GEOHYDROLOGY AND GROUND-WATER FLOW AT VERONA WELL FIELD, BATTLE CREEK, MICHIGAN

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 85-4056

Prepared in cooperation with the

CITY OF BATTLE CREEK, MICHIGAN

GEOHYDROLOGY AND

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FIELD, BATTLE CREEK, MICHIGAN

By N. G. Grannemann and F. R. Twenter

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GEOHYDROLOGY AND GROUND-WATER FLOW AT VERONA WELL FIELD, BATTLE CREEK, MICHIGAN

BY

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ABSTRACT

The city of Battle Creek has 30 wells in the Verona well field capable of yielding 300 to 1,000 gallons per minute each for municipal supply. In early 1984, however, only 9 to 12 of the wells were being used. Water in and near the other wells was contaminated by volatile hydrocarbons.

Ground water at and near Verona well field generally flows toward Battle Creek River except where directions are altered by pumping. During summer, especially during periods when withdrawals are as much as 12,000 gallons per minute, a large cone of depression develops and water is drawn to the well field from several thousand feet away. During winter, when withdrawals are as little as 6,000 gallons per minute, the cone is smaller.

Ground-water flow is in three aquifers--a sand and gravel aquifer of Pleistocene age and upper and lower sandstone aquifers of the Marshall Formation of Mississippian age. Model-simulated data that best matched measured data indicate horizontal hydraulic conductivities ranging from 15 to 110 feet per day for the sand and gravel aquifer, 150 feet per day for the upper sandstone aquifer, and 550 feet per day for the lower sandstone aquifer. Recharge was simulated at rates ranging from 8 to 13 inches per year.

Model simulations to evaluate the feasibility of installing new supply wells immediately north of the present field indicate that pumping 3,750 gallons per minute from new wells at the site would produce about 7 feet of drawdown in the lower sandstone aquifer in the vicinity of the new wells. Because the new wells tap only the lower sandstone aquifer, the pumping would have little effect on the potentiometric surfaces for the two overlying aquifers.

INTRODUCTION

The city of Battle Creek in Calhoun County, Michigan (fig. 1), obtains its municipal water supply from wells in the Verona well field[1]. The field, established in 1903 in the valley of Battle Creek River, has 30 operational wells on the east and west sides of the river (fig. 2).

In 1981, volatile organic hydrocarbons were found in water from eight municipal wells. In an effort to protect the well field by purging contaminants before they reached producing wells, two wells were pumped to waste at a combined rate of 2,000 gal/min. This effort was discontinued in September 1982 as evidence accumulated that the pumping, rather than producing the desired result, might be accelerating the movement of contaminants to the field.

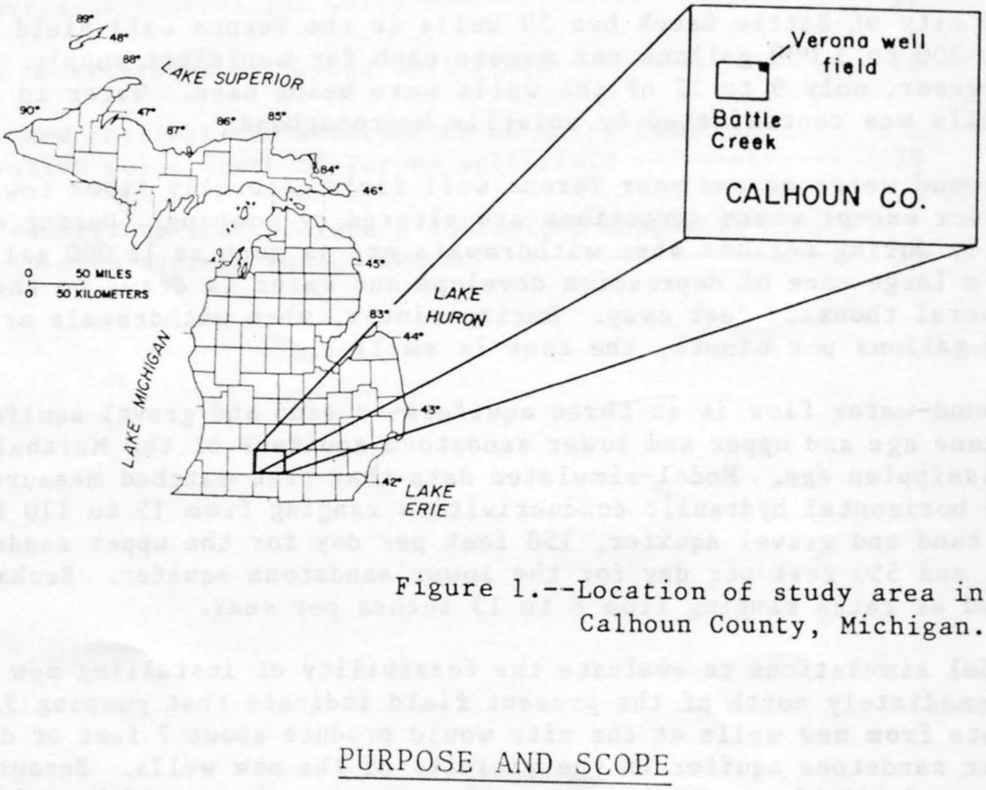

Figure 1.--Location of study area in Calhoun County, Michigan.

PURPOSE AND SCOPE

This report describes the results of a study to determine (1) the geohydrology and the direction and rate of ground-water flow at and near the Verona well field, (2) how pumping affects flow, (3) the feasibility and effect of installing new supply wells north of the present field, and (4) pumping conditions needed to provide a sufficient supply of potable water. To more accurately evaluate ground-water conditions the study area was extended beyond the immediate vicinity of the well field.

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[1] Commonly referred to as "field" in this report.

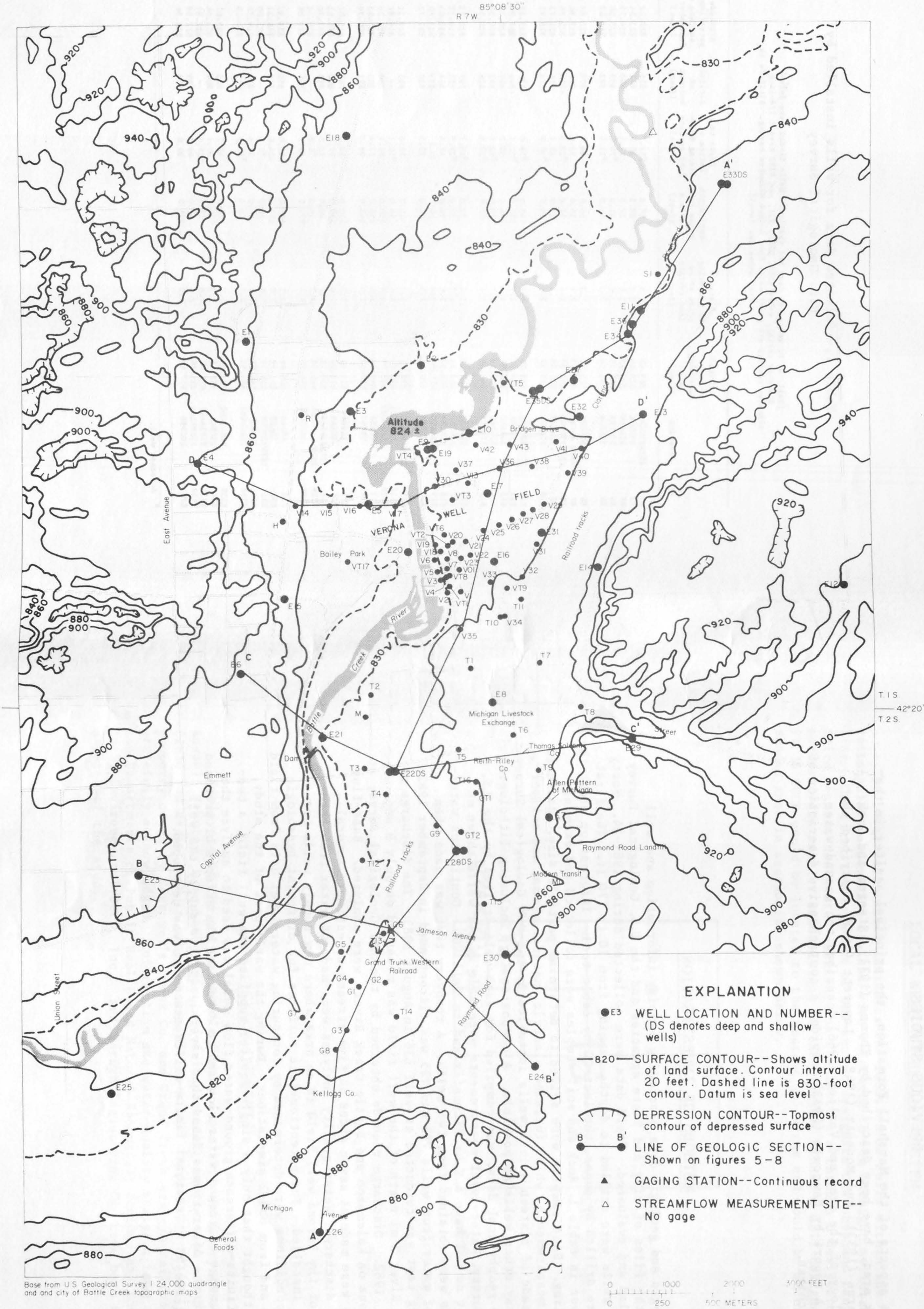


Figure 2.--Physical features and well locations in study area.

PREVIOUS STUDIES

Various aspects of the Marshall Formation, the principal aquifer in the Battle Creek area, have been described by Thomas (1931), Stearns and Cook (1931), Stearns (1933), and Monnett (1948). Leverett (1918) described the glacial geology of the area and Vanlier (1966) described the ground-water resources. A report by Newcombe (1933) provides a comprehensive description of rocks in Michigan.

METHODS OF INVESTIGATION

Hydrologic and geologic data, including pumping information and well records in the files of city and State agencies and the U.S. Geological Survey were assembled and evaluated. Field data were collected during 1981-84. Forty observation wells were drilled to depths ranging from 10 to 170 ft. The first 20 wells were drilled by auger, the last 20 by cable tool. Information about the wells is given in table 1. Rock and soil samples were collected and examined during drilling. Some samples were seived to determine particle size. Borehole geophysical measurements, which included electric, natural gamma, and caliper logs, were made of sixteen 4-inch wells installed by the U.S. Geological Survey and of as many other wells as possible. A composite log, including lithologic and borehole geophysical data, was compiled for each well drilled by the U.S. Geological Survey. Water-level measurements were made in all wells shown on figure 2 that do not have a V or VT prefix and in well V01. Continuous water-level records were obtained from two wells. A recovery test was made when withdrawal of water from wells V32 and V35 was discontinued in September 1982 and a pumping test was conducted at well E36 in August 1983. The discharge of Battle Creek River 2 mi north of the well field was measured on July 9 and September 7, 1982. Discharge records obtained by the U.S. Geological Survey at gaging stations on Kalamazoo and Battle Creek Rivers were analyzed. Base-flow measurements were made at seven sites on five streams to estimate natural ground-water discharge. Water-quality analyses were made of water from three wells north of the Verona well field in an area where new supply wells are likely to be installed. The potentiometric surfaces for different hydrologic and pumping conditions were determined by contouring water-level data from field measurements and from model simulations. During the early part of the study, when it was thought that only a single aquifer supplied the well field, a two-dimensional finite-difference ground-water flow model was used to analyze the effects of pumpage on ground-water flow and to determine the effects of proposed remedial actions. After it was found that several aquifers supply the well field, a quasi three-dimensional finite-difference model was developed.

Table 1.--Selected data for wells installed by U.S. Geological Survey

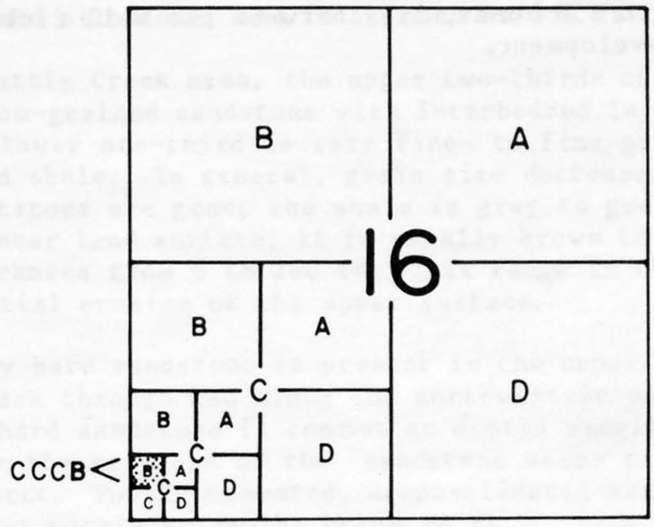
[Well: D, S; indicates deep and shallow. Wells E1-E20 have 2-inch diameter casing; wells E22S, E28S, E31, and E33S have 1 1/4-inch diameter casing; all other wells have 4-inch diameter casing. Altitude in feet above sea level]

Well	Location	Altitude of measuring point (feet)	Distance of measuring point above land surface (feet)	Well depth below land surface (feet)	Depth to bottom of casing below land surface (feet)	Altitude of bedrock (feet)	Altitude of potentiometric surface on September 1983 (feet)
E1	1S7W29CCDA	865.42	2.3	57.0	[a]51.7	815	828.22
E2	29DDCC	829.66	0.9	28.5	26.6	802	823.34
E3	32ABBC	830.73	3.6	27.5	23.4	800	824.79
E4	32BCBA	883.16	2.0	81.0	[a]70.0	803	823.50
E5	32ACCA	831.54	2.0	14.0	[a]11.0	822	819.62
E6	32CCDA	875.33	.3	60.0	44.7	828	822.88
E7	2S7W 4BCBD	868.28	2.1	55.0	51.9	836	837.86
E8	1S7W32DDDD	847.89	2.6	31.0	[a]28.9	<814	825.26
E9	32AACC	831.48	.9	17.0	15.1	816	821.73
E10	32AADB	835.92	2.0	35.0	[a]30.0	824	816.92
E11	28CDAC	842.02	3.3	43.0	[a]39.0	<796	823.35
E12	33DADA	907.43	1.9	100.0	[a]97.1	<806	867.84
E13	33BAAC	856.94	3.8	54.0	53.2	801	820.13
E14	33CBAD	878.79	2.2	70.0	[a]62.8	832	820.58
E15	32CACA	848.38	2.1	37.0	[a]33.9	826	823.38
E16	32DAAD	834.97	1.8	42.0	[a]29.7	797	820.78
E17	32ADAD	835.84	1.7	32.0	[a]27.8	830	818.12
E18	29ACBB	848.92	3.6	24.0	17.4	834	832.65
E19	32AACC	831.86	1.4	34.0	24.6	819	821.76
E20	32DBAA	830.44	2.5	21.0	13.5	820	821.72
E21	2S7W 5BAAC	831.41	1.4	25.0	16.6	815	823.31
E22S	5ABCC01	840.21	3.4	14.0	[a]10.1	—	824.97
E22D	5ABCC02	841.23	4.4	130.0	55.6	800	824.38
E23	6DABA	849.04	3.6	155.0	77.4	805	825.63
E24	9BBBC	890.42	2.5	163.0	98.0	821	850.36
E25	7ABDA	825.91	1.8	110.0	58.2	787	815.02
E26	8CAAB	873.04	2.0	135.0	91.0	806	816.63
E27	1S7W33BBAA	830.13	2.7	80.0	18.0	813	822.70
E28S	2S7W 5ADCC01	840.98	3.2	10.0	[a]6.8	--	829.38
E28D	5ADCC02	841.99	4.3	130.0	49.7	796	828.06
E29	4BABD	866.06	2.5	156.0	52.0	856	839.97
E30	5DADD	861.58	2.0	139.0	104.0	769	846.22
E31	1S7W33BCDB	835.79	3.4	10.0	[a]6.6	--	<823.00
E32	33BBAD	844.39	1.6	60.0	36.4	818	819.26
E33S	28ACDC01	845.53	2.7	18.0	[a]15.3	—	825.18
E33D	28ACDC02	845.50	2.7	170.0	43.3	809	825.67
E34	28CDCA	838.45	2.9	155.0	79.1	806	821.94
E35S	33BBBA01	833.80	2.9	22.0	[a]17.1	--	822.81
E35D	33BBBA02	833.36	2.5	81.0	49.5	795	822.98
E36	28CDBD	837.65	2.2	125.0	80.0	798	822.36

[a] Screened well.

LOCAL WELL NUMBERING SYSTEM

The local well number indicates the location of wells within the rectangular subdivision of land with reference to the Michigan meridian and base line. The first two segments of the number designate township and range, the third segment designates section, and the letters A through D designate successively smaller subdivisions of the section. Thus, a well designated as 1S 7W 16 CCCB would be located to the nearest 2.5 acres and would be within the shaded area in section 16 shown below.



ACKNOWLEDGMENTS

Employees of the city of Battle Creek, especially Mr. Larry Osborn and Mr. Russell Schuler, have been most helpful in providing information about the well field and assistance in other phases of the study. Permission to drill wells on property owned by Consumer's Power Co. and Grand Trunk Western Railroad Co. is gratefully acknowledged. Information and water-quality analyses from the Michigan Departments of Public Health and Natural Resources; Ecology and Environment, Inc.; Environmental Data, Inc.; and Warzyn Engineering Co. have been helpful in aspects of the study.

PHYSICAL SETTING

The valley of Battle Creek River is 1 mi wide at Verona well field and has altitudes ranging from 824 to 840 ft (fig. 2). Upstream, the valley is 1.5 mi wide; downstream, it narrows to 0.5 mi. The valley walls rise sharply on the east to 910 ft and gradually on the west to about the same altitude. A dam near Emmett St ponds the river at an altitude of 824 ft for a 1.5-mile reach that passes through the well field. North of the well field, there are no commercial-industrial developments within the study area. South of the field, however, are eight large and several small companies. A railroad complex, including a switching yard, lies along the east side of the well field and a landfill is 1 mi southeast. The Verona Valley Subdivision, a residential section composed of 100 to 150 homes, lies between the well field and the commercial-industrial development.

SOURCES OF WATER

Water for municipal supplies and most commercial-industrial activity is pumped from wells that tap sandstones in the Marshall Formation; most of these wells are 100 to 160 ft deep. Large-diameter wells in the sandstone can yield several thousand gallons per minute.

The city of Battle Creek municipal supply wells range in depth from 110 to 152 ft (table 2). Sixteen of these wells consistently yield 1,000 gal/min. From 1970 through 1981, average pumpage by the city was about 5,000 gal/min. During 1982, average pumpage was 8,300 gal/min; during 1983 it was 6,650 gal/min. During periods of peak pumping, 12,000 to 14,000 gal/min are withdrawn.

In the past, water for residential supplies in the Verona Valley Subdivision was obtained from 20- to 60-foot deep wells in the Marshall Formation and the overlying glacial deposits. Today (1985) most residences are connected to the Battle Creek municipal system.

Table 2.--Selected data for city of Battle Creek's wells

[Pump capacity: N, not operational. Symbol "--" indicates data not available. Altitude in feet above sea level]

Production wells

Well number	Altitude of land surface (feet)	Well depth below land surface (feet)	Depth to bottom casing below land surface (feet)	Diameter of casing (inches)	Altitude of top of bedrock (feet)	Pump capacity (gallons per minute)	Year drilled
V1	836	124	45	10	793	N	1915
V2	834	124	41	8	802	N	1915
V3	830	113	47	10	800	N	1918
V4	830	129	60	6	800	N	1904
V5	832	128	50	10	815	N	1915
V6	831	121	50	6	816	N	1913
V7	833	126	52	8	806	N	1915
V8	833	121	32	8	819	N	1913
V13	836	127	18	12	822	1000	1936
V14	840	129	39	12	802	1000	1939
V15	836	141	--	12	804	1000	1939
V16	834	134	--	12	812	750	1939
V17	831	133	33	12	824	N	1939
V18	833	126	46	10	819	500	1915
V19	832	125	48	8	817	300	1915
V20	834	140	21	8	822	300	1904
V21	834	131	44	8	822	300	1915
V22	833	113	77	10	793	750	1919
V23	832	110	46	8	793	300	1913
V24	835	118	41	8	823	300	1926
V25	835	115	36	8	823	300	1926
V26	836	115	38	8	825	300	1926
V27	837	116	46	8	815	300	1926
V28	836	115	47	8	810	300	1926
V29	835	121	51	8	800	300	1926
V30	831	151	--	8	796	500	1904
V31	837	125	76	16	784	1000	1948
V32	838	120	57	16	794	1000	1948
V33	837	150	49	16	792	1000	1948
V34	840	140	67	16	792	1000	1948
V35	840	132	59	16	805	1000	1948
V36	840	147	44	16	825	1000	1957
V37	832	145	44	16	817	1000	1957
V38	838	152	--	16	823	1000	1959
V39	839	145	37	16	812	1000	1960
V40	842	148	42	16	812	1000	1962
V41	840	147	44	16	822	1000	1962
V42	833	150	--	16	--	1000	1968
V43	835	148	26	6	827	1000	1976

Table 2.--Selected data for city of Battle Creek's wells--Continued

Well number	Altitude of land surface (feet)	Well depth below land surface (feet)	Depth to bottom casing below land surface (feet)	Diameter of casing (inches)	Altitude of top of bedrock (feet)	Pump capacity (gallons per minute)	Year drilled
Test wells							
VT1	834	40	--	2	790	--	1903
VT1A	834	48	--	2	790	--	1903
VT2	834	70	--	2	820	--	1903
VT3	834	75	--	2	828	--	1903
VT4	828	76	--	2	820	--	1903
VT5	833	50	--	2	--	--	1903
VT5A	833	55	--	2	--	--	1903
VT6	830	95	10	6	825	--	1903
VT7	834	142	--	--	--	--	--
VT8	830	27	--	2	--	--	1904
VT9	838	150	--	2	--	--	1904
VT10	--	20	--	2	--	--	1904
VT11	838	49	--	2	798	--	1904
VT12	836	28	--	2	--	--	1904
VT13	832	45	--	2	778	--	1904
VT14	838	53	--	2	798	--	1904
VT15	836	38	--	2	804	--	1904
VT16	832	27	--	2	820	--	1904
VT17	833	71	--	2	827	--	1905
VT18	832	51	--	2	802	--	1905
VT19	--	29	--	2	--	--	1905
VT20	--	16	--	2	--	--	1913
VT21	--	18	--	2	--	--	1913
VT22	--	16	--	2	--	--	1913
VT23	--	18	--	2	--	--	1913
VT24	833	34	--	2	816	--	1913
VT25	--	27	--	2	--	--	1913
VT26	--	25	--	2	--	--	1913
VT27	--	27	--	2	--	--	1913
VT28	--	20	--	2	--	--	1913
VT29	--	35	--	2	--	--	1913
VT30	833	25	--	2	819	--	1913
VT31	--	29	--	2	--	--	1913
VT32	831	46	--	2	788	--	1918
VT33	833	61	--	2	812	--	1920
VT37	--	59	--	2	--	--	1920
VT38	830	55	--	2	792	--	1921
VT39	836	44	--	8	816	--	1904
VT40	836	40	--	8	816	--	1904

The lithology of the Marshall Formation and glacial deposits in wells installed by the U.S. Geological Survey is given in table 3 (at end of report).

MARSHALL FORMATION

Lithology and Thickness

The Marshall Formation underlies much of the Lower Peninsula of Michigan. The formation is a very fine to coarse sandstone containing layers of shale, sandy shale, and siltstone, and is as much as 550 ft thick at places.

In the Battle Creek area, the upper two-thirds of the Marshall Formation is fine- to medium-grained sandstone with interbedded layers of siltstone and shale (fig. 3). The lower one-third is very fine- to fine-grained silty sandstone, siltstone, and shale. In general, grain size decreases with depth. The sandstone and siltstone are gray; the shale is gray to greenish gray. Where the formation is near land surface, it is usually brown to yellow. The formation ranges in thickness from 0 to 200 ft. This range in thickness results primarily from differential erosion of the upper surface.

Extremely hard sandstone is present in the upper few feet of the formation from Bailey Park through and along the northwestern part of the well field. Hard to very hard sandstone is common at depths ranging from 5 to 60 ft. Differences in the hardness of the sandstone seems to be due to differences in amount of cement. Poorly cemented, unconsolidated sandstone has been reported at some places; mostly at depths below 80 ft.

A small outcrop of the Marshall Formation is at the eastern foot of the dam on Battle Creek River near Emmett St (fig. 2). Sandstone of the formation was quarried for building stone about 4 mi southeast of the Verona well field.

Major lithologic units of the Marshall Formation defined on figure 3 can be identified on gamma-ray logs for many wells; logs for three wells are shown on figure 4. The principal marker beds in the type column are the upper siltstone and the shale. Geologic sections, figures 5 to 8 show stratigraphic relations of the major units.

The upper sandstone, upper siltstone, and part of the lower sandstone have been eroded near well G6 (figs. 5 and 6) and in the southwestern part of the study area. All bedrock units are present, however, in the rest of the area.

