated by another ice lobe extending southeastward along Gregg Creek (see the section on the geology of Brown County). If indeed an ice lobe blocked part of the major now-buried valley, drainage could have escaped southeastward through T. 4 S., R. 14 E.; T. 5 S., R. 13 E.; and T. 5 S., R. 12 E., in addition to other small valleys (see plate 1).

In Nemaha County the main buried channel may be as much as 3 mi (5 km) wide and 400 ft (120 m) deep from the land surface to the bedrock bottom of the channel. In southwestern Nemaha County (E–E′ in plate 1 and fig. 59), test holes were drilled and geophysical techniques were used to evaluate the channel deposits (Denne et al., 1982, 1984). The surface topography and field data for the profile are shown in fig. 60. The outer limits of the valley system along this profile are defined at least by bedrock exposures at the south end (site J) and 1 mi (1.6 km) north of site A. Data from sites B and D indicate a steeply sloping northern valley wall. The deepest part of the channel occurs between sites D and E, and these test holes contain 8–19 ft (2–5.8 m) of basal gravel and sand. Test hole F, with 8 ft (2 m) of basal sand and gravel, appears to be on the gently sloping southern side of the valley, as is site G, which has 149 ft (45.4 m) of silty and fine-grained sandy glaciofluvial material overlain by 52 ft (16 m) of till.

Although the main buried valley is fairly well defined, the extent and orientation of the numerous tributaries are difficult to determine from the available data. Nevertheless, it appears that a significant channel drained generally southeastward around some bedrock "islands" to the southeastern part of T. 3 S., R. 13 E. (plate 1). The South Fork Big Nemaha River is broad and lacks bedrock exposures where it apparently crosses the buried drainage (e.g., secs. 14, 23, and 35, T. 2 S., R. 12 E.). The circular shape formed by Turkey Creek and the South Fork Big Nemaha River may reflect structural control and/or ice-marginal drainage, and these valleys and their modern tributaries may be at least partly connected to the buried-channel system. A deep buried valley under the town of Bern (sec. 16, T. 1 S., R. 13 E.) and used for the public water supply is difficult to trace, but it may extend southwestward to Deer Creek and then either southeastward or westward to the South Fork Big Nemaha River.

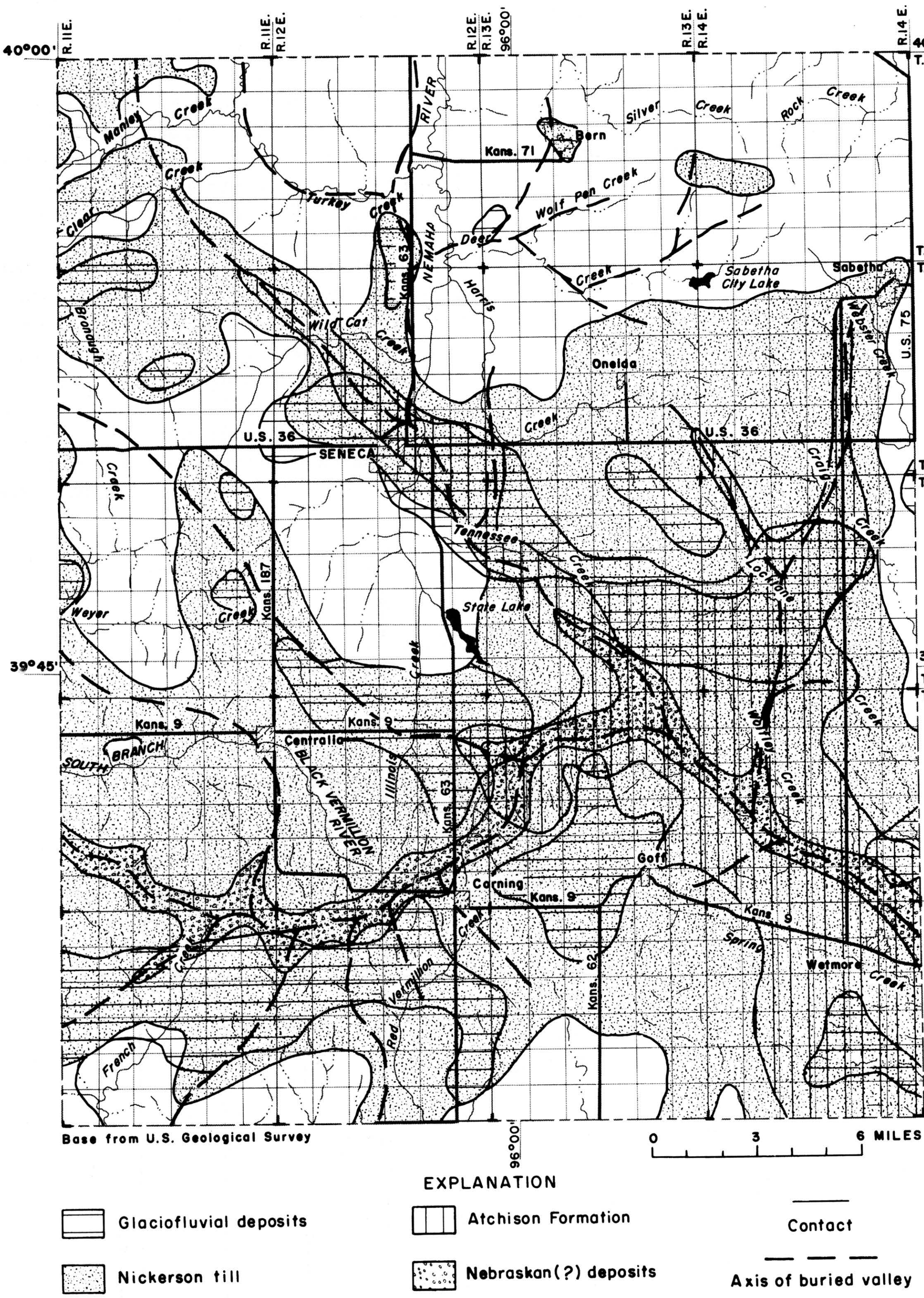

FIGURE 58—Distribution of pre–Cedar Bluffs Pleistocene units, Nemaha County. From Ward (1974, fig. 4).

It is interesting to note that Frye and Leonard (1952) showed a major drainage flowing from north to south slightly west of the center of the county during Wisconsinan time. This stream could have followed the course of the South Fork Big Nemaha River and Illinois Creek (both reversed with respect to their present flow directions) and then crossed the modern divide to the Red Vermillion Creek. Southward flow of the South Fork Big Nemaha River could explain the peculiar entrance angles for tributaries such as Deer, Wildcat, and Fisher creeks, although the buried valleys that cross below them may also influence their orientation.

Test holes drilled near Centralia and logs from more isolated areas in western Nemaha County suggest the presence of several narrow tributaries that drained southward to the major east-west buried valley (plate 1). Water wells and test holes in the vicinity of Woodlawn also indicate a deep valley, and core samples from NENWNE sec. 16, T. 3 S., R. 14 E., show much water-deposited material filling the channel there [for additional information, see the discussion of core W in Denne et al. (1984)]. Another buried tributary appears to have flowed southward across Deer and Harris creeks to the previously described intersection of T. 3 and 4 S., R. 13 and 14 E. If the location and orientation have been correctly interpreted, that valley is close to faults mapped by Cole (1976) and DuBois (1978).

The relationship between structure and geomorphology in Nemaha County should be studied in more detail because it may reveal significant clues to understanding both modern and buried drainages. Several possible correlations have already been discussed. In addition, recent microearthquakes suggest that the Humboldt fault zone is still active (Steeples et al., 1979), and a lineament formed by Negro Creek and the upper reaches of the North Fork Black Vermillion River may be the result of recent movements in glacial deposits (DuBois, 1978). Especially on the west side of the Humboldt fault (where the sedimentary rock sequence is relatively thin), DuBois (1978) believed that the structure exerted considerable control on drainage.

In Nemaha County the depth to bedrock (fig. 61) ranges up to 400 ft (120 m) (NWNWNW sec. 28, T. 4 S., R. 13 E.). Values exceeding 300 ft (90 m) are common in the main buried valley, especially at and on the western side of the sharp bend in the valley (northeastern corner of T. 4 S., R. 13 E.). Toward the southeast from the bend, near the modern Wolfley Creek, the depth to bedrock in the buried valley is generally within the range of 150–250 ft (46–76 m). A buried tributary

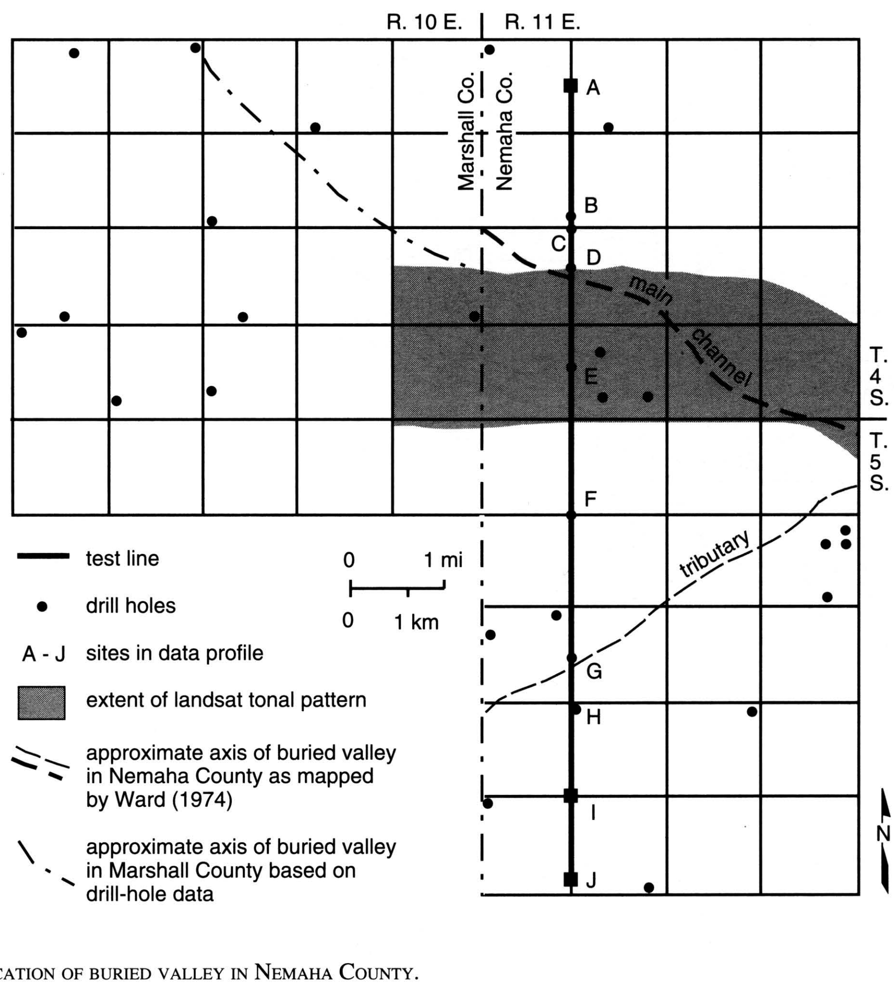

FIGURE 59—Location of buried valley in Nemaha County.

that underlies part of Spring Creek has 100–200 ft (30–60 m) of alluvial and glacial deposits. Several other southern tributaries to the main buried channel (e.g., in T. 5 S., R. 13 E., and T. 5 S., R. 12 E.) contain deposits thicker than 100 ft (30 m).

The buried valley that extends northeastward through T. 3 S., R. 14 E., into T. 2 S., R. 14 E., contains up to 310 ft (94 m) of sediments in the area near Woodlawn. If mapped correctly, the tributary that trends northward from the sharp bend in the main channel contains 37–368 ft (11–112 m) of unconsolidated material, with the smallest amounts underlying the modern Deer Creek. The depth to bedrock is difficult to determine in test holes in SWSWSW sec. 23, T. 3 S., R. 13 E., and NWNENW sec. 14, T. 3 S., R. 13 E., but it appears to be 368 ft (112 m) and 255 ft (77.7 m), respectively. The former test hole would then be in a deep part of the channel [bedrock elevation of 952 ft (290 m)], and the latter, which has more sand and gravel and a 1,090-ft (332.2-m) bedrock elevation, would be on the valley wall. These two test holes are also significant because the 1979 gamma, self-potential, and resistivity logs are almost identical for depths below 370 ft (110 m) in sec. 23 and below 285 ft (86.9 m) in sec. 14. If we assume that there is stratigraphic equivalence and no dip, then there would be a 110-ft (34-m) offset between bedrock units at these sites, which are only 2 mi (3 km) apart. Seismic work (Steeples, 1981, figs. 8–12) indicates that one of the test holes (SWSWSW sec. 23, T. 3 S., R. 13 E.) is in a graben, whereas the test hole in NWNENW sec. 14, T. 3 S., R. 13 E., is on the upthrown side of the northernmost of the two faults bounding the graben. If the graben controlled the location of the now-buried drainage, a valley may have extended northeastward from the test hole in sec. 23, T. 3 S., R. 13 E., toward SW sec. 7, T. 3 S ., R. 14 E. (across the bedrock high as now mapped).

Other significant thicknesses of glacial deposits occur in the northern tributaries to the main channel (e.g., in the southwestern part of T. 3 S., R. 13 E., the southeastern part of T. 3 S., R. 12 E., most of T. 4 S., R. 12 E., and the eastern edge of T. 4 S., R. 11 E.). Northward extensions of these valleys also contain up to 180 ft (55 m) of sediments. The buried channel underlying Bern is at least 120 ft (37 m) deep. In general, however, the glacial cover is much thinner in the northern half of the county than in the southern half.

The total thickness of sand and gravel in Nemaha County (fig. 62) is greatest in the buried valleys. The largest values [207–264 ft (63.1–80.5 m)] occur in

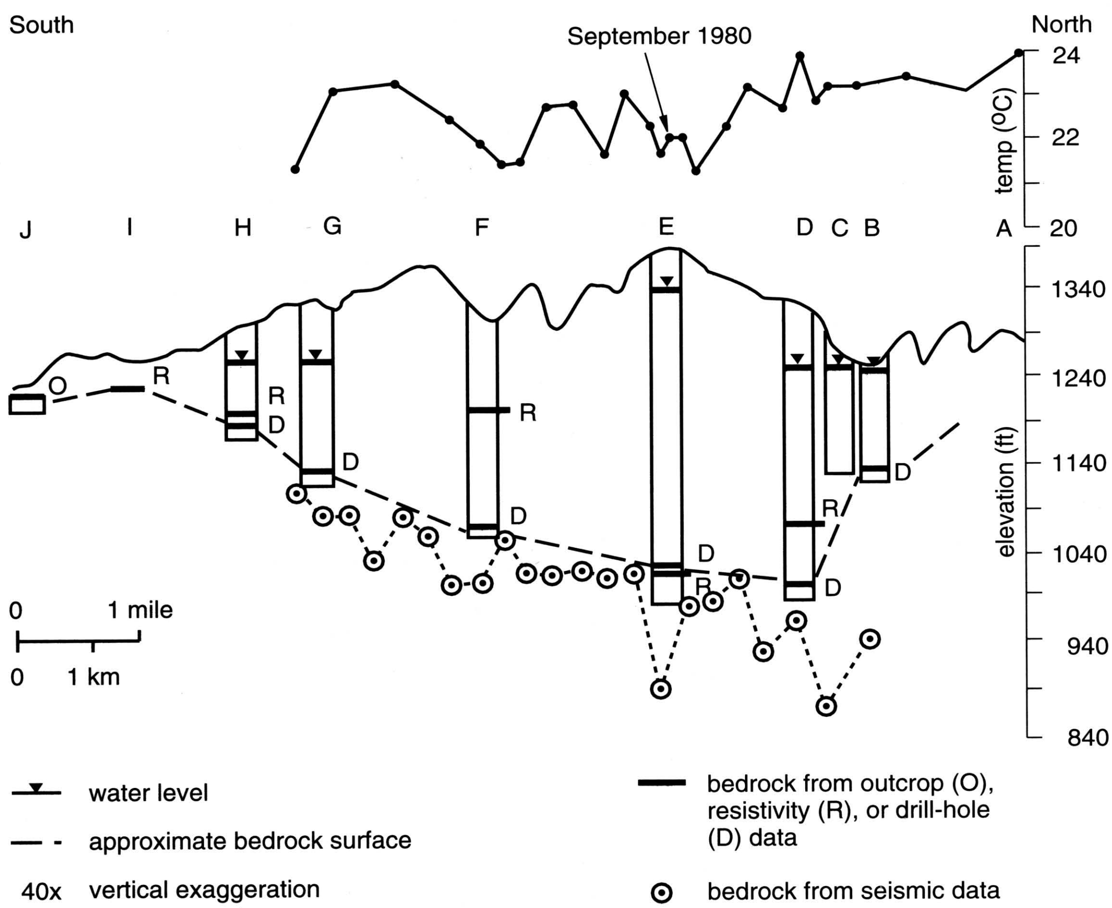

FIGURE 60—Surface topography and field data for cross section E–E´, Nemaha County. Location of section shown in plate 1 and fig. 59.

SWNW sec. 25, T. 3 S., R. 13 E., NENENW sec. 11, T. 4 S., R. 13 E., SENESE sec. 3, T. 5 S., R. 11 E., and SENENE sec. 10, T. 5 S., R. 11 E. [see Denne et al. (1990a)]. These sites generally contain clay with layers of fine-grained sand beginning relatively near the land surface, fine- to coarse-grained sand at greater depths, and sand and gravel at or near the bedrock surface. In places the fine-grained sand [which ranges up to 200 ft (60 m) in thickness] may actually be dominated by and is sometimes logged as silt; thus some differences in total sand and gravel thickness may be the result of field estimation of grain size by various individuals. However, the sequence of sediments often does vary greatly within short distances, making test drilling important in evaluating the aquifer in an area and in optimizing selection of a well site. For example, test holes in sec. 32, T. 4 S., R. 11 E., had 0–18 ft (0–5.5 m) of basal gravel, and the driller estimated that a well in SE sec. 32 could yield 900 gpm (0.06 m^3/s) (personal communication from the landowner, 1981).

A detailed analysis of the sand and gravel layers would help to determine the drainage history of Nemaha County. Some areas (e.g., in T. 3 S., R. 13 and 14 E., and T. 5 S., R. 14 E.) have sand and gravel deposits relatively high in the sediment column. These coarse-grained materials may be outwash or buried-channel deposits from a later episode and possibly a different orientation from that responsible for the basal sand and/or gravel layers that locally underlie them.

In the relatively recent alluvial deposits, sand and gravel layers are 0–15 ft (0–4.6 m) thick. The coarse material is generally at or near the bedrock surface. Where modern streams cross or are coincident with buried valleys, the total thickness of sand and gravel may be much greater than 15 ft (4.6 m) (e.g., parts of Tennessee and Harris creeks and South Fork Big Nemaha River near Seneca, Spring Creek, and Wolfley Creek). The oil logs along Gregg Creek (part of the lobate drainage system in Brown County) indicate 45 ft (14 m) of sand in NENESE sec. 28, T. 2 S., R. 14 E., and 35 ft (11 m) of "surface boulders." Throughout most of Nemaha County (except for the northeastern-most township), sand and gravel deposits can be found at least locally in the alluvial and glacial deposits. The coarse-grained materials are generally good sources of ground water. Where wells are sited in areas with fine-grained sand and silt, however, they must be carefully constructed and developed to prevent clogging of well screens or pumping of excessive sediment with the water.

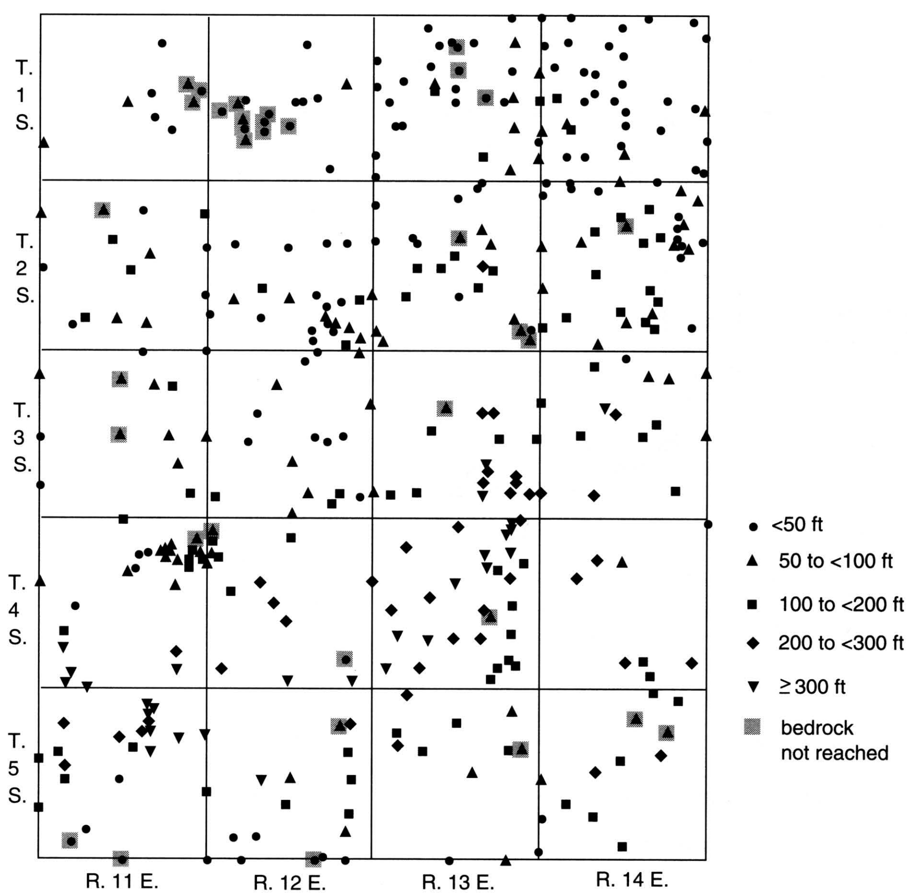

FIGURE 61—Depth to bedrock, Nemaha County.

Ground water

In Nemaha County wells in the glaciofluvial deposits may yield up to 900 gpm (0.06 m^3/s) (estimate for test hole in SE sec. 32, T. 4 S., R. 11 E.), but generally they produce 200 gpm (0.01 m^3/s) or less. Reported yields, which have not been corrected for well diameter or other variables, are shown in fig. 63. They are greatest in the main buried valley and in the channel deposits underlying the South Fork Big Nemaha River near Seneca (SWNWSW sec. 26, T. 2 S., R. 12 E.). Yields from the smaller buried tributary valleys are commonly less than 100 gpm (0.006 m^3/s). Elsewhere, glacial deposits (especially the sand and gravel layers in them) may provide small amounts of water. Alluvial deposits along modern rivers yield 0–30 gpm (0–0.002 m^3/s) (or more, where they overlie glacial buried valleys).

As previously discussed in the geology section, the Quaternary deposits vary both vertically and laterally; therefore a detailed test-drilling program should be done before large-capacity wells are constructed. In general, the coarsest and most permeable deposits are the basal gravels (such as those in SE sec. 32, T. 4 S., R. 11 E.). Ward (1974) gave estimated yields and specific-capacity values for the different aquifers of less than 200 gpm (0.01 m^3/s) and 15–20 gpm/ft (0.0031–0.0041 m^2/s) drawdown for the basal gravels, 10–100 gpm (0.0006–0.006 m^3/s) and less than 2 gpm/ft (0.0004 m^2/s) drawdown for the Atchison Formation, 50–200 gpm (0.003–0.01 m^3/s) and 5–10 gpm/ft (0.001–0.002 m^2/s) drawdown from outwash deposits between the two tills, and commonly less than 10 gpm (0.0006 m^3/s) and 2 gpm/ft (0.0004 m^2/s) drawdown for terrace and alluvial deposits. The Nickerson and Cedar Bluffs tills are relatively impermeable and do not yield much water where they are thin (especially near streams and bedrock highs), but local sand and gravel lenses may yield up to 10 gpm (0.0006 m^3/s) where they are large enough and/ or receive adequate recharge (Ward, 1974).

Bedrock units in Nemaha County yield 0–100 gpm (0–0.006 m^3/s) of water. The highest yields are from the Council Grove Group of Permian age in the northeastern (e.g., secs. 1, 8, 16, and 36, T. 1 S., R. 14 E., and secs. 13 and 14, T. 2 S., R. 14 E.) and in south-central (e.g., NESWSE sec. 15, T. 5 S., R. 13 E.) parts of the county. Unfortunately, bedrock units that yield the largest quantities generally have the poorest water quality. Sulfate levels are particularly high where gypsum layers in the limestone and shales have been dissolved.

The bedrock aquifers have been described by Ward (1974). The Pennsylvanian rocks are not generally aquifers, except for sandstone lenses in the Scranton

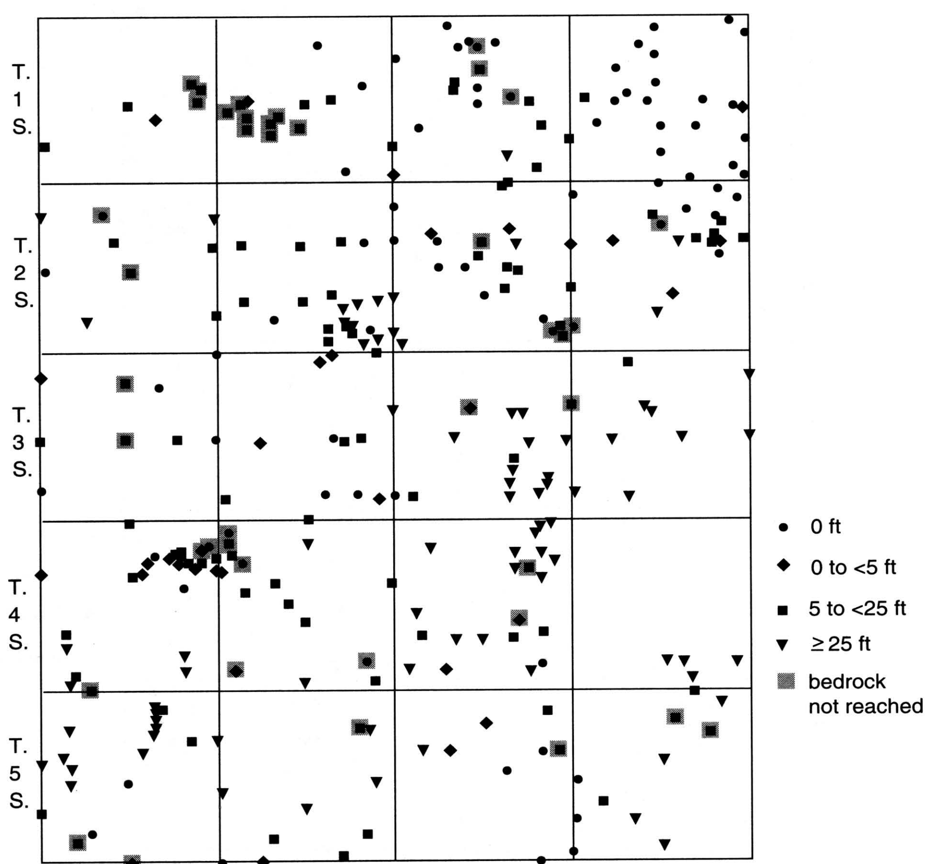

FIGURE 62—Total Pleistocene sand and gravel thickness, Nemaha County.

Shale, which yield up to 10 gpm (0.0006 m^3/s), and in the Willard, Pillsbury, and Root Shales and the Wood Siding Formation, which yield less than 5 gpm (0.0003 m^3/s) to wells. Small quantities [<1 gpm(<0.00006 m^3/s)] can be obtained from weathered and fractured zones of some other Pennsylvanian formations near their outcrop areas. In contrast, the Foraker and Grenola Limestones of Permian age yield as much as 50 gpm (0.003 m^3/s), and the Red Eagle, Beattie, and Wreford Limestones may yield 10 gpm (0.0006 m^3/s) to wells. Solution channels and fractures are important for water occurrence in these limestones. Sandstone lenses in the Janesville Shale of Permian age locally yield less than 5 gpm (0.0003 m^3/s).

The depth to water levels are reported by Denne et al. (1990a). No attempt was made to contour water-elevation data because many values represent multiple aquifers and because the potentiometric surface is not continuous throughout the county. It is evident, however, that the elevations of water decline along the main buried valley from 1,200 ft (365 m) in the west to 1,050 ft (320 m) near the Jackson County border on the east.

The depths to water (fig. 64) are also of limited usefulness because of their composite nature. Head differences between various aquifers may be significant, as demonstrated by a nest of three piezometers installed in SWSWNW sec. 32, T. 4 S., R. 11 E., where water levels on August 2, 1983, were 144 ft (43.9 m), 136 ft (41.5 m), and 8 ft (2.4 m) for wells completed in the basal gravel at 350 ft (110 m), the intermediate fine-grained sand at 180 ft (55 m), and the uppermost glacial till at 80 ft (24 m), respectively. The clayey sediments isolate the aquifers, but the use of a continuous gravel pack along wells penetrating multiple aquifers allows interconnection of the aquifers.

Despite the complications in interpretation of the data, the greatest depths to water (when water was encountered in a drill hole) were reported to be 186 ft (56.7 m) and 172 ft (52.4 m) in the main buried valley in NWSENE and NESENE sec. 2, T. 4 S., R. 13 E. Other large depths [up to 150 ft (46 m)] occur in bedrock wells in northeastern Nemaha County. A rather anomalously deep value [138 ft (42.1 m)] was also reported for the buried channel in SENESE sec. 20, T. 2 S., R. 12 E., but the elevation [1,087 ft (331.3 m)] is comparable to others in the South Fork Big Nemaha River modern and buried drainage system. Although the depths to water in the glacial and bedrock aquifers vary considerably, values are commonly between 5 ft (2 m) and 25 ft (8 m) in the alluvial deposits.

