GROUND WATER IN THE SPRINGFIELD-SALEM PLATEAUS OF SOUTHERN MISSOURI AND NORTHERN ARKANSAS

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 80-101

Report prepared on behalf of the
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Average ground-water conditions have not changed significantly in the Springfield-Salem plateaus section of southern Missouri and northern Arkansas in the past 25 years except in the vicinity of well fields. The amount of ground water pumped is approximately 200 cubic feet per second, which is about 5 percent of the total discharge at the 80 percent point on flow-duration curves for major streams.

Ground-water recharge is variable and occurs through sinkholes, by infiltration in upland areas of good permeability, and through streambeds. Main water-bearing zones lie in the Potosi Dolomite and the lower dolomite and sandstone of the Gasconade Dolomite.

Cavernous connections from ground surface to depths as much as 1,500 feet below land surface in the West Plains area, Mo., result in deep circulation of water. Municipal well-water in the area often becomes turbid after rainstorms, despite well depths of 1,500 feet and 950 to 1,000 feet of pressure-grouted casing.

Ground water generally moves north and south from the crest of the Springfield-Salem plateaus, which extend across southern Missouri southwest from the St. Francois Mountains. Interbasin diversion of surface- and ground-water flow is common.

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December 1980

UNITED STATES DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS

The following factors may be used to convert the inch-pound units published herein to the International System of Units (SI).

Multiply inch-pound units	By	To obtain SI units
acre	0.407	hectare (ha)
foot (ft)	0.3048	meter (m)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch (in.)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)

To convert temperature in °C (Celsius) to °F (Fahrenheit) multiply by 1.8 and add 32.

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

GROUND WATER IN THE SPRINGFIELD-SALEM PLATEAUS OF SOUTHERN MISSOURI AND NORTHERN ARKANSAS

By Edward J. Harvey

ABSTRACT

Average ground-water conditions have not changed significantly in the Springfield-Salem plateaus section of southern Missouri and northern Arkansas in the past 25 years except in the vicinity of well fields. The amount of ground water pumped is approximately 200 cubic feet per second, which is about 5 percent of the total discharge at the 80 percent point on flow-duration curves for major streams. Because only a small part of the available water is used and large increases in use are not predicted, it is unlikely that declines in ground-water levels of extended duration will occur.

Because of the three-dimensional flow of water through the entire body of dolomite in the Salem Plateau, a thickness of 1,000 feet or more of dolomite must be considered in any hydrologic study. Main water-bearing zones lie in the Potosi Dolomite and the lower dolomite and sandstone of the Gasconade Dolomite. The source of most of the municipal water supplies is the Potosi Dolomite, which has the largest permeability.

Ground-water recharge is variable and occurs through sinkholes, by infiltration in upland areas of good permeability, and through streambeds that lose flow. In stream-valley profiles through recharge areas, wells of different depths have different altitudes at which water levels stand below stream level. In discharge areas, wells of different depths have more uniform water levels that stand above stream level.

Ground-water movement is generally north and south from the crest of the Springfield-Salem plateau, which extends across southern Missouri southwest from the St. Francois Mountains. Fracturing associated with faulting tends to channel water to points of resurgence such as springs. Interbasin diversion of surface- and ground-water flow is common.

Cavernous connections from ground surface to depths as great as 1,500 feet occur in south-central Missouri and result in deep circulation of water. Municipal well-water in the West Plains area, for example, often becomes turbid after rainstorms, despite well depths of 1,500 feet and as much as 1,000 feet of pressure-grouted casing.

Ground water is hard and its principal constituents are calcium, magnesium and bicarbonate in water from dolomite rocks, and calcium and bicarbonate are common in water from limestone rocks.

INTRODUCTION

Most city dwellers, farmers and rural inhabitants, and many of the industries in the Ozark Plateaus Province, popularly known as the Ozarks of Missouri and Arkansas, are dependent for their water supplies on the aquifers in the dolomites and sandstones of Cambrian and Ordovician age. It is estimated by the author that between 100 and 500 cubic miles of water are stored in these aquifers. Precipitation has ready access to the aquifers by several different means. While this is beneficial to the replenishment of the water supply, the ready infiltration of precipitation and runoff poses a potential water-quality problem.

The Environmental Protection Agency is considering (1980) designating the karst region of Missouri and Arkansas as a sole-source aquifer. This report describes the aquifers in the region and provides background data on drinking-water sources for the area. The report can be used to help evaluate the impact of federal financially-assisted projects on the aquifer.

This report presents a generalized summary of the hydrology of the aquifers in the Cambrian and Ordovician section in Missouri and Arkansas. Information compiled in the report at the request of the Environmental Protection Agency consists of the following:

1. A description of the aquifers and hypotheses concerning the causes for differences in storage and yield characteristics of the aquifers.
2. A description of the methods by which recharge to the aquifers occurs. This includes a qualitative analysis of the three-dimensional flow scheme inherent in the aquifer system.
3. Direction of ground-water movement.
4. The use of ground water and its relation to the volume of ground-water discharge from the area.
5. A description of the quality of water in the aquifers and its relation to the flow system.
6. The methods of waste disposal and location of facilities.
7. Projection of future water use.
8. Feasibility of development of alternative water sources.

Description of Study Area

The project is in the east-central part of the United States (fig. 1). It includes the Springfield-Salem plateaus section of the Ozarks Plateaus Province and contiguous parts of the Osage Plains and Dissected Till Plains sections of the Central Lowland Province (Fenneman, 1938). It does not include the Boston "Mountains" section in Arkansas and the igneous rock outcrops of the St. Francois Mountains in eastern Missouri.

Much of the Ozark region is wooded and hilly. Many manmade lakes and reservoirs and temperate climate are elements that have contributed to the influx of people and the probability of future growth. The region contains the largest area of exposed Cambrian and Ordovician carbonate rocks in the United States that is uninterrupted by confining beds of shale and undisturbed by thrust faulting. The region is more or less equidimensional and encloses a core of igneous rock exposed in the St. Francois Mountains in the eastern part of the region.

The emphasis in the report is on the outcrop area of Cambrian and Lower Ordovician formations because this is the recharge area of the principal aquifers. Therefore, the boundary of the area of emphasis is the contact between the dolomitic rocks of the Lower Ordovician formations and overlying formations on the perimeter, whatever age they may be (fig. 2). This is essentially the Salem Plateau. Because municipal well-water supplies developed on the Springfield Plateau and on small parts of the Osage Plains are replenished by recharge from the Salem Plateau, the project area embraces these sections. The project area also includes a part of the Dissected Till Plains north of the Missouri River even though it is not recharged from the Salem Plateau.

The region extends from the Missouri River on the north, to the White River basin in Arkansas on the south, from near the Mississippi River on the east, to the Kansas and Oklahoma state boundaries on the west (fig. 3). The main area of Precambrian rocks that crop out in the St. Francois Mountains is excluded, and for all practical purposes, the area that contains those formations older than the Potosi Dolomite in the area surrounding the Precambrian knobs of the St. Francois Mountains also is excluded. Only those formations above the Davis Formation and below the Middle Ordovician are emphasized in this study because these are the formations that contain the principal aquifers in the project area and are the source of most of the municipal water supplies.

A description of the formations is given in table 1 and a geologic profile from the Mississippi River to the western border of the State is shown in figure 4.

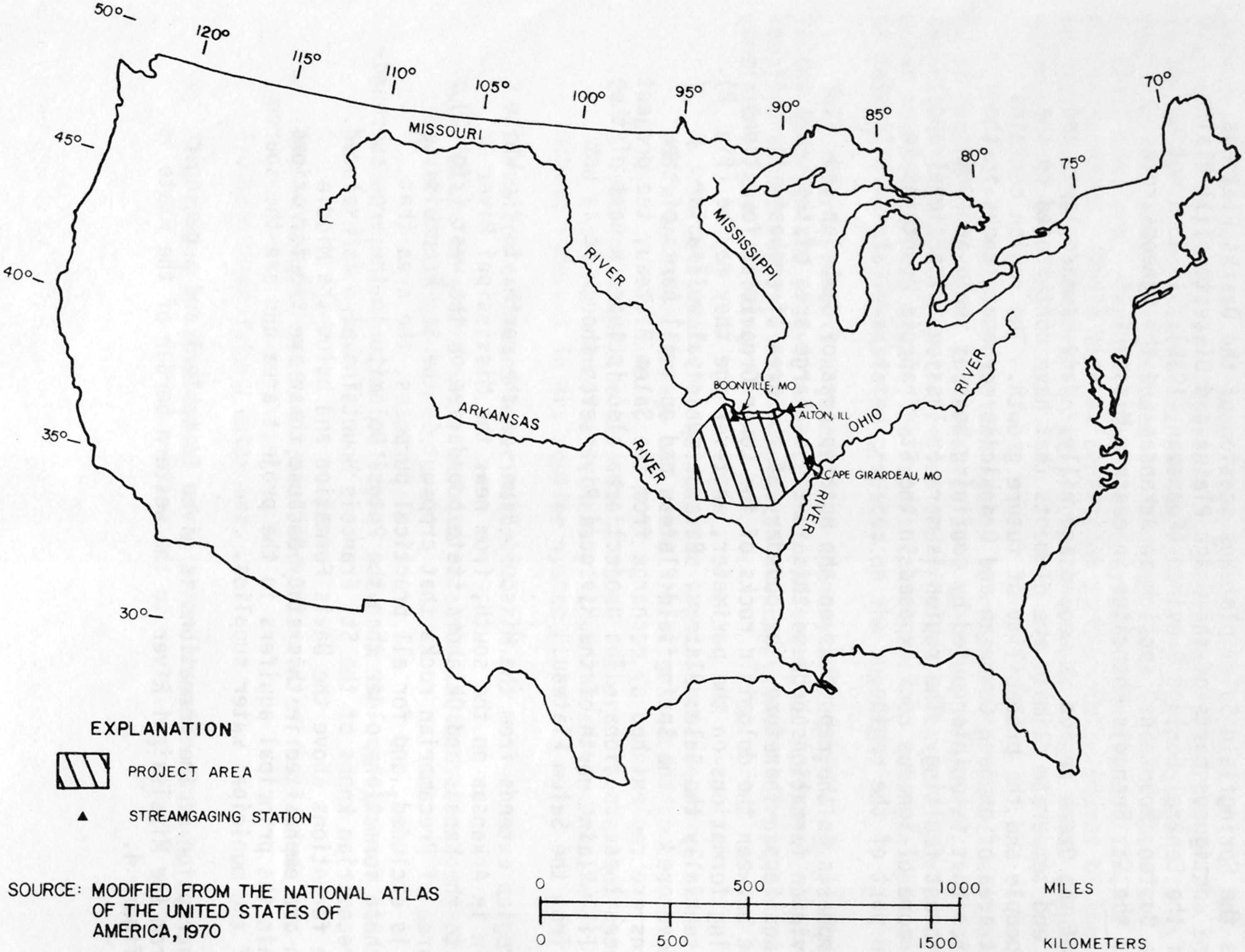


Figure 1.--Location of the project area.

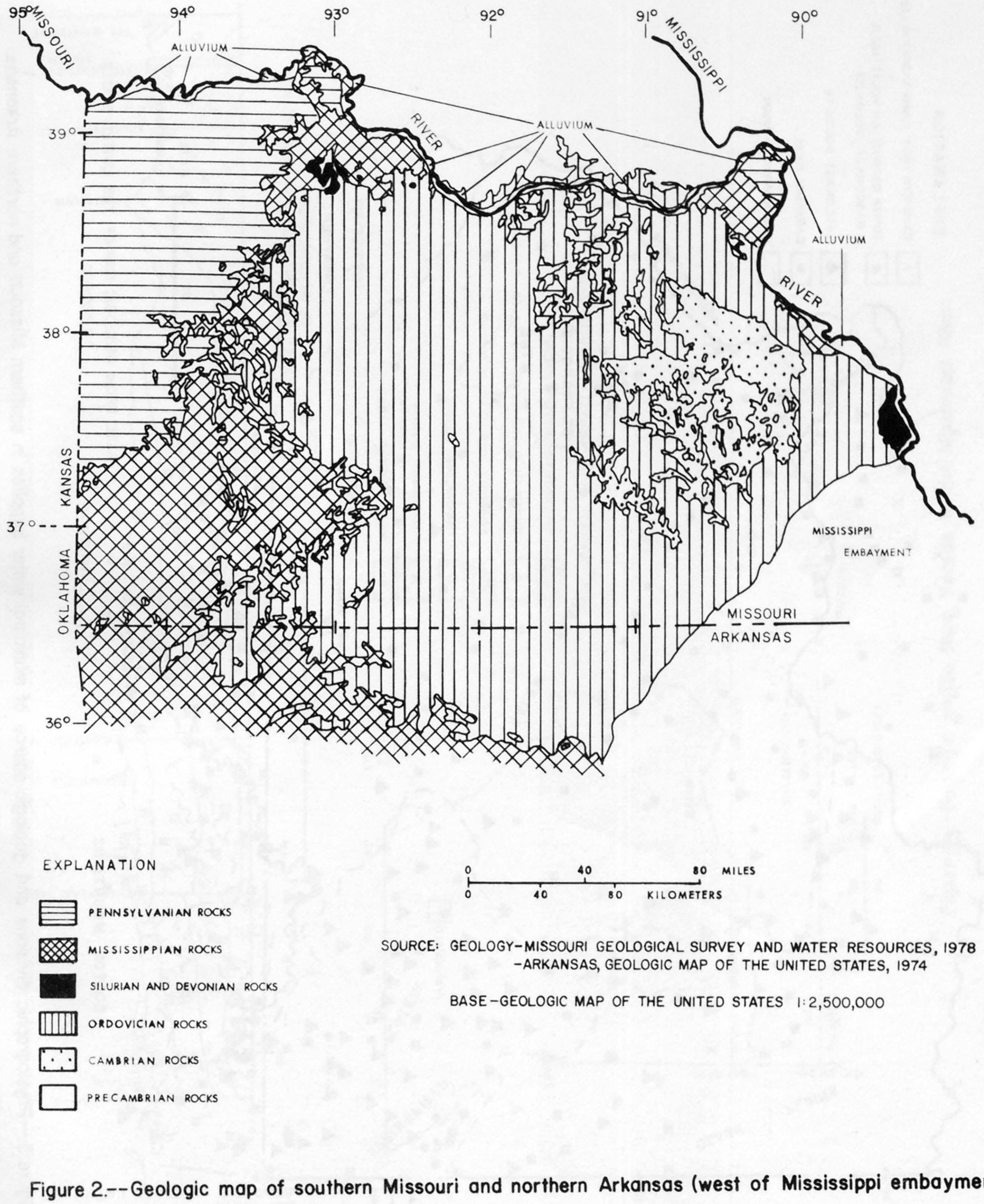


Figure 2.--Geologic map of southern Missouri and northern Arkansas (west of Mississippi embayment).

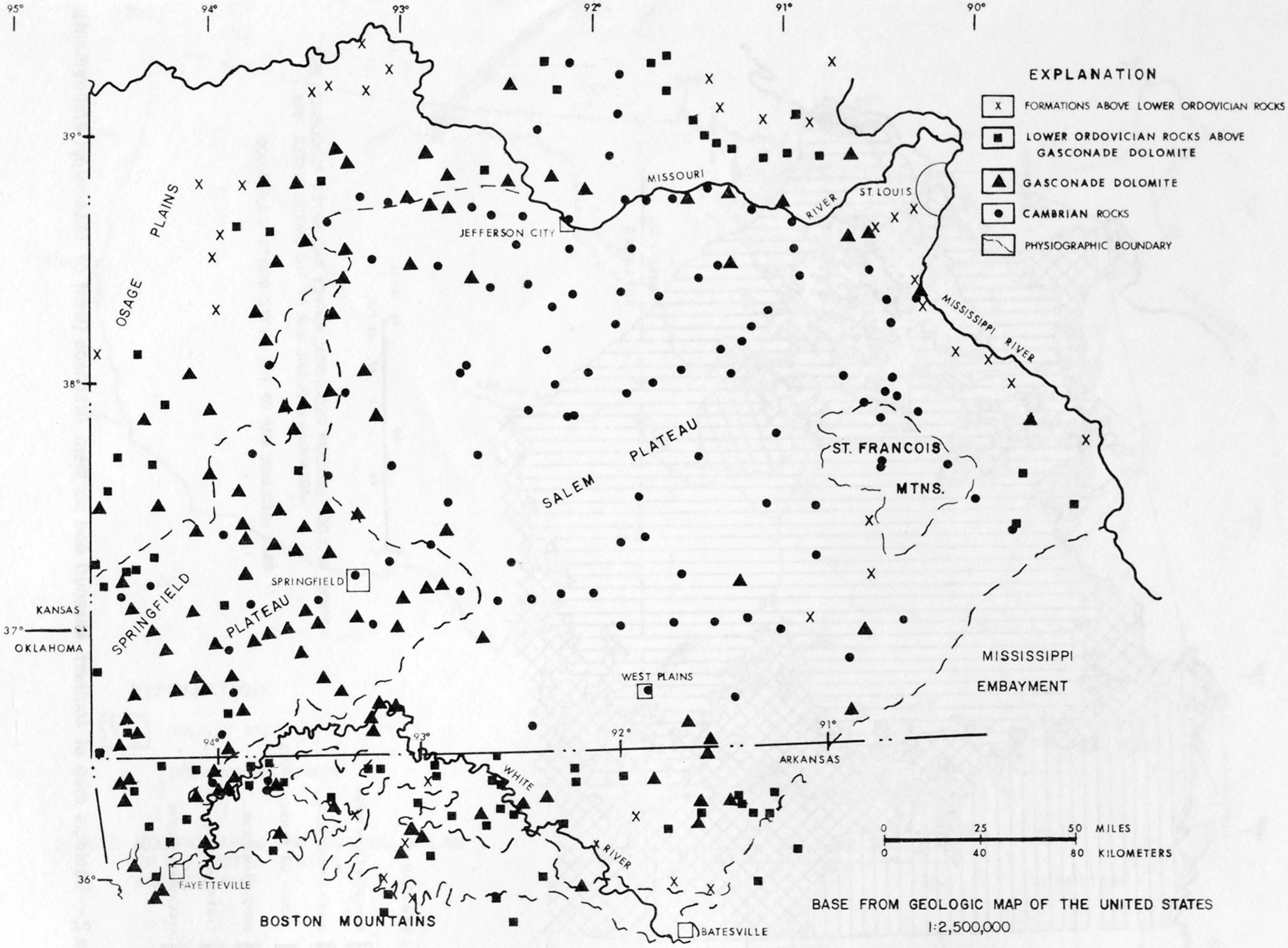


Figure 3.--Physiographic divisions and geologic source of municipal water supplies in southern Missouri and northern Arkansas.

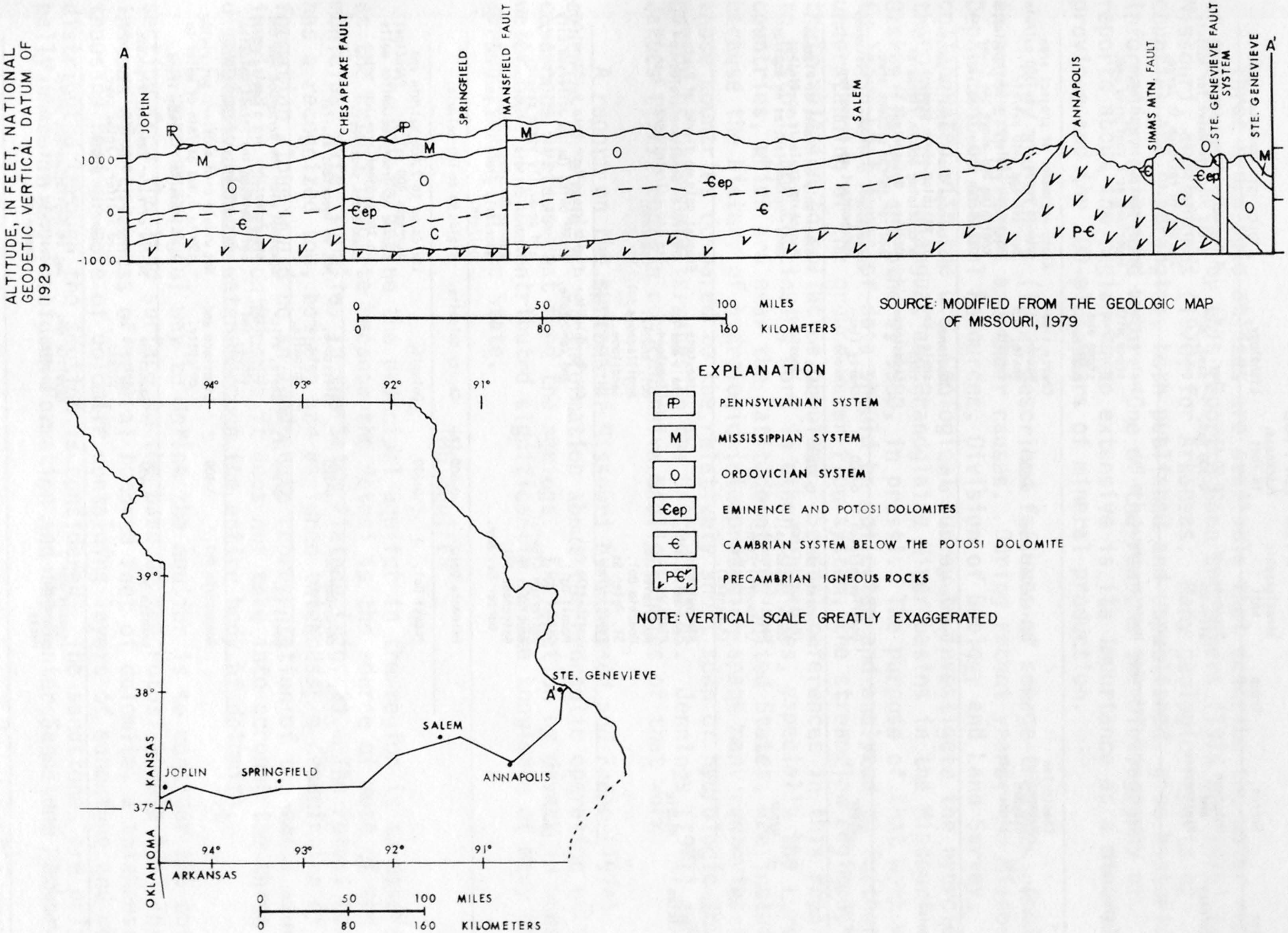


Figure 4.--Geologic profile from Kansas to the Mississippi River.