Drillers' descriptions of materials in most municipal wells identify the glacial deposits as "sand and gravel" and most of the Marshall Formation as "hard or soft sandstone". A "blue shale" unit is identified at the bottom of many wells (fig. 9). For some wells, notations are made concerning "openings". For several wells, as for V36, a more complete description of the materials is given, revealing that the "sandstone" in some zones is silty and shaly and that a silty or shaly bed was found about half way down the borehole.

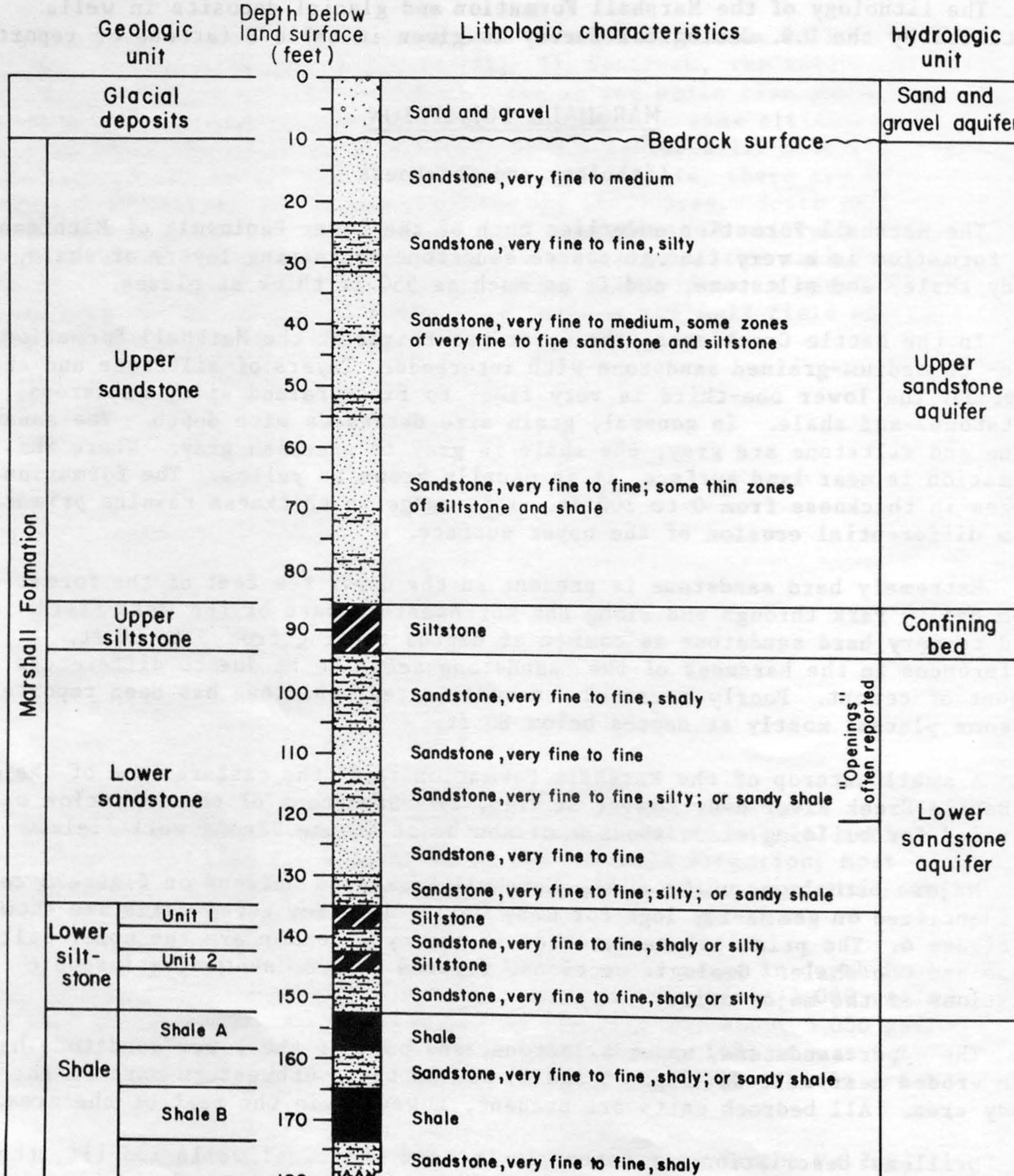


Figure 3.--Type lithologic column of Marshall Formation in Verona well field area.

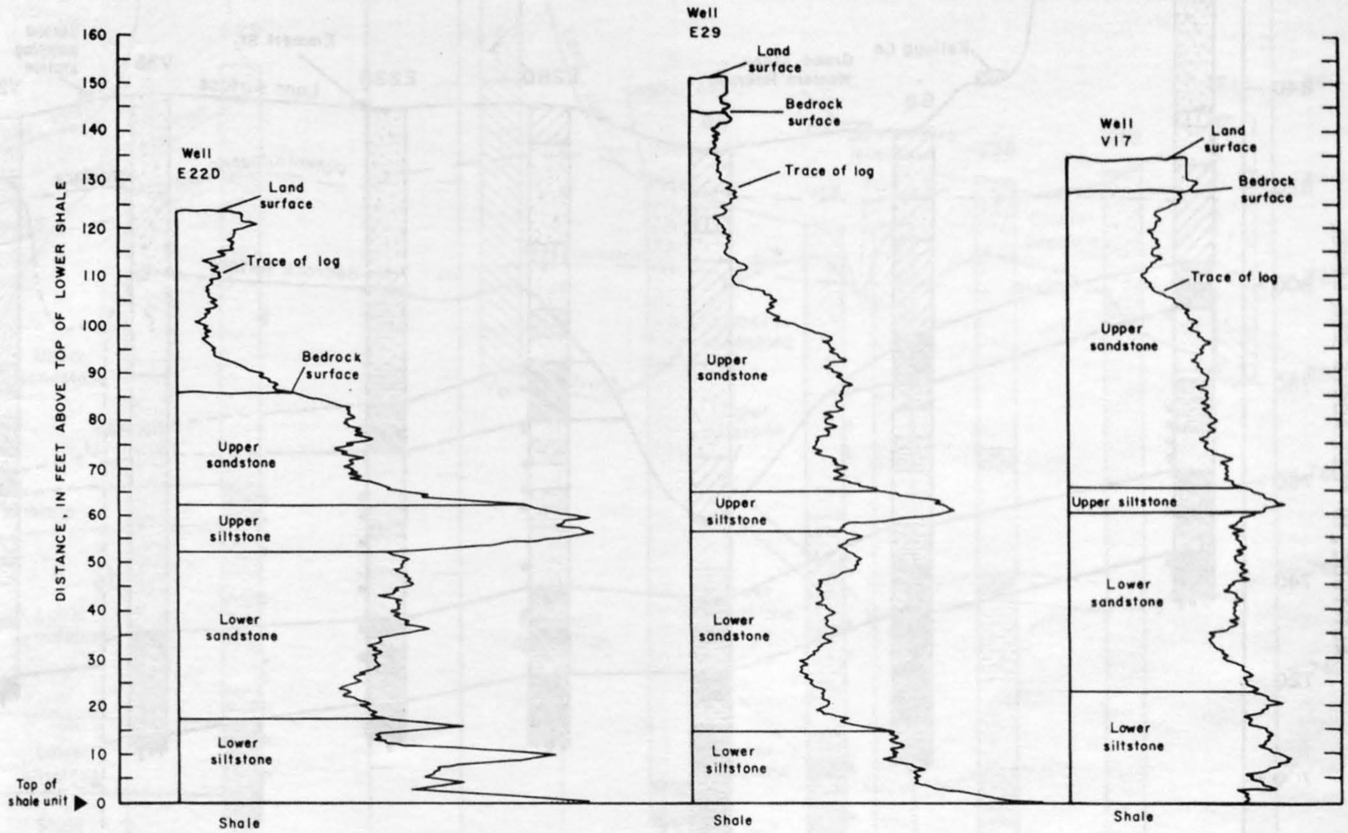


Figure 4.--Units of Marshall Formation identified on gamma-ray logs of several wells (Gamma count increases left to right).

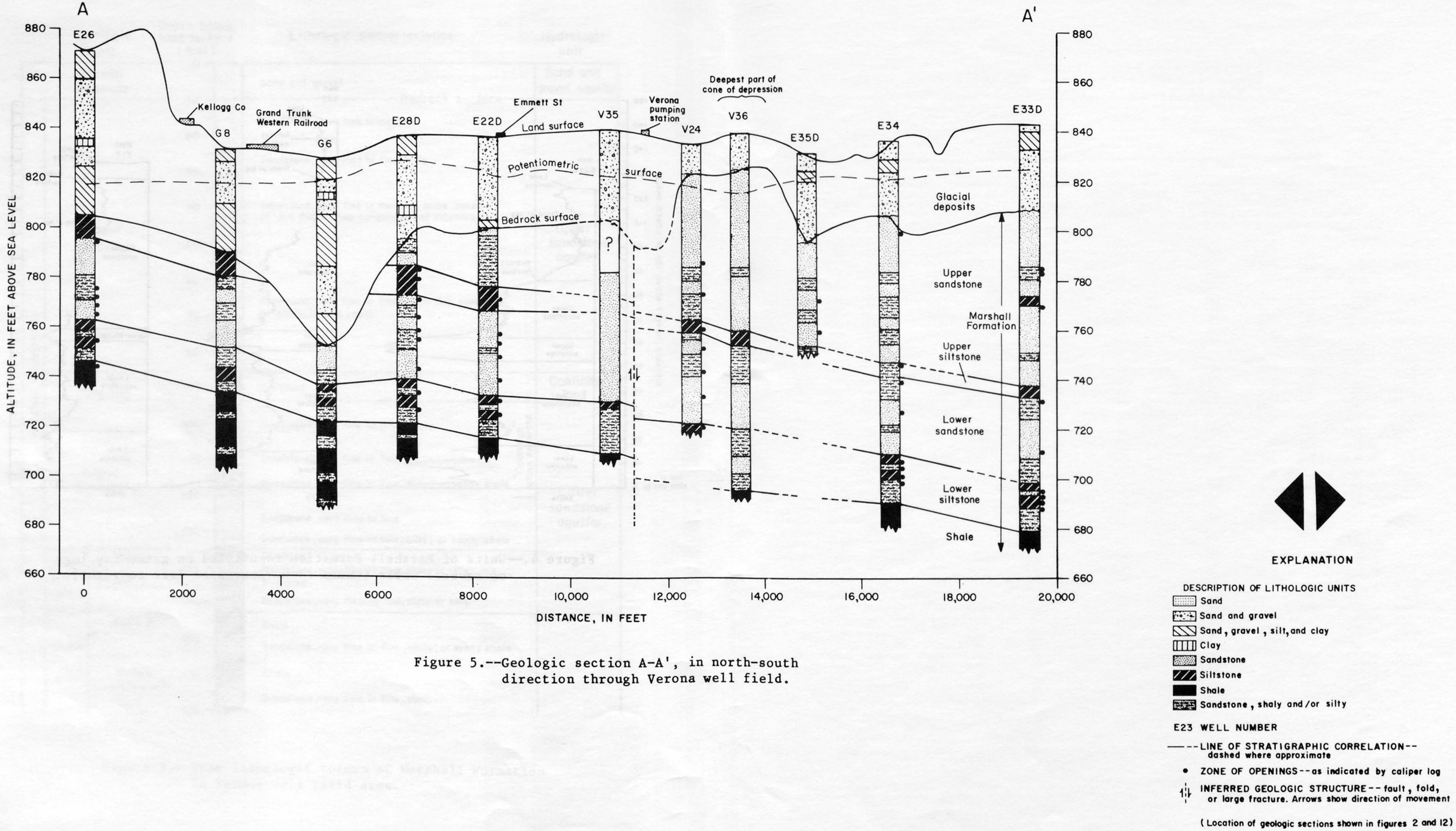


Figure 5.--Geologic section A-A', in north-south direction through Verona well field.

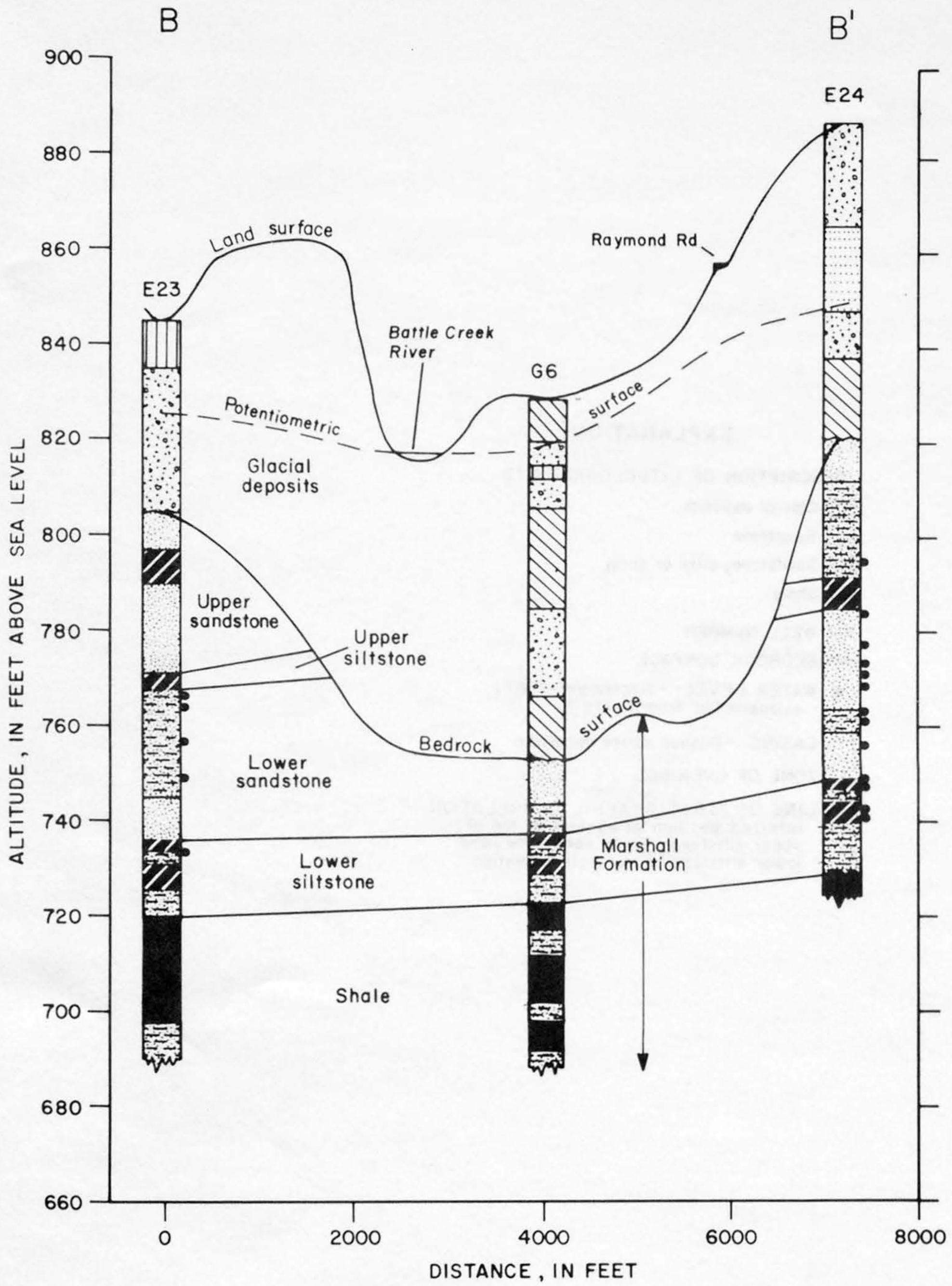


Figure 6.--Geologic section B-B', in east-west direction through southern part of study area.

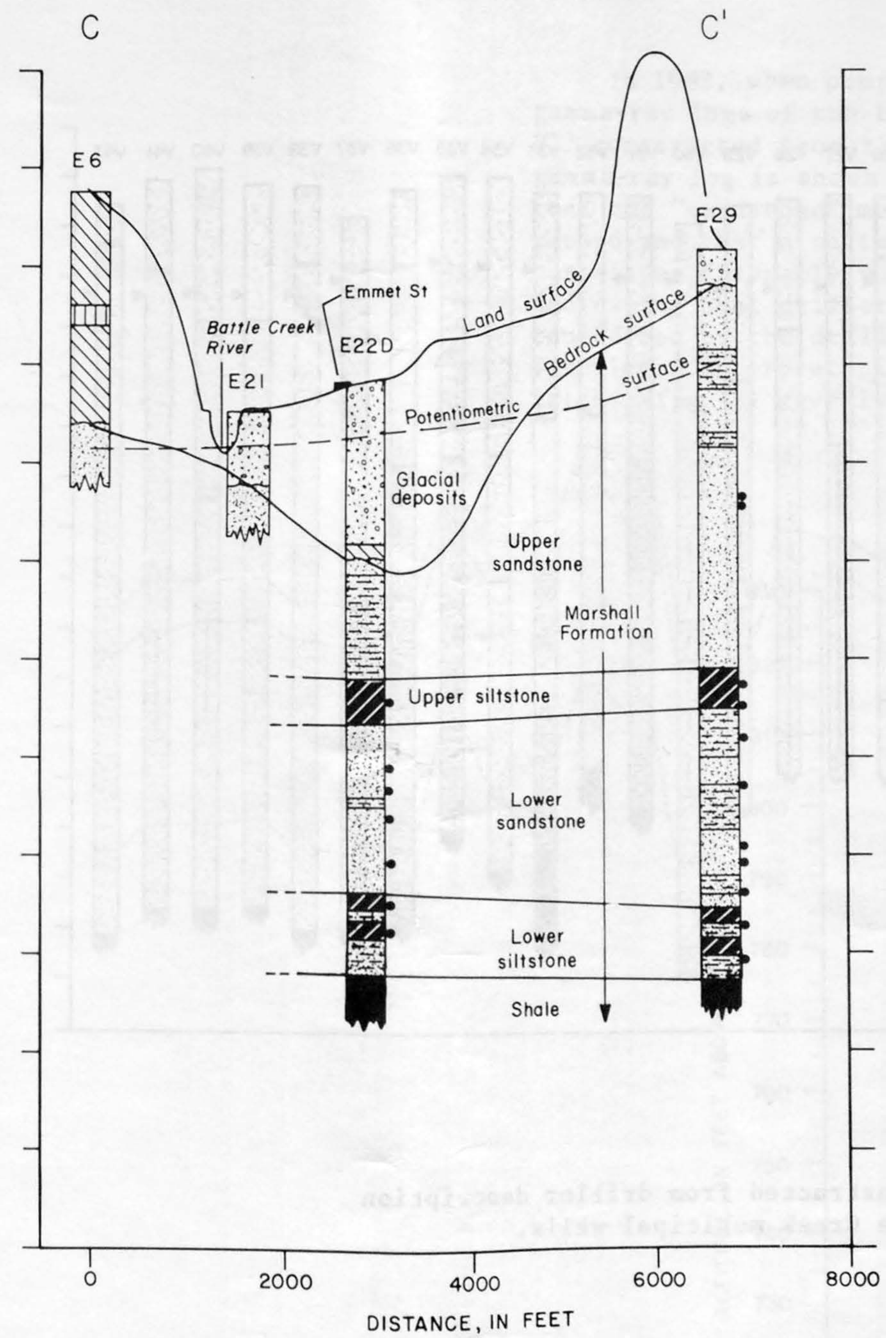


Figure 7.--Geologic section C-C', in east-west direction along Emmett St.

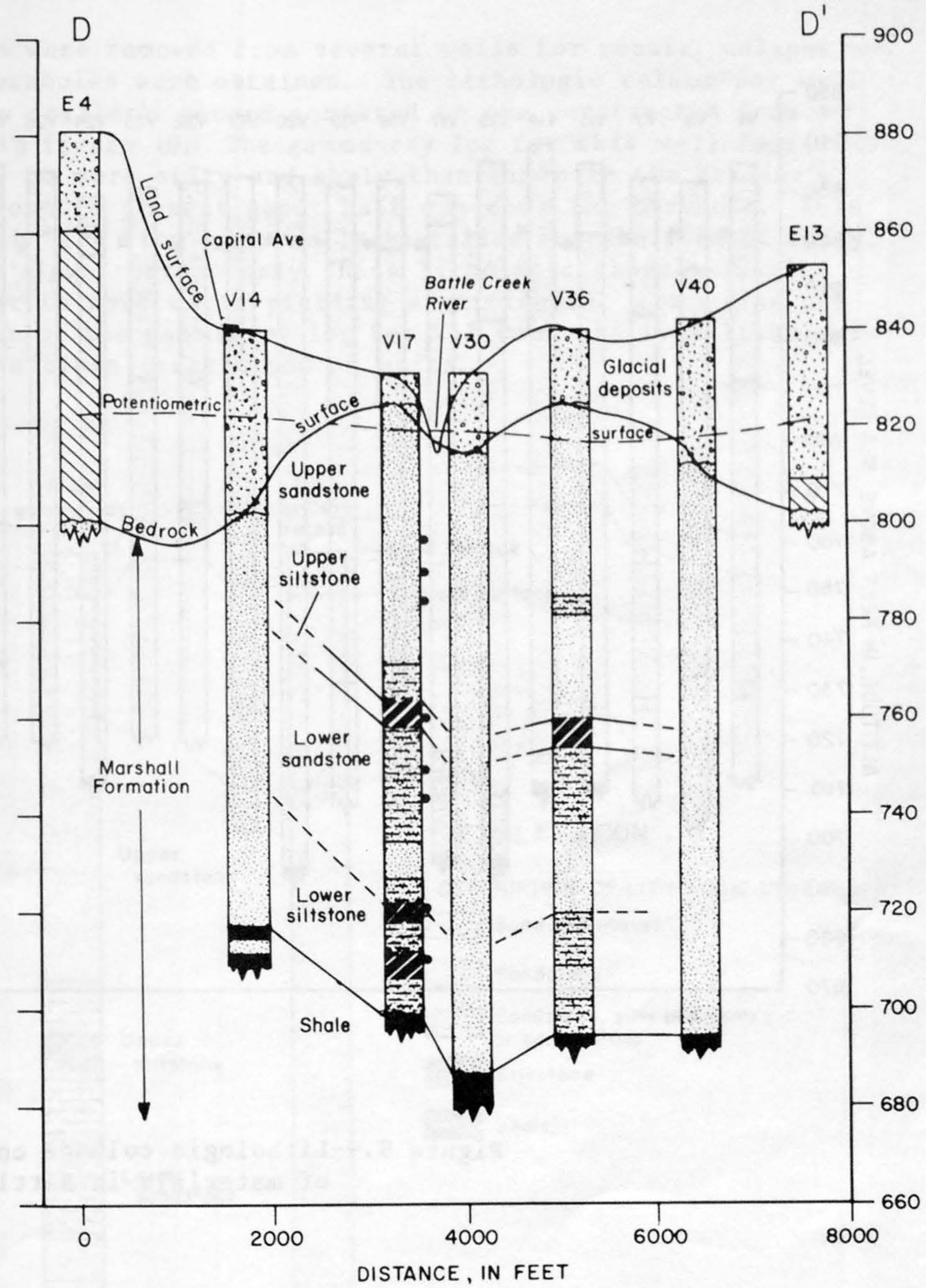


Figure 8.--Geologic section D-D', in east-west direction through Verona well field.

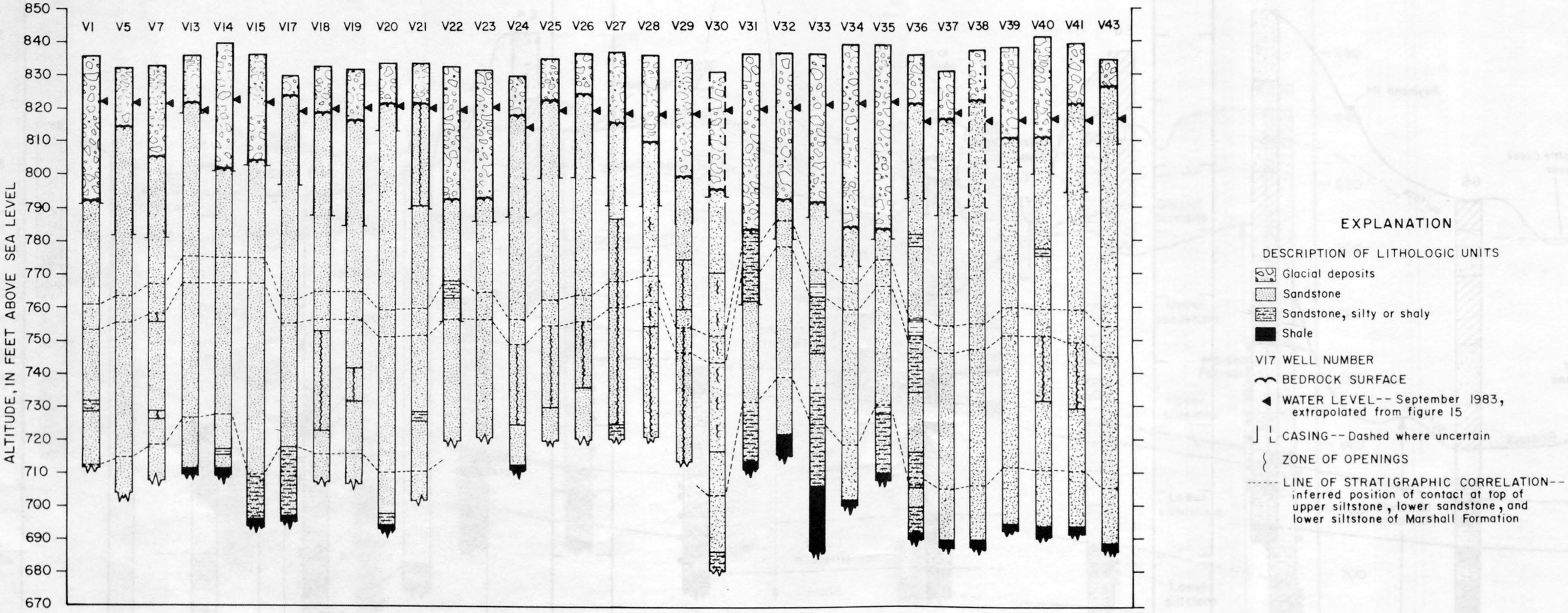


Figure 9.--Lithologic columns constructed from driller description of materials in Battle Creek municipal wells.

