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DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

GROUND-WATER RESOURCES OF AUDRAIN COUNTY, MISSOURI

By L. F. Emmett and J. L. Imes

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CONVERSION FACTORS

For readers who prefer to use metric units, conversion factors for terms used in this report are listed below.

Multiply inch-pound unit	By	To obtain metric unit
acre	0.4047	hectare
acre-foot	0.001233	cubic hectometer
cubic foot	0.02832	cubic meter
foot	0.3048	meter
foot per mile	0.1894	meter per kilometer
gallon per day per foot	0.0124	square meter per day
gallon per day per square mile	0.00146	cubic meter per day per square kilometer
gallon per minute	0.06308	liter per second
gallon per minute per foot	0.2070	liter per second per meter
micromho per centimeter at 25°Celsius	1.000	microsiemen per centimeter at 25°Celsius
mile	1.609	kilometer
million gallons per day	0.04381	cubic meter per second
square foot per second	0.09290	square meter per second
square mile	2.590	square kilometer

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows: °F=1.8°C+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, called NGVD of 1929, is referred to as sea level in the text of this report.

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ABSTRACT

The deep aquifer in Audrain County has an average thickness of about 1,300 feet and is composed of dolomite and minor quantitites of sandstone and limestone of Cambrian and Ordovician age. The deep aquifer is the source of water for all public-supply and irrigation wells in Audrain County. Yields range from 500 to 1,000 gallons per minute from wells open to the full thickness of the deep aquifer. The shallow (minor) aquifer ranges in thickness from 50 to 280 feet and is composed of limestone, chert, and dolomite of Mississippian age. Well yields from the shallow aquifer generally are less than 15 gallons per minute.

The northernmost limit of freshwater in the deep aquifer generally coincides with the northern boundary of Audrain County. North and west of Audrain County water in the deep aquifer has a dissolved-solids concentration of more than 1,000 milligrams per liter and generally is a sodium chloride-type water. In Audrain County water in the deep aquifer has dissolved-solids concentrations ranging from 1,200 milligrams per liter in the north to less than 400 milligrams per liter in the south and varies from a sodium bicarbonate to a calcium magnesium bicarbonate type.

By May 1979, pumpage from the deep aquifer had caused a decrease in hydraulic head of as much as 200 feet since 1900 in the vicinity of Mexico, Missouri. Calculations from a two-dimensional digital model of the deep aquifer indicate that the drawdown would increase 10 to 25 feet from May 1979 levels throughout most of Audrain County by May 2000 in the absence of irrigation pumpage and if public-supply wells continue to pump at the 1980 rate. If the additional stress due to seasonal irrigation is continued at 1980 pumping rates, 60 ± 20 feet of drawdown is predicted by May 2000. Lowered water levels in the aquifer may allow water with a larger dissolved-solids concentration to move into the area.

Available hydrogeologic information for the deep aquifer does not permit an accurate evaluation of potential lateral saltwater encroachment. However, movement of water through the deep aquifer has been estimated at 5 to 15 feet per year near the freshwater-saltwater boundary in the northeast and northwest part of Audrain County. Vertical encroachment of more mineralized water possibly could occur by way of the underlying Bonneterre Formation and Lamotte Sandstone. An estimate of vertical encroachment rates cannot be made at this time because no hydraulic-head and water-quality data are available for the Bonneterre Formation and Lamotte Sandstone in this area.

INTRODUCTION

Two aquifers in Audrain County are the source of ground water for municipal, domestic, and farm use. The shallow aquifer is a 50- to 280-foot thick unit of limestone, chert, and dolomite of Mississippian age. Wells completed in the shallow aquifer generally yield less than 15 gallons per minute. The deep aquifer, composed of dolomite and minor quantities of sandstone and limestone of Cambrian and Ordovician age, has an average thickness of about 1,300 feet. The deep aquifer is the principal source of water for all public-supply and irrigation wells in the county. Yields of 1,000 gallons per minute can be obtained from wells open to the full thickness of the aquifer. Approximately 87 percent of the water used for public supply in Audrain County (2.1 million gallons per day) is withdrawn from the deep aquifer. Only the city of Vandalia is supplied from a surface-water source. The population served by public water supply has increased from about 16,400 during 1962 to about 19,500 during 1980 (Missouri Division of Environmental Quality, 1962-80).

Irrigation wells in Audrain County range from 1,100 to 1,600 feet deep, and the wells are pumped at rates ranging from 500 to 1,000 gallons per minute. As of March 1981, there were 24 deep irrigation wells in the area. All the irrigation wells penetrate the deep aquifer and are open to the Gasconade Dolomite. Three wells are completed to the Potosi Dolomite.

The city of Mexico tapped the deep aquifer for its municipal water supply during the late 1800's. Municipal and industrial use of ground water from the deep aquifer increased to approximately 1.7 cubic feet per second (1.1 million gallons per day) by 1965, mostly due to ground-water use by the city of Mexico. The potentiometric surface of the aquifer decreased by about 75 to 100 feet in the vicinity of the city of Mexico by 1965. By 1979 ground-water use had increased to about 3.4 cubic feet per second (2.2 million gallons per day) and the maximum decline in the potentiometric surface was as much as 200 feet.

During the mid 1970's, farmers drilled irrigation wells to maintain crop production during periods of drought. The rate of well installation increased during late 1978 and early 1979. By summer 1979, 18 irrigation wells were completed and were being used in the county, primarily east and southeast of Mexico. To investigate the effect of the rapidly increasing demand on ground-water supplies in the deep aquifer, irrigation wells were monitored during 1979 and 1980. Measurements of hydraulic head before and after the irrigation seasons and pumping rates during the irrigation season provided valuable data on the response of the deep aquifer to the increased stress. During 1979 ground water was withdrawn from the deep aquifer at an annual rate 264 percent larger than the 1965 rate, or about 6.2 cubic feet per second (4.1 million gallons per day). The combined pumping rate for the 18 irrigation wells monitored during the 1979 irrigation season was 11 cubic feet per second (7.6 million gallons per day) and the total pumpage for the estimated 92-day pumping season was 700 million gallons. Nonirrigation pumpage for the same 92-day period was 200 million gallons.

The northernmost limit of freshwater (water containing less than 1,000 milligrams per liter of dissolved-solids) in the deep aquifer generally coincides with the northern boundary of Audrain County (fig. 1). North and west of Audrain County water in the deep aquifer has a dissolved-solids concentration greater than 1,000 milligrams per liter.

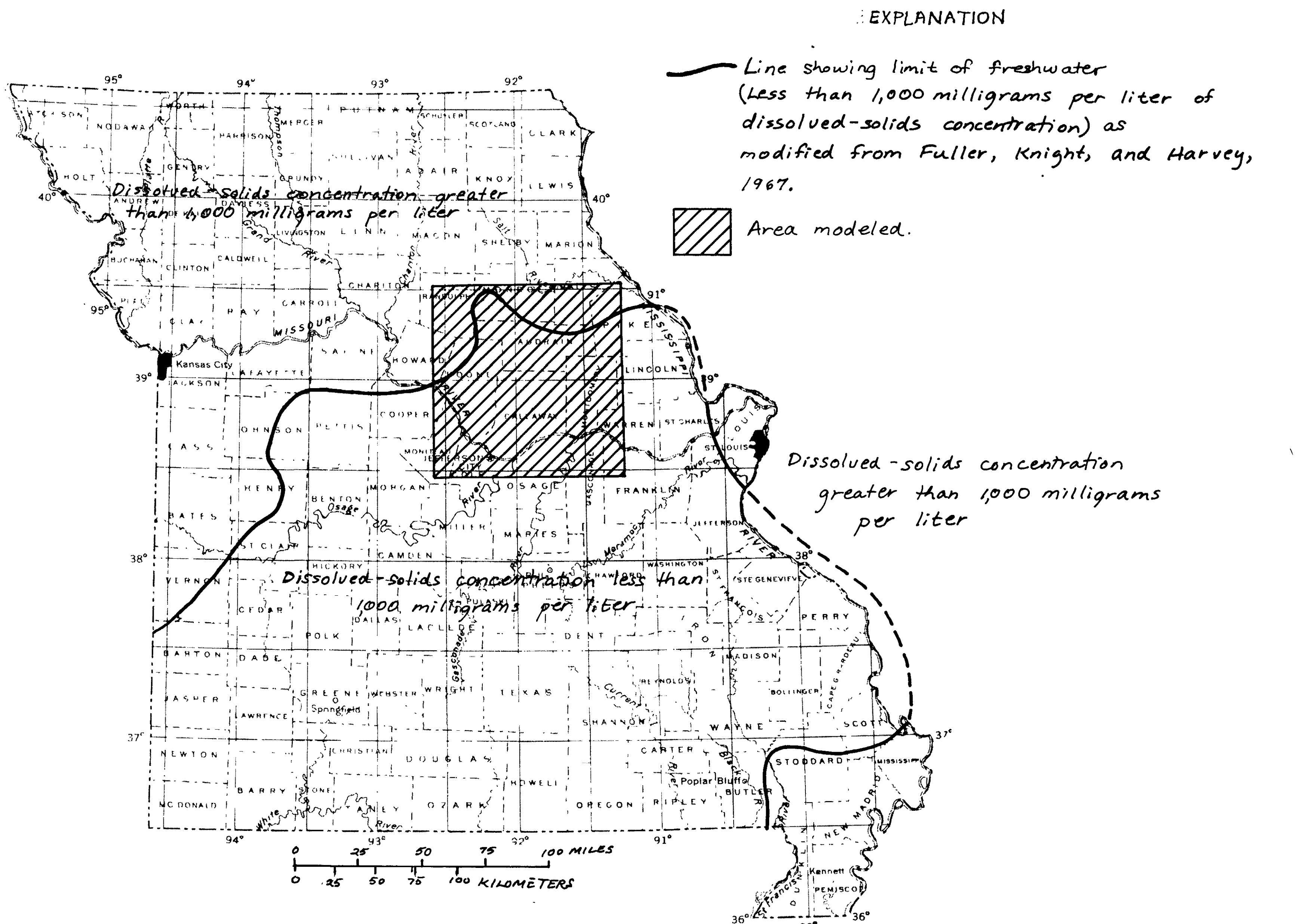

Figure 1.--Location of Audrain County, area modeled, and approximate limit of freshwater in the Cambrian-Ordovician rocks of Missouri.

Purpose and Scope

The purpose of this study is to determine the movement of ground water in Audrain County and assess the quantity and quality of ground water available for municipalities, industries, and cropland irrigation. This report focuses on the deep aquifer. The study area includes a broad region around Audrain County (fig. 1) because municipal pumpage in adjacent counties affect water levels in Audrain.

Records of water-level measurements reported since the early 1900's were compiled and analyzed to identify the historic and recent ground-water flow patterns. Water-level measurements were made in approximately 130 wells during the spring and fall of 1979 and 1980 to supplement existing data and identify changes in the ground-water flow pattern induced by irrigation pumpage.

Water samples obtained at municipal and irrigation wells were analyzed for selected inorganic chemical constituents. The pumping rates of irrigation wells in Audrain County were monitored for two irrigation seasons. These data, coupled with published and estimated pumpage for municipal wells, provide a picture of the changing pattern of water use in the Audrain County area.

A ground-water flow model was constructed to determine whether the recent introduction of irrigation wells in Audrain County and the subsequent large increase in ground-water pumpage will have an adverse effect on ground-water supplies from the deep aquifer. The model is extended south to the Missouri River to take advantage of the relatively simple hydraulic boundary of the river and to include the effect of municipal pumpage at cities in adjacent counties on the deep aquifer in Audrain County.

Location and Drainage

Audrain County is in the southern part of the glaciated region of northeastern Missouri and has an area of 692 square miles ($4.429X10^5$ acres). The topography is a slightly rolling upland with local relief less than 100 feet.

About 70 percent of the county is drained to the north by tributaries of the Salt River, and about 20 percent of the eastern part of the county is drained by tributaries of the Cuivre River (fig. 2). Both drainage systems are tributary to the Mississippi River, which is about 36 miles east of the county. Streams in the extreme southern part of Audrain County (fig. 2) drain into the Missouri River 25 miles south of the county.

Previous Investigations

Gann and others (1971) presented a general summary of information concerning the availability, distribution, use, and quality of surface and ground water in northeastern Missouri.

Howe and others (1972) described the Cambrian strata from a core obtained from a 2,826-feet deep exploration hole in Audrain County. This test hole is important because it is the only recorded well that penetrates the entire Cambrian section in Audrain County.

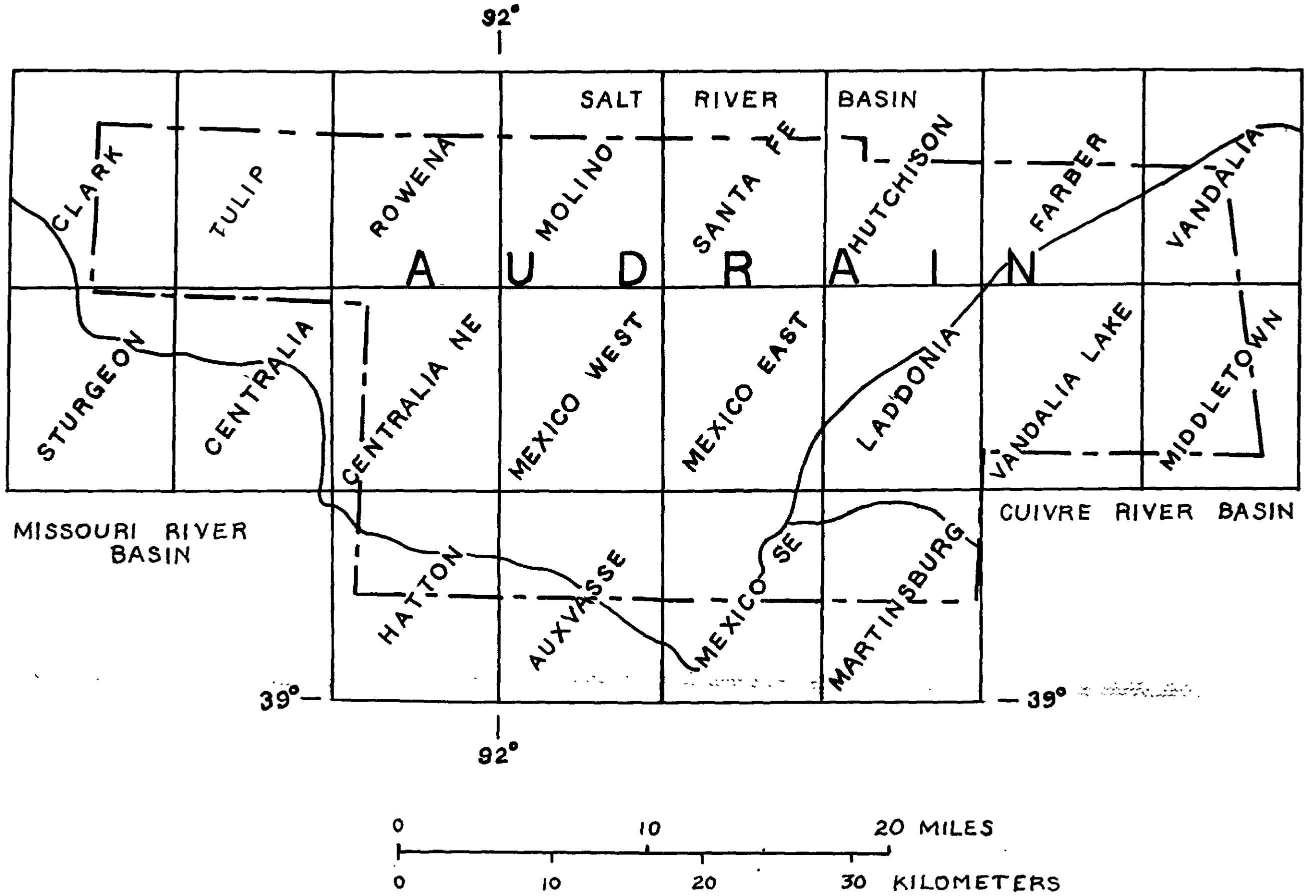

FIGURE 2.--MAJOR DRAINAGE BASINS AND 7½-MINUTE TOPOGRAPHIC MAP COVERAGE IN AUDRAIN COUNTY.

Imes (1984) has shown that, prior to extensive development of the deep aquifer, an eight-county region (including Audrain County) immediately north of the Missouri River contained a local freshwater-flow system independent of the regional saline-water flow system to the north. A north-trending potentiometric divide in the freshwater area of western Audrain County prevented the regional flow of saline water from entering the freshwater area. The saline water divided; some water flowed southwest to discharge into Chariton and southern Howard Counties adjacent to the Missouri River, and the remainder of the water flowed east into Illinois. Ground-water pumpage from the deep aquifer in Audrain and adjacent counties is modifying this historic flow pattern.

Acknowledgments

The authors thank the representatives of municipalities and industries and the many landowners who allowed access to their wells for the collection of data used in this report.

We especially thank Anthony and Joseph Becker for allowing us to make an aquifer test using their irrigation well. We also thank Bill and Norbert Fennewald of Martinsburg, Mo., for providing assistance during the aquifer test.

Well-Location System

The location of the wells cited in this report is given according to the General Land Office Survey system in this order: Township, range, section, quarter section, quarter-quarter section, and quarter-quarter-quarter section (10-acre tract). The quarter subdivisions are designated A, B, C, and D in counterclockwise direction beginning in the northeast quarter. If several wells are in a 10-acre tract, they are numbered serially after the above letters and in the order in which they were inventoried (fig. 3).

The directions of townships and ranges are not used in numbering wells because all townships in the report area are north of the base line and all ranges are west of the principal meridian.

GEOLOGIC SETTING

Repeated glaciation during Pleistocene time covered Audrain County and the rest of northern Missouri with glacial drift consisting of clay, silt, sand, and gravel. The thickness of drift in Audrain County ranges from 0 to 135 feet. The Missouri River, in general, marks the southern limit of glaciation. The drift is thinnest along the streams, and in some stream channels the drift has been eroded exposing the underlying bedrock.

The glacial deposits in Audrain County are underlain by as much as 2,500 feet of virtually flat-lying Paleozoic sedimentary rocks resting on the Precambrian basement (Howe and others, 1972). Generally, the bedrock immediately underlying the glacial drift is of Pennsylvanian age (fig. 4) and is predominately composed of shale, sandstone, and lesser quantities of silt and interbedded coal deposits. Well logs show the maximum recorded thickness of the Pennsylvanian rocks in Audrain County is 185 feet. In a few areas these rocks have been removed by erosion before glaciation, and the glacial deposits rest directly on rocks of Mississippian age (fig. 4).

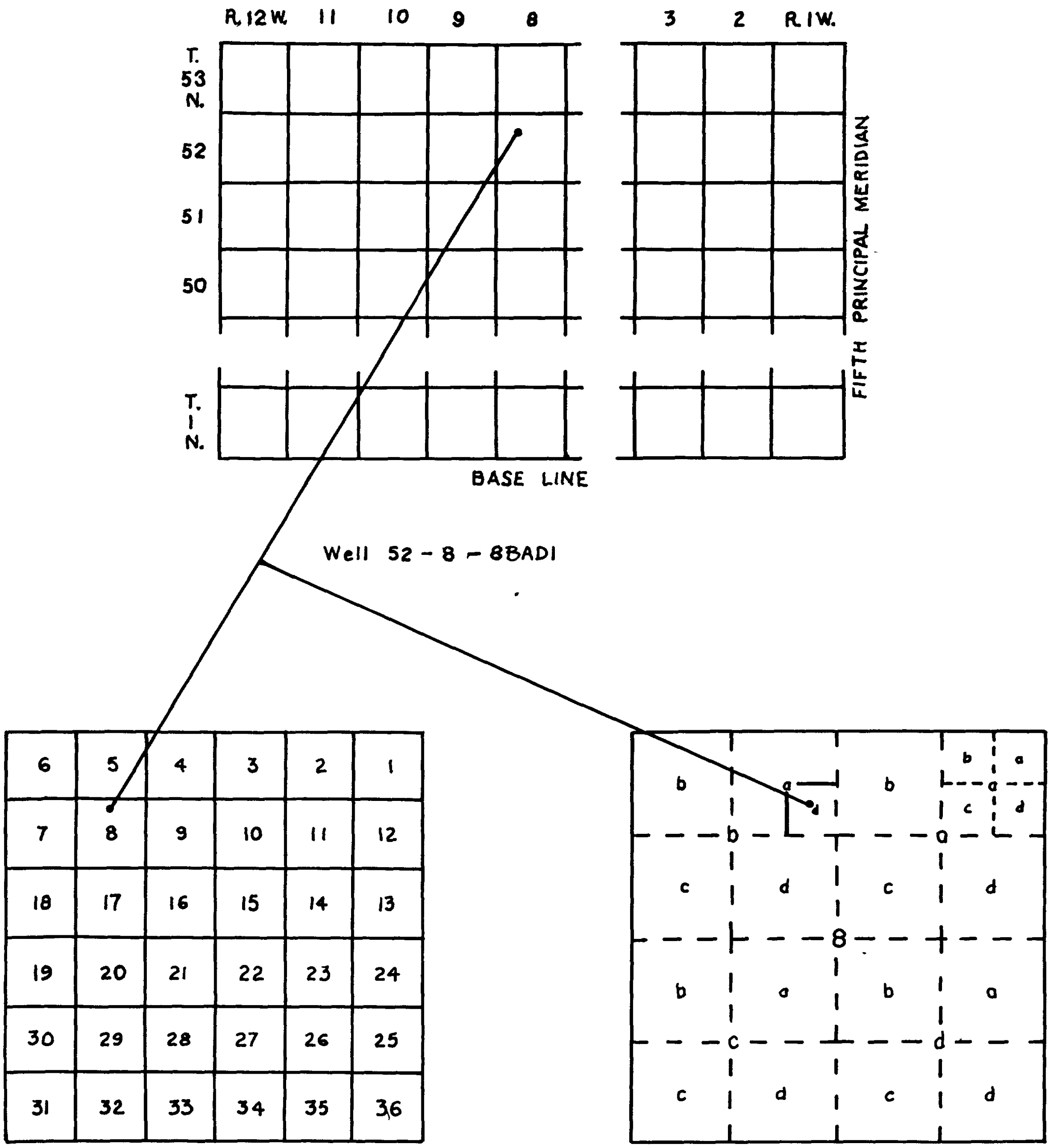

FIGURE 3.-- WELL-LOCATION SYSTEM.

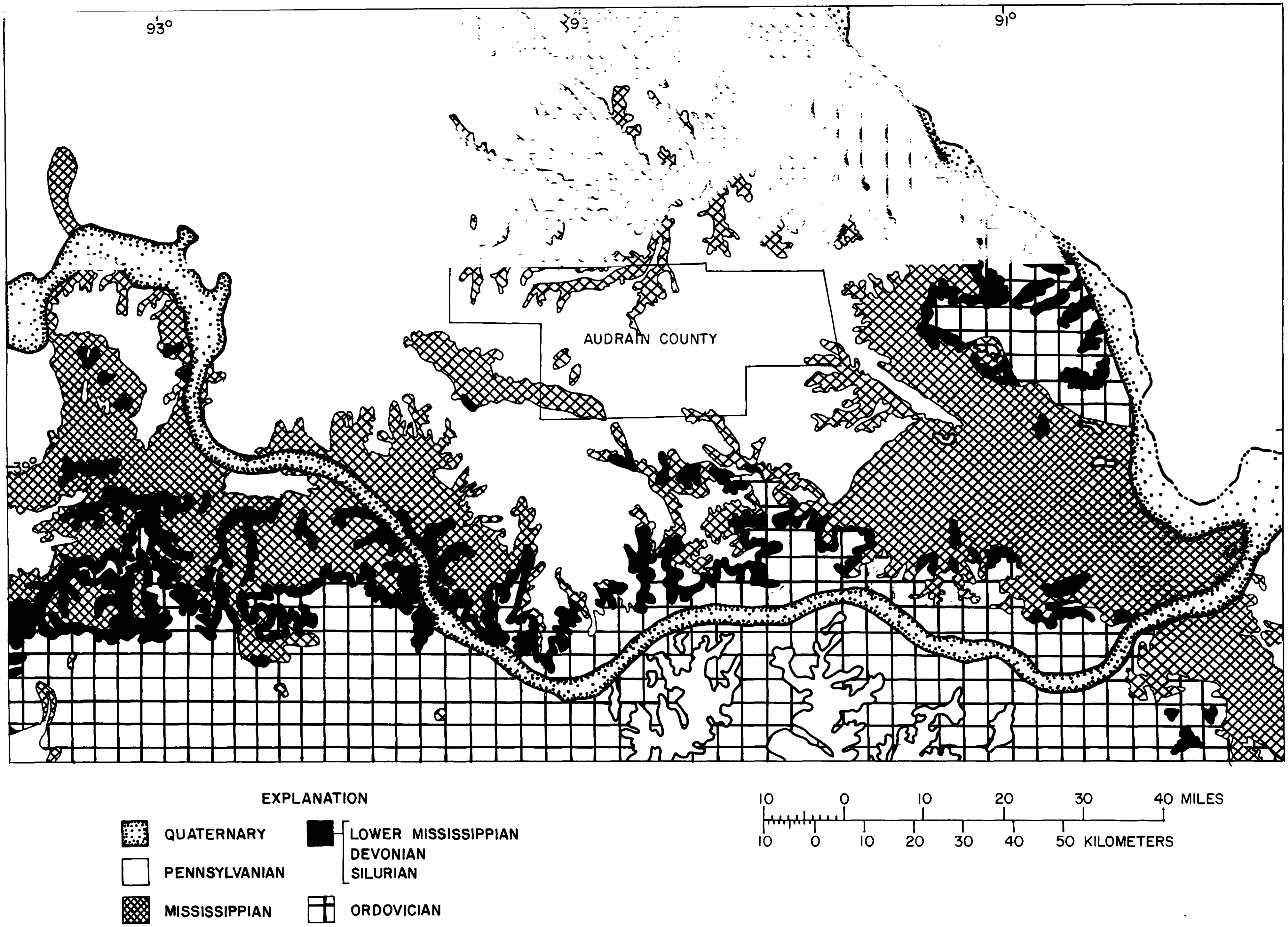

FIGURE 4.-- GENERALIZED GEOLOGIC MAP OF AUDRAIN COUNTY AND VICINITY.

Rocks of Mississippian age are the oldest rocks exposed and are composed of limestone, cherty limestone, dolomite, and minor quantitites of shale. The Mississippian residuum (Burlington-Keokuk detrital zone) contains much residual chert embedded in a clay matrix. These rocks have a maximum thickness of 300 feet.

Rocks of Devonian age, principally limestone with some sandstone and shale, range in thickness from less than 20 to more than 100 feet in Audrain County. The thickest deposits occur along a north-south line passing through the central part of the county.

Rocks of Late and Middle Ordovician age are present in order of increasing age as follows: The Maquoketa Shale is present only in the extreme northeast; the Kimmswick and Decorah Formations are present in the northeast one-third of the county; the Plattin Formation is present in the east one-half of the county; the Joachim Dolomite is present throughout the county, except in the extreme northwest; the St. Peter Sandstone and Everton Formation are present throughout the county, except locally where erosion has removed the deposits. Underlying the Everton Formation is a thick sequence of dolomitic rocks ranging from the shallowest Powell Dolomite to the deepest Derby-Doerun Dolomites. Although the lithology of this rock sequence is predominantly dolomitic, there are well-developed sand bodies in the Roubidoux Formation and Gasconade Dolomite (Gunter Sandstone Member), and chert and lesser quantities of sandstone in the Cotter Dolomite and Jefferson City Dolomite. Table 1, a generalized succession of stratigraphic units, and figure 5, a geologic section traversing west-to-east, clearly depict the stratigraphic relationship of these formations in Audrain County.

No producing wells in Audrain County penetrate formations below the Cambrian Derby-Doerun Dolomite. However, a test hole 2,826 feet deep was drilled by the St. Joe Lead Company in southeast Audrain County, T. 50, R. 7, sec. 6, and the Cambrian formations penetrated have been described by Howe and others (1972). The top of the Davis Formation was reached at 1,815 feet below land surface. The Davis Formation is 160 feet thick and is composed of "***repeated sequences of furrowed silty to sandy shale and slabby impure limestone or dolostone that are terminated by the development of irregular zones of mud-chip breccia***." (Howe and others, 1972, p. 13). Underlying the Davis Formation are 325 feet of the Bonneterre Formation composed of predominantly oolitic limestone and dolomite. The upper 33 feet immediately underlying the Davis Formation consist of shaly to silty dolomite and siltstone. Underlying the base of the Bonneterre Formation at 2,300 feet below land surface are 245 feet of Lamotte Sandstone composed of medium- to coarse-grained sand with pebbly zones. The altitude of the top of the Precambrian was reached at 2,545 feet below land surface. Kisvarsanyi (1975) described the Precambrian rock from this hole as being norite with granite dikes.

The structural attitude of the lowermost Ordovician rocks in and near Audrain County is shown in figure 6. The Ozark uplift in southeast Missouri controls the structural attitude of the lowermost Paleozoic rocks throughout the State. The uplift has caused the rocks to dip away in all directions from an area around St. Francois, Iron, and Madison Counties. The effect of the uplift on the regional dip and strike in northeast Missouri is shown in figure 6.