In some wells in Nemaha County, water rises above the land surface. Ward (1974) mapped several areas of

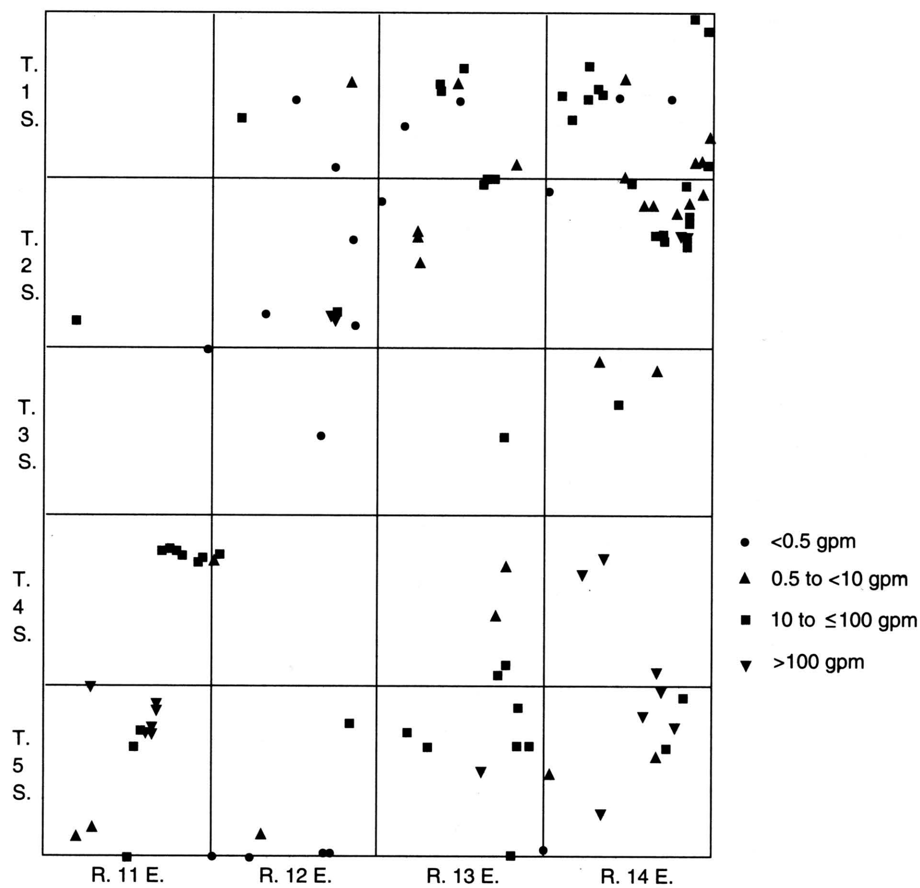

FIGURE 63—Estimated well yields, Nemaha County.

artesian flow near Gregg and Muddy creeks in T. 3 S., R. 14 E., and Coal Creek in T. 5 S., R. 12 E. Each of these areas has alluvial and/or glacial deposits. In his report Ward (1974) cited a few flowing wells from Permian limestones and at least one from the Atchison Formation or older glaciofluvial deposits.

Because the depth to water is used to calculate saturated thickness (fig. 65), the saturated-thickness values must be viewed with some caution. In addition, it should be recognized that a large saturated thickness does not necessarily include much good aquifer material. To choose a location for a large-capacity well, therefore, both saturated thickness and the presence of permeable sand and gravel deposits should be considered.

In Nemaha County the greatest saturated thicknesses occur in the main buried valley and its tributaries (fig. 59). The largest value [358 ft (109 m)] occurs at two sites where significant differences can be observed: in SWSWSW sec. 23, T. 3 S., R. 13 E., the dominant material is clay with sand and gravel between the depths 110 ft (34 m) and 120 ft (37 m), whereas in NENESE sec. 33, T. 4 S., R. 12 E., three layers of gravel total 22 ft (6.7 m) and fine-grained sand makes up 72 ft (22 m) of the sediment column.

The saturated thickness of alluvial deposits is commonly within the range 0–30 ft (0–9 m). As Ward (1974) observed, the smallest saturated thicknesses of glacial deposits generally occur near the walls of the modern valleys and over bedrock highs, but where 20–30 ft (6–9 m) of saturated thickness occurs, thin sand and gravel layers should still provide an adequate supply of water for domestic use.

In Nemaha County ground-water discharge is primarily to streams, springs, and wells. Recharge may be considerably more complicated. The topographic relief and the permeability of the exposed geologic units influence recharge directly from precipitation. Leakage between the unconsolidated aquifers and the bedrock aquifers (upward or downward, depending on the head relationships) also contributes to recharge. Little is currently known about the head differences between the various Quaternary, Permian, and Pennsylvanian aquifers, but Ward (1974, p. 11) stated that "where water moves from the Permian aquifers into glacial deposits within buried valleys, the hydrostatic level in the glacial deposits appears to equalize with that in the bedrock formation." Additional research is needed on this topic because it is important to the understanding of both the quantity and quality of water available.

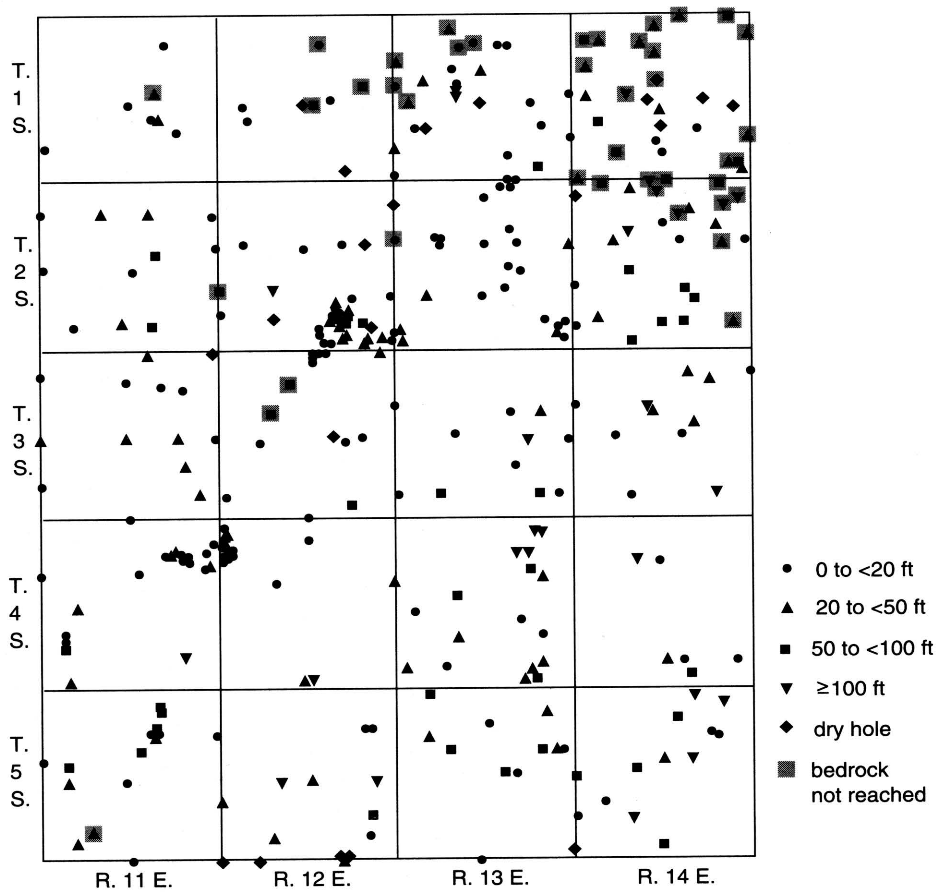

FIGURE 64—Depth to water in wells and test wells, Nemaha County.

Shawnee County

Geology

The geology of Shawnee County has been described by Johnson and Adkison (1967) and Johnson and Wagner (1967). The area is in the western part of the Forest City basin, a predominantly post-Mississippian structure. Exposed rocks strike 15°–30° and dip northwest at 15–40 ft/mi (2.8–7.6 m/km). The regional dip is interrupted locally by minor folds. The total thickness of unexposed sedimentary rocks, which range in age from Late Cambrian to Late Pennsylvanian, may be as much as 3,300 ft (1,000 m). Exposed sedimentary rocks include more than 1,000 ft (300 m) of the Shawnee and Wabaunsee Groups of Late Pennsylvanian age and the Admire and Council Grove Groups of Early Permian age (fig. 5). Formations of the Shawnee Group exposed in eastern Shawnee County include, in ascending order, the Oread Limestone, the Kanwaka Shale, the Lecompton Limestone, the Tecumseh Shale, the Deer Creek Limestone, the Calhoun Shale, and the Topeka Limestone. The Severy Shale, Howard Limestone, Scranton Shale, Bern Limestone, Auburn Shale, Emporia Limestone, Willard Shale, Zeandale Limestone, Pillsbury Shale, Stotler Limestone, Root Shale, and Wood Siding Formation make up the Wabaunsee Group. In western Shawnee County the Admire Group includes the Onaga Shale, the Falls City Limestone, and the Janesville Shale, and the Council Grove Group is represented by the Foraker Limestone and the Johnson Shale.

The stratigraphic sequence in Shawnee County includes cyclic deposits of shale, siltstone, sandstone, and limestone (Johnson and Adkison, 1967; Johnson and Wagner, 1967). Coal and conglomerate occur locally. In several areas large thicknesses of strata were eroded from channels, and sandstones filling the channels are part of the Calhoun, Severy, Scranton, Onaga, and Janesville Shales and the Wood Siding Formation. The Oread, Topeka, and Foraker Limestones contain some chert; the Howard Limestone locally includes gypsum; and several formations have inclusions of barite and/or celestite. Iron (limonite or pyrite) occurs in most formations. The rock units are gray, brown, black, orange, olive, yellow, red, or white. Where exposed, most of the formations are jointed, and the orientations of the two major sets of vertical joints are 60°–70° and 20°–30° (Johnson and Wagner, 1967).

Overlying bedrock in some parts of Shawnee County are colluvium, chert gravel deposits, till, outwash, loess,

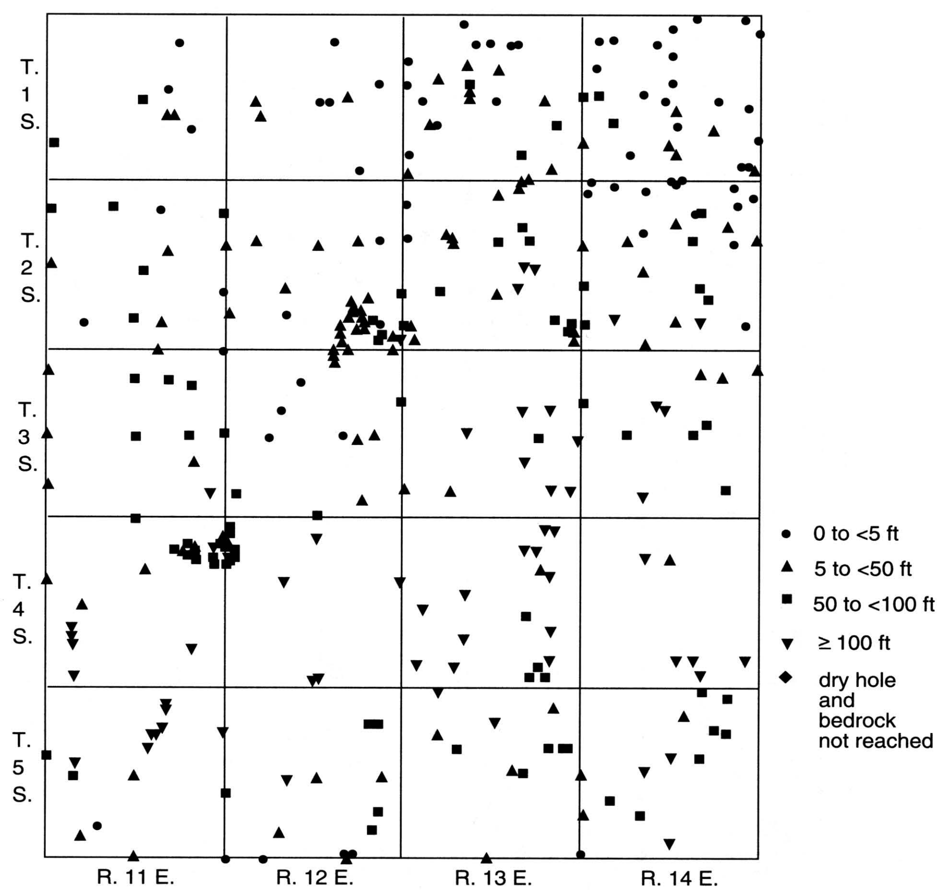

FIGURE 65—Saturated thickness of Pleistocene deposits, Nemaha County.

and alluvium (fig. 9). These materials have been described by Johnson and Adkison (1967) and Johnson and Wagner (1967). The colluvium consists primarily of clay, silt, and very fine grained sand. The deposits are thin and occur throughout much of the area, including the back side of stream terraces.

Remnants of late Tertiary or early Quaternary chert gravel deposits have been described at 10 upland sites in Shawnee County (Johnson and Adkison, 1967; Johnson and Wagner, 1967). The chert gravel also commonly contains limestone gravel, may be in a matrix of clay, silt, or sand, and is locally cemented. The chert was derived from the west, especially from the Wreford and Barneston Limestones of Early Permian age. It was deposited in the late Tertiary or early Quaternary valleys of the Kansas and Wakarusa rivers and a few tributaries, but subsequent erosion left some of the deposits high above the modern floodplains. A deposit northwest of Silver Lake, for example, overlies bedrock more than 150 ft (46 m) above the Kansas River floodplain (Davis and Carlson, 1952). When the county was glaciated, some of the chert gravel was incorporated into till and outwash deposits.

Johnson and Adkison (1967) and Johnson and Wagner (1967) mapped both glacial till and outwash as one unit. However, locally the till deposits are interbedded with outwash. The till is generally unstratified and consists of unsorted clay with silt, sand, gravel, cobbles, and boulders. Most of the gravel and larger fraction consists of limestone, igneous and metamorphic rocks, chert, sandstone, ironstone, quartz, and shale. The weathered till is light brown or reddish brown, and the unweathered till is gray. Where deeply weathered, the fine-grained material has been removed, leaving a concentration of gravel- to boulder-size material. The largest boulder reported in the area (Davis and Carlson, 1952) is in sec. 19, T. 10 S., R. 16 E., between Halfday and Indian creeks. This pink conglomeratic quartzite boulder consists of two pieces whose above-ground dimensions are 23 × 11 × 8 ft and 18 × 7 × 2 ft (7.0 × 3.4 × 2.4 m and 5.5 × 2.1 × 0.6 m).

Glacial outwash occurs primarily near the Kansas River and in the terminal area of the ice advance. The outwash, as described by Johnson and Adkison (1967) and Johnson and Wagner (1967), includes stratified clay, silt, sand, gravel, cobbles, and boulders deposited by meltwater during the advance (Atchison Formation) and retreat (Grand Island and Sappa Formations) of the Kansan ice sheet. The use of these three formation terms in Shawnee County is now rare. Johnson and Adkison (1967) and Johnson and Wagner (1967) stated that the formations were difficult to differentiate, but their Atchison Formation was commonly gravel and sand, sometimes overlain by silt. Their Grand Island Formation commonly included gravel and sand; and their Sappa Formation consisted primarily of glaciofluvial and glaciolacustrine silt. The outwash deposits range from well to poorly sorted, and some are crossbedded or have structures indicating deposition in a delta. Within the county the gravel ranges from deposits dominated by local rock types (e.g., limestone and chert with some shale and sandstone) to those with an abundance of erratics. The coarse-grained sediments are commonly subrounded to subangular. Some of the deposits are cemented by calcite. The Menoken terrace and Meade formation, as described by Beck (1959) and Davis and Carlson (1952), include the classical Kansan Stage Grand Island and Sappa Formations, but these three formation names are not now used in northeastern Kansas. The Menoken terrace was named by Davis and Carlson (1952, p. 212) "from the township [northwest of Topeka] where it is typically developed."

Although loess occurs on stream divides in Shawnee County, it is thin and poorly exposed and was not mapped by Johnson and Adkison (1967) and Johnson and Wagner (1967). Mudge and Burton (1959) described two exposures of Peoria (Wisconsin) loess just to the west of the Shawnee County border in Wabaunsee County. The material is typically tannish-gray to gray, locally iron-stained clay and silt that is leached of calcium carbonate in the upper part. The Illinoian Loveland loess and the Sangamon Soil also occur in Shawnee County.

In Shawnee County remnants of the Illinoian Buck Creek terrace (which is commonly covered and obscured by colluvium and loess) have been described and mapped by Johnson and Adkison (1967), Johnson and Wagner (1967), Beck (1959), and Davis and Carlson (1952). In the Kansas River valley, the Buck Creek terrace is generally less than 0.25 mi (0.4 km) wide and is 30–80 ft (9–24 m) above the river. Near the western border of the county, one test hole (NENENE sec. 19, T. 10 S., R. 13 E.) in the terrace deposits showed a 15-ft (4.6-m) basal layer of silty clay overlain by 14 ft (4.3 m) of clayey sand and gravel below 20 ft (6.1 m) of pebbly clay, silty clay, sandy silt, silt, and clay [the upper 15 ft (4.6 m) of which may be colluvium]. Near the eastern border of the county (north of Tecumseh), an exposure of the Buck Creek terrace includes at least 12 ft (3.7 m) of gravel below 10 ft (3.0 m) of silt with the Sangamon soil below loess. In the Wakarusa River valley, the Buck Creek terrace ranges up to 0.5 mi (0.8 km) in width, is generally 5–10 ft (2–3 m) above the adjacent Newman terrace, and consists of reddish-brown clayey silt with some pebbles, including chert and quartzite. On the west side of Cross Creek, the Buck Creek terrace is 20–90 ft (6–27 m) above the stream and almost 1 mi (1.6 km) wide. Along Mission Creek the height range is 15–45 ft (4.6–14 m) above stream level, and the width is generally less than 0.5 mi (0.8 km).

The Newman terrace occurs in the Kansas and Wakarusa River valleys and major tributaries in Shawnee County and has been mapped and described by Johnson and Adkison (1967), Johnson and Wagner

(1967), Beck (1959), and Davis and Carlson (1952). In the Kansas River valley, the terrace is 20–45 ft (6–14 m) above the river, averages 1 mi (1.6 km) in width [although it ranges from 100 ft (30 m) to 2 mi (3 km)], and is best preserved on the northern side of the river, except near Topeka where the Shunganunga Creek enters the valley. In the Kansas River valley the Newman terrace fill, which ranges up to 90 ft (27 m) in thickness, includes a basal layer of coarse-grained sand, gravel, and cobbles overlain by clay, silt, and fine-grained sand. The material in the upper part is similar to sediments now carried by the river. The Newman terrace makes up most of the floodplain of the Wakarusa River and major creeks in the county.

Post-Newman (middle and late Holocene) alluvial deposits in Shawnee County also have been mapped and described by Johnson and Adkison (1967), Johnson and Wagner (1967), Beck (1959), and Davis and Carlson (1952). Along the Kansas River the alluvium ranges from 0.75 mi to 3.5 mi (1.2–5.6 km) in width, and together with the Newman terrace it forms the floodplain. The alluvial deposits include silt and silty clay over fine- to coarse-grained sand, which continues to grade downward to gravel and some boulders. There are some clay lenses, particularly in meander scars. Along the major tributaries of the Kansas River alluvial deposits are narrow [e.g., <150 ft (<46 m) wide along the Wakarusa River], and the scarp to the Newman terrace is commonly less than 5 ft (2 m) high.

In Shawnee County the southern bank of the Kansas River valley is generally steep, and the river currently flows along the southern side of the valley except where the Shunganunga Creek enters it in Topeka. As Davis and Carlson (1952, p. 215–216) noted, tributaries on the northern side of the Kansas River "are larger and more numerous. Thus the sediment supply from northern tributaries is much greater and produces a delta effect in the Kansas River channel which forces the river to the south. It is significant that the river shifts to the northern bluff line only opposite points at which large northward-flowing tributaries enter the channel." Somewhat in conflict with this idea is the Mission Creek entrance, where the Kansas River flows across the mouth of its valley. Perhaps the upstream junctions of the Kansas River with Cross Creek and several small tributaries on the north outweigh the influence of Mission Creek.

The southern limit of glaciation in Kansas extends east-west across Shawnee County, although its exact position is unknown (see fig. 7). The state geologic map (Kansas Geological Survey, 1992) indicates the position of the limit to be approximately halfway between the Kansas and Wakarusa rivers. Johnson and Adkison (1967) believed that the southern extent of ice in eastern Shawnee County was at the Wakarusa River but that it may not have gone over the east-facing escarpment formed by the Bern Limestone in the central part of the county. They suggested that the ice front extended northwestward along Lynn Creek from its junction with the Wakarusa River toward the town of Pauline to the Shunganunga Creek. Smyth (1898) described the terminal moraine buried in the Shunganunga valley. Farther west, Johnson and Wagner (1967) suggested that ice movement was limited by the divide between the Kansas and Wakarusa rivers and extended generally westward from the Shunganunga Creek and then southwestward along Mission Creek to the border with Wabaunsee County at about the position where Mission Creek bends to the south.

That the glacial limit may have been somewhat farther south than the area described by Johnson and Adkison (1967) and Johnson and Wagner (1967) is suggested by some well logs [e.g., SWSWSW sec. 16, T. 12 S., R. 15 E., where 55 ft (17 m) of glacial deposits were reported; NENESW sec. 28, T. 12 S., R. 14 E., which includes glacial clay and boulders from 17 ft to 28 ft (5.2–8.5 m); NWNWNE sec. 24, T. 13 S., R. 14 E., where brown clay with sand and/or gravel was encountered from 2 ft to 30 ft (0.6–9 m); and SENENW sec. 26, T. 13 S., R. 15 E., with 25 ft (7.6 m) of clay to sandy clay; all these sites, incidentally, are in areas mapped by previous investigations as bedrock]. Exposures near Auburn, such as in SWSESE sec. 24, T. 13 S., R. 14 E., and NWNENW sec. 29, T. 13 S., R. 15 E., also should be evaluated to determine whether the pebbly to bouldery clay, which includes both local and erratic rock types (chert, brown quartzite, and greenstone), is glacial till or outwash. Exposures of deposits that are more obviously outwash are known to occur nearby in the North Branch Wakarusa River valley and are described later.

Three miles (5 km) north of the glacial limit at the border between Shawnee and Wabaunsee counties [as mapped by Johnson and Wagner (1967)], a small preglacial valley was cut into Pennsylvanian shales. This channel (secs. 10 and 11, T. 12 S., R. 13 E.) is filled with ice-contact deposits of poorly stratified sand, gravel, cobbles, and boulders of the Atchison Formation(?) and glacial till (Johnson and Wagner, 1967; Mudge and Burton, 1959). Elsewhere in the county, glaciation had a more profound effect on the drainage system.

In early Pleistocene time the main drainage was probably to the east, approximately as it is now. When ice covered the area during pre-Illinoian time, many temporary drainage changes occurred. When the Kansas River was dammed by ice at St. George in Pottawatomie County (Smyth, 1898; Mudge, 1955; Mudge and Burton, 1959; Dort, 1987a), flow was diverted southeastward across northern Wabaunsee County to the present junction of Mill and Dry creeks near Maple Hill and then along Dry Creek. Water ponded in that area to an elevation of 1,115 ft (339.9 m) and then spilled southeastward across the divide between Dry and Mission creeks into Shawnee County (Mudge, 1955).

Below its junction with the recent Haskell Creek, the Mission Creek valley (which together with Dry Creek forms a lobate shape) was also blocked by ice. Water beyond the ice ponded and then spilled over the divide southeastward into the North Branch Wakarusa River west of Auburn (Todd, 1911; Johnson and Wagner, 1967). Evidence for drainage along the North Branch includes outwash remnants (lag concentration of gravel- to boulder-size limestone and glacial erratics plus a few small sand and gravel deposits). Most of the erratics occur 5–60 ft (2–18 m) above the stream on the east side of the valley. Beyond the North Branch water flowed through the Wakarusa River to the Kansas River east of Lawrence in Douglas County (Todd, 1911; Johnson and Adkison, 1967; Johnson and Wagner, 1967). In addition to flow along the Wakarusa system, water also may have drained eastward from Mission Creek to Shunganunga Creek (Johnson and Wagner, 1967).

As ice blocked the major drainageways, several other temporary diversion channels were developed. Johnson and Wagner (1967) described a channel extending from sec. 29, T. 11 S., R. 15 E., southward to the Shunganunga Creek in sec. 16, T. 12 S., R. 15 E. A north-flowing tributary to the Kansas River now occupies a broad [locally almost 1 mi (1.6 km) wide] valley in the northern half of this former diversion channel. In the southern half a recently acquired water-well record for SW sec. 4, T. 12 S., R. 15 E. (not field checked for location) indicates that the depth to bedrock is greater than 37 ft (11 m), the thickness of fine- to medium-grained sand is greater than 23 ft (7.0 m), and the yield is 40 gpm (0.003 m^3/s). As the glacier retreated north of the Kansas River valley, it provided a large amount of outwash to the valley, and several other diversion channels developed. As described by Johnson and Wagner (1967), these include possible channels that flowed westward across the divide between Cross and Soldier creeks in the northern halves of sec. 1, T. 10 S., R. 13 E., and sec. 6, T. 10 S., R. 14 E., and southeastward near the common corners of secs. 1 and 12, T. 10 S., R. 13 E., and secs. 6 and 7, T. 10 S., R. 14 E. In NW sec. 33, T. 10 S., R. 15 E., meltwater may have temporarily drained eastward. Little Soldier Creek formerly flowed through the eastern half of sec. 18 and NW sec. 19, T. 10 S., R. 15 E. An exposure of sediments in SWNE sec. 18, T. 10 S., R. 15 E., includes 17 ft (5.2 m) of somewhat cemented gravel that seems to dip southwest and overlies bedrock.

A bedrock topographic map of Shawnee County (plate 1) was constructed using 436 logs (Denne et al., 1990a), county geologic maps (Johnson and Adkison, 1967; Johnson and Wagner, 1967; Ward and O'Connor, 1983), and metric topographic maps (U.S. Geological Survey, 1982). Where bedrock is exposed at the land surface, the bedrock and surface topography are equivalent.

A test hole in SWSE sec. 18, T.10 S., R. 15 E., confirms the presence of channel deposits more than 66 ft (20 m) deep, with sand and gravel from 8 ft to 36 ft (2–11 m), near Little Soldier Creek. As described earlier, flow may have been southwestward, directly from sec. 18 to sec. 19, T. 10 S., R. 15 E. (between two bedrock "islands"). Alternatively, flow could have been southward in a valley now buried by glacial deposits between Little Soldier and Messhoss creeks. The latter possibility is supported by a well log in SWNENE sec. 31, T. 10 S., R. 15 E., that indicates sand and gravel layers from 13 ft to 64 ft (4–20 m), a depth to bedrock of 107 ft (32.6 m), and a reported yield of 70 gpm (0.004 m^3/s). Several other small, now-buried valleys that probably flowed southerly toward the Kansas River are indicated by drill logs in NWSWNW and SWNWSW sec. 32, T. 10 S., R. 14 E.; SESESE sec. 32, T. 10 S., R. 15 E.; NWNE sec. 4, T. 11 S., R. 15 E.; and NENENE and NESENE sec. 10 and NWSWNW and SENESW sec. 11, T. 11 S., R. 15 E., as well as others nearby.

A map view of the glacial-drift deposits that cover the area southeast of the South Branch Shunganunga Creek and the town of Pauline suggests a delta or outwash fan. Logs in this region include SESENE sec. 31 and SWSWNE sec. 33, T. 12 S., R. 16 E., and NENWNW, NWSWNW, and SWSWNW sec. 4, SESWSE sec. 8, NENENW sec. 14, and NENE sec. 18, T. 13 S., R. 16 E., several of which show a basal sand. One well in particular [SESENE sec. 31, T. 12 S., R. 16 E., with a 72-ft (22-m) depth to bedrock and a thick sand] indicates a now-buried valley that may have been connected with Lynn Creek. Additional research should be done in this area to evaluate the character of the deposits, define the extent of the channel (whether it is narrow or part of a broader outwash system), and determine whether the glacial ice extended to the Wakarusa River west of Lynn Creek (either by overriding or being funneled around the bedrock high that begins to the west in central Shawnee County).

The valley of the Shunganunga Creek widens from 0.25 mi to 0.5 mi (0.4–0.8 km) across secs. 10 and 11, T. 12 S., R. 15 E. Whether this is due to the underlying Severy Shale bedrock and/or to the earlier drainage history is unclear.

The depth to bedrock in Shawnee County is shown in fig. 66. The largest known values occur in buried valleys north of the Kansas River and east of Soldier Creek. An oil borehole log in NWNE sec. 4, T. 11 S., R. 15 E., suggests that bedrock is at 120 ft (37 m) with gravel at 24–26 ft (7.3–7.9 m) and sand at 67–75 ft (20–23 m) and 82–120 ft (25–37 m) deep. A water-well record in SWNENE sec. 31, T. 10 S., R. 15 E., indicates sand and gravel layers between 13 ft (4.0 m) and 64 ft (20 m) and bedrock at 107 ft (32.6 m). The next largest depth to bedrock [93 ft (28 m)] occurs below the Newman terrace in the Kansas River valley.

Of 117 borehole logs in alluvial deposits [as mapped by Johnson and Adkison (1967) and by Johnson and Wagner (1967)] in the Kansas River valley, 60 do not report reaching bedrock. Of the 57 remaining, 25% (14) identify bedrock between 40 ft (12 m) and 50 ft (15 m) and another 25% (14) indicate bedrock between 70 ft (21 m) and 80 ft (24 m). The largest value is 86 ft (26 m), and all but two sites (near the southern valley wall) have more than 30 ft (9 m) of unconsolidated deposits. In the Newman terrace deposits of the Kansas River valley, logs for 52 wells (out of 126) report bedrock depths. Seventeen (33%) of these depths are between 50 ft (15 m) and 60 ft (18 m). All but three sites (two of which are near the southern valley wall) have more than 40 ft (12 m) of unconsolidated deposits, and the deposit thicknesses range up to 92 ft (28 m). In the Kansas River valley, the depth to bedrock below the alluvial and terrace deposits tends to be greatest [>65 ft (>20 m)] in northeastern Shawnee County near the Muddy Creek junction in adjacent Jefferson County; locally, near the mouth of Shunganunga Creek, especially where the Kansas River shifts from the southern to the northern side of its valley; between the junctions of the Soldier and Halfday Creek valleys with the Kansas River; and near the Cross Creek valley entrance downstream to the Mission Creek junction. The greatest depths correspond to the deepest part of the channel underlying the recent Kansas River valley, as shown on the bedrock topographic map.

The depth to bedrock below alluvial surfaces in other stream valleys in Shawnee County is not well known because of limited data. In the Wakarusa River valley, eight borehole logs indicate that the depths range at least from 18 ft to 36 ft (5.5–11 m). Along Soldier Creek, stream deposits at four sites are 19–54 ft (5.8–16 m) thick. The Shunganunga Creek valley has 18 ft (5.5 m) of alluvial deposits at two sites, while one depth to bedrock value along the South Shunganunga Creek is 27 ft (8.2 m). Mission Creek has 41 ft and 42 ft (13 m) of valley fill at two sites. Deposits along Halfday Creek and its tributaries range from 26 ft to 44 ft (7.9–13 m) in thickness. Two depth to bedrock values in the Big Muddy Creek valley are 22 ft (6.7 m) and 23 ft (7.0 m). Elsewhere in the county, most stream deposits are between 10 ft (3 m) and 35 ft (11 m) thick.

The depth to bedrock below Buck Creek terrace deposits in Shawnee County is known for only two sites. The values are 31 ft (9.4 m) and 49 ft (15 m) for deposits along Cross Creek and the Kansas River, respectively.

Of 90 drill holes in glacial till and outwash deposits, 83 reportedly reached bedrock. Thirty-three (40%) of the depths to bedrock are in the range 20–40 ft (6–12 m), with a fairly even distribution of most of the other 50 in the remainder of the 10-ft (3-m) increments between 10 ft (3 m) and 80 ft (24 m). The thickness of the glacial deposits tends to be greater north of the Kansas River than south of it. The largest values [120 ft (37 m) and 107 ft (32.6 m), as previously described, and many others from 65 ft to 85 ft (20–26 m)] are associated with small buried valleys that drained southward to the river (e.g., sec. 32, T. 10 S., R. 14 E.; sec. 18, T. 10 S., R. 15 E.; and secs. 10 and 11, T. 11 S., R. 15 E.). Elsewhere in the deposits mapped as Menoken terrace by Davis and Carlson (1952) and Beck (1959), the depth to bedrock commonly ranges from 30 ft to 60 ft (9–18 m). The glacial-drift deposits become thinner farther to the north of the river, with values commonly between 15 ft (4.6 m) and 45 ft (14 m). To the south of the river the glacial drift is generally less than 25 ft (7.6 m) thick, although a thickness of 55 ft (17 m) was reported just south of Shunganunga Creek in SWSWSW sec. 16, T. 12 S., R. 15 E., and values up to 72 ft (22 m) occur in the fan-shaped area of deposits southeast of Pauline.