In 1983, when pumps were removed from several wells for repair, caliper and gamma-ray logs of the boreholes were obtained. The lithologic column for well V17 constructed from the driller's record compared to one constructed from a gamma-ray log is shown in figure 10. The gamma-ray log for this well indicates that the "sandstone" may be more silty and shaly than shown in the driller's record and that a siltstone is present about half way down the borehole. This correlates favorably with data from many wells installed for the present study, indicating that drillers' logs contain only those lithologic characteristics considered by the driller to have water-yielding significance. Comparing the lithologic interpretation of the gamma-ray log for V17 with the type lithologic column (fig. 3) reveals a close correlation of units.

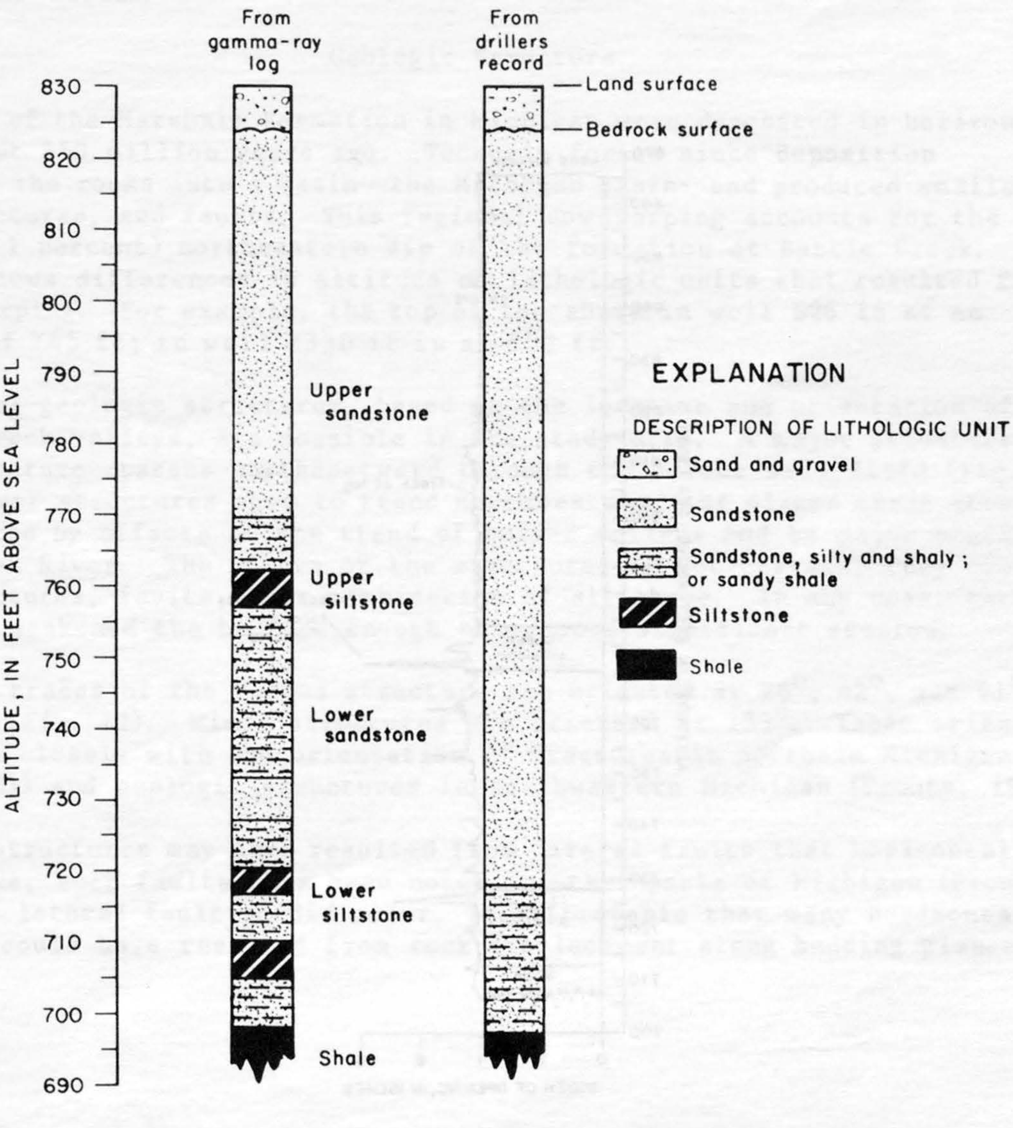


Figure 10.--Lithologic columns of Marshall Formation constructed from driller's record and gamma-ray log for well V17.

Any sandstone bed in the well field that is hard or silty and shaly seems likely to contain "openings" or horizontal fractures. The location of the larger openings detected by caliper logging are shown on the geologic sections (figs. 5 to 8). An example of a caliper log for one well, well E29, is shown in figure 11. Some larger "openings" are present at the contacts between sandstone and siltstone; more "openings" were observed in the lower sandstone than in the upper. Also, as noted in drillers' logs, "openings" are commonly abundant in a zone directly under the upper siltstone. Video pictures of boreholes at wells V17 and V29 indicate some large circular openings. Drillers' records for some wells in the Verona well field note that there are "sufficient openings to carry away all drillings", which seems to indicate that the openings have significant lateral extension. If they are extensive, this could account, in part, for the excellent yields of the well field (as much as 14,000 gal/min with only 7 to 10 ft of drawdown).

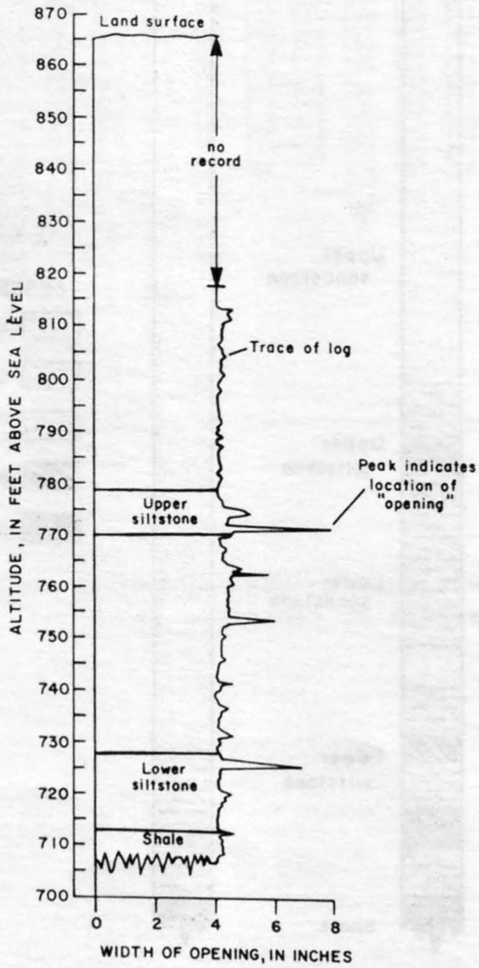


Figure 11.--Caliper log showing "openings" (probable horizontal fractures) in Marshall Formation penetrated by well E29.

Bedrock Surface

The bedrock surface, now buried under glacial deposits, is rolling and hilly (fig. 12). It is highest, 860 ft, in the eastern part of the study area. Northeastward trending major valleys have been carved in the surface. Evidence seems to indicate that drainage from these valleys was both to the northeast and southwest away from a high in the vicinity of Verona well field. Geologic sections A-A' and D-D' (figs. 5 and 8) show the relation of the valleys to the bedrock high under the well field. The valley south of the well field is as much as 75 ft deep at Jameson Ave.

Bedrock is exposed at the northeast abutment of the dam on Battle Creek River at an altitude of 818 ft. Near well E20, bedrock may form the streambed of the river. From the dam eastward along Emmett St, bedrock forms a ridge that, under present pumping conditions, approximates the location of a major ground-water divide.

Geologic Structure

Rocks of the Marshall Formation in Michigan were deposited in horizontal layers about 350 million years ago. Tectonic forces since deposition downwarped the rocks into a basin--the Michigan Basin--and produced smaller folds, fractures, and faults. This regional downwarping accounts for the slight (less than 1 percent) northeastern dip of the formation at Battle Creek. Figure 5 shows differences in altitude of lithologic units that resulted from the downwarping. For example, the top of the shale in well E26 is at an altitude of 745 ft; in well E33D it is at 680 ft.

Several geologic structures, based on the location and orientation of buried bedrock valleys, are possible in the study area. A major structure--the Verona structure--passes northeastward through the Verona well field (fig. 12). Several minor structures seem to trend northwestward; at places these structures are indicated by offsets in the trend of buried valleys and by major bends in Battle Creek River. The nature of the structures is not certain; they could be folds, fractures, faults, or a combination of all three. In any case, they apparently weakened the bedrock enough to promote significant erosion.

Major traces of the Verona structure are oriented at 28°, 42°, and 61° from true north (fig. 12). Minor structures are oriented at 133°. These orientations agree closely with the orientation of fractures in northern Michigan (Holst, 1983) and geologic structures in southwestern Michigan (Prouty, 1983).

Some structures may have resulted from lateral faults that horizontally offset rocks; such faults have been noted in other parts of Michigan (Prouty, 1983). If lateral faulting did occur, it is probable that many horizontal "openings" could have resulted from rock displacement along bedding planes.

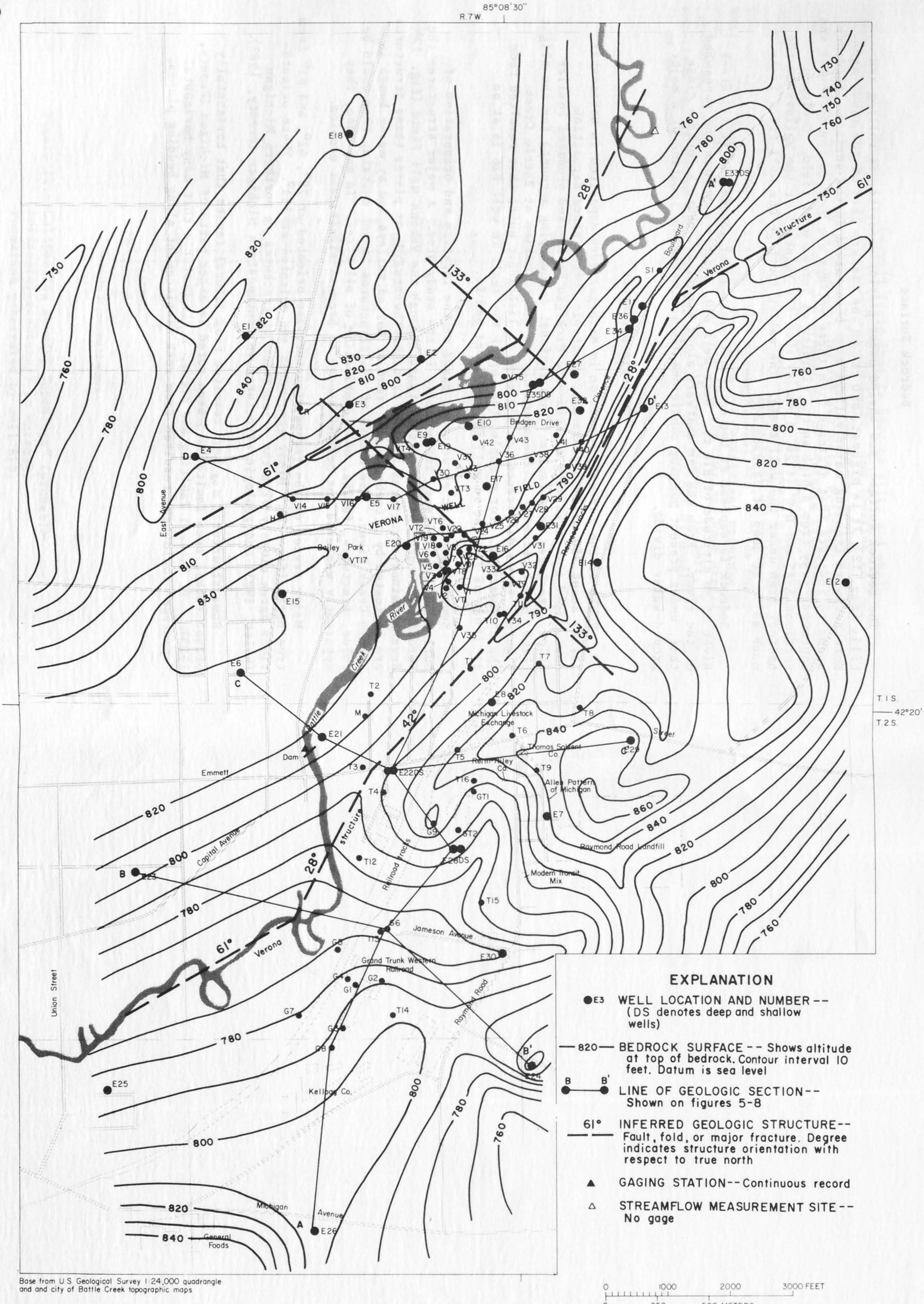


Figure 12.--Configuration of bedrock surface and probable location of some geologic structures.

GLACIAL DEPOSITS

Unconsolidated materials of glacial and fluvial origin overlie the Marshall Formation in most of the study area. These materials were deposited by glaciers and glacial meltwater streams more than 12,000 years ago and by streams of more recent age. Glacial deposits consist of till, outwash, and channel deposits.[2] The areal distribution of glacial deposits near Battle Creek is shown on figure 13.

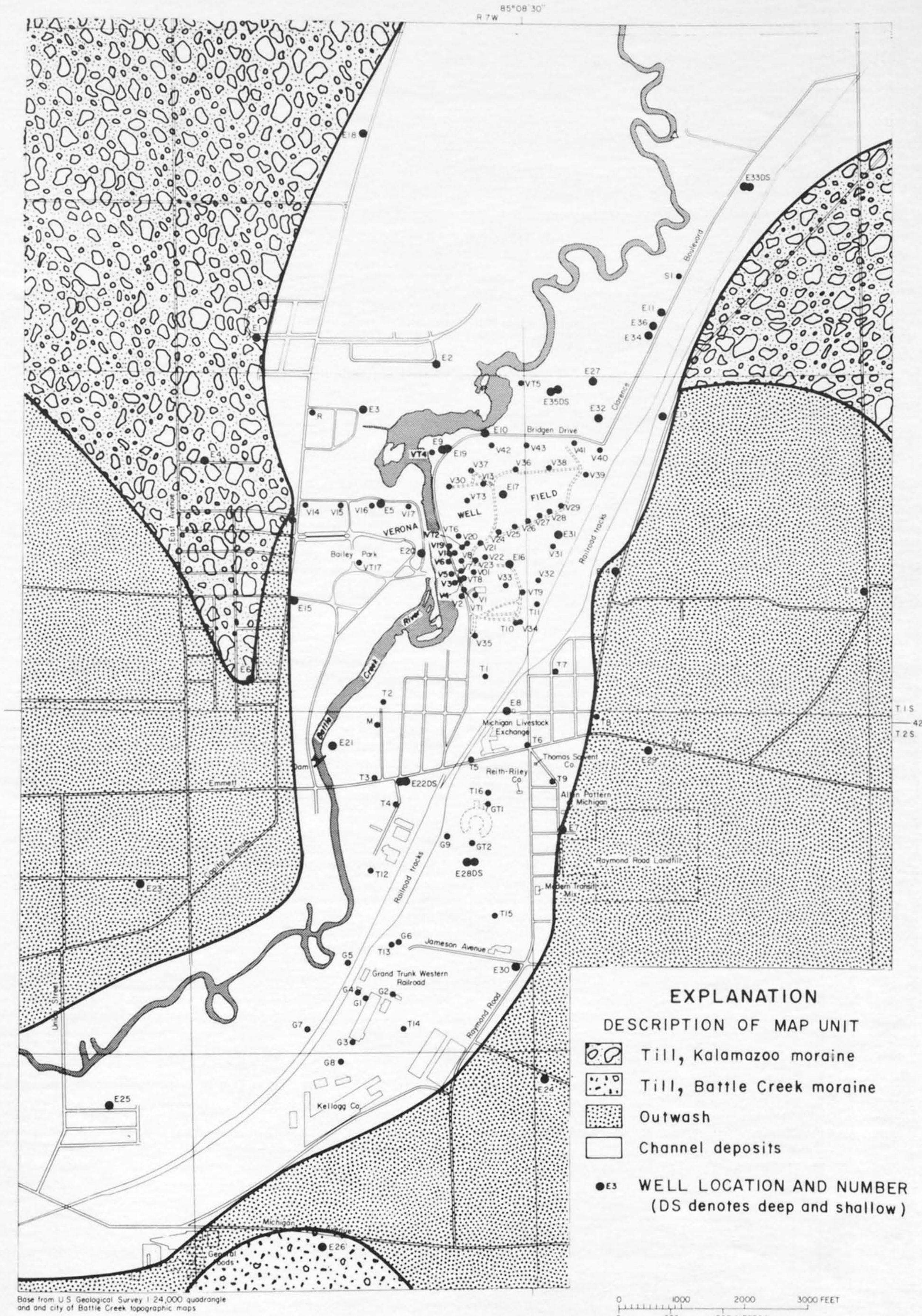


Figure 13.--Areal distribution of glacial deposits.

Till

Till is a mixture of sand, silt, clay, gravel, and, in places, boulders. These materials, picked up, transported, and deposited by ice, formed end moraines where glacial ice maintained its outer edge for some period of time, and ground moraines where the ice sheet retreated. Ground moraines underlie most of the area except where they have been eroded by subsequent stream action. The following grain-size distribution of materials in well E26 between 55 and 57 ft below land surface is typical of till:

Grain size	Percent distribution, by weight
Gravel	13.8
Very coarse sand	5.1
Coarse sand	7.2
Medium sand	27.3
Fine sand	27.3
Very fine sand	9.1
Silt and clay	10.2

The above analysis indicates that all grain sizes are well represented and that about 50 percent of the particles are medium-sized sand or larger.

Thickness of till differs considerably throughout the area; it is thickest in morainal areas (Leverett, 1918). In the Kalamazoo moraine, it is as much as 125 ft thick. It is 45 ft thick at well E6 and 20 ft thick at well E26. Thin till layers probably underlie most outwash deposits, but underlie channel deposits in only a few places.

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[2] Channel deposits consist of recent alluvium and glacial-stream deposits that are interconnected and have similar hydrologic characteristics. In this report, they are considered as one unit.

Clay was found in six wells installed by the U.S. Geological Survey. No clay was found in wells installed by Ecology and Environment, Inc. (1982). Two wells in the Verona well field, wells V23 and V34, had clay or clayey material directly overlying sandstone. At Grand Trunk repair shop, glacial deposits contain a thick zone of sandy, silty clay (Environmental Data, Inc., 1982). Here the deposits are consistently more fine grained than till and may represent another origin, such as deposition in an ice-dammed lake.

Outwash

Outwash, deposited by water from melting glaciers, is mostly fine to coarse sand containing some gravel. Much of the upland area directly east and west of the well field has outwash at land surface. The following grain-size distribution of materials in well E23 between 20 and 35 ft below land surface is typical of outwash:

Grain size	Percent distribution, by weight
Gravel	2.4
Very coarse sand	13.9
Coarse sand	30.9
Medium sand	36.4
Fine sand	11.9
Very fine sand	1.7
Silt and clay	2.8

About 85 percent of the particles are medium sand or larger.

Thickness of outwash varies depending largely on depth to the underlying bedrock. Maximum thickness is 100 ft near well E12.

Channel Deposits

Unconsolidated materials deposited in the floodplain of Battle Creek River by glacial meltwater streams and by more recent flood waters are referred to as channel deposits. The grain size of materials in these deposits is generally larger than that in outwash. However, size distribution varies from place to place depending on location of the deposit relative to the main stream channel. The following grain-size distribution of materials in well E30 between 31 and 33 ft below land surface is typical of channel deposits:

Grain size	Percent distribution, by weight
Gravel	3.3
Very coarse sand	31.8
Coarse sand	31.1
Medium sand	22.0
Fine sand	7.7
Very fine sand	1.9
Silt and clay	2.2

About 90 percent of the particles are medium sand or larger.

In many wells in channel deposits, gravel-sized coal particles were encountered at depths ranging between 20 and 30 ft. At wells E3, E11, E31, and E36, black, organic deposits are present near land surface (table 3).

Thickness of channel deposits varies depending largely on the topography of the underlying bedrock surface. In Bailey Park, where bedrock is near land surface, channel deposits are 6 to 8 ft thick. One-half mile north of the park, the deposits are 5 ft thick; bedrock was encountered during excavation for the area's sewer system. At wells E33 and E22, channel deposits are 34 and 37 ft thick, respectively.

HYDROLOGY

Precipitation, the primary source of water in the Battle Creek area, averages 33 in. annually (National Oceanic and Atmospheric Administration, 1981). Of this, one third infiltrates the ground and percolates to the water table; the remainder flows to streams and lakes or is discharged from the area by evapotranspiration.

SURFACE WATER

Since 1935 a gaging station on Battle Creek River at the dam near Emmett St has been operated by the U.S. Geological Survey. Annual average discharge at the station is 200 ft^3/s. Discharge between October 1981 and September 1982, ranged from 52 to 2,510 ft^3/s; average monthly discharge during this 12-month period ranged from 398 ft^3/s in March to 83 ft^3/s in August (U.S. Geological Survey, 1982). The lowest expected discharge for a 7-day period with a probability of occurring at 10-year intervals is 33 ft^3/s.

Discharge measurements were made at a site 2 mi northeast of the gaging station (fig. 2) on July 9 and September 7, 1982. These measurements indicate that the flow of Battle Creek River decreased 2.5 ft^3/s on July 9 and 1.0 ft^3/s on September 7 between the gaging station and the upstream site. (Discharge at the gaging station was 102 ft^3/s on July 9; 56 ft^3/s on September 7. This takes into account an inflow of 4.5 ft^3/s from purge wells V32 and V35.) On the basis of these measurements, and using standard U.S. Geological Survey techniques of evaluation, an average loss of 2.5 ft^3/s from the river was estimated. Most of the loss represents water induced from the river by municipal pumping; a minor part may have resulted from evapotranspiration. Accurate measurements could not be made nearer the well field because of slow-moving currents in that reach of the river.

GROUND WATER

Recharge

Ground water that discharges to streams and sustains perennial flow is ground-water runoff. By estimating ground-water runoff to Battle Creek River and assuming a steady-state condition (a condition wherein the amount of ground water discharged from the aquifers equals the amount of recharge they receive), it is possible to obtain a reasonable estimate of recharge. Ground-water runoff values, based on baseflow separations of hydrograph records during years with nearly average streamflow, are 133 ft^3/s at Battle Creek and 79 ft^3/s at Bellevue (8 mi northeast of Battle Creek). Thus, the amount of ground-water discharge to the river between Bellevue and Battle Creek is 54 ft^3/s. To this, 2.5 ft^3/s was added to account for the loss to Verona well field. Using the resulting 56.5 ft^3/s and a drainage area between the two gages of 63 mi^2, ground-water recharge is estimated to be 12 in./yr[3]. Similar calculations for Wanadoga Creek, 1.5 mi north of Verona well field, indicate recharge to be 8 in./yr.

Water Levels and Potentiometric Surfaces

Water levels in wells (table 4) installed by the U.S. Geological Survey, Ecology and Environment, Inc. (1982), and Environmental Data, Inc. (1982), mostly reflect water-table conditions even though some wells are cased into the upper sandstone aquifer (fig. 3). A few wells cased into the lower sandstone aquifer reflect confined conditions. In areas of channel deposits, water moves easily between these deposits and the upper part of the upper sandstone aquifer. In areas of till and outwash underlain by till, however, resistance to vertical flow between aquifers is increased by finer grained particles of the till.