Table 1-- Generalized stratigraphic column for Audrain County, Missouri[1]

Erathem	System	Series	Geologic unit	Thickness (feet)	Predominant lithology	Aquifer	Water-bearing characteristics
Cenozoic	Quaternary	Pleistocene	Glacial drift	0-135	Clay, silt, sand, gravel		Well yields dependent on presence of sand and gravel; not a dependable source of water in this area.
Paleozoic	Pennsylvanian	Desmoinesian	Cherokee Group undivided	0-185	Shale, sandstone, limestone, silt, clay, some coal.		Small yields from sandstone; water may contain large concentrations of sulfate and iron.
	Mississippian	Osagean	Burlington-Keokuk detrital zone	0-40	Chert (broken), Clay		Yields small quantities of turbid water; generally cased out.
			Burlington-Keokuk Limestones	20-170	Limestone, Chert, Dolomite	Shallow aquifer	Generally yields less than 15 gallons per minute to wells. Constitutes the shallow aquifer.
		Kinderhookian	Chouteau Group undivided	0-130	Limestone, dolomite, some chert.		
			Hannibal Shale	0-50	Shale, sandstone, limestone	Upper confining layer	Unimportant as an aquifer. Shale is a confining layer. Limestone is a less effective confining layer.
	Devonian	Upper Devonian	shale undivided	0-60	Shale, some sandstone		
		Middle Devonian	Limestone undivided	10-115	Limestone, some sandstone and shale		
	Ordovician	Upper Ordovician	Maquoketa Shale	0-55	Shale		
		Middle Ordovician	Kimmswick Formation	0-115	Limestone	Deep aquifer	Well yields generally less than 10 gallons per minute.
			Decorah Formation	0-30	Limestone, Shaly		Unimportant as an aquifer.
			Platin Formation	0-50	Limestone, dolomite		
			Joachim Dolomite	0-60	Dolomite		
			St. Peter Sandstone	0-130	Sandstone		Yields as much as 25 gallons per minute to wells. Used for home, small industry, and farm use.
			Everton Formation	0-65	Dolomite, sandstone and shale		Unimportant as an aquifer.
		Lower Ordovician	Powell Dolomite	0-75	Dolomite, chert, shale		Provides small quantities of water to wells.
			Cotter Dolomite	200-300	Dolomite, sandstone, chert, shale		
			Jefferson City Dolomite	135-175	Dolomite, chert, sandstone		Locally may yield as much as 25 gallons per minute to wells.
			Roubidoux Formation	90-125	Dolomite, sandstone, chert, shale		Yields 50 to 200 gallons per minute to wells. Used by small towns and industry.
			Gasconade Dolomite Gunter Sandstone Member	200-300	Dolomite, chert, sandstone		Yields 300 to 500 gallons per minute to wells. Many public-supply and most irrigation wells are completed in this formation.
	Cambrian	Upper Cambrian	Eminence Dolomite	75-125	Dolomite		May yield as much as 700 gallons per minute to wells. A few public-supply and irrigation wells bottom in this formation. Water probably is mineralized north and west of Audrain County area.
			Potosi Dolomite	50-110	Dolomite		May yield as much as 1100 gallons per minute to wells in the southern part of the area. Water probably is mineralized north and west of Audrain County area.
			Derby-Doerun Dolomite	200	Dolomite		Yield characteristics unknown; unimportant as an aquifer farther south.
			Davis Formation	160	Dolomite, shale, siltstone, limestone		Lower confining layer.
			Bonneterre Formation	325	Limestone, dolomite, siltstone		Aquifer characteristics unknown.
			Lamotte Sandstone	245	Sandstone		
Precambrian			Igneous and metamorphic				Not an aquifer.

[1] The stratigraphic nomenclature used in this report is that of the Missouri Division of Geology and Land Survey and differs somewhat from the current usage of the U.S. Geological Survey.

In Audrain County the attitude of the Paleozoic rocks is also affected by two northwest-trending anticlines. The larger of these two structures is the Lincoln fold, which extends northwest from the Cap au Gres fault through Lincoln, Pike, Ralls, Monroe, Shelby, and Knox Counties. The other structure affecting the attitude of the Paleozoic rocks is the Brown Station anticline that crosses northern Boone County. The manner in which these anticlines affect the geologic structure in and around Audrain County is shown by geologic section and structural contour maps presented by Imes (1984). Audrain County is situated in the trough between the anticlines. Middle Ordovician rocks underlie the county at an altitude of 300 feet in the northwest to 500 feet in the southwest and east. Generally, the dip of Middle Ordovician rocks into the syncline in northeast Audrain County is about 8 to 10 feet per mile. For more discussion of structural features in Missouri the reader is referred to McCracken (1971).

GROUND WATER IN AUDRAIN COUNTY

Description of Aquifers and Confining Beds

In Audrain County there are two aquifers of regional extent. The less productive aquifer consists of limestone, dolomite, and chert of Mississippian age and is called the shallow aquifer (table 1) in this report. The more productive aquifer, called the deep aquifer in this report, consists of Ordovician and Cambrian formations below the Maquoketa Shale and above the Davis Formation (table 1).

Shallow Aquifer

The shallow aquifer consists of sedimentary rocks of Mississippian age (table 1), specifically the Burlington-Keokuk Limestones of the Osagean Series and the Chouteau Group of the Kinderhookian Series. The Burlington-Keokuk is present throughout Audrain County and most of the modeled area (fig. 1), except where the older underlying formations crop out along the Missouri River. In Audrain County the Osagean Series lies beneath Pennsylvanian limestone and shale ranging from 0 to 185 feet thick. In the north-central part of the county, Osagean strata have been exposed along tributaries of the Salt River by erosion (fig. 4). In the extreme southwestern corner of the county, Pennsylvanian rocks were removed from atop a small anticline (Davis Creek) by erosion and subsequently replaced by surficial deposits of glaical drift, which cover the entire county (figs. 4 and 6). The Burlington-Keokuk Limestones contain minor quantities of dolomite and a large percentage of imbedded chert nodules. The network of extensive fractures and well-developed solution channels found throughout this limestone make it the most important water-yielding formation in the shallow aquifer. The altitude of the top of the Burlington-Keokuk (fig. 7) is greatest in the extreme southwest corner of Audrain County, where it exceeds 850 feet, and least in the extreme southeast corner at 500 feet. Generally, the lower altitudes occur along a trough extending from the southeast corner westward to Mexico and in the vicinity of Farber. The thickness of the Burlington-Keokuk (fig. 8) ranges from 205 feet in the northwest to 10 feet in the east-central part of the county. The majority of area where the formation is less than 50 feet thick lies in five of the easternmost townships. The Chouteau Group contains a much smaller percentage of chert and less well-developed system of fractures and solution channels than the Burlington-Keokuk Limestones.

Older domestic and stock-supply wells commonly were completed in the shallow aquifer and yield 10 to 15 gallons per minute. Even many modern domestic and stock-supply wells that penetrate the upper part of the deep aquifer are constructed so that they also are open to the shallow aquifer. However, public-supply and irrigation wells, all of which are completed in the deep aquifer, generally are constructed so that the shallow aquifer is cased out. Casing out the shallow aquifer in these large-capacity wells prevents dewatering of nearby wells that may be completed in the shallow aquifer. Water in the shallow aquifer is under confined conditions where the aquifer is overlain by thick Pennsylvanian shale. Elsewhere leaky artesian conditions prevail.

Upper Confining Layer

Shale and limestone, ranging in age from Upper Ordovician to Lower Mississippian impede the downward movement of water from the shallow to the deep aquifer (table 1). The Mississippian and Devonian shales are in contact and comprise the upper part of the confining layer. The Maquoketa Shale, which exists only in the extreme northeast corner of the model area, is separated from the other shale units by Devonian limestone. Areal distribution and composite thickness of the shale formations within the confining layer are shown in figure 9. The shale units that contribute to the composite thickness are the Hannibal Formation (Mississippian), shale of Late Devonian age, and the Maquoketa Shale (Ordovician). In Audrain County the composite shales are thickest (approximately 120 feet) in the extreme northwest where the Maquoketa Shale is present. The shale beds thin quickly to the southwest so that throughout 95 percent of the county the thickness of the composite shales is less than 30 feet. Shale is absent from the confining layer through a wide area in the southeastern part of the county (fig. 9). This area represents about 35 percent of the county. In the model area, about 45 percent of the confining layer has few or no shale confining beds.

Comparison of the water levels in the shallow and deep aquifers and preliminary modeling efforts show that confining beds separate the shallow and deep aquifer, even in the region not underlain by the shale units. Evidence from selected well logs north of the model area (Imes, 1984) and from generally accepted information throughout the model area (Gann and others, 1971) indicates that Devonian limestone may be included as a confining bed in addition to the more significant shales. The limestone attains a maximum thickness in Audrain County of about 100 feet in the north-central, south-central, and southwest parts of the county (fig. 10). The southernmost areas of maximum thickness of these relatively impermeable limestones lie within the area devoid of shale confining beds.

Deep Aquifer

The deep aquifer includes formations that are predominately dolomite or cherty dolomite and, with the exception of the St. Peter Sandstone, contains only minor quantities of sandstone. The composite thickness of the formations composing the deep aquifer, figure 11, ranges from 1,000 feet in western Audrain County to a maximum thickness of about 1,600 feet in the east. The maximum thickness occurs along a northwest-trending synclinal axis, parallel to the Lincoln fold anticline to the northeast, and the Browns Station anticline to the southwest of Audrain County. The aquifer is thinnest in the model area atop the Browns Station anticline in Callaway County (fig. 6).

Data are insufficient to quantitatively describe the relative productivity and hydraulic heads of the various formations within the deep aquifer, but some general statements can be made. The more productive formations in the deep aquifer (table 1), in order of increasing yields, are the St. Peter Sandstone, Roubidoux Formation, Gasconade Dolomite, Eminence Dolomite, and Potosi Dolomite. North of Audrain County, where the Maquoketa Shale is absent, there is evidence from drillers' logs that the first occurrence of water below the impermeable Hannibal Formation and Upper Devonian shale is in the Kimmswick Formation (Imes, 1984). Thus the Kimmswick is assumed to be the top of the deep aquifer in this region. In Audrain County the Kimmswick is separated from the productive St. Peter Sandstone by one or more of the Decorah Formation, Plattin Formation, and Joachim Dolomite (see "Geologic Setting"). Southeast of Audrain County, outside the model area, the Decorah Formation consists of a relatively uniform layer (about 20-30 feet thick) of shale. The formation thins to the west and northwest and becomes predominantly limestone or dolomitic limestone. Only in the extreme northwest corner of Audrain County does the Decorah contain significant quantitites of shale. The Plattin Formation is a dolomitic limestone within Audrain County and the Joachim Dolomite is primarily dolomite with varying quantities of limestone, chert, and sandstone. Although the Decorah and Plattin Formations and the Joachim Dolomite are less permeable than the Kimmswick Formation and St. Peter Sandstone, they probably contribute small quantitites of water to the aquifer.

The Everton Formation, a sandstone and dolomite occasionally containing significant quantities of shale, produces little water and may locally be a semipermeable barrier to the vertical movement of water within the aquifer. No hydraulic-head data are available to confirm or deny this speculation. It is unlikely that the Everton is a confining bed.

The uppermost formation in the deep aquifer ranges from the younger Kimmswick Formation in the east to the Everton Formation in the west (fig. 12). Generally, the top of the aquifer is older where Ordovician strata were uplifted along the Browns Station anticline and subsequently eroded, and younger where the sedimentary rocks dip into the northwest-trending syncline in eastern Audrain County (Imes, 1984).

The Lower Ordovician formations are similar in lithology, the dominant rock type being dolomite. Generally, small quantitites of shale, which may impede the movement of water, are interbedded in the Powell and Cotter Dolomites. These formations usually do not yield significant volumes of water. The underlying Jefferson City Dolomite, Roubidoux Formation, and Gasconade Dolomite are characterized by an increase in the quantity of sandstone. The Gasconade contains a hydrologically important unit, the Gunter Sandstone Member. Yields to wells are better in these formations than in the overlying Powell and Cotter Dolomites.

The Eminence and Potosi Dolomites of Late Cambrian age are the largest contributors of water from the aquifer. Both are composed of massive, medium-grained dolomites that have well-developed solution channels. Yields in excess of 1,000 gallons per minute have been attained by wells that penetrate these formations. The underlying Derby-Doerun Dolomite, a thick medium-grained dolomite formation, is not penetrated by wells in Audrain County. The formation is relatively unimportant as an aquifer near its outcrop area south of the Missouri River. However, the dolomite is interbedded with siltstone and shale in that region, whereas in northern Missouri it appears to be primarily dolomite with occasional sandstone.

The newer stock-and domestic-supply wells generally are completed in the St. Peter Sandstone or sometimes in the Cotter-Jefferson City Dolomites. A few of the older public-supply wells in small towns are completed in the St. Peter Sandstone. Small towns in the area now have wells that penetrate the Roubidoux Formation. For example, Martinsburg, Rush Hill, Laddonia, and Farber are served by wells that are completed in the Roubidoux Formation. Mexico, the largest city in Audrain County, has three wells open to the Gasconade Dolomite. Two of these wells are completed in the Eminence Dolomite.

Lower Confining Layer

The deep aquifer is underlain by the Davis Formation that dips from a maximum altitude of -500 feet in southwest Audrain County to -1,100 feet in the northeast (fig. 13). The dip and strike are controlled by the Browns Station anticline, the Lincoln fold anticline, and the intervening syncline. The Davis Formation is considered to be the lower confining bed of the deep aquifer because of the relatively large quantities of siltstone and shale it contains. The Davis separates the deep aquifer from the underlying Bonneterre Formation and Lamotte Sandstone.

Description of the Ground-Water Flow System

Predevelopment Conditions

Historically, little ground water entered Audrain County by horizontal flow through the shallow aquifer; instead, freshwater recharged the aquifer by downward leakage through overlying Pennsylvanian formations and glacial drift, then exited the county by lateral flow through the shallow aquifer or leaked downward into the deep aquifer. Recharge through the Pennsylvanian strata, which are locally in excess of 100 feet thick in the county, is greatly impeded by the large fraction of clay and shale in these deposits. However, at several places in Audrain County the Pennsylvanian overburden has been breached by erosion, allowing deposits of glacial drift and soil to contact the shallow aquifer (see fig. 4). In southwestern Audrain County, Pennsylvanian rocks were eroded from atop an anticline. This eroded area also is coincident with the region of greatest land-surface elevation in the county. Hydraulic heads measured in wells open to the shallow aquifer depict a mound in the aquifer's predevelopment potentiometric surface located in southwestern Audrain County (fig. 14). The mound is a reflection of the higher land surface and greater quantity of recharge received by the aquifer in the area devoid of Pennsylvanian rocks.

The direction of movement of water in an aquifer can be determined from a potentiometric map. In an isotropic aquifer, water moves in a direction that is at right angles to contours depicting the configuration of the potentiometric surface and in the direction of decreasing hydraulic head. The potentiometric surface displayed in figure 14 shows three distinct subregions of ground-water flow in Audrain County, separated by ground-water divides. In the extreme west and southwest parts of the county, ground water flowed westward in the shallow aquifer. In the central and north-central parts of the county, ground-water flow converged toward an area in northern Audrain County where southern tributaries of the Salt River have eroded Pennsylvanian rocks and are in contact with the Mississippian shallow aquifer (see fig. 4). Water in the shallow aquifer probably discharged along these tributaries or flowed farther north to discharge into the Salt River. Ground-water flow in the east and southeast part of the county was to the southeast.

Hydraulic-head difference between the shallow and deep aquifers, the configuration of the predevelopment potentiometric surface of the deep aquifer, and the presence of freshwater in the deep aquifer indicate that the principal recharge to the deep aquifer in Audrain County was derived from downward leakage. In Audrain County the hydraulic head in the shallow aquifer was as much as 150 feet higher than the hydraulic head in the deep aquifer. An analysis of the regional ground-water flow in northeastern Missouri shows that the area between the northern boundary of Audrain County and the Missouri River was a separate flow system from the regional saline-water flow system to the north (Imes, 1984). Apparently, little or no ground water, saline or fresh, passed into Audrain County through horizontal flow in the deep aquifer. The prepumping potentiometric surface of the deep aquifer (fig. 15) was mapped using water-level measurements obtained during the early stages of the development of the deep aquifer as a ground-water source. The water levels are from wells that penetrate the aquifer to different depths and were measured at various dates, but are believed to adequately represent the predevelopment hydraulic heads. A ground-water divide was present in western Audrain County before the development of ground-water wells at Mexico. On the west side of the divide, ground-water movement was toward the southwest; on the east side of the divide, ground-water movement was toward the east.

Postdevelopment Conditions

The volume of water withdrawn from the shallow aquifer since the turn of the century is unknown, but is undoubtedly quite small relative to that pumped from the deep aquifer. The shallow aquifer has been used primarily as a source of domestic water supply. Water levels measured in the late 1970's show that potentiometric heads in the shallow aquifer have changed little during this century. The measurements also show that water levels in the shallow aquifer do not fluctuate seasonally in phase with irrigation pumpage from the deep aquifer. It is evident that hydrologically the shallow aquifer is weakly connected to the deep aquifer in Audrain County even in the areas devoid of shale confining layer.

The deep aquifer was first tapped for its freshwater during the late 1800's by the city of Mexico. The deep aquifer has become the major source of water for irrigation and public supply in Audrain County. By 1980 water being withdrawn from the deep aquifer for public supply in Audrain County averaged about 2.1 million gallons per day, or 2,372 acre-feet per year (Missouri Division of Environmental Quality, 1980). The city of Mexico now accounts for more than 90 percent of the water pumped for public supply in Audrain County. The first deep irrigation wells were drilled during the mid-1970's as farmers attempted to increase their crop yields. Most of the irrigation wells have been drilled since 1978 and only a few were operating before the summer of 1979. During 1979 an estimated 2,500 acre-feet of water was pumped from the deep aquifer for irrigation in Audrain County. During 1980 the quantity of water pumped for irrigation increased to 2,660 acre-feet.

The locations of wells that have been completed in formations of the deep aquifer are shown in figure 16. The measured and estimated pumping rates for these wells presented in table 2 (public-supply and industrial wells) and table 3 (irrigation wells). Each well or well field listed in table 2 and table 3 is identified by a well number that locates the well on figure 16.

Average annual pumping rates for municipal, industrial, and irrigation wells for 1900 to 1980 were estimated from several sources. Data for the first 60 years were calculated from published census figures and an estimated per capita use. During 1962 the Missouri Division of Environmental Quality began to publish pumping rates for all public water supplies at 2- to 3-year intervals. The rate of ground-water withdrawal from the aquifer during 1960 to 1980 was estimated by averaging data from these intermittent records for 5-year periods. Most of the irrigation wells were installed during or after 1978 and were not used until 1979. Average pumping rates for the irrigation wells were obtained from onsite surveys during the 1979 and 1980 irrigation seasons. Pumping time for each irrigation well was determined from a combination of irrigation records and the use of vibration timers at most installations. The average rate of flow from each well was determined by periodically measuring the volume of ground water pumped at each site with a Clampitron[1] flowmeter and prorating the total pumpage (average rate of flow times length of pumping period) through the June-August irrigation season.

During past years ground-water withdrawal for public supply has changed the configuration of the potentiometric surface. A comparison of the measured prepumping potentiometric surface of the deep aquifer (see fig. 15) with the measured potentiometric surface of the deep aquifer at the end of May 1979 (fig. 17) shows the extent to which public-supply and industrial pumpage has affected the aquifer since 1900. The historic potentiometric surface has been altered so that saline ground water in the deep aquifer north of Audrain County now flows south and southeast toward the cones of depression formed by pumpage from public-supply wells at Mexico and Centralia. Similarly, water that formerly exited Audrain County to the southwest and southeast is now diverted to Centralia and Mexico.

The direction of ground-water movement remains virtually the same during irrigation in western and central Audrain County, but small cones of depression form around the cluster of irrigation wells in the southeast. A potentiometric map based on measurements made shortly after the irrigation season during October 1979 is shown in figure 18. Water levels at Mexico declined by about 100 feet from May to October. In southeastern Audrain County, irrigation pumpage decreased water levels as much as 75 feet. By May 1980, the water levels in the irrigation wells had largely recovered (fig. 19). Although water levels at Mexico recovered to some extent, they still did not rise to pre-irrigation levels. A potentiometric map prepared from measurements made at

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[1] The use of the brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Table 2.--Pumping rates for public-supply and industrial wells

[PWSD, Public Water-Supply District]

Well number (fig. 11)	Public-supply or industrial	Location (see fig. 3)	Average annual pumping rate, in cubic feet per second: 1900 thru 1909	1910 thru 1919	1920 thru 1929	1930 thru 1939	1940 thru 1949	1950 thru 1959	1960 thru 1964	1965 thru 1969	1970 thru 1974	1975 thru 1979	1980
	Audrain County												
1	Clay refractory	52-06-14CCB1	--	--	--	--	--	--	0.30	0.30	0.30	0.30	0.30
2A	Farber	52-06-21AAD1	--	--	--	--	--	0.02	.03	.04	.05	.05	.08
2B		52-06-21ADC1											
2C		52-06-21ADC2											
3A	Laddonia	52-07-35DDD1	--	--	--	--	--	.02	.05	.05	.10	.08	.08
3B		52-07-36CBD1											
4	Martinsburg	50-07-24BBD1	--	--	--	--	--	--	--	.02	.03	.04	.05
5A	Mexico	51-09-26BCD1	0.19	0.21	0.32	0.44	0.60	.80	1.31	1.88	2.30	2.94	2.94
5B		51-09-26CAA1											
5C		51-09-27ACC1											
6	Rush Hill	51-07-07DDA1	--	--	--	--	--	--	--	.01	.02	.02	.02
	Boone County												
7A	Ashland	46-12-10DD	--	--	--	--	--	.02	.04	.04	.06	.13	.09
7B		46-12-10DDD1											
7C		46-12-15BAA1											
7D		46-12-15BAA2											
8A	Boone County consolidated PWSD 1	46-12-16BBD1	--	--	--	--	--	--	--	.19	.48	.85	1.27
8B		46-12-22ADC1											
8C		47-12-04AA											
8D		47-12-06BB											
8E		47-13-05ADD1											
9A	Boone County PWSD 1	49-12-19CD	--	--	--	--	--	--	--	.10	.15	.23	.28
9B		49-13-25CA											
10A	Boone County PWSD 2	49-12-26	--	--	--	--	--	--	--	.05	.15	.23	.29
10B		49-12-33DCD1											
11A	Boone County PWSD 4	50-11-18	--	--	--	--	--	--	--	.04	.18	.28	.30
11B		50-12-14											
12A	Boone County PWSD 7	49-13-02AC	--	--	--	--	--	--	--	.05	.07	.12	.18
12B		50-13-34AB											
13A	Boone County PWSD 9	48-12-12BD	--	--	--	--	--	--	--	.20	.30	.54	.70
13B		48-12-23											
13C		48-12-23AD											
13D		49-11-08DAA1											
14	Boone County PWSD 10	51-11-29DD	--	--	--	--	--	--	--	--	--	--	.30
15A	Centralia	51-11-10CDC1	--	.07	.11	.13	14	.08	.77	.77	.54	.77	.93
15B		51-11-10CDC2											
15C		51-11-10DCC1											
15D		51-11-15AAD1											
16A	Columbia	48-12-05BBC1	--	.29	.54	.79	1.16	1.75	5.88	5.88	2.06	2.40	2.32
16B		48-12-06CDA1											
16C		48-12-06CDA2											
16D		48-12-08BAB1											
16E		48-13-10DBD1											
16F		48-13-15CBB1											
16G		48-13-16BBA1											
17	Hallsville	50-12-13CAD1	--	--	--	--	--	.02	.04	.04	.10	08	09
18	Harrisburg	50-14-11ACC1	--	--	--	--	--	--	--	.01	02	.02	
19A	University of Missouri at Columbia	48-12-18BDC1	--	--	--	--	1.62	1.62	3.44	3.25	3.25	3.25	3.25
19B		48-13-13ACB1											
19C		48-13-24AAA1											
19D		48-13-24BCA1											
	Callaway County												
20A	Auxvasse	49-09-14CDC1	--	--	.01	.03	.06	.06	.06	.06	.06	.07	.14
20B		49-09-23ABB1											
21A	Callaway County PWSD 1	45-09-32	--	--	--	--	--	--	--	--	.40	.72	.92
21B		45-10-07CBA1											
21C		45-11-24ADA1											
21D		45-11-36ABB1											
22	Callaway County PWSD 2 (NE)	48-08-19	--	--	--	--	--	--	--	--	--	.06	.07
23	Callaway County PWSD 2 (SW)		--	--	--	--	--	--	--	--	--	.10	.12
24	Cedar City	44-11-16BAD1	--	--	--	--	--	--	.02	.05	.04	.04	.08
25A	Fulton	47-09-16BBD1	--	--	--	--	.50	.71	1.24	1.40	1.55	1.86	1.86
25B		47-09-16BBD2											
25C		47-09-17ABB1											
25D		47-09-20CAA1											
26	Mokane	45-09-13AAA1	--	--	--	--	--	--	.02	.02	.04	04	05
27	New Bloomfield	46-10-31BDD1	--	--	--	--	--	--	.02	.03	.03	.04	.06
	Montgomery County												
28	Bellflower	49-04-22BB31	--	--	--	--	--	--	--	.01	.03	06	.04
29	High Hill	48-04-32DDB1	--	--	--	--	--	--	--	01	02	02	.04
30A	Jonesburg	47-03-07CAA1	--	--	--	--	--	--	.02	.04	05	.06	.06
30B		47-04-12ADC1											
31	Middletown	50-06-02CDB1	--	--	--	--	--	--	--	02	.02	.02	02
32A	New Florence	48-05-23CCA1	--	--	--	--	--	01	.03	.05	06	.06	.13
32B		48-05-23CCD1											
32C		48-05-23CDC1											

Table 3.-- Pumping rates for irrigation wells

Well number (fig. 11)	Location[1]	Average pumping rate, in cubic feet per second	
		1979 irrigation season[2]	1980 irrigation season[2]
	Audrain County		
33	50-07-02DAC1	1.05	0.78
34	50-07-05DBD1	.95	.45
35	50-07-08DBD1	.40	.25
36	50-07-09BAA1	1.41	1.00
37	50-07-12CAB1	.56	.26
38	50-08-04DCA1	.61	.51
39	50-09-05ACC1	--	.64
40	50-09-05BCC1	.51	.75
41	50-09-17DCC1	.38	.69
42	50-10-13BCD1	.64	.88
43	51-06-30CBC2	--	.70
44	51-06-31CDA1	.85	1.03
45	51-07-10BCD1	.84	.81
46	51-07-31AAB1	.80	.65
47	51-07-36CCA1	.44	.45
48	51-08-08DDB1	.37	.50
49	52-10-34DDC1	.24	.21
50	52-11-26BCC1	.41	.42
51	52-11-33BAC1	.24	.41
52	52-12-26DDC1	.30	.87
	Boone County		
53	51-12-10	.10	.22
	Callaway County		
54	49-08-09AAA1	1.24	.79
55	49-08-11CBC1	.96	.90
	Montgomery County		
56	50-06-02CDB1	.29	.25
	Ralls County		
57	53-06-33BCB1	.24	.14

[1] Location is given by township, range, and section. All townships are north; all ranges are west.

[2] Averaged from a 92-day pumping season (May 31-September 1).

the end of 1980 irrigation season (fig. 20) shows the combined effects of ground-water withdrawal by public-supply and irrigation wells for September 1980. Water levels in Audrain County are lowest along a line between Mexico and the concentration of heavily pumped irrigation wells in the northeast corner of T. 50., R. 7. Water levels in the irrigated area show a maximum net decline of 100 feet from the prepumping water levels.

Estimates of Recharge, Discharge, and Lateral Flow Rates of Ground Water Under Predevelopment Conditions

A rough estimate of the recharge to, discharge from, and lateral flow through the shallow and deep aquifers in Audrain County prior to development was calculated. This was accomplished by using hydraulic gradient and head data interpolated from the predevelopment potentiometric surface maps of the shallow and deep aquifers (see figs. 14 and 15), estimates of leakage coefficients for the shale and limestone upper confining bed, and an estimate of the hydraulic conductivity of the shallow and deep aquifer. Virtually all the ground water that entered the shallow aquifer under predevelopment conditions was by leakage through the overlying Pennsylvanian strata and glacial drift deposits; the ground water then exited Audrain County by flow through the shallow aquifer or leaked to the deep aquifer. The water budget for the shallow aquifer can be written:

$$R_s = D_s + L_{sd} \qquad (1)$$

where R_s is the rate at which water recharges the shallow aquifer through overburden (L^3T^{-1});

D_s is the rate at which water exits the county by horizontal flow through the shallow aquifer (L^3T^{-1}); and

L_{sd} is the rate at which water leaks from the shallow aquifer to the deep aquifer (L^3T^{-1}).

For convenience, the digital ground-water flow model grid was used to calculate the net flow rate of water from Audrain County by summing flow rates between neighboring cells across the county boundary:

$$D_s = K \sum_i (A_i I_i) \qquad (2)$$

where K is the shallow aquifer hydraulic conductivity (LT^{-1});

A_i is the cross-sectional area of the ith flow path at the county boundary (L^2); and

I_i is the hydraulic gradient across the county boundary along the ith flow path (dimensionless).

The hydraulic conductivity of the shallow aquifer was estimated to be about $1.0X10^{-6}$ feet per second (or about one-tenth the hydraulic conductivity of the deep aquifer) based on comparison of the relative yields and thickness of the two aquifers. This estimate is supported by estimates of transmissivity derived from specific-capacity measurements of several wells in Audrain County that are completed to the base of the shallow aquifer. All the measured specific capacities are about 0.1 gallon per minute per foot of drawdown, which translates to a transmissivity of $3.1X10^{-4}$ square feet per second, assuming the rule-of-thumb relationship of 1 gallon per minute per foot of drawdown is approximately 2,000 gallons per day per foot (Walton, 1970, p. 314). Thus the hydraulic conductivity is estimated at $1.5X10^{-6}$ feet per second using an average saturated thickness of 200 feet for the shallow aquifer. The total discharge of ground water from Audrain County through the shallow aquifer is estimated to have been 0.1 cubic foot per second.

The total leakage through the upper confining bed into the deep aquifer was obtained by first determining the effective confining-bed vertical hydraulic conductivity, then summing the volumetric leakage for each of the 506 model grid cells within Audrain County. A value of $7.7X10^{-11}$ feet per second was chosen for the vertical hydraulic conductivity of the shale confining beds. This value was presented by Walton (1960, 1965) for the vertical permeability of the Maquoketa Shale in northeastern Illinois. The limestone formations were assumed to have a vertical hydraulic conductivity of $7.7X10^{-10}$ feet per second, 10 times more permeable than the Maquoketa. This value lies within the range of conductivities given by Freeze and Cherry (1979) for limestone. The total vertical leakage for Audrain County was computed to have been 2.4 cubic feet per second; the actual leakage rate at any specific location depends on the leakage coefficient and hydraulic gradient across the confining bed at that point.

The total recharge to the shallow aquifer determined from the water budget (eq. 1) is 2.5 cubic feet per second, which is equivalent to an areal recharge rate of approximately $1.3X10^{-10}$ feet per second (2,235 gallons per day per square mile). At present (1984) there are no independent measurements or studies that verify or contradict this estimate. Of the water that recharged the shallow aquifer through overlying strata, 4 percent left Audrain County via the shallow aquifer under predevelopment conditions and 96 percent leaked downward into the deep aquifer. The estimated rate of recharge to the shallow aquifer through the Pennsylvanian and glacial drift overburden indicates that these overlying strata generally have small permeability, similar to the upper confining bed.

The rate of movement of ground water out of Audrain County via the deep aquifer was estimated from contoured predevelopment hydraulic-head data and a value for the hydraulic conductivity of the deep aquifer ($1.5X10^{-5}$ feet per second) estimated from a 24-hour single-well aquifer test in eastern Audrain County (unpublished data, 1980, U.S. Geological Survey, Rolla, Mo.). Again, for convenience, the model grid was used to calculate flow between grid cells across the county boundaries and the individual flow rates were summed to attain the resultant flow. The net flow out of the county was calculated to have been 2.0 cubic feet per second.