In areas mapped as bedrock [by Johnson and Adkison (1967) and by Johnson and Wagner (1967)] and those areas that do not have an obviously unmapped cover of glacial deposits, 65 logs indicate that the depth to bedrock is less than 25 ft (7.6 m), and more than half of the values are less than 10 ft (3 m). The unconsolidated material may include loess, colluvium, or residuum. Only one site showed any sand or gravel [sand from 6 ft to 9 ft (2–3 m) in NWNWNE sec. 12, T. 12 S., R. 16 E.], and this may actually be a thin glacial-drift deposit.

Total thicknesses of sand and gravel layers in Shawnee County are shown in fig. 67. The largest values [>82 ft (>25 m) in the Newman terrace in SENWNW sec. 12, T. 11 S., R. 13 E., and 74–79 ft (23–24 m) in alluvial deposits in SW sec. 18, T. 11 S., R. 14 E., SESWNE sec. 30, T. 11 S., R. 16 E., NWNWSW sec. 27, T. 11 S., R. 17 E., and NESESW sec. 27, T. 11 S., R. 17 E.] occur in the Kansas River valley. Of the remaining 32 logs (out of 65) that reached bedrock below the alluvial deposits of the Kansas River valley, the sand and gravel thickness ranges from 8 ft to 68 ft (2–21 m), with half of the values between 30 ft (9 m) and 50 ft (15 m). In 77 of the 91 logs (85%) of alluvial deposits, sand or gravel begins within 20 ft (6 m) of the land surface. The material generally becomes coarser with depth and includes a basal sand and gravel or gravel layer, which may be 60 ft (18 m) or more thick (e.g., NWSENW sec. 25, T. 10 S., R. 12 E., and SW sec. 18, T. 11 S., R. 14 E.). Below the Newman terrace of the Kansas River valley, 33 logs for wells that reached bedrock include sand and gravel deposits from 0 to 67 ft (20 m) thick, with 13 (40%) logs each in the ranges 22–40 ft (6.7–12 m) and 50–67 ft (15–20 m). In 85 of 100 logs for Newman terrace deposits, sand or gravel begins 10–40 ft (3–12 m) below the land surface. As in other alluvium, the material generally becomes coarser with depth, although the sequence is sometimes reversed. As might be expected, most of the thickest sand and gravel deposits in the Kansas River valley occur in the same areas as previously described, where the depth to bedrock is greatest. Much of the deeper and coarser material probably is glacial outwash deposited directly into the Kansas River or indirectly through the major tributaries.

The total thickness of sand and gravel that presently remains in the smaller stream valleys is known only from a limited number of data points. Almost all values are less than 15 ft (4.6 m), if there is any thickness at all. Where there is sand and/or gravel, it is almost always just above bedrock. At eight sites along the Wakarusa River, the Newman terrace has up to 4 ft (1 m) of sand or gravel, whereas along Soldier Creek there is 0–17 ft (0–5.2 m) at four sites. Based on three sites each, Mission Creek stream deposits have 3–8 ft (0.9–2 m) of coarse material; alluvial deposits of the Shunganunga and South Shunganunga creeks have 1–5 ft (0.3–2 m) of basal sand and/or gravel; and Halfday Creek and a tributary have 0–22 ft (0–6.7 m). Two logs in the Big Muddy Creek valley show no sand or gravel.

Two logs in Buck Creek terrace deposits show 5 ft (2 m) of sand and gravel in the Cross Creek valley and 14 ft (4.3 m) in the middle of the unconsolidated deposits in the Kansas River valley.

Of 81 logs for test holes that reached bedrock through glacial deposits, 30% (24) had no sand or gravel and another 55% (45) had values between 1 ft (0.3 m) and 20 ft (6 m). In the other wells the thickness of coarse-grained sediments ranged up to 57 ft (17 m) (NWNWNW sec. 11, T. 11 S., R. 15 E.). The larger values tend to be associated with the small buried valleys north of the Kansas River (e.g., sec. 32, T. 10 S., R. 14 E.; secs. 18 and 31, T. 10 S., R. 15 E.; and sec. 4, T. 11 S., R. 15 E.), and they include alternating layers of sand and gravel that do not necessarily extend to the bedrock surface. Elsewhere in deposits mapped as Menoken terrace, sand and gravel thicknesses range up to 43 ft (13 m), but they are commonly less than 15 ft (4.6 m).

In the fan-shaped area of glacial drift extending southeast from Pauline, the one obvious channel deposit (SESENE sec. 31, T. 12 S., R. 16 E.) contains 28 ft (8.5 m) of sand just above bedrock, but only three of six other sites in this area have any [1–10 ft (0.3–3 m)] basal sand or sand and gravel.

Ground water

The greatest quantities of ground water available in Shawnee County are from Newman terrace deposits and other alluvium in the Kansas River valley. Well yields range up to 2,500 gpm (0.16 m^3/s), with values of at least 2,000 gpm (0.13 m^3/s) reported in SWNWNW sec. 24 and NWSENW and NESWSW sec. 25, T. 10 S., R. 12 E.; SENWNW sec. 12, T. 11 S., R. 13 E.; NWSWNE sec. 15, NW sec. 16, NESWSE sec. 17, and SW sec. 18, T. 11 S., R. 14 E.; NESENE sec. 14, T. 11 S., R. 15 E.; and NESESW sec. 27, T. 11 S., R. 17 E. Reported well yields (uncorrected for such factors as well diameter and length of aquifer screened) are shown in fig. 68.

In the Kansas River valley alluvial deposits, yields were reported for 80 wells. Seventy percent (56) of the wells produce at least 100 gpm (0.006 m^3/s), and 40% (32) yield at least 1,000 gpm (0.06 m^3/s). Most of the remaining yields are between 20 gpm (0.001 m^3/s) and

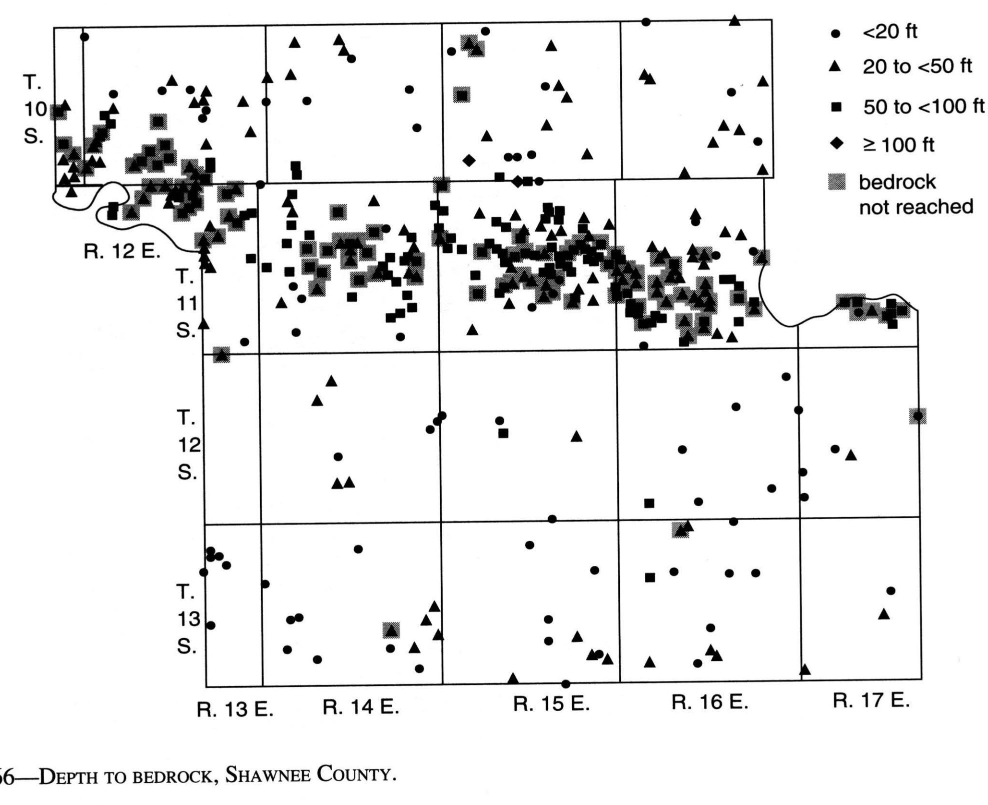

FIGURE 66—Depth to bedrock, Shawnee County.

50 gpm (0.003 m^3/s). In the Newman terrace deposits of the Kansas River valley, 47 (50%) of 95 wells reportedly produce at least 100 gpm (0.006 m^3/s), and 23 (25%) have yields of 1000 gpm (0.06 m^3/s) or more. Most of the other wells have values between 10 gpm (0.0006 m^3/s) and 60 gpm (0.004 m^3/s).

In the smaller stream valleys of Shawnee County well yields are generally 20 gpm (0.001 m^3/s) or less. In the Newman terrace deposits of the Wakarusa River valley, seven values range from 0.5 gpm to 10 gpm (0.00003–0.0006 m^3/s). Along Soldier Creek stream deposits yield 4–20 gpm (0.0003–0.001 m^3/s) to three wells. Alluvial deposits of the Shunganunga and South Shunganunga creeks produce 7–10 gpm (0.0004–0.0006 m^3/s) to another three wells. One well in the Buck Creek terrace deposits of Cross Creek produces 10 gpm (0.0006 m^3/s).

Sixty-seven wells in the glacial-drift deposits reportedly yield up to 100 gpm (0.006 m^3/s). Forty-five percent (30) produce 1–5 gpm (0.00006–0.0003 m^3/s), and 30% (20) yield 10–20 gpm (0.0006–0.001 m^3/s). The largest value [100 gpm (0.006 m^3/s) in NESWSE sec. 10, T. 11 S., R. 16 E.] apparently comes from 8 ft (2 m) of basal sand and gravel below a small modern tributary valley to the Kansas River. Several other values of 25 gpm to 70 gpm (0.0016–0.0044 m^3/s) (SWNENE sec. 31, T. 10 S., R. 15 E.; SESWSW sec. 6, SENWNE sec. 10, and NWNWNW sec. 11, T. 11 S., R. 15 E.) also are connected with buried valleys and/or the Menoken terrace on the northern side of the Kansas River and in glacial or high-terrace deposits north of the Wakarusa River (NENWSE sec. 21, T. 13 S., R. 17 E). Two other wells north of the Wakarusa River (NWNWNE and SWSENW sec. 24, T. 13 S., R. 14 E., in the Auburn area, as previously described) have relatively high yields [15–20 gpm (0.0009–0.001 m^3/s)], which apparently come from clay with sand and gravel and possibly the underlying 3-ft (0.9-m) sandstone layer in the SWSENW sec. 24 well.

The yields of 43 wells that obtain most of their water from bedrock units in Shawnee County range from 0 to 12 gpm (0.00076 m^3/s). Thirty percent (13) produce less than 1 gpm (0.00006 m^3/s), and 45% (19) yield 1–5 gpm (0.00006–0.0003 m^3/s). The larger values generally seem to be associated with sandstones in the Onaga, Scranton, and Severy Shales and with weathered near-surface rocks, including the Calhoun Shale and the Deer Creek Limestone. All or part of the water from some wells in glacial and tributary stream deposits also comes from underlying bedrock units. Notable examples include a well near a tributary of Halfday Creek (SESWSW sec. 14, T. 10 S., R. 15 E.), which reportedly produces 40 gpm (0.003 m^3/s) from a 1-ft (0.3-m) limestone layer (probably the Rulo Limestone Member of the Scranton Shale) that underlies 31 ft (9.4 m) of clay, and wells in SWSWNE sec. 15, T. 10 S., R. 13 E., SWSENE sec. 3, T. 11 S., R. 14 E., and SESWSE sec. 20, T. 12 S., R. 17 E., which yield 15–20 gpm (0.00095–0.0013 m^3/s).

The depth to water reported for wells in Shawnee County (fig. 69) must be viewed with the same caution as described previously for other counties. The measurements were not taken at a consistent time and may include wells that were not yet fully developed, pen-

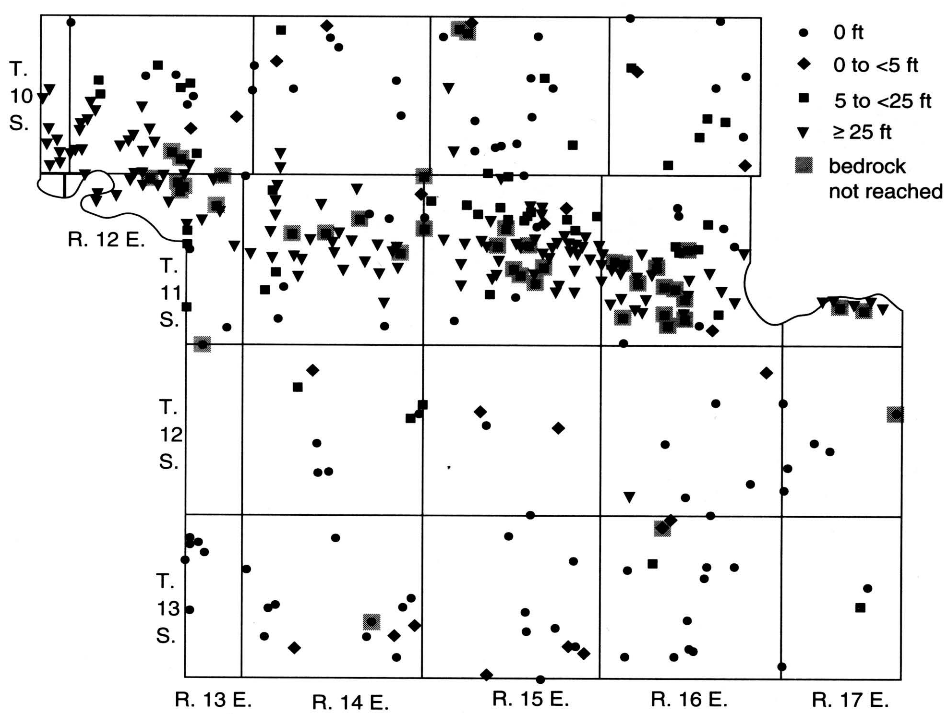

FIGURE 67—Total Pleistocene sand and gravel thickness, Shawnee County.

etrate a confined aquifer, and/or obtain water from more than one aquifer and therefore provide only composite water levels. Nevertheless, some generalizations can be made. Where water is encountered in drill holes, the levels are relatively shallow. The largest values [65–80 ft (20–24 m)] are found in wells penetrating bedrock and/or glacial deposits (including the Menoken terrace) in SWNWNE sec. 32 and NENWNW sec. 33, T. 10 S., R. 15 E., and SESWSW sec. 6, NWNESW sec. 9, and NWNWNW sec. 11, T. 11 S., R. 15 E.

Water levels in 35 of 42 bedrock wells were fairly evenly distributed among 10-ft (3-m) incremental values less than 50 ft (15 m). The remainder ranged from 50 ft to 80 ft (15–24 m). In glacial deposits 40% (29) of 73 wells had water levels between 10 ft (3 m) and 19 ft (5.8 m), whereas 10% (7) had depths to water of less than 10 ft (3 m) and seven each had depths in the 10-ft (3-m) intervals between 20 ft (6 m) and 49 ft (15 m). The remaining wells had values between 50 ft (15 m) and 70 ft (21 m). Three test holes that went only to or slightly below the bedrock contact were dry. The depth to water in two Buck Creek terrace deposit wells ranged from 17 ft to 20 ft (5.2–6 m).

Newman terrace water levels ranged from 9 ft to 34 ft (3–10 m) in 112 wells in the Kansas River valley, and 95% (106) of the wells had values greater than 15 ft (4.6 m). Depths to water in seven wells in the Wakarusa River valley Newman terrace deposits were all between 10 ft (3 m) and 20 ft (6 m). Elsewhere in the county, Newman terrace water levels ranged from 4 ft to 30 ft (1–9 m), and some wells in the terrace deposits obtained water from the underlying bedrock units.

The depth to water in alluvium in the Kansas River valley ranged from 6 ft to 37 ft (2–11 m) in 103 wells, with 50% (52) from 9 ft to 19 ft (3–5.8 m) and 41% (42) from 20 ft to 30 ft (6–9 m). In other valleys water levels in the alluvial deposits ranged from 7 ft to 15 ft (2–4.6 m) in six wells.

The elevations of water in the Kansas River valley range from 915 ft (279 m) near the western border of Shawnee County to 830 ft (250 m) near the eastern border. This indicates an average hydraulic gradient in the valley of 3 ft/mi (0.6 m/km). Elsewhere in the county a gross contour map of the water elevations indicates a reflection of the land-surface topography, with a drainage divide and ground-water flow toward the Wakarusa River in the southern townships and flow toward the Kansas River and its tributaries in the northern part of the county. Heavy pumpage, especially in the Kansas River valley, may cause local depressions in the water level.

The total saturated thickness of Pleistocene unconsolidated deposits in Shawnee County (fig. 70) reflects the same limitations as the depth to water data from which these values were calculated. The largest thicknesses appear to occur in the glacial buried valleys [72 ft (22 m) in SWNWSW sec. 32, T. 10 S., R. 14 E., and SWNENE sec. 31, T. 10 S., R. 15 E.] and in the Kansas River alluvial and Newman terrace deposits [65–68 ft (20–21 m) in SENWNW sec. 12, T. 11 S., R. 13 E.;

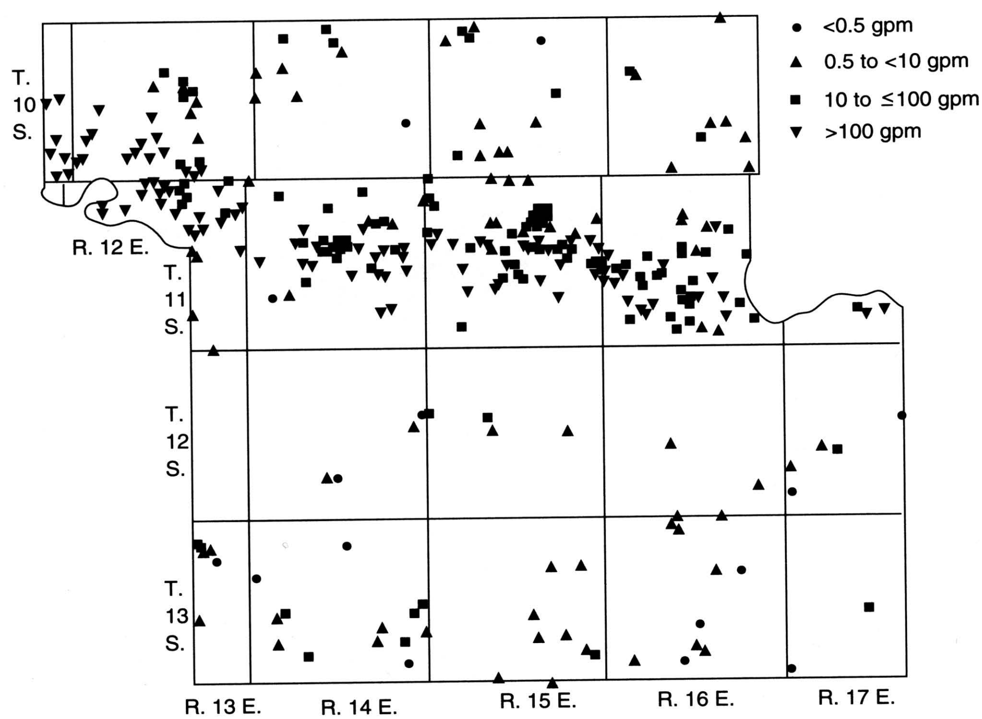

FIGURE 68—Estimated well yields, Shawnee County.

SENWSW sec. 14 and SWNENW sec. 23, T. 11 S., R. 14 E.; NENESE and SWNWSW sec. 13, T. 11 S., R. 15 E.; and NESESW sec. 27, T. 11 S., R. 17 E.].

Because many wells in Newman terrace deposits and other alluvium do not reach bedrock, the saturated thickness of unconsolidated deposits at these sites can only be stated as greater than the given numerical value. In the Kansas River valley the saturated thickness of alluvial deposits is greater than 65 ft (20 m). Of 44 wells that reach bedrock below the alluvium, 27–30% (12 or 13) have saturated thicknesses in each of the depth ranges 20–29 ft (6.1–8.8 m), 30–39 ft (9–12 m), and 50–59 ft (15–18 m). Six wells in alluvial deposits other than those of the Kansas River valley have saturated thicknesses of 3–25 ft (0.9–7.6 m).

The saturated thickness of Newman terrace deposits in the Kansas River valley ranges from 3 ft to 68 ft (0.9–21 m). Of 43 wells that reach bedrock below the terrace deposits, 50% (22) have saturated thicknesses of 20–40 ft (6–12 m) and 35% (15) have values of 50–68 ft (15–21 m). In the Wakarusa River valley, Newman terrace deposits have saturated thicknesses of 1–23 ft (0.3–7.0 m) at 7 sites. Three wells in Soldier Creek indicate values of 2–37 ft (0.6–11 m). Along other streams 14 sites indicate 0–17 ft (0–5.2 m) of saturated thickness.

Data are limited for the saturated thickness of Buck Creek terrace deposits. One well indicated 11 ft (3.4 m) along Cross Creek, and another indicated 32 ft (9.8 m) in the Kansas River valley.

The saturated thickness of glacial deposits in Shawnee County ranges from 0 to 72 ft (22 m) at 72 sites. Twelve percent (nine) are dry, and 80% (58) range from 1 ft to 29 ft (0.3–8.8 m). The larger values [>50 ft (>15 m)] are associated with the buried valleys east of Soldier Creek on the western side of T. 10 S., R. 15 E., and in southwestern T. 10 S., R. 14 E. The Menoken terrace deposits have saturated thicknesses ranging from 3 ft to 25 ft (0.9–7.6 m) at 13 sites. Five wells in the fan area near Pauline indicate saturated thicknesses of 0–29 ft (0–8.8 m).

In bedrock areas of Shawnee County the overlying unconsolidated deposits (residual soils or thin glacial deposits or loess) have saturated thicknesses of less than 15 ft (4.6 m). Of 48 sites, 41 (85%) actually have no saturated deposits above the rock.

Aquifer tests for four wells in the Kansas River valley that were pumped at 225–850 gpm (0.0142–0.0536 m^3/s) indicate transmissivity values from 14,700 ft^2/d to 48,000 ft^2/d [110,000–360,000 gpd/ft (1370–4460 m^2/d)] and storage coefficients from 0.02 to 0.09 (Fader, 1974). Based on well locations and Fader's geologic maps, the largest transmissivity value appears to be associated with alluvium, whereas the other three wells may be in Newman terrace deposits (two of which are near the border with alluvium).

In Shawnee County the major discharge of ground water is to wells, streams, and evapotranspiration. Ground-water recharge is primarily from precipitation and flooding of rivers. The most important source of ground water in the county is from deposits in the Kansas River valley and some glacial buried channels.

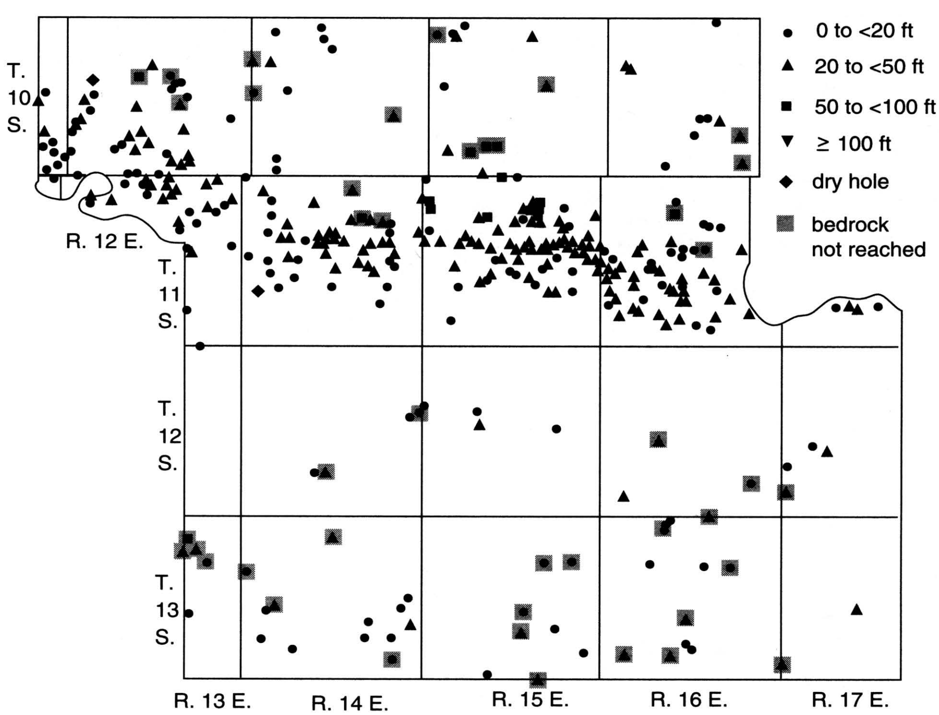

FIGURE 69—Depth to water in wells and test wells, Shawnee County.

Wabaunsee County

Geology

The geology of Wabaunsee County has been mapped and described by Mudge and Burton (1959). Fader (1974) and Beck (1959) also discussed deposits along the Kansas River in this area. Geologic units exposed in the county include alluvial, terrace, colluvial, loess, and glacial deposits and Upper Pennsylvanian and Lower Permian bedrock (figs. 5 and 9).

As described by Mudge and Burton (1959), the northern part of Wabaunsee County is a till plain with rounded hills; the eastern area is a broad, flat lowland with incised streams formed on easily dissected bedrock; the western and central parts of the county include the Flint Hills upland and escarpment [the bluff of which is 125 ft (38 m) above the lowland]. The drainage pattern is dendritic.

The structure of Wabaunsee County includes the post-Mississippian Forest City basin and the Nemaha and Alma anticlines and the pre-Mississippian North Kansas basin (Mudge and Burton, 1959). Other smaller structures include anticlines west of Alma and northeast of Eskridge, a basin northeast of Alta Vista, and small normal faults in the northwestern part of the county. Exposed rocks have a general dip to the northwest, although they are relatively flat lying. The average thickness of the rocks that are exposed in the county is 575 ft (175 m).

The oldest rocks exposed in Wabaunsee County are Upper Pennsylvanian in age, and outcrops occur mainly in stream banks and road cuts in the northern and eastern parts of the county (Mudge and Burton, 1959). The units include the Auburn Shale, the Emporia Limestone, the Willard Shale, the Zeandale Limestone, the Pillsbury Shale, the Stotler Limestone, the Root Shale, and the Wood Siding Formation of the Wabaunsee Group. These units range from 170–450 ft (52–140 m) in total thickness, with an average of 225 ft (68.6 m). Thin, dark, fossiliferous limestones and relatively thick, gray to olive-drab, nonfossiliferous shales predominate, but sandstone, sandy shale, conglomerate, and coal occur locally. Channel sandstones occur in and below the Pony Creek and Plumb Shale Members of the Wood Siding Formation, and sandstone lenses can be found in the Dry Shale Member of the Stotler Limestone, in the Wamego Shale Member of the Zeandale Limestone, and in the Pillsbury and Willard Shales. Iron stains are common on exposures of the Wabaunsee Group. Celestite occurs in some of the pores of the Tarkio Limestone Member of the Zeandale Limestone, and barite and gypsum occur locally in the Wood Siding Formation.

According to Mudge and Burton (1959), the lowermost 100 ft (30 m) of Permian (Admire Group) rocks in Wabaunsee County are similar in lithology to the Pennsylvanian units. They include thick, nonfossiliferous shales and thin limestones with some sandy shale, sandstone, coal, and conglomerate. The Admire Group is 100–220 ft (30–67 m) thick and is exposed primarily in northern and eastern Wabaunsee

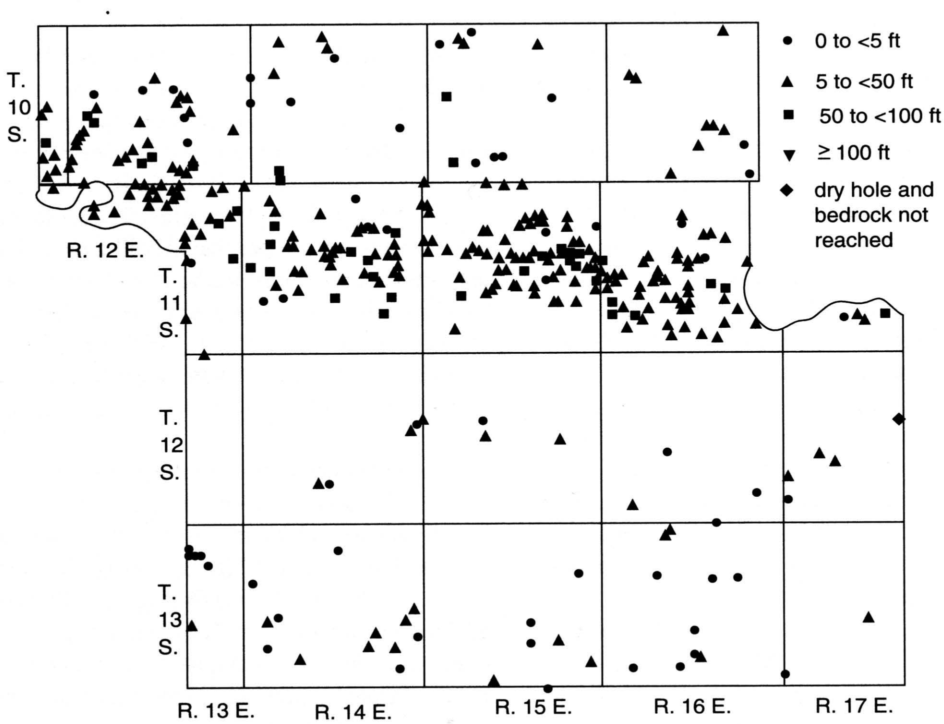

FIGURE 70—Saturated thickness of Pleistocene deposits, Shawnee County.

County. Channel deposits on the Towle Shale Member of the Onaga Shale are exposed from 4 mi (6 km) east of Keene to the Shawnee County border (which would be in or near sec. 3, T. 13 S., R. 13 E.). Local channel sandstones and lenses of sandstone also occur in the West Branch and Hamlin Shale Members of the Janesville Shale. Some seeps occur at the base of the Hamlin sandstones. One limestone unit in the West Branch Shale Member is porous to cavernous and has many small calcite-filled fractures, and a coquina limestone facies in the overlying Five Point Limestone Member is exposed in the northern to central part of the county. The Falls City Limestone lies between the Onaga and Janesville Shales. In the Admire Group the shales are gray; bluish, tan or brownish gray; grayish green; green; or maroon. The limestones are typically gray to tan or brownish gray. Charcoal or carbonized plant fragments and iron stains occur locally.