Water levels in adjacent deep and shallow wells indicate differences in direction of vertical flow. For example, at wells E33D and E33S which are 5 ft apart, water levels in well E33D were as much as 0.5 ft above levels in well E33S. At this location, ground water in the bedrock is moving slowly upward. Levels at wells E22 were 0.38 to 0.65 ft lower in the deep well than in the shallow; levels at wells E28 were 1.09 to 1.73 ft lower in the deep than in the shallow. At these sites, ground water in the shallow aquifer is moving slowly downward. At some sites, such as at wells G1, the level in one well at a given time may be higher or lower than in the other depending on amount of recharge.

[3] For Kalamazoo River, south of the study area, recharge is estimated to be 11 in./yr.

Table 4.--Water levels in observation wells

[Altitude in feet above sea level]

Well number	June 2, 1982	July 8, 1982	Aug. 26, 1982	Mar. 8, 1983	Apr. 21, 1983	May 26, 1983	June 16, 1983	July 11, 1983	Sept. 2, 1983	Feb. 1, 1984
	Date of measurement									
Wells installed by U.S. Geological Survey										
E1	829.39	829.01	828.12	829.04	830.46	830.82	830.48	829.59	828.22	828.48
E2	824.38	823.82	823.37	824.59	825.49	825.12	824.47	823.98	823.34	823.91
E3	824.49	823.93	823.10	824.33	825.17	825.45	825.36	824.79	824.85	825.17
E4	825.24	824.98	822.88	825.97	826.30	827.18	826.30	825.41	823.50	824.40
E5	823.04	822.52	821.34	823.93	825.04	824.54	819.94	820.22	819.62	818.90
E6	--	823.44	821.97	825.00	825.96	826.21	825.57	824.81	822.88	824.26
E7	838.05	837.77	837.03	838.46	839.24	840.10	839.98	839.40	837.86	838.35
E8	--	824.81	823.74	826.96	828.42	828.51	828.02	827.11	825.26	826.59
E9	822.63	822.02	821.85	820.60	824.87	824.01	823.23	822.46	821.73	822.37
E10	818.14	818.88	818.40	821.87	823.67	822.86	821.93	818.52	816.92	818.66
E11	824.73	824.08	823.04	825.03	826.13	825.75	825.27	824.57	823.35	824.79
E12	867.82	867.88	867.66	866.80	866.92	867.43	867.68	867.93	867.84	867.29
E13	822.34	821.20	--	823.15	824.33	823.70	823.08	822.46	820.13	823.13
E14	820.65	820.73	818.73	823.54	824.42	824.13	823.59	822.63	820.58	823.59
E15	823.55	823.45	821.90	824.19	825.01	825.48	825.34	824.87	823.38	824.11
E16	818.93	820.01	817.82	823.40	824.24	823.65	823.03	822.14	820.22	823.35
E17	818.63	818.38	816.64	821.76	823.53	822.47	821.82	820.23	817.56	820.93
E18	--	833.37	832.59	832.58	834.38	834.82	834.48	833.84	832.65	832.31
E19	--	822.35	821.89	823.69	824.89	824.15	823.21	822.35	821.76	822.35
E20	--	822.00	821.16	823.71	825.27	824.69	823.51	822.68	821.72	822.29
E21	--	--	--	--	--	--	--	824.68	823.31	824.59
E22S	--	--	--	--	828.28	828.35	827.76	826.95	824.97	826.40
E22D	--	--	--	--	827.75	827.89	827.22	826.30	824.38	826.02
E23	--	--	--	--	--	--	--	825.65	825.63	825.48
E24	--	--	--	--	--	--	--	851.00	850.36	849.94
E25	--	--	--	--	--	--	--	816.67	815.02	816.58
E26	--	--	--	--	--	--	--	818.95	816.63	819.64
E27	--	--	--	--	--	--	--	--	822.70	824.02
E28S	--	--	--	--	832.29	832.65	831.86	831.09	829.38	830.37
E28D	--	--	--	--	831.10	831.37	830.77	829.36	828.06	829.14
E29	--	--	--	--	--	--	--	--	839.97	840.42
E30	--	--	--	--	--	--	--	847.09	846.22	846.18
E31	--	--	--	--	826.70	825.80	824.44	822.91	DRY	825.06
E32	--	--	--	--	--	--	--	--	819.26	822.67
E33S	--	--	--	--	827.57	827.14	826.70	825.98	825.18	825.94
E33D	--	--	--	--	828.04	827.66	827.16	826.42	825.67	826.45
E34	--	--	--	--	--	--	--	823.17	821.94	823.75
E35S	--	--	--	--	--	--	--	--	822.81	--
E35D	--	--	--	--	--	--	--	--	822.98	824.12
E36	--	--	--	--	--	--	--	--	822.36	824.04

Table 4.--Water levels in observation wells--Continued

Well number	Date of measurement June 2, 1982	July 8, 1982	Aug. 26, 1982	Mar. 8, 1983	Apr. 21, 1983	May 26, 1983	June 16, 1983	July 11, 1983	Sept. 2, 1983	Feb. 1, 1984
Wells installed by Ecology and Environment, Inc.										
T1	823.08	823.47	822.11	825.77	827.10	827.05	826.51	825.51	823.84	825.40
T2	824.06	823.86	822.98	825.41	826.73	826.53	826.01	825.28	823.71	824.91
T3	824.76	824.42	823.57	825.90	827.20	827.18	826.64	825.84	823.86	825.42
T4	826.35	825.87	825.07	827.45	828.71	828.84	828.21	827.40	825.34	826.83
T5	827.61	827.34	826.45	829.08	830.35	830.68	830.14	829.31	827.46	828.55
T6	829.18	828.95	828.06	830.52	831.76	832.18	831.81	831.03	829.20	830.28
T7	822.81	823.37	821.76	826.03	827.24	827.45	826.99	825.93	823.92	825.82
T8	830.51	830.16	829.32	831.20	832.12	833.17	832.94	832.15	830.40	831.03
T9	834.84	834.45	833.66	835.30	836.16	837.04	836.90	836.27	834.59	835.04
T10	820.67	821.69	819.98	824.69	825.80	825.56	825.02	824.00	822.26	824.51
T11	820.04	820.67	818.86	823.96	825.02	824.73	824.14	822.88	821.26	823.94
T12	819.05	818.32	817.96	819.08	820.04	819.76	818.91	818.35	817.74	818.51
T13	--	819.14	818.73	819.58	820.53	820.53	819.78	819.24	818.70	819.20
T14	--	820.59	820.20	820.72	821.84	821.99	821.96	821.63	820.81	821.46
T15	--	835.79	835.14	836.30	837.52	837.91	837.34	836.71	835.47	835.78
T16	829.05	828.61	827.79	830.21	831.36	830.94	831.21	830.41	828.57	829.63
Wells installed by Environmental Data, Inc.										
G1	--	--	818.07	818.64	820.06	819.65	819.26	817.64	818.27	818.73
G1A	--	--	817.83	--	--	--	--	--	818.19	818.65
G1B	--	--	818.06	818.60	820.03	819.64	819.23	819.90	818.22	818.68
G1C	--	--	818.18	818.86	819.84	820.11	820.18	820.14	818.68	819.80
G2	--	--	818.67	819.10	820.60	820.25	819.86	819.35	818.83	819.21
G2A	--	--	818.66	819.10	820.59	820.23	819.85	819.35	818.91	819.22
G3	--	--	817.88	818.42	819.91	819.54	819.19	818.70	818.09	818.62
G3A	--	--	817.86	818.44	819.89	819.53	819.18	818.70	818.07	818.60
G4	--	--	817.80	818.39	819.79	819.36	818.92	818.44	817.91	818.43
G4A	--	--	817.77	818.39	819.76	819.36	818.88	818.44	817.87	818.40
G5	--	--	--	--	--	--	--	--	817.30	817.87
G5A	--	--	--	--	--	--	--	--	818.31	819.35
G6	--	--	--	--	--	--	--	--	822.94	824.98
G7	--	--	--	--	--	--	--	--	816.68	817.64
G7A	--	--	--	--	--	--	--	--	816.02	817.59
G8	--	--	--	--	--	--	--	--	817.91	818.82
G8A	--	--	--	--	--	--	--	--	818.37	819.76
G9	--	--	--	--	--	--	--	--	827.56	828.68
G9A	--	--	--	--	--	--	--	--	827.55	828.70
Miscellaneous Wells										
S1	--	--	--	--	826.97	826.63	826.09	825.34	824.45	824.44
V01	--	820.15	817.39	--	823.45	822.26	821.32	821.27	819.32	822.27
H	--	823.45	821.33	824.63	824.81	825.43	824.93	823.82	821.82	822.70
R	--	826.19	825.15	826.63	828.31	828.21	827.71	826.83	825.26	825.74
M	--	823.75	823.28	825.64	826.95	826.84	826.27	825.47	823.85	825.21

Water levels listed in table 4 and shown by potentiometric surfaces in figures 14, 15, and 16, reflect natural conditions except in the Verona well field. In the well field, the surface may be depressed 7 to 10 ft.

The general configuration of the potentiometric surface in the study area (fig. 2) and nearby areas is shown in figure 14[4]. Water levels range from 800 ft along Kalamazoo River west of Verona well field to 900 ft in the highland areas southwest and east of the well field. Ground-water flow is toward the Battle Creek and Kalamazoo Rivers and their tributaries.

The potentiometric surface at and near the well field for September 1983 (fig. 15) represents summer conditions. During this part of the year, when pumpage in the field is relatively high, flow in the shallow aquifer is almost directly northward to the well field from the Emmett St-Raymond Rd intersection.[5] The potentiometric surface during winter, as represented by measurements made in February 1984 (fig. 16), reflects reduced pumping rates in the field and increased recharge. During winter, flow from the Emmett St-Raymond Rd intersection is northwestward to its discharge point at Battle Creek River.

Hydraulic Properties of Aquifers

The size and degree of interconnection of rock pore spaces and other openings, such as fractures, are the primary factors controlling the movement and storage of water in aquifers. Good aquifers have large, interconnected spaces, such as are present in fractured sandstone of the Marshall Formation or in the sand and gravel of the outwash and channel deposits.

Hydraulic properties of the aquifers in the study area have been determined by pumping, specific capacity, and recovery tests. Most high-production capacities of the sandstone aquifers seem to relate to secondary permeability caused by fractures or faults. Materials in the Marshall Formation and most of those in the glacial deposits were deposited in water. As such, plate-shaped grains in the sediments (principally clay particles) tended to be deposited with their flat surfaces oriented parallel to the bedding plane. This orientation reduces vertical permeability (Weeks, 1969).

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[4] Area of map is larger than that of study area in figure 2 in order to include modeled area discussed in section titled "Ground-water flow simulations".

[5] Based on water quality data provided by the Michigan Department of Public Health, a significant source of contaminants is an area near the Emmett St-Raymond Rd intersection.

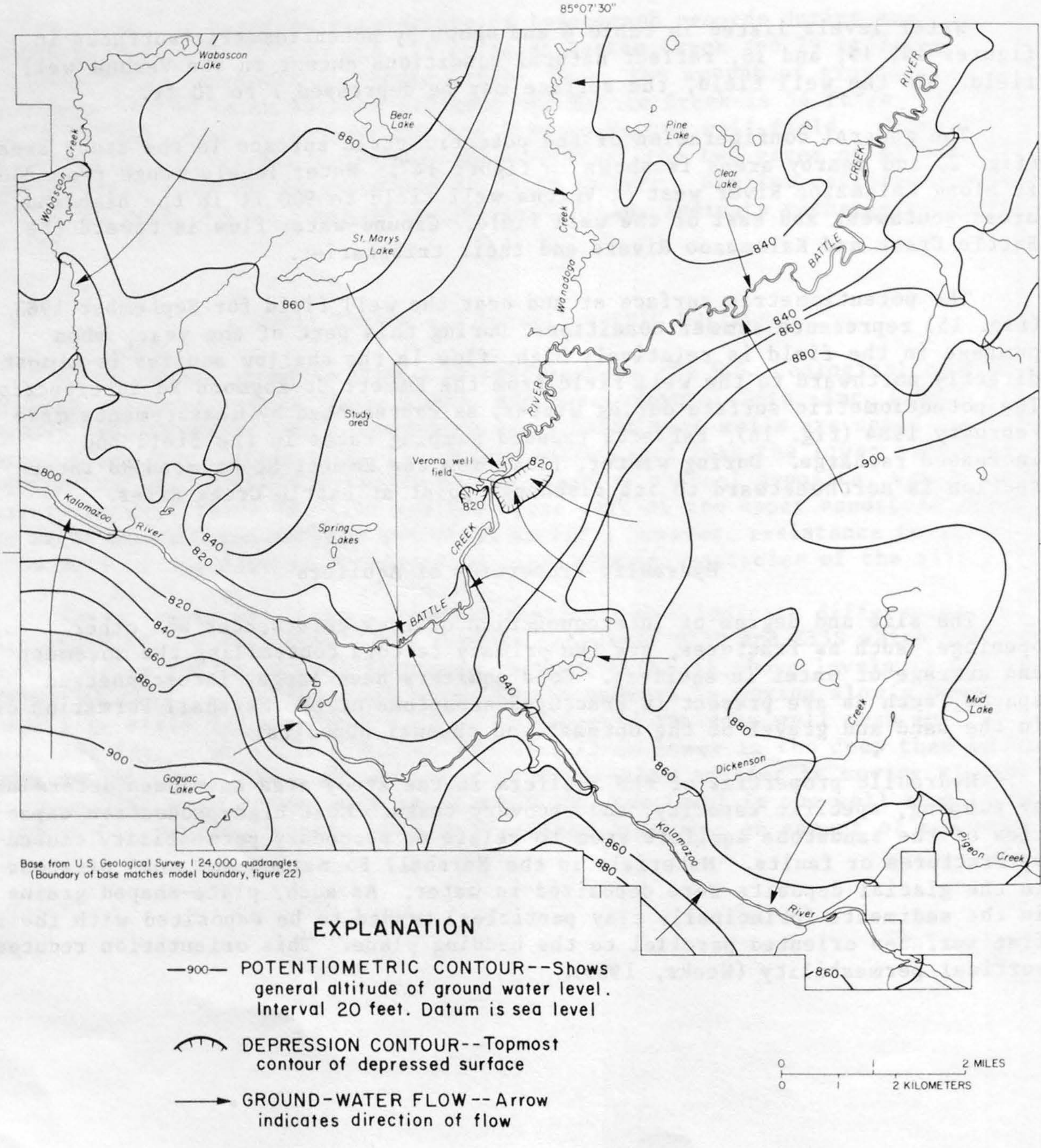


Figure 14.--Generalized average potentiometric surface of study area and area included in model (for model area see section titled "Ground-water flow model").

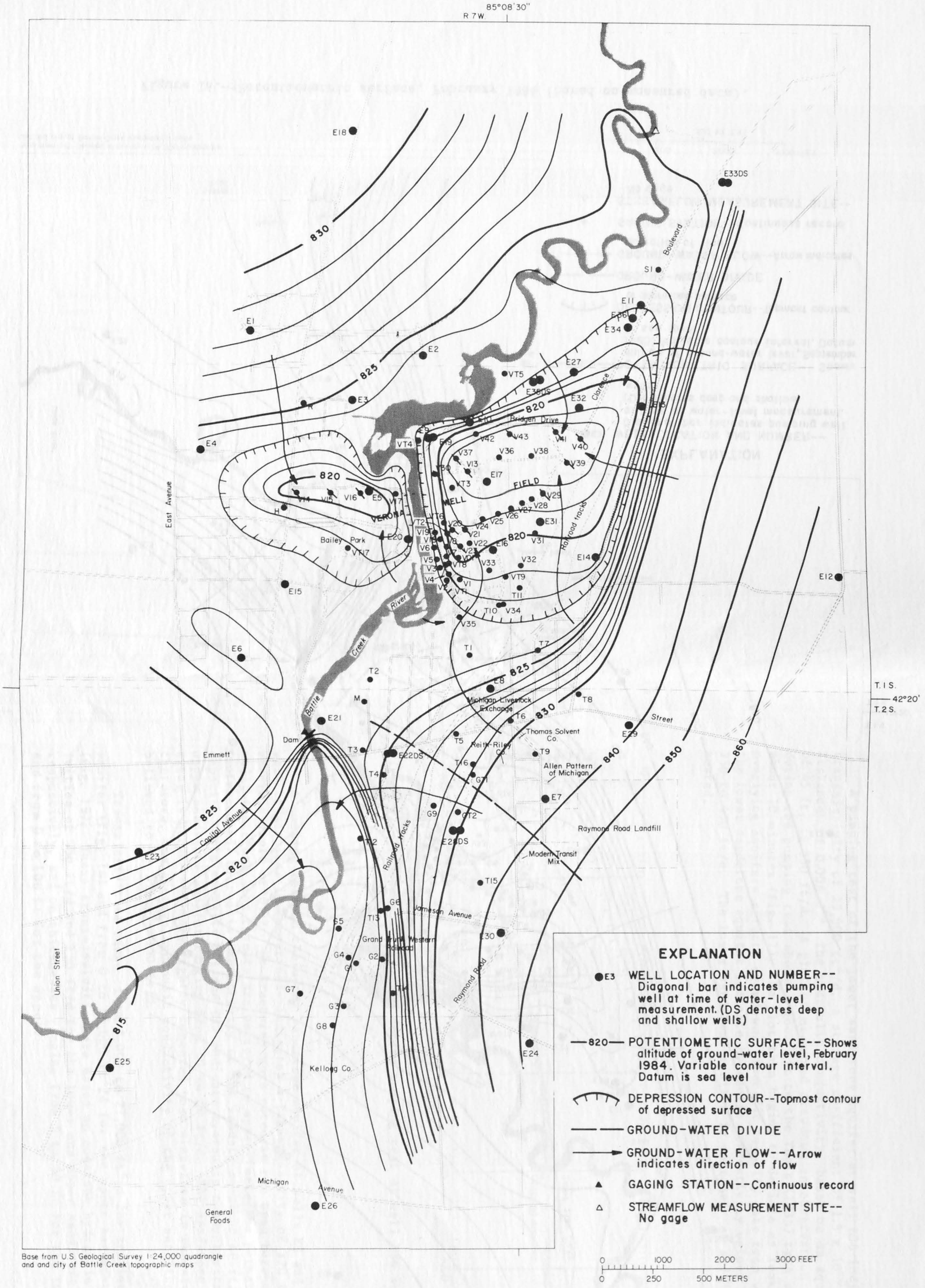


Figure 15.--Potentiometric surface, September 1983 (based on measured data).

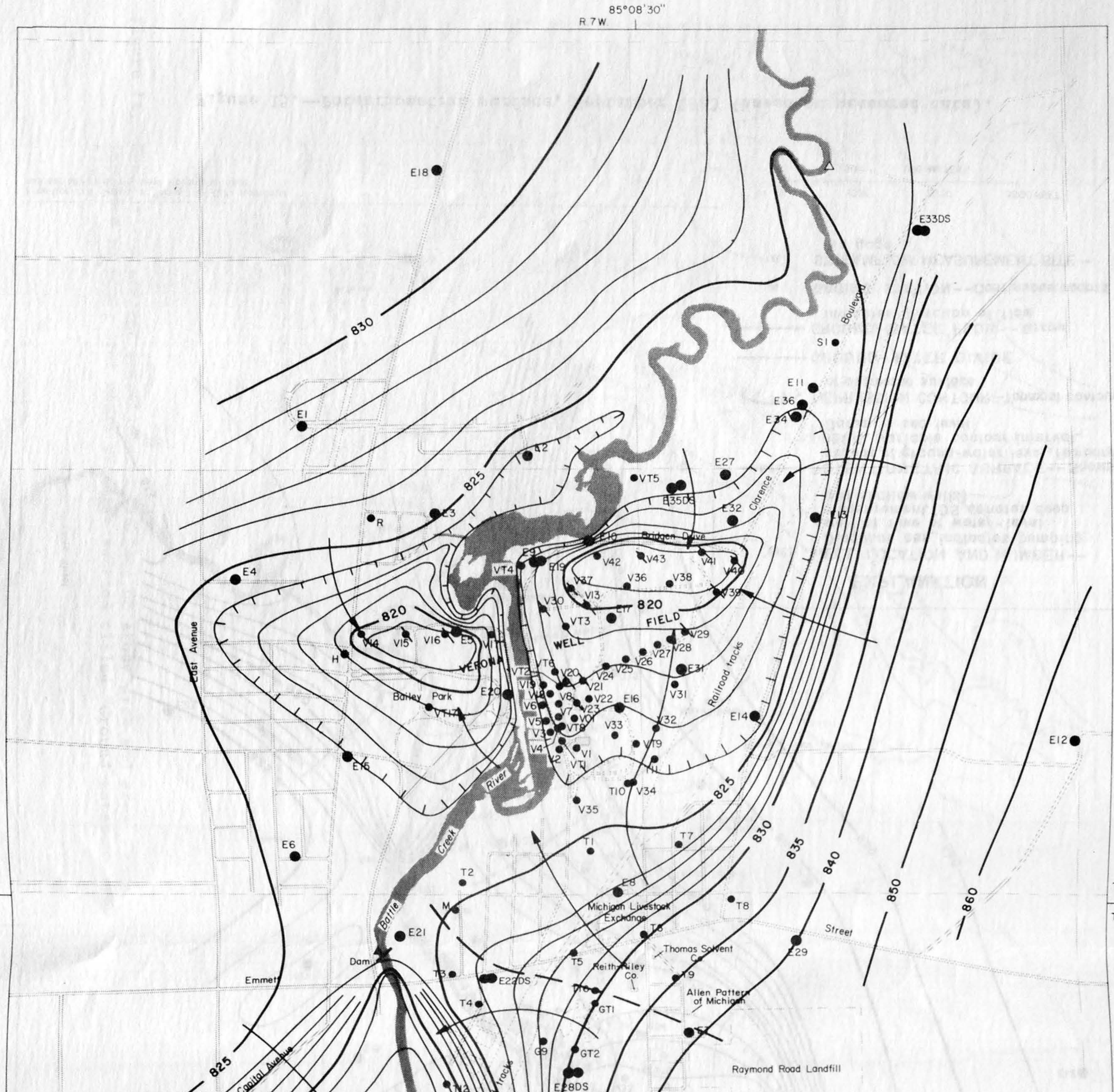


Figure 16.--Potentiometric surface, February 1984 (based on measured data).

A pumping test of the lower sandstone aquifer at well E36 indicates a transmissivity of 25,000 ft^2/d, a storage coefficient of 1.5×10^{-5}, and a leakance of 0.004 d^{-1}. The hydraulic conductivity, based on an aquifer thickness of 45 ft, is 550 ft/d. A plot of measured drawdown in observation well E34 during the pumping test shows a good fit to the Theis (1935) type curve for about 10 minutes (fig. 17); the plot then begins to deviate as leakage from the overlying aquifers affects drawdown. Specific capacity data from wells open in the lower sandstone aquifer indicate hydraulic conductivity values ranging from 250 to 450 ft/d. The lower sandstone aquifer is confined at all locations tested.