Table 1.--Stratigraphic column for southern Missouri and northern Arkansas showing lithologic and hydrologic characteristics

System	Series	Group	Stratigraphic unit	Thickness, in feet	Lithology	Hydrologic characteristics
Quaternary	Holocene and Pleistocene		Residuum and alluvium	0-50 Al. 0-300 Res.	Clay, silt, sand, and gravel.	A few wells along major streams yield adequate water for municipal water supply. Storage in residuum is large.
Pennsylvanian	Des Moinesian	Cherokee	Undifferentiated	0-100+	Shale and sandstone with thin limestone and coal beds.	Unimportant as an aquifer. Important as a confining bed.
Mississippian	Chesterian Meramecian Osagean Kinderhookian		Undifferentiated	0-600+	Cherty limestone, shale, and sandstone.	Along perimeter of project area yields range from 1 to 300 gal/min but average 5-10 gal/min. Northview Shale in Kinderhookian is confining bed above the Lower Ordovician dolomite aquifers.
Devonian			Undifferentiated	0-100	Limestone, shale, and thin sandstone.	Chattanooga Shale, usually about 10 ft thick where present, is a confining bed on flanks of Ozarks. Unimportant as an aquifer in the project area.
Silurian	Upper		Undifferentiated	0-200	Cherty limestone.	Present only on flanks of Plateaus. Unimportant as an aquifer.
Ordovician	Upper		Maquoketa Shale (Missouri)=Cason Shale (Arkansas). Cape Limestone[1] (Missouri)=Fernvale Limestone (Arkansas).	0-170	Shale and limestone.	Present only on flanks of Plateaus. Maquoketa Shale is confining bed. Unimportant as an aquifer.
	Middle		Kimmswick Ls. Decorah Fm. Plattin Ls. Rock Levee Fm.[1] Joachim Dol. St. Peter Ss. Everton Fm.	0-1,000	Limestone Shale and ls. Limestone Dol. and ls. Argillaceous dol. Sandstone Silty sandstone	Present only on flanks of Plateaus. St. Peter Sandstone yields up to 140 gal/min; others 3 to 50 gal/min.
	Lower		Smithville Fm. Powell Dol. Cotter Dol. Jefferson City Dol. Roubidoux Fm. Gasconade Dol. Gunter Ss. Mbr.	0-1,900	Cherty dolomite and sandstone.	Yields range from 2 to 2,000 gal/min. Lower units (below Jefferson City Dolomite) are the best producers and generally yield several hundred gal/min. Upper units (above Roubidoux Formation) generally yield less than 100 gal/min.
Cambrian	Upper		Eminence Dol.	0-600 (?)	Cherty dolomite.	Yields 20 to 100 gal/min.
			Potosi Dol.	0-330	Dolomite	Yields up to 2,000 gal/min and averages 400 gal/min. Principal source of ground water for wells in the project area but thins toward the southwest.
		Elvins	Derby-Doe Run Dolomite	0-200	Siltstone, shale, and dolomite.	Not an important aquifer.
			Davis Fm.	0-380 (?)	Shale, siltstone, limestone, and dolomite.	Combined with the Derby-Doe Run the two formations are a confining unit between the Potosi Dolomite and the Bonneterre Formation.
			Bonneterre Dol.	0-400	Limestone and dolomite.	Not widely used aquifer, but yields 450 to 5,000 gal/min of water to lead mines in Viburnum Trend.
			Lamotte Ss.	0-400	Sandstone arkosic in places.	Source of water near St. Francois Mountains. Otherwise not widely used aquifer. Thins over Precambrian highs.
Precambrian			Igneous and metamorphic rocks.		Rhyolite and granite.	Not an aquifer except where weathered in St. Francois Mountains.

[1]Of local usage.

Earlier Work

Three hydrologic atlases are available that describe the water resources of the area covered by this report: Gann and others (1974 and 1976) for Missouri, and Lamonds (1972) for Arkansas. Many geologic reports of counties and quadrangles, both published and unpublished, give historic information on ground water. One of the reasons the bibliography of reports about the region is so extensive is its importance as a mineral province and the 100-plus years of mineral production.

Aley and others (1972) described failures of sewage-treatment facilities in southern Missouri and their causes. During recent years, the Missouri Department of Natural Resources, Division of Geology and Land Survey, collaborated with the U.S. Geological Survey to investigate the hydrology of the Osage Fork, Niangua, and Grandglaize River basins in the Missouri Ozarks (Harvey and others, 1980, in press). The purpose of that work was to learn what types of data should be collected and analyzed to further an understanding of the ground-water flow system, the streamflow regimen, and their relation to pollution problems. Several references in this report to historic and continuing work in other countries, especially the European countries, which are near the latitude of the United States, are included because the history of hydrologic interpretation spans many centuries in those countries compared to the relatively short span of hydrologic investigation of carbonate terranes in the United States. Jennings (1971) and Jakucs (1977) contain comprehensive bibliographies of that work.

A report on the springs of Missouri by Vineyard and Feder (1974) contains an abundance of information about the hydraulic operation of the cavernous systems that feed the springs. Exploration by divers in underwater caverns has contributed significantly to the knowledge of many of the spring systems in the State.

THE AQUIFER

One way to define the principal aquifer in the region is to describe it as the Potosi Dolomite because the Potosi is the source of most of the municipal water supplies in the Salem Plateau (fig. 3). The Potosi Dolomite has a recognized top, bottom, and assigned thickness; a description of that formation alone would be an inadequate representation of the total aquifer involved in the region because it does not take into account the three-dimensional flow of water through the entire body of dolomite.

A more meaningful way to define the aquifer is to consider the entire section from the land surface to the base of the Potosi (table 1). Then, instead of a thickness of several hundred feet of dolomite, a thickness of a thousand feet or more of dolomite containing layers of sandstone and chert distributed through the section is considered. The sandstones are principally those in the Roubidoux Formation and the Gunter Sandstone Member of the Gasconade Dolomite. Underlying the dolomite section, which extends downward through the Derby-Doe Run Dolomite, is the Davis Formation. Admittedly, the largest permeability is generally in the Potosi Dolomite, but wells do produce several hundred gallons per minute from units above the Potosi in some places (table 1).

An answer to why there is not a more random distribution of good permeability throughout the thousand-foot section may partially lie in the description of a circulation system proposed by Jakucs (1977, p. 166-172). Solution of the dolomite rocks in the section, with the floor of active solution imposed by the Davis Formation, lends itself to Jakucs' explanation of the distribution of permeability.

An authigenic karst is defined by Jakucs (1977, p. 166) as one in which the surface drainage originates within the limestone or dolomite area and flows outward across a non-karstic area. See figure 5. The author considers the Salem Plateau to be mainly an authigenic karst. An allogenic karst is one in which the surface drainage enters a karstic area from a non-karstic area (fig. 5). Streams that rise in the igneous terrane of the St. Francois Mountains and flow across the Cambrian and Ordovician dolomite fit the scheme of an allogenic karst. Although most of the Springfield-Salem plateaus can be considered an authigenic karst, small areas may be better described as allogenic.

The four zones of an authigenic karst as depicted by Jakucs are the "b" zone=zone of infiltration; "a" zone=zone of downward filtration without significant carbonate dissolution; "l" zone=lenticular zone where calcium carbonate is dissolved; "i" zone=zone of the inactive deep karst. Figure 5, adapted from Jakucs (1977, p. 166-172), illustrates the relationship.

Several investigators have proposed (Thrailkill, 1968, p. 19-45; Bögli, 1964, p. 83-92; and Jakucs, 1977, p. 170) that under high hydrostatic pressure at depth, water from more than one individual source, even though saturated with calcium carbonate and magnesium carbonate, may become able on mixing to dissolve carbonate rocks. Water is recharged in the outcrop of the Potosi Dolomite. However, the outcrop of the formation is not the total extent of the recharge area. Throughout the uplands of the Salem Plateau, recharge is occurring continuously by vertical leakage through overlying beds and along "losing" streams to join the water moving downgradient toward a major stream or recharge area. Here is the opportunity for mixing that Jakucs and others have called on to explain the development of the lenticular zone, which is the zone where calcium carbonate is dissolved in response to pressure and mixing. Even though the phenomenon of mixing and solution is accepted, investigators disagree on its importance (Jennings, 1971, p. 28).

The system between Lebanon and Bennett Spring (fig. 6) is similar to that proposed by Jakucs. In the interval between the "b" zone and the "l" zone, which is represented by the geologic column from the Jefferson City or

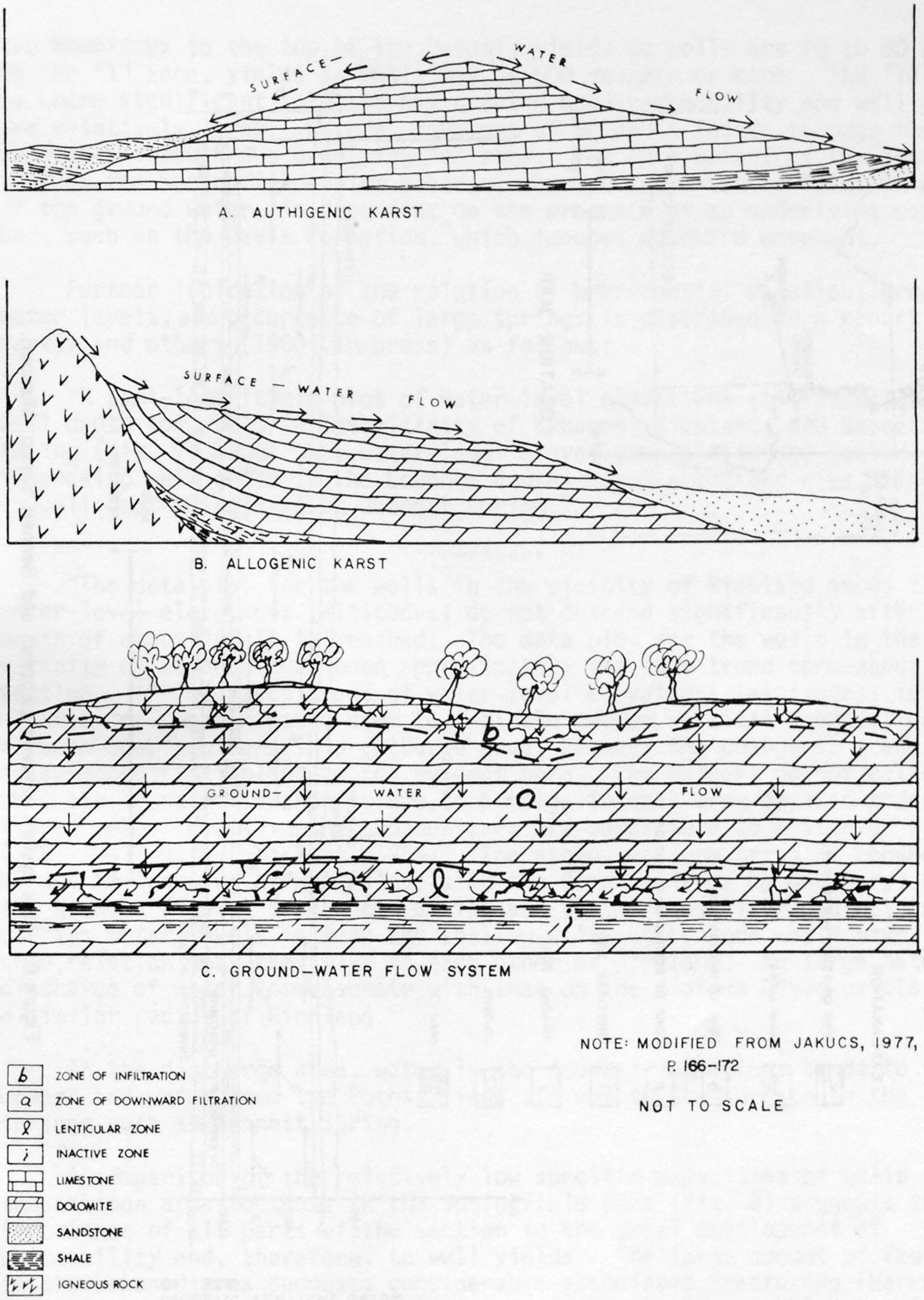


Figure 5.--Authigenic and allogenic karst and development of secondary permeability.

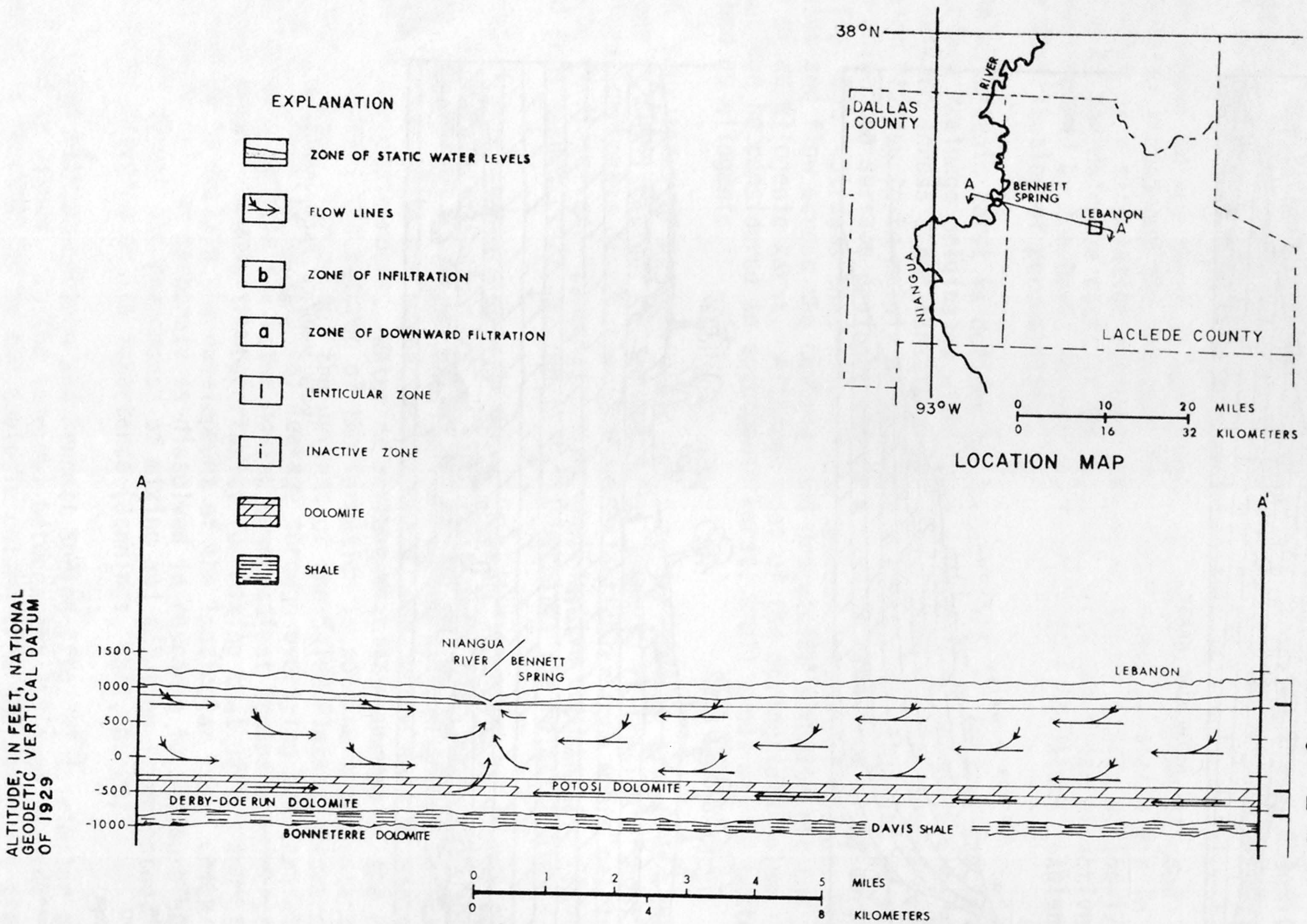


Figure 6.--Flow system between Lebanon and Bennett Spring, Missouri.

the Roubidoux to the top of the Potosi, yields to wells are 10 to 50 gal/min. In the "l" zone, yields to wells may be 500 gal/min or more. The "l" zone is where significant solution has created good permeability and well yields are relatively large. Lateral movement of water is faster through the "l" zone than through the overlying "a" zone. The development of the lenticular zone in the Springfield-Salem plateau, through the enhanced solution ability of the ground water, is dependent on the presence of an underlying confining bed, such as the Davis Formation, which impedes downward movement.

Further indication of the relation of preferential solution, ground-water levels, and occurrence of large springs is described in a report by Harvey and others (1980, in press) as follows:

"A semi-logarithmic plot of water-level elevations [altitudes] versus well depth for wells in the vicinity of Lebanon, Richland, and Bennett Spring (fig. 7) shows that water-level elevations [altitudes] decline with increasing well depth in the Lebanon and Richland areas and rise slightly as well depths increase at Bennett Spring."

****

"The data plot for the wells in the vicinity of Richland shows that water-level elevations [altitudes] do not descend significantly after a depth of about 400 ft is reached. The data plot for the wells in the vicinity of Lebanon continued approximately the same trend throughout the section. ***The steep trend of water-level elevations [altitudes] in the vicinity of Lebanon would seem to indicate poorer vertical [connection] between deep aquifers in a recharge area, because the change in trend experienced at Richland is not evident here. The authors do not believe that the trend at Lebanon is due to pumpage in that area because modern (1972) water levels in the Lebanon area are comparable to historic (1887-1947) data (Searight, 1955). The steep, uniform trend at Lebanon may be due to lowering of water levels in the deep aquifers by discharge along the Niangua River. If Bennett Spring and the Niangua River did not exist, perhaps water levels in deep and shallow wells at Lebanon would have the same relation that they have to each other at Richland. No large natural discharge of water commensurate with that on the Niangua River exists in a similar radius of Richland."

In the discharge area, water in the deepest formations tends to flow upward and water from the Potosi finds its way to the surface in the large springs such as Bennett Spring.

A comparison of the relatively low specific capacities of wells in the Lebanon area to those in the Springfield area (fig. 8) suggests the importance of all parts of the section to the areal development of permeability and, therefore, to well yields. The large amount of faulting in the Lebanon area suggests considerable associated fracturing (Harvey and others, 1980, in press). The fracturing tends to channel water to

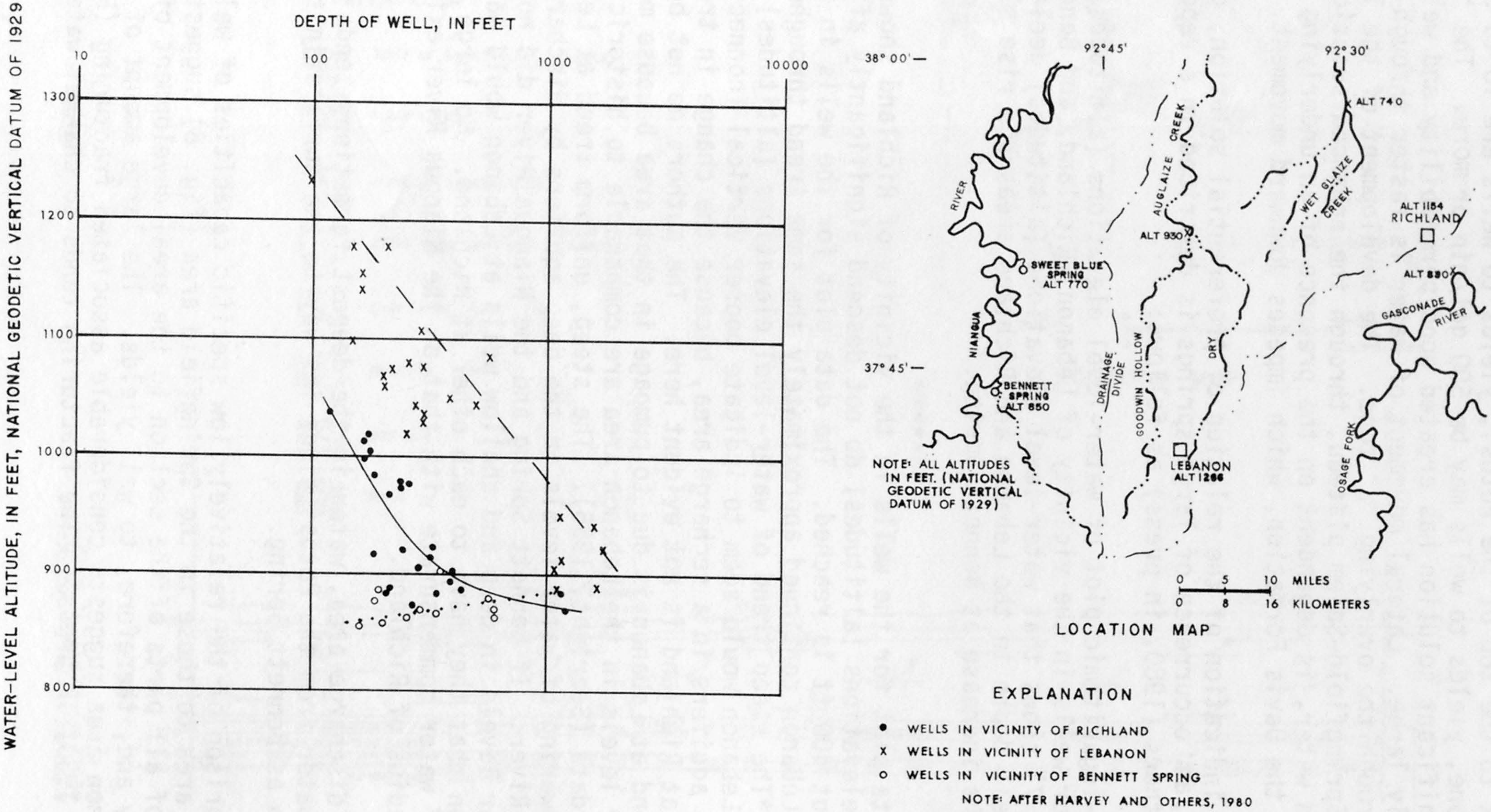


Figure 7.--Water-level altitude versus well depth of wells in selected areas.