No hydraulic head measurements are available for formations below the lower confining bed; therefore, the historic direction of ground-water flow across the confining bed cannot be determined from field measurements. It is possible, however, to use the previous water-budget calculations to determine the probable direction of this flow and to estimate a probable range of vertical hydraulic conductivities appropriate for the lower confining layer. Flow into the deep aquifer through the upper confining layer was estimated at 2.4 cubic feet per second for the entire county and the net flow out of the county laterally through the deep aquifer was estimated at 2.0 cubic feet per second. Thus in the absence of sources or sinks, which are not present under steady-state predevelopment conditions, 0.4 cubic foot per second of water was leaking vertically downward from the deep aquifer, through the lower confining layer, into the Bonneterre Formation and Lamotte Sandstone.

An estimate of the vertical hydraulic conductivity of the lower confining layer can be made by applying Darcy's Law to ground-water flow through the layer:

$$Q = K' A I \qquad (3)$$

where Q is the volumetric flow rate of water through the confining layer (L^3T^{-1});

K' is the vertical hydraulic conductivity (LT^{-1});

A is the cross-section area of the flow path (L^2); and

I is the hydraulic gradient across the confining layer (dimensionless).

The leakage rate of 0.4 cubic foot per second is a total rate for Audrain County (A = 692 square miles). Because the Davis Formation is thought to be conformable with the Bonneterre Formation and Derby-Doerun Dolomite, it is assumed that the thickness of 160 feet (table 1) obtained from the penetration of the Davis by a single well in Audrain County is representative of its thickness throughout the county. Thus, assuming a potentiometric difference of 10 to 100 feet across the lower confining layer (not unreasonable in light of hydraulic-head differences supported by the Davis Formation in southeast Missouri) the vertical hydraulic conductivity of the Davis Formation is estimated at $1X10^{-10}$ to $1X10^{-11}$ feet per second.

DIGITAL MODEL OF THE DEEP AQUIFER

The potentiometric surface of the deep aquifer was simulated using a two-dimensional finite-difference model developed by Pinder (1970) and modified by Trescott and others (1976).

Because no hydraulic-head data are available for formations beneath the lower confining bed and because water-level measurements from wells completed in the shallow aquifer show virtually no variation during the irrigation season, indicating a weak hydraulic connection between the shallow and deep aquifer, it was determined that a three-dimensional model was neither practical nor necessary for the purpose of this study. The weak hydraulic connection and the small volume of ground-water pumpage from the shallow aquifer relative to pumpage from the deep aquifer has allowed the potentiometric surface of the shallow aquifer to remain relatively stable at the altitude of its prepumping configuration. Leakage through the upper confining bed is assumed proportional to the difference between fixed potentiometric heads in the shallow aquifer and simulated potentiometric heads in the deep aquifer.

Most irrigation, municipal, and industrial wells in and near Audrain County withdraw water from the deep aquifer because yields are much larger than from the shallow aquifer. Deep wells in Audrain County generally are open to a range of formations in the deep aquifer rather than a specific producing unit and occasionally are not cased to the upper confining bed; therefore, available data cannot be used to distinguish between horizontal and vertical hydraulic-head variations in the deep aquifer. The water-level measurements are assumed to represent the hydraulic head as if the wells were fully penetrating the deep aquifer. All changes in hydraulic heads from one well to another are assumed to be entirely due to horizontal variations of head within the aquifer.

Although the model was developed to investigate the ground-water resources of Audrain County, especially the effect of recent irrigation pumpage on the deep aquifer, the areal extent of the model has been expanded southward to the Missouri River (see fig. 1). This expansion permits the southern border of the model to be a relatively simple constant-head boundary condition based on the average stage of the Missouri River. It also places the major pumping centers of Columbia and Fulton interior to the model, thus eliminating the need for complex time-varying boundary conditions near the region of interest.

The model is calibrated to the predevelopment steady-state potentiometric surface of the deep aquifer and to transient potentiometric surfaces before and after the 1979 and 1980 irrigation seasons. During the calibration process the physical properties of the deep aquifer (horizontal hydraulic conductivity, storage coefficient, and specific yield) and the upper confining bed (vertical hydraulic conductivity) are adjusted to provide a better agreement between observed and simulated heads. The model is then used to project the probable consequences of continued ground-water withdrawal from the deep aquifer.

The model area is subdivided by a variable grid (fig. 21) containing 1,480 grid cells (37 rows by 40 columns). The cells range in size from 0.62 to 33.6 square miles; the smaller cells are located around the city of Mexico in central Audrain County. The cells become progressively larger toward the model boundaries, but the rate of change in their size is constrained so that truncation errors are minimized (Trescott and others, 1976, p. 30).

Boundary Conditions

Boundary conditions for this model consist of specified-head and specified-flow nodes, as shown on figure 21. The deep aquifer crops out along much of the southern boundary of the model area immediately north of the Missouri River in southern Boone, Callaway, and Montgomery Counties (see fig. 4). A potentiometric surface map of historic water levels (see fig. 15) and a map of the more recent water levels of the aquifer (see fig. 17) indicate ground-water flow is virtually perpendicular to the Missouri River along this reach. Hydraulic-head data south of the Missouri River show that ground-water flow in the deep aquifer is northward toward the river. Thus where the Missouri River penetrates the aquifer, the river valley is a ground-water valley as well as a surface-water valley, and ground water does not flow under the river. Two possible approaches to treating this southern boundary are: (1) Use a leakage variable that simulates the impedance encountered by water flowing through the intervening units from the deep aquifer to the Missouri River, or (2) use a specified-head condition based on the average stage of the Missouri River at each boundary node. A regional model of the deep aquifer in northeastern Missouri (Imes, 1984) tested the validity of assigning specified-head values to this aquifer along the Missouri River. The difference between assigning specified-heads and using leakage was determined to be insignificant; therefore a constant-head boundary is assumed to be valid for this model. In this model the specified-head boundary of the Missouri River is sufficiently distant from Audrain County that boundary conditions at the south edge of the model will not significantly affect water levels in Audrain County.

The north, west, and east sides of the model are treated as specified-flow boundaries. The volumetric flow of ground water into or out of each boundary grid cell was calculated by application of Darcy's Law across the boundary of active nodes (fig. 22):

$$Q_b = K\,(b\,\Delta y)\,\frac{h_1 - h_2}{\Delta X} \qquad (4)$$

where K is the aquifer hydraulic conductivity (LT^{-1});

b is the aquifer thickness at the boundary face (L);

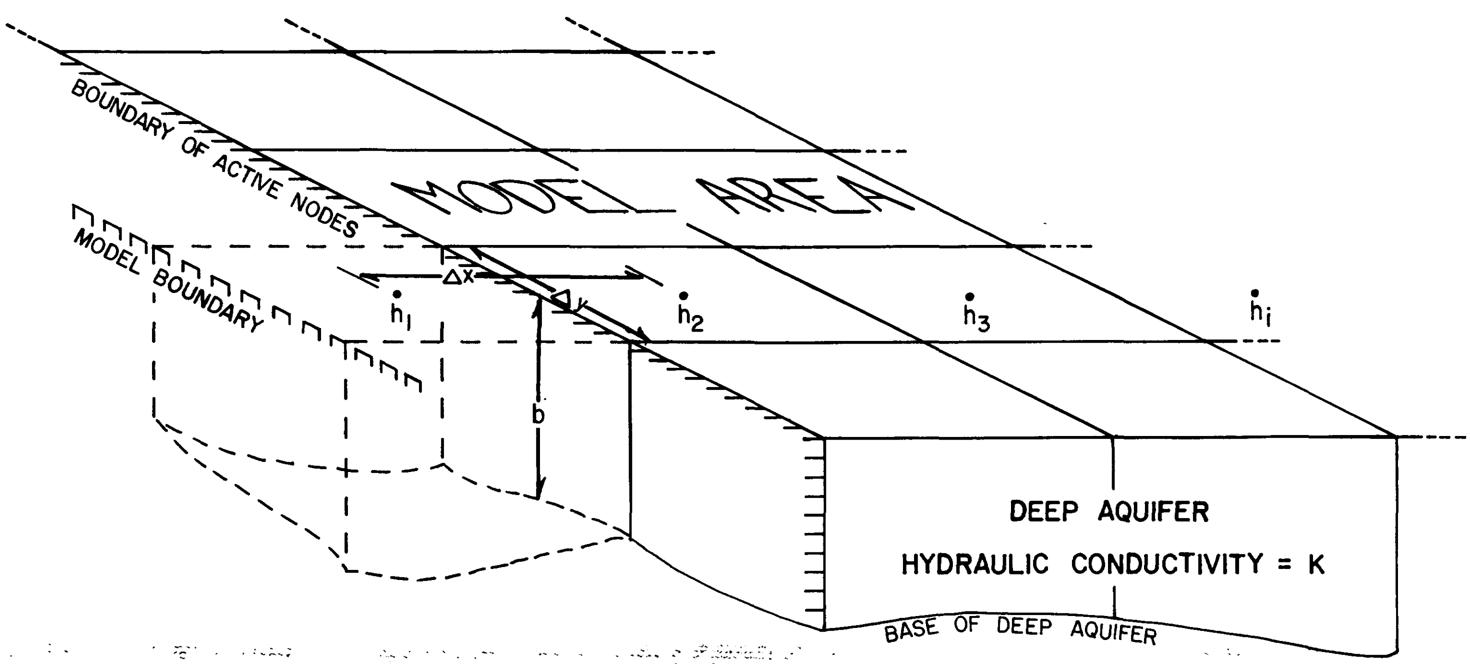
Δy is the length of cell edge coincident with the model boundary (L); and

$\frac{h_1 - h_2}{\Delta X}$ is the hydraulic gradient across the model boundary (dimensionless).

To estimate the boundary flow under predevelopment, steady-state conditions, the hydraulic gradient across the model boundary was derived using potentiometric head data from the predevelopment potentiometric surface map (see fig. 15). The hydraulic conductivity of the aquifer was determined during the steady-state calibration of the model. The rate at which ground water in the deep aquifer moved out of the model area across the western boundary, based on cell-to-cell calculations, was 1.36 cubic feet per second, and across the eastern boundary was 0.26 cubic foot per second. At the northern boundary, ground-water flow was into the model area at a rate of 0.11 cubic foot per second. Thus accounting for discharge to the Missouri River at 9.08 cubic feet per second, the net recharge to the deep aquifer in the model area from the shallow aquifer under steady-state conditions was 10.59 cubic feet per second.

Specified flows at the model boundaries determined from the steady-state calibration procedure were used as the initial boundary conditions in the stressed model. However, when pumping stresses are applied to the model, the boundary conditions can change with time, especially if significant drawdown occurs near the model boundaries. To improve the accuracy of the transient potentiometric surface simulations, the boundary-flow data were modified each decade as the effect of stresses within the model area migrated to the model boundaries.

$$Q_b = K(b\Delta y)\left(\frac{h_1 - h_2}{\Delta x}\right)$$



EXPLANATION

K HYDRAULIC CONDUCTIVITY OF DEEP AQUIFER

h_i HYDRAULIC HEAD IN THE DEEP AQUIFER AT THE ith MODEL NODE (L)

$b\Delta y$ CROSS-SECTIONAL AREA OF THE DEEP AQUIFER AT THE BOUNDARY FACE (L^2)

$\frac{h_1 - h_2}{\Delta x}$ HYDRAULIC GRADIENT AT THE MODEL BOUNDARY (DIMENSIONLESS)

Q_b VOLUMETRIC FLOW RATE

FIGURE 22.--VOLUMETRIC FLOW RATE AT THE MODEL BOUNDARY.

Specified flows at the boundaries were modified by first determining a set of boundary hydraulic-gradient values based on the May 1979 potentiometric-head map (see fig. 17). The associated boundary flow at this time was calculated using equation 4. Intermediate boundary-flow data were then generated by starting with the steady-state boundary conditions and observing the change of the near-boundary hydraulic gradients with time as stress was applied to the deep aquifer. When the simulated gradient adjacent to the model boundary changed from that of the previous period, the boundary condition was modified in the next pumping period to more closely resemble the characteristics of the May 1979 boundary-flow pattern. A set of graphs representing the time-varying volumetric flow rates for grid cells along the western boundary of the model are shown in figure 23. The lowermost plot represents the steady-state predevelopment boundary conditions. The flow rates remained the same during the first three pumping periods before the effect of pumping stresses migrated to the model boundary. Each higher graph represents a new set of boundary-flow conditions for the pumping period and time interval specified beneath the graph. The largest change in flow rate with time occurs at row numbers 24, 25, and 26 adjacent to the area of large ground-water withdrawal around the city of Columbia in central Boone County. Positive flow rates indicate ground-water flow into the model area.

The specified-flow boundary at the north edge of the model was treated similar to the west boundary, but the flow rates do not vary in time as much as those near Columbia and the direction of flow remains constant. Modification of the northern boundary flow rates from predevelopment values does not begin until pumping period 9 (1970) when the expanding cone of depression around Mexico reaches the northern boundary. The specified-flow boundary along the eastern edge of the model does not vary with time, but remains constant at the predevelopment, steady-state flow rates.

The base of the deep aquifer is treated as an impermeable barrier. Leakage between the deep aquifer and underlying Lamotte Sandstone probably does occur, but there are no potentiometric-head measurements or other data that can be used to verify whether leakage occurs or quantify the volume of leakage.

Model Calibration

The ground-water model was calibrated by adjusting hydrologic variables until the simulated hydraulic heads and potentiometric surfaces approximated measured water levels and potentiometric surfaces mapped from water-level measurements. The model was calibrated against the historical prepumping potentiometric surface and to selected water levels from wells drilled at the early stages of the deep aquifer's development as a ground-water source. The calibration was then extended to include simulation of four recent potentiometric surface configurations (May 1979, October 1979, May 1980, and September 1980) and water-level measurements at 12 wells located in Audrain County.

Steady-State

The purpose of the first model calibration was to approximate the steady-state potentiometric surface mapped from water levels measured before significant quantities of water had been withdrawn from the aquifer. Both the hydraulic conductivity of the aquifer (K), and the vertical hydraulic

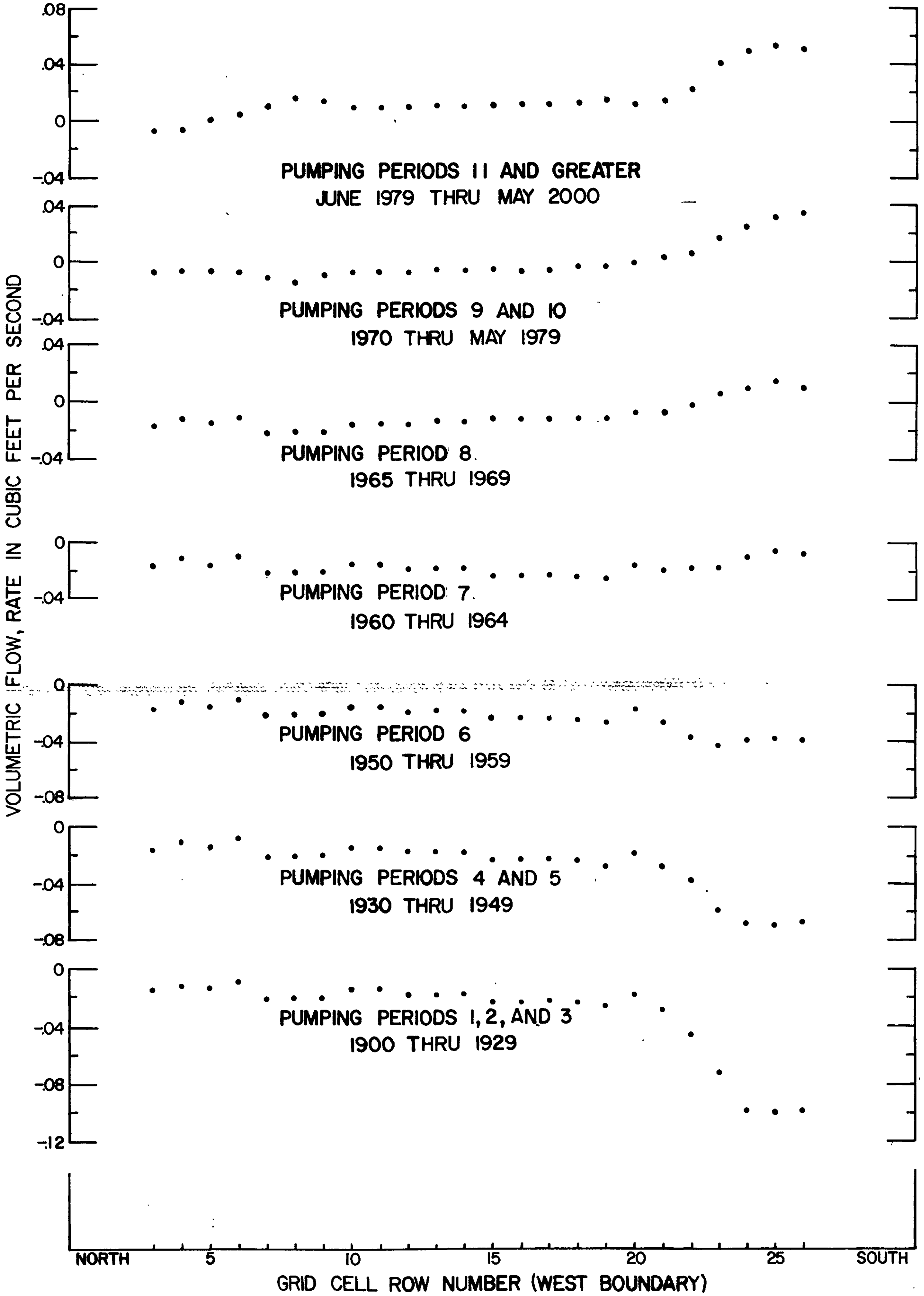


FIGURE 23.--SPECIFIED-FLOW BOUNDARY CONDITIONS AT THE WEST BOUNDARY OF THE MODEL.

conductivity of the confining bed (K') were adjusted in this process. A uniform hydraulic conductivity of 1.5×10^{-5} foot per second was used as the initial estimate of this variable in the preliminary model. This value was derived from the results of a single-well aquifer test in Audrain County. This initial hydraulic conductivity was adjusted until a reasonable representation of the predevelopment potentiometric surface was simulated. The calibration was then refined to more accurately simulate the potentiometric surface by spatially varying the hydraulic conductivity throughout the model. During the steady-state calibration, the volumetric flow across each constant-flow boundary cell was recalculated before each trial calibration to be consistent with the aquifer hydraulic conductivity at the border cell.

The vertical hydraulic conductivity of the upper confining bed was calculated from estimates of the individual vertical hydraulic conductivities of the shale and limestone confining layers (see figs. 8 and 9) using the series relationship:

$$\frac{K'}{m} = \left(\sum_i \frac{m_i}{K'_i} \right)^{-1} \qquad (5)$$

where K' is the effective vertical hydraulic conductivity of the upper confining bed, (LT^{-1});

m is the total thickness of the upper confining bed, (L);

K'_i is the vertical hydraulic conductivity of the ith confining layer (LT^{-1}); and

m_i is the thickness of the ith confining layer (L).

The ratio K'/m is defined as the leakage coefficient of the confining bed. The vertical hydraulic conductivity of the shale confining layer was originally set to 7.7×10^{-11} foot per second, a value approximating that published by Walton (1960, 1965) for the Maquoketa Shale in Illinois. The relatively impermeable Devonian limestones were assumed to be 10 times more permeable than the shale. Initially, trial simulations using an aquifer conductivity fixed at 1.5×10^{-5} foot per second and several different combinations of vertical hydraulic conductivity for the confining layers were made until the steady-state potentiometric surface was approximated. Thereafter, only the effective vertical hydraulic conductivity of the entire confining bed was treated as a variable during the model calibration.

To decrease the number of variables and decrease the possibility of rapid variations of the variables within small distances, the model was subdivided into zones and hydraulic conductivities were treated as single variables throughout each zone rather than adjusting their values at each node. Zone boundaries generally coincided with the terminus of the shale confining units of the upper confining bed (see fig. 6). The final values of aquifer hydraulic conductivity ranged from 6×10^{-6} to 1×10^{-5} foot per second, which are within acceptable percentages of the hydraulic conductivity determined from the aquifer-test data (1.5×10^{-5} foot per second). The effective vertical hydraulic conductivity of the upper confining bed ranged from 1.5×10^{-11} to 2.4×10^{-10} foot per second in the calibrated model.

Comparison of the simulated and measured steady-state potentiometric surface is shown in figure 24. The two surfaces differ by less than 5 feet throughout most of Audrain County, increasing to about 20 feet in the extreme northeast. The larger differences in the northeastern corner of the county may be caused by inaccurate boundary conditions.

The distribution of transmissivity in the deep aquifer, as determined by the model calibration, ranges from 7.1×10^{-3} to 13.1×10^{-3} feet squared per second (fig. 25). Generally, the transmissivity is smaller in northern Audrain County and along a north-south trend in the central part of the county. The areas of largest transmissivity occur in the southwest and southeast. The larger transmissivity in the southeast is due partly to the increased thickness of the aquifer in that region, whereas that in the southwest is related to as increase in the aquifer's hydraulic conductivity.

To determine whether the presence of shale in the upper confining layer was the dominant factor determining the distribution of leakage, an areal map of the volumetric leakage per unit area through the confining layer under predevelopment conditions was prepared (fig. 26). Leakage increases from north to south across Audrain County, but does not appear to mirror the distribution of shale confining layers. The area of maximum leakage is in southwestern Audrain County at the edge of the shale confining layers and near the area of maximum hydraulic gradient across the confining bed.

Transient

The model was calibrated under transient conditions by stressing the deep aquifer at historical pumping rates (fig. 16 and tables 2 and 3) and refining model variables until a best match was obtained between simulated and measured potentiometric surfaces and water levels during the spring of 1979 (before irrigation), fall of 1979 (after the irrigation season), and the spring and fall of 1980. In addition to the aquifer hydraulic conductivity and the vertical hydraulic conductivity of the upper confining bed, two new variables were introduced to the model during the transient calibration: (1) Specific yield (Sy), a measure of the storage capacity of unconfined aquifers; and (2) storage coefficient (S), a measure of the storage capacity of confined aquifers. Variations in specific yield values during calibration primarily affected the regional water-level configuration; that is, the general altitude of water levels in areas removed from the major pumping centers. This occurs because a considerable area along the southern boundary of the model converts from confined to unconfined conditions as ground water is pumped from the aquifer. The model replaces the deep aquifer's storage coefficient with a specific yield at each node where conversion takes place. Variations in storage coefficient during the model calibration mostly affected the rate at which cones of depression expanded and shrank. This pattern was most apparent in the rate at which water levels recovered from irrigation pumpage between irrigation seasons. The specific yield and storage coefficient variables used in the transient calibration ranged from 0.01 to 0.02, and 0.0001 to 0.0002.

A comparison between the May 1979 simulated and measured potentiometric surfaces (fig. 27) shows the surfaces agree within about 25 feet throughout much of the model area. The simulated surface approximates the measured cone of depression around Mexico and Centralia. The simulation is not as accurate in the immediate vicinity of Columbia where the model grid cells are 12 times larger than those around Mexico. Although the simulated 575-foot potentiometric contour closes around Mexico instead of opening toward the Columbia cone of depression, the actual difference between the measured and simulated potentiometric surfaces midway between Mexico and Columbia is no more than 10 feet. In Audrain County the largest discrepancies between the potentiometric surfaces occur in the eastern one-quarter of the county where simulated heads are greater than measured heads. Water-level measurements made during 1977 and 1978 in irrigation wells located within this area show some irrigation pumpage existed before 1979. There are no records to indicate how many newly drilled wells were used during the summers of 1977 and 1978; no data are available to incorporate this information into the model. As a result, the model does not depict the effect of the early stages of irrigation pumpage in Audrain County. The simulated water-level decline in the deep aquifer for May 1979 from the prepumping potentiometric configuration is shown in figure 28.

The simulated drawdown in the vicinity of Mexico, before the onset of irrigation pumping, is 200 to 225 feet. By comparison, the actual drawdown computed from measured water levels shown in figures 15 and 17 is approximately 225 to 250 feet. The stipled area in figure 28 shows the part of the deep aquifer that was unconfined during May 1979 primarily due to pumpage at Columbia and Fulton.

Comparisons between simulated and measured water levels in Audrain County during October 1979, May 1980, and September 1980 are shown in figures 29, 30 and 31, respectively. By October 1979, the potentiometric surface had begun to recover from drawdown caused by pumpage during the 1979 irrigation season (June through August), but still showed considerable drawdown near the concentration of irrigation wells in southeastern Audrain County. The water levels continued to recover until May 1980, at which time simulated regional water levels in Audrain County had risen to within 10 to 15 feet of their levels during May 1979. By September 1980, a broad cone of depression had again developed around the cluster of irrigation wells in southeastern Audrain County. The maximum simulated decline in water level during the irrigation period was about 100 feet and the maximum-measured drawdown was about 75 feet. In each case, October 1979, May 1980, and September 1980, the potentiometric surfaces of the calibrated model showed general agreement with the measured surfaces, but details of the actual potentiometric surfaces are not shown by the model. Comparison of simulated and measured potentiometric surfaces for these transient calibrations is limited to Audrain County after May 1979 because of the lack of measured potentiometric heads in the remainder of the model area.

Reliability and Sensitivity

The accuracy with which measured water levels are simulated by a given model is a measure of the accuracy of the hydraulic variables and the reliability of the model as a predictor of the effects of future pumpage on the aquifer's potentiometric surface. During the calibration of the model, the ability of the model to simulate measured water levels at selected well locations was improved.

Eight of the water levels used to estimate the potentiometric surface in the deep aquifer before extensive development of its ground-water resources (see fig. 15) were chosen to compare the accuracy of the model in predicting the effect of the early stages of ground-water withdrawal from the deep aquifer.

The criteria for choosing the wells were that they were the earliest measurements available and were located in or near Audrain County. A plot of the measured versus simulated hydraulic heads for these wells (fig. 32) shows a uniform scatter of data about the line of equal-measured and simulated heads. The simulated data are not taken from the modeled steady-state condition, but from the transient model at the year the water-level measurements were made. Simulated data are available only at 10-year intervals; therefore, data for other years are computed by linear interpolation of simulated head values at the beginning and end of the appropriate decade. The mean error between the simulated and measured data is 8.3 feet and the average percent of error is about 1.3 percent.

The sensitivity of a model to variations in a particular hydrologic variable can be used to evaluate the reliability of the model-derived variable. A 50 percent increase in the hydraulic conductivity of the aquifer from the value obtained during the model calibration decreases the simulated steady-state water level a maximum of 21 feet in northwest Boone County. In Audrain County water levels decline 15 to 20 feet, except in the east where they decline 5 to 15 feet. Under the steady-state conditions the aquifer hydraulic conductivity and confining bed vertical hydraulic conductivity are not independent variables, but mathematically occur as a ratio. A 50 percent increase in vertical hydraulic conductivity increases the simulated heads by the same magnitude as the changes produced by varying the aquifer hydraulic conductivity by 50 percent. The vertical bars in figure 32 represent the range of water levels simulated by the model when the hydraulic conductivity of the deep aquifer is increased or decreased by 50 percent. A 50 percent increase in aquifer conductivity decreases the simulated water levels to the values at the bottom of the bars, and a 50 percent decrease in aquifer conductivity increases simulated water levels to the values at the tops of the bars. Neither extreme of the vertical bars fit the line that depicts equal simulated and measured heads as well as the heads computed from the calibration aquifer conductivity; therefore, the ratio of the calibration aquifer conductivity and confining bed vertical hydraulic conductivity probably are in error by no more than 50 percent.

Water-level measurements also were chosen as specific calibration points from May 1979 to September 1980 when water levels began to fluctuate seasonally due to irrigation pumpage. The wells are areally distributed across Audrain County to better represent the distribution of water levels in the county. An attempt was made to choose wells that were approximately located at the center of a model grid cell and that were the only well within a cell. The comparison of measured and simulated water levels for these 12 wells for each calibration (fig. 33, upper graph) again shows a uniform distribution about the line of equal simulated and measured water levels. For May 1979, the mean error between the measured and simulated heads is 19.5 feet, which represents a 3.5 percent average error at these wells. The mean error decreases slightly to 15.4 feet, 15.4 feet, and 16.4 feet for the October 1979, May 1980, and September 1980 data, respectively. The mean error in September 1980 corresponds to about 3.0 percent average error. No attempt was made to simulate any one of the four transient calibration times in preference to the others; instead, the calibration variables were adjusted for the best average fit to the potentiometric surface and measured water levels for all the calibrations.