Younger Permian rocks exposed in Wabaunsee County are generally thicker light (white to gray to tan) limestones and thick, brightly variegated gray, olive, tan, green, maroon, and purple fossiliferous shales (Mudge and Burton, 1959). The limestone to shale ratio of these units is larger than in the Lower Permian and Upper Pennsylvanian rocks.

The Council Grove Group includes, in ascending order, the Foraker Limestone, the Johnson Shale, the Red Eagle Limestone, the Roca Shale, the Grenola Limestone, the Eskridge Shale, the Beattie Limestone, the Stearns Shale, the Bader Limestone, the Easly Creek Shale, the Crouse Limestone, the Blue Rapids Shale, the Funston Limestone, and the Speiser Shale. As described by Mudge and Burton (1959), the total thickness of the group is 250–425 ft (76–130 m), and it is dominated by limestones and shales with some local coal, sandstone (especially in the Easly Creek Shale), and conglomerate. The limestones are typically gray to brown, tan, blue or orange-gray. The shales are gray, grayish green, tan, olive, green, purple, maroon, or black. Exposures are most extensive in central Wabaunsee County, but they occur in approximately three-quarters of the county. Limestones that are or weather to porous to cavernous occur in the Foraker, Red Eagle, Grenola, Beattie, Bader, Crouse, and Funston Limestones and the Roca and Stearns Shales (including especially the Long Creek, Howe, Neva, Morrill, Cottonwood, Eiss, and Middleburg Limestone Members and the Bennett Shale Member). Seeps or springs are present in many of the same formations. Celestite occurs locally in the Foraker and Red Eagle Limestones, and the Red Eagle and Beattie Limestones contain some chert. Iron stains and carbonized plant fragments occur locally.

In Wabaunsee County the Chase Group (Permian) includes the Wreford Limestone, Matfield Shale, Barneston Limestone, and that part of the Doyle Shale below the Holmesville Shale Member (Mudge and Burton, 1959). These units are 130–225 ft (40–68.6 m) thick and are exposed in the western, central, and south-central parts of the county. The limestones are white, gray, or tannish brown to tannish gray. The shales are gray, grayish green, tannish gray, bluish gray, green, olive, maroon, and purple. Iron stains are common locally. Limestones that are or weather to porous to cavernous occur in the Wreford and Barneston Limestones, and many seeps and springs are associated with the Chase Group. The Threemile, Schroyer, and Florence Limestone Members of the Wreford and Barneston Limestones contain chert, and the Wreford is the oldest Permian formation of the Flint Hills escarpment.

The oldest unconsolidated deposits in Wabaunsee County are Tertiary or early Quaternary chert gravels. The chert was derived primarily from the Wreford and Barneston Limestones of the Chase Group, with some also from the Cottonwood Limestone Member of the Beattie Limestone (Council Grove Group) (Mudge and Burton, 1959). The chert is angular to subrounded in sand- to cobble-size fragments, but it is dominated by pebbles and granules. The chert generally has a reddish-brown clay (with some silt and very fine grained sand) matrix. The deposits are 0–15 ft (0–4.6 m) thick but average 8 ft (2 m). Locally, the lower foot is a well-cemented conglomerate. The deposits may indicate ancestral drainageways. Todd (1918b) described chert gravel deposits underlying red quartzite boulders at Alma and Paxico in the Mill Creek valley. Other thick chert gravel beds occur on strath (remnant) terraces along and 60–120 ft (18–37 m) above the modern streambeds of the Marais des Cygnes River, Rock Creek, and Mill Creek and its tributaries and in SENE sec. 5, T. 14 S., R. 9 E., and NE sec. 5, T. 14 S., R. 13 E. (Mudge and Burton, 1959). Johnson and Wagner (1967) also described deposits in SE sec. 32 and in eastern sec. 34, T. 13 S., R. 13 E. Other thick chert gravels extend from southwest of Alma to the Kansas River terrace in the southwestern part of T. 10 S., R. 12 E., and Mudge (1955) suggested that these gravels were deposited by a more direct-flowing preglacial Mill Creek. Those deposits that are north-northeast of Paxico are overlain by glacial till, and the two altitudes of chert gravels in sec. 6, T. 11 S., R. 12 E., may indicate episodes of aggradation and intermediate degradation (Mudge and Burton, 1959). Many seeps occur at the base of the chert gravels.

Glacial-till deposits in Wabaunsee County generally consist of 0–50 ft (0–15 m) of light-gray to gray-brown (locally tan to bluish) unstratified clay with some silt, sand, and gravel to boulders that range in size up to 18 × 17 × 6 ft (5.5 × 5.2 × 2 m) (Mudge and Burton, 1959). The coarse material includes local limestone, chert, shale, and sandstone and igneous and metamorphic erratics (granite, quartzite, greenstone, and gneiss). A concentration of boulders in northern and northeastern Wabaunsee County may indicate remnants of a terminal moraine and corresponds with Aber's (1988a, 1991) late Independence glacial limit (see fig. 7). Till deposits are north of the glacial limit, which, as interpreted by Mudge and Burton (1959), Smyth (1898), Schoewe (1930b, 1939), and Mudge (1955), extends from the northwestern corner of the county, eastward along Mill Creek from east of McFarland to Maple Hill, and then southeastward to sec. 27 or 34, T. 12 S., R. 13 E. Some banded or varved sediments in SESE sec. 28 and SE sec. 29, T. 11 S., R. 13 E., and SWSW sec. 7, T. 11 S., R. 12 E., include light and dark gray-brown very fine grained sand, silt, and clay with some erratic gravel (Mudge and Burton, 1959) and may represent the Atchison Formation of Johnson and Wagner (1967). Small, elongated northeast-trending ridges composed predominantly of erratic boulders and cobbles in NW sec. 25, T. 10 S., R. 10 E., may be drumlin remnants (Mudge and Burton, 1959). Exposures of till are commonly iron stained, contain some carbon, and have carbonate nodules in the upper parts. Seeps and springs occur locally above, within, or below the till deposits.

Glacial ice-contact deposits in secs. 9 and 10, T. 12 S., R. 13 E., have been described by Mudge and Burton (1959). The deposits average 30 ft (9 m) in thickness, where present, and include fine-grained sand to boulders (with cobbles common but smaller grains most abundant). The erratics are generally well rounded, and, as in the till, the larger pieces of granite are often decomposed. In addition to igneous and metamorphic erratics, some limestone, chert, shale, and blocks of till ranging up to 6 ft (2 m) in diameter are included. The deposits are locally cemented by calcium carbonate. Size sorting and crossbedding are not obvious. These ice-contact deposits overlie Pennsylvanian bedrock, and in sec. 10, T. 12 S., R. 13 E., they fill a small preglacial valley. Small springs occur below many of the gravel deposits.

Mudge and Burton (1959) also described deposits of what they termed the Grand Island, Sappa, and Sanborn formations in Wabaunsee County. These formation names are no longer used for this area. The first two are part of the classical Kansan Stage, and the third includes Illinoian and younger sediments.

The Grand Island Formation of Mudge and Burton (1959) includes an average of 3 ft (0.9) of limestone and chert gravels in the southeastern, unglaciated part of Wabaunsee County and 6 ft (2 m) of glacial outwash sands and gravels in the northern areas. In the north, deposits are exposed in secs. 7 and 16, T. 11 S., R. 12 E., secs. 14, 15, and 22, T. 11 S., R. 10 E., and the Paw Paw Creek valley. Some of these probably indicate drainageways of small outwash streams that flowed southward to Mill Creek. In addition to limestone and chert the outwash sands and gravels also include rounded erratics, red-brown silt, and clay balls. The northern outwash deposits commonly overlie glacial till, but sometimes they are intermixed. Other deposits are exposed southeast of Eskridge (secs. 9, 16, and 22, T. 14 S., R. 12 E., where the subrounded limestone, chert, and shale gravel is mixed with light-gray clay), north of Mission Creek [sec. 33, T. 12 S., R. 13 E., and secs. 5 and 6, T. 13 S., R. 13 E., where limestone gravel rests 50 ft (15 m) above the modern streambed], on opposite sides of Snokomo Creek south of Mill Creek (secs. 35 and 36, T. 11 S., R. 11 E.), and near the Marais des Cygnes River (sec. 7, T. 15 S., R. 12 E.). Johnson and Wagner (1967) described another deposit north of Mission Creek [9 ft (3 m) exposed in NWNW sec. 3, T. 13 S., R. 13 E.] that has subangular to subrounded gravel dominated by limestone but including chert, quartz, and ironstone and overlain by sand composed of limestone, sandstone, chert, quartz, ironstone, and fossil fragments and some well-cemented lenses of sand and gravel. The sand layers dip east-southeast. These Kansan terrace deposits, as classified by Johnson and Wagner (1967), make the Mission Creek valley wider in Wabaunsee County than it is downstream in Shawnee County. Seeps are common below the Grand Island gravels. The Sappa and Sanborn formations may overlie the Grand Island Formation of Mudge and Burton (1959).

Where present (e.g., in exposures southeast of Eskridge in secs. 9, 10, 16, and 22, T. 14 S., R. 12 E.), the Sappa Formation includes 3 ft (0.9 m) of dark-gray to gray-brown alluvial or colluvial clayey gravel and clay, locally with a buried soil at the top (Mudge and Burton, 1959). Calcium carbonate is abundant in the upper zones and in fracture and root (?) fillings. Kansan-age mollusks and ostracodes are common in the deposits (Frye and Leonard, 1952). Seeps occur locally at the top of the relatively impermeable buried soil.

As mapped and described by Mudge and Burton (1959), the Sanborn formation may include alluvial deposits of and younger than the Crete Formation, loess of the Loveland and Peoria formations, the Sangamon Soil, and colluvial and slope wash deposits and small amounts of the pre-Illinoian materials previously described. Typically, the deposits are 0–15 ft (0–4.6 m) thick. Gravels assigned to the Crete Formation occur 30–40 ft (9–12 m) above Mill Creek (e.g., NENW sec. 22 and NESE sec. 26, T. 11 S., R. 12 E.), near the upper reaches of Dragoon Creek (SE sec. 16, T. 14 S., R. 12 E.), and along Illinois, Middle Branch, Spring, Horse, and Rock creeks and the Marais des Cygnes River. The deposits, which generally range from 3 ft to 12 ft (0.9–3.7 m) in thickness, include chert, limestone, and/or shale gravel mixed with erratics in the northern areas. The gravels commonly have a grayish- to reddish-brown clay, silt, and/or fine-grained sand matrix. The basal portion of the Crete Formation may include a cemented conglomerate.

Loess deposits range from grayish- to tannish- to reddish-brown silt and clay. Deposits are locally iron stained. The Loveland loess (Illinoian) averages 4 ft (1 m) in thickness, whereas the Peoria loess (Wisconsin) is thicker [10 ft (3 m) on average] and more widespread. The reddish-brown Sangamon Soil and modern soils are locally developed in the upper Loveland loess and Peoria loess, respectively, and both are commonly leached of carbonates. Colluvial, slope wash, and some small tributary stream deposits range up to 15 ft (4.6 m) in thickness, include gravel (typically limestone and chert with some shale) in a gray to grayish-brown to reddish-brown clay to silty clay matrix and may be intermixed with loess and terrace deposits. Seeps occur commonly below gravel deposits, above the Sangamon Soil, and at bedrock contacts.

Alluvial deposits in Wabaunsee County include the Illinoian Buck Creek terrace and the Wisconsin to Holocene Newman terrace and modern alluvium (Mudge and Burton, 1959). Terraces occur along most streams, with widths up to 4 mi (6 km) in the Kansas River valley, 1.5 mi (2.4 km) along Mill Creek, and 0.5 mi (0.8 km) near other streams. The alluvial deposits range up to 60 ft (18 m) in thickness, and they typically include grayish-brown to reddish-brown silt and clay with basal limestone and chert gravel. Along the Kansas River, the Buck Creek and Newman terraces lie 50–60 ft (15–18 m) and 10–15 ft (3–5 m), respectively, above the modern streambed. Recent alluvium ranges up to 1.5 mi (2.4 km) wide along the Kansas River, but it is more commonly 0.5 mi (0.8 km) or less. Along other drainageways the alluvium ranges from approximately the stream width to 0.5 mi (0.8 km) wide. The deposits are generally tannish- to grayish-brown silt and clay overlying sand and gravel. In the Kansas River valley, the surficial deposits are coarser and consist of fine-grained sand, clayey silt, and some gravel lenses. The sand includes quartz, feldspar, and dark basic (mafic) minerals, but the gravel is dominated by limestone and chert. Alluvial deposits are less than 100 ft (30 m) thick.

Gray to light-gray porous calcium carbonate travertine deposits occur near three springs (SW sec. 12 and NE sec. 21, T. 12 S., R. 10 E., and SE sec. 4, T. 14 S., R. 11 E.) in Wabaunsee County (Mudge and Burton, 1959). The deposits are 3–12 ft (0.9–3.7 m) thick, contain leaf and wood fragments, and have steeply inclined beds.

The drainage history of Wabaunsee County has been described by Smyth (1898), Mudge (1955), Mudge and Burton (1959), and Johnson and Wagner (1967). Ice dammed the Kansas River at St. George in Pottawatomie County (just northwest of Wabaunsee County), and water flowed southeastward through diversion channels in northern Wabaunsee County to the modern junction of Mill and Dry creeks near Maple Hill, where water ponded and then spilled over the divide and drained toward the part of Mission Creek north of Dover in Shawnee County.

The bedrock topography of Wabaunsee County is shown in plate 1. This map was constructed using 328 bedrock-elevation data points [see Denne et al. (1990a)], the county geologic map (Mudge and Burton, 1959), and generalized surface topographic maps (U.S. Geological Survey, 1969a, b, 1974a,b) with modifications from some of the corresponding topographic quadrangle maps (1:62,500 scale). The valleys of the Kansas River and Mill Creek are the most prominent bedrock lows in the area.

A few buried valleys occur in Wabaunsee County. As previously described, the chert gravels from southwest of Alma to the Kansas River terrace in southwestern T. 10 S., R. 12 E., indicated the ancestral drainageway of Mill Creek to Mudge (1955). Additional bedrock-elevation data are needed to define any now-buried parts of this channel, especially between Paxico and Turkey Creek in northeastern T. 11 S., R. 11 E., and northwestern T. 11 S., R. 12 E. For a start, a water well in SWSWNW sec. 12, T. 11 S., R. 11 E., indicates 30 ft (9 m) of sand and gravel. Mudge and Burton (1959) also suggested that some of the deposits they classified as Grand Island Formation may represent former outwash streams that flowed southward to Mill Creek (e.g., secs. 7 and 16, T. 11 S., R. 12 E.; secs. 14, 15, and 22, T. 11 S., R. 10 E.; and the Paw Paw Creek valley). The modern Antelope, Wells, and Roberts Creek valleys are relatively wide and may indicate some relationship to former drainageways. The oil-borehole log for SWSWNE sec. 6, T. 11 S., R. 10 E., may help to define a buried valley west of the modern Antelope Creek. If correct, the oil logs for NENENE sec. 21, T. 12 S., R. 9 E., and NENWNE sec. 22, T. 13 S., R. 10 E., which report sand and gravel in the intervals 5–100 ft (2–30 m) and 30–80 ft (9–24 m), respectively, may indicate buried tributaries to the modern Spring and Middle Branch Mill creeks. On a small scale the glacial ice-contact deposits exposed in sec. 10, T. 12 S., R. 13 E., fill a small preglacial valley cut in Pennsylvanian bedrock (Mudge and Burton, 1959).

The depth to bedrock in Wabaunsee County is shown in fig. 71. The largest depth values are questionable; oil records for boreholes in SWNE sec. 6, T. 11 S., R. 10 E., SWNE sec. 26, T. 11 S., R. 11 E., NENENE sec. 21, T. 12 S., R. 9 E., SWSESE sec. 33, T. 13 S., R. 10 E., SESWNW sec. 3, T. 14 S., R. 10 E., and NWNWNW sec. 35, T. 14 S., R. 10 E., indicate bedrock depths between 90 ft (27 m) and 217 ft (66.1 m). Some of these depths may indicate buried valleys, whereas others (mostly in areas with rocks of the lower Chase, upper Council Grove, and upper Wabaunsee groups) may simply not provide enough information to differentiate unconsolidated sediments from bedrock.

Of well logs that indicate depth to bedrock (Denne et al., 1990a) in alluvial deposits, as mapped by Mudge and Burton (1959), five show depths from 36 ft to 70 ft (11–21 m) in the Kansas River valley and seven indicate depths between 33 ft (10 m) and 50 ft (15 m) along Mill Creek. Below Newman terrace deposits [again as mapped by Mudge and Burton (1959)], bedrock depths range from 29 ft to 85 ft (8.8–26 m) [with 24 of 27 values greater than 40 ft (12 m)] along the Kansas River, from 44 ft to 49 ft (13–15 m) for three sites in the Mill Creek valley, and from 30 ft to 35 ft (9–11 m) at three points along Wells and Hendricks creeks. Undifferentiated terrace deposits range from 24 ft to 60 ft (7.3–18 m) in thickness [with most of 13 values between 43 ft (13 m) and 49 ft (15 m)] along Mill Creek. One to three sites each indicate that the depth to bedrock below undifferentiated terrace deposits in the South Branch Mission, East Branch Mill, Snokomo, Paw Paw, and Mulberry Creek valleys ranges from 19 ft to 29 ft (5.8–8.8 m). The Buck Creek terrace deposits are 39–53 ft (12–16 m) thick at four sites along Mill Creek and 25–85 ft (7.6–26 m) thick [with most between 48 ft (15 m) and 69 ft (21 m)] along the Kansas River valley and its junctions with other drainages.

The depth to bedrock below deposits mapped by Mudge and Burton (1959) as the Sanborn Formation (which probably overlies glacial till in many cases) ranges up to 100 ft (30 m) (with several questionable values, as previously discussed). Nearly half of the 90 sites indicate depths between 10 ft (3 m) and 19 ft (5.8 m), with another 20% (18) between 20 ft (6 m) and 29 ft (8.8 m) and 10% (9) between 30 ft (9 m) and 39 ft (12 m). The larger depths occur in the northern, glaciated area of the county and parts of the southern townships. The thickness of glacial drift at four sites is 10 ft (3.0 m), 15 ft (4.6 m), 45 ft (14 m), and 52 ft (16 m). The Sappa and Grand Island Formations of Mudge and Burton (1959) are at least 14–16 ft (4.3–4.9 m) thick at two locations. Residual, colluvial, or other Quaternary deposits are typically less than 10 ft (3 m) thick over bedrock.

Total Pleistocene sand and gravel thicknesses in Wabaunsee County are shown in fig. 72. The oil-borehole record for NENENE sec. 21, T. 12 S., R. 9 E., as previously described, indicates 95 ft (29 m) of sand and gravel (which would be the maximum value for the county) in an area mapped by Mudge and Burton (1959) as marginal between the Sanborn Formation and bedrock, but the deposits may indicate a buried channel. Other large sand and gravel values [between 58 ft (18 m) and 74 ft (23 m)] occur in the Kansas River alluvium and Newman terrace deposits in NWNW sec. 22, T. 10 S., R. 12 E., SESESE sec. 16, T. 10 S., R. 12 E., and SESWNW sec. 10, T. 10 S., R. 11 E. Elsewhere along the Kansas River, the sand and gravel thickness ranges

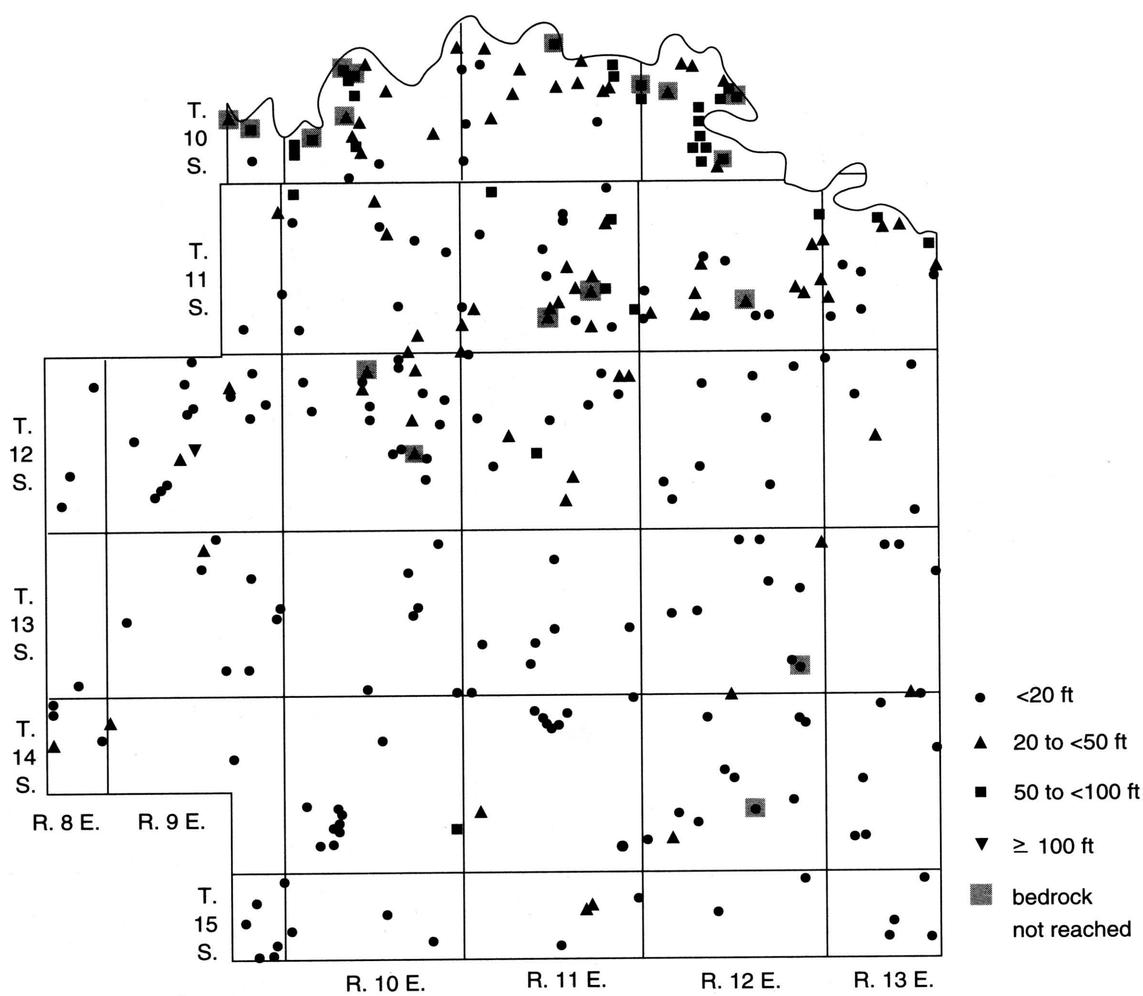

FIGURE 71—Depth to bedrock, Wabaunsee County.

are 0–28 ft (0–8.5 m) in the alluvium, 12–64 ft (3.7–20 m) in the Newman terrace deposits, and 9–41 ft (3–12 m) in the Buck Creek terrace. The largest thicknesses tend to be near the junctions with Antelope, Wells, and Mill creeks and near St. Mary's (ancestral Mill Creek connection). The coarse-grained material in the Kansas River valley commonly is finer near the land surface [beginning at depths of less than 20 ft (6 m) in the alluvium and Newman terrace and between 25 ft (7.6 m) and 40 ft (12 m) in the Buck Creek terrace] and becomes coarser with depth. A basal gravel [up to 54 ft (16 m) thick in SESWNW sec. 10, T. 10 S., R. 11 E.] typically overlies bedrock.

Basal gravel or sand and gravel also overlie bedrock below most of the other stream deposits in Wabaunsee County. Sand occurs locally above some of the basal gravels. The total sand and gravel thickness ranges up to 30 ft (9 m) along Mill Creek, 14 ft (4.3 m) in the Mulberry Creek valley, 7 ft (2 m) near Hendricks, Snokomo, and South Branch Mission creeks, and 5 ft (2 m) along other streams.

In deposits mapped as the Sanborn Formation and/or glacial till by Mudge and Burton (1959), 64 (75%) of 85 logs (Denne et al., 1990a) show no sand and gravel. Sixteen sites (19%) have 2–11 ft (0.6–3.4 m) of basal gravel or sand or both. Three other sites (4%) (NWNENE sec. 20, T. 12 S., R. 13 E., SWSWNW sec. 25, T. 10 S., R. 10 E., and SWSWNW sec. 12, T. 11 S., R. 11 E.) have 19–25 ft (5.8–7.6 m) of fine-grained sand, and the well in T. 11 S. has 10 ft (3 m) of basal gravel. One measured section in SESE sec. 16, T. 14 S., R. 12 E., shows 3 ft (0.9 m) of Grand Island Formation gravel overlying bedrock.

Sand and gravel in the alluvial and terrace deposits along the major drainageways and locally in the glacial deposits and some bedrock units are the major sources of ground water in Wabaunsee County.

Ground Water

Alluvial and Newman terrace deposits along the Kansas River produce the largest quantities of water to wells in Wabaunsee County. Figure 73 shows reported yields (uncorrected for well diameter, screen length, pump capacity, and other variables). Yields between 1,000 gpm (0.06 m^3/s) and 2,500 gpm (0.16 m^3/s) have been reported in sec. 17, T. 10 S., R. 10 E.; sec. 10, T. 10 S., R. 11 E.; secs. 8, 16, 17, and 22, T. 10 S., R. 12

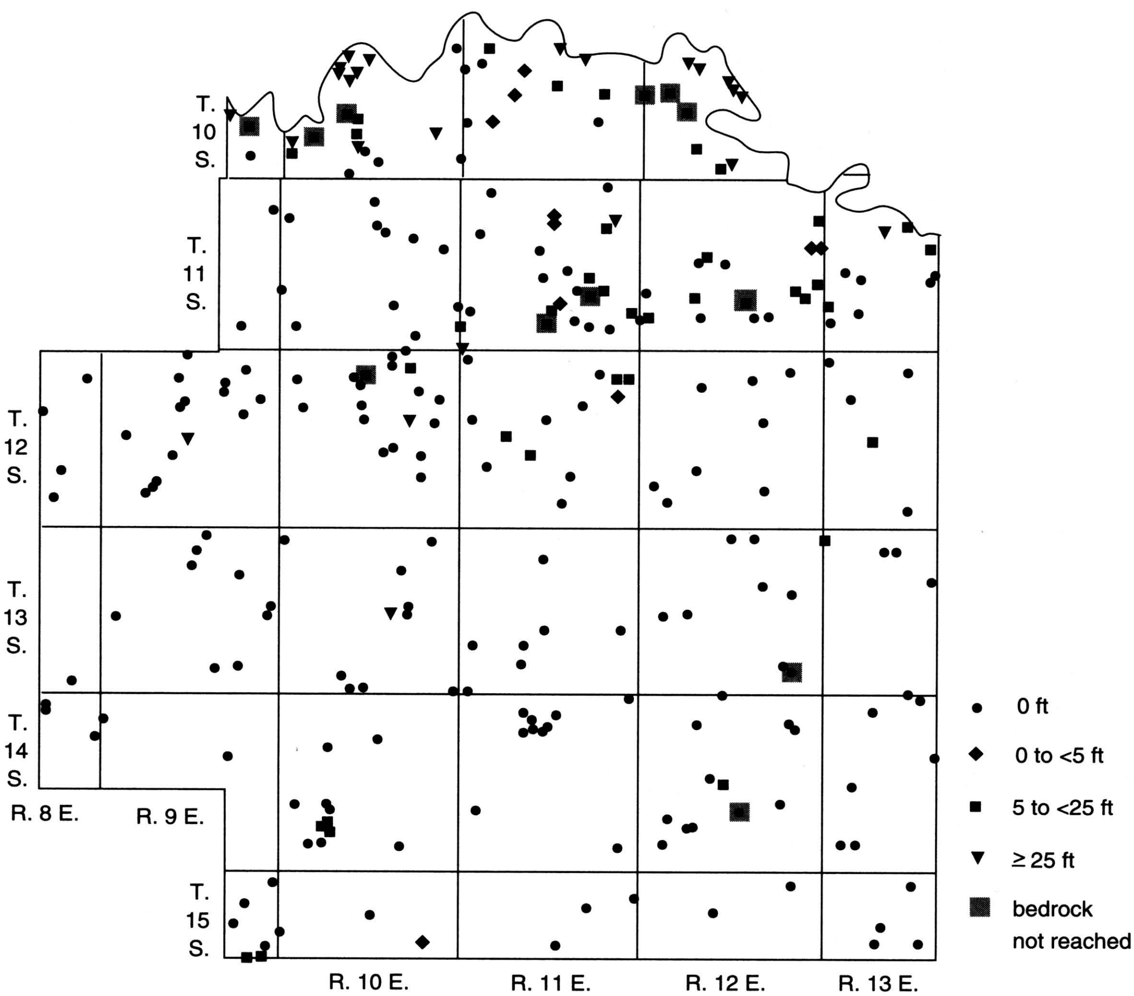

FIGURE 72—Total Pleistocene sand and gravel thickness, Wabaunsee County.

E.; and sec. 9, T. 11 S., R. 13 E. These large yields correspond to the areas with the greatest sand and gravel thicknesses. Other wells in the Newman terrace deposits along the Kansas River produce 25–450 gpm (0.0016–0.028 m^3/s), whereas wells in the Buck Creek terrace report yields of 20–50 gpm (0.001–0.003 m^3/s).

Wells in the Mill Creek alluvium and terrace deposits produce 6–125 gpm (0.0004–0.00790 m^3/s), with more than half of the 16 wells yielding 20–30 gpm (0.001–0.002 m^3/s). Yields from wells along other streams in the county generally produce 20 gpm (0.001 m^3/s) or less.

Wells in areas mapped by Mudge and Burton (1959) to include Sanborn Formation and glacial till report yields up to 80 gpm (0.005 m^3/s), but 40 (80%) of the 51 sites, including those with the largest yields, obtain all or part of their water from bedrock. Wells in SWSWNW sec. 12, T. 11 S., R. 11 E. (possibly part of a buried drainage), and NWNENE sec. 20, T. 12 S., R. 13 E., reportedly produce 50 gpm (0.003 m^3/s) and 20 gpm (0.001 m^3/s), respectively, but others in these unconsolidated deposits generally provide less than 5 gpm (0.0003 m^3/s).

At least 13 wells in bedrock in Wabaunsee County (Denne et al., 1990a) report production of 0.5 gpm (0.00003 m^3/s) or less. Another 43 wells indicate yields of 0.6–9 gpm (0.00004–0.0006 m^3/s). Only 30 wells that obtain all or part of their water from bedrock units produce 10–80 gpm (0.0006–0.005 m^3/s). These higher-yielding bedrock wells are scattered throughout the county (including secs. 3 and 10, T. 11 S., R. 10 E.; sec. 21, T. 11 S., R. 11 E.; sec. 35, T. 12 S., R. 8 E.; secs. 9 and 14, T. 12 S., R. 9 E.; secs. 3 and 22, T. 12 S., R. 10 E.; secs. 1 and 27, T. 12 S., R. 11 E.; sec. 3, T. 12 S., R. 12 E.; sec. 3, T. 13 S., R. 9 E.; sec. 14, T. 13 S., R. 10 E.; secs. 9 and 28, T. 13 S., R. 11 E.; sec. 26, T. 13 S., R. 12 E.; secs. 5 and 30, T. 14 S., R. 12 E.; sec. 17, T. 14 S., R. 13 E.; and secs. 2, 13, and 14, T. 15 S., R. 9 E.).