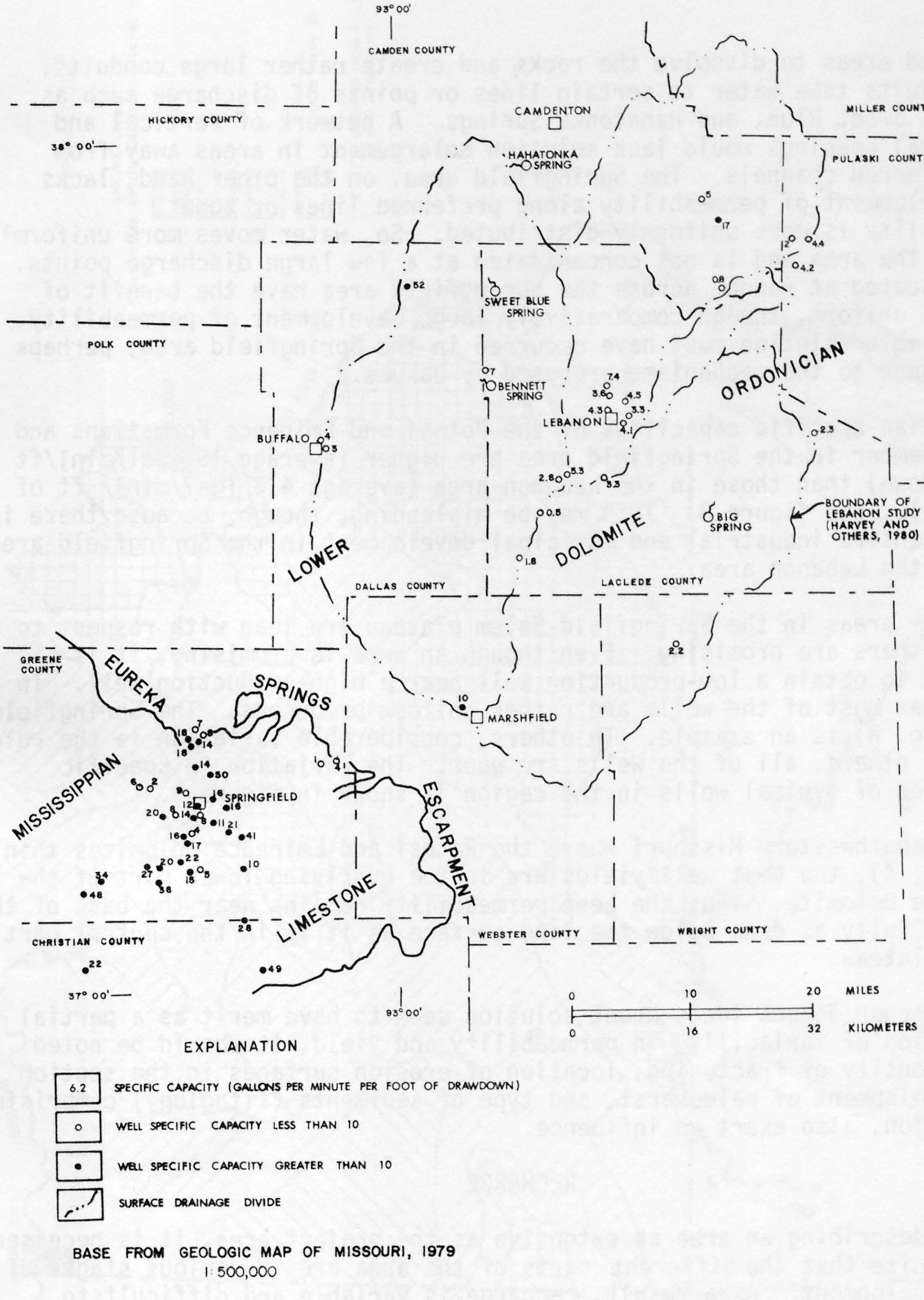


Figure 8.--Specific capacities of wells in Lebanon-Springfield area.

preferred areas to dissolve the rocks and create rather large conduits. The conduits take water to certain lines or points of discharge such as Bennett, Sweet Blue, and Hahatonka Springs. A network of vertical and horizontal openings would lack solution enlargement in areas away from the preferred channels. The Springfield area, on the other hand, lacks the development of permeability along preferred lines or zones. Permeability is more uniformly distributed. So, water moves more uniformly through the area and is not concentrated at a few large discharge points. Wells located at random across the Springfield area have the benefit of the more uniform, though comparatively large, development of permeability. Considerable solution must have occurred in the Springfield area, perhaps in response to the mechanisms proposed by Jakucs.

Median specific capacities of the Potosi and Eminence Formations and Gunter Member in the Springfield area are higher (average 15 [gal/min]/ft of drawdown) than those in the Lebanon area (average 4.3 [gal/min]/ ft of drawdown). See figure 8. This may be misleading, though, because there is more extensive industrial and municipal development in the Springfield area than in the Lebanon area.

Many areas in the Springfield-Salem plateau are lean with respect to water; others are promising. Even though an area is promising, it is possible to obtain a low-production well near a high-production well. In some areas most of the wells are rather uniform producers. The Springfield area (fig. 8) is an example. In others, considerable variation is the rule. In still others, all of the wells are poor. The variation in specific capacities of typical wells in the region is shown in figure 9.

In southwestern Missouri where the Potosi and Eminence Dolomites thin (see fig. 4), the best well yields are in the overlying lower part of the Gasconade Dolomite. Thus the best permeability remains near the base of the section, fully as deep below the land surface as it is in the central part of the Plateau.

Although Jakucs' ideas about solution seem to have merit as a partial explanation of variability in permeability and yield, it should be noted that intensity of fracturing, location of erosion surfaces in the section with development of paleokarst, and type of sediments (lithology) comprising the section, also exert an influence.

RECHARGE

In describing an area as extensive as the project area, it is necessary to recognize that the different parts of the area are in various stages of karst development. As a result, recharge is variable and difficult to predict.

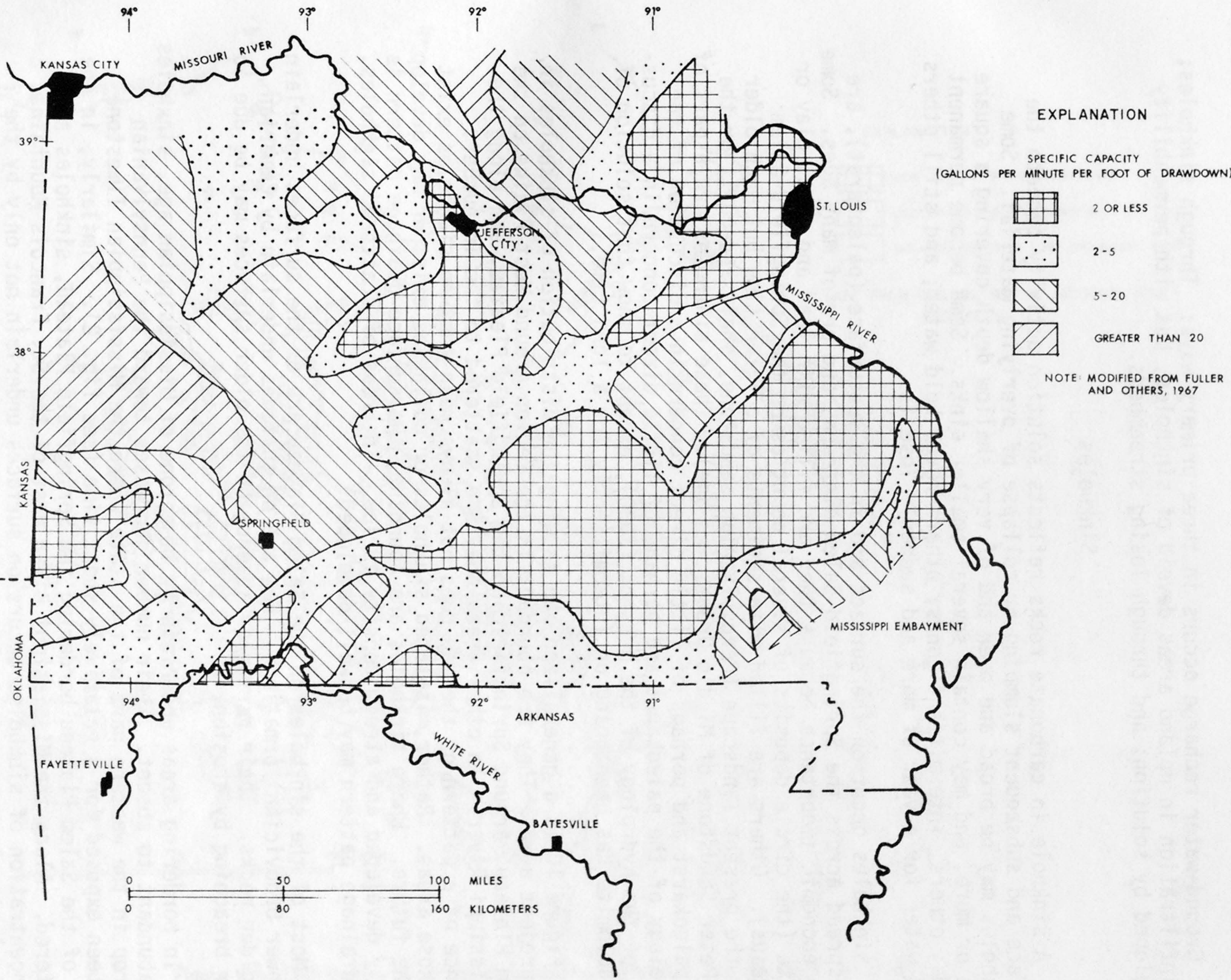


Figure 9.--Specific capacities of typical wells in southern Missouri.

Ground-water recharge occurs in three primary ways: Through sinkholes; by infiltration in upland areas devoid of sinkholes, but with permeability developed by solution; and through losing streambeds.

Sinkholes

A sinkhole in carbonate rocks reflects solution activity beneath the surface and subsequent slumping or collapse of overlying material. Some sinkholes may be broad and open and of very shallow depth covering a square mile or more, and may contain several smaller sinks. Some become permanent ponds; others, intermittent ponds; others never hold water; and still others hold water for a year of more and suddenly lose it.

Sinkholes occur on the surface and in the subsurface (paleokarst), are widespread across the Springfield-Salem plateaus, and are of many ages. Some have economic importance because they are filled with lead and zinc, clay or pyrite (the circle deposits of several counties on the Springfield-Salem plateaus). Others are filled with sediments of a later time but much older than the present landscape (Pennsylvanian sandstone, shale and coal, or the St. Peter Sandstone of Middle Ordovician age). These sinkholes are a part of the paleokarst and perhaps of little direct concern in a discussion of the hydrology of the paleokarst and perhaps of little direct concern in a discussion of the hydrology of the present (1980), except to show that solution of the dolomite has been going on intermittently for a long time.

Figure 10 is a generalized map showing the distribution of sinkholes in the project area. They are abundant in the region around West Plains on the Salem Plateau, around Springfield on the Springfield Pleatau, and along the Mississippi River. In other areas they are scattered to few in number. Absence of a pattern on the map does not always mean that no sinkholes exist in those areas. Rather, isolated sinkholes or collapses exist or may develop in the future. Where sinkholes are abundant, the surface drainage pattern is poorly developed and stream density is low. In areas of scattered sinkholes, the drainage pattern may be well developed.

Most of the sinkholes on the Salem Plateau are on the surfaces underlain by Lower Ordovician formations. Few are on surfaces underlain by Cambrian and older rocks. Their rarity or absence on the older surfaces may be due to their breaching by erosion.

In bordering areas underlain by limestone of Mississippian age, sinkholes are abundant to absent. Their number decreases toward the Pennsylvanian outcrop in the western part of the State where the Mississippian limestone has been exposed for a relatively short time (see fig. 2). Similarly, in the belt of the Salem Plateau bordering the Springfield Plateau, sinkholes are scattered. Along the Mississippi River east of the St. Francois Mountains, a concentration of sinkholes occurs on surfaces underlain not only by the Mississippian limestone, but also on limestone and dolomite of Middle Ordovician age. If the distribution shown on topographic maps is compared with the State geologic map, formation control is evident.

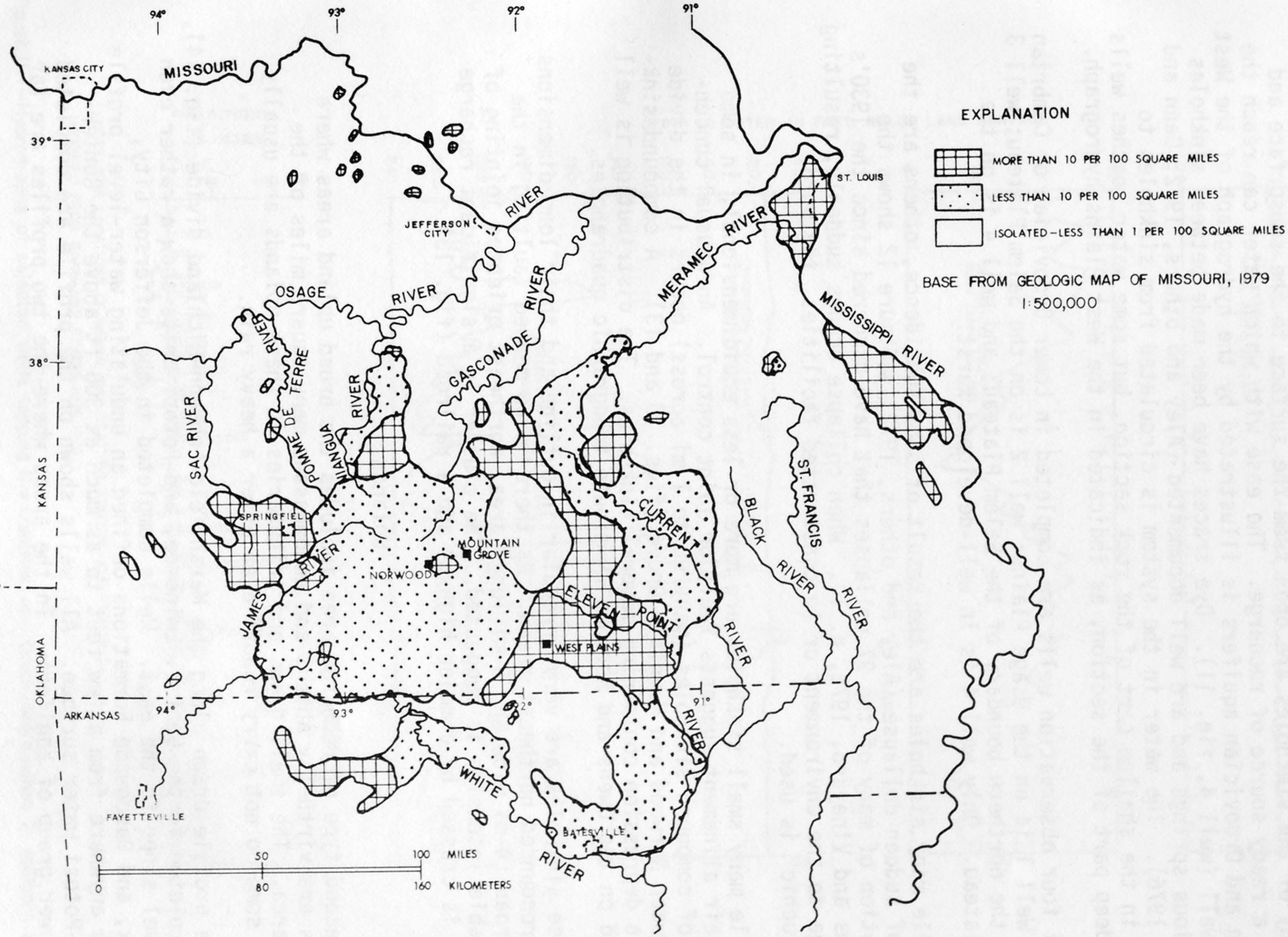


Figure 10.--Distribution of sinkholes in southern Missouri and northern Arkansas.

Many of the sinkholes are open from the surface to the subsurface and provide a ready source of recharge. The ease with which water can reach the Cambrian and Ordovician aquifers is illustrated by the hydrograph of the West Plains well (well 4, fig. 11). Dye traces have been made between sinkholes and various springs and are well documented (Aley and others, 1972; Gann and others, 1976). The water in the system is circulated from sinkholes to springs in the shallow part of the rock section, but some water reaches wells in the deep part of the section, as indicated in the West Plains hydrograph.

All four observation wells are completed in Lower Ordovician or Cambrian rocks. Well 1 is on the Osage Plains; well 2 is on the Salem Plateau; well 3 is near the northern boundary of the Salem Plateau; and well 4 is on the Salem Plateau. Only well 4 is in well-developed karst.

While many sinkholes are the result of slow subsidence, others are the result of sudden collapse (Aley and others, 1972). Figure 12 shows the distribution of many of the 97 collapses that have occurred since the 1930's (Williams and Vineyard, 1976, p. 1). When collapse occurs suddenly, resulting in damage to the environment or to constructed facilities, the word "catastrophic" is used.

While many small sinkholes are more or less equidimensional, in some areas their alinement suggests fault or joint control. An unusual concentration of compound sinkholes (many up to 1 mi across) occurs in the divide area between Norwood and Mountain Grove (figs. 10 and 13). A compound sinkhole is a depression containing several sinkholes. The distribution is well displayed on the Owens and Norwood 7½-minute topographic quadrangles.

These sinkholes are very irregular in outline and their long dimensions have a pronounced northeast trend. As there is no mapped faulting in the rather broad (4-mi wide and 8-mi long) area, northeast oriented jointing of considerable intensity is suggested. The cluster is a significant recharge area and is crossed by a major highway and a railroad (fig. 13).

Uplands

A second type of recharge area includes the broad upland areas where sinkholes are virtually absent and encompasses many square miles of the project area. The small draws and tributaries in these uplands are usually dry, and some do not carry runoff even after a heavy rain.

In a profile drawn along the Marshfield-Lebanon-Richland divide (fig. 14), wells completed in the Gunter, Eminence, and Potosi units show a rather even water-level slope to the east. Wells completed in the Jefferson City, Roubidoux, and Gasconade Formations defined an undulating water-level profile that lies anywhere from a few feet to as much as 300 ft above the Gunter-Eminence-Potosi water surface. All wells shown on the profile are completed in the lower group of aquifers. In the areas where the two profiles are far

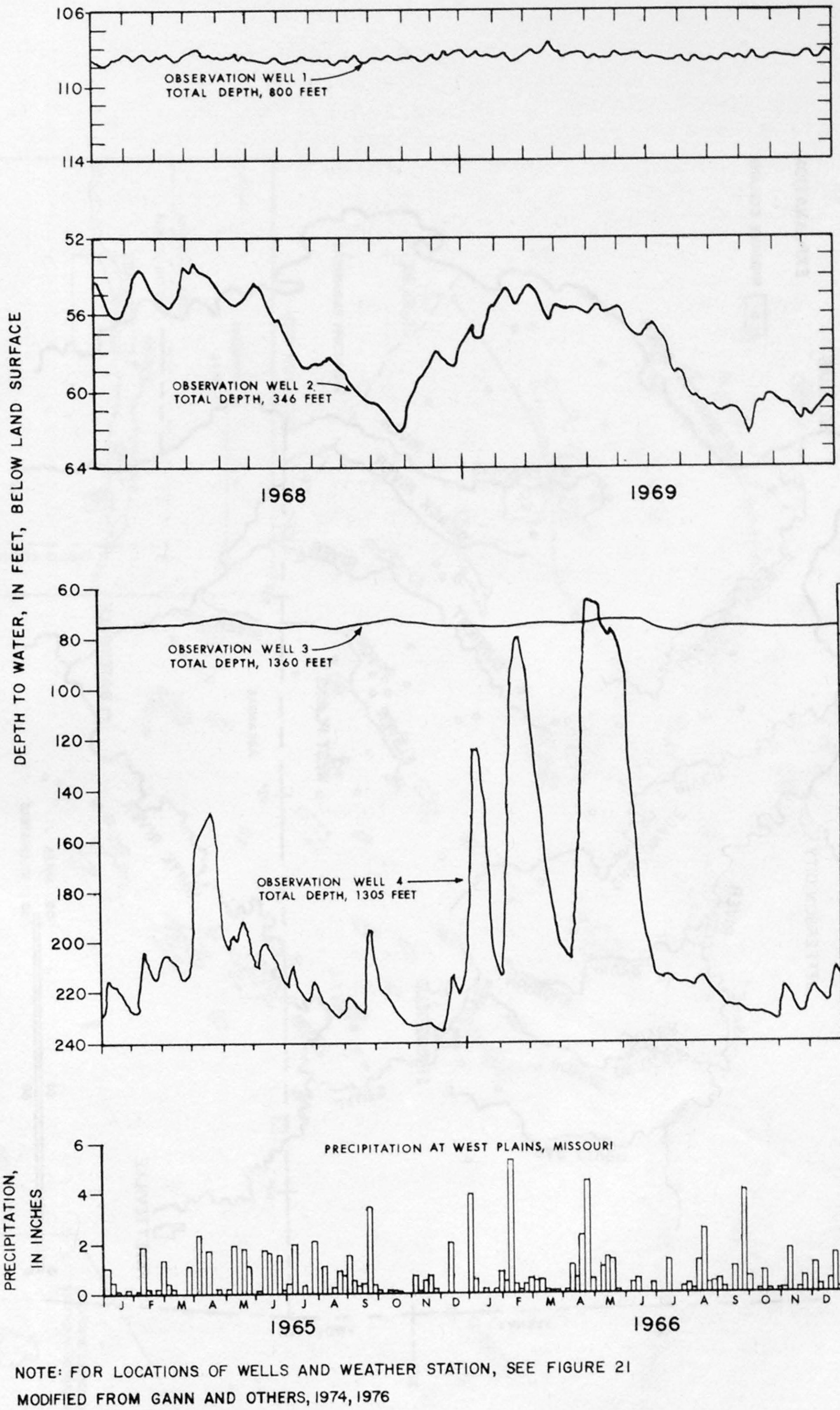


Figure 11.--Hydrographs of selected wells tapping the Cambrian and Ordovician aquifers in southern Missouri.