A graph showing the relative values of simulated and measured drawdown during the 1979 and 1980 irrigation seasons (fig. 33, lower graph) shows a bias in the distribution of points about the line of equal measured and simulated

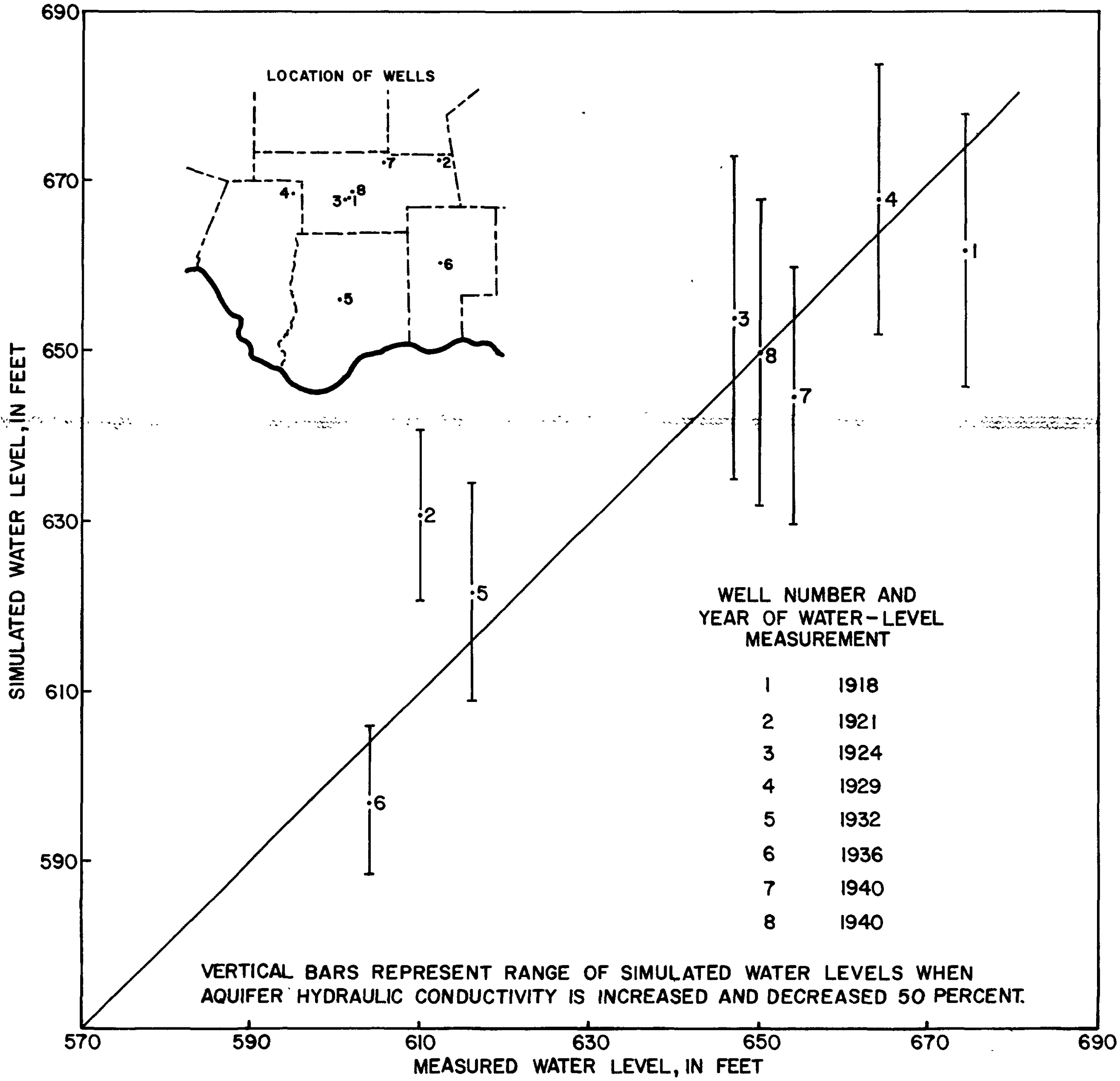


FIGURE 32.--COMPARISON OF MEASURED AND SIMULATED WATER LEVELS AT SELECTED WELLS IN THE MODEL AREA PRIOR TO EXTENSIVE AQUIFER DEVELOPMENT.

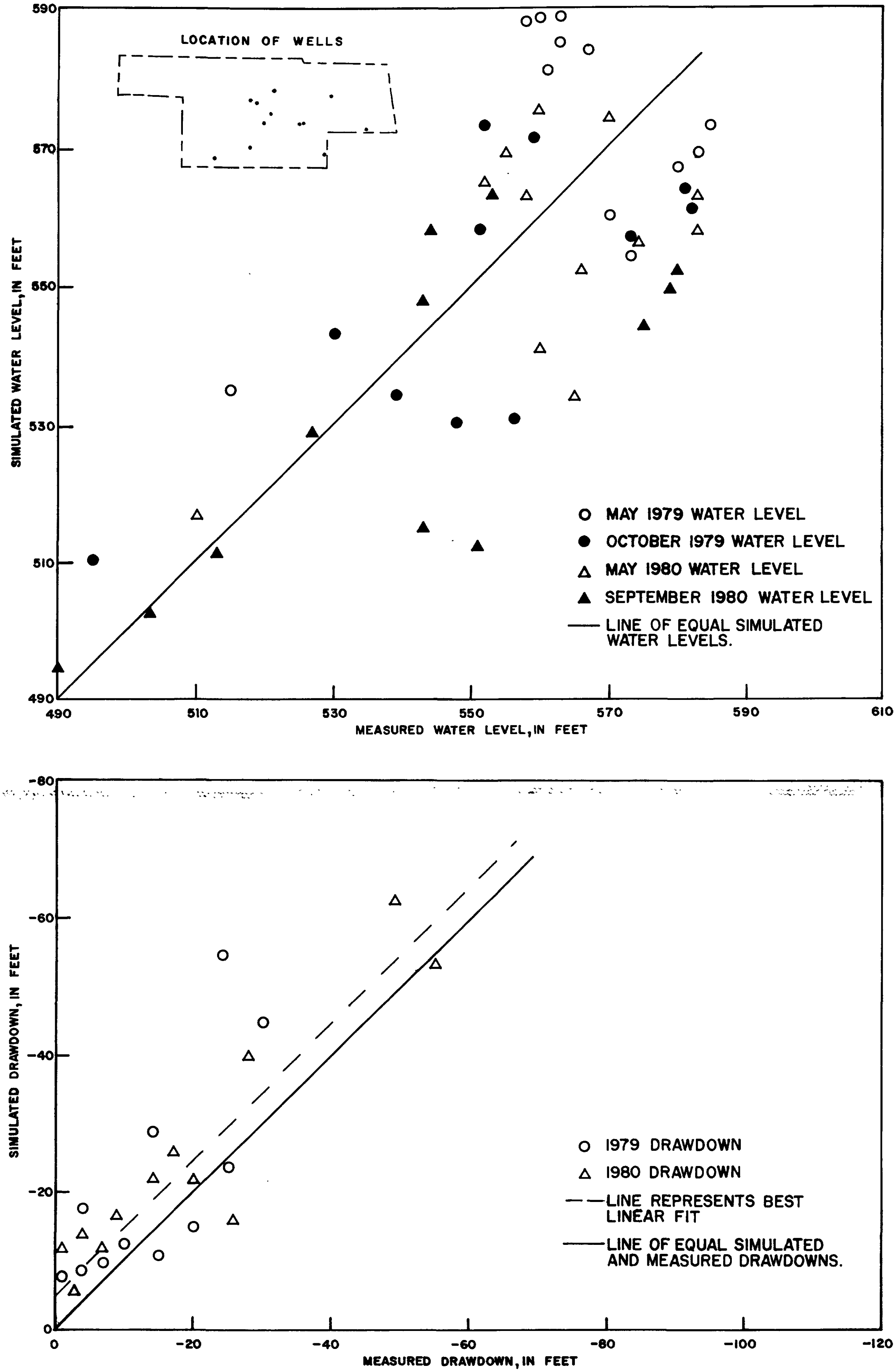


FIGURE 33.--COMPARISON OF MEASURED AND SIMULATED WATER LEVELS AND DRAWDOWNS FOR 1979 AND 1980 AT SELECTED WELLS IN AUDRAIN COUNTY.

drawdown. The mean error in drawdown is 8.0 feet and 7.8 feet for 1979 and 1980, respectively. The average percent errors for the data are 35.8 percent and 30.8 percent, relatively large compared to the average percentage of error in simulated and measured heads. The dashed line represents a better linear fit to the data and indicates the error is biased such that simulated drawdowns at these wells generally are about 7 feet too large. The error in drawdown simulation does not increase from the 1979 to 1980 irrigation seasons.

Model Results and Projections

The ground-water model of the deep aquifer was designed with the constraint that no water could pass through the lower confining bed; that is, the base of the deep aquifer was impermeable. In the steady-state model this constraint means the net volumetric flow of water through the upper confining bed in Audrain county must equal the net flow of water across the county boundaries. The model-calculated leakage through the upper confining bed in Audrain County is 1.0 cubic foot per second, 42 percent of the quantity calculated from estimates of shale and limestone leakage coefficients and aquifer hydraulic conductivity (see "Estimate of Recharge, Discharge, and Lateral Flow of Ground Water Under Predevelopment Conditions"). Net flow across the county boundary through the deep aquifer also was calculated to be 1.0 cubic foot per second (50 percent of the estimated flow).

By May 1979, before extensive irrigation, Audrain County had changed from a net exporter to a net importer of ground water. Net leakage to the deep aquifer through the upper confining bed increased to 2.6 cubic feet per second as ground-water pumpage from the deep aquifer lowered water levels and simultaneously increased the hydraulic gradient across the confining bed. Net flow crossing the county boundary through the deep aquifer during May 1979 is 0.7 cubic foot per second into the county. Therefore, pumpage since the turn of the century has altered the ground-water flow system in the deep aquifer such that ground water now flows into Audrain County rather than flowing from Audrain County to neighboring counties.

The calibrated model was used to simulate the long-range effects of irrigation ground-water withdrawal on water levels in the deep aquifer in Audrain County. Two projections were made: (1) Assuming continued public-supply and irrigation pumpage at the 1980 rate; and (2) assuming only public-supply pumpage. Both conditions were simulated to May 2000, and in both situations the regional water levels began stabilizing by 1990. A map depicting the simulated water-level changes in the deep aquifer from June 1979 thru May 2000 due to combined public-supply and irrigation pumping is shown in figure 34. By May 2000, water levels in central Audrain County will have declined by about 60±20 feet from May 1979 water levels. The uncertainty in this decline is derived from the estimated 30 to 35 percent error in simulated drawdown calculated using 1979 and 1980 simulated and measured irrigation drawdown. The region of maximum decline will be located around Mexico. Long-term trends in the regional water level can be clearly distinguished from the periodic seasonal fluctuations caused by irrigation pumpage (fig. 35). East of Mexico the water levels will annually rise and fall by about 23±8 feet due to the seasonal irrigation pumpage. Generally, the regional potentiometric surface in central Audrain County will decline at a rate of 0.7 foot per year from 1990 to 2000.

In the absence of irrigation wells, the area of greatest water-level declines from June 1979 thru May 2000 will not be located in central Audrain County but will be at the west boundary (fig. 36). The rate of decline of simulated water levels near Mexico had already decreased considerably by 1979 and the additional decrease without irrigation pumpage would be only about 20 feet during the next 20 years. Water levels in central Audrain County would remain 20 to 60 feet higher without the additional stress imposed by the irrigation pumpage. Much of the water-level decline in Audrain County under these assumptions results from continued drawdown at Centralia near the western edge of the county.

CHEMICAL QUALITY OF GROUND WATER IN THE DEEP AQUIFER

The chemical quality of ground water tends to remain more stable than surface water; however, ground water in Missouri usually has a greater concentration of dissolved solids than surface water, because it is in contact with the rocks and soil longer than surface water. Natural waters always contain dissolved solids in varying concentrations. Examples of the wide range of concentrations of dissolved solids in water are shown in table 4 (modified from Swenson and Baldwin, 1965). The concentration of dissolved solids in ground water is determined by the concentration in the influent water and the chemical composition of the rocks through which the water moves. The concentration of chemical species in ground water also is dependent on the length of time the water remains in contact with the rocks, a function of the rock permeability, the hydraulic gradient, and the length of the ground-water flow path from the recharge area to the point of discharge.

The U.S. Geological Survey classifies freshwater as containing less than 1,000 milligrams per liter of dissolved solids. The classification of saline water is shown in table 5 (Robinove and others, 1958). A generalized description of the distribution of freshwater and saline water in the Cambrian-Ordovician rocks of Missouri is shown in figure 1. Water from the deep aquifer north and west of the Audrain County area generally has a dissolved-solids concentration between 1,000 and 10,000 milligrams per liter, but some samples have concentrations of more than 40,000 milligrams per liter (Imes, 1984; and Fuller and others, 1967). Most of the water having a large dissolved-solids concentration is a sodium chloride type. Water from rocks of the deep aquifer south of the 1,000-milligram-per-liter line in northern Missouri (fig. 1) generally is a calcium magnesium bicarbonate type. Between these two types of water is a transition zone where the water contains various mixtures of sodium, calcium, magnesium, bicarbonate, chloride, and sulfate.

As part of this investigation, samples of water from the deep aquifer were analyzed to determine the chemical quality of the water and to evaluate its suitability for domestic and irrigation use. Location of wells sampled and the types of water from selected wells that are completed in the deep aquifer are shown in figure 37. Results of the analyses are given in table 6, and sources and significance of most dissolved-mineral constituents are given in table 7.

Of the 26 samples analyzed for this study, 9 (about 35 percent) exceed the recommended limit for drinking water of 500 milligrams per liter dissolved-solids concentration (U.S. Environmental Protection Agency, 1976). However, in areas of the United States where less mineralized water is not available, water containing more than 1,000 milligrams per liter of dissolved solids has been used for drinking without obvious detrimental effects on public health (Hem, 1970, p. 323).

Table 4.--Examples of the dissolved-solids concentration in natural waters

[Modified from Swenson and Baldwin, 1965]

Source of water	Dissolved-solids concentration, in milligrams per liter
Rain	10
Missouri River	360
Ocean	35,000
Brine well	125,000
Dead Sea	250,000

Table 5.--Classification of water by dissolved-solids concentration

Classification	Dissolved-solids concentration, in milligrams per liter
Slightly saline	1,000 to 3,000
Moderately saline	3,000 to 10,000
Very saline	10,000 to 35,000
Brine	More than 35,000

Table 6.--Chemical analyses of water from wells

[Irrigation wells analyses by U.S. Geological Survey; μmho, micromho per centimeter at 25° Celsius; Deg C, degrees Celsius; mg/L, milligrams per liter; μg/L, micrograms per liter]

Map no. (fig. 37)	Station number	Date of sample	Depth of well, total (feet)	Specific conductance (μmho)	pH (units)	Temperature (Deg C)	Hardness (mg/L as $CaCO_3$)	Hardness noncarbonate (mg/L $CaCO_3$)	Calcium dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as mg)	Sodium, dissolved (mg/L as Na)	Sodium adsorption ratio
1	390723091424401	80-07-16	--	750	7.6	21.0	270	0	60	29	55	1.5
2	390730091423001	80-07-15	1,410	850	7.6	18.5	270	0	61	29	74	2.0
3	390733091384301	80-07-16	1,240	1,120	7.6	21.5	260	0	57	28	140	3.8
4	390759091415601	80-07-16	1,440	780	7.6	19.5	260	0	59	28	62	1.7
5	390813091482201	80-07-16	--	630	7.8	21.0	280	0	67	28	21	.5
6	390814091391401	80-07-16	1,430	1,075	7.9	22.0	260	0	59	28	130	3.5
7	390815091424001	80-07-16	1,172	740	7.6	21.5	270	0	61	29	52	1.4
8	390833091550801	80-07-16	1,490	800	7.8	21.0	290	0	65	31	61	1.6
9	390904091372901	80-07-15	1,380	1,130	7.3	22.0	320	0	73	33	110	2.7
10	390907091383701	80-07-16	1,440	1,070	7.7	21.0	330	0	75	35	110	2.6
11	390957091374301	80-07-15	1,485	1,140	7.6	20.0	330	0	75	34	100	2.4
12	391305091405901	80-07-16	1,610	1,020	7.6	21.0	330	0	73	36	110	2.6
13	391305091405901	80-07-15	1,400	800	7.5	19.0	370	0	86	38	120	2.7
14	391529092131201	80-07-15	1,270	1,320	7.5	19.5	350	5	79	37	130	3.0
15	391543092071701	80-07-15	1,400	1,350	7.9	20.5	320	0	71	35	150	3.6
			Minimum	630	7.3	18.5	260	0	57	28	21	.5
			Maximum	1,350	7.9	22.0	370	5	86	38	150	3.8
			Median	1,020	7.6	21.0	290	0	67	31	110	2.6

Table 6--Chemical analyses of water from wells--continued

[Public-supply water analyses by Missouri Division of Environmental Quality]

Map no. (fig. 37)	Station number	Date of sample	Depth of well, total (feet)	pH (units)	Temperature (Deg C)	Hardness (mg/L as $CaCO_3$)	Hardness noncarbonate (mg/L $CaCO_3$)	Calcium dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as mg)	Sodium, dissolved (mg/L as Na)	Sodium adsorption ratio	Potassium, dissolved (mg/L as K)
16	383543092103001	70-03-25	935	7.9	15.5	244	0	58	24	54	--	5.4
17	385122091570501	64-05-11	1,175	7.1	--	298	0	67	32	34	--	7.4
18	385244091230101	70-07-06	1,005	7.9	--	280	82	78	39	69	--	8.0
19	385746092183401	63-12-11	1,200	7.2	--	288	0	57	36	48	--	8.2
20	385854091303001	68-11-07	1,150	7.3	--	260	0	66	23	140	--	14
21	390548091384301	71-04-23	1,150	7.8	--	242	0	50	28	130	--	14
22	390748091243601	71-07-20	620	7.4	--	180	0	37	22	200	6.4	19
23	390841092273201	71-05-13	1,100	7.7	--	331	150	110	40	328	--	15
24	391243092075001	71-03-08	1,375	7.0	--	299	0	60	31	69	--	13
25	391620091043501	64-10-20	630	7.4	--	256	0	60	28	300	--	19
26	392818092123601	71-06-21	680	7.7	--	262	0	46	36	188	5.0	15
			Minimum	7.1		180	0	37	22	34		5.4
			Maximum	7.9		331	159	118	48	328		19
			Median	7.7		262	0	66	31	140		14

Table 6.--Chemical analyses of water from wells--continued

Map no. (fig. 37)	Station number	Date of sample	Potassium, dissolved (mg/L as K)	Bicarbonate, (mg/L as HCO_3)	Carbonate, (mg/L as CO_3	Alkalinity field (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Solids, sum of constituents, dissolved (mg/L)	Nitrogen, nitrate total (mg/L as N)
1	390723091424401	80-07-16	11	400	0	330	69	12	2.0	8.5	444	0.00
2	390730091423001	80-07-15	10	400	0	330	83	29	2.0	9.1	494	.01
3	390733091384301	80-07-16	13	430	0	350	130	67	2.7	9.0	659	.00
4	390759091415601	80-07-16	11	400	0	330	71	19	2.0	8.4	458	.00
5	390813091482201	80-07-16	4.0	390	0	320	29	5.1	.9	9.6	357	.00
6	390814091391401	80-07-16	13	420	0	340	120	66	2.5	8.9	634	.00
7	390815091424001	80-07-16	10	410	0	340	57	16	1.8	8.5	437	.00
8	390833091550801	80-07-16	11	420	0	340	54	31	1.6	8.7	470	.00
9	390904091372901	80-07-15	11	430	0	350	130	77	1.8	8.9	657	.00
10	390907091383701	80-07-16	10	450	0	370	110	78	1.5	9.1	650	.00
11	390957091374301	80-07-15	10	430	0	350	120	82	1.4	8.9	643	.00
12	391238091492101	80-07-16	15	430	0	350	120	80	1.8	9.0	657	.00
13	391305091405901	80-07-15	10	470	0	390	140	110	1.5	9.2	746	.00
14	391529092131201	80-07-15	12	420	0	340	170	80	1.7	8.9	726	.00
15	391543092071701	80-07-15	14	450	0	370	110	150	2.2	9.0	763	.00
		Minimum	4.0	390	0	320	29	5.1	.9	8.4	357	.00
		Maximum	15	470	0	390	170	150	2.7	9.6	763	.01
		Median	11	420	0	340	110	67	1.8	8.9	643	.00

Table 6.--Chemical analyses of water from wells--continued

Map no. (fig. 37)	Station number	Date of sample	Bicarbonate (mg/L as HCO_3)	Carbonate, (mg/L as CO_3	Alkalinity field (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Solids, residue at 180 Deg C dissolved (mg/L)
16	383543092103001	70-03-25	352	0	289	35	29	1.1	5.0	477
17	385122091570501	64-05-11	388	0	318	52	13	1.0	8.0	420
18	385244091230101	70-07-06	336	0	276	160	42	1.9	8.0	670
19	385746092183401	63-12-11	371	0	304	34	43	1.2	9.0	471
20	385854091303001	68-11-07	431	0	353	150	57	1.9	10	730
21	390548091384301	71-04-23	444	0	365	110	22	2.4	6.0	634
22	390748091243601	71-07-20	567	0	465	150	11	1.0	6.0	888
23	390841092273201	71-05-13	403	0	331	112	548	.9	10	1,602
24	391243092075001	71-03-08	403	0	331	64	65	1.2	8.0	500
25	391620091043501	64-10-20	565	0	460	292	139	5.0	8.0	1,206
26	392818092123601	71-06-21	444	0	365	105	139	1.6	6.0	812
		Minimum	336	0	276	34	11	.9	5.0	420
		Maximum	567	0	465	292	548	5.0	10	1,602
		Median	403	0	331	110	43	1.2	8.0	678

Table 6.--Chemical analyses of water from wells--continued

Map no. (fig. 37)	Station number	Date of sample	Boron, total recov-erable (µg/L as B)	Iron, total recov-erable (µg/l as Fe)	Manga-nese, total recov-erable (µg/L as Mn)
1	390723091424401	80-07-16	740	120	0
2	390730091423001	80-07-15	890	90	0
3	390733091384301	80-07-16	1,500	790	10
4	390759091415601	80-07-16	770	120	0
5	390813091482201	80-07-16	140	260	0
6	390814091391401	80-07-16	1,300	170	10
7	390815091424001	80-07-16	620	90	0
8	390833091550801	80-07-16	710	100	0
9	390904091372901	80-07-15	1,100	110	0
10	390907091383701	80-07-16	1,000	150	20
11	390957091374301	80-07-15	920	260	0
12	391238091492101	80-07-16	1,400	120	10
13	391305091405901	80-07-15	920	110	10
14	391529092131201	80-07-15	870	80	0
15	391543092071701	80-07-15	1,200	120	10
		Minimum	140	80	0
		Maximum	1,500	790	20
		Median	920	120	0

Table 6.--Chemical analyses of water from wells--continued

Map no. (fig. 37)	Station number	Date of sample	Nitrogen, nitrate total (mg/L as NO_3)	Iron (µg/L as Fe)	Manganese (µg/L as Mn)
16	383543092103001	70-03-25	0.00	450	0
17	385122091570501	64-05-11	.20	2,000	0
18	385244091230101	70-07-06	.30	350	0
19	385746092183401	63-12-11	.00	170	--
20	385854091303001	68-11-07	.00	200	0
21	390548091384301	71-04-23	6.0	50	0
22	390748091243601	71-07-20	1.3	300	0
23	390841092273201	71-05-13	.00	1,500	0
24	391243092075001	71-03-08	.00	70	0
25	391620091043501	64-10-20	2.5	1,100	0
26	392818092123601	71-06-21	1.8	60	0
		Minimum	.00	50	0
		Maximum	6.0	2,000	0
		Median	.20	300	0

Table 7.--Major chemical constituents in water--their sources, concentrations, and effects on usability

[Concentrations, in milligrams per liter]

Constituents and properties	Major sources[1]	Concentration in natural water[1]	Effect upon usability of water[1]	Concentration in water from deep aquifer in Audrain County area[2] Maximum	Minimum	Median	Drinking water standards
Silica (SiO_2)	Feldspars, ferromagnesian and clay minerals, amorphous silicachert, opal.	Generally ranges from 1.0 to 30; although as much as 100 is fairly common; as much as 4,000 is found in brines.	In the presence of calcium and magnesium, silica forms a scale in boilers and on steam turbines that retards heat; the scale is difficult to remove. Silica may be added to soft water to inhibit corcorosion of iron pipes.	9.6	8.4	8.9	
Iron (Fe)	1. Natural sources: Igneous rocks: Amphiboles, ferromagnesian micas, ferrous sulfide (FeS), ferric sulfide or iron pyrite (FeS_2), magnetite (Fe_3O_4). Sandstone rocks: Oxides, carbonates, and sulfides of iron clay minerals. 2. Manmade sources: Well casing, piping, pump parts, storage tanks, and other objects of cast iron and steel which may be in contact with the water. Industrial Wastes.	Generally less than 0.50 in fully aerated ground water having a pH less than 8.0 may contain 10; rarely as much as 50 may occur. Acid water from thermal spring, mine wastes, and industrial wastes may contain more than 6,000.	More than 0.1 precipitates after exposure to air; causes turbidity, stains plumbing fixtures, laundry and cooking utensils, and imparts objectionable tastes and colors to foods and drinks. More than 0.2 is objectionable for most industrial uses.	0.79	0.08	0.12	0.3[3]
Manganese (Mn)	Managanese in natural water probably comes most often from soils and sediments. Metamorphic and sedimentary rocks and mica biotite and amphibole hornblende minerals contain large quantities of manganese.	Generally 0.20 or less. Ground water and acid mine water may contain more than 10. Reservoir water that has "turned over" may contain more than 150.	More than 0.2 precipitates upon oxidation; causes undesirable tastes, deposits on foods during cooking, stains plumbing fixtures and laundry, and fosters growths in resevoirs, filters, and distribution systems. Most industrial users object to water containing more more than 0.2.	0.02	0	0	0.05[3]
Calcium (Ca)	Amphiboles, feldspars, gypsum, pyroxenes, aragonite, calcite, dolomite, clay minerals.	As much as 600 in some western streams; brines may contain as much as 75,000.	Calcium and magnesium combine with bicarbonate, carbonate, sulfate, and silica to form heat-retarding, pipe-clogging scale in boilers and in other heat-exchange equipment. Calcium and magnesium combine with ions of fatty acid in soaps to form soap suds; the more calcium and magnesium, the more soap required to form suds. A high concentration of magnesium has a laxative effect, especially on new users of the supply.	86	57	67	
Magnesium (Mg)	Amphiboles, olivine, pyroxenes, dolomite, magnesite, clay minerals.	As much as several hundred in some western streams; ocean water contains more than 1,000 and brines may contain as much as 57,000.		38	28	31	
Sodium (Na)	Feldspars (albite); clay minerals; evaporites, such as halite (NaCl) and mirabilite ($Na_2SO_4 \cdot 10H_2O$); Industrial Wastes.	As much as 1,000 in some western streams; about 10,000 in sea water; about 25,000 in brines.	More than 50 sodium and potassium in the presence of suspended matter causes foaming, which accelerates scale formation and corrosion in boilers. Sodium and potassium carbonate in recirculating cooling water can cause deterioration of wood in cooling towers.	150	21	110	
Potassium (K)	Feldspars (orthoclase and microcline), feldspathoids, some micas, clay minerals.	Generally less than about 10, as much as 100 in hot springs; as much as 25,000 in brines.		15	4.0	11	

Table 7.--Major chemical constituents in water--their sources, concentrations, and effects on usability--continued

Constituents and properties	Major sources[1]	Concentration in natural water[1]	Effect upon usability of water[1]	Concentration in water from deep aquifer in Audrain County area[2] Maximum	Minimum	Median	Drinking water standards
Carbonate (CO_2)	Limestone, dolomite	Commonly 0 in surface water; commonly less than 10 in ground water. Water high in sodium may contain as much as 50 of carbonate.	Upon heating, bicarbonate is changed into steam, carbon dioxide, and carbonate. Carbonate combines with alkaline earths--principally calcium and magnesium--to form a crustlike scale of calcium carbonate that retards flow of heat through pipe walls and restricts flow of fluids in pipes. Water containing large quantities of bicarbonate and alkalinity are undesirable in many industries.	0	0	0	
Bicarbonate (HCO_3)		Commonly less than 500; may exceed 1,000 in water highly charged with carbon dioxide.		470	390	420	
Sulfate (SO_4)	Oxidation of sulfide ores; gypsum; anhydrite; industrial wastes.	Commonly less than 1,000 except in streams and wells influenced by acid mine drainage. As much as 200,000 in some brines.	Sulfate combines with calcium to form an adherent, heat-retarding scale. More than 250 is objectionable in water in some industries. Water containing about 500 of sulfate tastes bitter; water containing about 1,000 may be cathartic.	170	29	100	250[3]
Chloride (Cl)	Chief source is sedimentary rock (evaporites); minor sources are igneous rocks.	Commonly less than 10 in humid regions. About 19,300 in sea water; and as much as 200,000 in brines.	Chloride in excess of 100 imparts a salty taste. Concentrations greatly in excess of 100 may cause physiological damage. Food processing industries usually require less than 250. Some industries -- textile processing, paper manufacturing, and synthetic rubber manufacturing -- desire less than 100.	150	5.1	67	250[3]
Fluoride (F)	Amphiboles (hornblende), apatite, fluorite, mica.	Concentrations generally do not exceed 10 in ground water or 1.0 in surface water. Concentrations may be as much as 1,600 in brines.	Fluoride concentration between 0.6 and 1.7 in drinking water has a beneficial effect on the structure and resistance to decay of children's teeth. Fluoride in excess of 1.5 in some areas causes "mottled enamel" in children's teeth. Fluoride in excess 6.0 causes pronounced mottling and disfiguration of teeth.	27	0.9	1.8	0.8-1.7[4]
Nitrate (NO_3)	Atmosphere; legumes, plant debris, animal excrement, nitrogenous fertilizer in soil and and sewage.	In surface water not subjected to pollution, concentration of nitrate may be as much as 5.0 but is commonly less than 1.0. In ground water the concentration of nitrate may be as much as 1,000.	Water containing large quantities of nitrate (more than 100) is bitter tasting and may cause physiological distress. Water from shallow wells containing more than 45 has been reported to cause methemoglobinemia in infants. Small amounts of nitrate help reduce cracking of high-pressure boiler steel.	0.01	0.0	0.0	45[4]
Dissolved solids	The mineral constituents dissolved in water constitute the dissolved solids.	Surface water commonly contains less than 3,000 streams draining salt beds in arid regions may contain in excess 15,000. Ground water commonly contains less than 5,000; some brines contain as much as 300,000.	More than 500 is undesirable for drinking and many industrial uses. Less than 300 is desirable for dyeing of textiles and the manufacture of plastics, pulp paper, rayon. Dissolved solids cause foaming in steam boilers; the maximum permissible content decreases with increases in operating pressure.	763	357	643	500[3]

[1]Modified from Dufor and Becker, 1964.

[2]Based on analyses from 15 irrigation wells, see table 2.

[3]U.S. Environmental Protection Agency, 1977.

[4]U.S. Environmental Protection Agency, 1976.

The concentration and type of chemical species in water are important factors that determine its usefulness for irrigation (Hem, 1970, p. 325). An extensively used method to evaluate the usefulness of water for irrigation has been devised by the U.S. Salinity Laboratory Staff (1954). This method of classifying irrigation water uses a diagram (fig. 38) on which the sodium-adsorption ratio (SAR) and specific conductance value of the water are plotted. The interpretation of the diagram by the U.S. Salinity Laboratory Staff (1954) is as follows:

Low-salinity hazard (C1).--Water can be used for irrigation with most crops on most soils with little likelihood that soil salinity will develop. Some leaching is required, but this occurs under normal irrigation practices except in soils of extremely low permeability.

Medium-salinity hazard (C2).--Water can be used if a moderate amount of leaching occurs. Plants with moderate salt tolerance can be grown in most cases without special practices for salinity control.

High-salinity hazard (C3).--Water cannot be used on soils with restricted drainage. Even with adequate drainage, special management for salinity control may be required and plants with good salt tolerance should be selected.

Very high-salinity hazard (C4).--Water is not suitable for irrigation under ordinary conditions, but may be used occasionally under very special circumstances. The soils must be permeable, drainage must be adequate, irrigation water must be applied in excess to provide considerable leaching, and very salt-tolerant crops should be selected.