As described by Mudge and Burton (1959), the Americus Limestone Member of the Foraker Limestone, the Neva Limestone Member of the Grenola Limestone, and the Cottonwood Limestone Member of the Beattie Limestone [all of which are in the Council Grove Group (Permian)] are good aquifers in Wabaunsee County. In addition, the Fort Riley Limestone Member and Wreford Limestone of the Chase Group, the Funston, Crouse, Morrill, Red Eagle, and Long Creek Limestones and the Stearns and Roca Shales of the Council Grove Group, and the Tarkio Limestone Member of the Wabaunsee Group have local porous to cavernous zones.

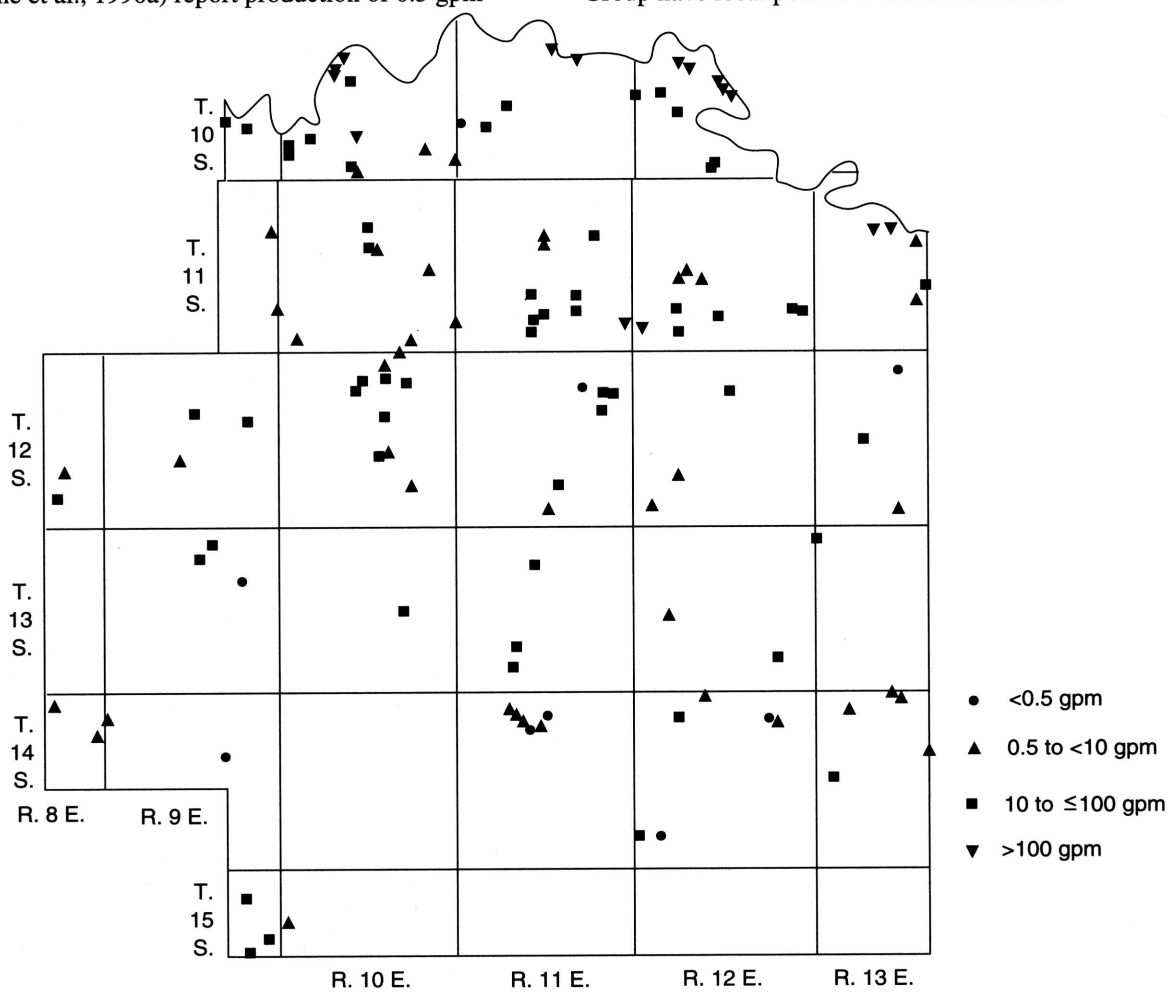

FIGURE 73—Estimated well yields, Wabaunsee County.

Figure 74 shows reported depths to water in Wabaunsee County, but the data are limited by several factors. For example, the water levels may represent unconfined, confined, and/or composites from multiple aquifers, some water levels may reflect nonequilibrium levels in newly constructed or pumped wells, and the water levels were not obtained for a consistent time (neither season nor year). Despite the data limitations, it is apparent that water is very deep in some bedrock wells [e.g., 85–150 ft (26–46 m) in NWSWSE sec. 10, T. 11 S., R. 10 E., NESWSW sec. 16, T. 11 S., R. 12 E., SWNENE sec. 3 and NESWNE sec. 26, T. 12 S., R. 10 E., NENWNW sec. 28, T. 13 S., R. 11 E., and NESWNW and SESWNW sec. 2, T. 14 S., R. 8 E.]. Other wells that receive all or part of their water from bedrock have depths to water that range from 10 ft to 80 ft (3–24 m).

Data for depths to water in the Sanborn Formation of Mudge and Burton (1959) and glacial drift are limited. Many of the wells that penetrate these unconsolidated deposits also obtain water from the underlying bedrock. For 11 sites water levels range from 10 ft to 50 ft (3–15 m) deep.

The depth to water below the Buck Creek terrace in the Kansas River and Mill Creek valleys ranges from 14 ft to 50 ft (4.3–15 m). Water levels below undifferentiated terraces along the various streams in the county generally are between 10 ft (3 m) and 34 ft (10 m). Except for one value of 4 ft (1 m), depths to water below the Newman terrace in the Kansas River and Wells, Mill, and Hendricks Creek valleys range from 13 ft to 38 ft (4–12 m). A few values indicate that water levels in alluvial deposits are 10–16 ft (3–4.9 m) near the Kansas River and 21–35 ft (6.4–11 m) along Mill Creek.

Water-elevation data indicate that the ground-water levels roughly parallel the land-surface topography, with ground-water flow toward and down the major stream valleys. The average hydraulic gradient is 2.5 ft/mi (0.5 m/km) along the Kansas River and 5–10 ft/mi (0.9–1.9 m/km) along Mill Creek below Alma.

Saturated thicknesses of unconsolidated deposits (determined by subtracting the questionable depth to water from the depth to bedrock at a given site) are shown in fig. 75. The largest saturated thicknesses [up to 68 ft (21 m)] are in the Kansas River valley near St. Mary's (e.g., NENENE sec. 24, T. 10 S., R. 11 E., and

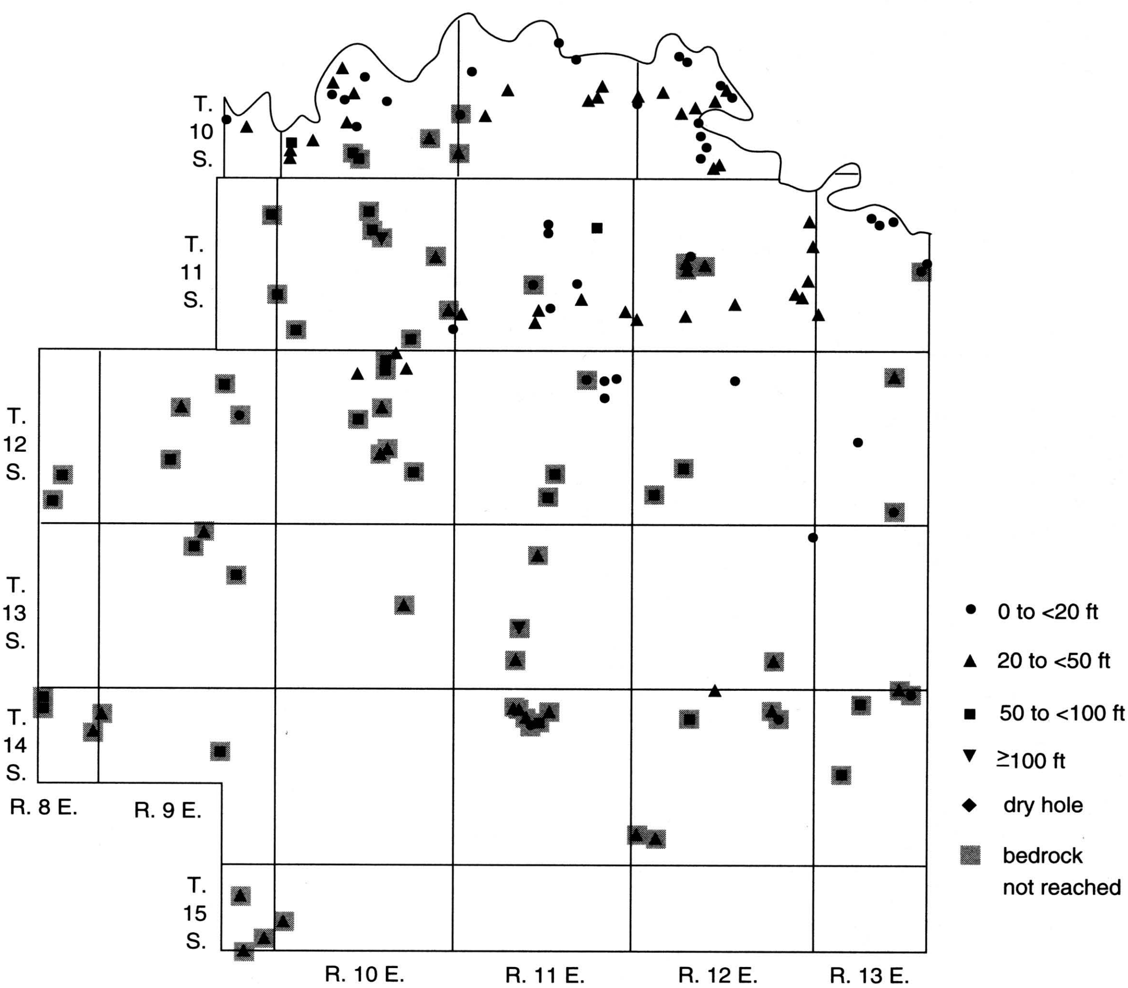

FIGURE 74—Depth to water in wells and test wells, Wabaunsee County.

NENESE sec. 20, NESWNE sec. 21, and NWNW sec. 22, T. 10 S., R. 12 E.). Most values in the alluvial and terrace deposits along the Kansas River are more than 15 ft (4.6 m). The Buck Creek, undifferentiated, and Newman terraces and the alluvium in the Mill Creek valley generally contain 10–30 ft (3–9 m) of saturated material. Along the smaller streams saturated thicknesses range from 0 to 10 ft (3 m), with 18 ft (5.5 m) reported at one site on Mulberry Creek.

In Wabaunsee County discharge is primarily to streams, springs, seeps, and wells. Seeps and springs are common in outcrops of Quaternary deposits (especially below lenses or layers of sand and gravel), the Fort Riley Limestone Member and Neva limestone member, and Wreford, Funston, Florence, and Cottonwood Limestones, and the Matfield and Stearns Shales. Recharge in the county is primarily from precipitation and movement of water from some of the bedrock units to the overlying or adjacent Quaternary deposits.

Wyandotte County

Geology

Although Wyandotte County is dominated by glacial, eolian, and alluvial deposits (fig. 9), bedrock does occur along many stream valleys and in some upland areas [as mapped by Jewett and Newell (1935) and Ward and O'Connor (1983)] (fig. 5). Pennsylvanian rocks exposed in the county include most of the Kansas City Group, all of the Lansing Group, and the lower part of the Douglas Group [Jewett and Newell (1935), with revised terminology from Zeller (1968)]. Limestones (several of which are cherty) and shales are most common, but sandstone of the Stranger Formation (Douglas Group) occurs in much of western Wyandotte County. The rocks dip northwest at an average of 10 ft/mi (1.9 m/km) in the general Prairie Plains homocline, but small folds locally modify the dip (Jewett and Newell, 1935).

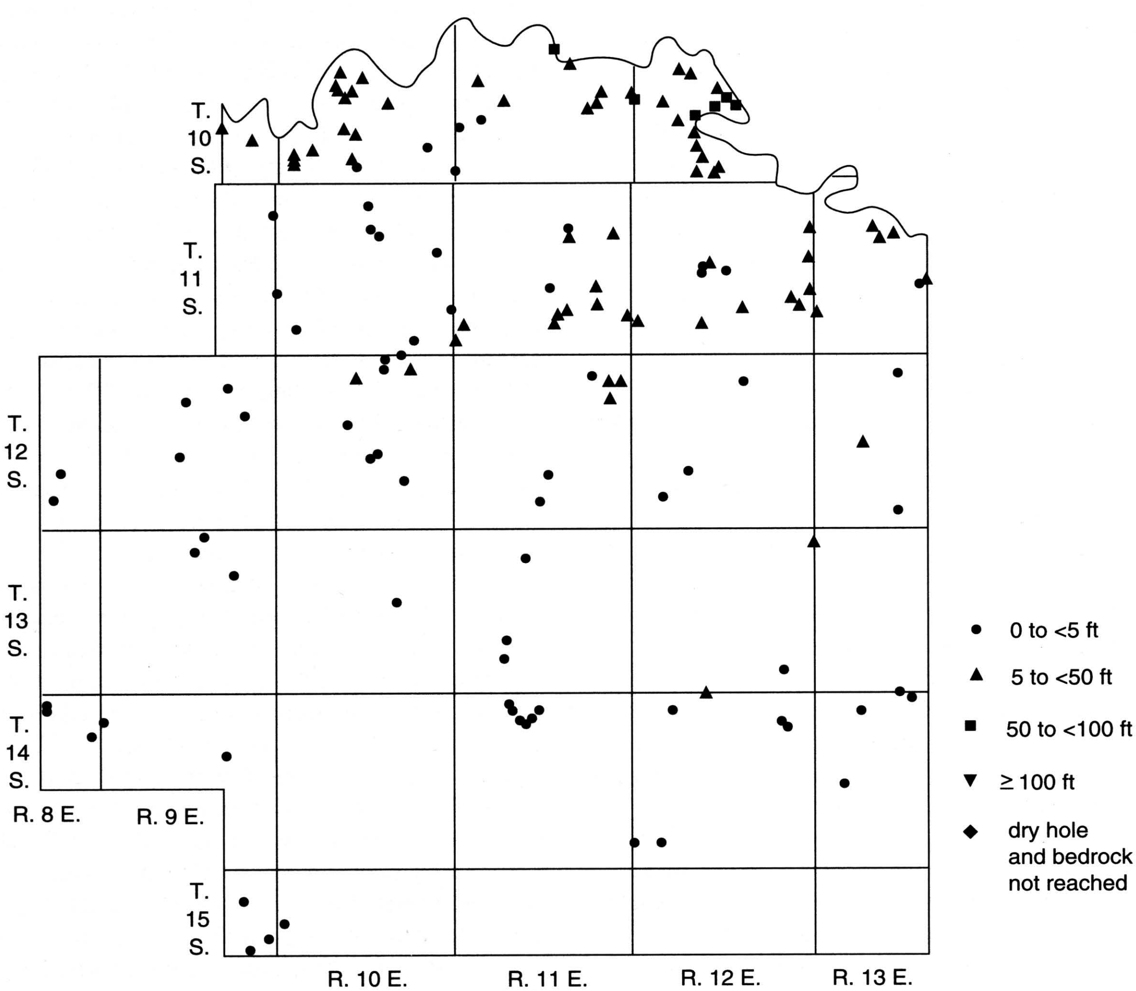

FIGURE 75—Saturated thickness of Pleistocene deposits, Wabaunsee County.

As evidenced by numerous glacial striations (see fig. 7), one or more advances of ice moved from 340° to 24° across Wyandotte County (Schoewe, 1941). At least locally, ice may have moved nearly east-west as indicated by striations oriented 290°–295° on the wall of Turkey Creek 0.25 mi (0.4 km) across the county border into Missouri (Jewett, 1934). In Wyandotte County the Kansas River valley apparently limited the southward movement of the glacier(s). Aber (1981, 1982) observed that the reentrant angles in the glacial border and the bends in the Missouri and Kansas rivers at Kansas City may reflect the division between two major lobes of ice, with Dakota ice to the west and Minnesota ice to the east.

In 1935 Jewett and Newell believed that deposits of glacial till in Wyandotte County occurred as isolated remnants on some hilltops and were generally less than 8 ft (2 m) thick. O'Connor and Fowler (1963) found Pleistocene deposits in Wyandotte County that ranged up to 116 ft (35.4 m) thick in areas outside of the Kansas and Missouri River valleys, and they stated that most of these deposits are till. Dufford (1958) mapped some pre-Illinoian sediments on the uplands north of the Kansas River as part of the Menoken terrace.

The youngest deposits in Wyandotte County include loess and alluvium. Loess covers much of the county and is thickest [locally up to 50 ft (15 m) according to Fishel (1948)] along the river bluffs, especially those of the Missouri River. Buck Creek (Illinoian) and Newman (Wisconsin) terraces have been mapped along Kaw Creek and Wolf Creek in southwestern Wyandotte County (Dufford, 1958), but other tributaries have not been mapped in detail. Wisconsin and Holocene alluvium is abundant. Alluvial deposits in the Kansas and Missouri River valleys and tributaries consist of clay, silt, sand, and gravel, with some boulders near bedrock in the larger valleys. Although the deposits generally progress from fine to coarse with depth, lateral and vertical variations are common.

LANDSAT imagery shows striking differences between the surficial deposits in the Kansas River valley compared with those in the Missouri River valley. False-color composite images covering northeastern Kansas (e.g., path 29, row 33, image ID 246716171 from May 3, 1976, and image ID 241316185 from March 10, 1976) indicate that the light-toned Kansas River alluvium is better drained (probably coarser near the surface) than the darker-toned (more moist) surficial deposits in the Missouri River valley. Although detailed laboratory studies of sediments would be needed to confirm the differences, Fishel et al. (1953, p. 38) state that in the Kansas River valley from Kansas City to Bonner Springs "several feet of the surficial material is composed largely of silt and clay, but most of it is slightly sandy." Fishel (1948, p. 18) suggested that "much of the alluvium in the Kansas Valley near Kansas City probably is of glacial origin, having been deposited as glacial outwash by the swollen streams that emanated from the melting ice sheets" and that such material would be relatively coarse. In contrast to the Kansas River, the Missouri River above Kansas City may not have developed until post-Kansan time (O'Connor and Fowler, 1963), although it may have developed "as an interlobate drainage during deglaciation" (Aber, 1981, p. 163).

In Wyandotte County the floodplain along the Kansas River [as mapped by Fader (1974)] generally ranges from 1 mi to 1.5 mi (1.6–2.4 km) in width. The Missouri River valley is 2 mi (3 km) wide, as mapped by Emmett and Jeffery (1969). Geologic sections along these two major river valleys are included in the reports by Fishel (1948), O'Connor and Fowler (1963), Emmett and Jeffery (1969), and Fader (1974).

The channels of the Missouri and Kansas rivers are the most prominent features on the bedrock topographic map of Wyandotte County (plate 1). The map was prepared using 385 drill logs, as described by Denne et al. (1990a), the geologic map by Ward and O'Connor (1983), and the surface topographic map with contours at 10-m intervals (U.S. Geological Survey, 1981d).

From the bedrock topographic map it is apparent that a deep, narrow channel underlies the broader main valley near the junction of the modern Missouri and Kansas rivers. In SWSWNW sec. 11, T. 11 S., R. 25 E., the Kansas Highway Commission found that the depth to bedrock is 239 ft (72.8 m) and that the bedrock elevation is 515 ft (157 m). O'Connor and Fowler (1963) described this core, which has 150 ft (46 m) of glacial till below the alluvium. The lower channel cuts through the relatively soft Pleasanton Group, whereas the Kansas River valley is confined by more resistant rocks of the Kansas City Group. The basal till is a gray calcareous clay with local and erratic sand grains, and O'Connor and Fowler believed that the till may have been mistaken for gray shale in other drill holes, including SESWSE sec. 10, T. 11 S., R. 25 E. [see Denne et al. (1990a)] from Fishel (1948), where, based on their reexamination of samples, depth to bedrock should be greater than 118 ft (36.0 m).

The U.S. Army Corps of Engineers log (obtained from the Missouri Geological Survey) for a test hole in NW sec. 23, T. 11 S., R. 25 E., indicates that bedrock is at a depth of 183 ft (55.8 m) and at an elevation of 576 ft (176 m). Although this drill hole may be in the same buried channel as that in SWSWNW sec. 11, T. 11 S., R. 25 E., it contains sand and gravel rather than till in the lower 150 ft (46 m). O'Connor and Fowler (1963) described the log for a well in the abandoned Turkey Creek valley in nearby Kansas City, Missouri, in which sand and gravel also make up most of the 242 ft (73.8 m) of sediments above bedrock at an elevation of 595 ft (181 m). Because of the nearly east-west striations along Turkey Creek, perhaps these last two wells represent drainage along the southern margin of an ice mass that may have covered SWSWNW sec. 11 and SESWSE sec. 10, T. 11 S., R. 25 E. Alternatively, the sites may have been associated with two different glacial lobes, such as those suggested by Aber (1981, 1982, 1988a).

O'Connor and Fowler (1963) included a rather detailed explanation for these narrow, deep channels. They believed that the ancestral Kansas River flowed across Wyandotte County (as it does now) and then followed the course of the modern Missouri River. At some time, glacial ice blocked the river in Missouri and caused ponding. The water eventually breached the divide and flowed into Turkey Creek. The channel below the Kansas River may have been scoured at nearly the same time by a subglacial stream, which was subsequently blocked by ice collapse and then filled with glacial till.

In north-central T. 11 S., R. 25 E., and south-central T. 10 S., R. 25 E., several data points suggest the presence of a major buried tributary that flowed southeast toward the Kansas River and its deep underlying channel. Well logs from the hills in SENENW sec. 4 and NWNENW and NWNWNW sec. 10, T. 11 S., R. 25 E., show depths to bedrock of 108–148 ft (32.9–45.1 m) and sand or sand and gravel layers that are 45–76 ft (14–23 m) thick. Similar but thinner deposits are found in T. 10 S., R. 25 E. (e.g., SWSWSW sec. 33 and NENESE sec. 32).

Other buried tributaries occur along the northern side of the Kansas River valley. For example, oil logs for NESW sec. 10 and SWSWNE sec. 16, T. 11 S., R. 24 E., indicate depths to bedrock of 116 ft (35.4 m) and 81 ft (25 m) and bedrock elevations of 761 ft (232 m) and 779 ft (237 m), respectively; these sites, with abundant sand and gravel, appear to be in former drainages on opposite sides of a small bedrock knob. It is possible that stream piracy has subsequently altered the related modern Mill and Muncie creeks. A buried tributary also appears to drain southward near Betts Creek. Logs for NWSW sec. 24 and SWSWNW sec. 25, T. 11 S., R. 23 E., show depths to bedrock of 70 ft (21 m) and 65 ft (20 m), respectively, with up to 34 ft (10 m) of sand and gravel.

Another buried channel is clearly evident in northwestern Wyandotte County, but delineation of the valley is difficult because it appears to cross or to be coincident with several modern streams (Wolf, Piper, and Honey creeks) and because the depth to bedrock values may be locally erroneous because of sandstone in the area. Viewed together with data and the bedrock topographic maps from Leavenworth County, it appears that the buried valley may have trended generally east-west, perhaps in an ice-marginal position. Flow may have been westerly toward the Stranger Creek drainage system, southerly toward Wolf Creek, and even easterly toward Connor Creek. The buried-channel deposits are significant in terms of thickness and sand and gravel content (e.g., note logs for SWSWSW sec. 14, SESENE sec. 15, SWSWNW sec. 18, NWNWNW sec. 19, NWNWNW sec. 20, and NWNE sec. 29, T. 10 S., R. 23 E.).

In Wyandotte County the depth to bedrock (fig. 76) is greatest in the deep, narrow channels that underlie the more recent Kansas River valley [e.g., 239 ft (72.8 m) in SWSWNW sec. 11, T. 11 S., R. 25 E., and 183 ft (55.8 m) in NW sec. 23, T. 11 S., R. 25 E.]. Other large thicknesses of unconsolidated deposits occur in buried tributaries, such as NWNWNW sec. 10, T. 11 S., R. 25 E., with 148 ft (45.1 m) of deposits, and NESW sec. 10, T. 11 S., R. 24 E., with 116 ft (35.4 m), in the Missouri River valley [e.g., 140 ft (43 m) in NESESE sec. 14, T. 10 S., R. 24 E., and NESENE sec. 28, T. 10 S., R. 25 E.], and the buried valley in northwestern Wyandotte County, where values range up to 133 ft (40.5 m) in NWNWNW sec. 19, T. 10 S., R. 23 E.

More typical thicknesses (than the maximum values) of alluvial deposits in the Missouri River valley are between 80 ft (24 m) and 125 ft (38 m), whereas in the Kansas River valley they commonly range from 50 ft to

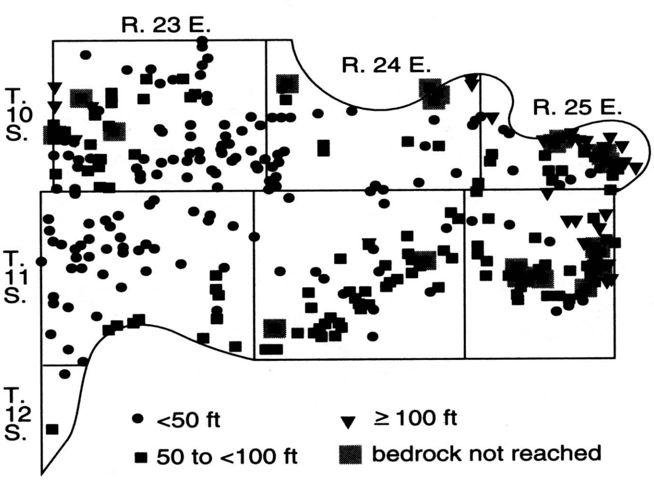

FIGURE 76—Depth to bedrock, Wyandotte County.

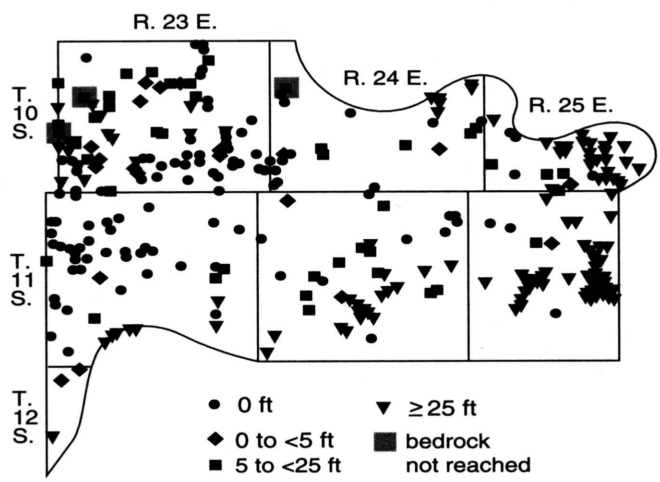

FIGURE 77—Total Pleistocene sand and gravel thickness, Wyandotte County.

80 ft (15–24 m). Alluvium in the Kansas River valley within 4 mi (6 km) of its junction with the Missouri River is thicker than in upstream areas and generally ranges from 70 ft to 110 ft (21–34 m) thick. In the smaller stream valleys of the county, alluvial deposits are commonly 5–35 ft (2–11 m) thick.

The thickness of glacial, glaciofluvial, and loess deposits in Wyandotte County ranges from 0 to 148 ft (45.1 m). The deposits are thinnest in the southwestern and southeastern parts of the county. Near the glacial limit, two small areas of glacial drift were mapped along the south side of the Kansas River valley by Ward and O'Connor (1983), and two drill holes (SWSENW and NWNWSW sec. 24, T. 11 S., R. 24 E.) show deposits 48–56 ft (15–17 m) thick with as much as 18 ft (5.5 m) of basal sand and gravel. North of the Kansas River, thicknesses determined from drill holes show a much greater range, with 25% greater than 60 ft (18 m) and 25% less than 21 ft (6.4 m). The largest values, of course, occur along the buried valleys. Thin residual, colluvial, and glacial deposits locally cover areas shown as bedrock on the geologic map.

The total thickness of sand and gravel layers in Wyandotte County (fig. 77) is greatest [146 ft (44.5 m)] in the deep, narrow channel underlying the Kansas River valley in NW sec. 23, T. 11 S., R. 25 E. Other large values occur in the Missouri River valley [e.g., 140 ft (43 m) in NESENE sec. 28, T. 10 S., R. 25 E., and 124 ft (37.8 m) in NESESE sec. 14, T. 10 S., R. 24 E.]. At most locations in the Missouri River valley values are at least 60 ft (18 m), whereas in the Kansas River valley they are commonly more than 30 ft (9 m). In the buried Kansas River tributaries sand and gravel thicknesses range from 10 ft to 90 ft (3–27 m). The buried drainageways in the northwestern part of the county contain at least 58 ft (18 m) of sand and gravel (SWSWSE sec. 20, T. 10 S., R. 23 E.) and possibly as much as 85 ft (26 m) (SWNWNE sec. 30, T. 10 S., R. 23 E.). Small modern stream valleys (unrelated to the buried channels) generally contain 0–10 ft (0–3 m) of sand and gravel, and thin lenses of sand and gravel occur near the bedrock surface below loess and/or glacial drift at a few localities scattered throughout the county.

Ground Water

In Wyandotte County alluvial deposits provide, by far, the largest ground-water supplies. Well yields (which have not been corrected for diameter or other well-construction characteristics) are given by Denne et al. (1990a) and are shown in fig. 78. Yields range up to 3,500 gpm (0.22 m^3/s) in the Missouri River valley (NESESE sec. 14, T. 10 S., R. 24 E.) and up to 1,610 gpm (0.102 m^3/s) in the Kansas River valley (NWSENE sec. 22, T. 11 S., R. 25 E.). Mean values are 1,030 gpm (0.0650 m^3/s) in the Missouri River valley (based on 18 wells) and 612 gpm (0.0386 m^3/s) in the Kansas River valley (based on 42 wells). Fishel (1948) reported similar averages of 980 gpm (0.062 m^3/s) for 22 wells in the Missouri River valley and 650 gpm (0.041 m^3/s) for 29 wells in the Kansas River valley. Yield data for tributaries are sparse, but 8–45 gpm (0.0005–0.0028 m^3/s) can be obtained locally from the Wolf Creek alluvium.