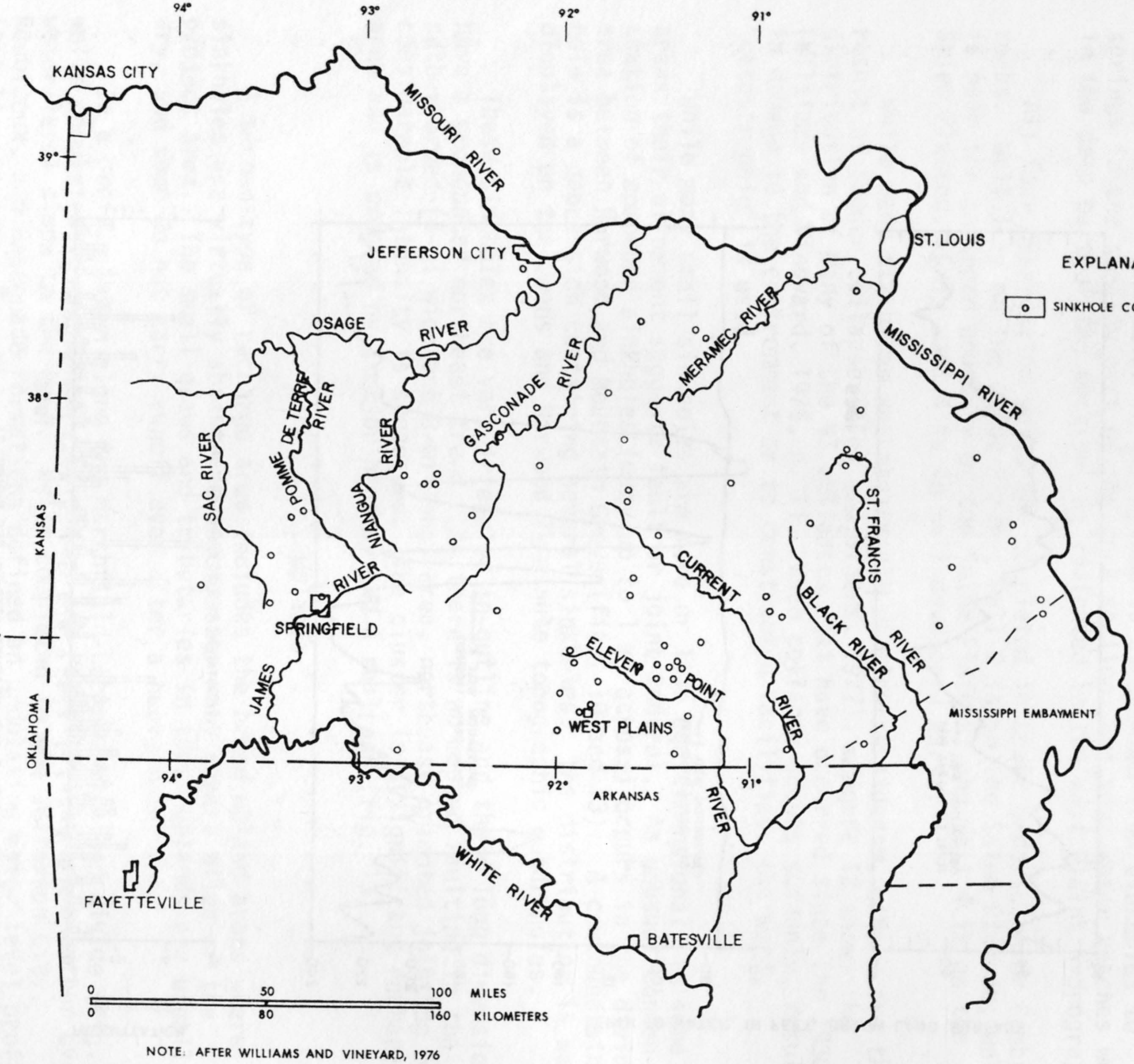


Figure 12.--Collapses in southern Missouri known to have occurred since the 1930's.

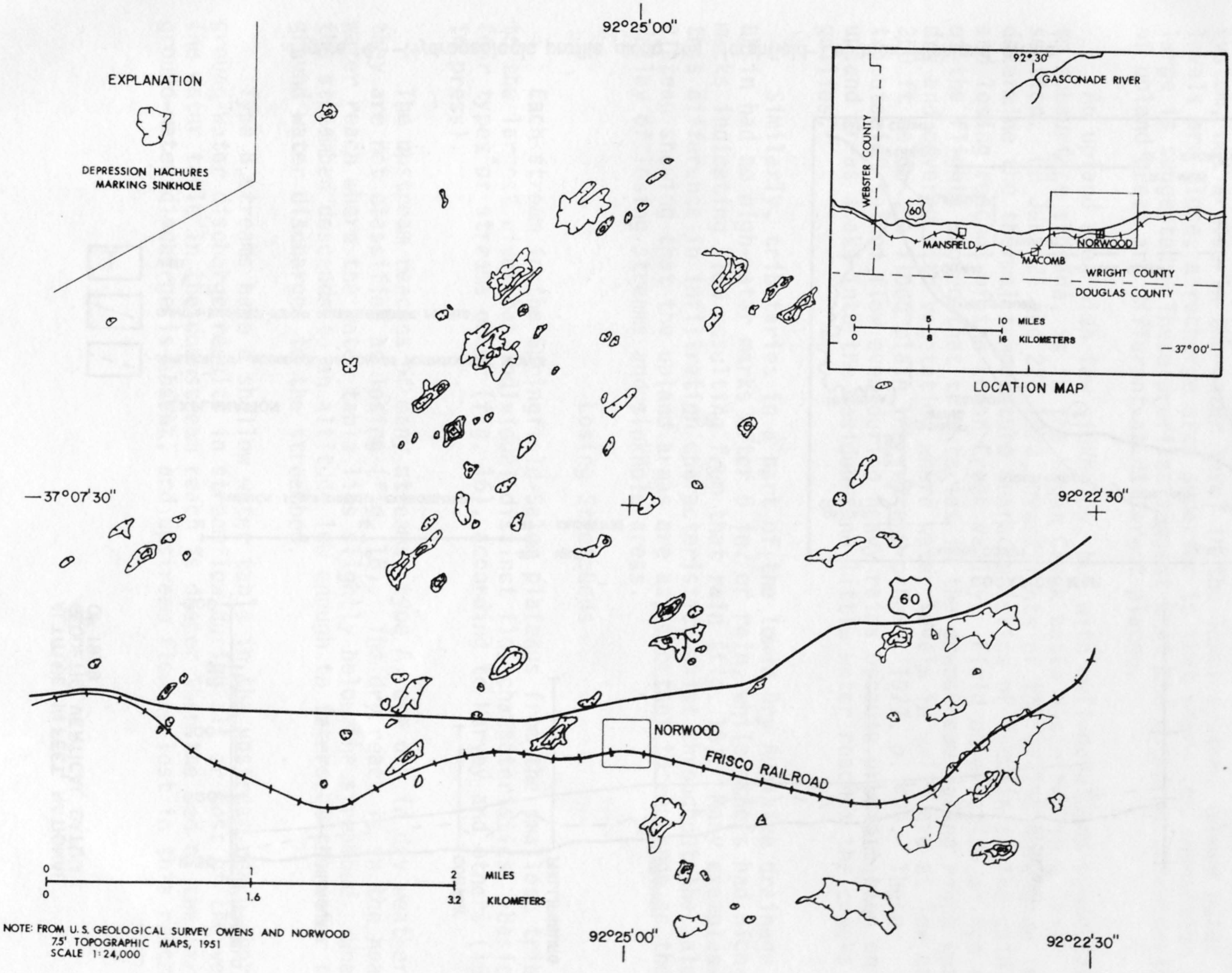


Figure 13.--Sinkhole distribution along a major transportation route on the main divide between the Missouri and White Rivers.

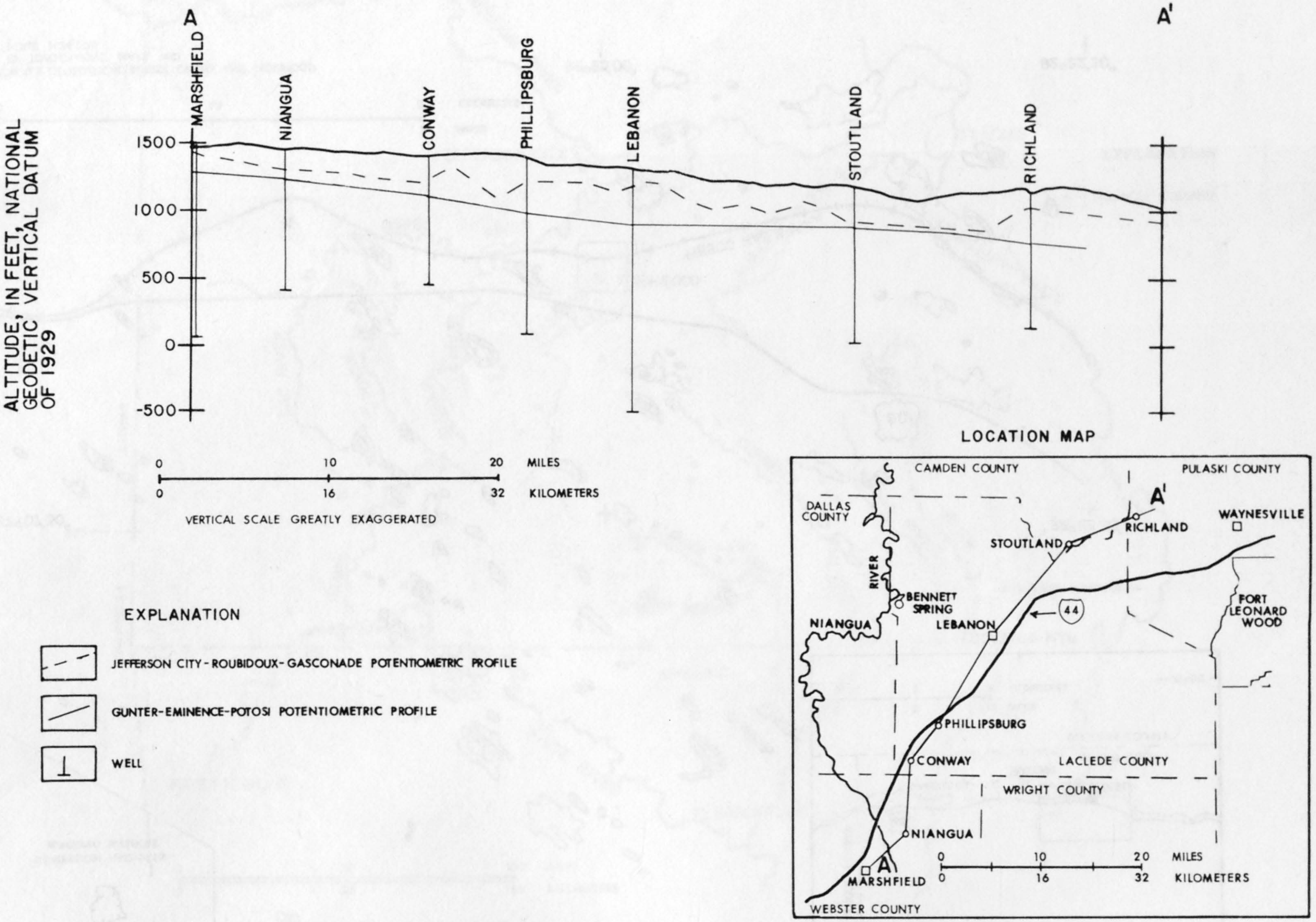


Figure 14.--Hydrogeologic profile along the Marshfield-Lebanon-Richland divide.

apart, slow vertical movement of water from the upper aquifer system to the lower aquifer system is indicated but the connection is poor. Where the profiles are close, their proximity is due to the decline of the water level in the upper aquifer system toward the water level in the lower aquifer system, not a rise in the water level in the lower system. Where water levels are close, a recharge area superior to that where the separation is large is suggested. These profiles suggest that the recharge characteristics of upland areas are different at different places.

An upland area with few sinkholes, but with well-developed connections to subsurface storage, is in the Logan Creek basin described in a later section. On June 21 and 22, 1973, overflights of the valley were made to determine the thermal temperature characteristics of terrain in the gaining and losing reaches of the Logan Creek valley. Field observation at the time of the flights showed that tributaries in the downstream losing reach were dry and covered with vegetation where water levels in wells are as low as 250 ft below the flood plain (Harvey and others, 1977, p. 49). These tributaries seldom flow even during heavy rains because precipitation on the upland areas soaks into the residuum and little water reaches the creeks and gullies.

Similarly, tributaries in a part of the lower Dry Auglaize drainage basin had no high-water marks after 6 in. of rain, while others had high-water marks indicating flow resulting from that rain (fig. 15). Many examples of this difference in infiltration characteristics exist throughout the Salem Plateau showing that the upland areas are as important to recharge as the valley of losing streams and sinkhole areas.

Losing Streambeds

Each stream in the Springfield-Salem plateaus from the smallest tributary to the largest river has individual distinct flow characteristics. Basically, four types of streams occur (fig. 16), according to Harvey and others (1980, in press).

The upstream reaches of many streams, type A, are dry in dry weather and they are not classified as losing (fig. 16). The dry reach is in the headwater reach where the water table lies slightly below the streambed. When the streambed descends to an altitude low enough to intersect the water table, ground water discharges to the streambed.

Type B streams have a shallow water table in the upstream reach where ground-water discharge results in streamflow during all or most of the year. The water table in the downstream reach is deeper than the bed of the stream, ground-water discharge is absent, and upstream flow is lost in this reach.

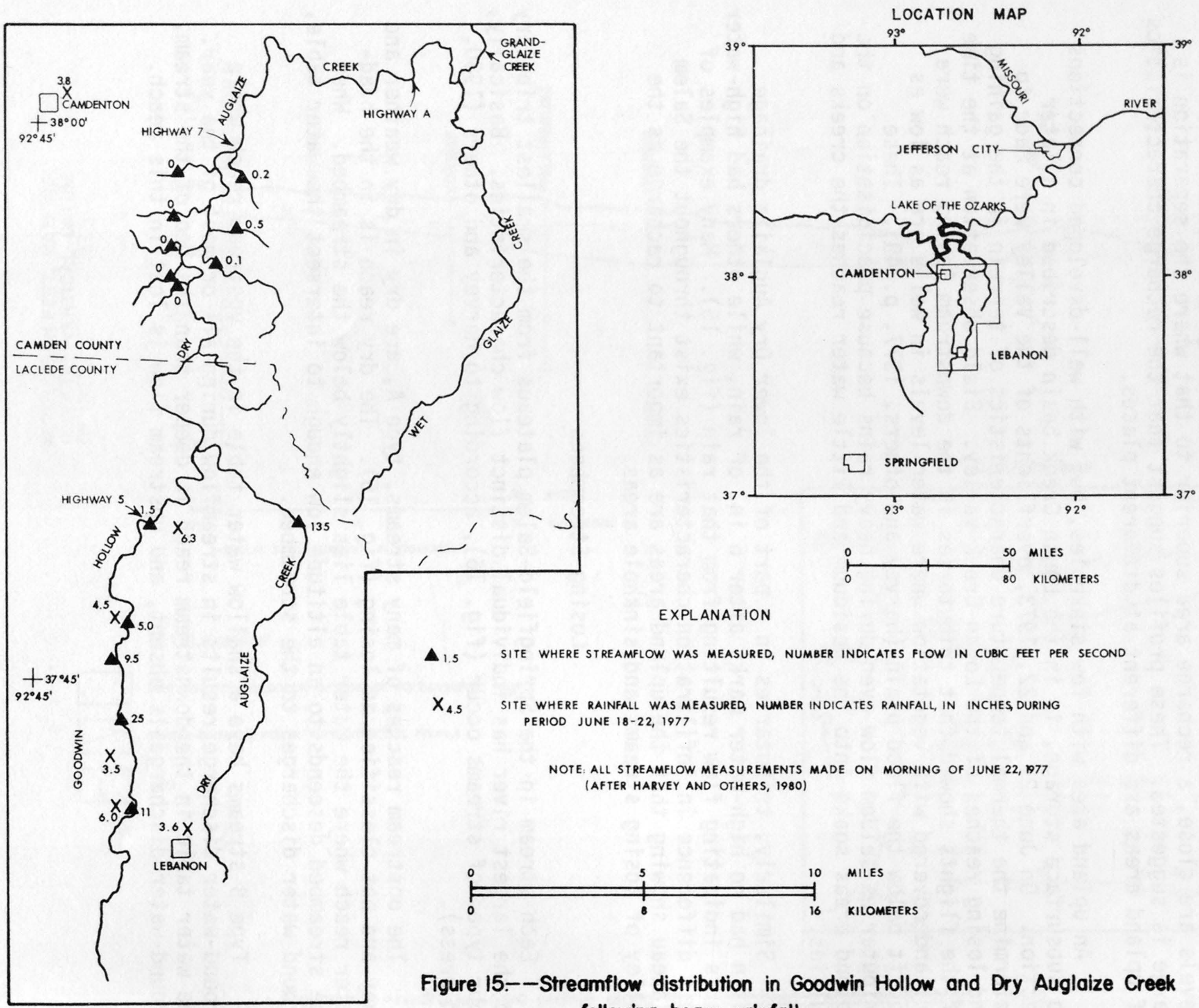


Figure 15.--Streamflow distribution in Goodwin Hollow and Dry Auglaize Creek following heavy rainfall.

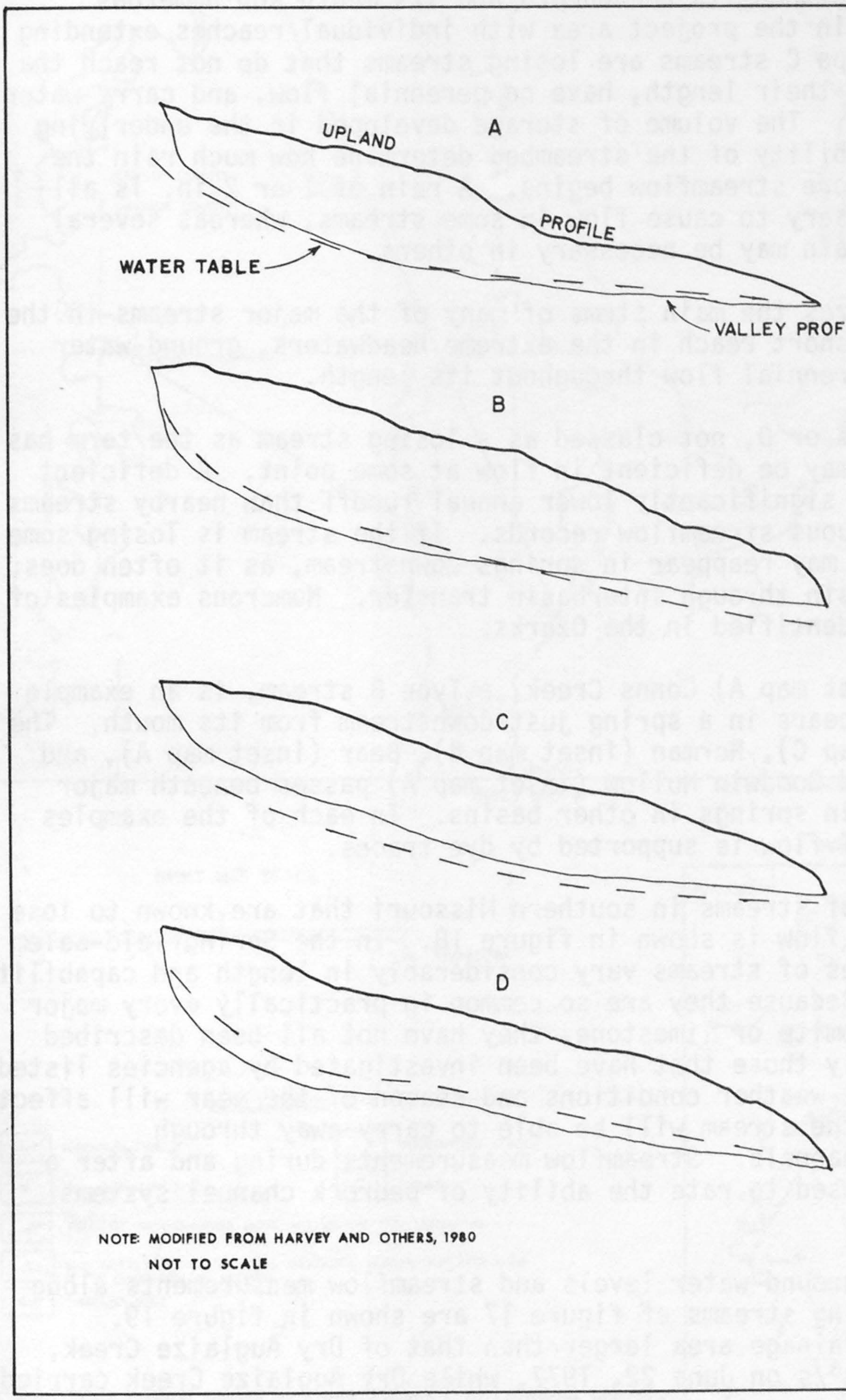


Figure 16.--Longitudinal profiles of stream types.

The sequence of gaining and losing reaches may be repeated several times in a stream's course between its headwaters and its mouth and numerous examples can be cited in the project area with individual reaches extending for several miles. Type C streams are losing streams that do not reach the water table throughout their length, have no perennial flow, and carry water only after heavy rains. The volume of storage developed in the underlying bedrock and the permeability of the streambed determine how much rain the valley will absorb before streamflow begins. A rain of 1 or 2 in. is all that is normally necessary to cause flow in some streams, whereas several times that amount of rain may be necessary in others.

Type D characterizes the main stems of many of the major streams in the Ozarks. Except for a short reach in the extreme headwaters, ground-water discharge maintains perennial flow throughout its length.

A stream of Type A or D, not classed as a losing stream as the term has been used previously, may be deficient in flow at some point. A deficient stream is one that has significantly lower annual runoff than nearby streams as indicated by continuous streamflow records. If the stream is losing some of its flow, the water may reappear in springs downstream, as it often does, or it may leave the basin through interbasin transfer. Numerous examples of both types have been identified in the Ozarks.

In figure 17 (inset map A) Conns Creek, a Type B stream, is an example of one whose flow reappears in a spring just downstream from its mouth. The flow of Logan (inset map C), Norman (inset map B), Bear (inset map A), and Dry Auglaize Creeks and Goodwin Hollow (inset map A) passes beneath major divides and reappears in springs in other basins. In each of the examples cited, the direction of flow is supported by dye traces.

The distribution of streams in southern Missouri that are known to lose a part or all of their flow is shown in figure 18. In the Springfield-Salem plateaus, losing reaches of streams vary considerably in length and capability of absorbing runoff. Because they are so common in practically every major basin underlain by dolomite or limestone, they have not all been described and figure 18 shows only those that have been investigated by agencies listed in table 2. Antecedent-weather conditions and season of the year will affect the quantity of water the stream will be able to carry away through subterranean bedrock channels. Streamflow measurements during and after a few rainstorms can be used to rate the ability of bedrock channel systems to accept runoff.