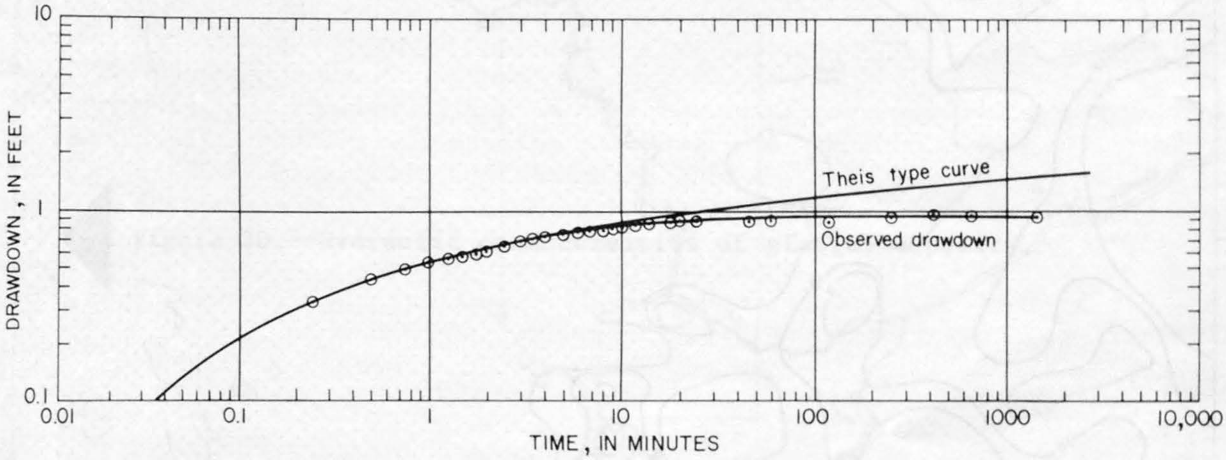
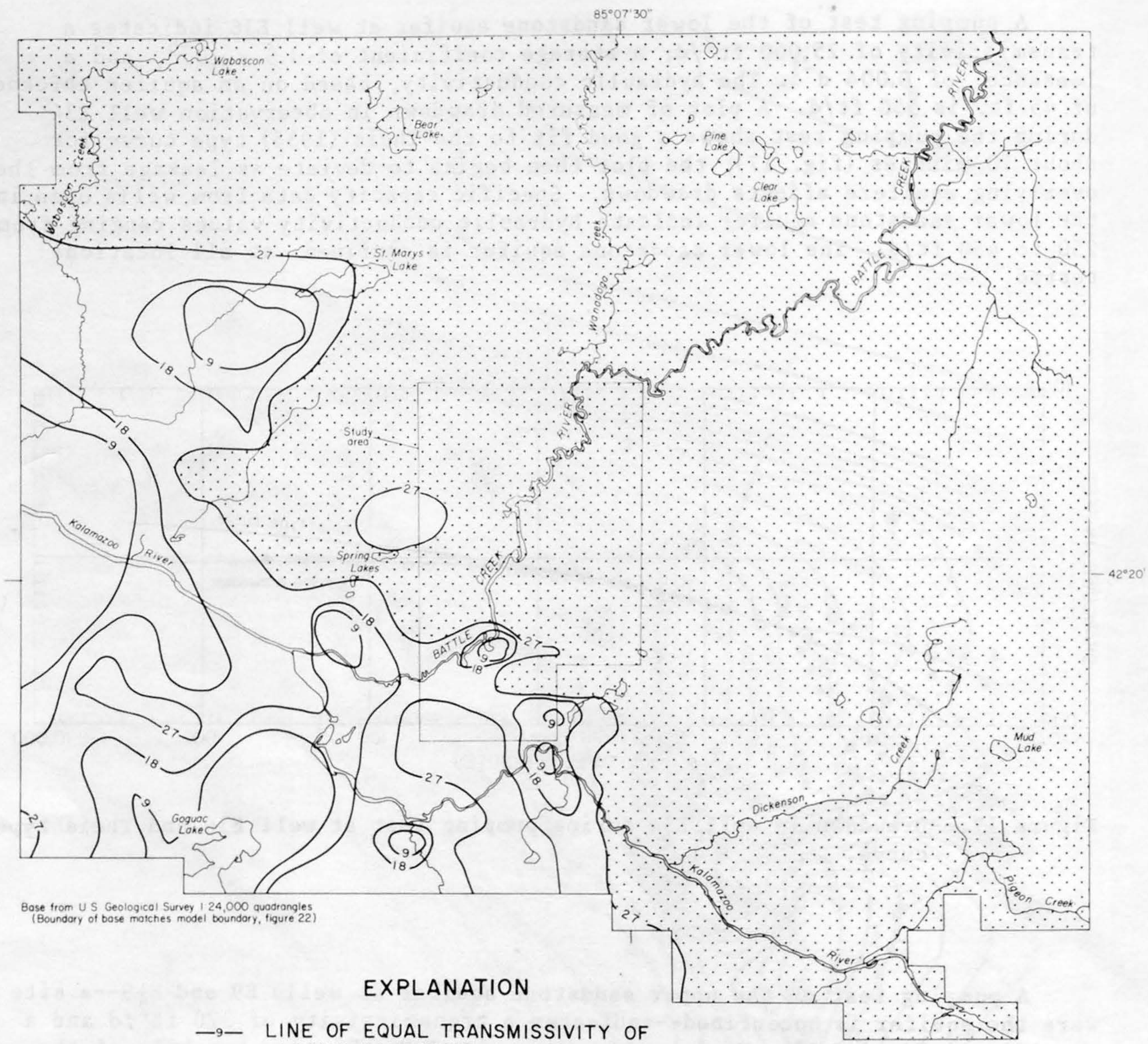


Figure 17.--Drawdown in well E34 during pumping test at well E36 and Theis type curve.

A pumping test on the upper sandstone aquifer at wells E9 and E19--a site were the aquifer is unconfined--indicates a transmissivity of 320 ft^2/d and a specific yield of 0.02. No fractures were noted in the open borehole of the well; therefore, the results are believed to approximate the primary (unfractured) hydraulic conductivity of the sandstone--about 10 ft/d. Specific capacity tests at wells E21 and E32 indicate hydraulic conductivities for the upper sandstone aquifer ranging from 40 to 80 ft/d. The sandstone at these sites is harder and more tightly cemented than elsewhere in the study area; therefore, the average hydraulic conductivity of the upper sandstone aquifer is believed to be higher--150 ft/d.

Transmissivities range from 3,000 to 27,000 ft^2/d for the lower sandstone aquifer (fig. 18) and from 0 to 15,000 ft^2/d for the upper sandstone aquifer (fig. 19). These transmissivities are based on constant hydraulic conductivities of 550 ft/d and 150 ft/d for the lower and upper sandstone aquifers, respectively, and on thicknesses ranging from 5 to 50 ft for the lower aquifer and from 0 to 100 ft for the upper.



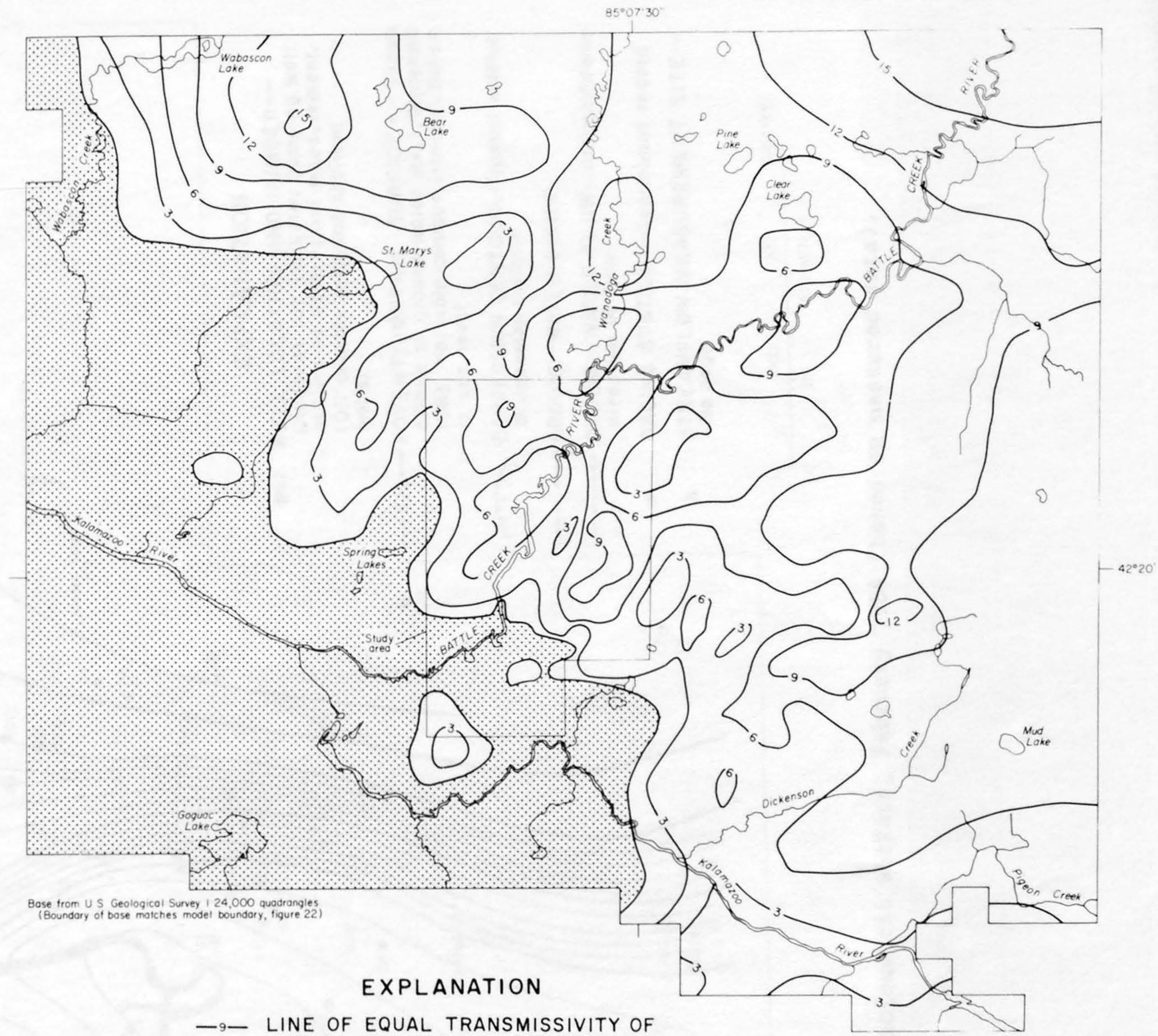
EXPLANATION

—9— LINE OF EQUAL TRANSMISSIVITY OF LOWER SANDSTONE AQUIFER--In thousands of square feet per day. Interval 9000 square feet per day

TRANSMISSIVITY OF LOWER AQUIFER--Equals 27,000 square feet per day

0 1 2 MILES
0 1 2 KILOMETERS

Figure 18.--Transmissivity of lower sandstone aquifer.



EXPLANATION

—9— LINE OF EQUAL TRANSMISSIVITY OF UPPER SANDSTONE AQUIFER--In thousands of square feet per day. Interval 3000 square feet per day

UPPER SANDSTONE AQUIFER--Missing due to erosion

0 1 2 MILES
0 1 2 KILOMETERS

Figure 19.--Transmissivity of upper sandstone aquifer.

The hydraulic properties of the glacial deposits differ with the type of deposit. Based on grain-size analysis and similarity with other deposits in Michigan, horizontal hydraulic conductivity is estimated to be 110 ft/d for channel deposits, 70 ft/d for outwash, and 15 ft/d for till (fig 20). In a transition zone near the edge of the Kalamazoo moraine, hydraulic conductivity of interlayered till and outwash is estimated to be 30 ft/d. The specific yield of outwash and channel deposits is estimated to be 0.15; the specific yield of till is not known. However, because till in the study area is coarse textured, its ability to store water may not be significantly less than that of other glacial deposits.

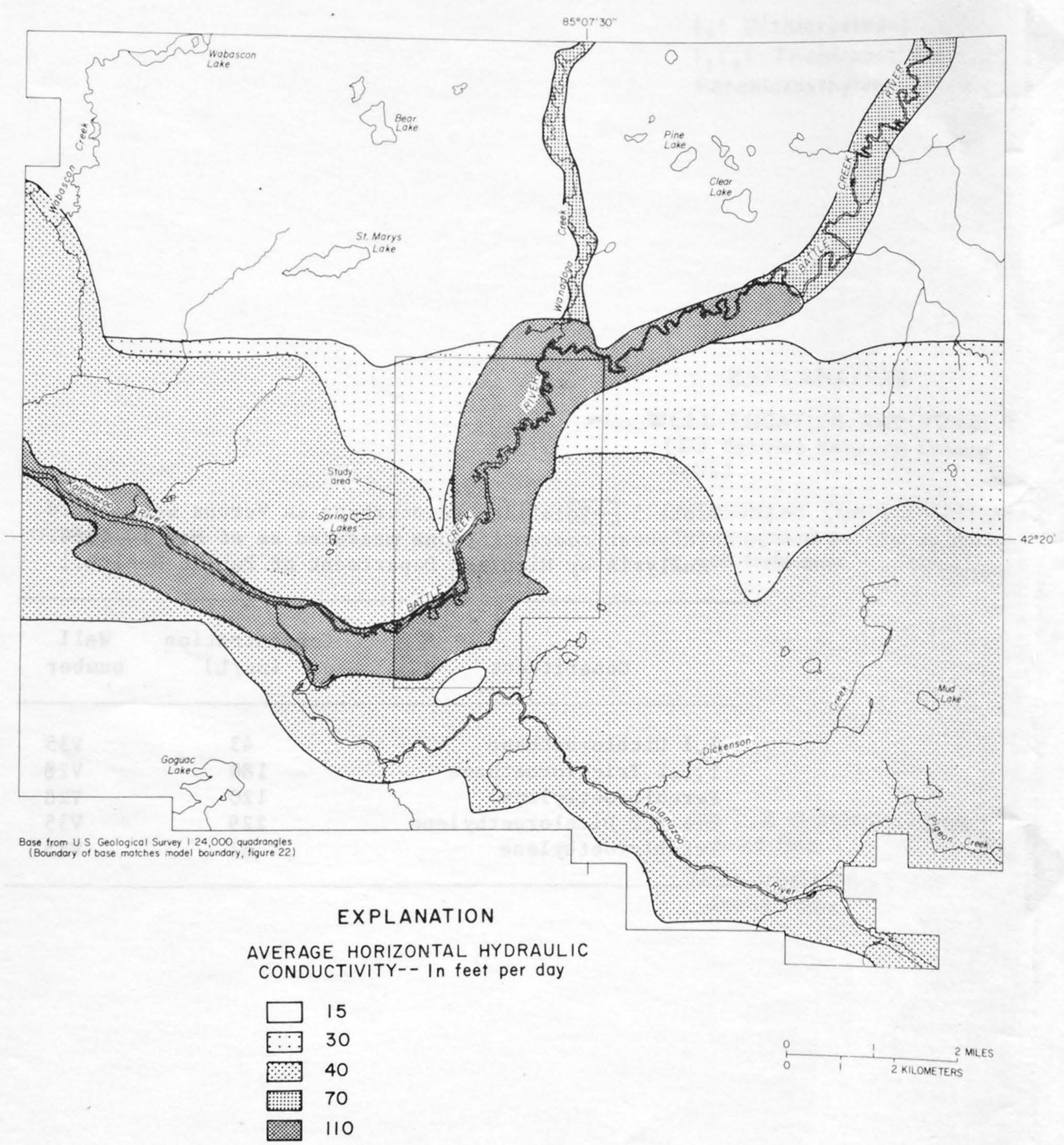


Figure 20.--Hydraulic conductivities of glacial deposits.

Velocity of Flow

Velocity of ground-water flow depends on the gradient of the potentiometric surface and on the hydraulic conductivity and effective porosity[6] of the aquifer. Along the margin of the Battle Creek River floodplain, the gradient of the potentiometric surface in the sand and gravel aquifer is steep (figs. 15 and 16), and ground water flow is comparatively rapid (as much as 9 ft/d); within the floodplain the gradient is less and flow is slower. An effective porosity of 0.15, an average hyraulic conductivity of 100 ft/d, and water-level data were used to calculate flow velocity in the sand and gravel aquifer. The average velocity in September 1983, for example, between the Emmett St-Raymond Rd intersection (see footnote [5]) and pumping wells V38-V43 in the well field, was 2 ft/d. The highest velocity, 4 ft/d, was at the intersection; the lowest, 1 ft/d, was near the south edge of the field. For February 1984, velocities in the sand and gravel aquifer were 4 ft/d at the intersection, 1.5 ft/d near the river, and 1 ft/d in the southern part of the well field.

Ground-water-flow velocities can also be calculated for the sandstone aquifers; however, they are less accurate because a value for effective porosity of the fractured bedrock cannot be determined accurately. In the upper sandstone aquifer, assuming a porosity similar to that of the sand and gravel aquifer, a hydraulic conductivity of 150 ft/d, and a gradient for the potentiometric surface of 0.0045, the velocity of flow would be 4.5 ft/d. In the lower sandstone aquifer, fracturing makes a reliable estimate of effective porosity difficult, and thus, precludes calculations of flow velocity.

On the basis of the above calculations, movement of contaminants in the well field may be at rates varying from 1 to 4 ft/d.

Quality of Water

Verona Well Field

Investigation of the quality of water in the well field was not part of this study. However, the Michigan Department of Public Health has analysed water from municipal wells for volatile hydrocarbons since the latter part of 1981. Using their data, distribution of hydrocarbons in the well field in 1982 and during the latter part of 1983 and early part of 1984 is shown in figure 21. Highest concentrations measured as of May 1, 1984, were as shown in table 5.

[6]Numerical values of specific yield, which are approximately equal to values of effective porosity, have been used in the calculations.

Table 5.--Volatile hydrocarbons in Verona well field
[Highest concentrations measured as of May 1, 1984. Analysis by Michigan Department of Public Health.]

Constituent	Concentration (μg/L)	Well number
1,1 Dichloroethane	43	V35
1,1,1 Trichloroethane	180	V28
Perchloroethylene	120	V28
cis 1,2 Dichloroethylene	229	V35
Trichloroethylene	67	V35

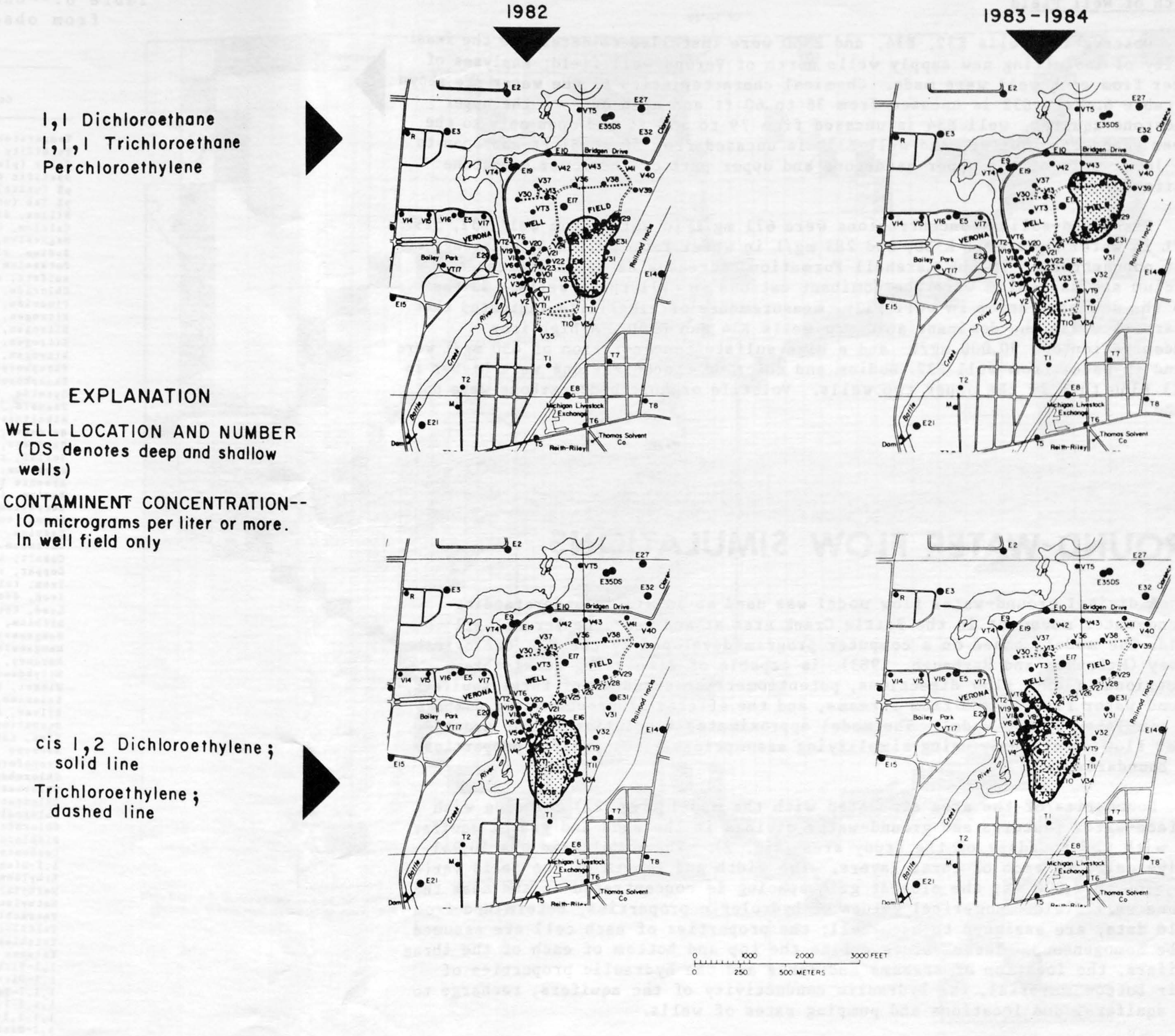


Figure 21.--Distribution of volatile hydrocarbons in Verona well field in latter part of 1981 and in latter part of 1983--early part of 1984 (based on data from Michigan Department of Public Health).

North of Well Field

Observation wells E32, E34, and E35D were installed to determine the feasibility of installing new supply wells north of Verona well field; analyses of water from each well were made. Chemical characteristics of the water are shown in table 6. Well E32 is uncased from 36 to 60 ft and open only to the upper sandstone aquifer, well E34 is uncased from 79 to 155 ft and open only to the lower sandstone aquifer, and well E35D is uncased from 50 to 81 ft and open to the lower part of the upper sandstone and upper part of the lower sandstone aquifers.

Dissolved-solids concentrations were 671 mg/L in water from well E32, 529 mg/L in water from well E35D, and 283 mg/L in water from well E34; this suggests that concentration in the Marshall Formation decreases as depth increases. Calcium and magnesium were the dominant cations in all three wells. Sulfate was the dominant anion in well E32; measurements of alkalinity indicated that bicarbonate was the dominant anion in wells E34 and E35D. A high iron concentration of 90,000 µg/L and a high sulfate concentration of 430 mg/L were found in water from well E32. Sodium and chloride concentrations were higher in well E35D than in the other two wells. Volatile organic hydrocarbons were not found.

GROUND-WATER FLOW SIMULATIONS

A digital ground-water flow model was used as an aid in understanding ground-water movement in the Battle Creek area at and near the Verona well field. The model, based on a computer program developed by the U.S. Geological Survey (McDonald and Harbaugh, 1983), is capable of simulating quasi-three-dimensional flow. Flow directions, potentiometric surfaces of three aquifers, ground-water flow to and from streams, and the effects of ground-water pumpage are simulated by the model. The model approximates a solution to the ground-water flow equation by using simplifying assumptions about aquifer properties and boundaries.

Boundaries of the area simulated with the model (fig. 22) coincide with surface-water features and ground-water divides in the sand and gravel aquifer, not with the boundary of the study area (fig. 2). The model grid has 10,943 active cells in each of three layers. The width and length of the cells varies from 100 to 2,000 ft; the closest grid spacing is concentrated at and near the Verona well field. Numerical values of hydrologic properties, determined from field data, are assigned to each cell; the properties of each cell are assumed to be homogeneous. These values define the top and bottom of each of the three aquifers, the location of streams and lakes and the hydraulic properties of their bottom material, the hydraulic conductivity of the aquifers, recharge to the aquifers, and locations and pumping rates of wells.