Although Fishel (1948) believed that glacial deposits in Wyandotte County were above the water table, and many are indeed dry, significant quantities of water can be obtained from the buried valleys in the northwestern part of the county. Yields from the channel deposits there are commonly 7–20 gpm (0.0004–0.001 m^3/s), with values up to 90 gpm (0.006 m^3/s) reported in sec. 20, T. 10 S., R. 23 E. Yield data for the buried Kansas River tributaries are unavailable, except for a field report of a 108-ft-deep (32.9-m-deep) dry hole in NWNENW sec. 10, T. 11 S., R. 25 E. Where saturated (e.g., SWSWNW sec. 25, T. 11 S., R. 23 E.; unfortunately, most of the other buried tributary sites do not have water-level measurements), the sand and gravel layers in

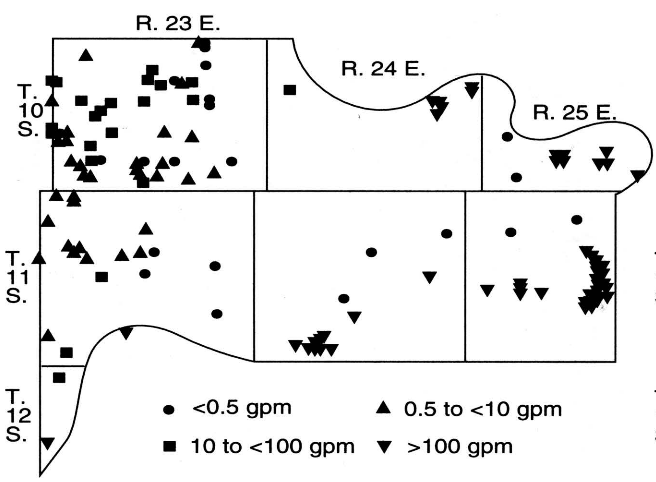

FIGURE 78—ESTIMATED WELL YIELDS, WYANDOTTE COUNTY.

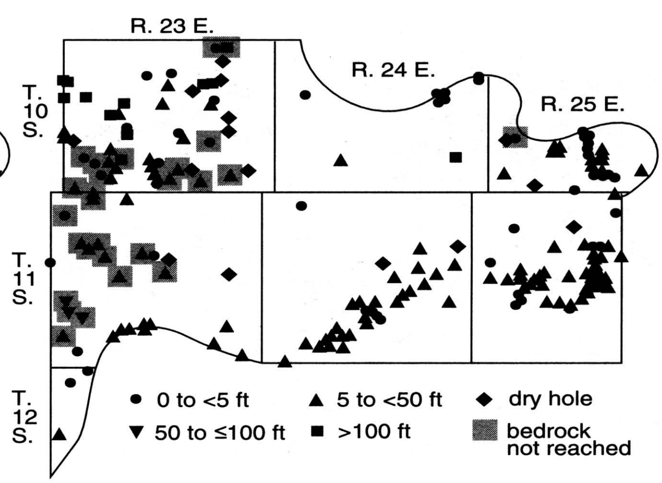

FIGURE 79—DEPTH TO WATER IN WELLS AND TEST WELLS, WYANDOTTE COUNTY.

these deposits should yield a significant quantity of water. One well in the Menoken terrace (NESWNE sec. 6, T. 12 S., R. 23 E.) indicates that 15 gpm (0.00095 m^3/s) can be obtained there. Elsewhere in the county, small supplies of water [generally less than 2 gpm (0.0001 m^3/s)] can be obtained locally from glacial deposits.

As in Johnson County, bedrock formations in Wyandotte County commonly yield no water, although they may provide small amounts locally. Fishel (1948) observed that many farm wells on the uplands obtain small water supplies from bedrock (except during dry years) and that limestones that produce water near outcrops include the Stanton, Plattsburg, Wyandotte, Iola, and Dennis Limestones. Based on well data given by Denne et al. (1990a), it appears that the Douglas Group sandstone in western Wyandotte County is the best bedrock aquifer. The log for a well in SWSESE sec. 17, T. 11 S., R. 23 E., shows a yield of more than 20 gpm (0.001 m^3/s) (presumably from the sandstone and possibly from "broken lime"), whereas other wells in sandstone (locally combined with glacial deposits) produce up to 12 gpm (0.00076 m^3/s) but more commonly 1–3 gpm (0.00006–0.0002 m^3/s). Other bedrock units in the county generally yield less than 0.5 gpm (0.00003 m^3/s).

The depth to water in Wyandotte County (fig. 79) is greatest in bedrock wells. The maximum reported value is 200 ft (60 m) in a 276-ft-deep (84.1-m-deep) well in NWNENW sec. 32, T. 10 S., R. 23 E., but a 100-ft-deep (30-m-deep) well nearby in NW sec. 32, T. 10 S., R. 23 E., had the same surface elevation, the same depth to bedrock, and the same sand layer at 25–27 ft (7.6–8.2 m) but a water depth of 40 ft (12 m). Other bedrock wells with large depths to water include SENESW and SESESW sec. 19 and NWNENE sec. 30, T. 11 S., R. 23 E., where values range from 142 ft to 180 ft (43.3–54.9 m). The water levels in other bedrock wells range from 7 ft to 50 ft (2–15 m).

In the glacial buried valley in northwestern Wyandotte County, depths to water are most commonly either 17–32 ft (5.2–9.8 m) or 55–79 ft (17–24 m). The full range of values, however, is 6–90 ft (2–27 m). In other glacial deposits throughout the county (where not dry), water levels are generally 24–45 ft (7.3–14 m), although they range from 4 ft to 55 ft (1–17 m).

Water levels are most consistent in the alluvial deposits. Along Wolf Creek two measurements were 15 ft (4.6 m). In the Missouri River valley the depth to water varied from 8 ft to 35 ft (2–11 m), with 27 (85%) of 32 values falling in the range 10–22 ft (3–6.7 m). Ninety-seven water-level measurements in the Kansas River alluvium indicated depths from 6 ft to 49 ft (2–15 m), with 76 (78%) in the range 20–40 ft (6–12 m). Where pumpage from these valleys is heavy, as it is near Kansas City, some of these water levels may reflect cones of depression rather than static surfaces.

The saturated thickness of unconsolidated deposits in Wyandotte County (fig. 80) is greatest in the Missouri River valley, where water levels are generally shallow and bedrock is deep. The saturated thicknesses there are commonly much greater than 60 ft (18 m), and the maximum values in the county [101–121 ft (30.8–36.9 m)] occur in NESESE sec. 14, T. 10 S., R. 24 E., and in SWNWSE and SWNW sec. 27 and NESENE sec. 28, T. 10 S., R. 25 E. In the Kansas River valley, saturated thicknesses commonly range from 40 ft to 90 ft (12–27 m) within 4 mi (6 km) of the junction with the Missouri River and from 25 ft to 50 ft (7.6–15 m) further upstream. It should be noted that no water-level measurements (and therefore no saturated thickness data) are available for the thick deposits in SWSWNW sec. 11 and NW sec. 23, T. 11 S., R. 25 E. In Wolf Creek the saturated thickness of the alluvium at two sites is 10 ft (3 m) and 19 ft (5.8 m).

The saturated thickness of glacial deposits is greatest in the buried valley in T. 10 S., R. 23 E., where values are commonly between 10 ft (3 m) and 60 ft (18 m). Along the northern bank of the Kansas River several sites have 13–41 ft (4.0–12 m) of saturated material, whereas on the southern side one drill hole indicates 11 ft (3.4 m). Elsewhere in the county small saturated thicknesses of glacial deposits and/or loess occur locally.

No attempt was made to contour water-level elevations because of discontinuities, multiple aquifers, and other problems with water-level measurements, as previously discussed. It is apparent, however, that elevations of water in the bedrock wells where water is deep (e.g., SENESW and, SESESW sec. 19 and NWNENE sec. 30, T. 11 S., R. 23 E.) are just slightly higher than those in the Kansas River alluvium, whereas water elevations are commonly 150 ft (46 m) higher in most bedrock and glacial wells to the north.

In the Kansas River valley the water table generally declines from 753 ft (230 m) in the southwest to 710 ft (220 m) near the junction with the Missouri River. Fader's (1974) map of the 1967 water table in the Kansas River valley indicates an average hydraulic gradient of 1.5 ft/mi (0.3 m/km) across Wyandotte County. Flow generally is toward the river, except where pumpage locally reverses the gradient or during flooding. Elevations along the Missouri River range from 702 ft to 735 ft (214–224 m). A contour map of the piezometric surface in the Missouri River valley in January 1968 (Emmett and Jeffery, 1969) indicates an average hydraulic gradient of 2 ft/mi (0.4 m/km) in Wyandotte County.

Although local water-quality problems occur in alluvial deposits and in deep bedrock formations, large quantities of water can be obtained from glacial buried valleys and the Kansas and Missouri River valley deposits in Wyandotte County. Pumpage near Kansas

City is already heavy in many areas, but additional water supplies are still available.

Aquifer tests on four wells in the Kansas River valley that were pumped at 525 gpm (0.0331 m^3/s), 560 gpm (0.0353 m^3/s), 610 gpm (0.0385 m^3/s), and 740 gpm (0.0467 m^3/s) indicate transmissivity values of 18,200–32,000 ft^2/d [136,000–240,000 gpd/ft (1,690–2,980 m^2/d)] and storage coefficients of 0.11–0.18 (Fader, 1974). Based on two pump tests, alluvium in the Missouri River valley locally has a coefficient of permeability (or hydraulic conductivity) of 3,000 gpd/ft^2 (120 m/d) (Fishel, 1948), which would give a transmissivity of 300,000 gpd/ft (4,000 m^2/d) for a 100-ft (30-m) saturated thickness.

Fishel (1948) reported that the average specific capacities of wells in the Kansas and Missouri River valleys were 60 gpm/ft (0.01 m^2/s) and 180 gpm/ft (0.037 m^2/s), respectively. Calculations from data in table 9 of Fishel's report indicate a range of 13–119 gpm/ft (0.0026–0.0246 m^2/s) [for 14 wells pumped from 200 gpm to 1,800 gpm (0.01–0.11 m^3/s) in the Kansas River alluvium] and 55–375 gpm/ft (0.011–0.0776 m^2/s) [for 18 wells pumped from 80 gpm to 1,580 gpm (0.005–0.0997 m^3/s) in the Missouri River deposits].

Recharge in Wyandotte County is predominantly from precipitation. Discharge is primarily to the rivers (except during floods) and to wells.

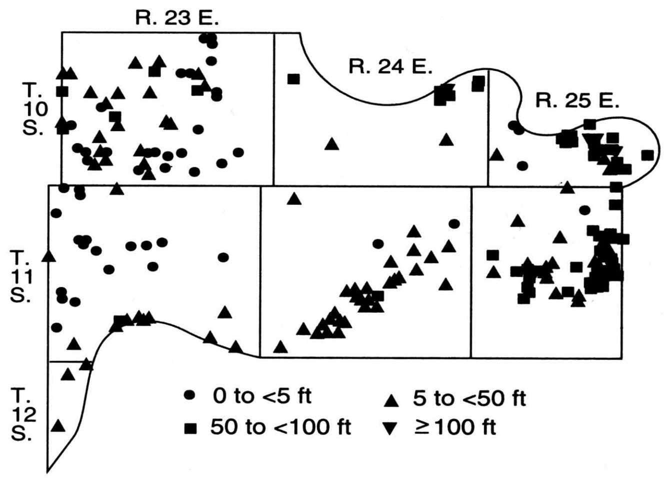

FIGURE 80—Saturated thickness of Pleistocene deposits, Wyandotte County.

Aquifer parameters

Aquifer tests are useful in determining hydraulic properties of water-bearing layers and confining beds and can be used to estimate well yields. Data obtained from a pump test usually consist of a time series of water-level measurements in the pumped well and observation well(s) after pumpage is initiated. The difference between the static water level and these water-level measurements is called the drawdown in the well. Transmissivity T and the storage coefficient S are hydrologic properties determined from the drawdown data.

The ability of an aquifer to transmit water is measured by T, which is the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of saturated aquifer under a unit hydraulic gradient. The units of T are usually given in gallons per day per foot (gpd/ft) or in cubic feet per second per foot (ft^3/s/ft or ft^2/s). From the transmissivity the hydraulic conductivity K can be determined. K is commonly reported in velocity units of feet per second (ft/s) or gallons per day per foot squared (gpd/ft^2). This parameter reflects the characteristics of the porous medium and of the fluid and is calculated by dividing the transmissivity by the aquifer thickness.

The storage coefficient S of an aquifer is defined as the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head. The storage coefficient for an unconfined aquifer is the specific yield, which is defined as the ratio of the volume of water that a saturated material will yield by gravity to its own volume.

We analyzed aquifer test data for glacial, alluvial, and bedrock aquifers in northeastern Kansas using automated fitting techniques to obtain transmissivity and storage values. A number of computer programs were available to find the best fit for T and S values from the original pump-test drawdowns. For a more detailed discussion of these programs and the 80 northeastern Kansas pump-test analyses performed, see Miller (1987), and for discussions of the Theis and Leaky automated fitting techniques, see McElwee (1980) and Cobb et al. (1982).

Aquifer evaluations in glacial materials are shown in table 2. This table is a compilation of the information available but does not include pump tests that had major problems, such as an insufficient pumping rate for the aquifer, a test duration that was too short, or an insufficient number of drawdown measurements to define a curve. T and S values that are accompanied by question marks indicate that there was difficulty in the test evaluation (because of insufficient data or large errors in fitting techniques) and that these values are the best possible estimations.

Glacial aquifers are seldom homogeneous in nature. Often they are characterized by lateral or layered heterogeneity; that is, their hydraulic conductivity can vary vertically or horizontally. The presence of clay lenses in these aquifers is also common and is sometimes indicated by a slight steepening of the data curve, which might be interpreted as a barrier boundary. Many of the glacial aquifer wells are screened in coarse-grained sand and gravel deposits that have materials of lower permeability, such as silty and clayey deposits, above them. Although the overlying materials have a lower hydraulic conductivity, they are usually saturated and contribute water as pumpage occurs. The shape of the curve in fig. 81 (data from the pump test in Wyandotte County) appears to reflect this situation. During the early part of the test, water was depleted from the coarser, screened aquifer material. As pumpage continued, the finer-grained overlying deposits were drained in a vertical direction; this delayed drainage depressed the drawdown curve. If the test had been continued for a long enough time period, a confining layer would have been reached and the curve would have responded by becoming steeper, as in the early part of the test.

Aquifer parameters in the major buried-valley system extending from Nemaha County to Atchison County include T values of 2,500–25,600 gpd/ft (31–318 m^2/d) and S values of 0.00002–0.002. Transmissivities in the deepest region of the buried valley in southwestern Nemaha County were 15,000–20,000 gpd/ft (190–250 m^2/d) and S values were very consistent—0.0001–0.0002. These test wells were 290 ft (88 m) and 314 ft (95.7 m) in depth and were probably screened only in 10–20 ft (3–6 m) of basal sand and gravel.

Buried tributaries belonging to the major buried-valley system had T values of 1,500–25,000 gpd/ft (19–310 m^2/d). The deepest test well [160 ft (49 m)], located in a buried-valley tributary aquifer in Jefferson County, was screened in 13 ft (4.0 m) of blue clay, coarse-grained sand, and gravel. However, in the same area high T values were obtained from shallower wells [40–127 ft (12–38.7 m) in depth]. The Everest and Horton tests were conducted in a northern buried drainage to the buried valley in Atchison County and yielded a T value of 7500 gpd/ft (93 m^2/d) and an S value of 0.0008. Tests performed for Winchester and McLouth in Jefferson County were located in a broad glacial drift area. T values for these aquifers ranged from 3,500 gpd/ft to 10,000 gpd/ft (43–120 m^2/d) and S was equal to 0.0004 in test wells that were 125 ft (38.1 m) and 127 ft (38.7 m) in depth.

The thickness of glacial sediments decreases eastward in the major buried valley. A 70-ft (21-m) test well in Atchison County was screened in 10 ft (3 m) of

TABLE 2—Pump-test data for glacial aquifers.

County, city, and legal description	Approximate transmissivity (gpd/ft)	Approximate storage capacity	Pump-test date	Pumping rate (gpm)	Number of observation wells	Duration of test (min)	Depth of test well (ft)	Screened depth interval (ft)	Screened materials
Atchison County									
Everest 5–18E–6ACC	180,000	–	Dec. 1968	302	None	270	59	44–59, gravel-packed	Brown medium-grained sand and lime gravel
Horton 5–18E–6CDC	7,500	0.0008	May 1978	Variable (60–100)	4	1,440	40	Unknown	12 ft of medium- to coarse-grained sand
Lincoln Grain 6–20E–20	2,500	–	Nov. 1967	75	None	330	70	53–58 and 65–70	Medium- to coarse-grained sand and gravel; medium to coarse gravel
Lincoln Grain 6–20E–20DBA	145	0.11 (?)	July 1973	10–20	None	320	150	145–150	Sandy clay; trace gravel; gray coarse- to medium-grained sand to fine-grained sand
Jefferson County									
RWD 12 7–19E–32ADD	25,000	0.002	May 1973	90	4	1,440	127	110–120	Pea gravel and fine-grained sand, cemented
RWD 12 7–19E–33	200,000 (?)	0.01	June 1973	90	2	1,515	105	95–105	Coarse-grained sand; small and pea gravel
RWD 12 8–19E–5CBB	1,500	0.0009	June 1973	18.4	2	280	160	147–160	Black clay and coarse-grained sand and gravel
Winchester 8–19E–26CBB	3,500	–	Oct. 1969	Variable (40–60)	None	447 (?)	125	41–46, 67–72, and 115–125	Silty clay, medium- to coarse-grained sand, some fine gravel; loose medium- to coarse-grained sand, some fine-grained; trace gravel; dense, weathered limestone and medium-grained shale and medium-grained gray sandstone

Table 2 continued

County, city, and legal description	Approximate transmissivity (gpd/ft)	Approximate storage capacity	Pump-test date	Pumping rate (gpm)	Number of observation wells	Duration of test (min)	Depth of test well (ft)	Screened depth interval (ft)	Screened materials
McLouth 9–20E–32CDD	10,000	0.0004	Apr. 1967	Variable (10–20)	3	1,400	27	22–27	Brown medium- to coarse-grained, wet, loose sand
RWD 3 10–17E–3A	100,000	0.0003	Dec. 1977	500	3	1,500	82	62–82	Brown medium- to coarse-grained sand with trace of fine-grained material and boulders
Nemaha County									
Oneida 1–13E–35CAC	22,000	0.00002	May 1966	25	None	510	40	35–40	Brown medium- to coarse-grained sand and gravel, boulders
Centralia 4–11E–12ABCC	361 (?)	–	July 1960	30	None	480	54	38–54	Medium- to coarse-grained sand and gravel and gray silty clay
Goff 4–13E–35ABC	26,000	–	Nov. 1966	Variable (80–160)	None	360	122	106–122	Medium- to coarse-grained sand
RWD 3 5–11E–2BCC	20,000	–	Apr. 1072	Variable (182–184)	1	1,440	314	Unknown and 298–314	20–30 ft of medium- to coarse-grained sand, gray coarse-grained sand, and gravel and chert gravel
Onaga 5–11E–10ADB3	15,000	0.0002	Aug. 1977	190, 199–212	2	500	290	270–282 and unknown	Gray medium- to coarse-grained sand and gravel with trace of fine-grained material and boulders
Corning 5–12E–1CBB	7,500	–	Jan. 1961	Variable (27–66)	1	180	54	41–48 and unknown	Coarse-grained sand, medium- and fine-grained sand and large boulders
Wyandotte County									
Dub's Dread Golf Course 10–23E–33DAB	28,000 and 55,000	0.04 and 0.0005 (?)	July 1973	61	3	1,500	48 (?)	22–37 and 37–48	Gravel and coarse-grained sand

medium- to coarse-grained sand and gravel. The well was located in the middle of the buried valley, and a *T* value of 2,500 gpd/ft (31 m^2/d) was determined.

Comparatively narrow buried valleys that are not part of the major buried-valley system had some of the highest *T* values of the glacial aquifers. The Jefferson County RWD 3 test well, located in a narrow buried channel [locally 500 ft (150 m) wide], is 82 ft (25 m) deep and has a *T* value of 100,000 gpd/ft (1,200 m^2/d). A 48-ft (15-m) test well in Wyandotte County is located in a narrow buried valley [up to 0.5 mi (0.8 km) wide] that connects the Stranger Creek and Missouri River valleys. The transmissivity in this coarse-grained sand and gravel aquifer is 28,000 gpd/ft (350 m^2/d). Storage values obtained for these tests are 0.04–and 0.0005.

Relating glacial depositional environments to the type of glacial sediments may help to delineate areas of high transmissivity. Kehew and Boettger (1986) report that the most productive aquifers are present along the valley sides rather than in the valley centers for certain types of glacial buried valley in North Dakota. As discussed previously, the narrow buried channel in Jefferson County contains more than 100 ft (30 m) of glaciofluvial sands and gravels and was probably cut and buried quickly by water flowing at a high velocity and/or under a steep gradient; the buried valley in Wyandotte County may have originated in association with ice-marginal drainage.

Low-transmissivity boundaries affected drawdown data in most of the glacial aquifer tests. The distribution of coarse-grained materials in aquifer bodies varies widely, and coarse-grained layers may grade into finer-grained materials horizontally within hundreds or even tens of feet. In a 1986 pump test for Nemaha County RWD 3, wells located in the major buried valley in southwestern Nemaha County had drawdowns that were affected within 50 minutes during the test by public water-supply wells operating 0.75 mi (1.2 km) away. These results suggest that the coarse-grained, high-transmissivity aquifer body is limited in its areal extent.

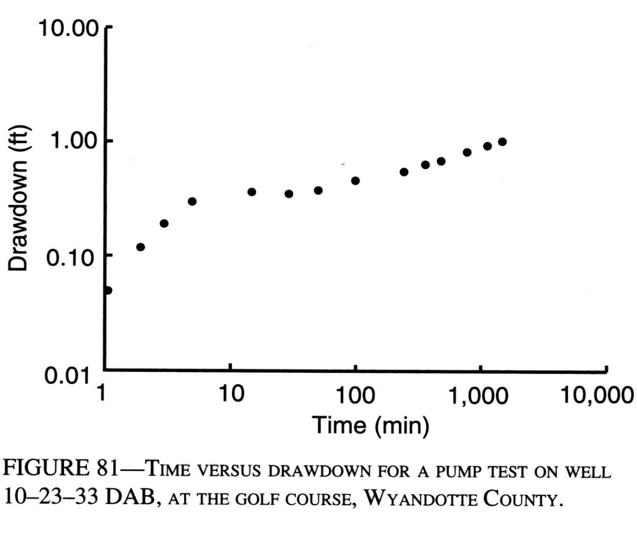

FIGURE 81—Time versus drawdown for a pump test on well 10–23–33 DAB, at the golf course, Wyandotte County.

Aquifer tests for alluvial aquifers in northeastern Kansas were mainly for wells located in the Kansas and Missouri River valleys (table 3). Tests along the Kansas River were performed in Douglas, Jefferson, Johnson, Shawnee, and Wyandotte counties and had transmissivities of 50,000–600,000 gpd/ft (600–7,000 m^2/d). Extensive tests were performed using various pumping rates [up to 1,100 gpm (0.069 m^3/s)] and various durations for an industrial facility located along the Kansas River in Topeka. Transmissivities from these tests ranged from 350,000 gpd/ft to 670,000 gpd/ft (4,300–8,300 m^2/d); and storage values were 0.03 and probably reflect semiconfined conditions. Many tests were conducted for Johnson County RWD 1 and along the Kansas River in Wyandotte County, and transmissivities ranged from 300,000 gpd/ft to 500,000 gpd/ft (4,000–6,000 m^2/d). Transmissivities were generally lower in Douglas and Jefferson counties, although most of the test wells were located farther from the river and in terrace deposits.

Pump tests for wells in the Missouri River alluvium were conducted in Atchison, Leavenworth, and Doniphan counties. Transmissivity values ranged from 200,000 gpd/ft to 600,000 gpd/ft (2,000–7,000 m^2/d), with most of the *T* values close to 300,000 gpd/ft (4,000 m^2/d). The highest transmissivities were in Leavenworth County at Ft. Leavenworth and in Atchison County at St. Benedicts, with transmissivities of 600,000 gpd/ft (7,000 m^2/d) and 500,000 gpd/ft (6,000 m^2/d), respectively. Storage values were between 0.0004 and 0.001.

In Jefferson County performance tests were done on the Delaware River alluvium, mostly along the periphery of Perry Lake. Transmissivity values were in the range of 5,000–25,600 gpd/ft (60–318 m^2/d). Test wells in the main part of the Delaware River alluvium were 45–64 ft (14–20 m) in depth and yielded transmissivities of 5,000–8,000 gpd/ft (60–100 m^2/d) and storage values of 0.0004. The highest *T* value [25,600 gpd/ft (318 m^2/d)] in this area is probably from an aquifer having a combination of glacial and alluvial sediments. The test well is not in the main part of the Delaware River alluvium and is screened in 26 ft (7.9 m) of sand and gravel. Aquifer tests in the Delaware River alluvium were affected by multiple boundaries, including bedrock barrier boundaries and recharge boundaries from Perry Lake, depending on the test's duration.

There was little available information for pump tests in bedrock aquifers in northeastern Kansas, and data were questionable in most cases (table 4). A pump test analysis in Nemaha County near the city of Sabetha gave a *T* value of 2500 gpd/ft (31 m^2/d) and a storage value of 0.0005 for an aquifer in a limestone fracture zone 60–140 ft (18–43 m) deep. About 5 mi (8 km) south of the city of Fairview in Brown County, we tested an aquifer in a limestone fracture zone [91–106 ft (28–32.3 m) deep] and obtained questionable transmissivities of 30–140 gpd/ft (0.4–1.7 m^2/d), but we did not measure drawdowns until 10 minutes after pumpage began. A 107-ft-deep (32.6-m-deep) test well screened in limestone and shale layers in Wabaunsee County gave a T value of 200 gpd/ft (2 m^2/d). A questionable aquifer test was done for a sandstone aquifer in Leavenworth County. The data for this test are confusing, and the discharge rate is so large that it seems unreasonable for even the best bedrock aquifers in this area.

We calculated hydraulic conductivity by dividing the calculated transmissivity value by the screened length of the well. The screened length does not represent the total aquifer thickness for most of the alluvial and glacial aquifers, and the true aquifer thickness is generally greater because of permeable layers above or below the screened section. Therefore the K value is more representative of the screened interval, not the total saturated aquifer.

Hydraulic conductivity K for the alluvial aquifers ranged from 554 gpd/ft^2 (22.6 m/d) in the Delaware River alluvium to 42,000 gpd/ft^2 (1700 m/d) in the Kansas River deposits near Bonner Springs. According to ideal aquifer K values (table 5), the lower value is characteristic of silty to clean sand and the upper value is typical of clean sand and gravel. Lower K values for the Kansas River had magnitudes of 10^3 gpd/ft^2 (10^1 m/d), with the remaining K values ranging from 13,000 gpd/ft^2 to 33,000 gpd/ft^2 (530–1,300 m/d). Hydraulic conductivities for the Missouri River alluvium ranged from 12,000 gpd/ft^2 to 30,000 gpd/ft^2 (490–1,200 m/d), with the highest value determined from a test in Atchison County (sec. 29, T. 5 S., R. 21 E.).

The glacial aquifers had hydraulic conductivities ranging from 115 gpd/ft^2 to 5,000 gpd/ft^2 (4.69–200 m/d). The lowest K values were for an aquifer in Jefferson County (sec. 5, T. 8 S., R. 19 E.) and for an aquifer in Nemaha County close to Turkey Creek. Hydraulic conductivities greater than 1,000 gpd/ft^2 (40 m/d), typical of clean sand, were determined for aquifers in Atchison, Jefferson, Nemaha, and Wyandotte counties. The highest K values were found in tests for Jefferson County RWD 3 and a golf course in Wyandotte County.

Water Use

The Division of Water Resources (DWR) in Kansas has kept records of water use and water appropriations since 1944 and has maintained a computerized data base of water-use information since 1981. Appropriated water volumes are generally 2.5 times larger than the actual reported use, with only 50–75% of the permit holders reporting (Kenny, 1986). Because of the relatively large and increasing population in northeastern Kansas, appropriations of water for public use and industrial use have been steadily increasing since 1944. In 1984, 28.4% [267 Mgpd (million gallons per day) (1.01×10^6 m^3/d)] of the water appropriated in eastern Kansas was from a ground-water source. Public supplies made up 11.6%, industrial supplies 11.5%, and irrigation 5.3%. The total volume of water appropriated for 1984 was 942 Mgpd (3.57×10^6 m^3/d).

The DWR reported a total water right volume of 147,920 acre-ft [132 Mgpd (5.00×10^5 m^3/d)] in 1981 for the 12-county region of northeastern Kansas (table 6). From the given well locations we interpreted aquifer types from available well logs and hydrogeologic maps. Ninety-four percent of the water allocated came from alluvial aquifers; only 4% of the water was from glacial aquifers and less than 2% was from rock aquifers (tables 7 and 8). Most of the water rights were found in counties bordering the Kansas and Missouri River valleys, where 98% of the appropriations from alluvial aquifers are located. The number of wells and water volumes are calculated for use and aquifer categories by county and for the total 12-county area (tables 7 and 8).

Fifty-two percent of the total rights were allocated for industrial use, and Wyandotte County had 51% of the total allocated volume for industrial use [39,078 acre-ft or 35 Mgpd (1.3×10^5 m^3/d)] in the 12-county area. Shawnee, Johnson, and Douglas counties were allocated 19%, 15%, and 13%, respectively, of the industrial volume. There were 142 industrial wells reported.

A volume of 41,746 acre-ft [37 Mgpd (1.4×10^5 m^3/d)], or 28% of the total volume for the study region, was allocated for municipal use. Although the number of municipal wells is almost twice that of industrial wells, the municipal use category was allocated about half the volume of water allocated for industrial use. Municipal-use allocations for the counties were generally related to population density, with Wyandotte County allocated 13,985 acre-ft [12.5 Mgpd (4.73×10^4 m^3/d)], or 33.5% of the total municipal volume, and Johnson and Douglas counties allocated 23% and 10.6%, respectively, of the municipal total. In Brown and Jackson counties, all the wells reported were for municipal use.

Irrigation ground waters make up 20% of the total allocated volume. Shawnee County was allocated 55% of the total volume for irrigation use, distributed among 187 wells. Wabaunsee and Jefferson counties also had substantial water volumes allocated for irrigation.

Less than 0.1% of the total water allocated was attributed to the domestic, stock, and recreation categories. However, domestic wells generally do not need a water right, and domestic well owners do not report water use to the DWR.

Alluvial aquifers (600 wells) supplied most of the water allocated for industrial, irrigation, and municipal uses. Thirty-six wells tapping rock aquifers were allocated water for municipal use in Douglas County (table 7).

TABLE 3—PUMP-TEST DATA FOR ALLUVIAL AQUIFERS.