Profiles showing ground-water levels and streamflow measurements along two of the typical losing streams of figure 17 are shown in figure 19. Goodwin Hollow has a drainage area larger than that of Dry Auglaize Creek, but carried only 1.5 ft^3/s on June 22, 1977, while Dry Auglaize Creek carried 135 ft^3/s after a heavy general rain of about 6 in. between June 18 and June 22 (see fig. 15). Ground-water levels stand as much as 50 ft below the

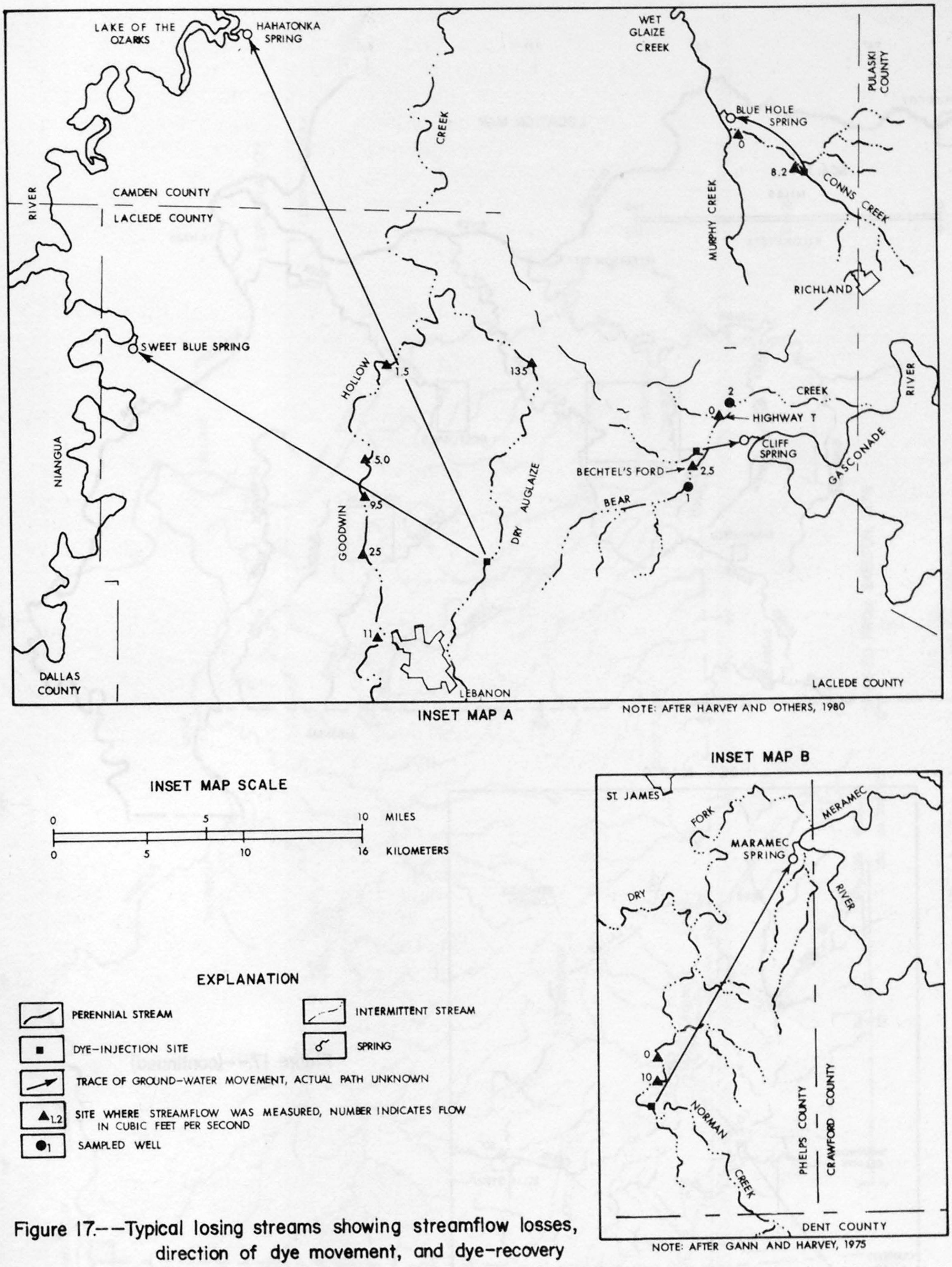


Figure 17.--Typical losing streams showing streamflow losses, direction of dye movement, and dye-recovery sites.

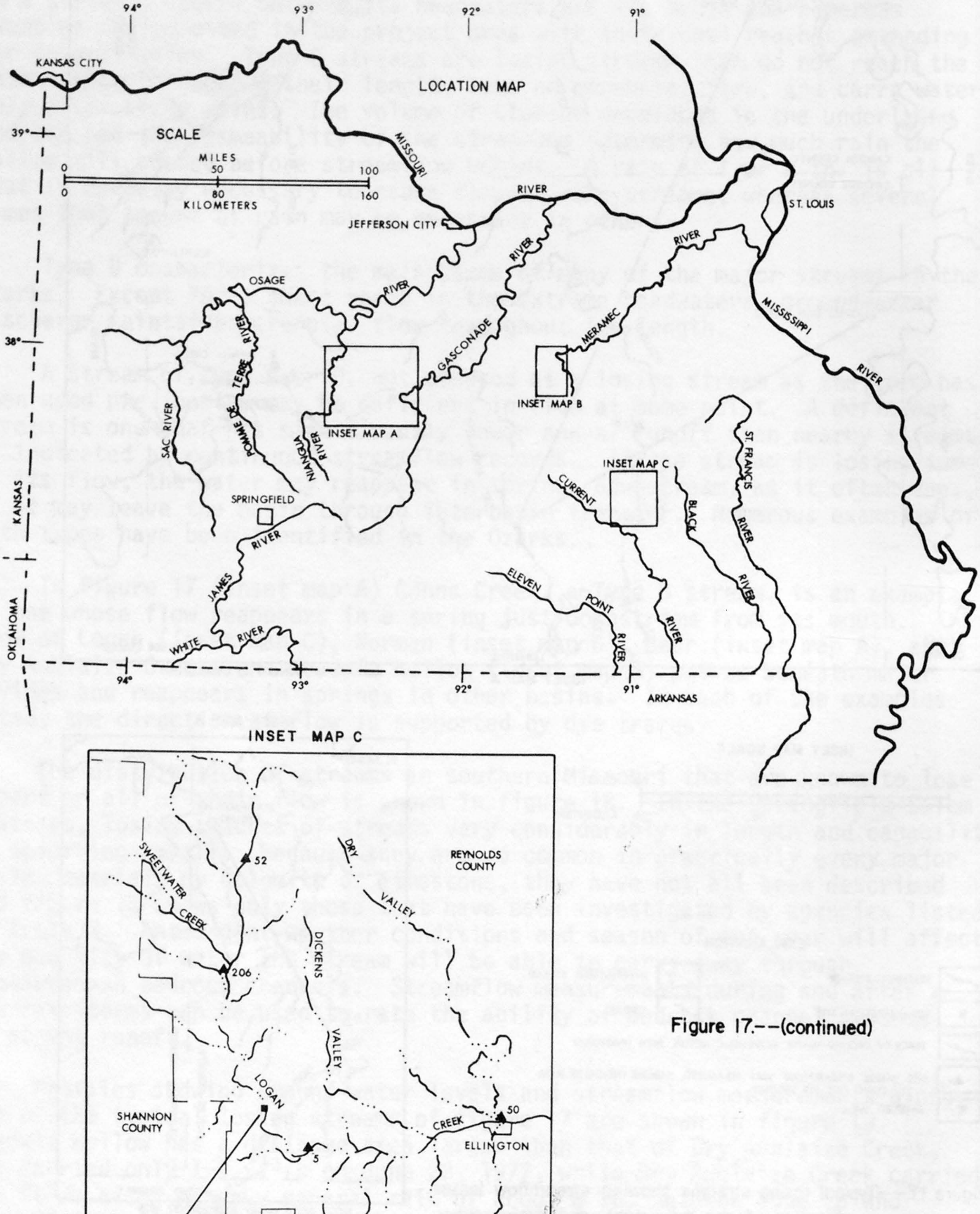


Figure 17.--(continued)

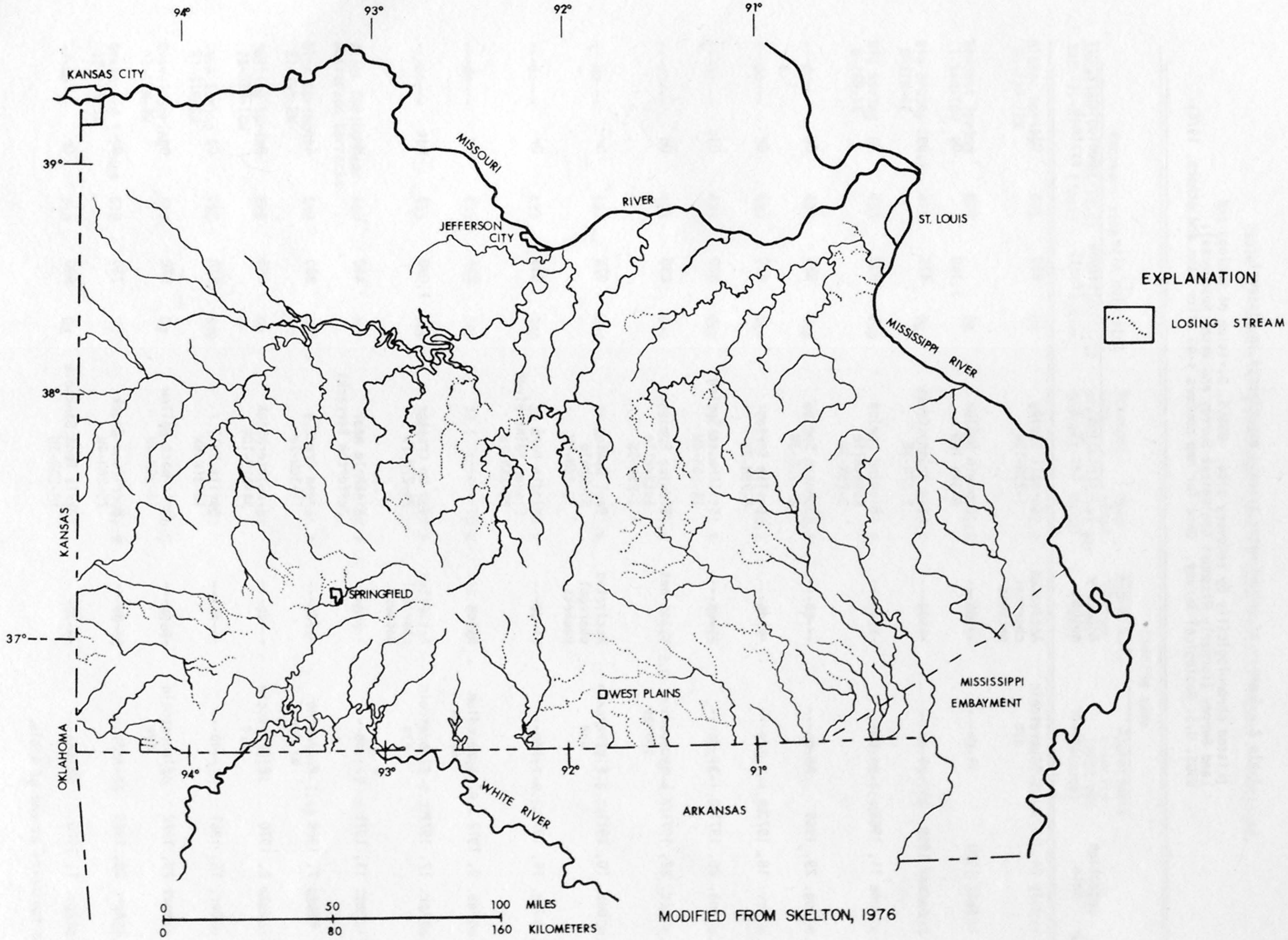


Figure 18.--Losing streams in southern Missouri.

Table 2.--Summary of ground-water tracing experiments in Missouri

[Listed chronologically by recovery site. DG&LS, Division of Geology and Land Survey (formerly Missouri Geological Survey and Water Resources); USGS, U.S. Geological Survey. Data for map numbers 1-45 after Gann and others, 1976]

Map No. (fig. 21)	Injection date	Tracer	Recovery method	Injection site: Location Sec.-T.-R.	Injection site: Altitude (feet)	Injection site: Geologic system[1]
1	July 24, 1972	Fluorescein dye	Activated charcoal packets	Cureall Spring 1-23N-10W	850	Ojc
2	Fall 1968	---do---	---do---	Goodwin Hollow 4-34N-16W	1,140	Og
3	Summer 1968	---do---	---do---	Big Brushy Creek 2-27N-3E	475	Og
4	June 11, 1968	---do---	---do---	Blowing Spring Estavelle 3-25N-3W	630	Og
5	Aug. 29, 1969	---do---	---do---	Johnson Spring 22-25N-3W	530	Og
6	Nov. 18, 1970	---do---	---do---	Leslie Spring 4-25N-3W	620	Or
7	Aug. 26, 1971	---do---	---do---	Stillhouse Spring 14-25N-6W	820	Ojc
8	Oct. 22, 1971	Lycopodium spores	Nylon net	Blowing Spring Estavelle 3-25N-3W	630	Og
9	Dec. 10, 1971	Fluorescein dye	Activated charcoal packets	Paul Dowler Sinkhole 12-26N-5W	975	Or
10	Jan. 18, 1972	---do---	---do---	Middle Fork Eleven Point River 25-25N-7W	835	Or
11	Feb. 9, 1972	Lycopodium spores	Nylon net	---do---	835	Or
12	Apr. 17, 1972	Fluorescein dye	Activated charcoal packets	Jam Up Creek 24-27N-7W	1,090	Ojc
13	Oct. 13, 1971	---do---	---do---	Sinkhole near Jefferson Barracks	440	Mm
14	Oct. 7, 1969	Rhodamine WT dye	---do---	Logan Creek 11-30N-2W	880	Ꞓep
15	July 8, 1970	Fluorescein dye	---do---	Slaughter Sink 34-37N-10W	850	Or
16	Dec. 10, 1961	---do---	---do---	Devils Well 16-31N-5W	870	Og
17	Mar. 29, 1972	Fluorescein dye	---do---	McCormack Hollow 24-25N-4W	570	Og
18	Apr. 30, 1969	---do---	---do---	Hurricane Creek 25-26N-4W	730	Or
19	Apr. 1, 1970	---do---	---do---	Davis Pond Sinkhole 18-25N-3W	900	Or

See footnotes at end of table.

Table 2.--Summary of ground-water tracing experiments in Missouri--continued

Recovery site			Straight-line distance (miles)	Mean slope (feet per mile)	Leading edge		Source
Location Sec.-T.-R.	Altitude (feet)	Geologic system[1]			Approximate elapsed time (days)	Approximate velocity (feet per minute)	
Althea Spring 25-23N-12W	605	Og	8.75	28.0	7-15	4.59-2.14	Forest Service[2]
Bennett Spring 1-34N-18W	870	Og	9.0	30.0	13	2.54	DG&LS[3]
Big Brushy Creek 8-27N-4E	415	Og	3.3	18.2	7-14	1.73-.86	Forest Service[4]
Big Spring 6-26N-1E	433	Ꞓep	17.0	11.6	7-14	8.92-4.46	Do.[5]
---do---	433	Ꞓep	18.0	5.4	17	3.89	Do.[5]
---do---	433	Ꞓep	17.5	10.7	6-13	10.7-4.94	Do.[5]
---do---	433	Ꞓep	33.5	11.6	57-75	2.16-1.64	Do.[5]
---do---	433	Ꞓep	17.0	11.6	11.2-13.0	5.59-4.81	Do.[5]
---do---	433	Ꞓep	25.3	21.4	7-14	13.3-6.64	Do.[5]
---do---	433	Ꞓep	39.5	10.2	13-17	11.1-8.52	Do.[5]
---do---	433	Ꞓep	39.5	10.2	5-14	29.0-10.4	Do.[5]
---do---	433	Ꞓep	38.1	17.2	8-15	17.5-9.32	Do.[2]
Black Spring near Jefferson Barracks	400	Mm	.45	88.9	<8.9	>.19	DG&LS[17]
Blue Spring 21-29N-2W	550	Ꞓep	9.5	34.7	3-10	11.6-3.48	USGS[6]
Boiling Spring 33-37N-10W	675	Og	.95	184	<2	>1.74	DG&LS[17]
Cave Spring 21-31N-5W	750	Ꞓep	1.1	109	<7	>.58	Do.[17]
Gravel Spring 25-25N-4W	530	Og	.5	80.0	<6.09	>.30	Forest Service[5]
Graveyard Springs 32-25N-3W	510	Og	7.6	28.9	55-62	.51-45	Do.[5]
---do---	510	Og	3.5	111	<8	>1.60	Do.[5]

Table 2.--Summary of ground-water tracing experiments in Missouri--continued

Map No. (fig.21)	Injection date	Tracer	Recovery method	Injection site: Location Sec.-T.-R.	Injection site: Altitude (feet)	Injection site: Geologic system[1]
20	June 14, 1972	Fluorescein dye	Activated charcoal packets	Horsetail Spring 11-25N-4W	750	Or
21	July 22, 1971	---do---	---do---	Dora Sinkhole Dump 8-24N-11W	890	OJc
22	July 20, 1972	---do---	---do---	Cane Creek 23-26N-4E	470	Og
23	Oct. 7, 1969	Rhodamine WT dye	---do---	Logan Creek 11-30N-2W	880	Ꞓep
24	Dec. 16, 1970	Fluorescein dye	---do---	Granny Meyers Spring 29-24N-5W	690	Ojc
25	June 14, 1972	---do---	---do---	Renfrow Spring Sink 10-24N-8W	1,000	Ojc
26	Aug. 23, 1972	Rhodamine WT dye	---do---	Norman Creek 7-36N-6W	930	Og
27	May 28, 1969	Fluorescein dye	---do---	Alton Sinkhole Dump 28-24N-4W	770	Ojc
28	June 20, 1967	Rhodamine BA dye	Grab samples	Radar Estavelle 18-28N-22W	1,120	Mo
29	July 7, 1967	---do---	---do---	Wilsons Creek 7-28N-22W	1,135	Mo
30	July 7, 1967	---do---	---do---	-----do-----	1,135	Mo
31	Oct. 29, 1968	Fluorescein dye	Activated charcoal packets	South Creek Sinkhole 5-28N-22W	1,145	Mo
32	Nov. 15, 1968	---do---	---do---	Subdivision Sinkhole 2-28N-22W	1,275	Mo
33	Nov. 22, 1968	---do---	---do---	Pfaff Cave 32-29N-22W	1,140	Mo
34	Mar. 13, 1973	---do---	---do---	Sinkhole 21-35N-9W	1,120	Or
35	Oct. ?, 1970	---do---	---do---	Roubidoux Creek 3-34N-12W	900	Og
36	July 28, 1970	---do---	---do---	Stream 2-31N-3E	730	Ꞓep
37	May 10, 1971	---do---	---do---	Dry Creek tributary 28-36N-11W	1,000	Or
38	June 9, 1971	---do---	---do---	Sediment basin 32-35N-11W	1,000	Or
39	Aug. 25, 1971	---do---	---do---	Dry Creek 2-35N-11W	900	Og

See footnotes at end of table.