The classification of irrigation waters with respect to SAR is based primarily on the effect of exchangeable sodium on the physical condition of the soil. Sodium-sensitive plants may, however, suffer injury as a result of sodium accumulation in plant tissues even when exchangeable sodium values are lower than those that can cause deterioration of the physical condition of the soil.

Low-sodium hazard (S1).--Water can be used for irrigation on almost all soils with little danger of the development of harmful levels of exchangeable sodium. However, sodium-sensitive crops, such as stone-fruit trees and avacados, may accumulate injurious concentrations of sodium.

Medium-sodium hazard (S2).--Water will present an appreciable sodium hazard in fine-textured soils having high cation-exchange capacity, especially under low-leaching conditions, unless gypsum is present in the soil. This water may be used on coarse-textured or organic soils with good permeability.

High-sodium hazard (S3).--Water may produce harmful levels of exchangeable sodium in most soils and will require special soil management--good drainage, high leaching, and organic matter additions. Gypsiferous soils may not develop harmful levels of exchangeable sodium from such waters. Chemical amendments may be required for replacement of exchangeable sodium, except that amendments may not be feasible with waters of very high salinity.

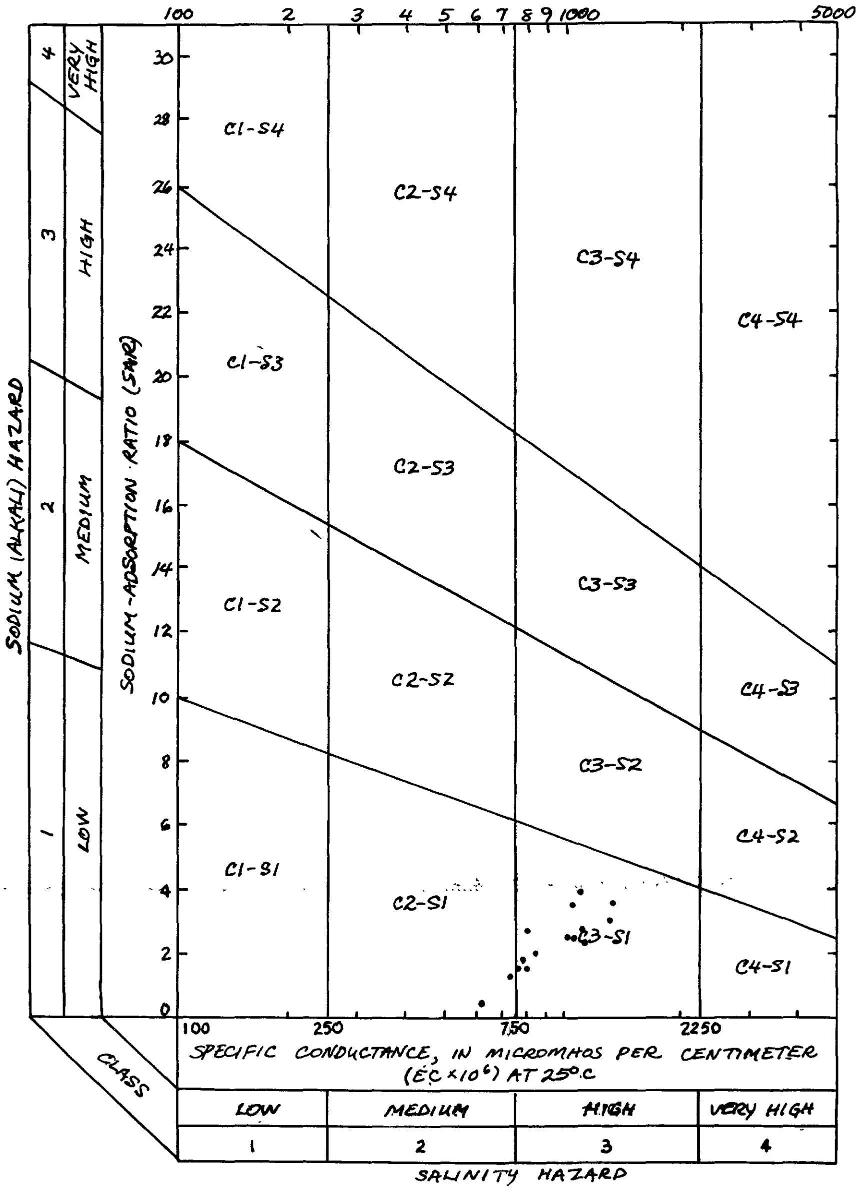


Figure 38.-- DIAGRAM FOR CLASSIFICATION OF IRRIGATION WATER FROM 15 WELLS COMPLETED IN THE DEEP AQUIFER IN AUDRAIN COUNTY.

(Modified from U.S. Salinity Laboratory Staff, 1954)

Very high-sodium hazard (S4).--Water generally is unsatisfactory for irrigation purposes except at low and perhaps medium salinity, where the solution of calcium from the soil or use of gypsum or other amendments may make the use of these waters feasible.

Based on chemical analyses of water from the 15 irrigation wells (table 6), ground water from the deep aquifer in Audrain County has a medium- to high-salinity hazard and a low-sodium hazard for irrigation (fig. 38). Of the water-sample analyses, 13 (or 87 percent) are in the C3-S1 classification of irrigation water.

Blancher (1977, p. 5) has suggested a maximum SAR (sodium-adsorption ratio) of 5 as an upper limit for water used for continuous irrigation in Missouri. He further states that "***if the soils are flushed by percolating water and gypsum or lime added to displace excess sodium, a larger SAR may be acceptable." All the irrigation-water samples have a SAR less than 5.

Boron, if present in water in concentrations greater than needed for plant nutrition, may be toxic to some plants. A rating table was developed by the Salinity Laboratory Staff (1954) that indicates the permissible boron concentrations in irrigation water for three classes of plants (table 8).

The largest boron concentration reported in table 6 is 1,500 micrograms per liter, or 1.5 milligrams per liter. Field crops grown in Missouri that may be irrigated, such as corn and milo, are semitolerant to boron, according to the U.S. Salinity Laboratory Staff (1954). Consequently, the analyses of water from the 15 irrigation wells would all rate good to permissible with respect to boron if applied to semitolerant crops.

SUMMARY AND CONCLUSIONS

Two aquifers are the main source of ground water in Audrain County. The shallow aquifer, a limestone of Mississippian age with well-developed solution channels, generally yields less than 15 gallons per minute. Domestic wells are completed in these rocks. The deep aquifer is a sequence of Cambrian and Ordovician formations primarily composed of dolomite with minor beds of sandstone. In Audrain County the average thickness of this aquifer is about 1,300 feet. Public-supply and irrigation wells are completed in the deep aquifer and constructed so that they are open to most of the aquifer. Yields of 500 to 1,000 gallons per minute can be attained from these wells. Smaller yielding (10 to 20 gallons per minute) domestic- and stock-supply wells are completed in the upper part of the deep aquifer.

Recharge to the shallow aquifer in Audrain County is by leakage through the overlying Pennsylvanian formations or glacial drift. The presence and location of ground-water divides in the shallow aquifer probably are affected by topographic relief and the relative thickness of the overburden. Lateral flow in this aquifer is to the southwest in the western part of the county, to the north in the central region, and to the southeast in the eastern part of the county. Ground water in the aquifer is constantly replenished from precipitation and saline water is prevented from entering the area by the

Table 8.--Rating of irrigation water for various crops on the basis of boron concentrations in the water

[Modified from U.S. Salinity Laboratory Staff, 1954]

Rating	Suitability for use Classification of water Grade	Boron concentration, in milligrams per liter Sensitive crops	Semitolerant crops	Tolerant crops
1	Excellent	0.33 --	0.67 --	-- 1.00
2	Good	.33 - 0.67	.67 - 1.33	1.00 - 2.00
3	Permissible	.67 - 1.00	1.33 - 2.00	2.00 - 3.00
4	Doubtful	1.00 - 1.25	2.00 - 2.50	3.00 - 3.75
5	Unsuitable	Less than 1.25	Less than 2.50	Less than 3.75

hydraulic gradient. The deep and shallow aquifers are separated by shale and limestone confining layers. Lower Mississippian and Upper Devonian shales are the principal confining beds in all but the central and southeastern part of Audrain County where Middle Devonian limestones are a less effective confining bed.

The deep aquifer is recharged by leakage through the confining layers. Historically, a ground-water divide in the deep aquifer passing north and south through west Audrain County caused part of the recharge to flow to the east and part to the west. The ground-water divide has, for the most part, kept saline water from entering Audrain County.

Immediately underlying the deep aquifer is the Davis Formation, a relatively impermeable formation that separates the deep aquifer from the Bonneterre Formation and Lamotte Sandstone. No producing wells in the Audrain County area are completed in these formations. Consequently, nothing is known about the hydraulic-head relationship with the overlying deep aquifer or the chemical quality of water in these formations.

North and west of Audrain County the water in the deep aquifer has a dissolved-solids concentration that generally ranges from 1,000 to 10,000 milligrams per liter. The more highly mineralized water is a sodium chloride type and is not used. The dissolved-solids concentrations of the water decreases toward the south and ranges from 400 to 1,200 milligrams per liter, but generally is less than 650 milligrams per liter in Audrain County. The water generally is a calcium magnesium bicarbonate type. Because of a lack of wells in the transition zone, it is difficult to determine an accurate boundary between the saline and freshwater areas.

Until recently, the city of Mexico has been the largest user of water from the deep aquifer in Audrain County. Pumpage from deep wells during the past 80 years has altered the potentiometric surface of the deep aquifer. Water levels in the vicinity of Mexico had declined as much as 200 feet below their predevelopment levels by May 1979. Since the summer of 1979, large quantitites of water have been withdrawn from the deep aquifer for irrigation purposes. These and future additional withdrawals can cause the potentiometric heads to decline from 40 to 80 feet in central Audrain County during the next 10 to 20 years. The additional decline would only be about 10 to 25 feet in the absence of irrigation pumpage. The deep aquifer is capable of supplying the water needed to continue irrigation at the present rate of withdrawal.

The large decline in the potentiometric surface of the deep aquifer in central Audrain County creates a potential for saltwater encroachment into former freshwater areas. The movement of saline water could occur laterally or vertically. The average rate of flow of saline water through the deep aquifer from the north into Audrain County has been estimated at 5 to 15 feet per year (Imes, 1984). Increasing salinity is more likely to occur in wells that are close to the poorly defined freshwater-saltwater boundary in the northeast and northwest parts of Audrain County, are open to the more permeable formations of the deep aquifer, and are operated at large pumping rates. Vertical encroachment of saltwater could come from the underlying Bonneterre Formation and Lamotte Sandstone. The potential for vertical encroachment from deeper formations cannot be evaluated because of the lack of hydraulic-head and water-quality data from these formations in this area.

Measurements of water quality, volume pumped, and water levels in selected large-capacity wells before and after each irrigation season would help in detecting any changes in water quality due to saltwater encroachment.

SELECTED REFERENCES

Anderson, K. H., coordinator, 1979, Geologic map of Missouri: Missouri Division of Geology and Land Survey, scale 1:500,000.

Ayers, R. S., 1977, Quality of water for irrigation: New York, American Society of Civil Engineers Proceedings, Journal of Irrigation and Drainage Division, v. 103, no. IR2, p. 135-154.

Blanchar, R. W., 1977, Water quality--The importance to the soil and the plant, in Proceeding of the Ninth Annual Irrigation Short Course: Columbia, University of Missouri, College of Agriculture.

Durfor, C. N., and Becker, Edith, 1964, Public water supplies of the 100 largest cities in the United States, 1962: U.S. Geological Survey Water-Supply Paper 1812, 364 p.

Freeze, R. A., and Cherry, J. A., 1979, Groundwater: New Jersey, Prentice-Hall, Inc., 604 p.

Fuller, D. L., 1963, Groundwater quality map of deep aquifer in Missouri, in Groundwater maps of Missouri: Missouri Division of Geology and Land Survey.

Fuller D. L., Knight, R. D., and Harvey, E. J., 1967, Ground water, in Mineral and water resources of Missouri: Washington, D.C., U.S. Government Printing Office, U.S. Senate Document 19, p. 218-313.

Gann, E. E., Harvey, E. J., Jeffery, H. G., and Fuller, D. L., 1971, Water Resources of northeastern Missouri: U.S. Geological Survey Hydrologic Investigations Atlas HA-372.

Hem, J. D., 1970, Study and interpretation of the chemical characteristics of natural water (2d ed.): U.S. Geological Survey Water-Supply Paper 1473, 363 p.

Howe, W. B., coordinator, and Koenig, J. W., editor, 1961, The stratigraphic succession in Missouri: Missouri Division of Geology and Land Survey, v. XL, 2d ser., 185 p.

Howe, W. B., Kurtz, V. E., and Anderson, K. H., 1972, Correlation of Cambrian strata of the Ozarks and Upper Mississippi Valley regions: Missouri Division of Geology and Land Survey, Report of Investigations no. 52, 60 p.

Imes, J. L., 1984, The ground-water flow system in northern Missouri with emphasis on the Cambrian-Ordovician aquifer: U.S. Geological Survey Professional Paper 1305 (in press).

Kisvarsanyi, E. B., 1975, Data on Precambrian in drillholes of Missouri including rock type and surface configuration: Missouri Division of Geology and Land Survey, Report of Investigations no. 5, 20 p.

Lohman, S. W., and others, 1972, Definitions of selected ground-water terms--Revision and conceptual refinements: U.S. Geological Survey Water-Supply Paper 1988, 21 p.

Lohman, S. W., 1979, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

McCracken, M. H., 1966, Major structural features of Missouri: Missouri Division of Geology and Land Survey, 1 sheet.

_____1971, Structural features of Missouri: Missouri Division of Geology and Land Survey, Report of Investigations no. 49, 1 pl., 99 p.

McQueen, H. S., 1943, Fire clay districts of east central Missouri: Missouri Division of Geology and Land Survey, v. XXVIII, 2d ser., 250 p.

Missouri Division of Environmental Quality, 1962-80, Census of Missouri public water supplies, 1962-80: Missouri Division of Environmental Quality (formerly Missouri Division of Health), 76 p. (Published annually.)

Missouri Division of Geology and Land Survey, 1980, Generalized geologic map of Missouri: Missouri Division of Geology and Land Survey, 1 sheet.

Robinove, C. J., Langford, R. H., and Brookhart, J. W., 1958, Saline water resources of North Dakota: U.S. Geological Survey Water-Supply Paper 1428, 72 p.

Schottman, R. W., 1977, Irrigation in Missouri--1976 and 1981: Proceedings of the Ninth Annual Irrigation Short Course, Columbia, University of Missouri, College of Agriculture, p. 1-8.

Schweitzer, Paul, 1892, Mineral water of Missouri: Missouri Division of Geology and Land Survey (formerly Missouri Geological Survey and Water Resources), v. III, 356 p.

Shepard, E. M., 1907, Underground water of Missouri: U.S. Geological Survey Water-Supply Paper 195, 224 p.

Steinhilber, W. L., and Young, H. L., 1979, Plan of study for the northern midwest regional aquifer-system analysis: U.S. Geological Survey Water-Resources Investigations Report 79-44, 20 p.

Stiff, H. A., Jr., 1951, The interpretation of chemical water analysis by means of patterns: Journal of Petroleum Technology, v. 3, no. 10, p. 15-17.

Swenson, H. A., and Baldwin, H. L., 1965, A primer of water quality: U.S. Geological Survey, 27 p.

Trescott, P. C., Pinder, G. F., and Larson, S. P., 1976, Finite-difference model for aquifer simulation in two dimensions with results of numerical experiments: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 7, Chapter C1, 116 p.

U.S. Environmental Protection Agency, 1976, National interim primary drinking water regulations: U.S. Environmental Protection Agency 570/9-76-003, 159 p.

_____1977, National secondary drinking water regulations: Federal Register, v. 42, no. 62, Thursday, March 31, 1977, Part I, p. 17143-17147.

U.S. Salinity Laboratory Staff, 1954, Diagnosis and improvement of saline and alkali soils: U.S. Department of Agriculture Handbook 60, 160 p.

Walton, W. C., 1960, Leaky artesian aquifer conditions in Illinois: Urbana, Illinois State Water Survey, Report of Investigation 39, 27 p.

_____1965, Ground-water recharge and runoff in Illinois: Urbana, Illinois State Water Survey, Report of Investigation 48, 55 p.

_____1970, Groundwater resource evaluation: New York, McGraw-Hill, 664 p.

GLOSSARY

Acre-foot - The volume of water required to cover 1 acre to a depth of 1 foot: 1 acre-foot=43,560 feet, or 325,851 gallons.

Anticline - An upfold or arch of rock strata, the core of which contains the older rocks; it is convex upward.

Aquifer - A formation, group of formations or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Confining bed - A body of relatively impermeable material stratigraphically adjacent to one or more aquifers.

Hydraulic conductivity - The volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

Hydraulic gradient - The change in static head per unit of distance in a given direction. The direction is that of the maximum rate of decrease in head.

Permeability - A measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient.

Potentiometric surface - A surface which represents the static head. As related to an aquifer, it is defined by the levels to which water will rise in tightly cased wells.

Recharge - The addition of water to the zone of saturation. Infiltration and percolation from land surface to the zone of saturation is a form of natural recharge.

Sodium-adsorption ratio (SAR):

$$SAR = \frac{(Na^{+})}{\sqrt{\frac{(Ca^{+2}) + (Mg^{+2})}{2}}}$$

where Na^{+}, Ca^{+2}, and Mg^{+2} are the sodium, calcium, and magensium ion concentrations expressed in milliequivalents per liter.

Specific capacity - The volumetric discharge of water from a well per unit of drawdown. If a well yields 500 gallons per minute, and has a drawdown of 100 feet, its specific capacity is 500/100 or 5 gallons per minute per foot of drawdown.

Specific conductance - A measure of the ability of water to conduct an electrical current at 25° Celsius. Specific conductance varies with the quantities of dissolved mineral constituents and with the degree of ionization of the constituents. It is useful in indicating the approximate concentration of mineral matter in water.

Specific yield - The ratio of the volume of water which the rock, after being saturated, will yield by gravity to the volume of the rock.

Storage coefficient - The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

Transmissivity - The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient.

Water table - That surface in an unconfined water body at which the pressure is atmospheric.

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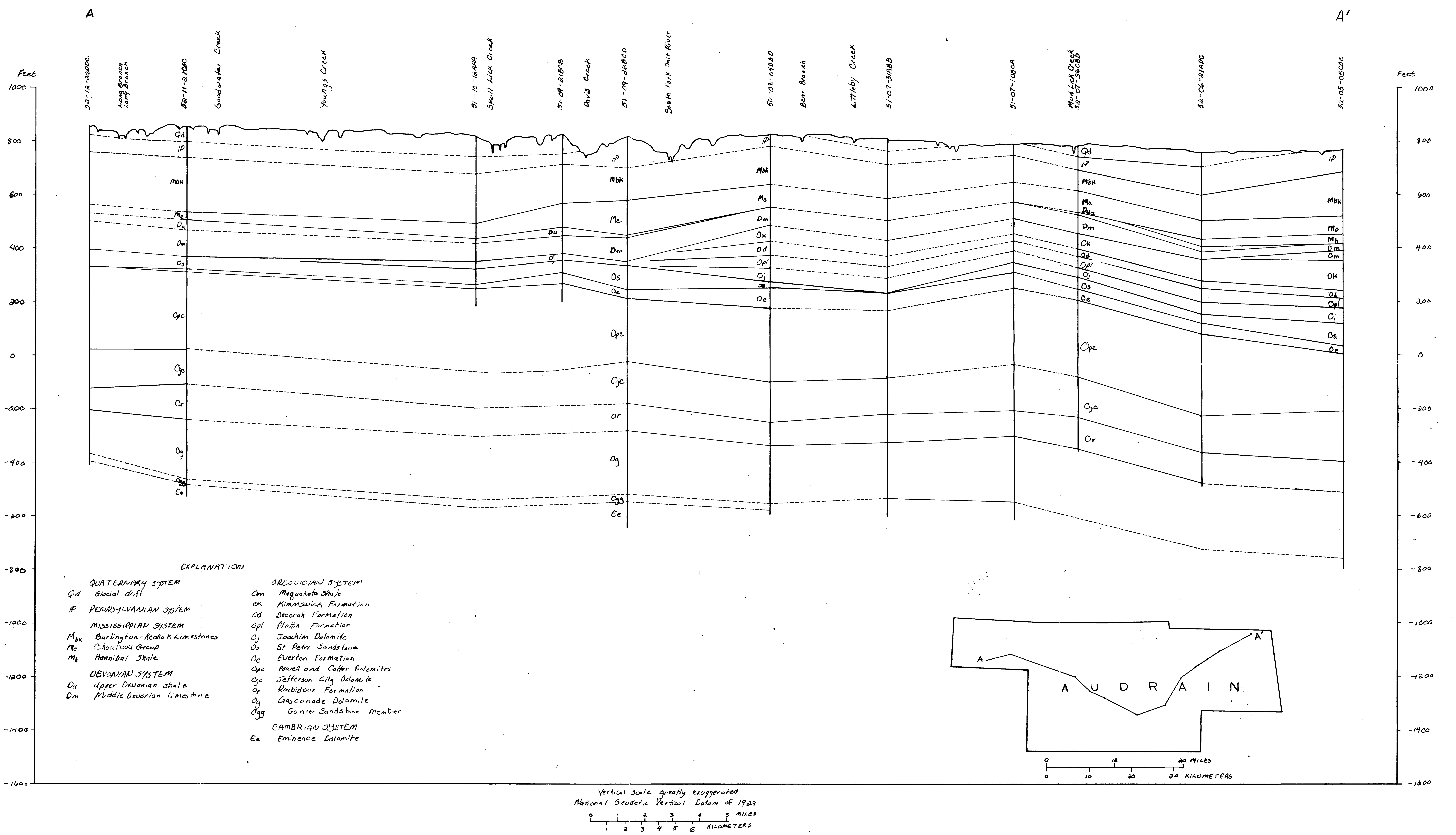

Figure 5.--Geologic Section A-A'.

84-245

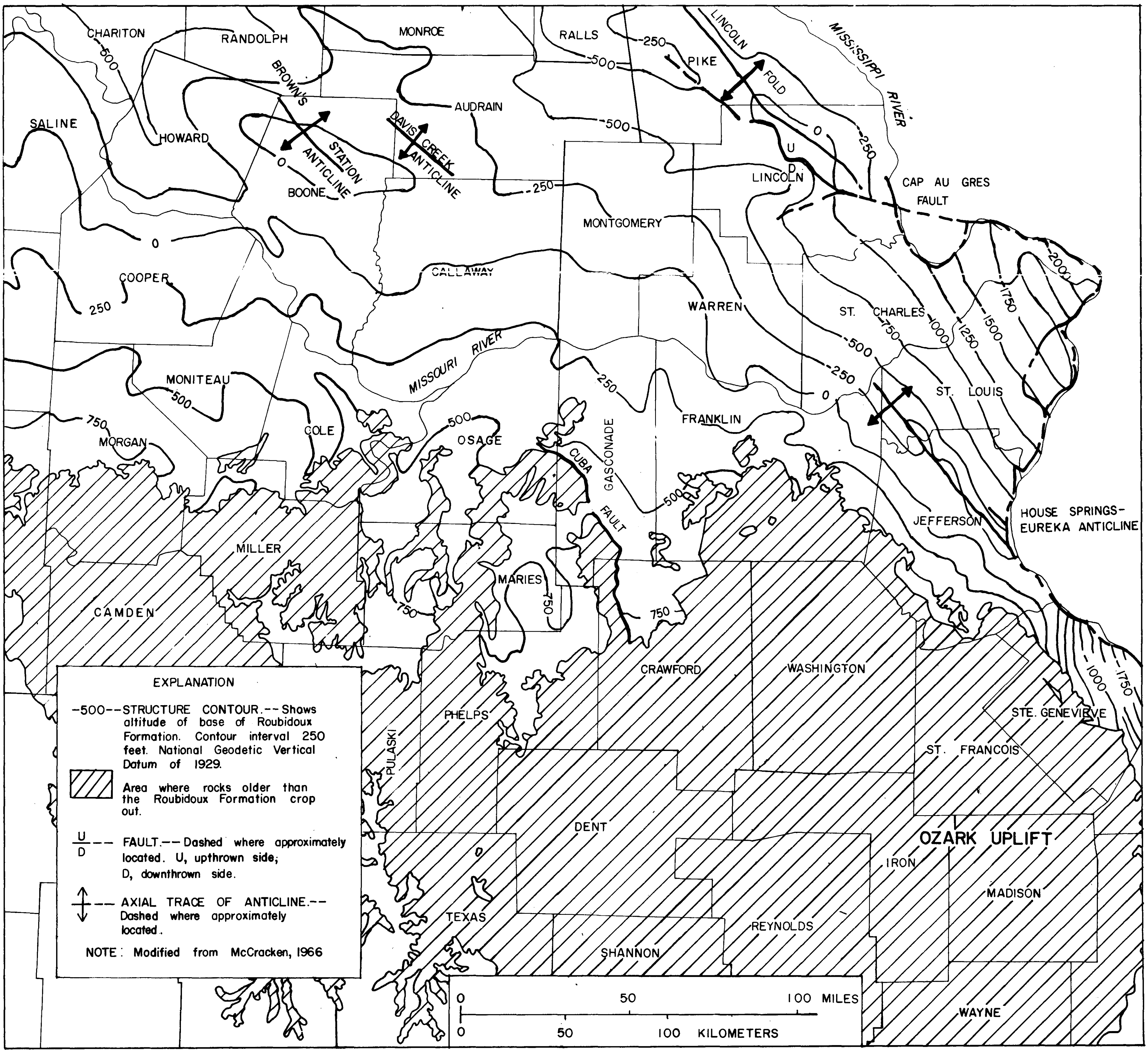

Figure 6.-- Major structural features of Audrain County and vicinity.

84-245

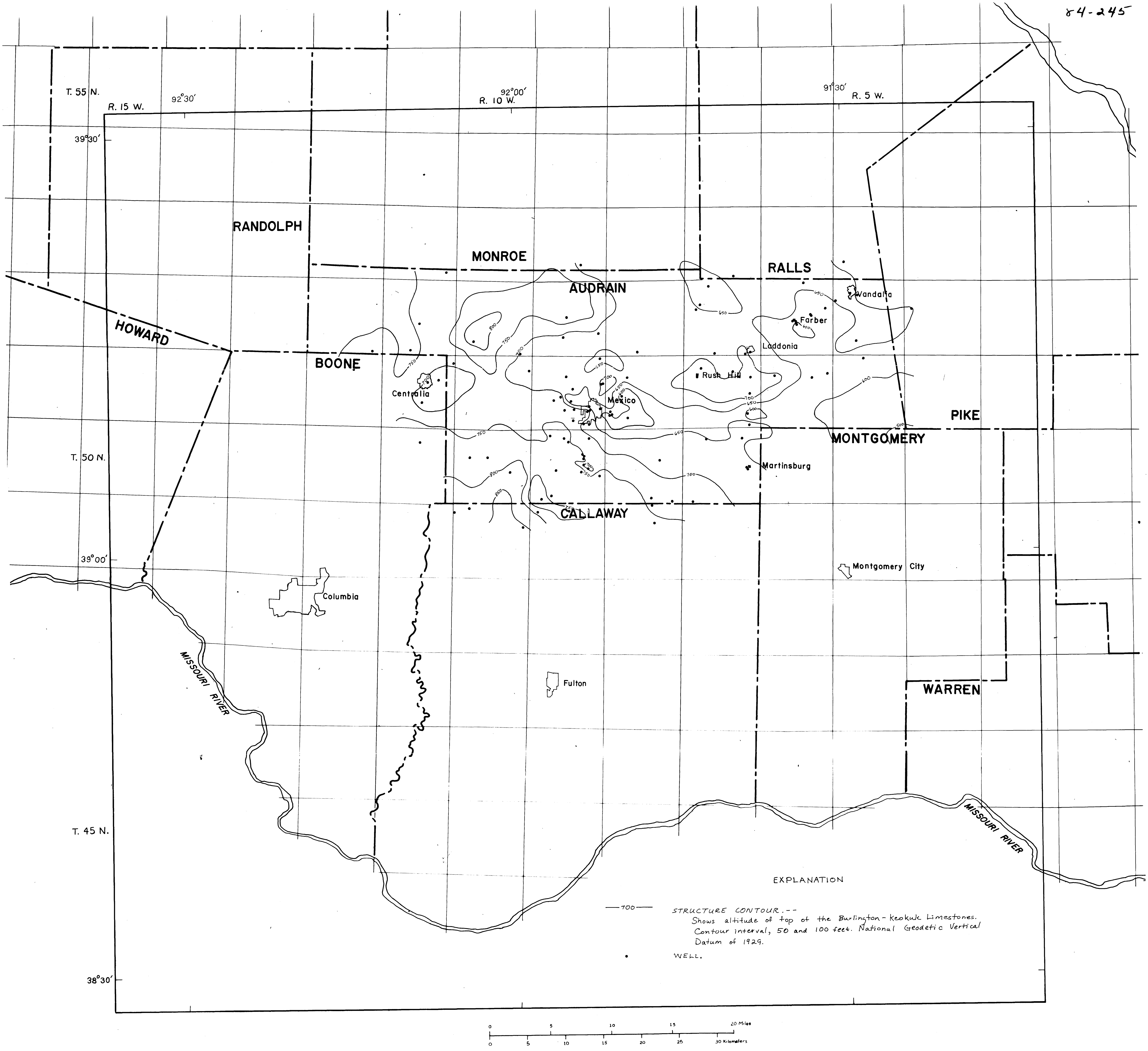

Figure 7.--Altitude of the top of the Burlington-Keokuk Limestones in Audrain County.