Table 6.--Chemical and physical characteristics of water from observation wells north of Verona well field

Constituent or property	Well E32	Well E34	Well E35D
Temperature (deg. C)	11.0	11.0	11.0
Turbidity (ntu)	100	1.1	3.0
Color (platinum cobalt units)	15	10	2.0
Specific conductance (micromhos)	841	470	834
pH (units)	6.6	7.5	7.0
pH lab (units)	4.7	7.5	7.1
Silica, dissolved (mg/L as SiO_2)	45	14	13
Calcium, dissolved (mg/L as Ca)	59	68	100
Magnesium, dissolved (mg/L as Mg)	25	21	27
Sodium, dissolved (mg/L as Na)	3.2	6.6	24
Potassium, dissolved (mg/L as K)	2.1	.9	1.1
Sulfate, dissolved (mg/L as SO_4)	430	30	57
Chloride, dissolved (mg/L as Cl)	2.2	7.0	130
Fluoride, dissolved (mg/L as F)	1.6	.2	.1
Nitrogen, ammonia total (mg/L as N)	<.10	<.10	<.01
Nitrogen, nitrite total (mg/L as N)	<.01	<.01	<.01
Nitrogen, ammonia + organic total (mg/L)	.10	<.10	.30
Nitrogen, NO_2 + NO_3 total (mg/L as N)	<.10	<.10	<.10
Phosphorus, ortho, total (mg/L as P)	.06	<.01	<.01
Phosphorus, total (mg/L as P)	.07	.02	.04
Cyanide, total (mg/L as Cn)	--	<.01	<.01
Phenols, total (µg/L)	2	2	2
Alkalinity, lab (mg/L as $CaCO_3$)	1	141	195
Hardness, (mg/L as $CaCO_3$)	250	260	360
Hardness, noncarbonate (mg/L $CaCO_3$)	--	116	166
Solids, residue at 180 deg. C dissolved	671	283	529
Aluminum, total recoverable (µg/L as Al)	10	50	30
Arsenic total (µg/L as As)	2	1	2
Barium, total recoverable (µg/L as Ba)	<100	100	300
Beryllium, total recoverable (µg/L as Be)	<10	<10	<10
Boron, total recoverable (µg/L as B)	20	<20	<20
Cadmium, total recoverable (µg/L as Cd)	2	1	<1
Chromium, total recoverable (µg/L as Cr)	10	10	10
Cobalt, total recoverable (µg/L as Co)	33	1	2
Copper, total recoverable (µg/L as Cu)	55	2	46
Iron, total recoverable (µg/L as Fe)	90,000	420	1,000
Iron, dissolved (µg/L as Fe)	--	420	830
Lead, total recoverable (µg/L as Pb)	7	4	2
Lithium, total recoverable (µg/L as Li)	80	<10	10
Manganese, total recoverable (µg/L as Mn)	640	60	80
Manganese, dissolved (µg/L as Mn)	650	60	82
Mercury, total recoverable (µg/L as Hg)	<.1	<.1	<.1
Molybdenum, total recoverable (µg/L as M)	<1	1	9
Nickel, total recoverable (µg/L as Ni)	96	6	<1
Selenium, total (µg/L as Se)	<1	<1	<1
Silver, total recoverable (µg/L as Ag)	<1	<1	2
Strontium, total recoverable (µg/L as Sr)	90	110	130
Zinc, total recoverable (µg/L as Zn)	330	60	90
Benzene (µg/L)	<1	<1	<1
Bromoform (µg/L)	<1	<1	<1
Chlorobenzene (µg/L)	<1	<1	<1
Chloroethane (µg/L)	<1	<1	<1
Chloroethylene (µg/L)	<1	<1	<1
Chlorodibromomethane (µg/L)	<1	<1	<1
Chloroform (µg/L)	<1	<1	<1
Dichlorobromomethane (µg/L)	<1	<1	<1
Carbontetrachloride (µg/L)	<1	<1	<1
1,2-Dichloroethane (µg/L)	<1	<1	<1
Ethylbenzene (µg/L)	<1	<1	<1
Methylbromide (µg/L)	<1	<1	<1
Methylene chloride (µg/L)	<1	<1	<1
Tetrachloroethylene (µg/L)	<1	<1	<1
Trichloroethylene (µg/L)	<1	<1	<1
Trichloroeflouromethane (µg/L)	<1	<1	<1
Toluene (µg/L)	<1	<1	<1
1,1-Dichlorethane (µg/L)	<1	<1	<1
1,1-Dichloroethylene (µg/L)	<1	<1	<1
1,1,1-Trichloroethane (µg/L)	<1	<1	<1
1,1,2-Trichloroethane (µg/L)	<1	<1	<1
1,1,2,2-Tetrachloroethane (µg/L)	<1	<1	<1
1,2-Dichloropropane (µg/L)	<1	<1	<1
1,3-Dichloropropane (µg/L)	<1	<1	<1
2-Chloroethylvinylether (µg/L)	<1	<1	<1
Dichlorodifluoromethane (µg/L)	<1	<1	<1
Vinyl chloride (µg/L)	<1	<1	<1

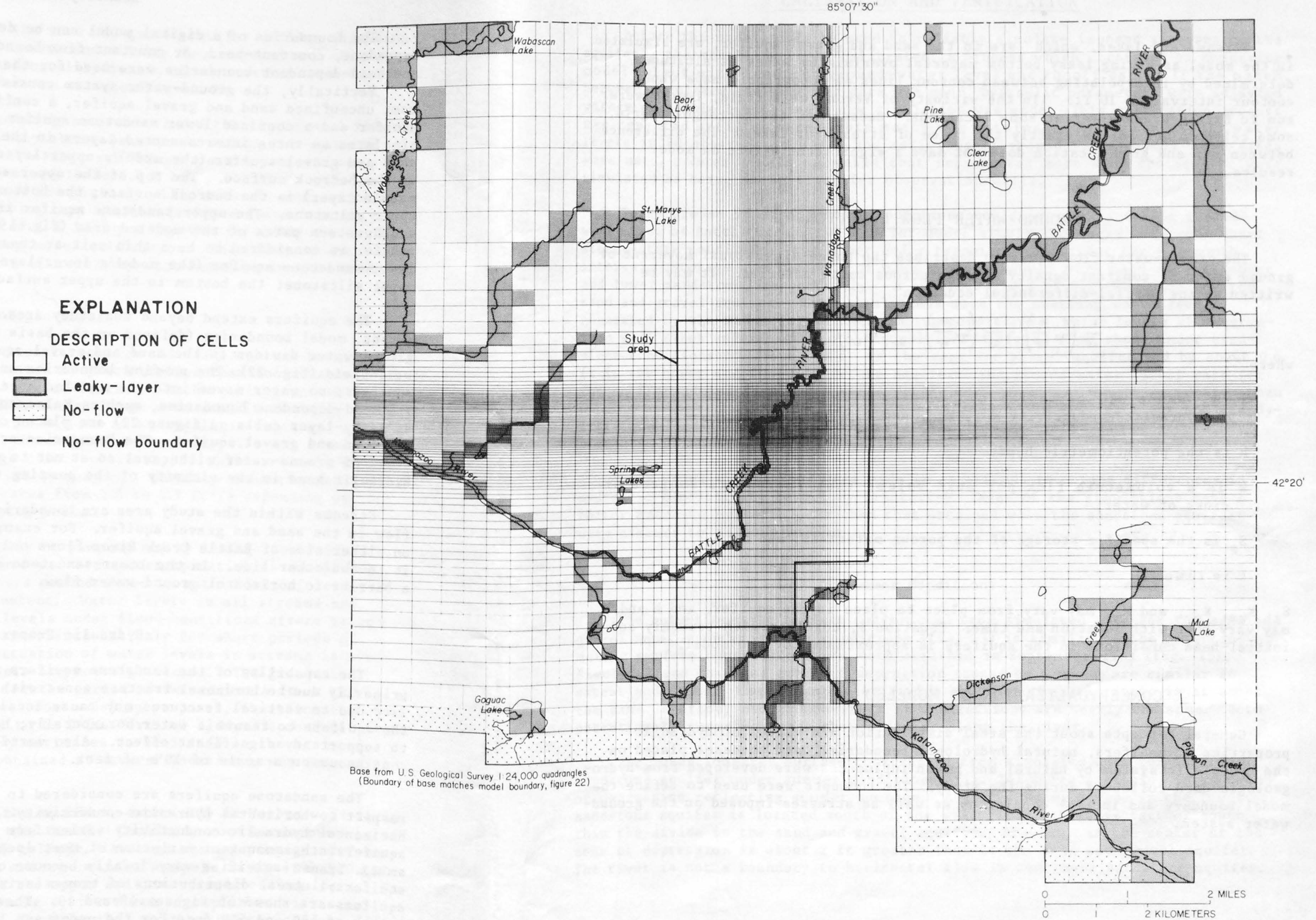


Figure 22.--Boundaries and grid spacing used in digital model.

Streams and lakes, which are in the sand and gravel aquifer, are simulated in the model as having leaky bottom material overlain by water at altitudes determined by interpolating between contour lines on topographic maps whose contour interval is 10 ft. In the vicinity of Verona well field, levels were run to Battle Creek River at some locations. Because of the rectangular grid, some cells do not follow exactly the trace of streams or lakes. The difference between map and grid location does not have a significant effect on model results.

GROUND-WATER FLOW EQUATION

The ground-water flow equation describes the three-dimensional movement of ground water of constant density through porous earth material. It may be written as the partial-differential equation

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) - W = S_s\frac{\partial h}{\partial t} \qquad (1)$$

where

x, y, and z are cartesian coordinates aligned along the major axes of hydraulic conductivity K_{xx}, K_{yy}, and K_{zz};

h is the potentiometric head;

W is a volumetric flux per unit volume that represents sources or sinks of water;

S_s is the specific storage of the porous materials; and

t is time.

S_s, K_{xx}, K_{yy}, and K_{zz} may vary from place to place in the aquifer, and h and W may vary both with location and time. Equation 1, together with boundary and initial-head conditions in the aquifer, is approximated by the model.

CONCEPTUALIZATION OF MODELED CONDITIONS

General concepts about the areal distribution and values of hydraulic properties of aquifers, natural hydrologic boundaries, and stresses placed on the hydrologic system by natural and human influences were developed from hydrogeologic data collected during the study. The concepts were used to define the model boundary and initial conditions as well as stresses imposed on the ground-water system.

Boundary Conditions

The boundaries of a digital model can be defined by no-flow, head-dependent, constant-head, or constant-flux boundary conditions. Only no-flow and head-dependent boundaries were used for the Battle Creek model.

Vertically, the ground-water system consists of three aquifers--an uppermost unconfined sand and gravel aquifer, a confined-unconfined upper sandstone aquifer and a confined lower sandstone aquifer (fig. 3). The three aquifers are simulated as three interconnected layers in the digital model. The top of the sand and gravel aquifer (the model's upper layer) is the water table; the bottom is the bedrock surface. The top of the upper sandstone aquifer (the model's middle layer) is the bedrock surface; the bottom is the upper surface of the upper siltstone. The upper sandstone aquifer is missing in the western and southwestern parts of the modeled area (fig. 19). For modeling purposes, this aquifer is considered to be a thin unit at these locations. The top of the lower sandstone aquifer (the model's lower layer) is the lower surface of the upper siltstone; the bottom is the upper surface of the shale unit.

The aquifers extend beyond the study area. To limit their horizontal extent, model boundaries (defined on the basis of surface-water features and ground-water divides in the sand and gravel aquifer) were set 4 to 7 mi from the well field (fig. 22). The no-flow boundaries are coincident for all three aquifers; no water moves into the modeled area from outside these boundaries. The head-dependent boundaries, such as Kalamazoo River and Wabascon Creek (shown as leaky-layer cells on figure 22) are placed only in the layer that simulates the sand and gravel aquifer. The boundaries are distant enough from the major areas of ground-water withdrawal so as not to effect the calculation of hydraulic head in the vicinity of the pumping wells.

Streams within the study area are boundaries for horizontal ground-water flow in the sand and gravel aquifer. For example, ground water in this aquifer on either side of Battle Creek River flows only to or from the river, not beyond it to the other side. In the lower sandstone aquifer, however, the river is not a barrier to horizontal ground-water flow.

Hydraulic Properties

The capability of the sandstone aquifers to transmit water horizontally is primarily due to horizonal fracture zones within the rocks. Secondary permeability due to vertical fractures may cause local differences in the capability of the aquifers to transmit water horizontally; however, there is little evidence to support any significant effect. Also vertical fractures are not known to be continuous on a scale of 10's of feet.

The sandstone aquifers are considered to be homogeneous and isotropic with respect to horizontal hydraulic conductivity. Although it is known that horizontal hydraulic conductivity varies from place to place in the sandstone aquifers, the amount of variation at most locations, based on available data, is small. Transmissivities vary locally because of varying thickness of the aquifers. Areal distributions of transmissivity used to simulate the sandstone aquifers are shown on figures 18 and 19. These figures represent constant values of 150 and 550 ft/d for the upper and lower sandstone aquifers respectively.

The hydraulic conductivity of the sand and gravel aquifer differs depending on the type of deposit. Till has a lower conductivity than outwash and channel deposits. Areal distribution of horizontal hydraulic conductivities used to simulate the sand and gravel aquifer are shown on figure 20.

The vertical flow of ground water is more restricted than horizontal flow because of zones of lower permeability above, below, and within the aquifers. From model simulations, leakance values between the sand and gravel and the upper sandstone aquifers were determined to be 1.8 X 10^{-5}, 4 X 10^{-5}, and 2.5 X 10^{-2} per day, respectively, for areas underlain by till, outwash, and channel deposits. Based on analysis of pumping test data, a leakance value between the upper and lower sandstone aquifers of 4 X 10^{-3} per day was initially used. This value was raised to 1.2 x 10^{-2} during model calibration. Near Jameson Avenue, a value of 1.2 X 10^{-3} was used because of more clay-rich deposits in that area.

Hydrologic Stresses

The aquifers are stressed by natural recharge and discharge and by ground-water pumpage. Most recharge originates as precipitation that infiltrates the soil and percolates to the sand and gravel aquifer. Recharge is greatest in areas of outwash and channel deposits; the recharge rate used in the model for these deposits is 13 in./yr. Recharge is less in metropolitan areas and areas of till; the recharge rates used in the model for these deposits are 8 and 10 in./yr, respectively. Local recharge occurs where supply wells are near streams and water is induced from the streams by pumping. Baseflow measurements indicate that water is induced at rates from 1.0 to 3.5 ft^3/s depending on pumping rates and locations of pumping wells.

Ground-water is discharged mostly by pumping and by leakage to streams, lakes, and swamps. Discharge by ground-water evapotranspiration is considered insignificant because the places where ground water is within 5 ft of land surface are few and small in areal extent. Water levels in all streams are assumed to be constant. High water levels under flood conditions affect ground-water levels and flow directions near streams but only for short periods of time. During other periods, the fluctuation of water levels in streams is minor and the effects on ground-water levels are not significant. The greatest measured difference in gage height for the period of record was 4 ft at the gaging station on Battle Creek River. For modeling purposes, the thickness of streambeds and lakebeds was assumed to be 3 ft. Vertical hydraulic conductivity of streambeds and lakebeds, initially estimated to be 5 ft/d on the basis of sieve analyses of bottom material obtained at several locations, was reduced to 4 ft/d during model calibration.

Ground-water pumpage stresses the aquifers, especially in Verona well field and in the industrial area south of the field. Combined, continuous pumpage of several industries is 3,000 to 6,000 gal/min. Average summer pumpage at Verona well field is about 8,000 gal/min; average winter pumpage is about 6,300 gal-/min. Most wells produce from both the upper and lower sandstone aquifers. In the model, distribution of pumpage among aquifers was accomplished with a multi-aquifer well-simulation program (M. G. McDonald, written communication, 1984) similar to a well-simulation technique outlined by Bennett and others (1982).

CALIBRATION AND VERIFICATION

Before the model could be used to reliably simulate imposed stresses on the aquifers, the model had to be calibrated, a process which consisted of comparing model output with measured ground-water level and runoff data. If the match between simulated and measured data was poor, hydraulic parameters were adjusted within plausible limits and a new simulation was made. This calibration process was repeated until an acceptable match was attained. For calibration, water levels in 80 observation wells and estimates of ground-water runoff at 9 sites were used. Water levels in wells that represented more than one aquifer were simulated as being in multiaquifer observation wells.

To determine if steady-state conditions could accurately define ground-water flow at Battle Creek, two similar model simulations were made--one under steady-state conditions, the other under transient conditions for a 3-month interval. Storage coefficients of 0.00015 and 0.000015 were used for the upper and lower sandstone, respectively. A specific yield of 0.15 was used for the sand and gravel aquifer. Both simulations used the starting water levels generated by the model for winter pumping conditions. Water levels at observation well sites under steady-state conditions differed from those under transient conditions by about 1.0 ft in the sand and gravel aquifer and by about 0.6 ft in the upper and lower sandstone aquifers. The ground-water runoff rate for the entire modeled area under steady-state conditions was 0.6 ft^3/s greater than under transient conditions. The small differences between transient and steady-state model results indicates that the ground-water system can be accurately simulated using steady-state conditions.

Some model simulations were made in an attempt to define differences in hydraulic conductivity caused by fracturing. None of the simulations gave a better match to measured data than that obtained when the sandstone aquifers were assumed to be homogeneous.

Summer Conditions

The potentiometric surface constructed from simulated data for the sand and gravel aquifer under summer conditions (fig. 23) is similar to the potentiometric surface constructed from data obtained in September 1983 (fig. 15). Simulated and observed cones of depression caused by pumping are similar in extent and depth. The ground-water divide south of the well field is at about the same location, and ground-water flow directions are nearly the same. Both potentiometric-surface maps show a divide along the river.

The potentiometric surface constructed from simulated data for the lower sandstone aquifer under summer conditions (fig. 24) shows a single, large cone of depression reflecting summer pumpage. A ground-water divide in the lower sandstone aquifer is located south of the well field but it is farther south than the divide in the sand and gravel aquifer. Drawdown in the center of the cone of depression is about 2 ft greater than in the sand and gravel aquifer. The river is not a boundary to horizontal flow in the lower sandstone aquifer.

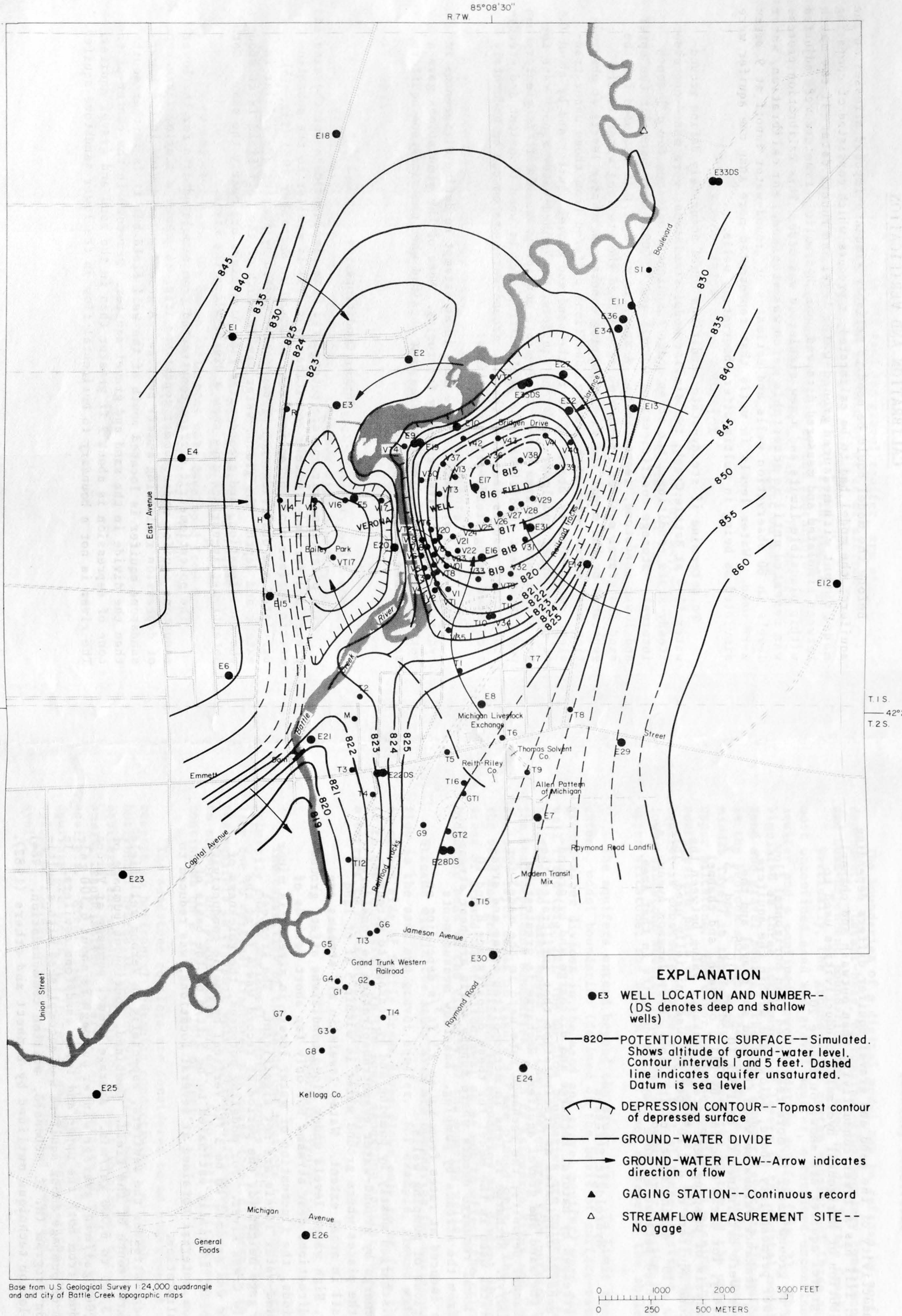


Figure 23.--Simulated potentiometric surface of sand and gravel aquifer under summer conditions.

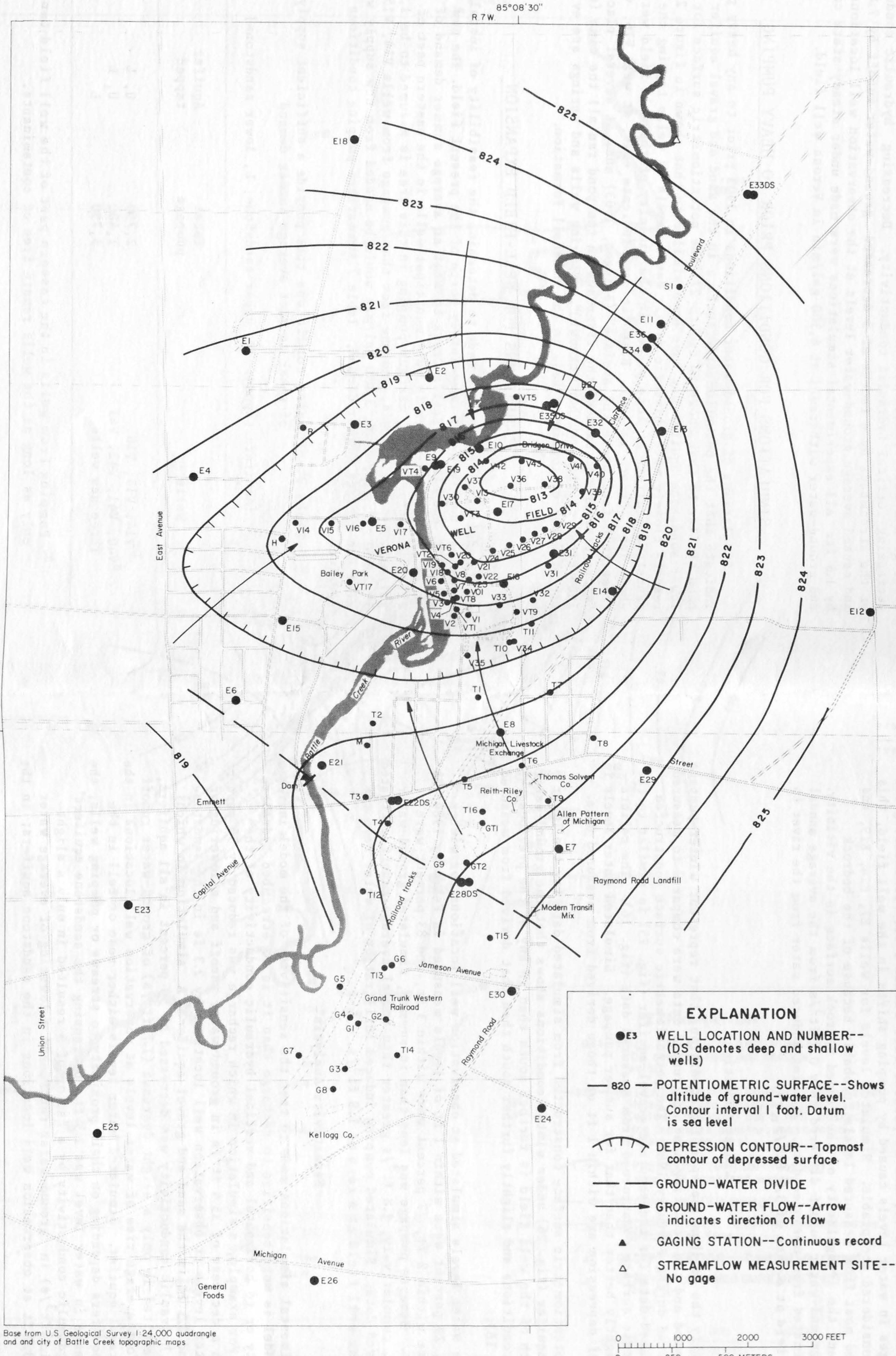


Figure 24.--Simulated potentiometric surface of lower sandstone aquifer under summer conditions.

Of the water levels simulated at observation well locations for summer conditions, 45 percent were within 2 ft of levels measured in September 1983, 63 percent were within 3 ft, and 84 percent were within 5 ft. Considering the rapid changes in water levels caused by pumping shifts in the well field, this match is considered acceptable. Simulated levels for wells E7, E24, E29, and E30 differed most from measured levels, probably because of the bedrock structure and the irregularity of the eroded bedrock surface in the vicinity. Simulated ground-water runoff differed only 0.5 ft^3/s from the average annual runoff estimated from measured data. Pumping induced water from the river to the well field at a rate of 3.0 ft^3/s.

Winter Conditions

To verify the calibration, pumping conditions that represent winter pumpage were simulated and the resulting head and runoff data were compared to measured data collected during February 1984. The potentiometric surface constructed from simulated data for the sand and gravel aquifer (fig. 25) is similar to the potentiometric surface constructed from measured data (fig. 16). The calibration is slightly better than that for summer pumpage. Simulated water levels in the cones of depression are within 1 ft of those derived from measured data.

The potentiometric surface constructed from simulated data for the lower sandstone aquifer (fig. 26) under winter conditions shows that the ground-water divide south of the well field is further south than in any of the previous simulated conditions and slightly further south than that derived from measured data (fig. 16).

Of the water levels simulated at observation well locations for winter conditions, 29 percent were within 1 ft of levels measured in February 1984, 53 percent were within 2 ft, 77 percent were within 3 ft, and 83 percent were within 5 ft. Because pumpage was less than in summer, simulated ground-water runoff was, cumulatively, 1.8 ft^3/s greater than annual average runoff estimated from measured data. Simulated pumping induced infiltration of water from the river to the well field at a rate of 1.9 ft^3/s.