County, city, and legal description	River	Transmissivity (gpd/ft)	Pump storage	Pumping test date	Rate (gpm)	Number of observation wells	Duration of test (min)	Depth of test well (ft)	Screened depth interval (ft)	Screened materials
Atchison County										
St. Benedicts 5–21E–29BAA	Missouri	500,000	–	May 1967	1,305	3	330	–	–	No log
Midwest Solvent 55–37W–19CCA (in Missouri)	Missouri	300,000	0.00001	July 1967	1,000–1,950	None	180	92	67–92	Medium- to coarse-grained sand and gravel
Doniphan County										
White Cloud 1–19E–15BBB	Missouri	26,000	–	Aug. 1963	50–150	None	360	60	55–60	Medium- to coarse-grained sand and gravel, boulders
Douglas County										
Baldwin 13–20E–9	Kansas	212,000	7.4×10^{-7}	July 1972	221	1	480	75	5 screened	–
Eudora 13–13–21E–5DB	Kansas and Wakarusa	117,000	4×10^{-8}	July 1974	459	None	240	71	10 screened	Coarse- to medium-grained sand and trace boulders
Jefferson County										
Oskaloosa RWS 9–18E–31DBA	Delaware	8,000	4×10^{-4}	May 1967	30	2	420	50	33–46	Coarse- to fine-grained sand and gravel
RWD 8 10–10–17E–27AAA	Delaware/ Rock Creek	26,000	–	Apr. 1969	15–45	None	360	53	15–19	Medium- to coarse-grained sand and gravel, sandy clay, and gravel
RWD 15 11–17E–17CCC	Kansas	260,000	–	Feb. 1979	280	None	480	67	47–67	–
RWD 10–18E–19DAA	Delaware	5,000	4×10^{-4}	Dec. 1968	20	1	360	60.5	54–60	Coarse- to medium-grained sand and gravel

Table 3 continued

County, city, and legal description	River	Transmissivity (gpd/ft)	Pump storage	Pumping test date	Rate (gpm)	Number of observation wells	Duration of test (min)	Depth of test well (ft)	Screened depth interval (ft)	Screened materials
New Ozawkie 9–17E–25DAC	Delaware	18,000	0.01	Feb. 1966	50	None	1,440	54	44–54	Medium- to coarse-grained sand and gravel
Perry 11–18E–22DAA	Kansas	460,000	2×10^{-8}	Apr. 1966	100–201	None	180	83	73–83	Medium- to coarse-grained sand and gravel with boulders
Leavenworth County Ft. Leavenworth 8–22E–13BAA	Missouri	600,000	–	July 1974	860–1,750	None	720	93.5	45 screened	–
Shawnee County Goodyear Tire and Rubber Co. 11–15E–13DAD and 13DAA	Kansas	300,000–600,000	0.0001 (?)	Apr. 1960	225–990	4	~1,740	81 and 49	–	–
Wyandotte County Inland Underground Storage 11–24E–27BAC	Kansas	360,000	–	Jan. 1965	200–500	None	240	64	44–64	–
Johnson County RWD 1 11–24E–29CDC	Kansas	330,000	–	Dec. 1959	607	7	4,320	65	50–65 (?)	Medium- to coarse-grained sand and gravel
Superior Sand Co. 11–23E–31DAB	Kansas	400,000	–	Mar. 1971	703	None	240	59	39–59	Medium- to coarse-grained sand and gravel

TABLE 4—Pump-test data for bedrock aquifers.

County, city, and legal description	Transmissivity (gpd/ft)	Storage capacity	Pump-test date	Pumping rate (gpm)	Number of observation wells	Duration of test (min)	Depth of test well (ft)	Screened depth interval (ft)	Screened materials
Brown County JBN Tel. Co. 3-15E-28DDD	30–140	–	Mar. 1968	8	None	120	97	92–97	Limestone
Leavenworth County Tonganoxie 11-21E-10CAB	–	–	May 1974	385–405	2 (?)	1,500	80 (?)	–	Sandstone
Nemaha County Sabetha 2-14E-13BBC	2,500	5×10^{-4}	Feb. 1979	50	3	1,500	100	78–98	Limestone and shale
Wabaunsee County Wabaunsee East USD 3 13-12E-3BDA	200	–	Feb. 1970	None	None	345	107	–	Limestone and shale

TABLE 5—Range of values of hydraulic conductivity.

Unconsolidated aquifer material	Range of K (gpd/ft^2)
Unweathered marine clay	10^{-6}–10^{-2}
Glacial till	10^{-5}–10
Silt, loess	10^{-2}–10^{2}
Silty sand	10^{-1}–10^{3}
Clean sand	10–10^{5}
Gravel	10^{4}–10^{6}

Adapted from Freeze and Cherry (1979).

Ground water allocated from glacial aquifers was predominantly for municipal use and included 93 wells. One well in a glacial aquifer located in Shawnee County had an industrial use, and two glacial aquifer wells located in Wabaunsee and Nemaha counties were used for irrigation.

Table 6 shows ground-water use in 1981 and 1982, as reported to the DWR by February 16, 1984, for northeastern Kansas. Thirty-four percent was reportedly pumped for municipal supplies, 6% for irrigation, and 60% for industrial use in 1981. This amounted to 37% of the appropriated ground-water rights. In 1982, 49% was reportedly pumped for municipal supplies, 10% for irrigation, and only 41% for industrial use. Reported actual pumpage for 1982 was close to 36% of the allocated ground-water rights.

Wyandotte County reported the largest pumpage for municipal supplies, with 33% and 47% in 1981 and 1982, respectively; Shawnee County reported the largest pumpage of ground water for irrigation, averaging 56% of the total reported irrigation supplies for 1981 and 1982. Douglas and Wyandotte counties reported the largest pumpage for industrial purposes in 1981, with 26% and 34%, respectively. In 1982 Wyandotte County dominated the industrial-use category, reportedly pumping 41% of the allocated water rights.

The fluctuation of use reported to the DWR may not reflect actual changes in use; rather, the fluctuations may reflect inconsistencies in the reports sent to the DWR. These inconsistencies make reliable comparisons from year to year difficult and of doubtful accuracy.

According to DWR records, no county in the 12-county region surpassed allocated ground-water rights; in several cases counties reported use of less than 20% of the allocated volume (see table 6). Leavenworth County reported the greatest percentage of use: 72% and 92% for 1981 and 1982, respectively. Atchison County reported the lowest percentage of use compared to allocated volume, with 12% and 17% for 1981 and 1982, respectively.

Allocations for wells associated with the main buried channel amount to 1,466 acre-ft of ground water from Atchison, Jackson, and Nemaha counties (table 9). Tributaries associated with the main buried channel contribute an additional 837 acre-ft of ground water, and these sources together account for 43% of the ground water used in 1981 for public supplies [750 Mgal (2.8 million m^3)]. An additional 214 acre-ft from the three counties were derived from wells tapping a combination of glacial and alluvial deposits.

We also collected public water-use information for northeastern Kansas from the Kansas Department of Health and Environment (KDHE) files (table 10). We gathered as much information as possible for 1981, but for many supplies we had to use data from other years or part of a year in place of the unavailable 1981 data. The water volumes were usually reported from cities and rural water districts and used meter readings as a reference, although in some cases volumes were estimated. It was not clear for some supplies how much water was sold to or acquired from other districts.

The largest percentage differences (>96%) in DWR and KDHE reported public ground-water use were from Atchison, Jackson, and Wyandotte counties. Use reported to the DWR for Atchison and Jackson counties was low, and volumes reported to the KDHE for Wyandotte County were also low. Large percentage differences were also apparent in Johnson, Shawnee, and Wabaunsee counties. Overall, volumes reported to the KDHE were 27.9% greater than those reported to the DWR.

According to water-well records, which have been required by the state since 1975, the greatest number of wells drilled were for domestic use (59.5%). Ten counties in the 12-county area of northeastern Kansas (excluding Wyandotte and Johnson counties) had the highest percentage of wells in the domestic category (table 11). Johnson and Wyandotte counties are affected by the great amount of industrial development in the Kansas City area. Johnson County had 116 observation wells drilled, and Wyandotte County had 282 wells in the observation-well category and other categories (e.g., dewatering, relief, and monitoring). There were records for 123 observation and monitoring wells drilled by the Sunflower Army Ammunitions Plant located in Johnson County.

Shawnee County had the greatest number of water-well records, including 216 domestic wells and 87 irrigation wells. Leavenworth County was second in the number of water-well records, with 90.1%, or 327 wells reported for domestic use. The number of wells in these two counties probably reflects the suburban growth in the Kansas City and Topeka areas. The lawn and garden–stock category was significant in Shawnee, Atchison, and Doniphan counties, with Shawnee County having 63 wells in this category.

Shawnee County had the largest percentage of irrigation wells, with 55.2% of the total number of irrigation wells in the 12-county region. Other counties with irrigation wells are Atchison (six wells), Leavenworth (six wells), Jefferson (13 wells), Douglas (18 wells), and Wabaunsee (19 wells). These irrigation wells are in the Kansas and Missouri River alluvium.

The "Priority List for Technical Assistance" was created by the Kansas Department of Health and Environment (KDHE, 1983) to help "determin[e] priorities for action in dealing with communities to establish more reliable and better quality water supplies." Water districts in northeastern Kansas included in this list as of April 1983 are separated into three priority categories: high, intermediate, and potential. Problems associated with the high-priority category include a severe lack of an adequate quantity of water; the intermediate category indicates pressure and treatment

TABLE 6—1981–1982 VOLUME OF GROUND-WATER PUMPAGE BY TYPE IN NORTHEASTERN KANSAS.[a]

County	Municipal use[b] 1981	Municipal use[b] 1982	Irrigation use[b] 1981	Irrigation use[b] 1982	Industrial use[b] 1981	Industrial use[b] 1982
Atchison	1,107,893	71,048,552	49,529,352	0	0	0
	(3)	(218)	(152)			
Brown	263,668,853	230,243,058	0	0	0	0
	(809)	(707)				
Doniphan	156,411,738	215,446,164	20,307,034	8,100,655	0	0
	(480)	(661)	(62)	(25)		
Douglas	464,562,512	457,061,422	152,615,574	82,104,676	3,967,418,401	1,258,306,221
	(1,426)	(1,403)	(468)	(252)	(12,176)	(3,862)
Jackson	5,637,222	108,632,206	0	0	0	0
	(17)	(333)				
Jefferson	270,544,309	238,011,345	48,167,294	83,942,476	8,732,806	9,606,087
	(830)	(730)	(148)	(258)	(27)	(29)
Johnson	1,310,898,573	1,285,156,344	1,381,608	377,987	498,623,717	355,008,147
	(4,023)	(3,944)	(4)	(1)	(1,530)	(1,090)
Leavenworth	1,087,615,692	1,350,971,728	2,219,045	34,422,899	0	0
	(3,338)	(4,146)	(7)	(106)		
Nemaha	226,388,240	363,239,143	0	0	55,189,383	60,481,204
	(695)	(1,115)			(169)	(186)
Shawnee	164,118,114	176,601,466	552,728,017	1,013,507,399	2,228,276,668	2,202,837,481
	(504)	(542)	(1,696)	(3,110)	(6,839)	(6,761)
Wabaunsee	120,708,244	36,009,794	28,632,527	462,910,447	36,935,210	32,128,908
	(370)	(111)	(88)	(1,421)	(113)	(99)
Wyandotte	2,016,284,525	3,975,043,314	141,885,300	94,998,600	3,910,915,838	3,102,955,249
	(6,188)	(12,200)	(435)	(292)	(12,003)	(9,523)
Total	6,087,945,915	8,507,464,536	997,465,751	1,780,365,139	10,706,092,020	7,021,323,297
	(18,684)	(26,110)	(3,061)	(5,464)	(32,858)	(21,549)

a. As reported to the Division of Water Resources by February 16, 1984.
b. Reported to the Division of Water Resources in gallons. Acre-feet given in parentheses. Conversion: acre-feet = gallons (1 ft^3/7.48 gal)(1 acre-ft/43,560 ft^3).
c. Pending rights (in acre-feet) as of May 1983 given in parentheses.

plant problems, water-quality problems, or less severe quantity problems; and the potential category indicates possible problems with a district's quality or quantity of water. There were no priority listings for Douglas, Jackson, Shawnee, and Wyandotte counties.

The Eskridge district in Wabaunsee County is listed as high priority, having both quantity and quality problems. Eskridge has two wells but is planning to obtain water from Lake Wabaunsee in the future. Wabaunsee County RWD 1, also listed as high priority, has only two wells, which are reported to have poor water quality because of high iron and manganese concentrations.

Leavenworth County RWD 1 is listed under the high-priority category because it has distribution, storage, and pressure problems. The city of Linwood, listed as intermediate priority, has two wells with water-quality problems, specifically high iron and manganese levels. Tonganoxie is listed as a potential problem because of the low quantity of water during drought seasons. Leavenworth County RWD 6 obtains its water from Tonganoxie and consequently is also listed in the potential category.

Brown County has two intermediate-priority districts, including Powhattan and Robinson. Powhattan has two wells with quantity and quality (high nitrate and selenium levels) problems, and Robinson has six wells with quantity and nitrate problems. Brown County RWD 1, which has six wells, is reported to have a distribution problem.

Doniphan County has two intermediate-priority districts: RWD 2 (with only one well) and RWD 3 (with two wells). Both districts have high nitrate concentrations.

Winchester, in Jefferson County, is listed as an intermediate-priority area because of water-quantity and -quality problems. Winchester district's one well has a high nitrate concentration, and its two springs are inadequate to meet user demands. Districts listed as potential problems in Jefferson County include RWD 1, RWD 6, RWD 7, RWD 15, McLouth, and Summerfield. Water-quantity problems exist in RWD 6, RWD 15, and

(Table 6, continued)

County	Domestic use[b] 1981	Domestic use[b] 1982	Total use[b] 1981	Total use[b] 1982	Ground-water rights allocated as of May 1983 (acre-ft)[c]	Percentage of rights reportedly pumped for use 1981	Percentage of rights reportedly pumped for use 1982
Atchison	0	0	50,637,245	71,048,552	1,302	12	17
			(155)	(218)			
Brown	0	0	263,668,853	230,243,058	1,266	62	55
			(809)	(707)			
Doniphan	0	0	176,718,772	223,546,819	1,313	41	52
			(542)	(686)			
Douglas	0	0	4,584,596,487	1,797,472,319	16,559	85	33
			(14,071)	(5,517)			
Jackson	0	0	5,637,222	108,632,206	922	2	36
			(17)	(333)			
Jefferson	0	0	327,444,409	331,559,908	6,298	16	16
			(1,005)	(1,018)	(37)		
Johnson	0	0	1,810,903,898	1,640,542,478	21,285	26	24
			(5,558)	(5,035)	(5)		
Leavenworth	0	0	1,089,834,737	1,385,394,627	4,619	72	92
			(3,345)	(4,252)	(4)		
Nemaha	0	0	281,577,623	423,720,347	1,687	51	77
			(864)	(1,300)	(270)		
Shawnee	5,998,916	58,653	2,951,121,715	3,393,004,999	33,283	27	31
	(18)	0	(9,057)	(10,413)	(380)		
Wabaunsee	0	0	186,275,981	531,049,149	4,967	12	33
			(572)	(1,630)	(132)		
Wyandotte	0	0	6,069,085,663	7,172,997,163	54,419	34	40
			(18,627)	(22,015)			
Total	5,998,916	58,653	17,797,502,610	17,309,211,630	147,920	37	36
	(18)	(0)	(54,622)	(53,124)	(828)		

McLouth; and problems with distribution systems exist in RWD 1 and RWD 7. Summerfield has water-quality problems, specifically high sulfate and selenium concentrations. All these districts in Jefferson County obtain their water from wells, except McLouth, which has two springs and seven wells.

Two districts in Nemaha County were listed as intermediate priority. The interconnected RWD 1 and Bern water systems have five wells. Water-quantity problems and high iron levels were cited as reasons for the intermediate rating.

Johnson County has five intermediate-priority areas: Edgerton, Spring Hill, RWD 6, RWD 6A, and RWD 7. All these districts were reported to have water-quantity problems. Spring Hill and RWD 7, which obtain their water from Olathe, have a limited purchase amount, as do RWD 6 and RWD 6A, which obtain their water from DeSoto. Edgerton obtains its water from a reservoir that dries up during droughts and from RWD 7, which has a limited purchase amount. A few of these districts have plans to connect with other water districts to solve their water demands.

A study of northeastern Kansas water supplies was done by Associated Engineers, Inc., and a draft report was completed in May 1980. This study provides basic data and planning information concerning the municipal and industrial water needs in a large region of northeastern Kansas. In general, the study plans for large water-supply systems that have centralized treatment plants and extensive distribution systems. Three sources of water were investigated: impounded surface water (from proposed and existing reservoirs), river water, and ground water. Certain rural water districts and urban areas were chosen as priority areas because of their lack of a sufficient number of wells, high nitrate concentrations, the existence of old wells, water shortages, water shortage during drought, contract problems, high sulfate concentrations, silting of reservoirs, and other impoundment problems. Plans were proposed to meet the needs of these priority areas, the future needs of all areas to the year 2035, and the needs of the present unserved population.

Associated Engineers proposed meeting the water needs of northeastern Kansas chiefly by using surface-water sources and planning many small reservoirs. Water supply systems along the Missouri River would be largely dependent on the river water, either from an intake system or from alluvial wells. Leavenworth, Atchison, and Doniphan counties are currently largely dependent on Missouri River alluvial waters. Two

TABLE 7—1983 GROUND-WATER RIGHTS BY USE AND AQUIFER FOR NORTHEASTERN KANSAS COUNTIES.

Water use and aquifer type[a]	Number of wells	Percentage of volume (acre-ft)	Total volume for county
Atchison County			
(eight water rights)			
Irrigation			
Alluvial	4	976	75
Municipal			
Alluvial	1	34	3
Glacial	10	292	22
Total	15	1,302	100
Brown County			
(11 water rights)			
Municipal			
Alluvial	4	24	2
Glacial	15	1,017	78
Rock	8	225	20
Total	27	1296	100
Doniphan County			
(11 water rights)			
Irrigation			
Alluvial	3	505	38
Municipal			
Alluvial	7	614	47
Glacial	6	194	15
Total	16	1,313	100
Douglas County			
(65 water rights)			
Industrial			
Alluvial	21	9,947	60
Rock	3	82	0
Irrigation			
Alluvial	27	2,096	13
Rock	1	2	0
Municipal			
Alluvial	19	3,451	21
Glacial	1	0	0
Rock	36	981	6
Total	108	16,559	100
Jackson County			
(six water rights)			
Municipal			
Alluvial	1	7	1
Glacial	5	890	96
Rock	2	25	3
Total	8	922	100
Jefferson County			
(70 water rights			
Industrial			
Alluvial	3	373	6
Irrigation			
Alluvial	36	3,223	51
Municipal			
Alluvial	20	1,779	28
Glacial	23	923	15
Total	82	6,298	100
Johnson County			
(14 water rights)			
Industrial			
Alluvial	13	11,233	53
Rock	2	5	0
Irrigation			
Alluvial	5	357	2

continued next column

Water use and aquifer type[a]	Number of wells	Percentage of volume (acre-ft)	Total volume for county
Johnson County (cont.)			
Municipal			
Alluvial	22	9,690	45
Total	42	21,285	100
Leavenworth County			
(20 water rights)			
Irrigation			
Alluvial	10	833	18
Municipal			
Alluvial	20	3,131	68
Glacial	1	62	1
Rock	14	593	13
Total	45	4,619	100
Nemaha County			
(23 water rights)			
Industrial			
Rock	3	138	8
Irrigation			
Glacial[a]	1	70	4
Municipal			
Glacial[a]	30	1,479	88
Total	34	1,687	100
Shawnee County			
(217 water rights)			
Domestic			
Alluvial	1	6	0
Industry			
Alluvial	26	14,820	45
Glacial	1	129	0
Irrigation			
Alluvial	187	16,242	49
Municipal			
Alluvial	17	2,086	6
Rock	1	3	0
Total	233	33,283	100
Wabaunsee County			
(54 water rights)			
Industrial			
Alluvial	7	534	11
Irrigation			
Alluvial	41	4,107	83
Glacial (?)	1	65	1
Municipal			
Alluvial	11	169	3
Rock	7	92	2
Total	67	4,967	100
Wyandotte County			
(35 water rights)			
Industry			
Alluvial	63	39,078	72
Irrigation			
Alluvial	3	1,356	2
Municipal			
Alluvial	28	13,816	25
Glacial	2	169	1
Total	96	54,419	100

a. Glacial and alluvial aquifers are included where wells penetrate both aquifers.

TABLE 8—SUMMARY OF WATER RIGHTS BY USE AND SOURCE FOR THE 12-COUNTY STUDY AREA (totals): 1983.

Water use and aquifer	Number of wells	Volume (acre-ft)	Percentage of total volume
Domestic			
Alluvial	1	3	0
Total	1	3	0
Industry			
Alluvial	133	75,985	51
Rock	8	225	0
Glacial	1	129	0
Total	142	76,342	52
Irrigation			
Alluvial	316	29,695	20
Rock	1	2	0
Glacial	2	135	0
Total	319	29,832	20
Municipal			
Alluvial	150	34,801	24
Rock	68	1,919	1
Glacial	93	5,026	3
Total	311	41,746	28
Total	773	147,920	100

TABLE 9—ALLOCATED GROUND WATER FROM WELLS ASSOCIATED WITH THE MAIN BURIED CHANNEL ACROSS NORTHEASTERN KANSAS.

Well location	Reported volume (acre-ft)
Atchison County	
NESWNW sec. 22, T. 6 S., R. 18 E.	58.3
NESWNW sec. 22, T. 6 S., R. 18 E.	43.0
Subtotal	101.3
Jackson County	
NESWNW sec. 7, T. 6 S., R. 16 E.	293.5
NESWNW sec. 7, T. 6 S., R. 16 E.	293.5
Subtotal	587.0
Nemaha County	
NWSENW sec. 2, T. 5 S., R. 11 E.	260.8
NWSWNW sec. 2, T. 5 S., R. 11 E.	107.0
NWSWNW sec. 2, T. 5 S., R. 11 E.	135.0
NWSENE sec. 10, T. 5 S., R. 11 E.	101.5
SWSWNW sec. 10, T. 5 S., R. 11 E.	135.0
SESWNENE sec. 10, T. 5 S., R. 11 E.	13.8
NWSENE sec. 10, T. 5 S., R. 11 E.	24.6
Subtotal	777.7
Total[a]	1,466

As of May 1983.

All wells are public supply wells.

Volume of ground water from tributaries to the main buried channel = 837 acre-ft (273 Mgpd). Volume of ground water from tributaries to the main buried channel tapping both glacial and alluvial sources = 214.4 acre-ft (70 Mgal or 0.2 Mgpd).

a. 1,466 acre-ft = 477 Mgal = 1.3 Mgpd.

TABLE 10—WATER-USE DATA: VOLUME REPORTED FOR PUBLIC USE (1981).

County	KDHE data		DWR data	Absolute difference	% Difference
	Mgal	Acre-ft	(acre-ft)	(acre-ft)	(larger volume)
Atchison	82.16	267.8	3	264.8	99
Brown	202.65	660.4	809	148.6	18.4
Doniphan	123.89	403.8	480	76.2	15.9
Douglas	315.08	1,026.8	1,426	399.2	28
Jackson	341.8	1,113.9	17	1,096.9	98.5
Jefferson	157.13	512.1	830	317.9	38.3
Johnson	5,272.17	17,182.0	4,023	13,159	76.6
Leavenworth	733.38	2,390.1	3,338	948	28.4
Nemaha	303.93	990.5	695	295.5	29.8
Shawnee	301.433	982.4	504	478.4	48.7
Wabaunsee	55.79	181.8	370	188.2	50.9
Wyandotte	59.81	194.9	6,188	5,993.1	96.8
Total	7,949.22	25,906.5	18,684	7,222.5	27.9

TABLE 11—WATER USE INDICATED BY WATER-WELL RECORDS (1975–October 1983).

	Use (%)[a]								
County	Domestic (based on 1358.3 WWRs)	Lawn and garden, stock (based on 123.8 WWRs)	Public supply (based on 73 WWRs)	Industrial and commercial (based on 56.5 WWRs)	Observation (based on 323 WWRs)	Irrigation (based on 151.8 WWRs)	Other[b] (based on 146.5 WWRs)	Number of WWRs for county	Percentage of total WWRs for 12 counties
Atchison	71.1	16.2	2.8	1.4	–	8.4	–	71	3.1
Brown	87.9	3.4	2.6	6.0	–	–	–	116	5.1
Doniphan	78.1	15.6	1.6	3.1	–	–	1.6	64	2.8
Douglas	55.8	3.7	5.0	2.7	13.0	7.7	12.0	238	10.4
Jackson	91.5	3.5	2.1	–	2.1	–	0.7	141	6.2
Jefferson	68.6	3.6	8.6	1.4	6.4	9.3	2.1	140	6.1
Johnson	23.1	–	6.4	–	67.0	1.2	2.3	173	7.6
Leavenworth	90.1	0.6	3.3	0.6	3.3	1.6	0.6	363	1.6
Nemaha	63.2	7.0	8.8	–	12.3	–	8.8	57	2.5
Shawnee	55.2	16.1	0.8	2.0	3.1	22.3	0.5	392	17.2
Wabaunsee	79.6	5.0	3.7	1.1	0.6	10.1	–	189	8.3
Wyandotte	8.3	0.3	0.6	7.7	38.9	–	44.2	339	14.8
Total								2283	100.0
Percentage of total water wells	59.5	5.4	3.2	2.5	14.1	6.6	8.6		

WWR, water-well record.

a. Fractions indicate wells that have more than one use.

b. Uses include test wells, dewatering, and relief wells.

reservoirs in Atchison County and one in Doniphan County were proposed. In Jackson County a combination of sources is presently in use, including ground water from various alluvial deposits (e.g., the Delaware River) and water from Perry Reservoir. Another reservoir east of the city of Holton was proposed. Perry Lake and the Kansas River alluvium supply water to areas of Jefferson County, and two reservoirs were proposed to be located north of the city of Winchester. Shawnee and Wabaunsee counties are largely dependent on the Kansas River, and reservoirs were proposed in both of these counties. In these two counties water from the Kansas River would be piped to all parts of the counties.

Glacial aquifers were considered in Brown and Nemaha counties. A well field was proposed north of the city of Hiawatha in Brown County, and a well field was proposed in sec. 11, T. 3 S., R. 12 E., in Nemaha County. Brown and Nemaha counties presently depend on glacial aquifers and ground water in general, although the city of Sabetha (Nemaha County) obtains water from a small reservoir.

Chemical Quality of Ground Waters in Northeastern Kansas

Observations Regarding the Aquifer Systems

Within the confines of the glaciated area of northeastern Kansas, wells have been developed in Pennsylvanian and Permian bedrock units, deposits of glacial origin, and alluvial deposits of modern drainageways. The nature of these ground-water sources and the quality of water they contain have been described previously in various county reports (Bayne, 1973; Bayne and Schoewe, 1967; O'Connor, 1960, 1971; Walters, 1953; Ward, 1973, 1974; Winslow, 1972).

In general, the alluvial deposits are the major source of ground water in northeastern Kansas. These deposits, especially those in valleys of major drainageways, are known to produce hard calcium bicarbonate (Ca^{2+}–HCO_3^-) waters that may contain several milligrams per liter of iron (Fe). The sand and gravel layers associated with deposits of glacial origin yield varying quantities and quality of water; we used a calcium bicarbonate classification and the possibility of elevated iron levels to characterize waters from these glacial buried-valley aquifers. The bedrock aquifers seem to be more limited in yield, and they often produce water of lower quality that might contain appreciable amounts of iron sulfate (SO_4^{2-}), and chloride (Cl^-).

Federal regulations concerning primary drinking-water standards establish a maximum level of 44.3 mg/L for nitrate as NO_3, or 10 mg/L nitrate as N (U.S. Environmental Protection Agency, 1975). Secondary drinking-water standards set maximum levels of 250 mg/L for chloride and sulfate, 500 mg/L for total dissolved solids, 0.3 mg/L for iron, and 0.05 mg/L for manganese (Mn) (U.S. Environmental Protection Agency, 1979b).

Nitrate (NO_3) concentrations in excess of 45 mg/L have been noted in waters from a number of wells of varying depth and aquifer source in the area of study. Denne (1980), in reviewing the historical water quality data for northeastern Kansas, observed that 312 of 1,223 wells sampled in a 15-county area have nitrate concentrations in excess of 45 mg/L. Nearly two-thirds of these wells obtain water from deposits of Pleistocene age, and 41–50 ft (12–15 m) is the median-depth range for the wells containing high nitrate concentrations. A number of the wells also produce waters that exceed the limits of the secondary water-quality standards.

Factors Influencing Water Quality

A number of factors contribute to the quality of ground waters from the different aquifer sources: land use, nature of the geologic deposits, subsurface geologic structure, well location, and well-construction features. The study area is predominantly rural in character, with sorghum, wheat, corn, and soybeans being the major crops and cattle and hogs dominating livestock production (Kansas State Board of Agriculture, 1981). The impact of these agricultural factors on the quality of ground water is expected to be the greatest for shallow water sources, especially recent alluvial deposits, or for wells without an adequate surface seal. The influence of home septic systems and discharge from community sewage treatment facilities and the effects of oil and gas exploration and production also contribute to the deterioration of water quality locally, notably in shallow aquifers or in poorly constructed wells. The contribution of one or more of these elements probably is significant at many of the well sites in the study area where high ground-water nitrate levels have been observed.

Cores taken from the glacial buried-valley aquifer system in Nemaha County typically exhibit buff to brown sediments in the upper zone and gray to black sediments deeper in the sediment column, presumably reflecting oxidizing and reducing conditions, respectively (Denne et al., 1984). Humic debris, including wood fragments, is evident in the gray to black zone. The clay minerals exhibit great uniformity throughout the unconsolidated sediment column, with montmorillonitic clay (smectite) dominating in all samples analyzed (G. W. James, personal communication, 1984). Thick zones of clayey materials commonly serve as effective aquitards in the isolation of aquifer units in the buried-valley systems. The presence of reducing hydrogeochemical conditions in portions of the buried-valley system can be expected to influence water quality. The stability of various chemical species found in natural waters can be affected by hydrogeochemical conditions. For example, nitrate and sulfate, which are the dominant stable forms of nitrogen and sulfur in an aerobic environment, give way to ammonia (NH_3) and hydrogen sulfide (H_2S) in the presence of anaerobic conditions. Also, iron and manganese can be mobilized from the sediment materials under reducing conditions.

Gypsiferous limestone units of Permian age yield calcium sulfate (Ca^{2+}–SO_4^{2-}) waters. Where the glacial buried-valley systems incise these bedrock units, there may be an influx of calcium sulfate waters into the lower aquifers of the buried-valley system. The sandstone aquifers of Pennsylvanian age often exhibit an increase in salinity with depth or downdip in the formation. O'Connor (1960) suggested that base exchange reactions are responsible for the sodium bicarbonate (Na^+–HCO_3^-) waters found in southwestern Douglas County. Waters from the sandstone bedrock aquifers are frequently high in iron.

The Humboldt fault system enters Kansas from the north in Nemaha County and extends southwestward through Wabaunsee County in the study area. DuBois (1978) suggested that faulting associated with this system has influenced modern surface drainage in Nemaha County. Comparison of DuBois's fault map (plate 1) and Ward's (1974) buried-valley map suggests that this influence in Nemaha County extends back to Pleistocene time. Oil exploration and production in Nemaha County are related to structural traps associated with the fault system. Oil-related activities may produce saline water from great depths. In addition, different fault planes can serve as conduits or paths for the vertical movement and mixing of ground waters of different quality.