84-245

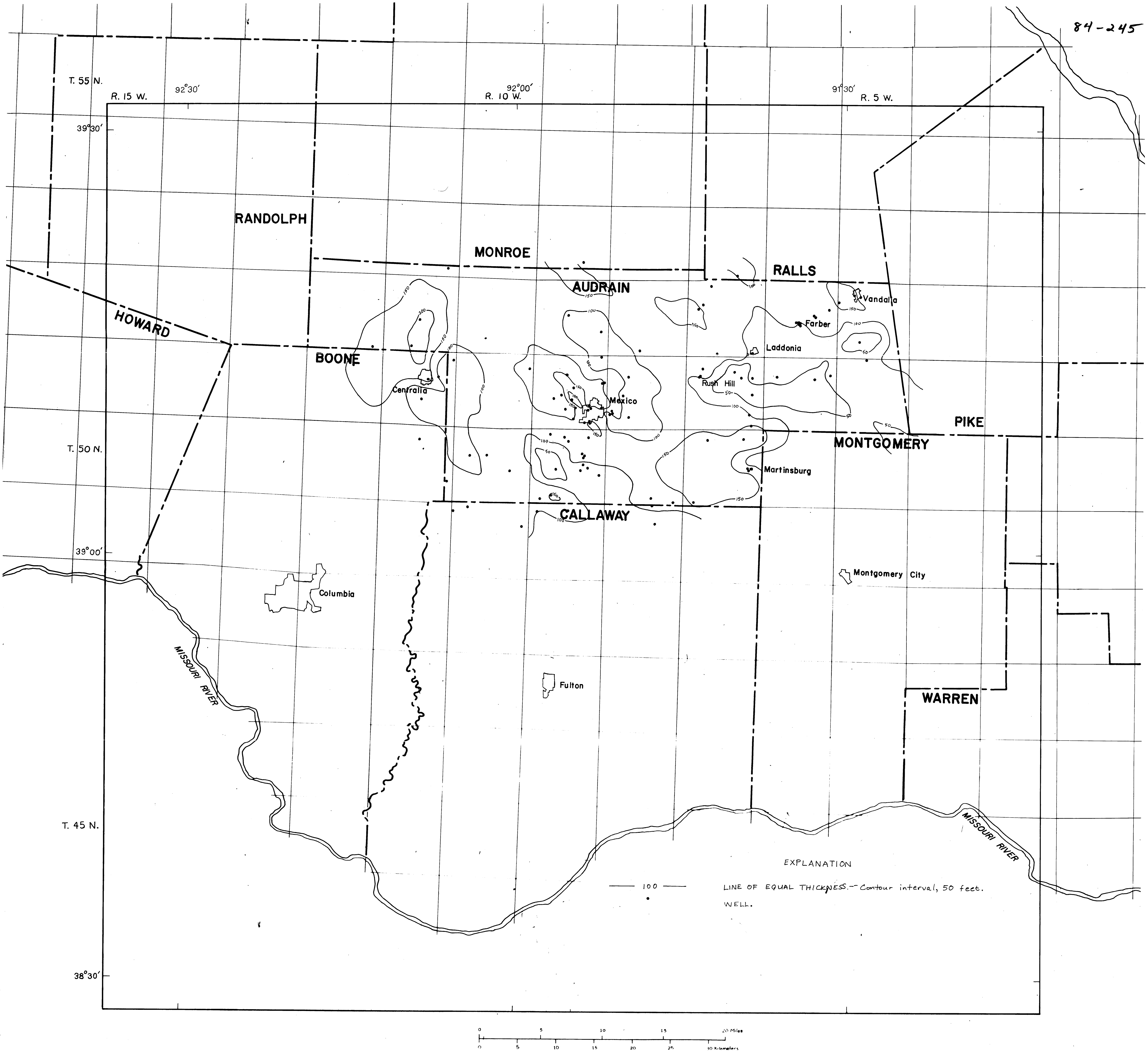

Figure 8.--Thickness of the Burlington-Keokuk Limestones in Audrain County.

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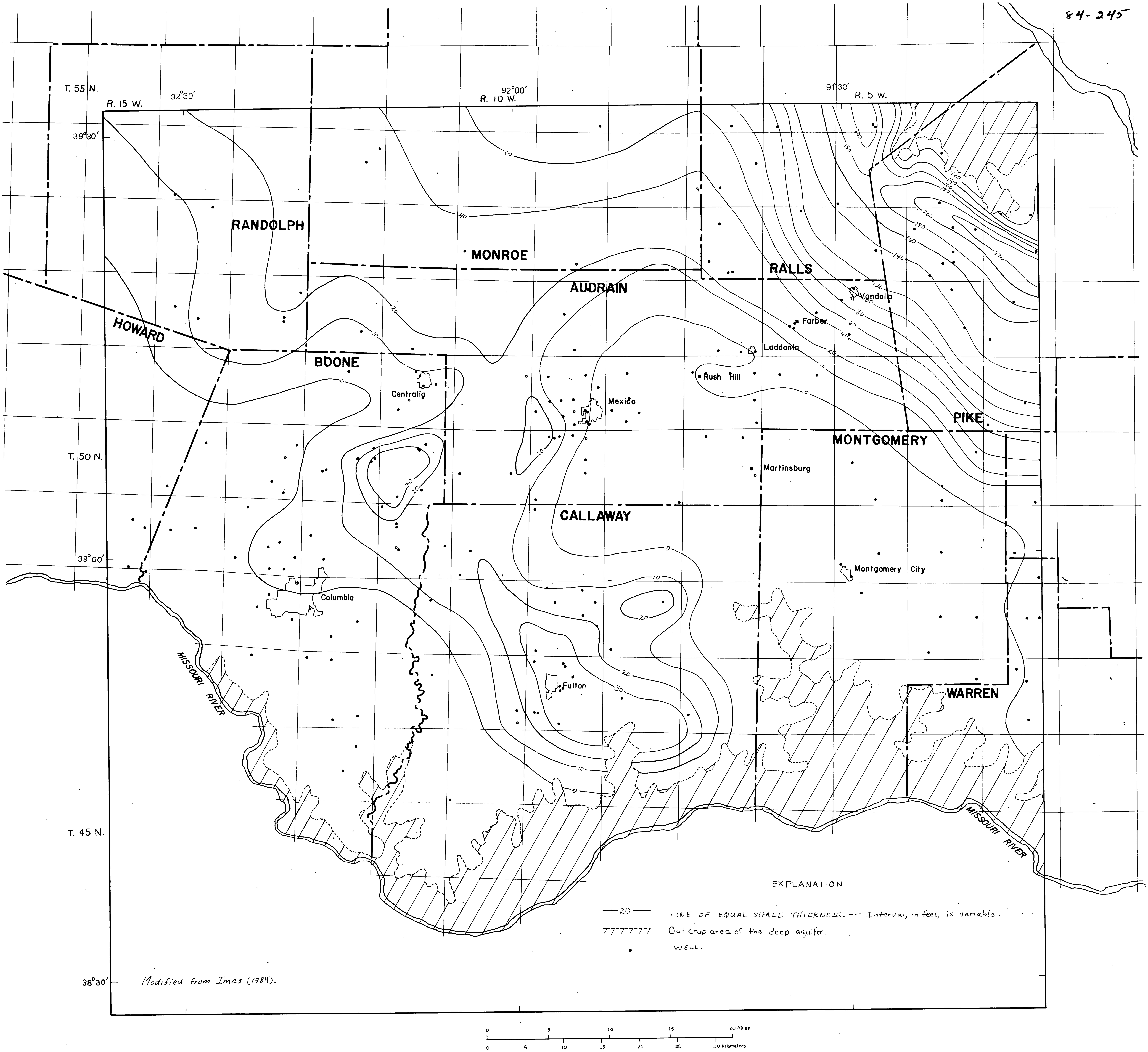

Figure 9.--Areal distribution and composite shale thickness in the upper confining layer.

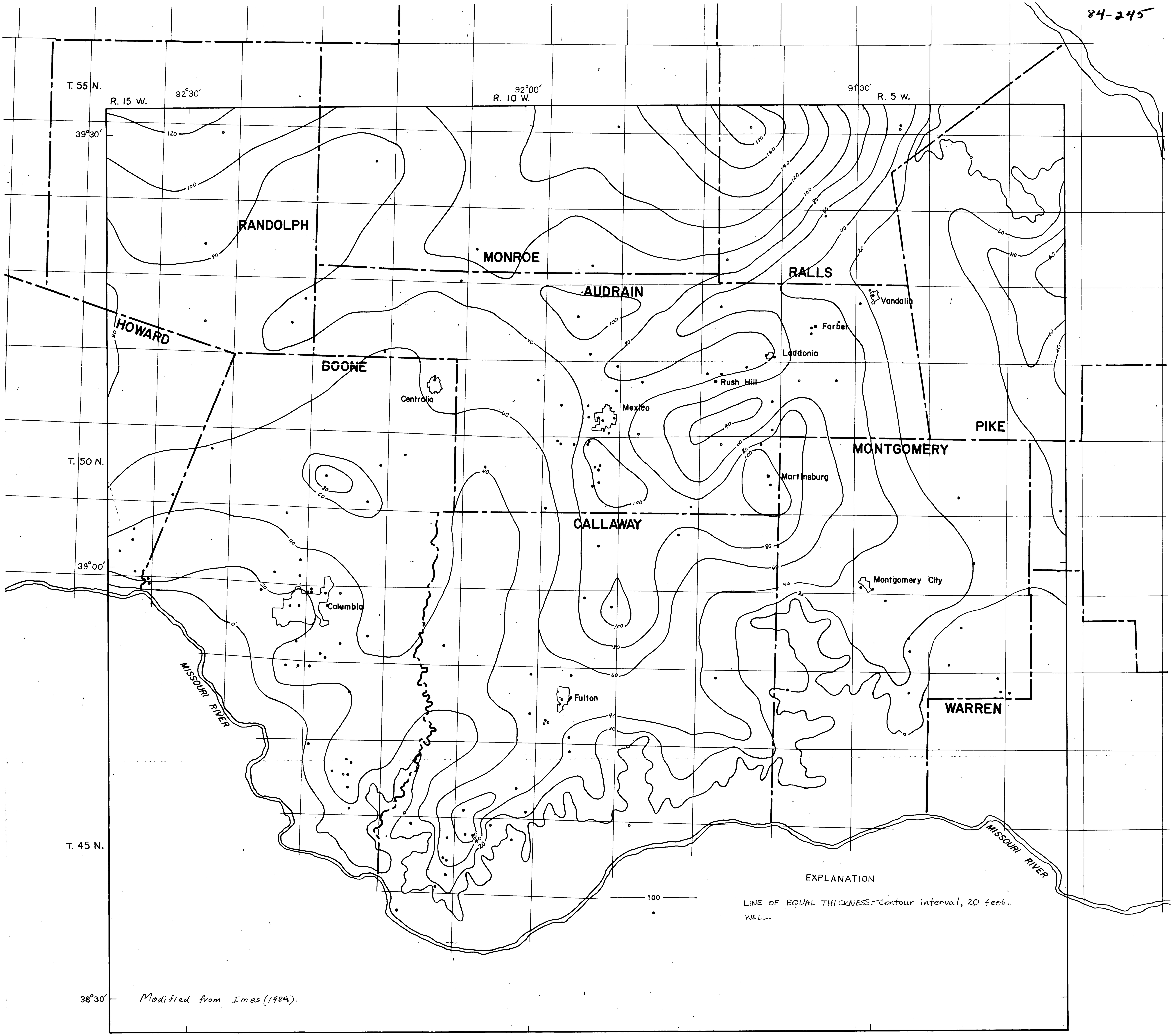

Figure 10.--Areal distribution and thickness of the Devonian limestone.

84-245

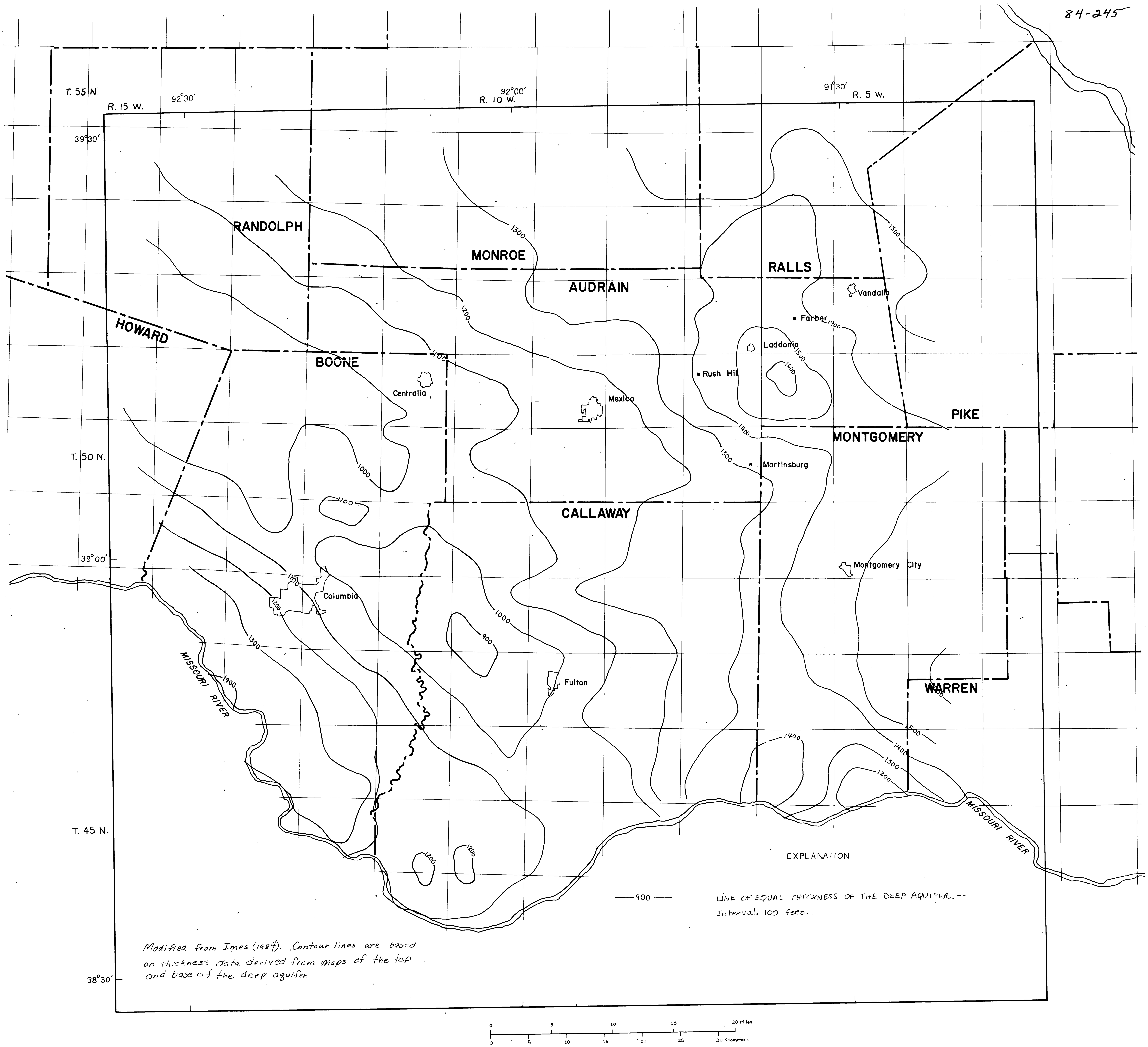

Figure 11.--Thickness of the deep aquifer.

84-245

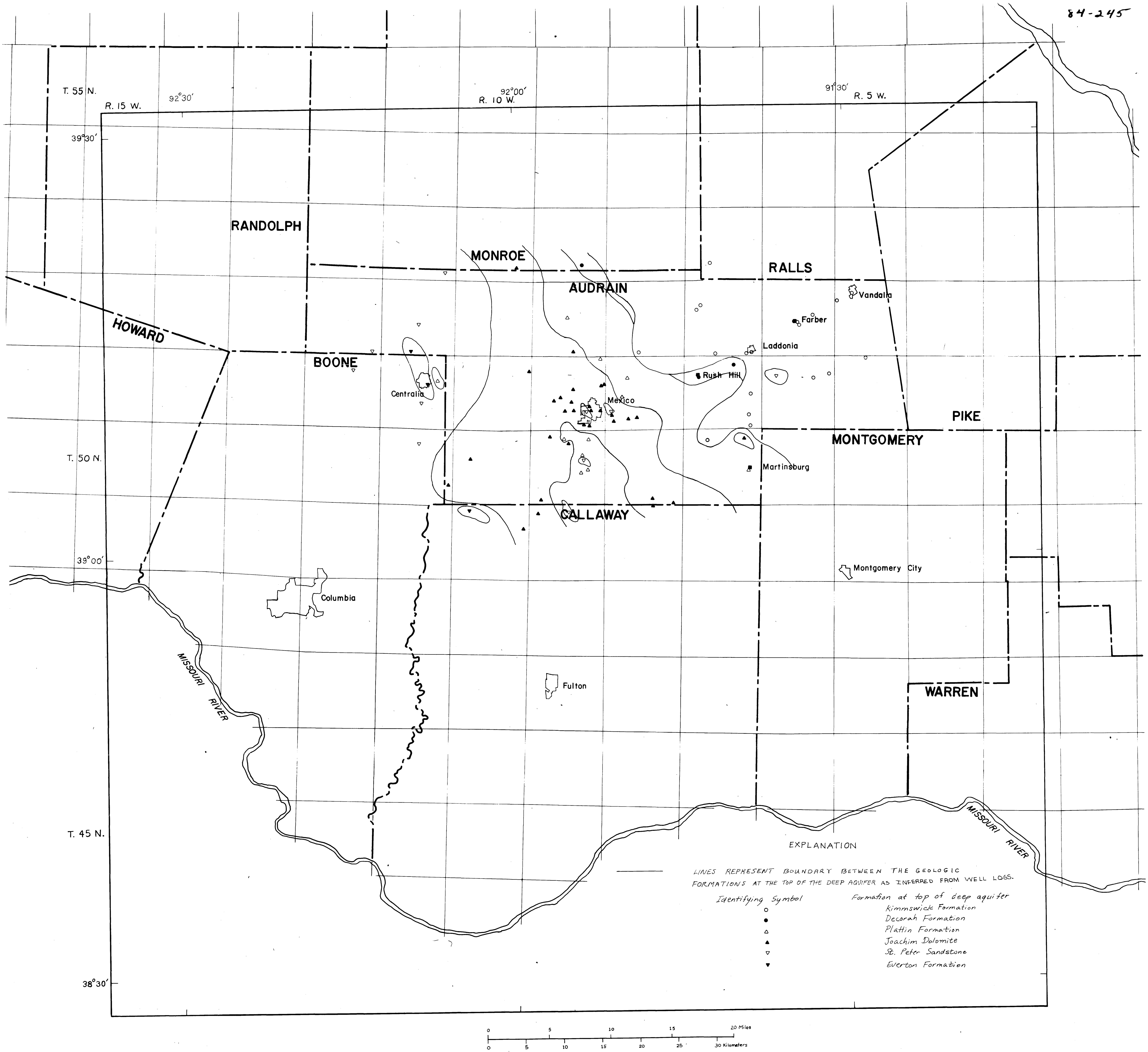

Figure 12.--Geologic formations at the top of the deep aquifer in Audrain County.

84-145

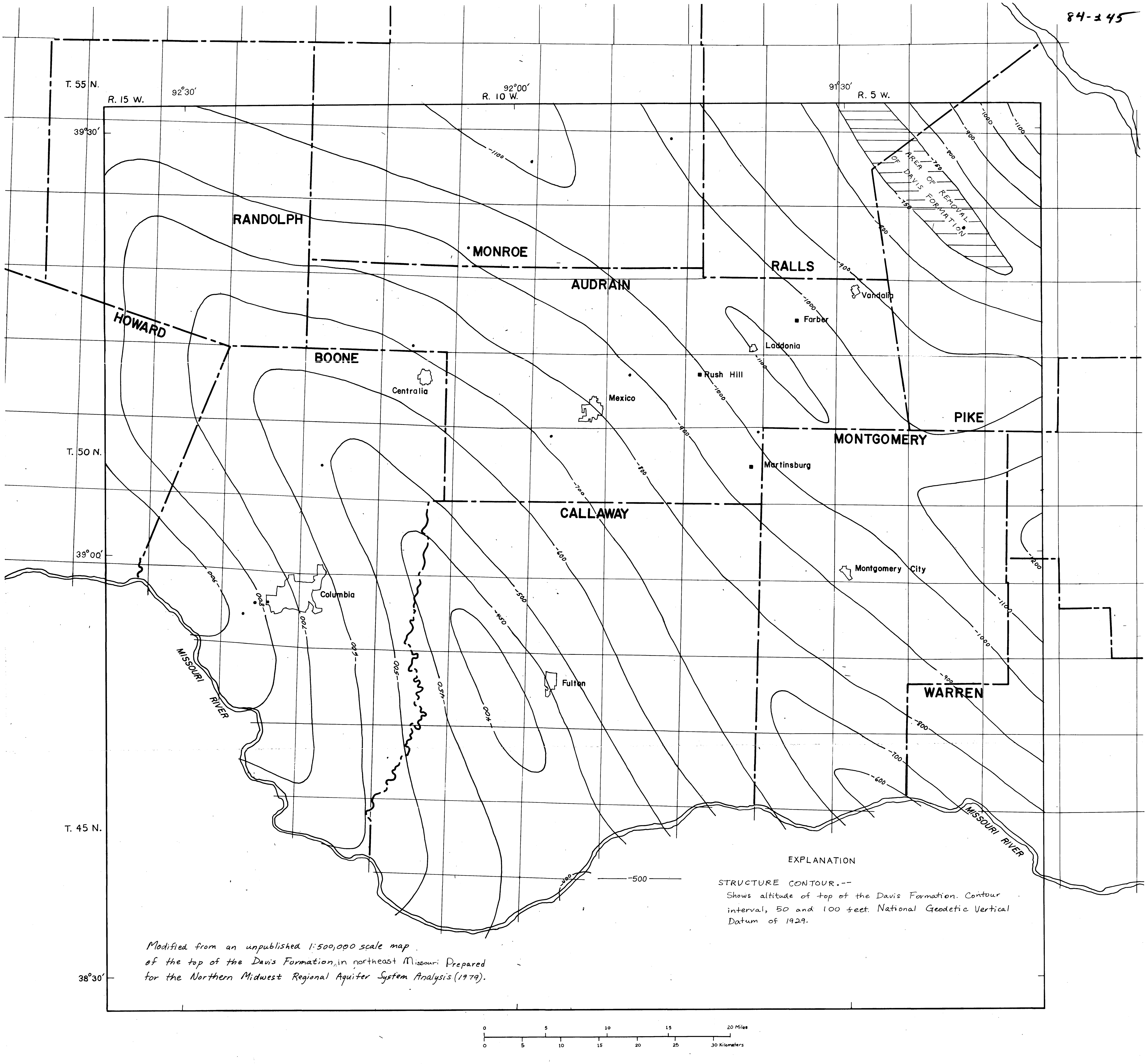

Figure 13.--Altitude of the top of the Davis Formation.

84-245

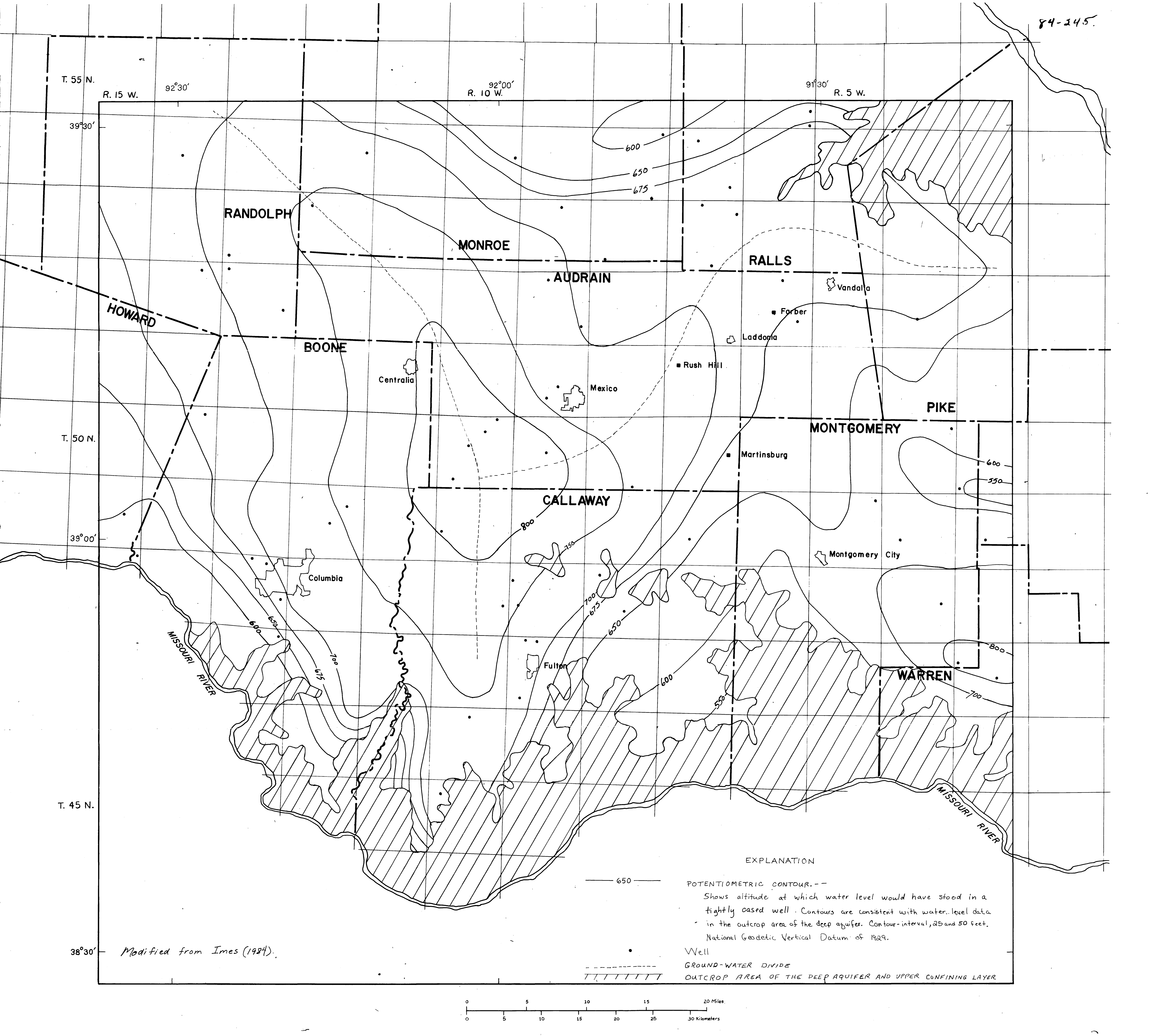

Figure 14.--Altitude of the predevelopment potentiometric surface of the shallow aquifer in the model area.

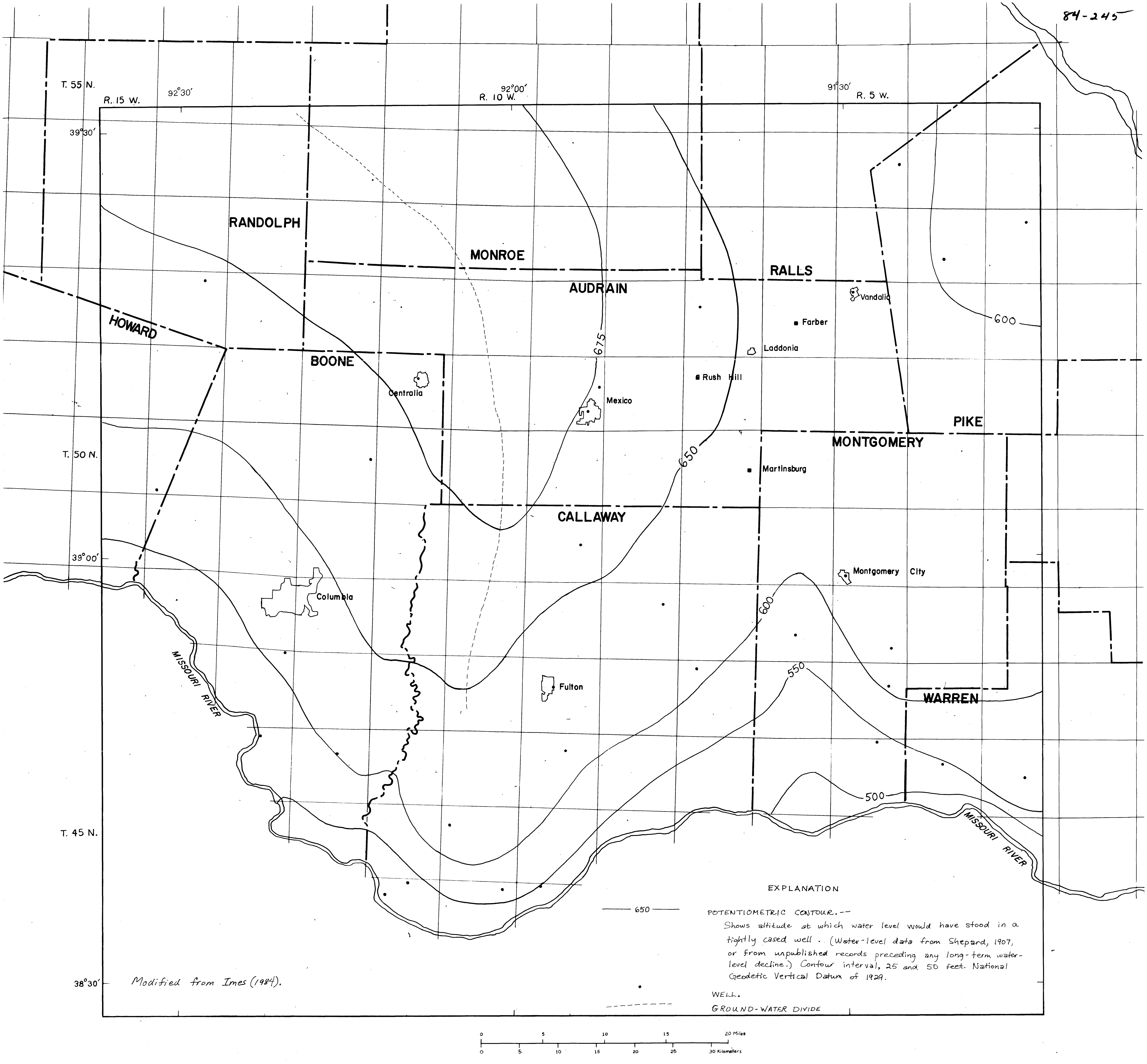

Figure 15.--Altitude of the predevelopment potentiometric surface of the deep aquifer in the model area.