Sensitivity Analysis

Experimental simulations made to test the sensitivity of the model indicate that the model is more sensitive to recharge than it is to streambed hydraulic conductivity or to horizontal and vertical hydraulic conductivity of the aquifers. For example, a simulation in which recharge was reduced by 50 percent resulted in a decrease of 35.4 ft^3/s in ground-water runoff and a lowering of average water levels at observation well locations by 2.3 ft in the sandstone aquifers and 3.3 ft in the sand and gravel aquifer. A simulation in which horizontal hydraulic conductivity was decreased by 50 percent in all aquifers, however, resulted in only a slight decrease (1.7 ft^3/s) of ground-water runoff and a 2.0-foot average rise of water levels at observation well locations in the sand and gravel aquifer. Simulated water levels either rose or fell in the sandstone aquifers depending on their proximity to streams or pumping wells; the average change in water level was 1.3 ft. Decreasing the sandstone aquifers' vertical hydraulic conductivity by a factor of 5 resulted in only a slight decrease (1.9 ft^3/s) in ground-water runoff and a lowering of average water levels by 3.5 ft at observation well locations in the sandstone aquifers; in the sand and gravel aquifer, simulated water levels changed by 1.1 ft. Increasing vertical hydraulic conductivity of the aquifers resulted in a greater change in total ground-water runoff but smaller changes in water levels than was caused by decreasing vertical hydraulic conductivity. Decreasing hydraulic conductivity of the streambeds by a factor of 5 decreased ground-water runoff by 7.8 ft^3/s and caused average ground-water levels at the observation well locations to rise by 1.6 ft. All experimental simulations were made under steady-state conditions and ground-water withdrawal at 6,300 gal/min in Verona well field.

SIMULATIONS FOR CONDITIONS PRIOR TO HEAVY PUMPING

Simulations of ground-water conditions in 1903 prior to any heavy pumping indicate that the potentiometric surface in the sand and gravel aquifer may have been similar to that shown in figure 27; the potentiometric surface for the lower sandstone aquifer may have been similar to that shown in figure 28. The results closely match historic data. Water levels in wells tapping the sandstone aquifers at some places in the vicinity of the well field were at or above land surface in 1903. Historic data indicate that, at well VT6, water "rose to 6 feet above the surface" (Bridgen, 1903) and, at several places, "springs along the bank of the river and in the pond ran all the time (note on a 1904 cross section, author unknown)". Flowing wells and springs are evidence of the presence of confining beds in the Marshall Formation.

SIMULATIONS FOR WELL-FIELD EXPANSION

Model simulations were made to determine the feasibility of installing new municipal supply wells immediately north of the present field. The new wells are needed by the city of Battle Creek to meet an average summer demand of 7,900 gal/min. Because water in many municipal wells in the eastern part of the well field is contaminated, maximum pumping in this area is assumed to be 1,400 gal/min. Because of this, and the fact that pumpage from wells V14, V15, and V16 is 2,750 gal/min, about 3,750 gal/min would be needed from new supply wells to meet the average summer demand. Table 7 summarizes pumping conditions and the aquifers tapped.

Table 7.--Pumping conditions that provide a sufficient supply of water to meet average summer demand

[Aquifers tapped: U, upper sandstone; L, lower sandstone]

Wells	Total pumpage	Aquifer tapped
V14, V15, V16	2,750	U, L
[a]V40, V41, V42, V43	1,400	U, L
Three new wells	3,750	L

[a] Pumping from wells in the eastern part of the well field can continue only as long as the wells remain free of contaminants.

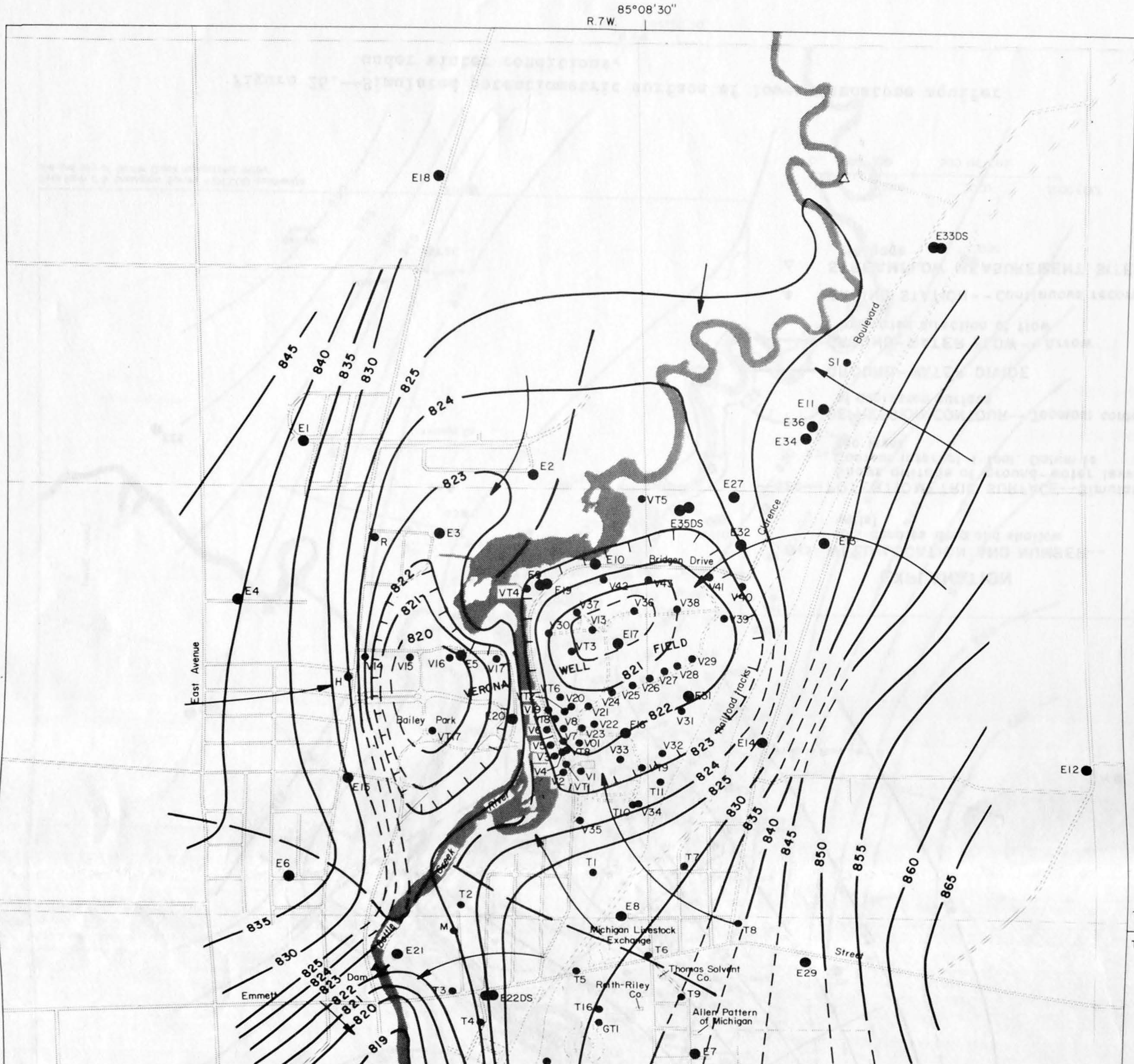


Figure 25.--Simulated potentiometric surface of sand and gravel aquifer under winter conditions.

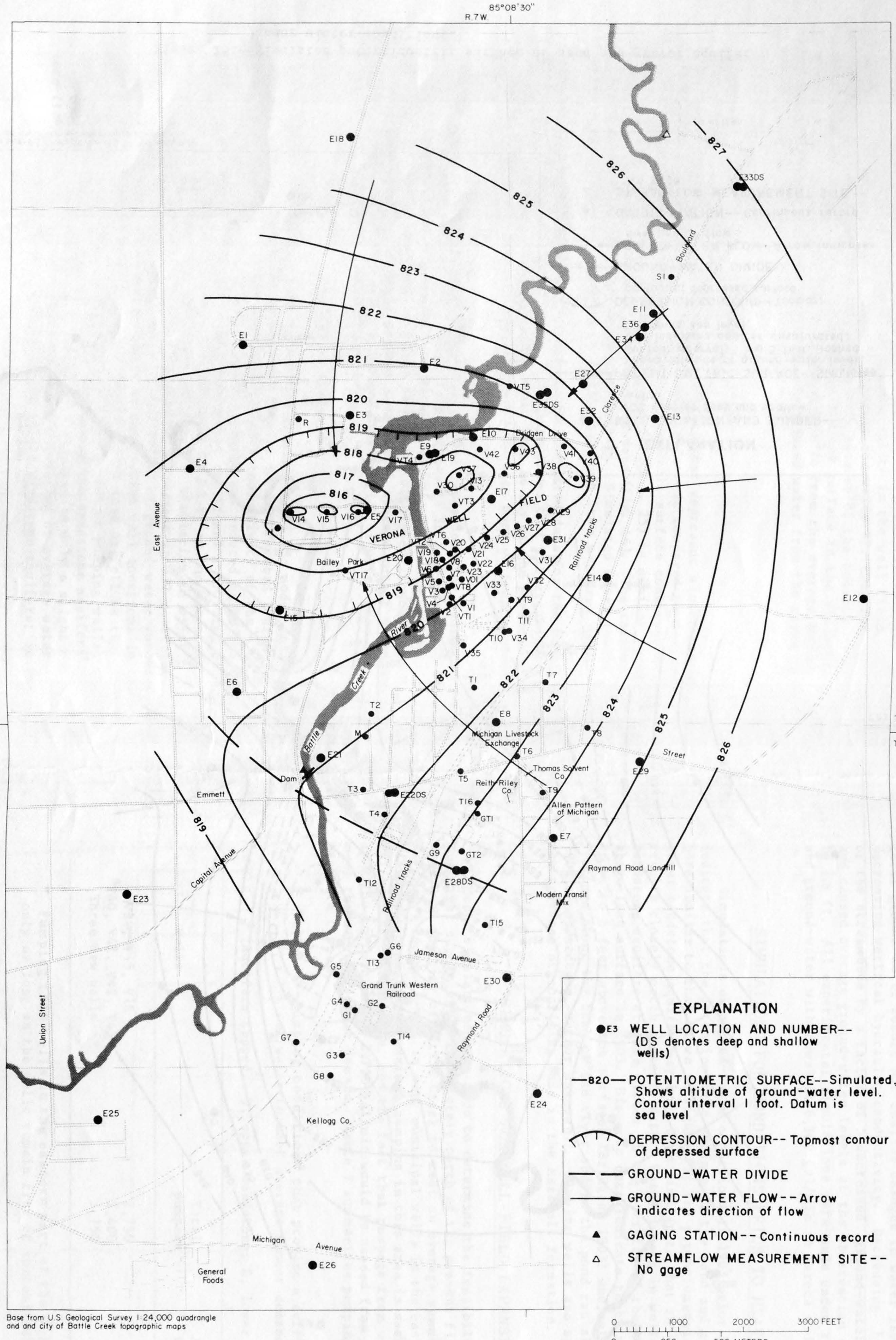


Figure 26.--Simulated potentiometric surface of lower sandstone aquifer under winter conditions.

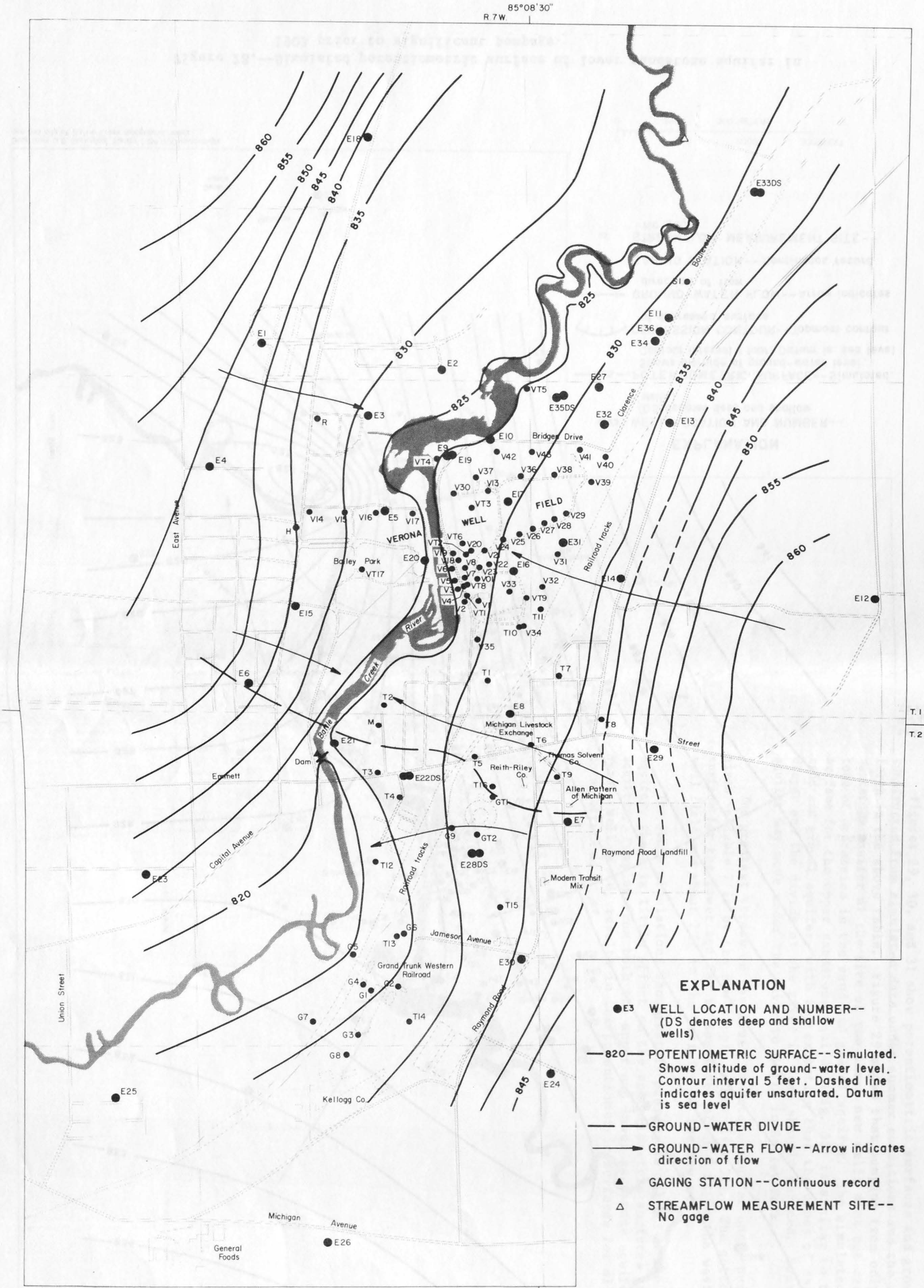


Figure 27.--Simulated potentiometric surface of sand and gravel in 1903 prior to significant pumpage.

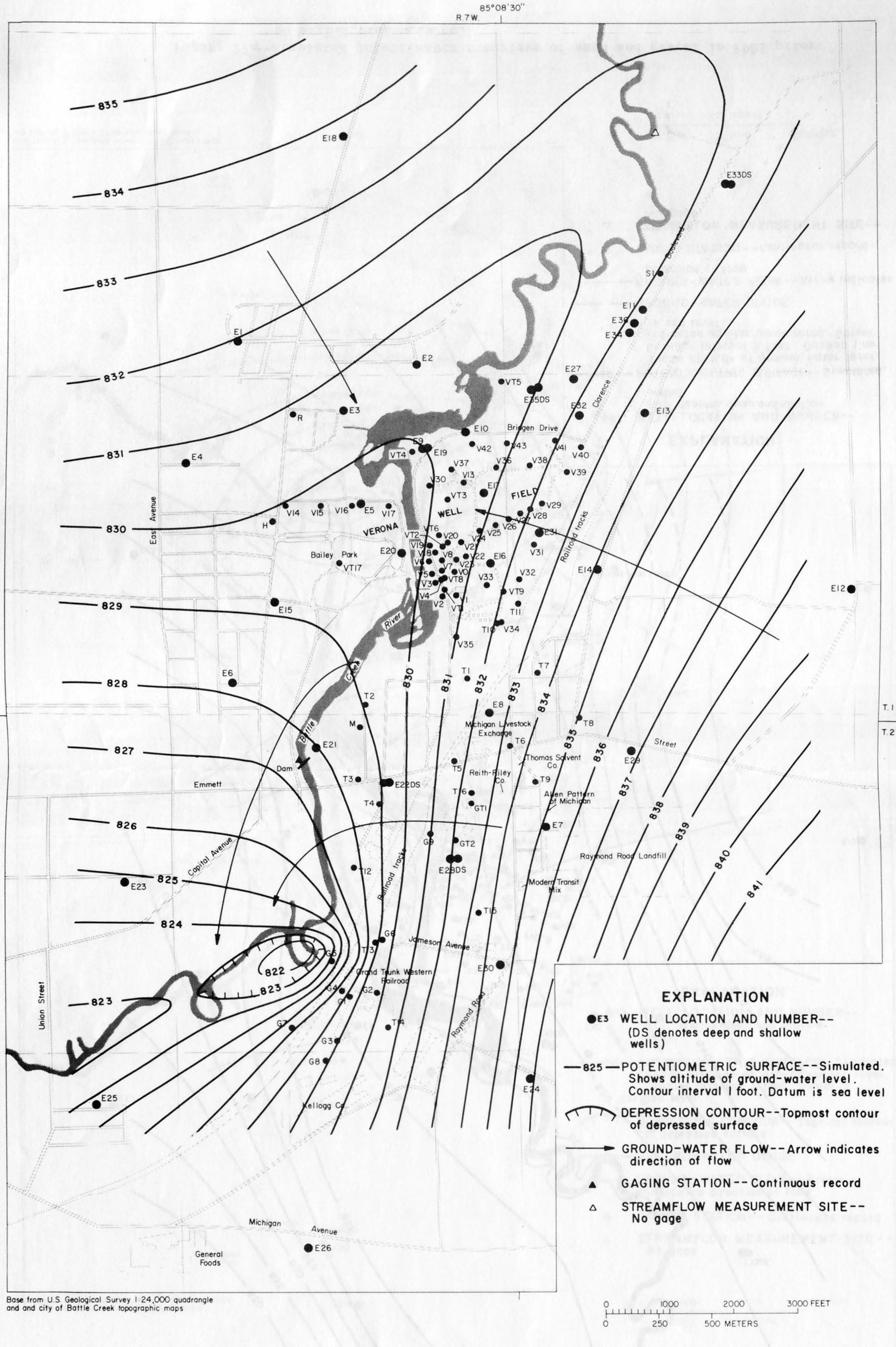


Figure 28.--Simulated potentiometric surface of lower sandstone aquifer in 1903 prior to significant pumpage.

Figures 29, 30, and 31 show potentiometric surfaces and ground-water flow constructed from simulated data under summer conditions and the conditions set forth in the above table. Figure 29 shows that pumping from only the lower sandstone aquifer at the site of the three new wells does not create a separate cone of depression in the sand and gravel aquifer. The simulated potentiometric surface for the upper sandstone aquifer (fig. 30) is similar to that for the sand and gravel aquifer, with the exception that the cones of depression are deeper and the divide at the river is less sharply defined. Some flow in this aquifer may move under the river to wells in Bailey Park.

The greatest stress on the lower sandstone aquifer under pumping conditions given in table 7 is by the new supply wells (fig. 31). The potentiometric surface for the lower aquifer is depressed about 5 ft in the western part of the well field and about 7 ft in the vicinity of the new wells.

The above simulations show that if pumping is only from the lower sandstone aquifer, there is little effect on the potentiometric surfaces in the other two aquifers. Pumping from both the upper and lower sandstone aquifers, as in the Verona well field, results in the potentiometric surfaces for all three aquifers being effected.

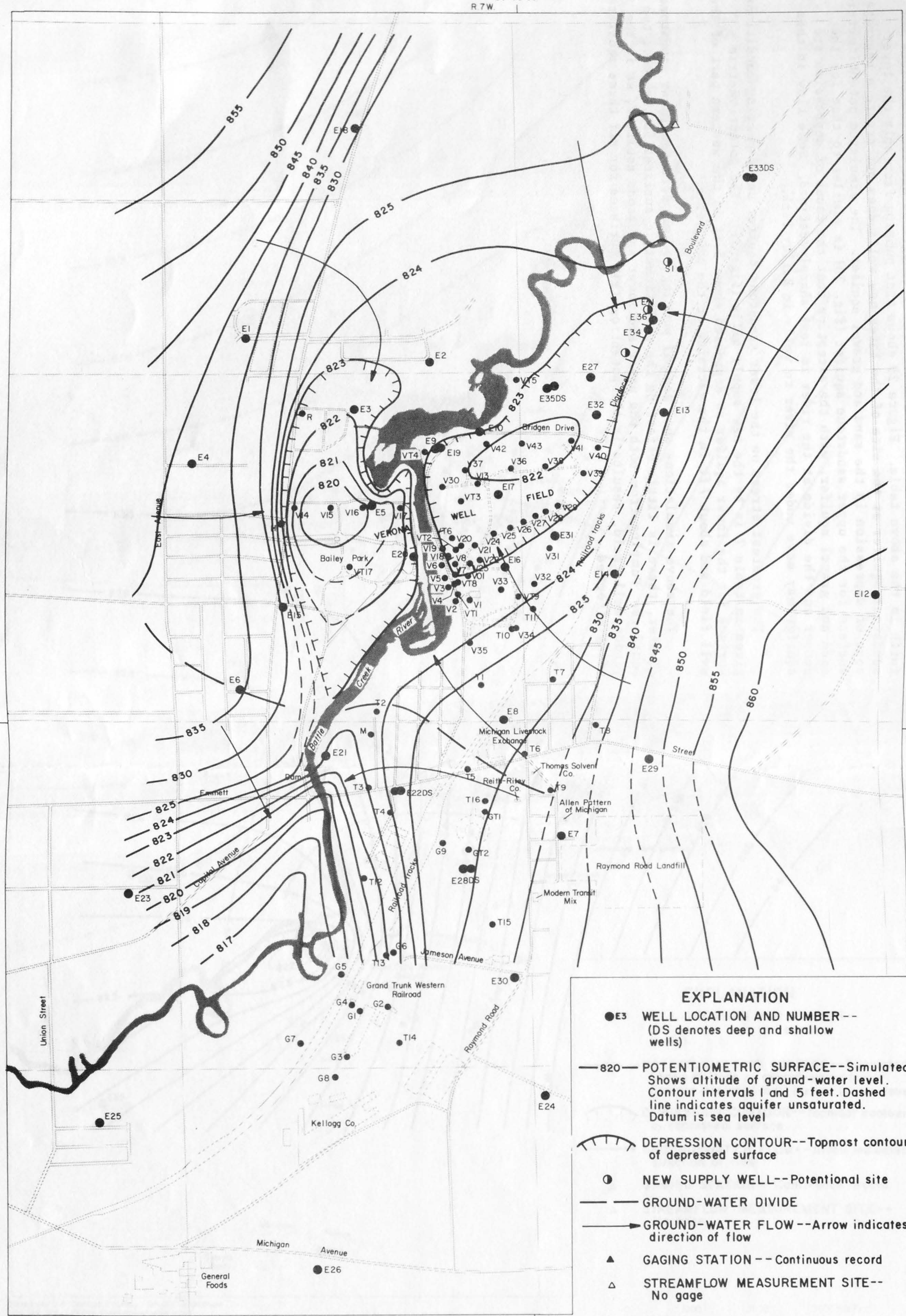


Figure 29.--Simulated potentiometric surface of sand and gravel aquifer under summer conditions with three new supply wells immediately north of Verona well field pumping a total of 3,750 gal/min from the lower sandstone aquifer (supply wells V14, V15, V16 pump a total of 2,750 gal/min; supply wells V40, V41, V42, and V43 pump a total of 1,400 gal/min. Interdiction wells not simulated).