Table 2.--Summary of ground-water tracing experiments in Missouri--continued

Recovery site			Straight-line distance (miles)	Mean slope (feet per mile)	Leading edge		Source
Location Sec.-T.-R.	Altitude (feet)	Geologic system[1]			Approximate elapsed time (days)	Approximate velocity (feet per minute)	
Graveyard Springs 32-25N-3W	510	Og	5.25	45.7	<9	>2.14	Forest Service[2]
Hodgson Mill Spring 34-24N-12W	660	Og	5.6	41.1	12-20	1.71-1.03	Do.[5,7]
Keener Spring 4-26N-5E	360	Og	4.9	22.4	<20	>.90	DG&LS[17]
Logan Creek 31-30N-2E	590	Ꞓep	14.0	20.7	3-10	17.1-5.14	USGS[6]
Mammoth Spring 5-21N-5W	510	Ojc	14.5	12.4	15-24	3.55-2.22	Forest Service[5]
---do---	510	Ojc	25.0	19.6	8-21	11.5-4.37	Do.[2]
Maramec Spring 1-37N-6W	785	Og	8.7	16.7	68-75	.47-.42	USGS
Morgan Spring 16-22N-2W	390	Or	15.5	24.5	75-89	.76-.64	Forest Service[5,8]
Rader Spring 18-28N-22W	1,115	Mo	.2	25.0	.052	14.1	USGS[9]
Rader Estavelle 18-28N-22W	1,120	Mo	1.25	12.0	.188	24.4	USGS[9]
Rader Spring	1,115	Mo	1.35	14.8	.233	21.2	USGS[9]
---do---	1,115	Mo	1.8	16.7	1.62	4.06	DG&LS[10]
---do[11]---	1,115	Mo	4.8	33.3	<3.00	>5.86	DG&LS[10]
---do[11]---	1,115	Mo	3.4	7.4	<3.21	>3.88	DG&LS[10]
Relfe Spring 36-35N-10W	825	Og	2.8	104	8-16	1.31-.65	Forest Service[16]
Roubidoux Spring 25-36N-12W	780	Og	10.5	11.4	5	7.70	DG&LS[12]
Sabula Cave 3-31N-3E	700	Ꞓep	.57	52.6	<13	>.16	DG&LS[17]
Shanghai Spring 24-36N-11W	750	Og	2.8	89.3	14	.73	DG&LS[12]
---do---	750	Og	9.2	27.2	23-30	1.47-1.12	Forest Service[13]
---do---	750	Og	3.2	46.9	28	.42	Do.[13]

Table 2.--Summary of ground-water tracing experiments in Missouri--continued

Map No. (fig.21)	Injection date	Tracer	Recovery method	Injection site: Location Sec.-T.-R.	Injection site: Altitude (feet)	Injection site: Geologic system[1]
40	Oct. 27, 1971	Fluorescein dye	Activated charcoal packets	Dry Creek 2-35N-11W	900	Og
41	1963	---do---	---do---	Carroll Cave Siphon 11-37-15W	760	Og
42	1968	---do---	---do---	Hodge Creek 21-32N-4W	1,020	Ꞓep
43	Fall 1968	---do---	---do---	Parkcrest Subdivision Sinkhole 12-28N-22W	1,240	Mo
44	Feb. 23, 1973	---do---	---do---	Mill Creek 4-35N-9W	960	Og
45	Jan. 24, 1973	---do---	---do---	Deep Hollow Creek 32-36N-9W	895	Og
46	Nov. 3, 1976	Rhodamine WT dye	---do---	Dry Auglaize Creek 30-35N-15W	1,110	Or
47	Nov. 3, 1976	---do---	---do---	-----do-----	1,100	Or
48	Apr. 20, 1978	---do---	---do---	Bear Creek 7-35N-14W	950	Or
49	Mar. 23, 1977	Fluorescein dye	---do---	Conns Creek 26-37N-14W	830	Or
50	Apr. 5, 1979	Rhodamine WT dye	---do---	Grove Creek 13-27N-32W	1,030	Mo
51	(?)	Fluorescein dye	---do---	Pond Creek 31-29N-23W	1,130	Mo
52	(?)	---do---	---do---	West Plains Sewage Lagoon 26-24N-8W	920	Oc

Table 2.--Summary of ground-water tracing experiments in Missouri--continued

Recovery site			Leading edge				
Location Sec.-T.-R.	Altitude (feet)	Geologic system[1]	Straight-line distance (miles)	Mean slope (feet per mile)	Approximate elapsed time (days)	Approximate velocity (feet per minute)	Source
Shanghai Spring 24-36N-11W	750	Og	3.2	46.9	19	0.62	Forest Service[13]
Toronto Spring 30-38N-14W	710	Og	3.0	16.7	14-21	.79-.52	DG&LS[14]
Twin Spring 21-31N-4W	780	Ꞓep	5.0	48.0	17	1.08	Forest Service[15]
Ward Spring 14-28N-22W	1,170	Mo	1.1	63.6	2.5-7	1.61-.58	DG&LS[10]
Wilkins Spring 20-36N-9W	815	Og	3.5	41.4	10-17	1.28-.76	Forest Service[16]
Yelton Spring 29-36N-9W	850	Og	1.35	33.3	6-12	.83-.41	Do.[16]
Sweet Blue Spring 30-36N-17N	770	Og	13.4	24.6	23-32	2.14-1.53	USGS
Hahatonka Spring 2-37N-17W	680	Og	18	23.4	45-53	1.47-1 25	USGS
Cliff Spring 9-35N-14W	850	Og	1.5	67	<2	>3.7	DG&LS
Blue Hole Spring 17-37N-14W	760	Og	3.5	20	2-7	6.4-1.2	DG&LS
Scotland Spring	980	Mo	2.2	23	.9	8.8	USGS
Unnamed Spring on Sac River 19-29N-23W	1,110	Mo	1.8	11	(?)	(?)	DG&LS
Mammoth Spring 5-21N-5W	506	Co	22.3	19	(?)	(?)	DG&LS

Table 2.--Summary of ground-water tracing experiments in Missouri--continued

Footnotes:

[1]Mm, MISSISSIPPIAN, Meramecian Series; Mo., MISSISSIPPIAN, Osagean Series; Og, ORDOVICIAN, Gasconade Dolomite; Ojc, ORDOVICIAN, Jefferson City Dolomite; Or, ORDOVICIAN, Roubidoux Formation; Oc, ORDIVICIAN, Cotter Dolomite; Gep, CAMBRIAN, Eminence and Potosi Dolomites.

[2]T. Aley, written commun., September 18, 1972.
[3]Division of Geology and Land Survey [formerly Missouri Geological Survey and Water Resources](1969).
[4]C. Tryon, oral commun., June 22, 1972.
[5]T. Aley, written commun., July 24, 1972.
[6]Feder and Barks (1972).
[7]Aley (1972).
[8]Aley (1969).
[9]Harvey and Skelton (1968)
[10]U.S. Environmental Protection Agency (1969).
[11]Dye also recovered in Rader Estavelle.
[12]T. Dean, oral commun., June 8, 1972.
[13]C. Tryon, written commun., June 28, 1972.
[14]Helwig (1965).
[15]Tryon (1972)
[16]C. Tryon, written commun., 1973.
[17]J. Vineyard, written commun., 1974.

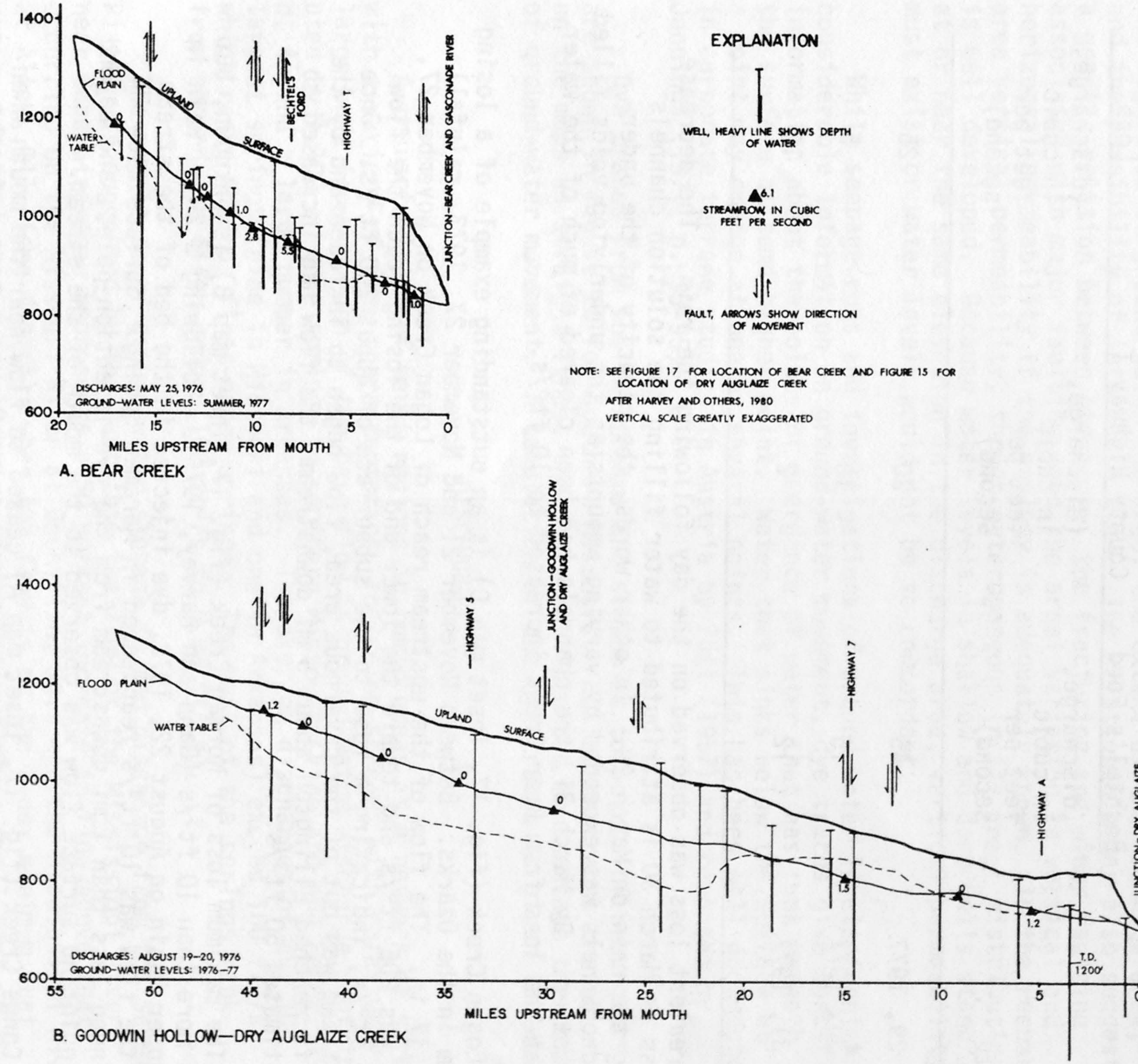


Figure 19.--Profiles of ground-water levels along typical losing streams in southern Missouri.

streambed along about 25 mi of Goodwin Hollow and this provides a large volume of storage to accommodate heavy rains. Bear Creek, a tributary of the Gasconade River, loses its flow to Cliff Spring about 1 mi east on the Gasconade River (fig. 17, inset map A). Three sets of streamflow estimates were made following 2.25 in. of rain on March 27 and 28, 1977.

Date	Bechtel's Ford (discharge, in cubic feet per second)	County Highway T (discharge, in cubic feet per second)	Loss (discharge, in cubic feet per second)
March 29, 1977	45	20	25
March 30, 1977	15	10	5
March 31, 1977	12	2	10

The greatest loss was observed on the day following the rain. The decrease in loss on March 30 is attributed to water filling the solution channels during the rain on March 29. In other words, the capacity of the underground channels was exceeded by varying amounts as the underlying voids filled and emptied. By March 31, the channels had been cleared of much of the water so that the loss from Bear Creek increased to 10 ft^3/s.

Logan Creek (fig. 17, inset map C) is an outstanding example of a losing stream in the Ozarks. Between November 21 and November 27, 1973, rainfall was 5.17 in. The flow of the upstream reach of Logan Creek on November 27, 1973, was 206 ft^3/s and toward the lower end of the losing reach the flow was 5 ft^3/s, indicating a loss to the subsurface of about 200 ft^3/s. Once the stream was out of the cavernous area, flow began to increase and by the time it reached Ellington about 5 mi downstream, the flow had increased to an estimated 50 ft^3/s.

The maximum loss of Norman Creek (fig. 17, inset map B) is unknown, but it is more than 10 ft^3/s (Gann and Harvey, 1975). Following a 2-in. rain in the upper basin on August 22, 1972, dye injected in the bed of the stream when the flow was 10 ft^3/s reappeared in Maramec Spring. Surface flow continued less than 1 mi downstream from the dye-injection point, and beyond this point no surface flow was observed to the mouth of the stream.

Conns Creek (fig. 17, inset map A) ceased to flow near the mouth when the upstream flow was 8.2 ft^3/s on April 1, 1976, after 1.3 in. of rain, but flowed through its entire length on March 31, 1977, when upstream flow was 10.5 ft^3/s after 2.5 in. of rain in the area.

In stream-valley profiles through the recharge area, water levels stand at different altitudes in wells of different depths. Note the recharge area in figure 19 where the water levels stand below stream level. In the discharge areas, wells of different depths have more uniform water levels that stand at or above stream level. A similar relationship is shown for Goodwin Hollow and Dry Auglaize Creek (fig. 19). Thus profiles along streams can be used to relate the presence or absence of streamflow, the magnitude of ground-water recharge, the extent of the recharge area, and the possibility of interbasin flow. The relationship may also suggest a genetic relation between structure, the fracturing and minor faulting associated with major faulting, and the areal variation in vertical and horizontal permeability if the geology is adequately known. In the recharge area vertical permeability, though heterogeneous in its areal distribution, is well developed. Because water levels in shallow and deep wells stand at or near the same elevation in the discharge area, vertical permeability must exist or water levels would not be so concordant.

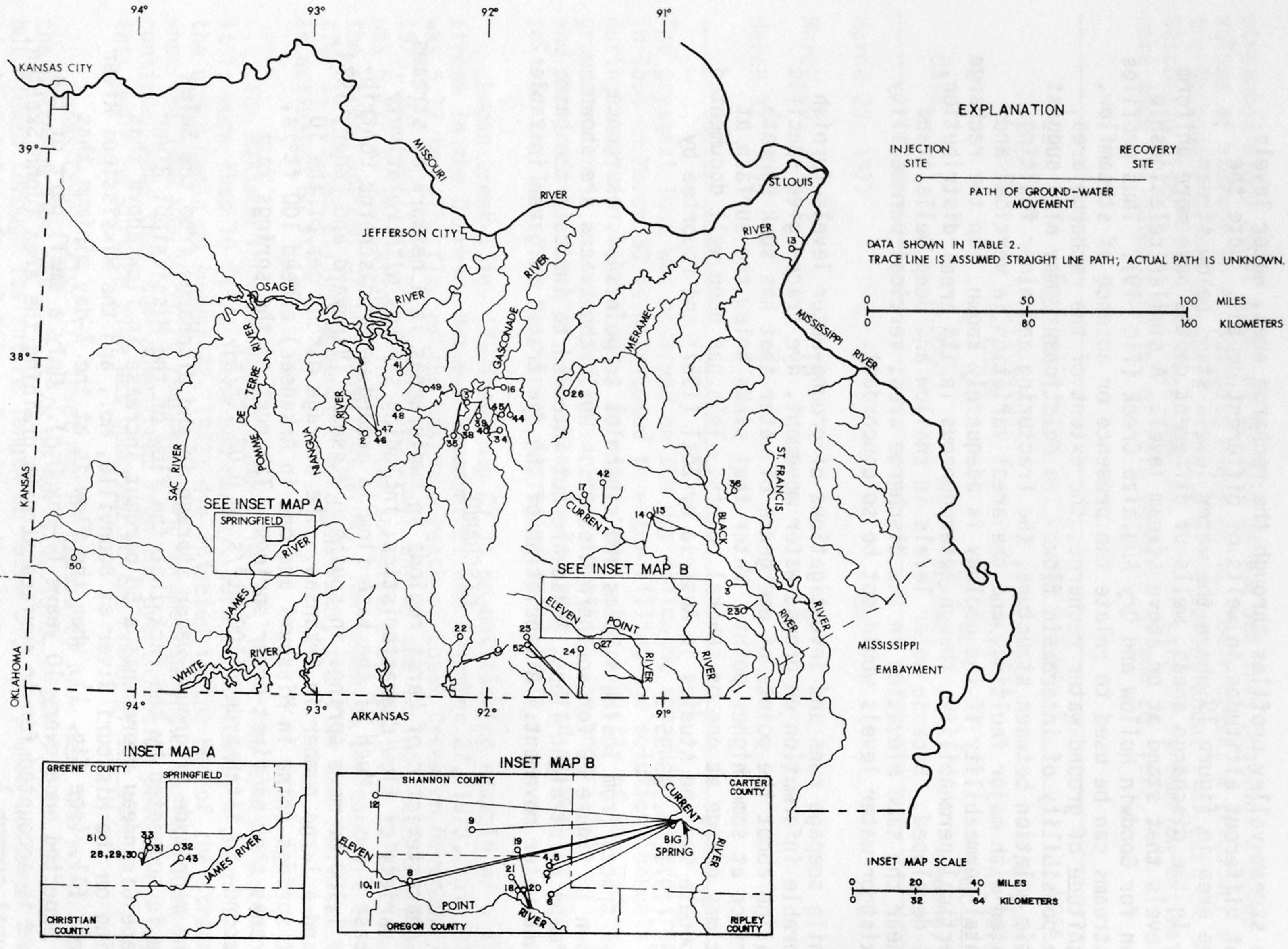
While seepage runs and investigations of ground-water levels furnish considerable information on ground-water movement, dye traces give specific information about the points of emergence of water that has sunk beneath the surface at some higher point. Water that sinks below the surface at a point may emerge at one or several points. This has been well documented in carbonate terrane studies in Austria by Zötl (1957) and reported by Jennings (1971, p. 93-95).

Dye traces from losing streams and sinkholes to points of resurgence are shown in figure 20 for southern Missouri. While the traces are shown on the maps as straight lines, these are not intended to indicate the path of ground-water movement. A tabulation of the dye traces is given in table 2.

DISCHARGE

A characteristic of karst regions in humid areas is a network of streams with a variety of flow characteristics, including streams with relatively large base flows. Much of the base flow is ground-water discharge contributed by 1,100 or more springs in southern Missouri (Vineyard and Feder, 1974, p. 4) and a large number in Arkansas. The average discharges of the 10 largest springs (nine in Missouri and one in Arkansas) exceed 100 ft^3/s, which ranks them as first-order springs. The rest of the springs rank from second- to fifth-order (100 ft^3/s to 0.02 ft^3/s).

The magnitude of ground-water storage in and discharge from the Salem Plateau is suggested by the fact that the flow of the Mississippi River near Cape Girardeau represents a 50 percent increase in flow above that occurring on the Missouri River at Boonville, Mo., and the Mississippi River at Alton, Ill. (see fig. 1), when the flow is at the 7-day minimum that can be expected once every 10 years (7-day Q_{10}). Only a small part of the increase is accounted for in surface streams draining the area (John Skelton, 1980, oral commun.)



NOTE: MODIFIED FROM GANN AND OTHERS, 1976

Figure 20.--Dye traces in southern Missouri.

GROUND-WATER MOVEMENT

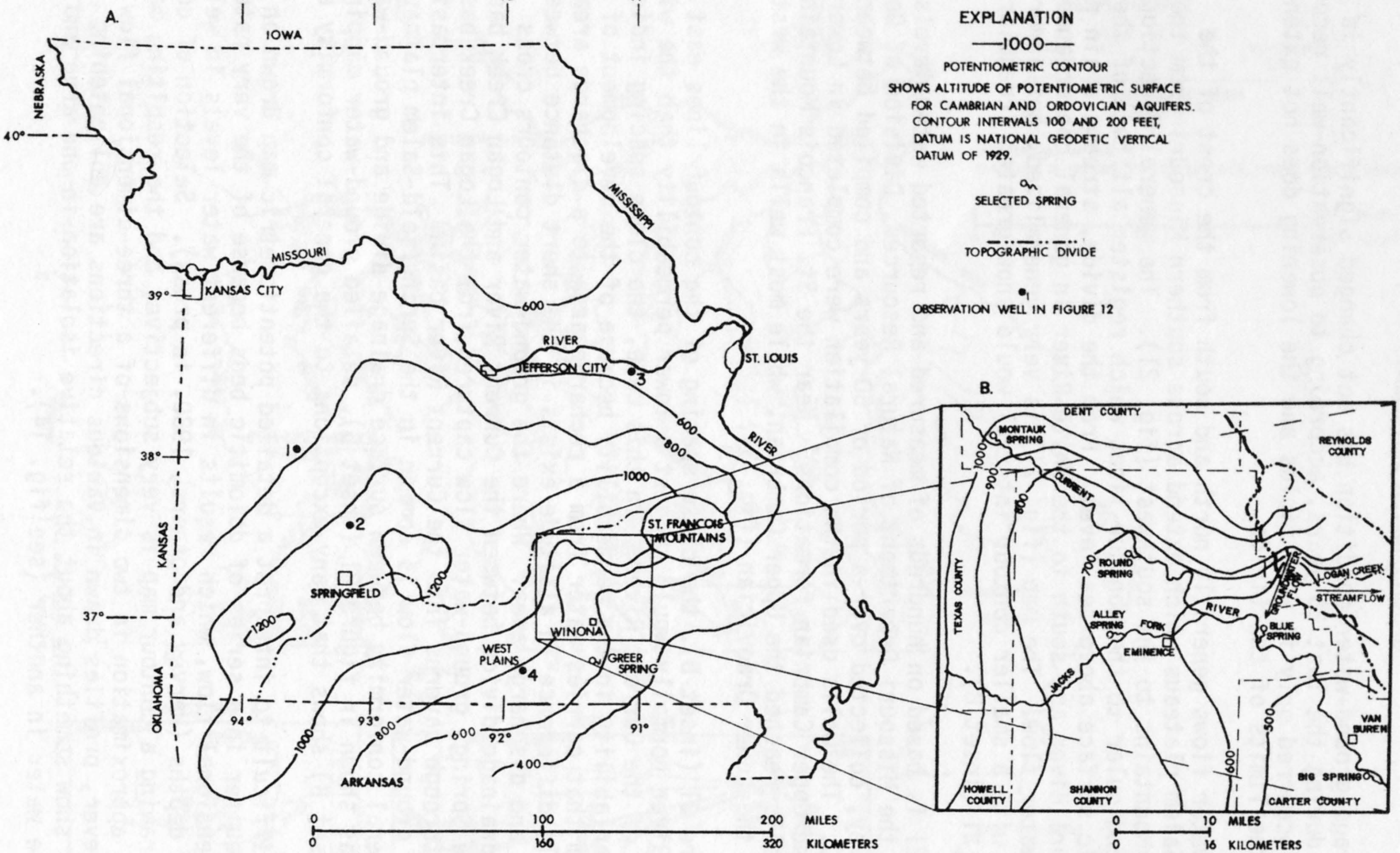
The average ground-water condition has not changed significantly in the project area during the last 25 years, according to observation-well records. Lowering has occurred only in well fields and the lowering does not extend much beyond the limits of the fields.

Ground water flows generally north and south from the crest of the Springfield-Salem plateaus which extend across southern Missouri from the St. Francois Mountains to the southwest (fig. 21). The general direction of flow is perpendicular to the contour lines which register altitude of the potentiometric surface above sea level. From the divide, streams drain north to the Missouri River and south to the White River in general concordance with ground-water flow. The map (fig. 21) is very generalized, but a more detailed map with a smaller contour interval would show greater irregularity as in figure 21 (inset B).

Figure 21 is based on hundreds of measured and reported water levels in the files of the Missouri Department of Natural Resources, Division of Geology and Land Survey, collected over a period of 50 years and compiled between 1965 and 1970. The wells used in the compilation were completed in Lower Ordovician and Upper Cambrian formations. Near the St. Francois Mountains all of the wells reached the Upper Cambrian, while most wells in the western part reached the Lower Ordovician (fig. 3).

In figure 21 (inset B), the close spacing of the contour lines east of the Current River normally would suggest a lower permeability than the wide spacing west of the Current River. In this case, the close spacing indicates an extreme variability in the permeability because of the development of a cavern system that carries water from a recharge area to a discharge area and a considerable difference in altitude exists in the short distance between the recharge and discharge area. Where the ground-water contours cross the surface drainage divide between the Current River and Logan Creek basins north of Blue Spring, ground-water flow captured from the Logan Creek basin is diverted through caverns into the Current River basin. This interbasin diversion of ground-water flow is common in the Springfield-Salem plateaus. Though a general conformity between surface drainage divide and ground-water flow exists as shown in figure 21 (inset B), detailed ground-water mapping (fig. 21, inset B) shows that many exceptions to the general conformity exist.

It is difficult to interpret a detailed potentiometric map drawn on a particular aquifer in a series of dolomitic beds because of the very nature of three-dimensional flow, which results in different water levels in wells of different depths (Harvey and others, 1980, in press). Selection of control points for drawing a contour map is very subjective, and the resulting map is only a crude approximation in two dimensions of a three-dimensional flow system. However, profiles drawn in various directions are enlightening because they show something about the relative isolation in one area and mixing of the water in another (see fig. 14).