84-245

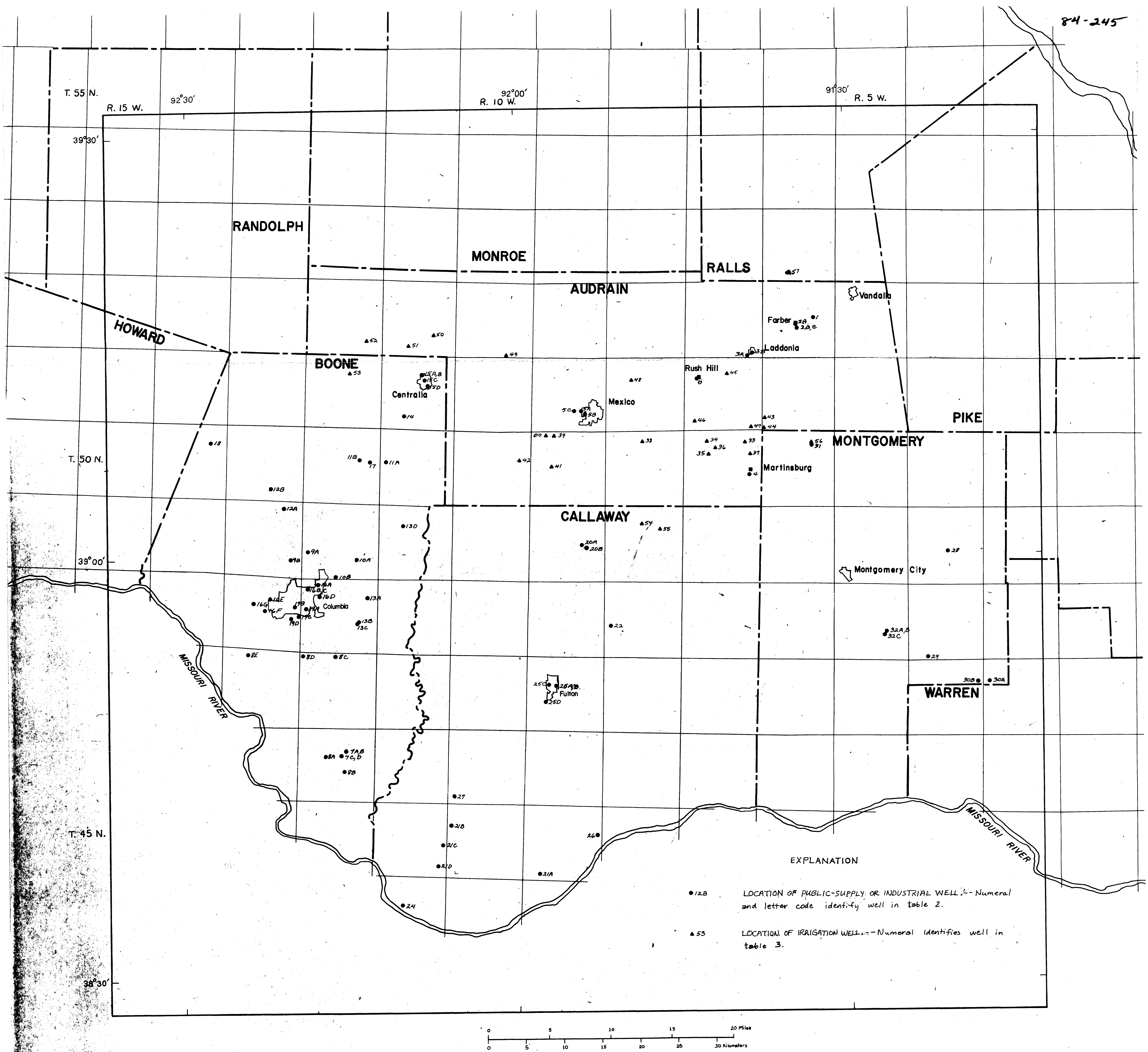

Figure 16.--Locations of public-supply, industrial, and irrigation wells completed in the deep aquifer.

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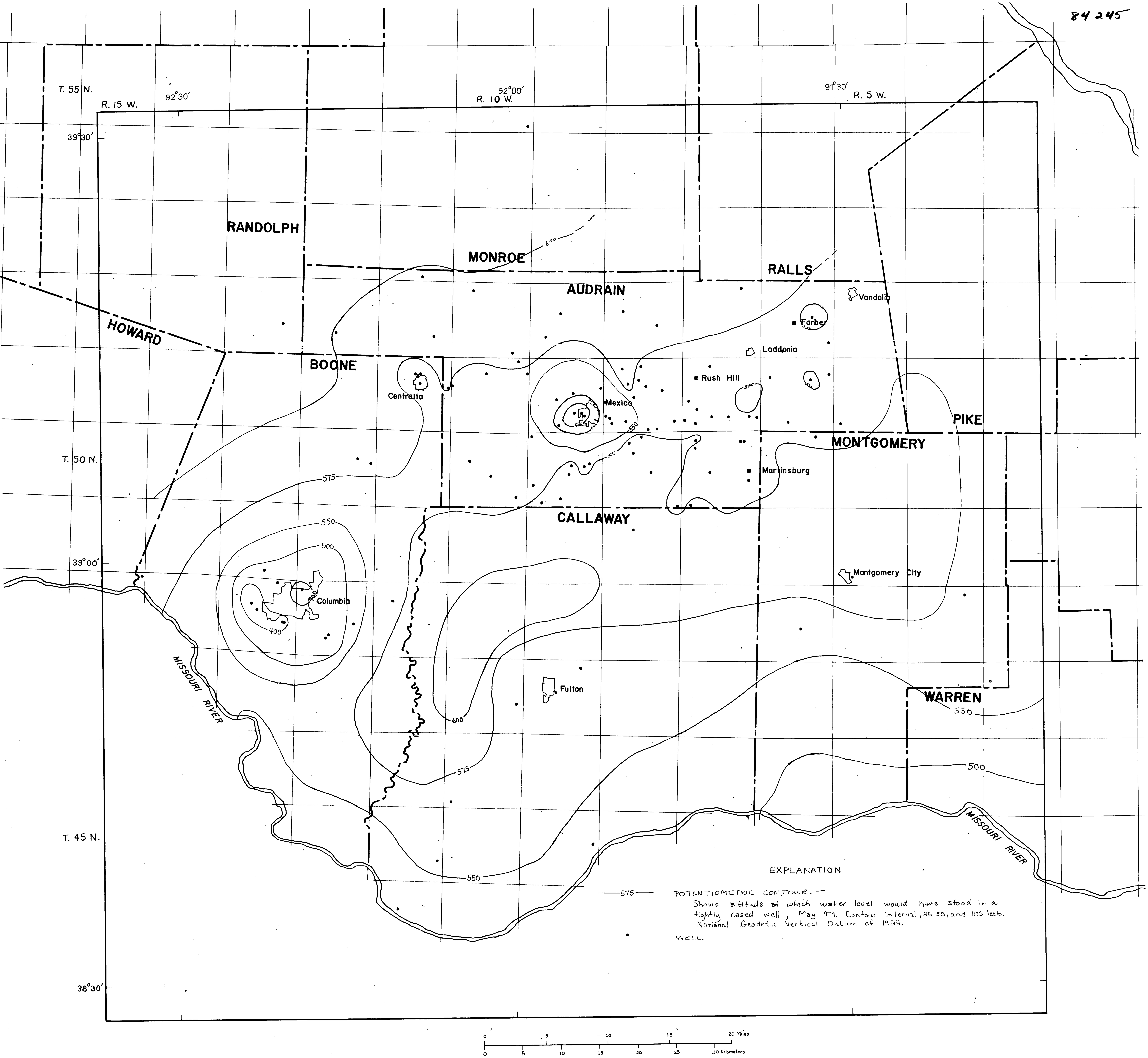

Figure 17.--Potentiometric surface of the deep aquifer in the model area, May 1979.

84-245

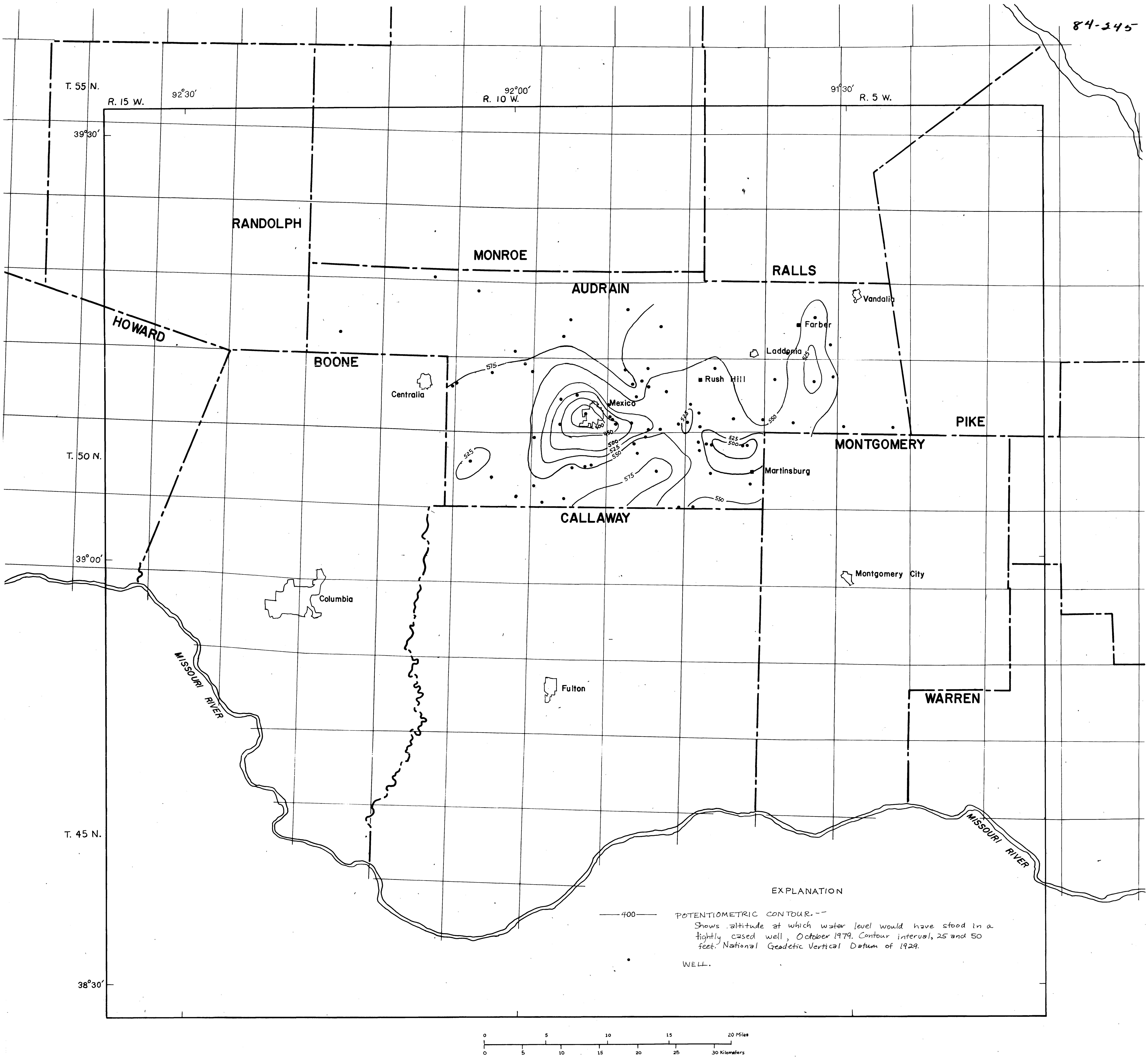

Figure 18.--Potentiometric surface of the deep aquifer in Audrain County, October 1979.

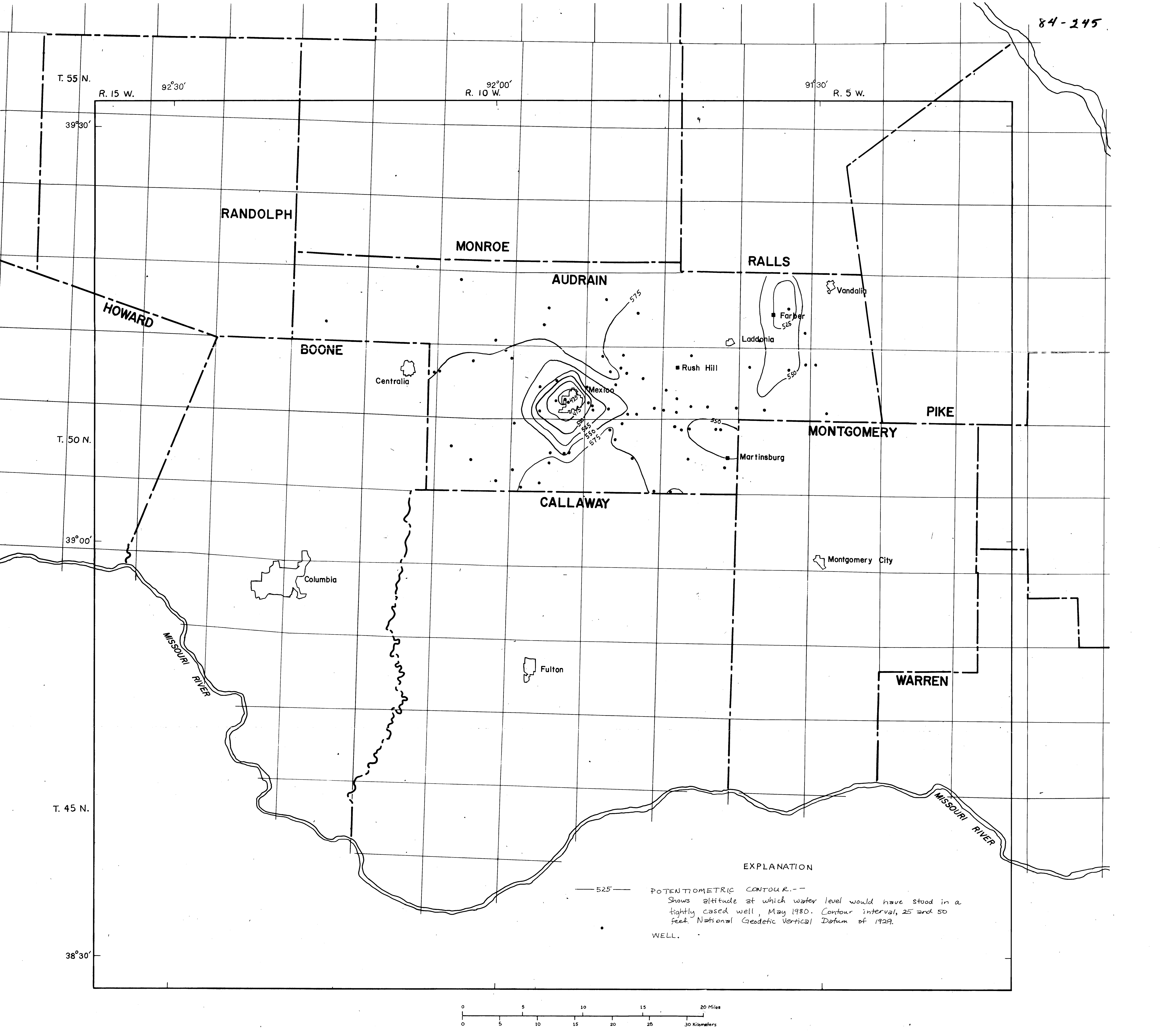

Figure 19.--Potentiometric surface of the deep aquifer in Audrain County, May 1980.

84-245

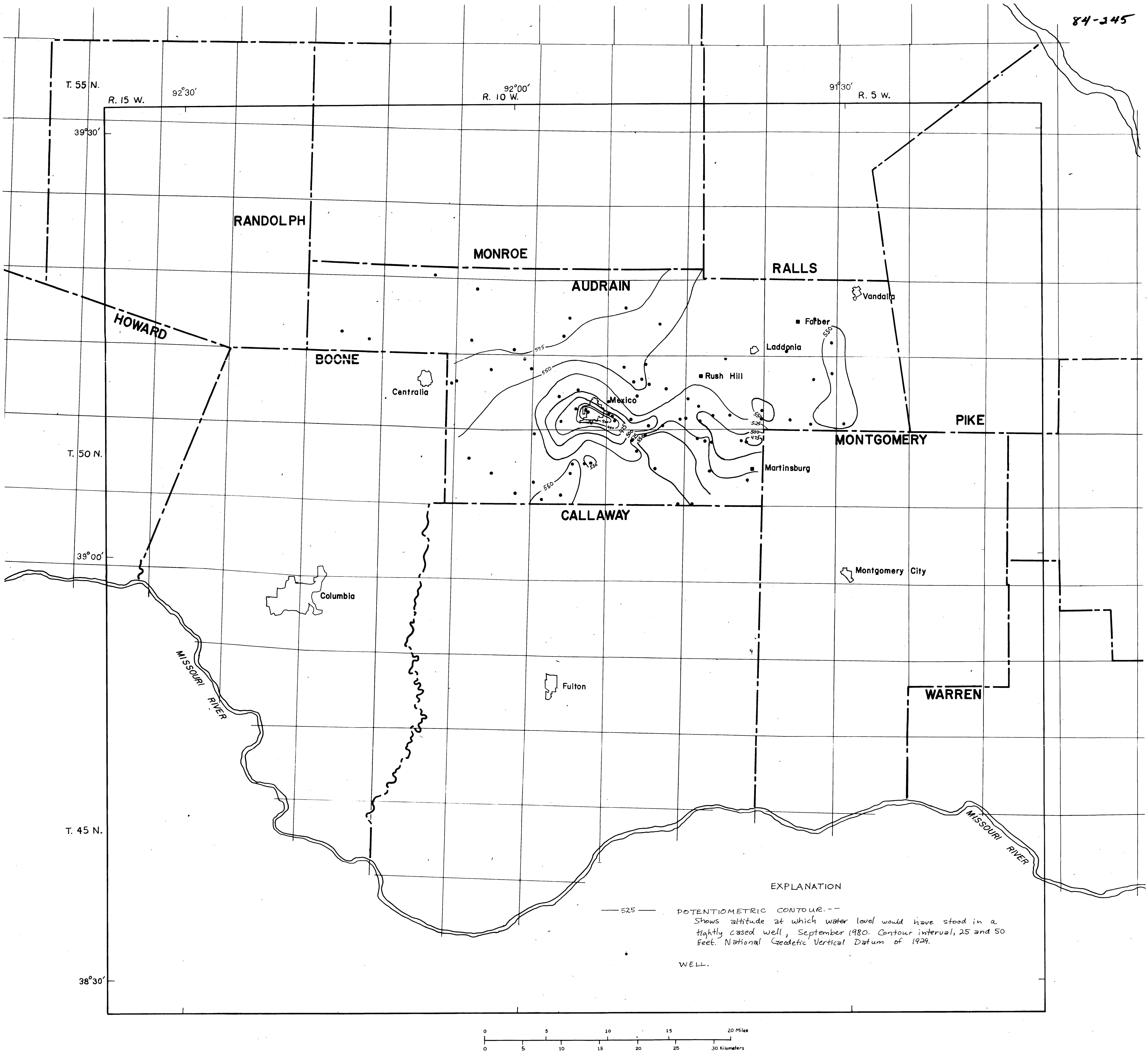

Figure 20.--Potentiometric surface of the deep aquifer in Audrain County, September 1980.

84-245

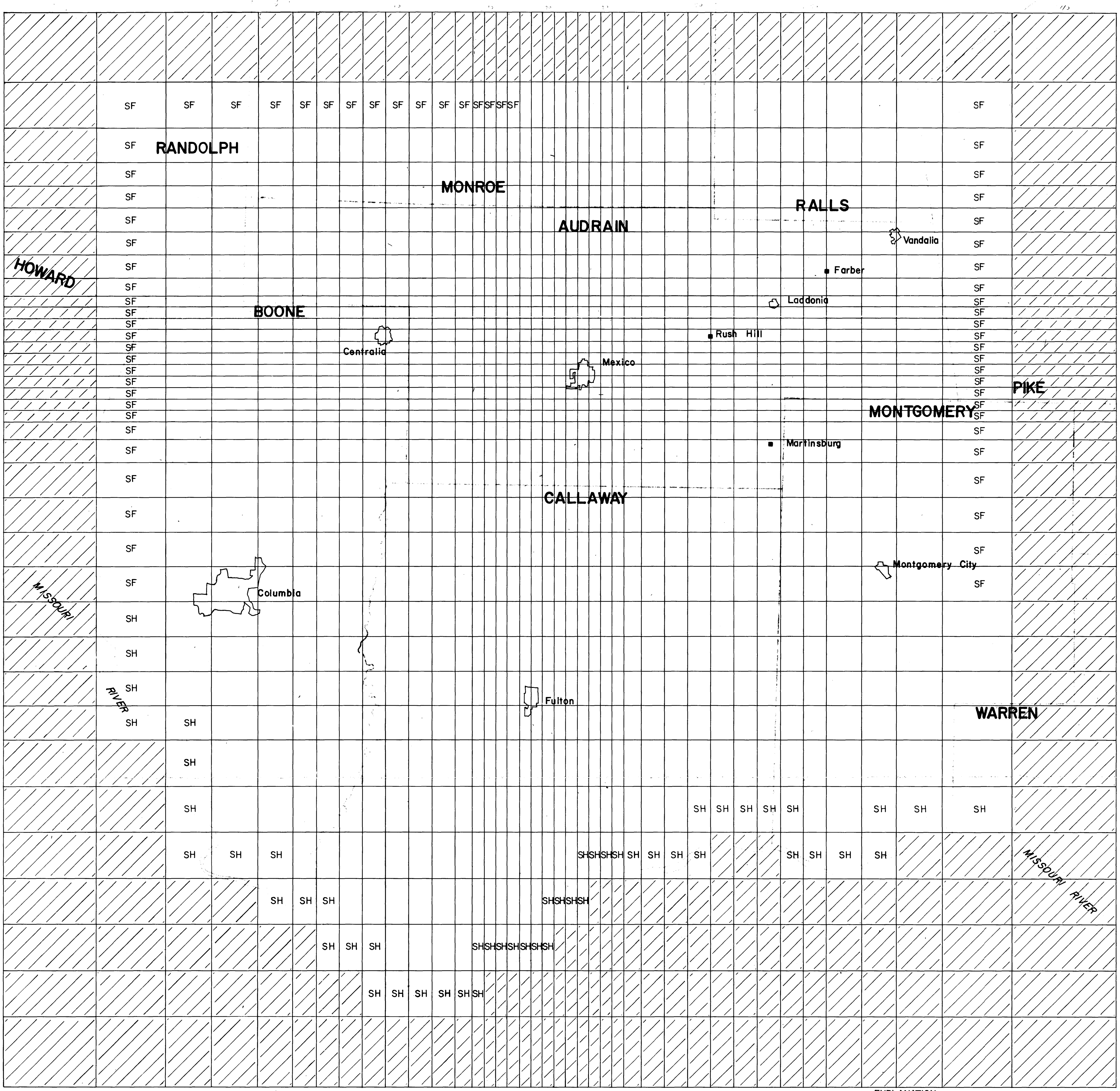

Figure 21.--Ground-water flow model grid showing location of specified-head and specified-flow boundary nodes.

EXPLANATION

INACTIVE NODE

SH SPECIFIED-HEAD

SF SPECIFIED-FLOW

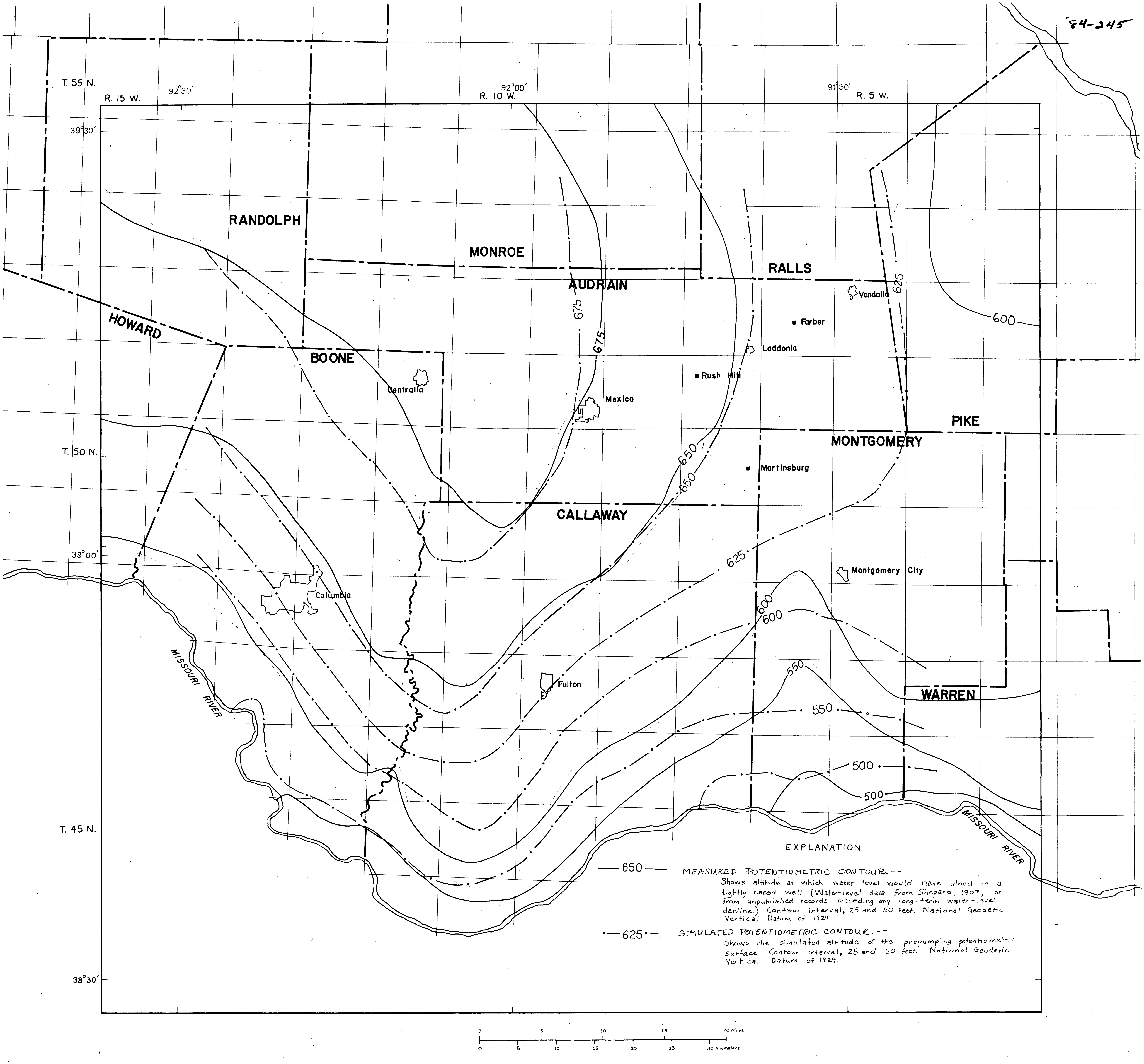

Figure 24.--Reported and simulated predevelopment potentiometric surfaces of the deep aquifer in the model area.

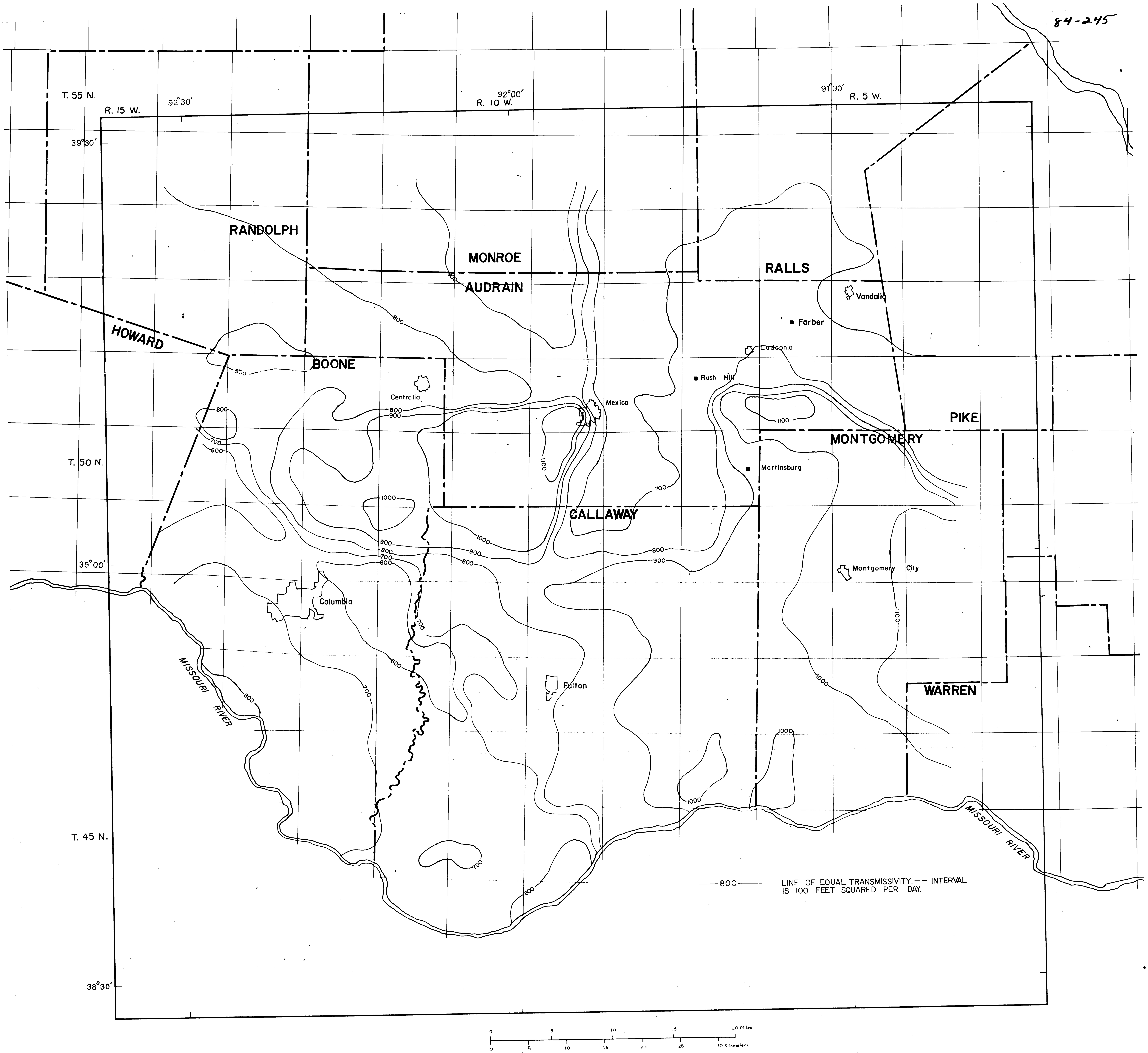

Figure 25.--Distribution of transmissivity in the deep aquifer.