The placement and construction of a well are factors that often are driven by considerations of well yield or nearness to the point of water utilization rather than by a concern for the quality of water produced. The location of wells in animal pens, downslope from pens or septic systems, or near drainageways collecting water from agricultural areas can lead to the production of water with elevated concentrations of chloride and nitrate. This possibility is greatest for shallow wells but may also extend to deeper wells because of the standard well-construction methods used in northeastern Kansas. Common practice includes placing 10 ft (3 m) of screen near the bottom of the well, packing gravel along the entire length of the screen, casing to within 10 ft (3 m) of the land surface, and grouting to seal at least the upper 10 ft (3 m). This construction allows interconnection of aquifers and permits only the determination of composite water levels and chemistries. Shallow hand-dug wells are also prone to chemical and bacterial contamination, as are wells located downgradient in the aquifer from septic systems.

1981 Sampling Procedures

Water-well records filed with the Kansas Geological Survey between 1975 and 1981 provided the primary pool from which the sites were selected. A few wells from outside this group have been included to provide better areal coverage. The sites represent the general quality of ground water in the counties and in major aquifers, especially glacial units, in the study area. Some "nests" of wells (several individual wells at one site completed and screened at different depths) have also been included to determine vertical differences in water quality in a given aquifer. Most of the wells are private wells, but some are public supply and industrial wells and a few are irrigation wells.

During the spring of 1981, staff members of the Kansas Geological Survey and the U.S. Geological Survey collected 148 water samples from wells with logs and known construction characteristics. Controlled conditions were observed during sampling, handling, and analysis of these samples. These procedures included field filtration, acid preservation of samples for nutrient and trace metal analyses, and refrigeration of samples during transport to the laboratory and during storage at the laboratory.

Field measurement of temperature, specific conductance, and pH were made at all sample sites. The inorganic composition of the ground-water samples was analyzed at the laboratories of the Kansas Department of Health and Environment. Results from these field and laboratory determinations for the well waters from the 12-county study area constitute the primary data base used for the following discussion of ground-water quality in northeastern Kansas (Denne et al., 1990b).

Discussion of the 1981 and Related Ground-water Quality Data for Northeastern Kansas

Of the water samples analyzed from the spring 1981 collection period, 147 of the wells fall within the 12-

county area of this study. The remaining site is in the Missouri River alluvium of Buchanan, Missouri, at a location across the state line from Atchison, Kansas. Four of these 147 wells were found to have been subjected to chlorination or water-softening treatment and were dropped from consideration. Water-quality data for all wells sampled are presented by Denne et al. (1990b). The location of the remaining 143 wells and the type of aquifer units they tap are presented in fig. 82. The distribution of aquifer types is nine bedrock aquifer wells, 26 alluvial aquifer wells, and 108 glacial aquifer wells. Depths of these wells range from 20 ft to 300 ft (6–91 m).

Shown in fig. 83 are water-type classifications for the well waters, which are based on percent milliequivalent contributions of the various chemical species to the total number of milliequivalents per liter of ions. The mixed category implies that no single cation and/or anion was dominant in the water's chemistry. From this figure it can be seen that calcium bicarbonate waters are the principal water type in the study area. This basic pattern can be modified through such factors as bedrock units containing sodium chloride (Na^+–Cl^-) or calcium sulfate waters, the introduction of surface water containing various dissolved solids, and base exchange reactions. Figure 84 shows the locations of wells with waters that exhibit some sodium bicarbonate alkalinity. These sites probably reflect locations at which the ground water experiences natural softening through ion-exchange processes.

Water-type classifications convey general information about the chemical composition of solids dissolved in the ground waters, but they do not impart any data about the amount of solids dissolved. Table 12 provides a summary of the data for the spring 1981 collection period.

Figures 85–89 are maps of the nitrate, sulfate, chloride, iron, and manganese water-quality data. Nitrate concentrations in excess of 45 mg/L are more common in the northern half of the study area. However, it should be noted that there are a number of sites at which nitrate levels are below 5 mg/L and iron and/or manganese are above 0.3 mg/L. This latter observation is consistent with the presence of reducing conditions, a situation that has been found in the glacial buried-valley system at several locations in Nemaha County (Denne et al., 1984). Sulfate and chloride concentrations in excess of the Secondary Drinking Water Standards (EPA, 1979b) seem to be confined to a zone trending southward from the Nemaha–Brown County area into Jackson County. This trend roughly parallels the subcrop boundary of Permian units and may arise from an upward movement of saline waters in parts of the Humboldt fault system or in parts of the deep incision made by the Pleistocene drainage system.

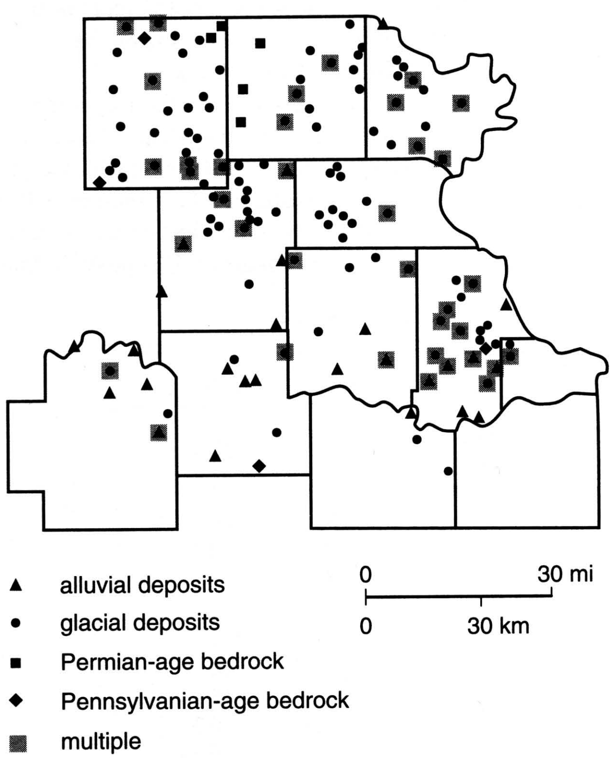

FIGURE 82—Locations and designations of water-producing wells sampled in spring 1981. Wells with more than one type of aquifer are indicated by the multiple symbol (shaded box) but are given the overall designation of the major contributing aquifer.

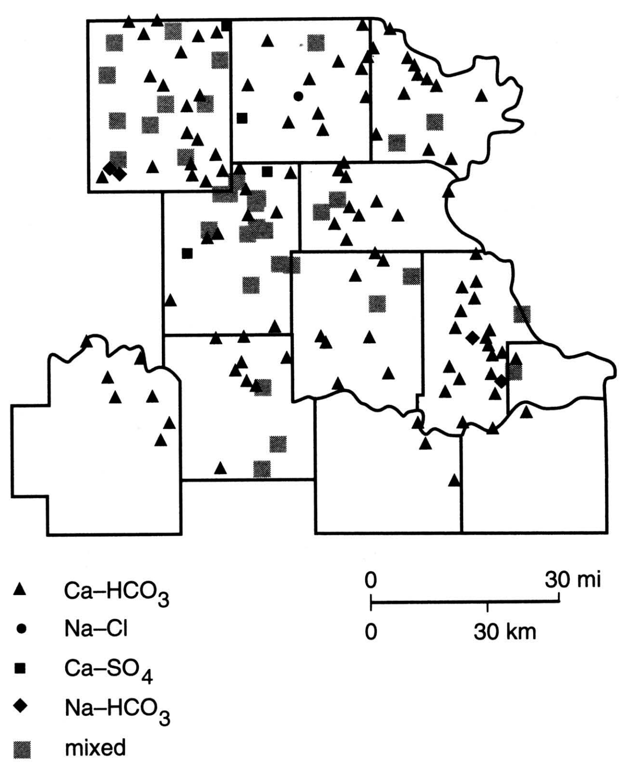

FIGURE 83—Water-type classifications for samples collected in spring 1981.

Water-quality data from the 1981 sampling program were processed using SAS (SAS Institute Inc., 1985), a computerized data-analysis program. A univariate statistical analysis of the data by aquifer type indicated that the concentration of most constituents approaches a normal distribution in samples from bedrock aquifers, but only silica (SiO_2) and bicarbonate had normal distributions in samples from alluvial and glacial aquifers. Because bedrock aquifers in the study area yield limited amounts of good-quality water and because the number of water samples from these units was small, further statistical testing focused on water samples from alluvial and glacial deposits.

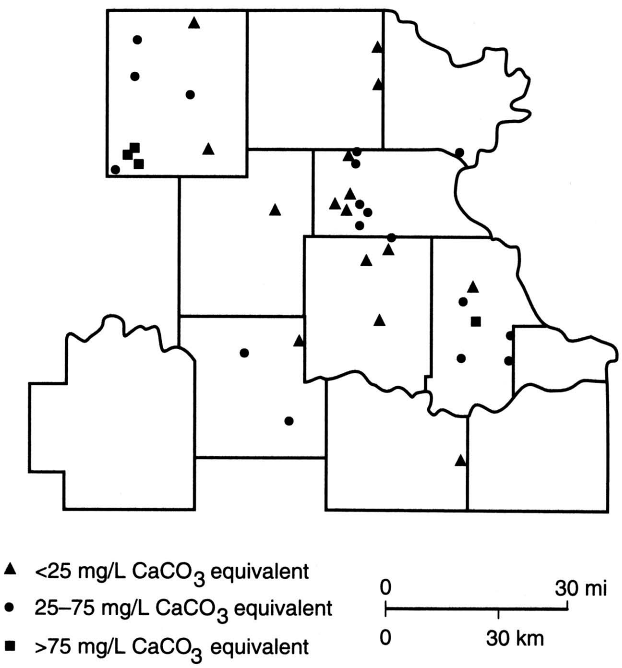

FIGURE 84—CONCENTRATIONS FOR SAMPLES EXHIBITING $NaHCO_3$ ALKALINITY. Samples collected in spring 1981.

We used the Spearman rank-sum correlation coefficient for nonnormal distributions [method of Snedecor and Cochran (1982)] to correlate well depths, specific conductance, and chemical constituents of waters derived from wells located in unconsolidated aquifers. Because the waters from the alluvial and glacial deposits are sufficiently different, we determined the correlations for them separately (tables 13 and 14). The unequal number of wells in the two data sets makes comparison of correlation coefficients (r) difficult; the 95% confidence level ($|r|$ 0.33) in table 13 is given for comparison with the 99.9% confidence level ($|r|$ 0.30) of table 14. Little interpretive weight should be given to any single isolated correlation, especially those of table 13. Inspection of the two tables implies that the waters from the alluvial deposits are much simpler, with correlations being primarily related to major chemical components of the ground waters. Significant positive correlations between specific conductance or total dissolved solids and chemical constituents (calcium, magnesium, sodium, bicarbonate, sulfate, and chloride) simply reflect the dominance of these ions in the ground waters of the alluvial and glacial deposits. Direct correlations suggest that bicarbonate in waters from alluvial deposits is associated with calcium and magnesium, whereas sources of calcium sulfate and sodium chloride seem responsible for influxes of sulfate and chloride ions, respectively. Table 14 may reflect a more extensive interaction between ground water and sediment of the glacial deposits and blending of waters from the unconsolidated sediments and bedrock.

Wells in glacial deposits are generally deeper than those in alluvial materials, averaging almost twice the depth. The modifying influence that well construction, in particular the gravel packing of all but the upper 10 ft (3 m) of the unexposed well casing, has on the correlations of tables 13 and 14 is unknown. It is possible that

TABLE 12—Summary of ranges, means, and medians for 1981 chemical quality data.

Variable[a]	**Minimum**	**Maximum**	**Mean**	**Median**
Specific conductance (μmhos at 25°C)	244	8100	957	710
Total dissolved solids (TDS), calculated	169	3050	564	436
Silica (SiO_2)	11	47	24	25
Calcium (Ca)	28	593	108	89
Magnesium (Mg)	3.5	155	25	20
Sodium (Na)	5.4	632	49	27
Potassium (K)	0.4	19	2.5	1.4
Bicarbonate (HCO_3)	81	540	339	344
Sulfate (SO_4)	5.0	1550	119	42
Chloride (Cl)	1.0	840	41	13
Fluoride (F)	0.1	1.1	0.4	0.3
Nitrate (NO_3)	BQL[b]	399	27	5.3
Phosphate (PO_4)	BQL[b]	1.1	0.08	0.03
Iron (Fe)	BQL[b]	19	1.2	0.04
Manganese (Mn)	BQL[b]	3.9	0.28	0.03

a. All chemical components measured in milligrams per liter.
b. Below quantifiable limits.

the significance of relationships, such as those related to depth, has been obscured by averaging the water chemistries of the different aquifer zones that contribute to the overall yield of the wells. Also, other factors that are not included directly in the statistical analysis (such as differences in sediment type of the aquifer units, heterogeneity of the sediment column, presence of humic materials, and presence of microbiologic activity) may have important but unrecognized influences on the correlations. The presence of aerobic or anaerobic conditions in the aquifer at a well site can have a marked influence on water quality as a result of oxidation-

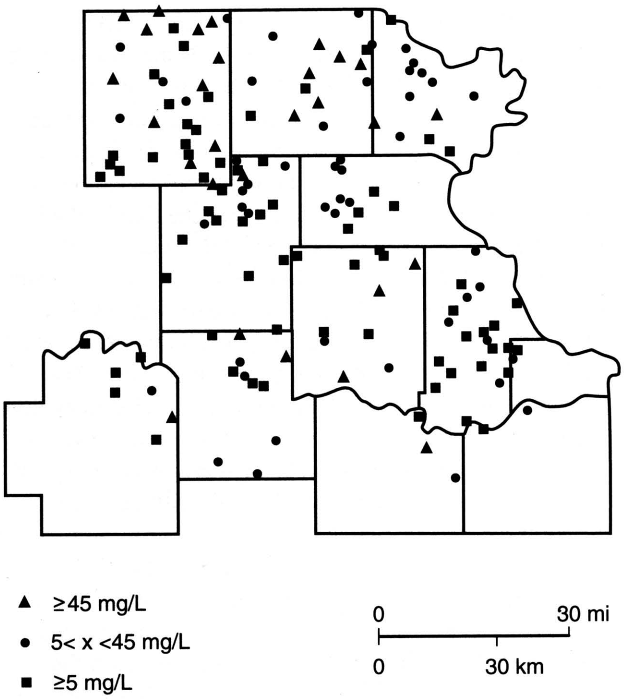

FIGURE 85—NITRATE (NO_3) CONCENTRATION FOR SAMPLES COLLECTED IN SPRING 1981.

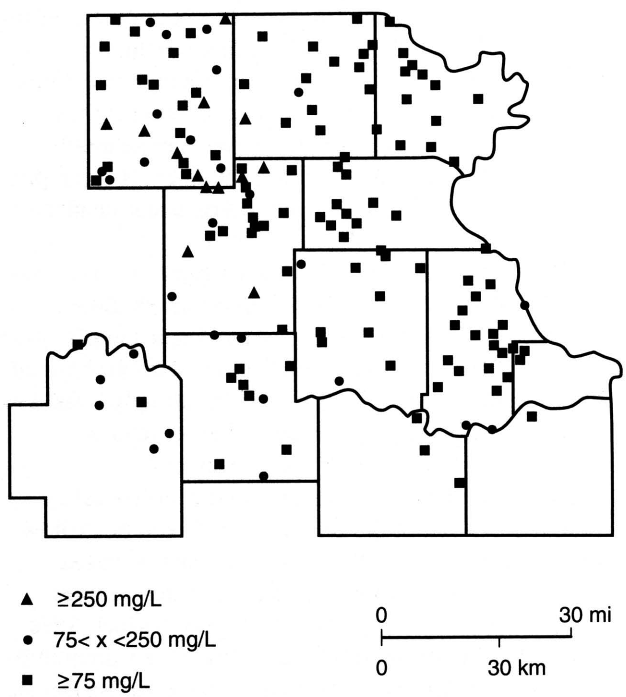

FIGURE 86—SULFATE (SO_4) CONCENTRATION FOR SAMPLES COLLECTED IN SPRING 1981.

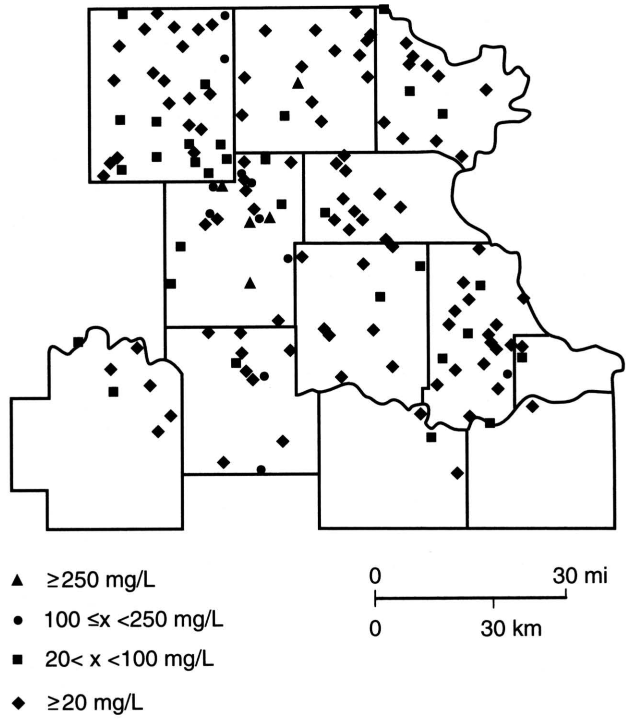

FIGURE 87—CHLORIDE (CL) CONCENTRATION FOR SAMPLES COLLECTED IN SPRING 1981.

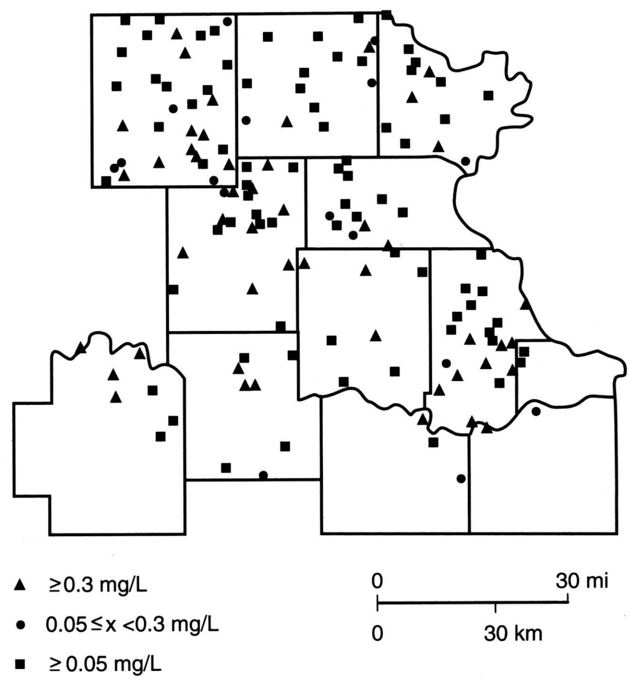

FIGURE 88—IRON (FE) CONCENTRATION FOR SAMPLES COLLECTED IN SPRING 1981.

reduction and complexation reactions and mineral solubility equilibria that serve to control the stability and mobility of a number of chemical species of hydrogeochemical interest. Thus general differences in environmental conditions within the alluvial and glacial deposits contribute to the dissimilarity of tables 13 and 14.

Additional information is needed to help clarify interpretations that use the correlation relationships. As an example, significant inverse relationships noted for ground waters are depth-nitrate, depth-phosphate (PO_4), iron-nitrate, and manganese-nitrate in glacial deposits and sodium-nitrate and iron-nitrate in alluvial deposits. These may represent near-surface sources for nitrate and phosphate, the influence of a reducing environment within water-producing zones (especially in glacial deposits), or combinations of such factors.

Preliminary surveys made after the 1981 sampling program of less commonly determined dissolved organic carbon (DOC) and ammonium ion (NH_4^+) contents of the ground waters yielded concentrations of 0.9–2.4 mg/L for DOC and <0.1 mg/L to 4.8 mg/L for ammonium. These data suggest that the chemistry of waters from the buried-valley aquifer systems poses two different potential problems if the waters are subjected to a chlorine disinfection treatment, as required for all public water-supply drinking water in Kansas. First, organic carbon and reduced species such as Fe^{2+}, Mn^{2+}, H_2S and NH_4^+ present in the waters undergo side-reactions that consume chlorine, giving rise to difficulties in maintaining required residual levels of free or combined chlorine (Denne et al., 1984). Second, the reaction of chlorine with organic carbon in water can lead to the production

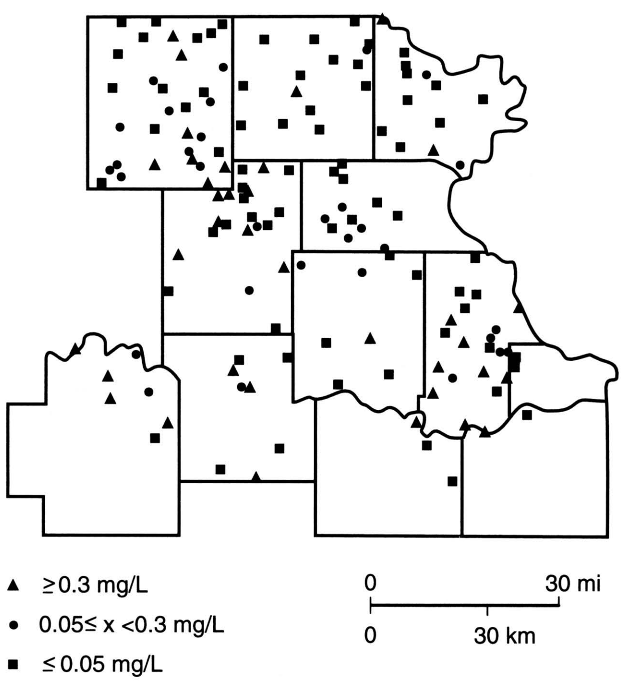

FIGURE 89—MANGANESE (MN) CONCENTRATION FOR SAMPLES COLLECTED IN SPRING 1981.

of chlorinated organic compounds, including trihalomethanes. Initial measurements of total trihalomethane-formation potential for ground waters from Nemaha and eastern Marshall counties are 9–98 µg/L (Hathaway et al., 1984). The higher measured concentrations approach the maximum contaminant level of 100 µg/L THM for drinking water established by the U.S. Environmental Protection Agency (1979b). Clearly, a more detailed knowledge of water chemistry for wells that feed public-supply systems within the study area could prove beneficial in achieving a satisfactory finished product.

Denne et al. (1987), in a subsequent investigation, examined in more detail the geologic and geochemical factors that influence water quality in the major glacial buried valley of southeastern Marshall County and southern Nemaha County. They took core sections from holes drilled from the ground surface to bedrock and drilled "nests" of two to four observation wells screened in different water-bearing sediments at six sites. The core materials were subjected to physical, chemical, and microbial examination. The nests of observation wells were used to obtain seasonal ground-water samples and to evaluate variations in water quality with depth or location along the channel.

The tan upper sediments were found to be low in extractable ammonium and had total organic carbon (TOC) and extractable nitrate contents that decreased with depth below the surface soil zone. At depth the sediment color abruptly changed to gray. Below the color-transition zone, the concentrations of TOC and extractable ammonium increased, whereas the concentration of extractable nitrate remained negligible. Higher extractable ammonium concentrations generally were found at sites having higher TOC levels, but the concentration profiles of the two species in the sediment columns were dissimilar. Active microbial populations were found throughout the sediment columns of the investigated sites. The bacteria present are generally small in size and relatively few in number (10^5–10^6 per gram of dry sediment); their impact on water quality requires further assessment.

There appeared to be seasonal changes in concentrations of DOC, iron, and manganese in the shallow ground water, but the deeper ground-water samples were more consistent in quality and failed to exhibit seasonal trends. Water quality was found to be strongly related to depth, with the tan-gray contact in the sediments appearing to divide the aerobic and anaerobic hydrogeochemical environments in the buried-valley aquifer. High nitrate levels were found only in shallow wells screened above the tan-gray contact, whereas ammonium concentrations in ground-water samples increased with depth below the tan-gray contact. Sites having higher concentrations of extractable ammonium and TOC in sediments tended to have higher levels of ammonium, DOC, and trihalomethane formation potential in the ground water. Average concentrations of

TABLE 13—Correlation matrix for 26 samples from alluvial deposits.

	Depth	Specific conductance	TDS	pH	SiO_2	Ca	Mg	Na	K	HCO_3	SO_4	Cl	F	NO_3	PO_4	Fe	Mn
Depth	++																
Specific conductance	0	++															
TDS	0	++	++														
pH	0	0	0	++													
SiO_2	0	0	0	0	++												
Ca	0	++	++	0	0	++											
Mg	0	++	++	0	0	+	++										
Na	0	+	++	0	0	0	0	++									
K	0	0	0	0	0	0	0	+	++								
HCO_3	0	++	++	0	0	++	++	0	0	++							
SO_4	0	++	++	0	0	++	+	0	0	0	++						
Cl	0	++	++	0	0	0	0	++	0	0	+	++					
F	0	0	0	0	0	0	0	0	0	0	0	0	++				
NO_3	0	0	0	0	0	0	0	=	–	0	0	0	0	++			
PO_4	0	0	0	0	++	0	0	0	0	0	0	0	=	0	++		
Fe	0	0	0	0	0	0	0	+	0	0	0	0	0	=	0	++	
Mn	+	0	0	0	0	0	0	++	0	0	0	0	0	–	0	++	++

0, Correlation not significant at the 95% confidence level.
+, Positive correlation significant at the 95% confidence level ($|r| = 0.33$).
–, Negative correlation significant at the 95% confidence level ($|r| = 0.33$).
++, Positive correlation significant at the 99% confidence level ($|r| = 0.46$).
=, Negative correlation significant at the 99% confidence level ($|r| = 0.46$).

TABLE 14—Correlation matrix for 108 samples from glacial deposits.

	Depth	Specific conduc-tance	TDS	pH	SiO_2	Ca	Mg	Na	K	HCO_3	SO_4	Cl	F	NO_3	PO_4	Fe	Mn
Depth	++																
Specific conductance	0	++															
TDS	0	++	++														
pH	0	0	0	++													
SiO_2	0	0	0	0	++												
Ca	0	++	++	=	0	++											
Mg	0	++	++	0	0	++	++										
Na	0	++	++	0	0	+	++	++									
K	0	++	++	0	0	0	++	++	++								
HCO_3	0	++	++	0	0	++	++	++	++	++							
SO_4	0	++	++	0	0	++	++	++	++	++	++						
Cl	0	++	++	0	0	++	++	++	0	++	++	++					
F	0	0	0	0	0	0	+	0	0	0	0	0	++				
NO_3	=	0	0	0	0	0	0	0	=	–	0	0	0	++			
PO_4	=	–	–	0	0	–	–	–	0	–	0	0	0	0	++		
Fe	0	++	++	0	0	+	++	++	++	++	++	0	0	=	0	++	
Mn	0	++	++	0	0	++	++	++	++	++	++	++	0	=	–	++	++

0, Correlation not significant at the 99% confidence level.
+, Positive correlation significant at the 99% confidence level ($|r| = 0.22$).
–, Negative correlation significant at the 99% confidence level ($|r| = 0.22$).
++, Positive correlation significant at the 99.9% confidence level ($|r| = 0.30$).
=, Negative correlation significant at the 99.9% confidence level ($|r| = 0.30$).

DOC and trihalomethane for the six sites were 2.65 μg/L and 123 μg/L, respectively, with the latter value being slightly above the maximum trihalomethane level of 100 μg/L permitted by state and national drinking-water standards. Calcium and sulfate concentrations also were observed to increase with depth at certain sites, presumably in response to Permian gypsiferous bedrock units at these sites. Unlike observed trends with respect to depth, no clear pattern was noted for water quality relative to channel position (upgradient versus downgradient or proximity to the channel axis).

The water-quality data derived from the 1981 regional sampling program and other studies indicate complex hydrogeochemical relationships in the glacial buried-valley aquifers. The presence of DOC, ammonium, iron, and manganese complicate water treatment of public supplies. The impact of microbial activity in the aquifer on water quality and relationships between TOC or DOC and trace-element mobility in the ground water are subjects needing further investigation. A search for a supply of ground water in this region must carefully couple considerations of aquifer properties that control yield and quality of water produced.

Additional Research Needs

Additional research is needed to understand in more detail the relation of water chemistry to structure and faulting, seasonal water-quality changes with depth, water quality in relation to the mineralogy of the sediment columns, oxidizing and reducing conditions, organic content, and bacterial activity in the aquifers. This information will help in the siting of wells and screens and/or in treating ground water to obtain water that meets Federal and State quality standards.

More detailed information is needed in some of the counties to define more accurately the location, character, and extent of buried valleys, the character of valley-fill deposits, and the ground-water-flow paths between recharge and discharge areas. A better understanding of the glacial processes involved in formation of the buried valleys and better knowledge of the stratigraphy and correlations could help to locate channels and the most promising units for water supplies.

The role of improperly constructed wells, improperly plugged test holes, and unserviceable or abandoned wells in providing pathways for the rapid transport of shallow contaminated ground or surface water to the deeper confined aquifers and to seasonal water-quality changes needs further investigation. This will help to define major problems and to suggest possible solutions and future methods of minimizing additional contamination.

Conclusions

Ground water in the glacial deposits of a 12-county area of northeastern Kansas is an important resource for an area that is increasing in population size and water use. Maps for each of the 12 counties show the depth to bedrock, the depth to water, the total sand and gravel thickness, the estimated yield of wells, and the thickness of saturated unconsolidated deposits, which are largely glacial deposits. Plate 1 shows the bedrock topography and is based on geologic and topographic maps, about 5,000 water, oil and gas, and well logs, and measured sections. These maps provide a basis for the further exploration and development of ground-water resources in glacial aquifers. Denne et al. (1990a) list the location and numerical hydrologic information for all the wells used in the study.

The location of the preglacial drainageways shown in fig. 2 and plate 1 indicates that buried valleys may be up to 3 mi (5 km) wide, 400 ft (120 m) deep, and more than 75 mi (120 km) long. Well yields in these deposits may be as high as 900 gpm (0.06 m^3/s) but more commonly are less than 500 gpm (0.03 m^3/s). Water levels are commonly between 5 ft (2 m) and 50 ft (15 m) below land surface but locally exceed 100 ft (30 m).

The greatest ground-water pumpage in the 12 northeastern Kansas counties is from alluvial aquifers, primarily in the Missouri and Kansas River valleys. The second largest source of ground-water pumpage is from glacial aquifers, and the Pennsylvanian and Permian bedrock aquifers are the source of the least amount of ground-water usage.

Historical water-quality data for more than 1,200 wells provide a picture of the general water quality of ground water from the glacial, alluvial, and bedrock aquifers. In 1981, 143 new water samples were collected from wells with geologic log information and known construction characteristics. These samples were analyzed under controlled conditions of sampling, handling, and analysis. Glacial aquifers contain water of the calcium bicarbonate type, which is generally of good quality. Locally, the concentrations of nitrate, sulfate, chloride, iron, and manganese occur in excess of drinking water standards. The 143 wells sampled include samples from nine bedrock aquifer wells, 26 alluvial aquifer wells, and 108 glacial aquifer wells. Denne et al. (1990b) list all the analyses of water samples collected during 1981.

Information given in this report should provide the basis for efficiently locating, developing, and protecting ground-water supplies from the glacial deposits in buried valleys.

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Kansas Geological Survey
1930 Constant Avenue
The University of Kansas
Lawrence, Kansas 66047–3726