NOTE: MODIFIED FROM GANN AND OTHERS, 1976.

Figure 21.--Potentiometric surface in the Cambrian and Ordovician aquifers in southern Missouri and northern Arkansas.

Feder (1970, p C214-C217) showed the relationship between ground-water flow in the shallow and deep parts of the section in his investigation of the carbonate saturation of springflow when he analyzed the relationship between carbonate saturation and springflow recession. He differentiated between the contribution to springflow from rainfall in the early part of the recession and the increasing contribution from the regional aquifer system in the late part of the recession as indicated by the increase in carbonate saturation of the springwater.

Tritium determinations for water collected from three wells and two springs in September 1968, further support the evidence in the hydrograph (fig. 11, well 4) and carbonate-saturation data. Feder (1970, p. 57-63) reported the following concentrations of tritium:

Sample location[1]	Well depth (feet)	Date of sampling	Tritium concentration (TU)[2]
Alley Spring---Park well.	434	Sept. 5, 1968	3.4 ± 0.3
Winona well----	1,110	Sept. 5, 1968	1.2 ± 0.2
West Plains----Well.	1,535	Sept. 5, 1968	67.3 ± 3.6
Alley Spring---	-----	Sept. 5, 1968	28.2 ± 1.5
Greer Spring---	-----	Sept. 5, 1968	50.5 ± 2.8

[1]See figure 21 for locations.
[2]TU=trituum units.

The high value for the West Plains well is commensurate with those for Alley and Greer Springs indicating the samples contained some water that was recharged after 1954. These values contrast with lower values from the Alley Spring Park and Winona wells and indicate that less of the water was recharged after 1954.

THE USE AND AVAILABILITY OF WATER

Ground water is used by most of the rural residents, towns, public water-supply districts, subdivisions, trailer courts, and many of the industries in the project area. Table 3 shows the quantities in southern Missouri and northern Arkansas by type of public use and geologic source.

Table 3.--Source and use of ground water for public water supplies in southern Missouri and northern Arkansas

[Results reported in million gallons per day]

Stratigraphic unit	Municipal	Public water-supply districts	Subdivisions[1]	Trailer courts[1]	Total
Lamotte----------	1.383	-----	-----	-----	1,383
Bonneterre---------	2.128	0.033	0.010	0.060	2.231
Potosi-----------	26.776	2.536	1.140	.060	30.512
Eminence----------	6.100	1.642	.720	.060	8.522
Gunter------------	8.056	.815	.360	.060	9.291
Gasconade---------	5.546	.585	.260	.070	6.461
Roubidoux---------	4.020	.77	.360	.070	5.227
Jefferson City-----	.218	.079	.050	.060	.407
St. Peter---------	1.746	.217	.100	.060	2.123
Mississippian------	.046	-----	-----	-----	.046
Pennsylvanian------	.040	-----	-----	-----	.040
Total---------	56.059	6.684	3.000	0.500	66.243

[1]Estimated

By far the greatest quantities are used by municipalities, and wells completed in the Potosi Dolomite also obtain water from the overlying geologic formations that are not cased out in the construction of the wells. Figure 3 shows the distribution of municipal ground-water supplies by geologic unit.

Although most large-capacity wells draw on the Potosi Dolomite and some of the overlying beds, it is possible to obtain a large supply of water from younger rocks. For example, in the NE¼ sec. 22, T. 44 N., R. 17 W., 30 mi west of Jefferson City in Moniteau County, a yield in excess of 1,000 gal/min was encountered on driving a drift through fractured Jefferson City Dolomite in a lead-zinc mine when the drift encountered the intersection of solution-enlarged north- and west-oriented joints (Van Horn, 1905, p. 90). The probability of drilling a hole to intersect such a supply of water is small, but the occasional occurrence of a large-capacity shallow well can certainly be explained by such an occurrence. It demonstrates the importance of rock fractures and solution in the storage and movement of water.

Figure 3 and table 3 show that more than 50 percent of the water for municipal water supplies obtained from wells is from Cambrian units. Near the St. Francois Mountains, the Bonneterre Dolomite is the source of water. In the west and southwest, the Cambrian units are thin, and the permeability is greater in the overlying Gasconade Dolomite. In the western and southwestern areas, the Roubidoux Formation also becomes an important aquifer as the formations dip to greater depths.

Few towns obtain water from streams or impoundments. Springfield, Mo., which obtains its water supply from impoundments and a spring, has incorporated deep wells in its system. However, Neosho and Lamar, Mo., have abandoned their wells; Neosho obtains water from Shoal Creek, and Lamar obtains water from an impoundment. A few towns have converted from the Cambrian and Ordovician aquifer to another source. Columbia, Mo., for example, has abandoned deep wells in favor of a supply from the Missouri River alluvium.

The following table lists the numbers of residents in the study area using ground and surface water. These figures are based on censuses of water use, populations served, and the 1970 population census (Arkansas, 1979; Missouri, 1977).

	Population, in thousands			
	Ground water			
	Municipal[1]	Private[2]	Surface water	Total
Missouri---	630	605	1,275[3]	2,510
Arkansas---	23	132	135	290
Total	653	737	1,410	2,800

[1]Includes a small population served by public water-supply districts and subdivisions whose supplies are furnished by a nearby town.

[2]Includes remainder of county population consisting of self-supplied rural, public water-supply districts, subdivisons, and mobile-home courts. Industries and institutions are not included.

[3]Includes St. Louis County, which was estimated to be about 1 million during 1977.

The availability of ground water is suggested by the magnitude of the ground-water discharge in the major streams discharging out of the Springfield-Salem plateaus. Flows of the major streams at the 80 percent point on the flow-duration curves are shown in table 4. These data represent base-flow contributions from ground-water discharge to these streams.

The amount of ground water pumped from Lower Ordovician and Cambrian aquifers in the Springfield-Salem plateaus and contiguous areas is approximately 200 ft^3/s. This is about 5 percent of the total discharge at the 80 percent point on the streamflow-duration curves (table 4). It is apparent that only a small part of the water available is used for public water supplies and explains the absence of extended declines in ground-water levels. Based on population projections (James Vandike, Missouri Division of Geology and Land Survey, 1979, written commun.) for the years 2000 and 2030, the percentages of ground-water discharge that will be used are 5.3 and 8.9, respectively.

Because of the areal differences in infiltration capacities of the terrane, the duration value for ground-water discharge also must differ. Note in table 4 the variation from 0.09 to 0.61 $(ft^3/s)/mi^2$ at the 80 percent duration value. Undoubtedly, the duration value for ground-water discharge in some areas exceeds 80 percent where infiltration capacities are low and may be much lower than 80 percent in other areas where infiltration capacities are high. For example, in the West Plains area where sinkhole topography is widespread, infiltration capacites are high. These also are areas of the greatest danger of ground-water contamination. The flow characteristics of the streams are an index of the infiltration capacity of the terrane drained by those streams just as the incidence of losing streams are an index of the infiltration capacity of the region.

WATER QUALITY

Ground water in the Ozarks is hard and its principal constituents are calcium, magnesium and bicarbonate in water from dolomitic rocks, and calcium and bicarbonate in water from limestone rocks.

Typical analyses of well water are listed in table 5. Chemical analyses of all public water supplies are given in the Census of Missouri Public Water Supplies, 1977 (Division of Environmental Quality, 1977). Similar data are available for Arkansas (Bureau of Public Health Engineering, 1977).

The total mineralization of water increases from 200 to 300 mg/L (milligrams per liter) along the crest of the Springfield-Salem plateaus to 400 to 500 mg/L on the flanks (fig. 22). The low mineralization of water in the southwestern corner of Missouri is tentatively explained by Feder and others (1969, p. 16) as occurring in an area where the Northview Formation and the Chattanooga Shale lie between the shallow and deep aquifers and the water "is influenced in some way by the membrane properties of these shales."

The calcium magnesium ratio of water from dolomitic rocks normally is close to 1.0. For limestone the ratio is more than 1.0 and ranges as high as 10.0 or more. On the Springfield Plateau where the Mississippian limestone blankets the area, the calcium magnesium ratio for water from dolomitic rocks increases to 2.0 or 3.0 even though the wells are cased and cemented through the limestone, and the Northview Formation separates the Mississippian limestone from the Cambrian and Ordovician dolomites and sandstones. Slow leakage of water from the limestone to the dolomite over a long period of time has resulted in an increase in the ratio.

Deep circulation of water originating at the surface occurs where cavernous connections extend to great depth. At West Plains, Howell County, where an extensive sinkhole plain surrounds the city, municipal wells must be cased to depths exceeding those at most other localities in the Springfield-Salem plateaus. Wells at West Plains are 1,300 to 1,500 ft deep and have 950 to 1,000 ft of casing that is pressure grouted in place.

Table 4.--Duration of flow of major streams discharging out of southern Missouri

[Data from Skelton, 1976, p. 62-66. (ft^3/s)= cubic feet per second; (ft^3/s)/mi^2=cubic feet per second per square mile]

Stream	80 percent (ft^3/s)	Yield (ft^3/s)/mi^2
Black River-------------------------	130	0.27
Bryant Creek------------------------	155	.27
Castor River------------------------	74	.17
Current River-----------------------	1,250	.61
Eleven Point River------------------	290	.37
Gasconade River---------------------	650	.20
Meramec River-----------------------	670	.18
North Fork River--------------------	300	.53
Osage River[1]----------------------	565	.09
St. Francis River-------------------	85	.09
Total-------------------------------	4,169	

[1]Estimated for the reach between Osceola and St. Thomas, Mo.

Table 5.--Quality of water from wells tapping Cambrian and Ordovician aquifers in southern Missouri and northern Arkansas

[Results reported in milligrams per liter, except as indicated. Analyses by Department of Natural Resources, Division of Geology and Land Survey and Division of Environmental Quality: Arkansas analyses by Bureau of Public Health Engineering, Arkansas Department of Health]

Owner and owner's number[1]	State and County	Section	Township (N)	Range	Depth (ft)	System[2]	Date of collection	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (N)	Dissolved solids (residue at 180°C)	Hardness as $CaCO_3$: Calcium Magnesium	Hardness as $CaCO_3$: Noncarbonate	pH (units)
	MISSOURI																						
Mexico No. 5	Audrain	27	51	9W	1,500	Є	1-8-59	1.2	1.0	----	49	49	76[3]	---	450	66	24	1.2	0.00	540	324	0	7.0
Monett No. 6	Barry	32	26	27W	1,550	Є	9-1-61	8.0	.05	----	37	21	2.8[3]	---	206	12	4.5	---	----	208	180	14	7.6
Marble Hill	Bollinger	5	30	10W	600	Ø	10-11-68	12	.06	0.00	49	34	1.5	0.5	333	1.6	2.2	.1	.36	293	263	0	7.3
Camdenton	Camden	25	38	17W	794	Є	3-14-66	8.0	.01	----	58	33	3.2	1.3	333	4.5	6.4	.1	.63	308	273	5	7.3
Cole County PWSD 1	Cole	18	44	12W	1,035	Є	-------	8.0	.30	.00	57	36	6.2	3.2	343	20	4.1	.2	.00	353	280	8	7.4
Salem	Dent	18	34	5W	1,500	Є	5-11-65	2.0	1.4	.00	46	27	3.5[3]	---	266	1.6	2.7	0	.00	228	218	5	7.5
West Plains	Howell	29	24	8W	1,545	Є	- -77	---	.04	----	52	37	6.5	.6	267	17	7.7	.1	6.5	193	285	--	8.2
Jefferson County PWSD 8, No. 1	Jefferson	25	42	3E	1,015	Є	4-28-71	8.0	.17	.00	61	31	3.2	.4	367	15	2.6	.1	.04	359	280	3	7.7
Sedalia	Pettis	22	45	21W	1,530	Є	3-15-60	10	.30	----	49	26	9.0[3]	---	269	17	8.6	.1	----	279	221	7	7.6
Nevada Hospital 3	Vernon	33	36	31W	1,100	Ø	9-20-55	8.0	.06	----	85	39	300[3]	---	264	72	520	---	----	1,410	217	155	7.3
	ARKANSAS																						
Gassville	Baxter	28	19	14W	1,625	Ø	4- -73	---	<.05	<.01	56	37	2[3]	---	287	9.0	5.0	.2	.12	298	294	--	7.4
Decatur	Benton	11	19	33W	1,700	Ø	3- -76	---	<.05	<.01	27	12	5[3]	---	115	6.0	17	<.2	.85	138	115	--	7.7
Omaha	Boone	26	21	21W	1,315	Ø	2- -75	---	.07	<.01	45	24	10[3]	---	191	40	2.0	.2	.08	346	213	--	8.1
Leslie	Searcy	27	14	15W	1,210	Ø	8- -75	---	2.2	.04	87	15	28[3]	---	220	60	10	.4	.12	359	278	--	7.9
Ash Flat	Sharp	10	18	6W	1,525	Ø	8- -75	---	.06	----	52	30	11[3]	---	255	3.0	1.5	<.2	.02	282	274	--	8.1

[1]Locations on figure 22.

[2]System: Ø, Ordovician; Є, Cambrian.

[3]Sodium plus potassium.

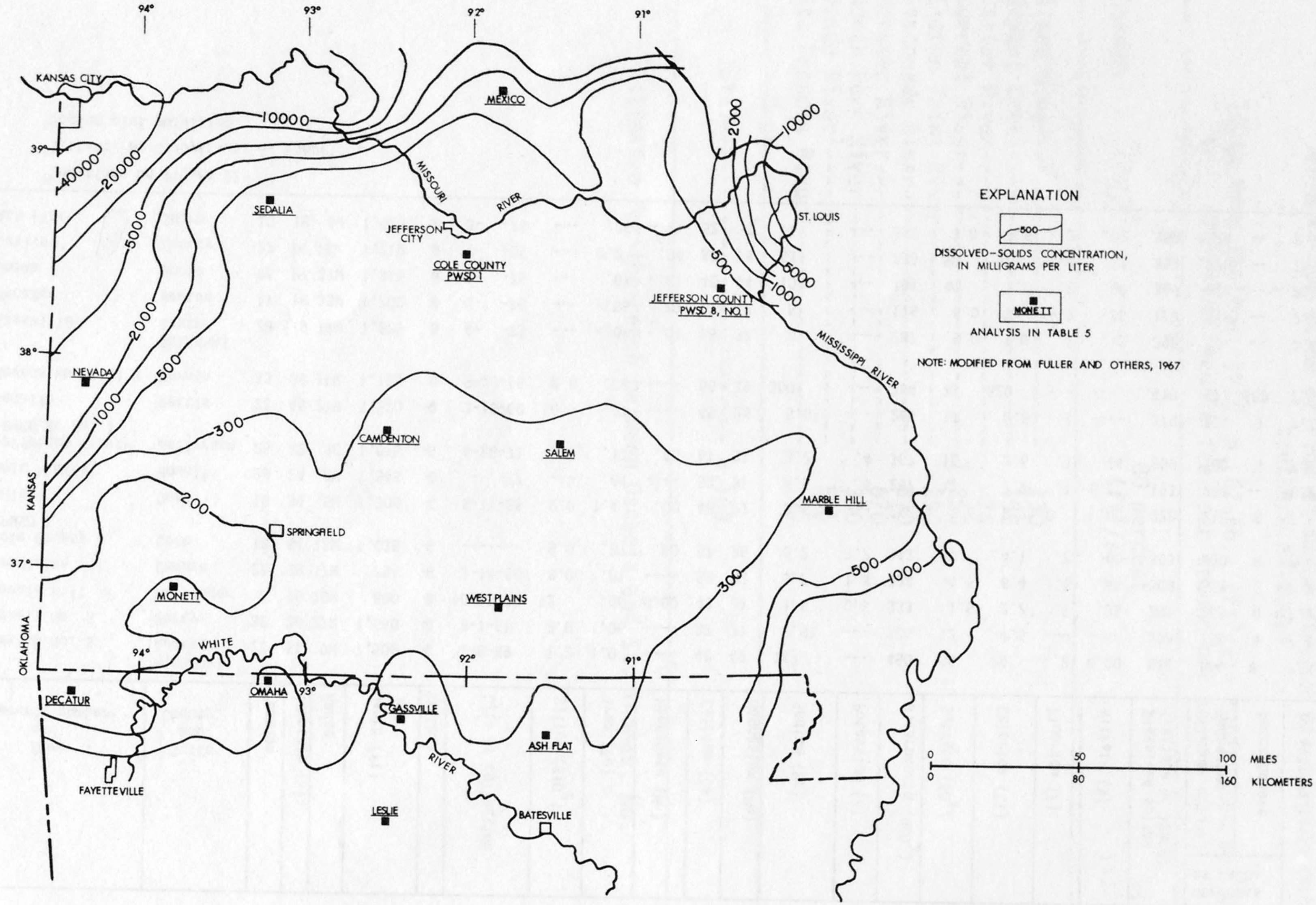


Figure 22.--Dissolved-solids concentration in ground water in Paleozoic aquifers in southern Missouri and northern Arkansas.

Despite these depths, the water often becomes turbid after rainstorms and in some wells may continue turbid for several months through a rainy season.

Less than 25 percent of the municipal and ground-water supplies in the project area are chlorinated. This is probably due to the fact that State agencies regulate municipal well construction, a necessity considering the nature of the land surface, the predominance of dolomitic rocks and solution development in the region. On the other hand, shallow domestic wells are more subject to contamination when minimum lengths of casing are used. The frequency of occurrence of bacterial contamination should vary according to the density of rural housing development, land use, and the infiltration characteristics of the soil, residuum, and bedrock.

The distribution of public water-supply districts in southern Missouri is shown in figure 23. Water districts may be a substitute for a proliferation of shallow private wells in an area where the contamination potential is large. Many Missouri districts have been built in urban areas or in areas where good water is hard to find at shallow depth. The additional financial capability available through a water district enables the drilling of deeper, safer wells with proper casing depth. Undoubtedly, they will be more common in the future.

TYPES OF PROBLEMS OR SOURCES OF POLLUTION

While the Springfield-Salem plateaus is a desirable region of the country in which to live or visit because of the temperate climate, scenic features and recreational facilities, it is a delicate environment subject to misuse. Some of the problems are listed below, followed by examples and conditions leading to the development of problems.

1. Sewage is discharged into losing streambeds. Figure 24 shows the location of municipal sewage-treatment plants in southern Missouri. Most discharges are into perennial streams; a few are not.

   Examples:

   a. Lebanon's treated sewage is discharged into Dry Auglaize Creek which goes underground and eventually reaches Sweet Blue and Hahatonka Springs on the Niangua River (Harvey and others, 1980, in press).

   b. Salem's treated sewage is discharged into Dry Fork, goes underground and probably resurges in Maramec Spring, as does the flow of its tributary, Norman Creek (Gann and Harvey, 1975).

   c. West Plains' treated sewage is discharged into Howell Creek and may resurface downstream in Warm Fork Spring River.

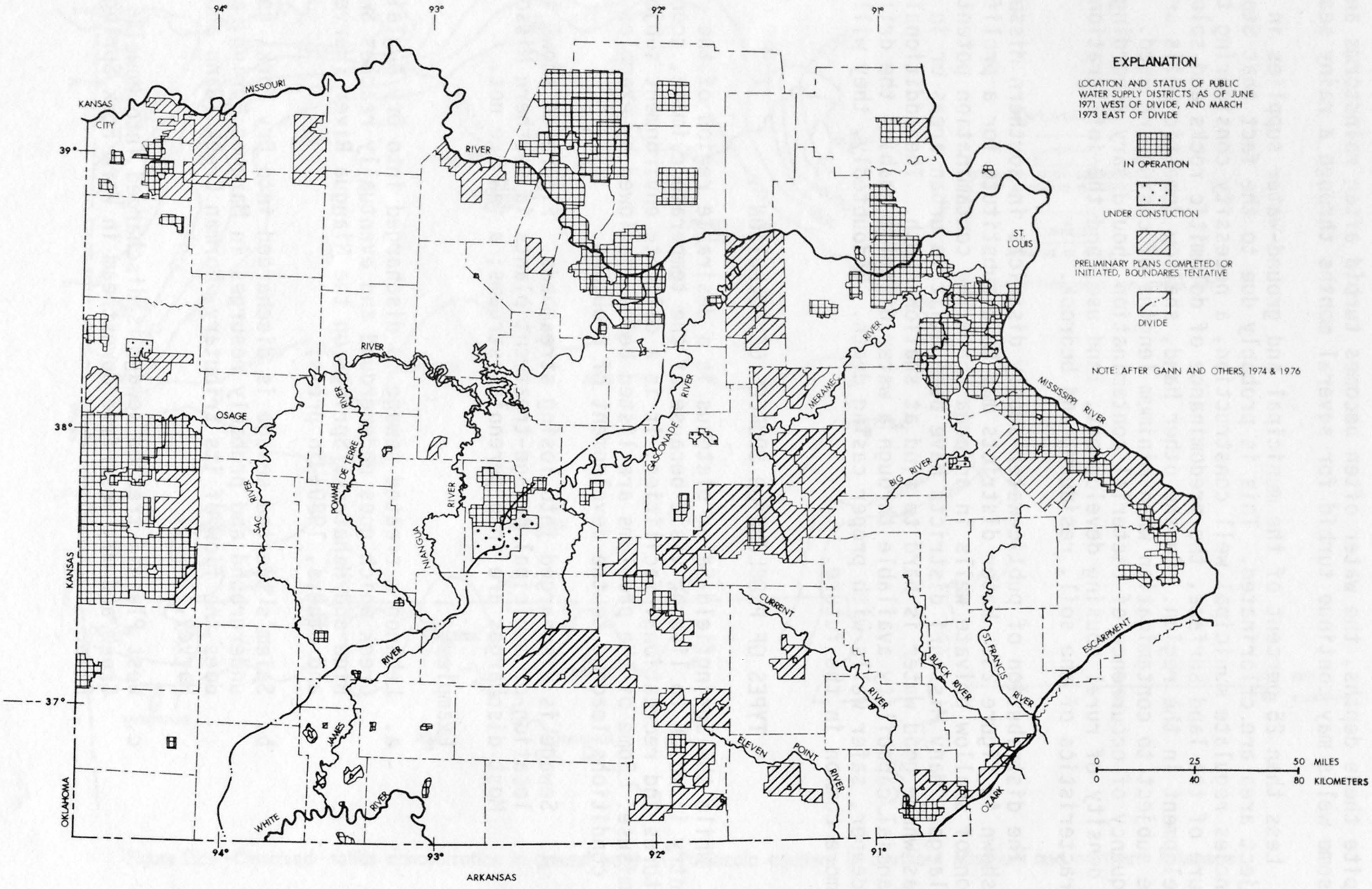


Figure 23.--Distribution of public water-supply districts in southern Missouri.