84-245

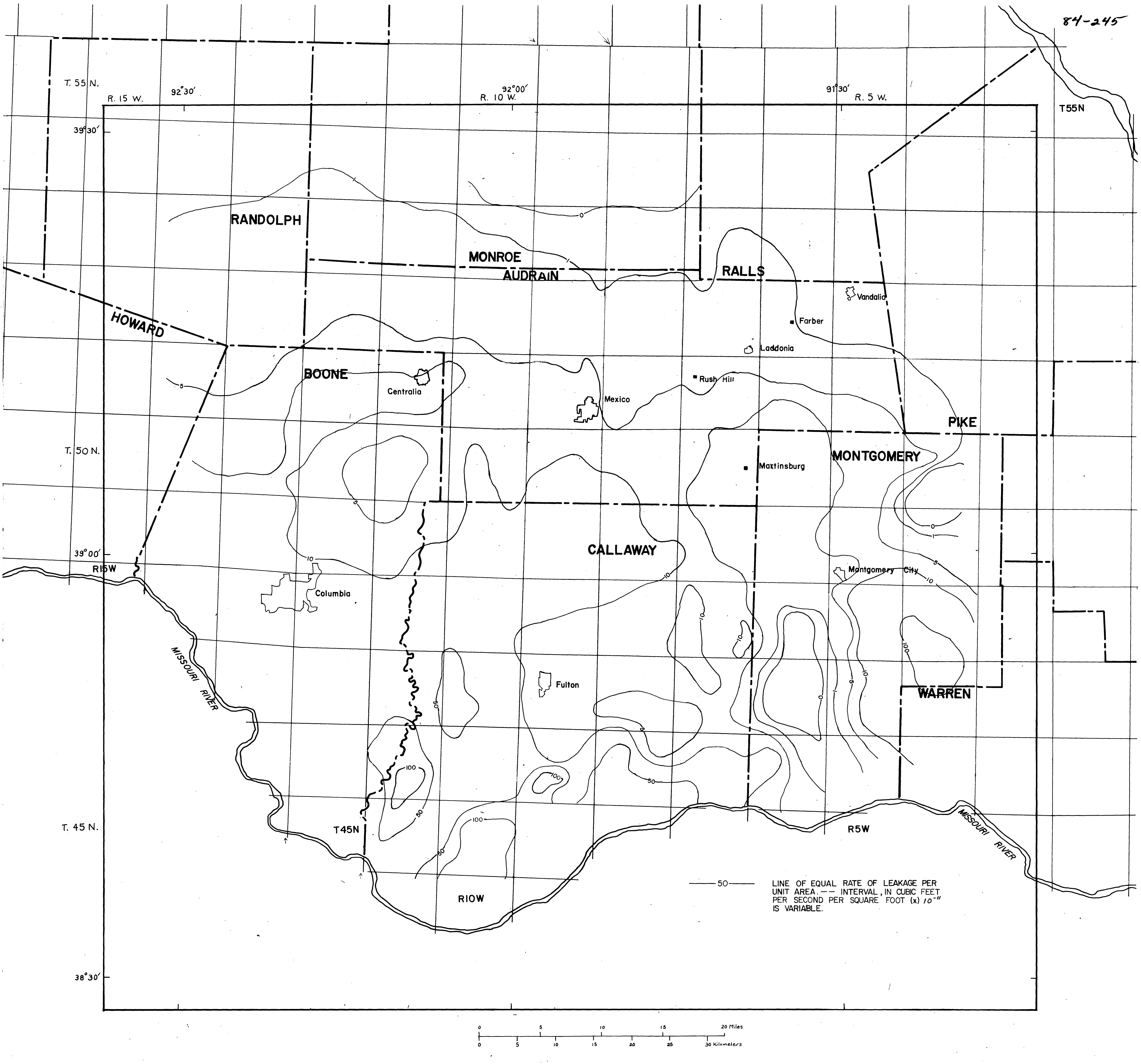

Figure 26.-- Rate of leakage per unit area through the upper confining layer under predevelopment conditions.

84-245

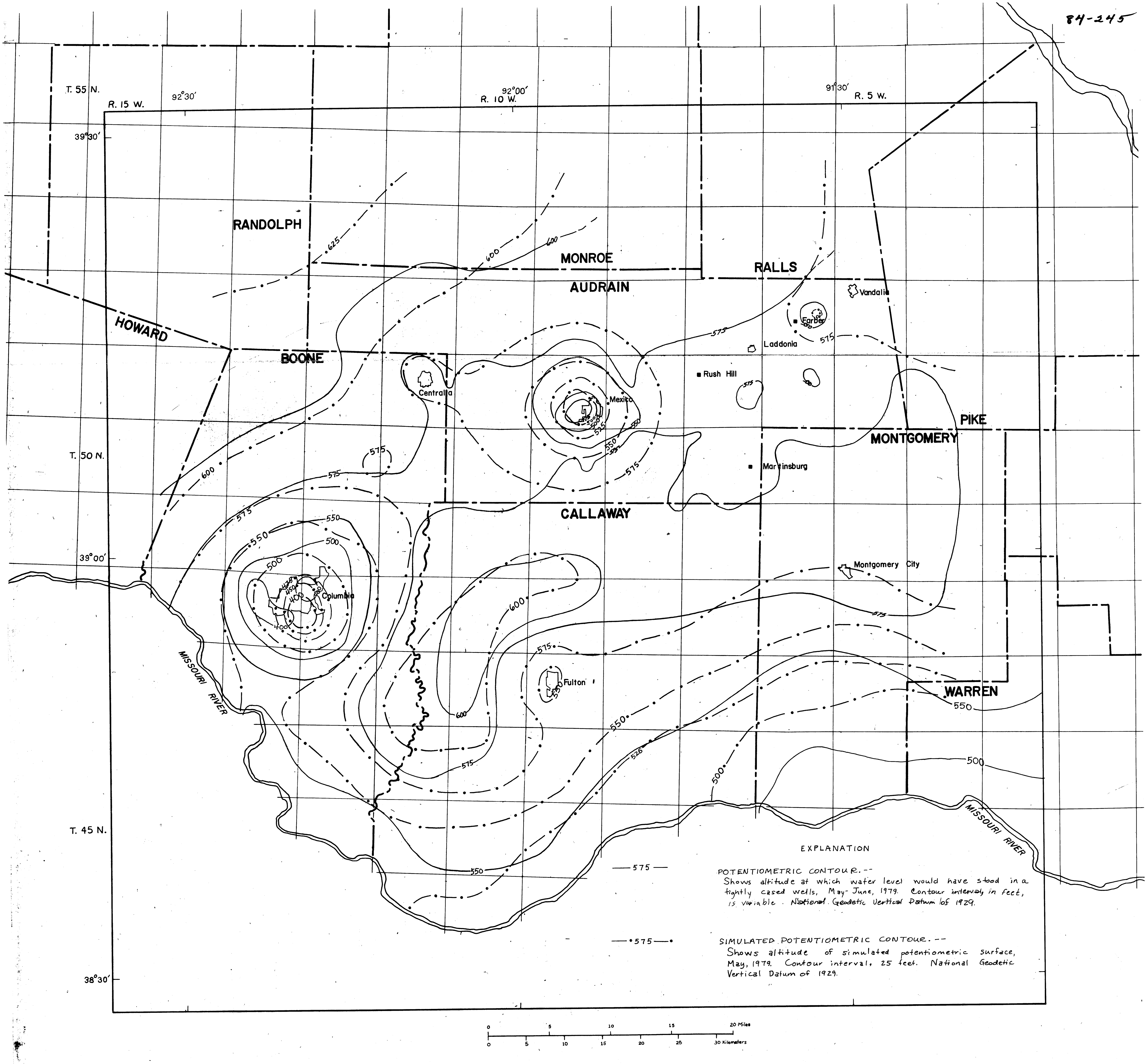

Figure 27.--Comparison of measured and simulated potentiometric surfaces of the deep aquifer in the model area, May 1979.

Missing

Fig. 28

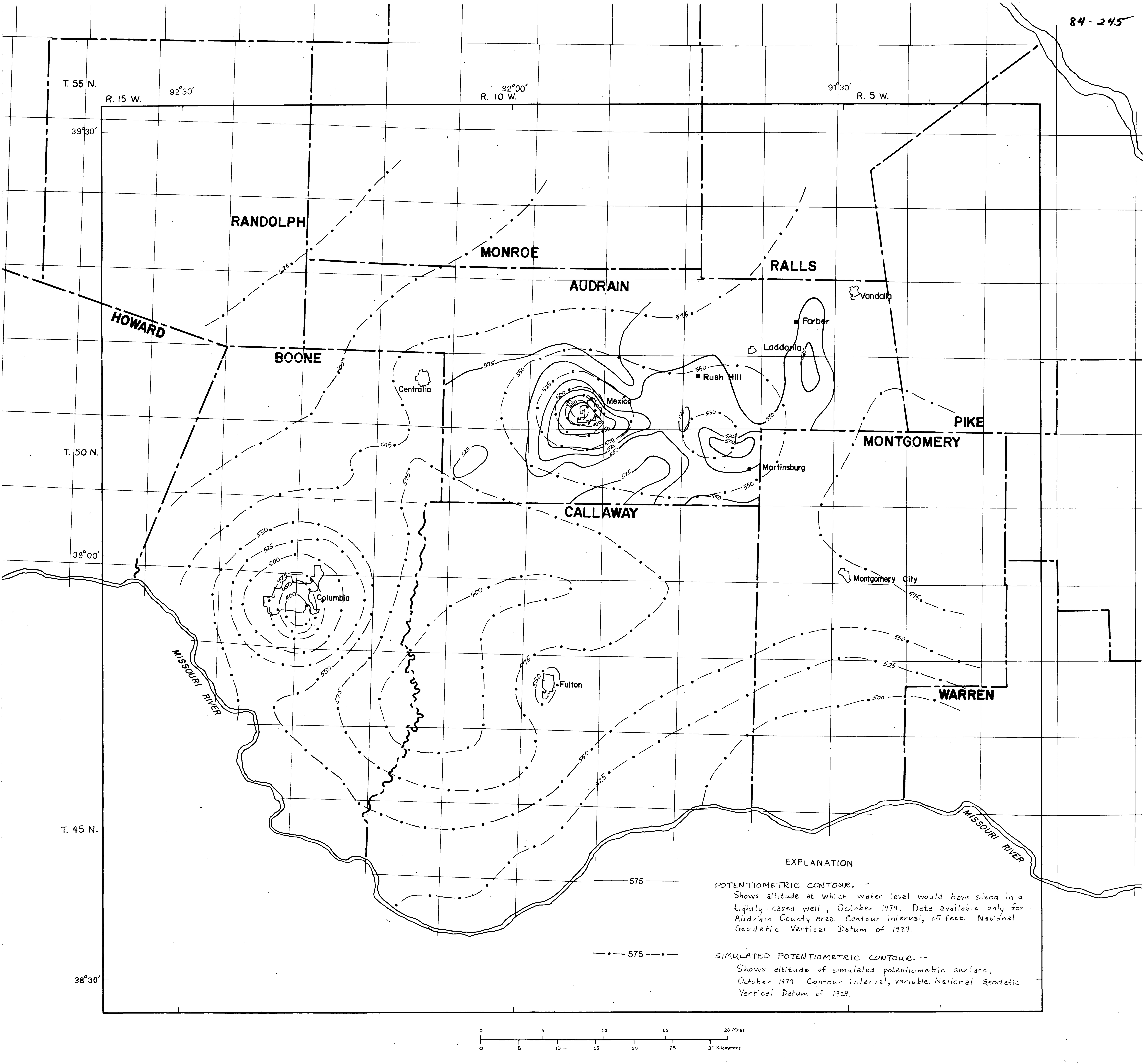

Figure 29.--Comparison of measured and simulated October 1979 potentiometric surfaces of the deep aquifer in Audrain County.

84-245

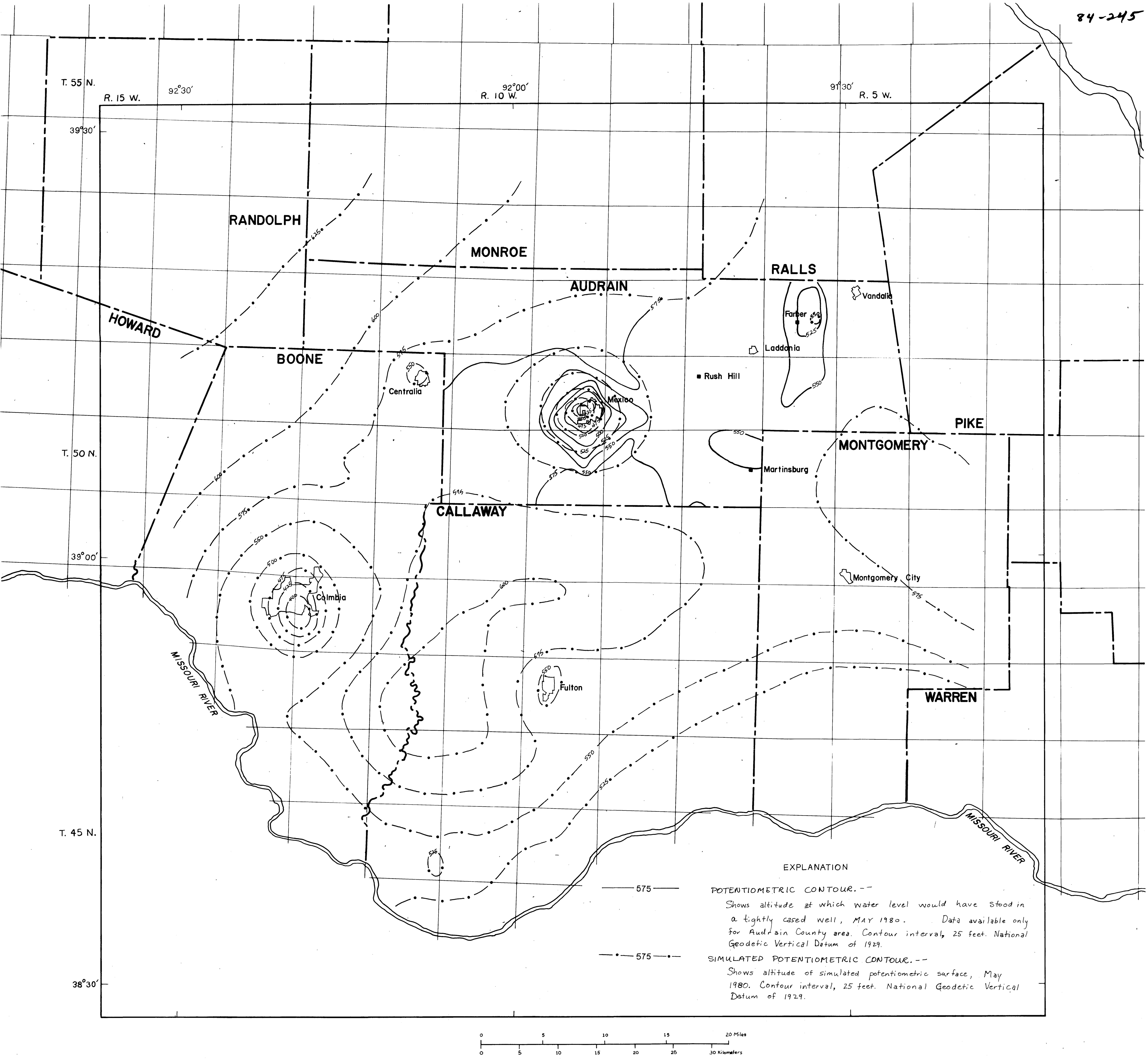

Figure 30.--Comparison of measured and simulated May 1980 potentiometric surfaces of the deep aquifer in Audrain County.

84-245

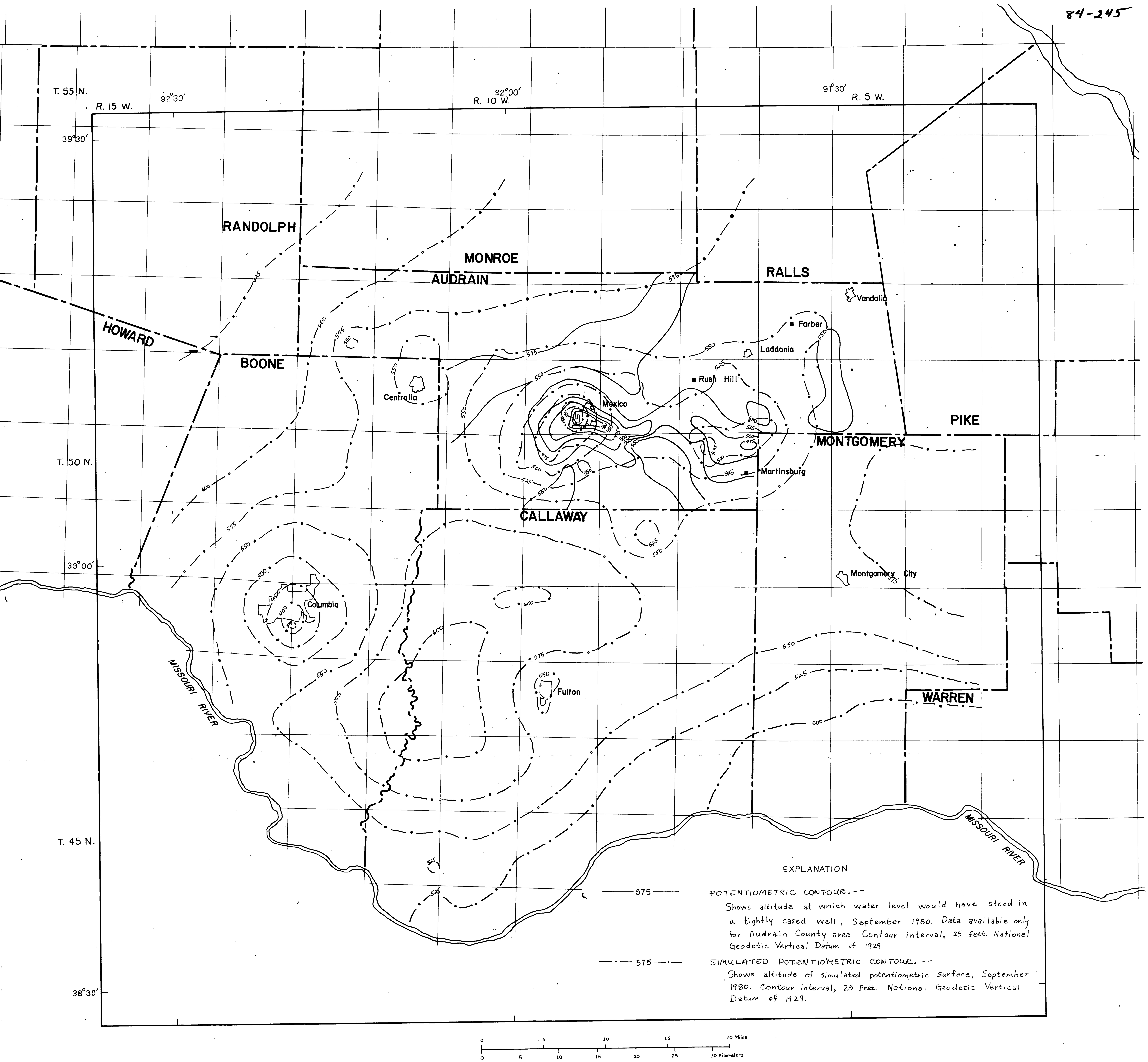

Figure 31.--Comparison of measured and simulated September 1980 potentiometric surfaces of the deep aquifer in Audrain County.

84-245

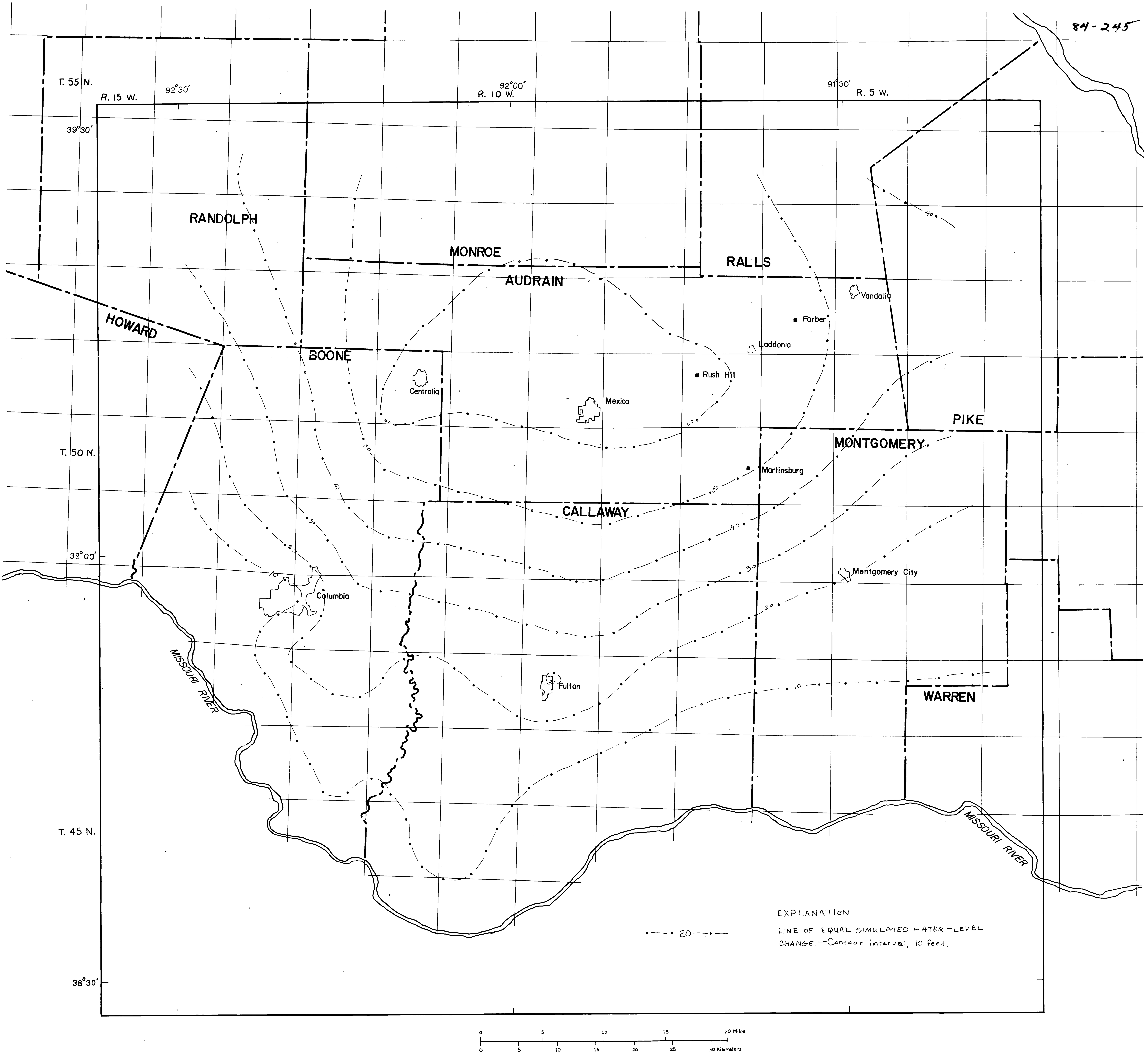

Figure 34.--Simulated water-level decline (June 1979 thru May 2000) in the deep aquifer resulting from public-supply and irrigation pumpage continued at the 1980 rate in the model area.

84-245

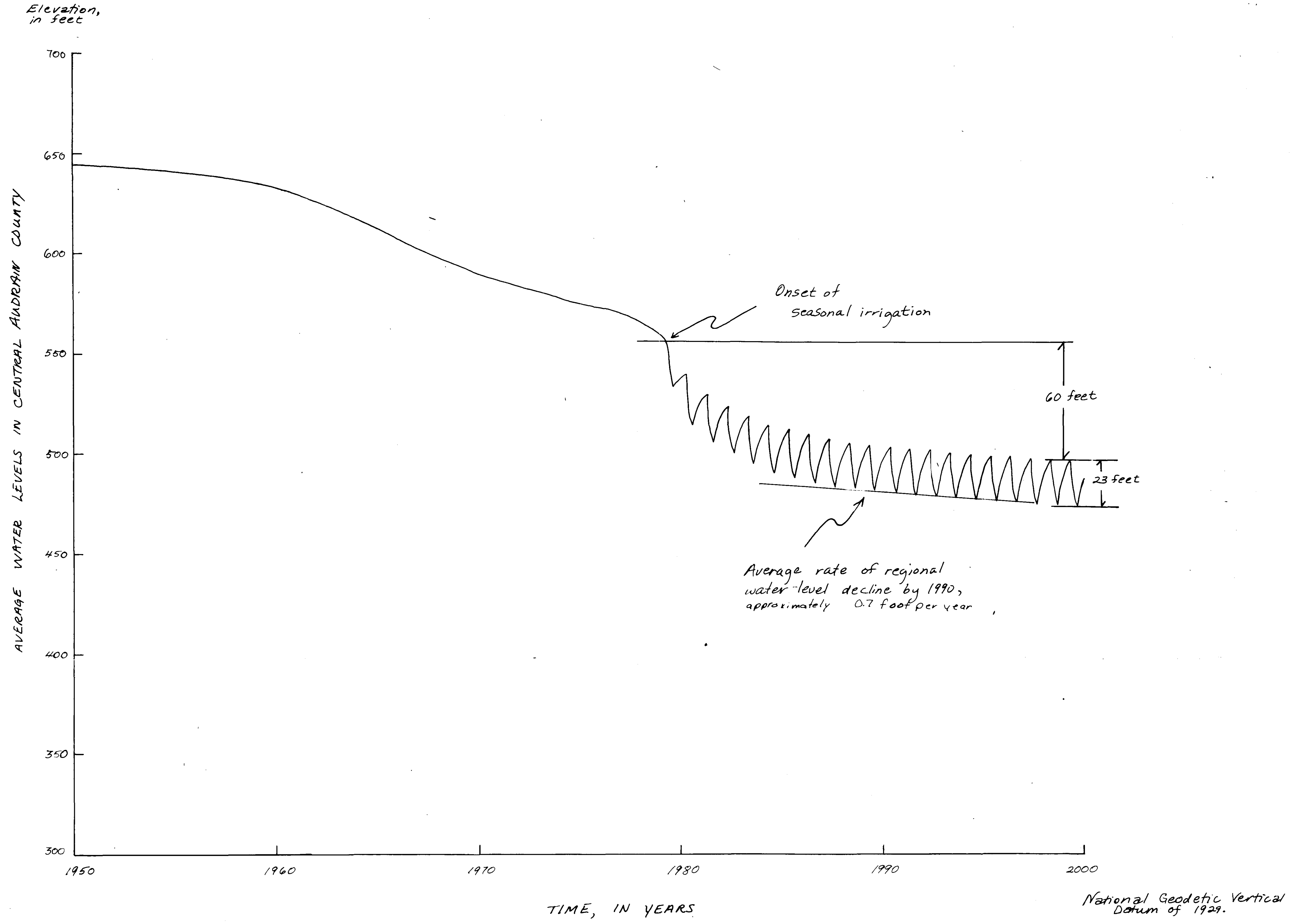

FIGURE 35.——Simulated water-level fluctuations in the deep aquifer in central Audrain County.

84-245

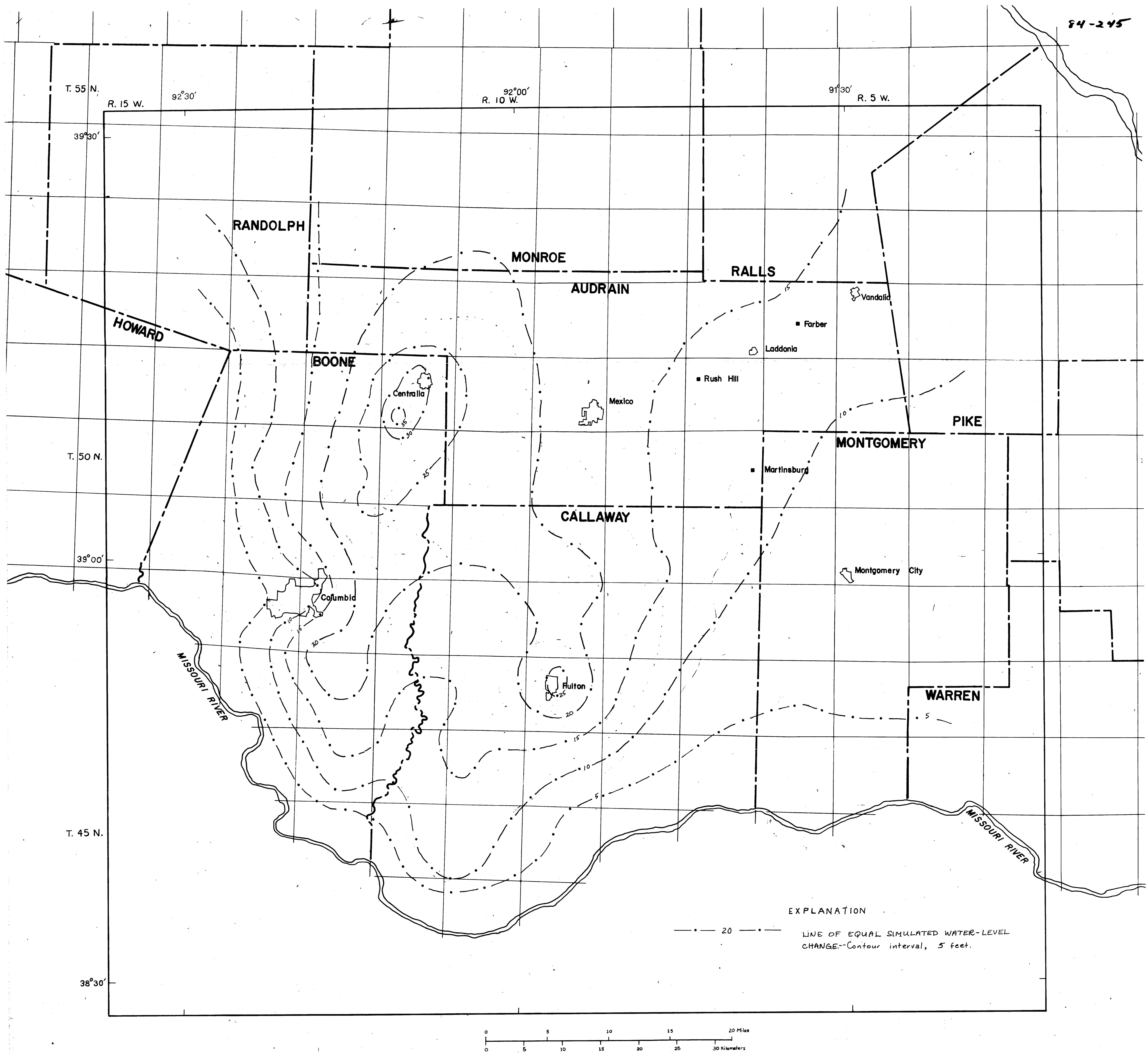

Figure 36.--Simulated water-level decline (June 1979 thru May 2000) in the deep aquifer resulting from public-supply pumpage continued at the 1980 rate in the model area.

Missing

Fig. 37