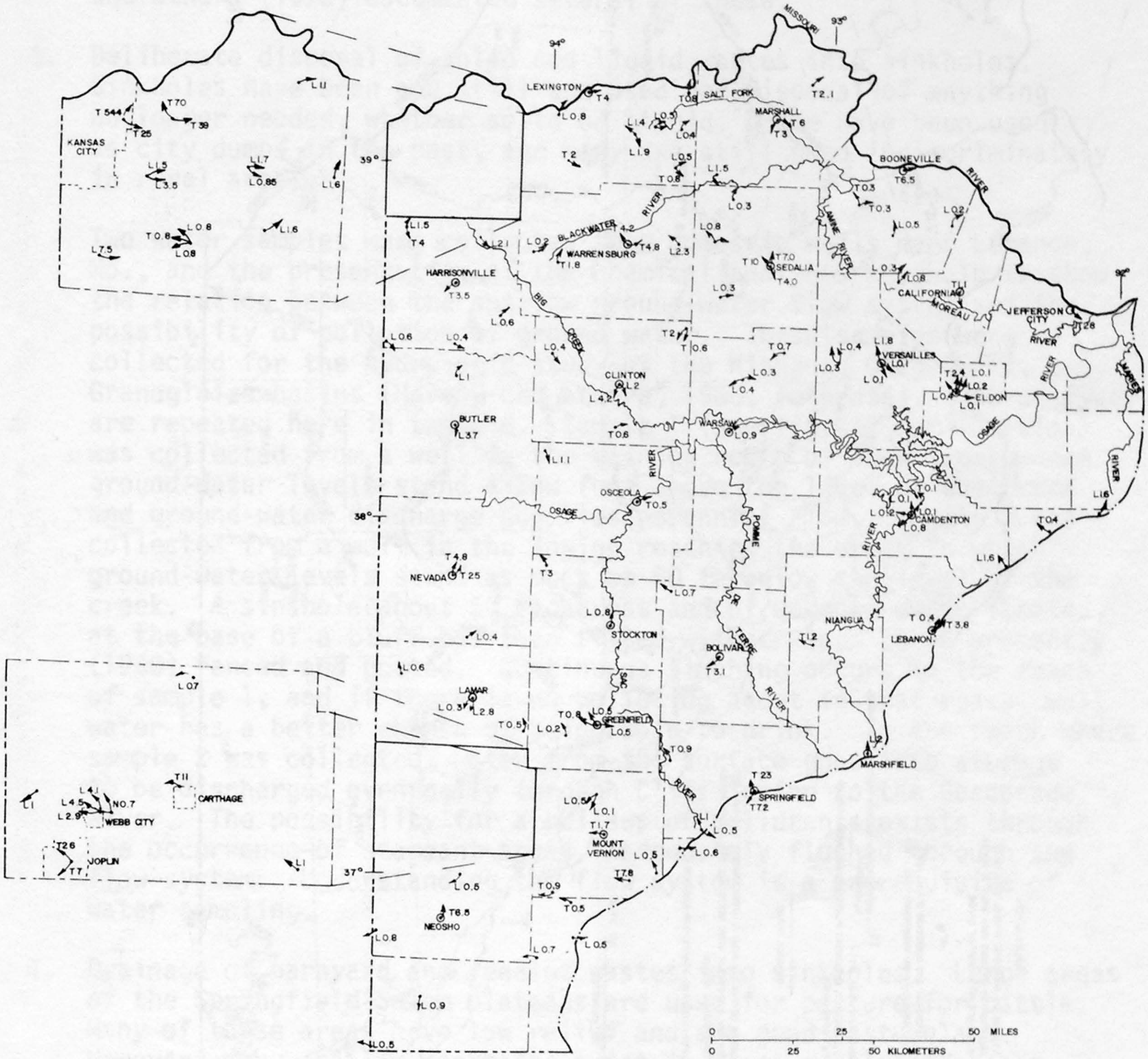


Figure 24.--Sewage-treatment facilities in southern Missouri.

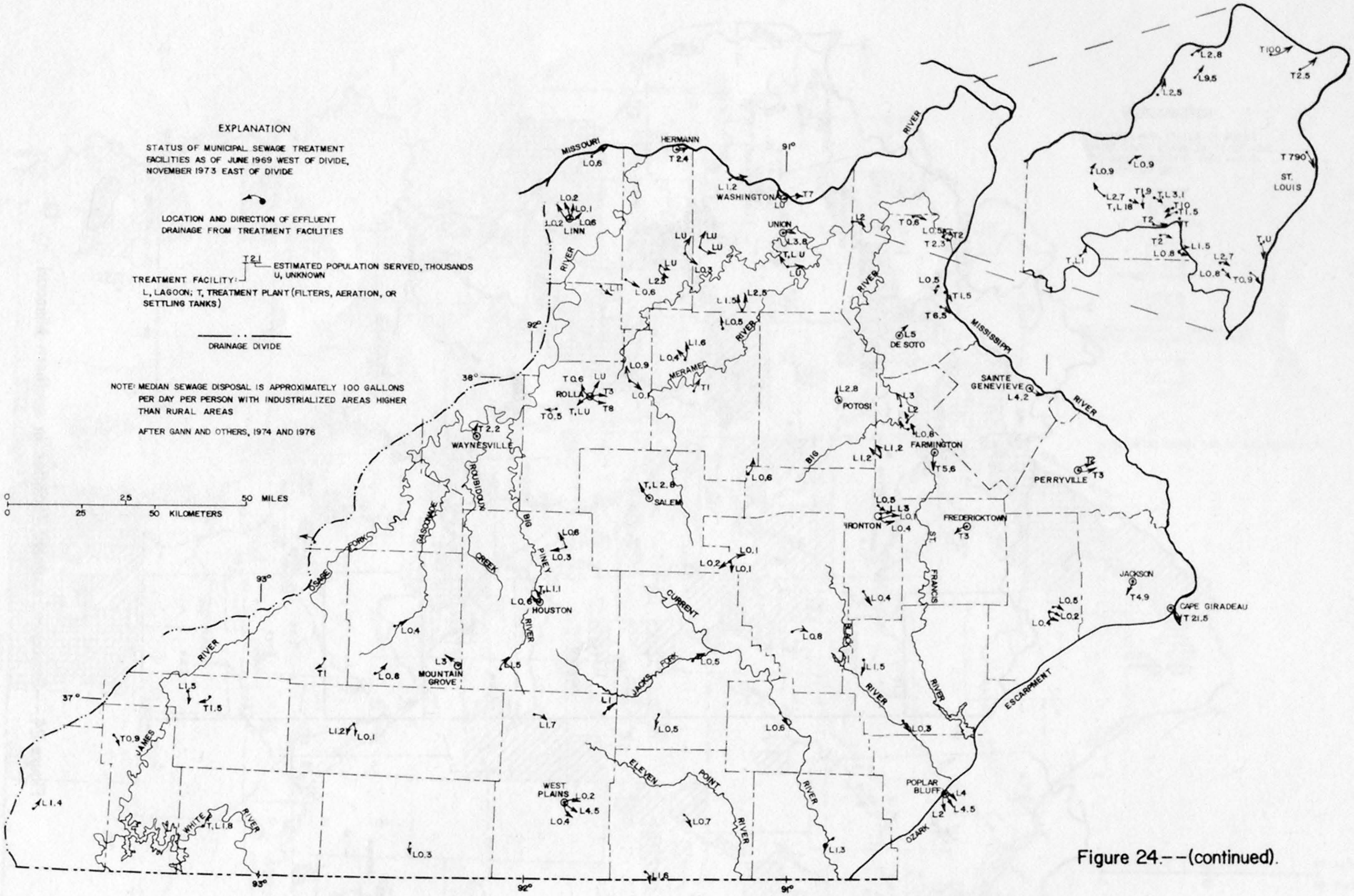


Figure 24.--(continued).

2. Accidental spills into sinkholes or losing stream valleys. Highway, railroad, and pipline networks alternately cross recharge and discharge areas. Figure 25 shows the network of transportation routes. Where they cross discharge areas, spills can be monitored in the receiving stream, but where they cross recharge areas the fate of the pollutant may be unknown. Railroad lines and major highways often follow topographic divides that are recharge areas. Better definition of the recharge areas is needed. See figure 13. Collapse of waste lagoons is included in accidental spills; Aley and others (1972) documented several of these.

3. Deliberate disposal of solid and liquid wastes into sinkholes. Sinkholes have been and still are used for disposal of anything no longer needed, whether solid or liquid. Some have been used as city dumps in the past, and many are still used indiscriminately in rural areas.

   Two water samples were collected from domestic wells near Lebanon, Mo., and the presentation of the chemical analyses may help to show the relation between the shallow ground-water flow system and the possibility of pollution of ground water. These samples were collected for the hydrologic study of the Niangua, Osage Fork, and Grandglaize basins (Harvey and others, 1980, in press). The analyses are repeated here in table 6. Sample 1 (see fig. 17 for location) was collected from a well in the gaining reach of Bear Creek where ground-water levels stand a few feet above the level of the creek and ground-water discharge supplies perennial flow. Sample 2 was collected from a well in the losing reach of the creek in which ground-water levels stand as much as 50 ft below the level of the creek. A sinkhole about 50 ft across and of unknown depth located at the base of a bluff has been filled with trash. It is presently (1980) fenced and posted. Continuous flushing occurs in the reach of sample 1, and if there is no polluting agent in that reach, well water has a better chance of being safe to drink. In the reach where sample 2 was collected, water from the surface goes into storage to be discharged eventually through Cliff Spring to the Gasconade River. The possibility for a buildup of pollutants exists through the occurrence of stagnant areas inadequately flushed through the flow system. Understanding the flow system is a prerequisite of water sampling.

4. Drainage of barnyard and feedlot wastes into sinkholes. Large areas of the Springfield-Salem plateaus are used for pasture for cattle. Many of these areas have low relief and are good pastureland. However, many shallow sinkholes exist in these rural landscapes, and they are both scattered and concentrated in their distribution.

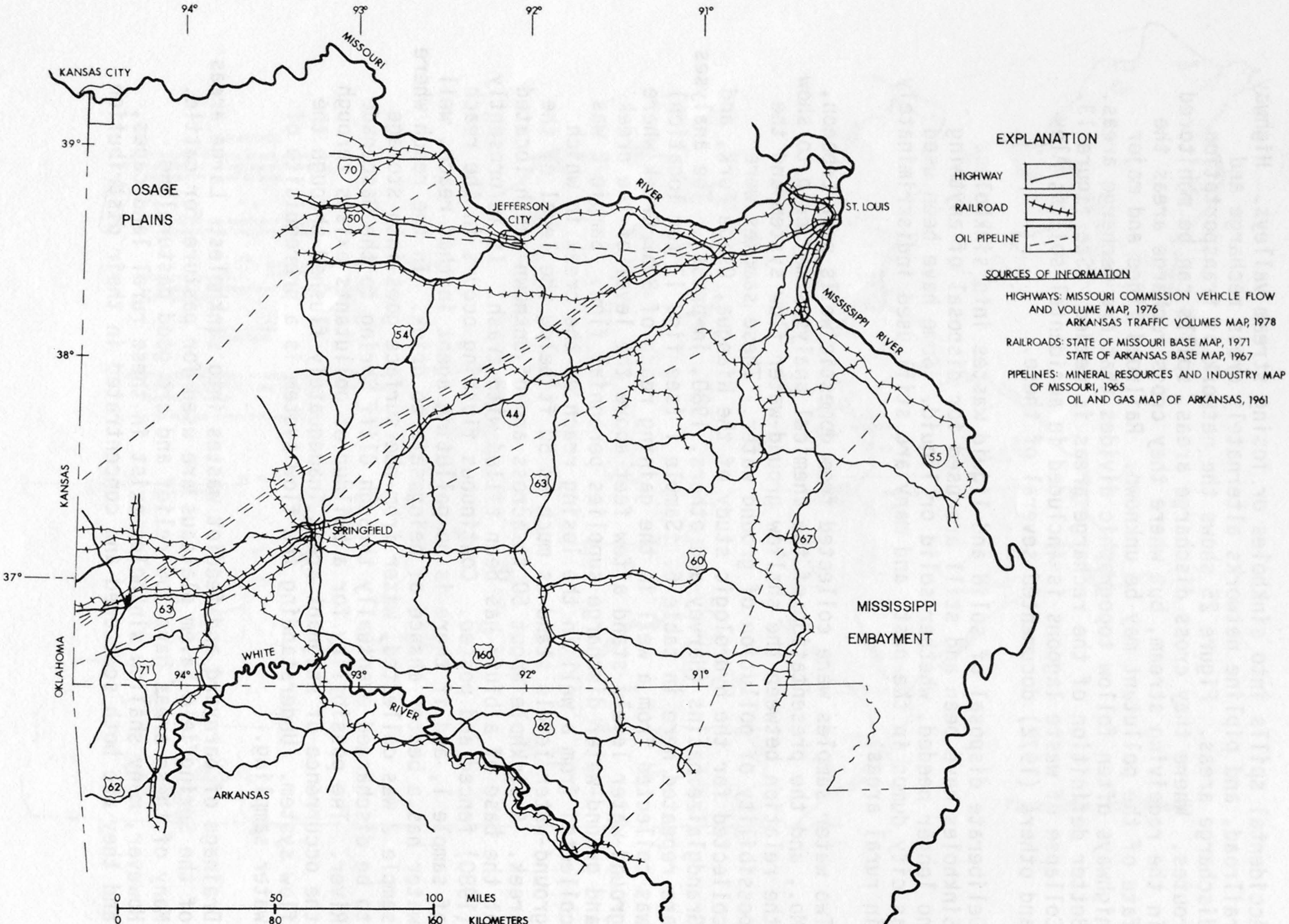


Figure 25.--Transportation and pipeline map of southern Missouri and northern Arkansas.

Table 6.--Water-quality analyses from two domestic wells near Lebanon, Missouri

[(ft)=feet; (°C)=degrees Celsius; (μmho/cm at 25°C)=micromho per centimeter at 25 degrees Celsius; mg/L=milligrams per liter]

Parameters	Sample 1	Sample 2
Location (see fig. 17)	35N-15W-24	35N-14W-5
Depth (ft)	140	200
Producing formation	Gasconade Dolomite	Gasconade Dolomite
Date sampled	8-23-77	8-23-77
Temperature (°C)	15	18
Specific conductance (μmho/cm at 25°C).	590	860
pH (standard units)	7.2	7.1
Calcium (Ca), in mg/L	64	85
Magnesium (Mg), in mg/L	38	49
Sodium (Na), in mg/L	3.0	2.6
Potassium (K), in mg/L	.4	3.0
Bicarbonate (HCO_3), in mg/L.	350	380
Carbonate, in mg/L	0	0
Sulfate (SO_4), in mg/L	9.9	22
Chloride (Cl), in mg/L	9.2	36
Fluoride (F), in mg/L	.1	.1
Total nitrate as N, in mg/L.	.68	17
Total nitrite as N, in mg/L.	.02	.01

5. Accelerated erosion and sediment transport. In drainage basins that have excessive slopes, accelerated erosion is caused by timber cutting and land clearing for raising livestock, extending suburban sprawl, highway building, and unreclaimed land of past mining activity.

   After an exhaustive study of Ozark vegetation in Missouri, Steyermark (1944, p. 408-421) discussed the effects of the misuse of the land on its ecology. A combination of overgrazing, repeated clearing and repetitive burning, especially in the summer, will reduce the soil cover and expose the underlying bedrock. Clearing wooded areas that have excessive slopes raises the specter of long-term gradual denudation, removal of soil, and exposure of bedrock. Jakucs (1977, p. 202-205) has documented the effects of 600 years or more of land clearing and denudation in the dolomite terrane of Yugoslavia. The recorded history of the Ozarks goes back only 200 years.

   Land clearing leading to increased grazing has resulted in the renewal of small springs in the Ozarks because of increased recharge due to lower evapotranspiration loss. As an index of historical change in the regimen of infiltration, Jakucs described changes in the lithology and rate of growth of dripstone formations in caverns. The beneficial effect measured in one way may obscure the detrimental effect of the event in another way.

SUGGESTIONS FOR FUTURE WORK

There are many kinds of work that could be done to further the understanding of the Springfield and Salem plateaus flow system and furnish useful interpretive data. Examples are as follows:

1. A network of observation wells for semiannual water-level measurements to rate infiltration characteristics across the region. Some observation wells have a seasonal amplitude of as much as 100 ft and others as little as 1 to 5 ft. An expanded array of observations would contribute to the small network of available observation wells. Used in conjunction with the results of dye tracing, seepage runs, potentiometric mapping and other studies, ground-water-level observations would contribute to identifying with greater precision ground-water-flow paths.

2. Monitor the chemical and bacteriological quality of the water, taking into account the density of urban, suburban, and rural development, recharge characteristics of the surrounding area, and local recharge characteristics. Make statistical analysis of existing bacterial and nitrate data for domestic wells.

3. A study of existing well logs, especially those based on good insoluble residue studies. It should be an intensive examination of all the events related to the construction of the well:

   a. Occurrence of faults intersecting the drill hole.

   b. Lithologic characteristics of the rock penetrated, including a study of thin sections and cores where available. Recrystalization and closing of voids.

   c. Occurrence of voids. Correlation with erosion periods.

   d. Change in water level with depth.

   e. Well production, including a correlation with lithologic characteristics and occurrence of voids.

   Stringfield (1966, p. 80) presents a summary of occurrence of cavities in wells drilled in the Orlando area (Orange County), Fla. Many cavities more than 1 ft in height occur to depths of 500 ft, but between depths of 500 and 1,100 ft none were recorded. Between 1,100 and 1,400 ft some cavities were recorded, but fewer than at shallow depth. While Stringfield described conditions in the Tertiary section in Florida, zones may be identified by detailed work in the Ordovician and Cambrian rocks of the project area.

4. A better detailing of overburden thickness. Study the relation of mineralogic assemblages of the several formations to the weathering characteristics of the rock and, in turn, the accumulation of residuum.

5. Relate stream characteristics such as flow and sediment transport to land use such as cutover and uncleared land. Include land information and analysis methods or studies.

6. Study of cave formations, both existing and forming; the record in cave formations of historical changes in the hydrologic regimen; and continuing changes and prediction of changes (Jakucs, 1977, p. 203-207).

7. Complete comprehensive basin studies leading to an overall evaluation of the variations in the physical components and processes affecting the hydrology of the region.

8. Better definition of ground-water-flow paths, both regionally and locally.

9. Study of active mines and literature about mineralization in the Springfield-Salem plateaus. The aquifer can be examined through study of well logs and production records of wells and well fields. Caves allow the examination of the effects of solution and carbonate rocks in an environment that formerly was in the saturated zone and further understanding of the development of the aquifer.

   Mines permit the examination of mineral deposits generally still in the zone of saturation. This results in a three-dimensional view of a mineral deposit that had been an aquifer before and during the mineralizing epoch. Some appreciation of structural and lithologic relationships may be realized that are helpful in understanding the development of permeability in an aquifer that is used as a source of water supply.

10. Map the density and distribution of perennial streams, whatever order they may be, and relate to surface geology and position of the potentiometric surface. As the distribution of sinkholes has some relation to surface geology and position of the water table, so must the distribution of perennial streams be related to these physical features.

CONCLUSIONS

The Cambrian and Ordovician aquifer in southern Missouri and northern Arkansas is an extensive reservoir of freshwater, readily recharged by the precipitation falling on its surface, but susceptible to pollution from wastes originating on the same surface. At present (1980) it is the source of water for most of the municipalities, even though a large part of the water used in the region is pumped from streams at a few population centers such as St. Louis and Springfield, Mo., and the larger towns of northern Arkansas.

The aquifer embodies the entire section of 1,000 to 1,500 ft of Cambrian and Ordovician dolomite and sandstone because no continuous confining bed exists until the Davis Formation is reached below the Cambrian and Ordovician dolomites. While all units in the section are not equally productive, all play a part in the movement of water to depths and areas of greatest yield. Main water-bearing zones lie in the Potosi Dolomite and lower dolomite and sandstone of the Gasconade above the Davis Formation. Here, the Davis Formation restricted major solution activity of meteoric water to the dolomite above it. The carbonate beds were subjected to intensive solution activity through the agencies of high hydrostatic pressure and mixing of saturated fluids percolating downward through the overlying rock section and down the dip from the outcrop area to create an aggressive fluid capable of dissolving the rock.

The aquifer can be examined through study of well logs and production records of wells and well fields. Caves allow the examination of the effects of solution of carbonate rocks in an environment that formerly was in the saturated zone and provide a further understanding of the development of the aquifer. A study of mines will reveal the chronology in the formation of an ore deposit that may be helpful in understanding the development of an aquifer.

The aquifer is recharged in the uplands, the areas dotted by sinkholes, and through many losing streams. The streams, the most spectacular of the three environments, are not equally capable of recharging water to the caverns underlying them. Some streams lose as much as 200 ft^3/s. Although many of these streams have been located, more probably exist than have so far been identified. Many have been found during dry-weather seepage runs. However, not all streams that are dry at such a time are losing. Some are dry only because of evapotranspiration loss and the absence of storage in the uplands through which they are cutting. In wet weather, or especially during summer rainstorms, striking differences between streams with drainage basins of comparable size are revealed. For example, during a June rainstorm in which precipitation was quite uniformly distributed in the Lebanon, Mo., area, Goodwin Hollow had only 1.5 ft^3/s of flow, while Dry Auglaize adjacent to it had 135 ft^3/s. In dry weather both streambeds are dry.

The amount of ground water pumped from Lower Cambrian and Ordovician aquifers in the project area is approximately 200 ft^3/s. This is about 5 percent of the discharge (assumed to be all ground-water outflow) at the 80 percent point on the flow-duration curves for the principal streams draining the Springfield-Salem plateaus.

Less than 25 percent of the municipal ground-water supplies in southern Missouri are chlorinated. State agencies regulate municipal well construction, a necessity considering the facility of downward movement of water and entrained materials in recharge areas.

While many ground-water samples have been analyzed, the hydrologic interpretation of the variations in the water quality has not been made. Two water samples collected from wells in the gaining and losing reaches of a stream near Lebanon, Mo., show that water from the gaining reach was less polluted than the sample from the losing reach. It is doubtful that this will always prove to be the case, but it does prove that understanding the operation of the flow system will be helpful in any water-quality monitoring program in the Ozarks.

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