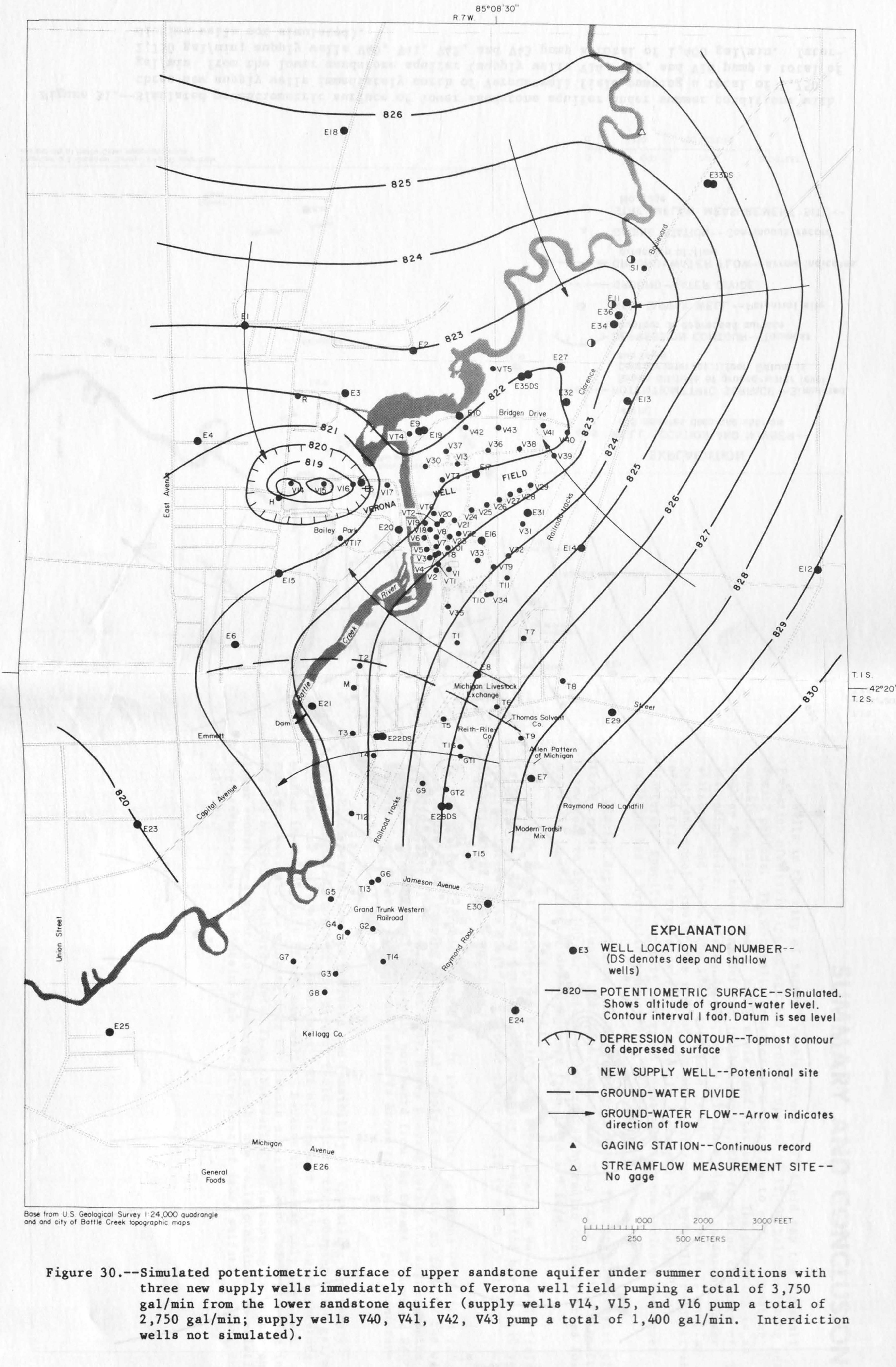


Figure 30.--Simulated potentiometric surface of upper sandstone aquifer under summer conditions with three new supply wells immediately north of Verona well field pumping a total of 3,750 gal/min from the lower sandstone aquifer (supply wells V14, V15, and V16 pump a total of 2,750 gal/min; supply wells V40, V41, V42, V43 pump a total of 1,400 gal/min. Interdiction wells not simulated).

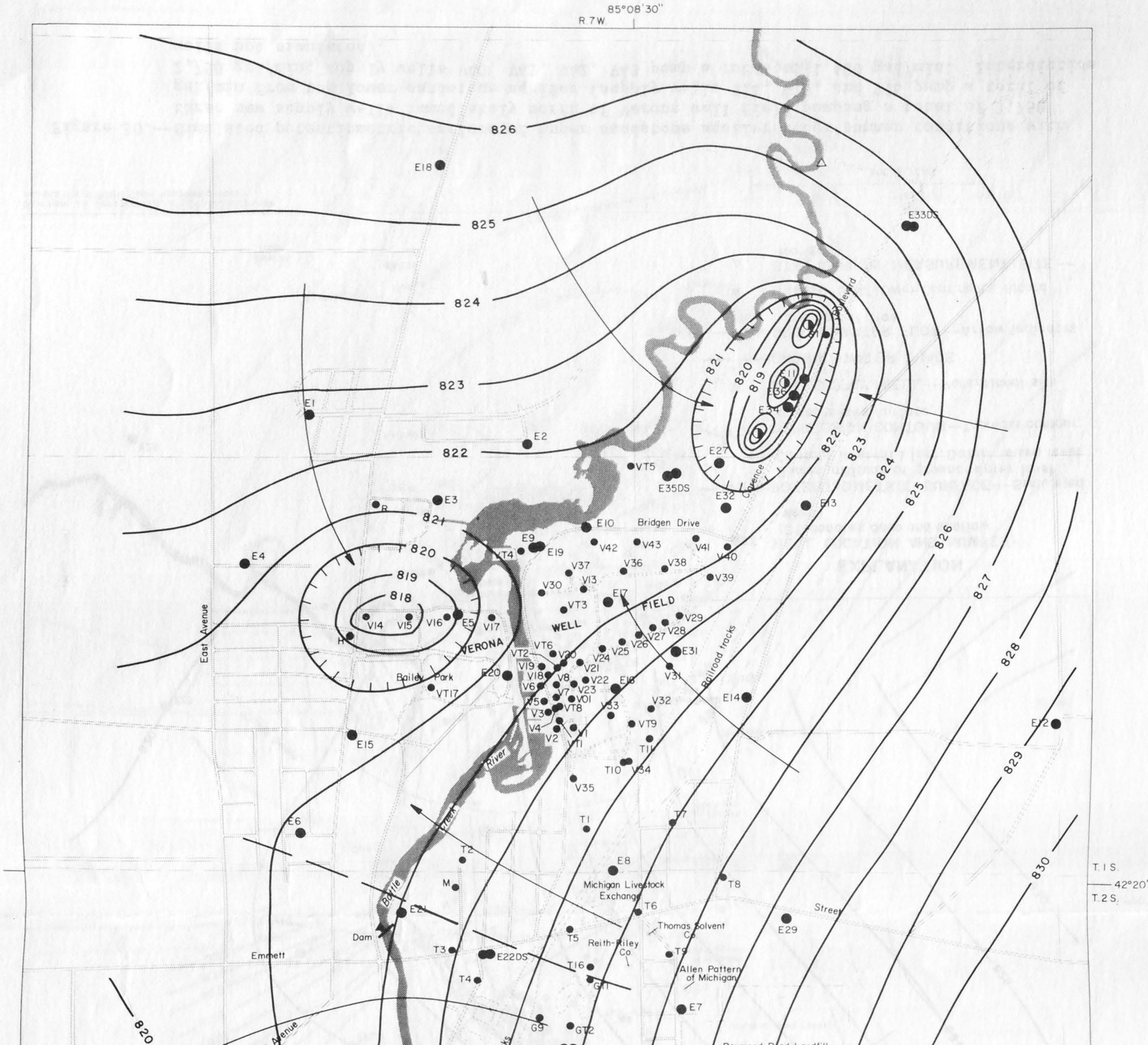


Figure 31.--Simulated potentiometric surface of lower sandstone aquifer under summer conditions with three new supply wells immediately north of Verona well field pumping a total of 3,750 gal/min from the lower sandstone aquifer (supply wells V14, V15, and V16 pump a total of 2,750 gal/min; supply wells V40, V41, V42, and V43 pump a total of 1,400 gal/min. Interdiction wells not simulated).

SUMMARY AND CONCLUSIONS

Wells in the city of Battle Creek's Verona well field tap the Marshall Formation of Mississippian age and produce upward of 12,000 gal/min during peak demand periods. The Marshall Formation is a very fine to medium sandstone containing layers of shale, sandy shale, and siltstone. The formation is as much as 200 ft thick. As defined in this report, the formation consists of, in descending order: Upper sandstone, upper siltstone, lower sandstone, lower siltstone, and shale. The lower sandstone is the principal aquifer; pumping tests and model simulations indicate it has a horizontal hydraulic conductivity of 550 ft/d. Its transmissivity is greatly increased by "openings" or fractures. Specific-capacity tests and model simulations indicate the upper sandstone has a hydraulic conductivity of 150 ft/d.

Glacial deposits overlie the Marshall Formation. The deposits consist of three types: Till, outwash, and channel deposits. They range in thickness from a few feet to about 100 ft. Values of horizontal hydraulic conductivities for materials in the glacial deposits range from 15 to 110 ft/d.

Average annual discharge of Battle Creek River near the Verona well field is 200 ft^3/s. The lowest expected discharge for a 7-day period having a 10-year recurrent interval is 33 ft^3/s. Ground-water runoff is about 55 ft^3/s. Recharge ranges from 8 to 13 in./yr.

Velocities of ground-water flow in the vicinity of Verona well field range from 1 to 4 ft/d. Pumping for municipal supply causes water to flow to the well field from several thousand feet away. Heavy pumping during the summer months causes ground water to flow directly northward from the Emmett St-Raymond Rd intersection, an area where ground water is known to contain significant contaminants.

Model simulations to evaluate the feasibility of installing new supply wells immediately north of the present field indicate that pumping 3,750 gal/min from the new wells will produce about 7 ft of drawdown in the lower sandstone aquifer in the vicinity of the new wells. Because these tap only the lower sandstone aquifer, the pumping does not create distinct cones of depression in the two overlying aquifers. Water from observation wells tapping the upper and lower sandstone aquifers in the vicinity of the new wells contained no volatile hydrocarbons, but did contain high concentrations of iron, sulfate, sodium, and chloride.

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DEFINITION OF TERMS

Altitude.--Vertical distance of a point or line above or below sea level. In this report, all altitudes are above sea level.

Aquifer.--A geologic 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. Also called a ground-water reservoir.

Base flow.--The discharge entering stream channels as inflow from ground water or other delayed sources; sustained or fair weather flow of streams.

Bedrock.--Designates consolidated rocks.

Concentration.--The weight of dissolved solids or sediment per unit volume of water expressed in milligrams per liter (mg/L) or micrograms per liter (μg/L).

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

Contour.--An imaginary line connecting points of equal altitude, whether the points are on the land surface, on a formation surface, or on a potentiometric surface.

Cubic feet per second.--A unit expressing rate of discharge. One cubic foot per second is equal to the discharge of a stream 1 foot wide and 1 foot deep flowing at an average velocity of 1 foot per second.

Dissolved solids.--Substances present in water that are in true chemical solution.

Divide.--A line of separation between drainage systems. A topographic divide delineates the land from which a stream gathers its water; a Ground-water divide is a line on a potentiometric surface on each side of which the potentiometric surface slopes downward away from the line.

Effective porosity.--Amount of interconnected pore space in rocks available for fluid transmission; the ratio of volume of pore space to volume of rock.

Evapotranspiration.--Water withdrawn from a land area by direct evaporation from water surfaces and moist soil and by plant transpiration, no attempt being made to distinguish between the two.

Fracture.--A structural break or opening in bedrock.

Grain size.--The classification range for the diameter of particles, in millimeters, is as follows:

Gravel	> 2.0
Sand, very coarse	1.0 - 2.0
Sand, coarse	0.5 - 1.0
Sand, medium	0.25 - 0.5
Sand, fine	0.125 - 0.25
Sand, very fine	0.0625 - 0.125
Silt and clay	< 0.0625

Ground water.--Water in the ground which is in the saturated zone from which wells, springs, and ground-water runoff are supplied.

Ground-water discharge.--The discharge of water from the saturated zone by 1) natural processes such as ground-water runoff and ground-water evapotranspiration and 2) artificial discharge through wells and other man-made structures.

Ground-water runoff.--Ground water that has discharged into stream channels by seepage from saturated earth materials.

Hardness of water.--Commonly refers to concentration of $CaCO_3$. The classification range for hardness; in milligrams per liter (mg/L) of $CaCO_3$, is as follows:

Very Hard -- more than 180
Hard -- 121 to 180
Moderately hard -- 61 to 120
Soft -- 0 to 60

Head.--The height of the surface of a water column above a standard datum that can be supported by the static pressure at a given point.

Hydraulic conductivity.--The volume of water at the prevailing 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. In general terms, hydraulic conductivity is the ability of a porous medium to transmit water.

Hydraulic gradient.--The change in static head per unit distance in a given direction. If not specified, the direction is generally understood to be that of the maximum rate of decrease in head.

Hydrograph.--A graph showing the variation of stage, flow, velocity, discharge, or other aspect of water with respect to time.

Potentiometric surface.--In aquifers, the levels to which water will rise in tightly cased wells.

Recharge.--The process by which water is infiltrated and added to the zone of saturation. Also, the quantity of water added to the zone of saturation.

Runoff.--That part of precipitation that appears in streams; the water draining from an area. When expressed in inches, it is the depth to which an area would be covered if all the water draining from it in a given period was uniformly distributed on its surface.

Specific capacity.--The rate of discharge of water from a well divided by the drawdown of water level within the well.

Specific conductance.--A measure of the ability of water to conduct an electric current, expressed in micromho (μmho) per centimeter at 25°C. Because the specific conductance is related to amount and type of dissolved material, it can be used for approximating the dissolved-solids concentration of water. For most natural waters the ratio of dissolved-solids concentration (in milligrams per liter) to specific conductance (in micromho) is in the range 0.5 to 0.8.

Specific storage.--The volume of water released from or taken into storage per unit volume of the porous medium per unit change in head.

Specific yield.--The ratio of the volume of water which rock, after being saturated, will yield by gravity, to the volume of 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. In an unconfined aquifer, the storage coefficient is equal to the specific yield.

Subcrop.--In this report, a bedrock formation or rock unit that directly underlies the glacial deposits and would be exposed if all glacial deposits were removed.

Theis type curve.--Graphic method of solution of aquifer characteristics developed by C. V. Theis (1935).

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. In general, the term refers to the ability of aquifer material to transmit water. It is equal to the product of hydraulic conductivity and aquifer thickness, and is expressed in units of length squared per unit time (L^2/t).

Water table.--That surface in an unconfined water body at which the pressure is atmospheric. It is defined by levels at which water stands in wells having shallow penetration into saturated materials.

TABLES

Table 3.--Description of rocks and soils from wells drilled by U.S. Geological Survey

Well number	Lithology	Depth feet
E1	Glacial deposits:	
	Sand (very fine to very coarse, tan) and gravel (fine to coarse with some cobbles, multicolored)	0-48
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to fine, gray)	48-57
E2	Fill	0-6
	Glacial deposits:	
	Sand (medium to very coarse, tan) and clay (brown)	6-27
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to fine, gray, hard)	27-28.5
E3	Glacial deposits:	
	Clay (black) and peat (black)	1-15
	Sand (fine to coarse, tan) and gravel (fine to coarse, multicolored) with some clay (brown to black)	15-27
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to fine, gray)	27-27.5
E4	Glacial deposits:	
	Sand (medium to very coarse, tan) and gravel (fine to coarse, multicolored)	0-20
	Sand (very fine to very coarse, tan) and silt (brown) with some gravel (medium, multicolored) and clay (brown)	20-52
	Sand (medium to very coarse, tan) and gravel (fine to coarse, multicolored) with silt (tan) and clay (brown)	52-72
	Sand (very fine, gray), gravel (fine, multicolored), silt (gray), and clay (gray)	72-78
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to fine, gray)	78-81
E5	Glacial deposits:	
	Sand (medium to very coarse, tan) and gravel (fine to coarse, multicolored)	0-8
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to fine, gray, very hard at top)	8-14
E6	Glacial deposits:	
	Clay (red to brown), silt (brown), sand (medium to very coarse, tan) and some gravel (fine to coarse, multicolored)	0-23
	Clay (red to brown, very sandy and silty)	23-27
	Clay (red to brown), silt (brown), sand (medium to very coarse, tan), and some gravel (fine to coarse, multicolored)	27-47
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to fine, gray)	47-60
E7	Glacial deposits:	
	Sand (medium to very coarse, tan)	0-30
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to fine, gray)	30-55
E8	Glacial deposits:	
	Sand (fine to coarse, reddish brown) with some gravel (fine, multicolored)	0-31
E9	Glacial deposits:	
	Sand (medium to very coarse, tan) and gravel (fine to medium, tan) with some silt (brown) and clay (brown)	0-15
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine, gray, very hard)	15-17
E10	Glacial deposits:	
	Sand (fine to medium, tan)	0-10
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to fine, gray)	10-35
E11	Glacial deposits:	
	Sand (fine to medium, reddish brown)	0-16
	Clay (sandy with much peat and other organic material, black)	16-28
	Sand (fine to very coarse, tan) and some gravel (medium, multicolored)	28-43
E12	Glacial deposits:	
	Sand (medium to coarse, tan) with some clay (brown)	0-10
	Sand (medium to coarse, tan)	10-15
	Sand (medium to coarse, tan) and gravel (fine, multicolored)	15-58
	Sand (fine to medium, tan), gravel (fine, multicolored), and clay (tan to brown)	58-60
	Sand (medium to very coarse, tan) and gravel (fine, multicolored)	60-80
	Sand (medium to very coarse, tan) and gravel (fine, multicolored) with some sandstone boulders	80-100
E13	Glacial deposits:	
	Sand (medium, brown) with some gravel (medium, multicolored)	0-44
	Sand (medium, gray to brown), silt (gray to brown), and clay (gray to brown)	44-52
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to fine, gray)	52-54
E14	Glacial deposits:	
	Sand (medium, tan) and gravel (fine, multicolored)	0-45
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to fine, gray)	45-70
E15	Glacial deposits:	
	Sand (fine to medium, tan)	0-4
	Sand (fine, tan), silt (tan), and clay (brown)	4-10
	Sand (fine to medium, tan)	10-20
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to fine, gray)	20-37
E16	Fill	0-2
	Glacial deposits:	
	Sand (fine to medium, tan) with some silt (tan) and clay (brown)	2-12
	Sand (medium to coarse, tan) and gravel (fine, multicolored)	12-36

Table 3.--Description of rocks and soils from wells drilled by U.S. Geological Survey--Continued

Well number	Lithology	Depth feet
E16 (cont.)	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to fine, gray)	36-42
E17	Glacial deposits:	
	Sand (fine to coarse, tan) with some gravel (fine, multicolored)	0-4
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to fine, gray)	10-32
E18	Glacial deposits:	
	Sand (very fine to medium, tan), silt (yellow to tan), clay (yellow to brown), and some gravel (fine to medium, multicolored)	0-11
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to fine, gray)	11-24
E19	Glacial deposits:	
	Sand (fine to coarse, tan) with some silt (brown) and gravel (fine, multicolored)	0-11
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to fine, gray)	11-34
E20	Glacial deposits:	
	Sand (very fine to coarse, tan) with traces of silt (brown) and gravel (fine, multicolored)	0-8
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (fine to medium, gray)	8-21
E21	Glacial deposits:	
	Sand (fine to very coarse, tan) and gravel (fine, mostly black and white) with traces of silt (brown)	0-15
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to fine, gray)	15-25
E22S	Glacial deposits:	
	Sand (fine to very coarse, tan) and gravel (fine to coarse, multicolored) with traces of silt (brown)	0-14.5
E22D	Glacial deposits:	
	Sand (fine to very coarse, tan) and gravel (fine to coarse, multicolored) with traces of silt (brown)	0-15
	Sand (very fine to very coarse, tan) and gravel (fine to very coarse, multicolored; coal fragments 20-30 ft)	15-33
	Sand (very fine to very coarse, tan) gravel (fine to coarse, multicolored), clay (gray), and silt (gray to tan)	33-37
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to medium, gray)	37-40
	Sandstone (silty, very fine to fine, gray with some brown)	40-59
	Upper siltstone:	
	Siltstone (sandy, gray)	59-70
	Lower sandstone:	
	Sandstone (very fine to fine, gray)	70-85
	Sandstone (silty, very fine to fine, gray)	85-87
	Sandstone (very fine to fine, gray)	87-105
	Lower siltstone	
	Siltstone (shaly, gray)	105-108
	Sandstone (shaly, very fine to fine, gray)	108-111
	Siltstone (shaly,gray)	111-115
	Sandstone (shaly and silty, very fine, gray)	115-124
	Shale:	
	Shale (dark gray)	124-130
E23	Glacial deposits:	
	Clay (gray), silt (gray), and sand (medium to coarse, tan)	0-10
	Sand (fine to very coarse, gray to tan) and gravel (fine to coarse, multicolored)	10-22
	Sand (fine to very coarse, tan), gravel (fine, multicolored), and some silt (brown)	22-35
	Sand (fine to very coarse, gray to tan), and gravel (fine to cobbles, multicolored)	35-40
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to medium, gray)	40-48
	Siltstone (sandy, gray)	48-55
	Sandstone (very fine to medium, gray)	55-74
	Upper siltstone:	
	Siltstone (shaly, gray)	74-77
E23 (cont.)	Marshall Formation:	
	Lower sandstone:	
	Sandstone (very fine to fine, gray) with thin layers of siltstone (gray)	77-100
	Sandstone (very fine to fine, gray)	100-109
	Lower siltstone:	
	Siltstone (shaly and sandy, gray)	109-111
	Sandstone (silty and shaly, very fine, gray)	111-114
	Siltstone (shaly, gray)	114-119
	Sandstone (silty, very fine, gray)	119-125
	Shale:	
	Shale (gray)	125-147
	Sandstone (shaly and silty, very fine, gray)	147-155
E24	Glacial deposits:	
	Sand (very fine to very coarse, tan), gravel (fine to coarse, multicolored), some silt (brown), and some clay (dark brown)	0-22
	Sand (very fine to very coarse, tan) and traces of silt (brown to tan)	22-40
	Sand (fine to very coarse, tan), and gravel (fine to medium, multicolored) with some coal fragments	40-50
	Silt (gray), sand (very fine to medium, tan to gray), clay (gray), and gravel (fine, multicolored)	50-67
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to medium, green to gray)	67-76
	Sandstone (very fine to medium, green to gray) with thin layers of siltstone (green to gray)	76-97
	Upper siltstone:	
	Siltstone (shaly, green to gray)	97-103
	Lower sandstone:	
	Sandstone (very fine to fine, gray)	103-124
	Sandstone (silty, very fine to fine, gray)	124-128
	Sandstone (very fine to fine, gray)	128-139
	Lower siltstone:	
	Siltstone (shaly, gray)	139-141
	Sandstone (silty, very fine to fine, gray)	141-144
	Siltstone (shaly, gray)	144-148
	Sandstone (silty, very fine to fine, gray)	148-159
	Shale:	
	Shale (dark gray)	159-163

Table 3.--Description of rocks and soils from wells drilled by U.S. Geological Survey--Continued

Well number	Lithology	Depth feet
E25	Glacial deposits:	
	Fill (sand, gravel, silt, clay)	0-5
	Peat (black) and clay (black)	5-8
	Sand (fine to very coarse, tan) and gravel (fine to medium, multicolored)	8-15
	Sand (very fine to medium, tan) with some coal fragments	15-30
	Sand (medium to very coarse, tan) and gravel (fine, multicolored)	30-37
	Marshall Formation:	
	Upper siltstone:	
	Siltstone (shaly, gray)	37-42
	Lower sandstone:	
	Sandstone (shaly, very fine to fine, gray)	42-47
	Sandstone (very fine to fine, gray)	47-60
	Sandstone (silty or shaly, very fine to fine, gray)	60-70
	Sandstone (very fine to fine, gray)	70-82
	Lower siltstone:	
	Siltstone (shaly, gray)	82-86
	Sandstone (silty, very fine to fine, gray)	86-88
	Siltstone (shaly, gray)	88-95
	Sandstone (shaly, very fine to fine, gray)	95-98
	Shale:	
	Shale (gray)	98-110
E26	Glacial deposits:	
	Sand (fine to coarse, tan), gravel (fine to medium, multicolored), silt (brown), and clay (brown)	0-10
	Sand (fine to coarse, tan), and gravel (fine to medium, multicolored)	10-35
	Clay (brown) and silt (brown)	35-38
	Sand (fine to coarse, tan) and gravel (fine to medium, multicolored) with traces of silt (brown) and clay (brown)	38-46
	Clay (brown), silt (brown), sand (very fine to very coarse, tan), and gravel (medium to coarse, multicolored)	46-65
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (silty,very fine to fine, gray)	65-67
	Upper siltstone:	
	Siltstone (shaly, gray)	67-75
	Lower sandstone:	
	Sandstone (very fine to fine, gray)	75-90
	Sandstone (very fine to fine, gray) with thin layers of siltstone (gray)	90-10
E26 (cont.)	Marshall Formation:	
	Sandstone (very fine to fine, gray)	100-108
	Lower siltstone:	
	Siltstone (shaly, gray)	108-111
	Sandstone (shaly or silty, very fine to fine, gray	111-115
	Siltstone (shaly, gray)	115-119
	Sandstone (shaly, very fine, gray)	119-125
	Shale:	
	Shale (dark gray)	125-135
E27	Glacial deposits:	
	Sand (fine to very coarse, tan) and gravel (fine to medium, multicolored) with traces of silt (brown) and clay (brown)	0-14
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to fine, gray)	14-25
	Sandstone (very fine to medium, gray)	25-54
	Upper siltstone:	
	Siltstone (gray)	54-56
	Sandstone (silty, very fine to fine, gray)	56-61
	Lower sandstone:	
	Sandstone (very fine to medium, gray)	61-68
	Sandstone (silty, very fine to fine, gray)	68-73
	Sandstone (very fine to fine, gray)	73-80
E28S	Fill (topsoil and bricks)	0-8
	Glacial deposits:	
	Sand (fine to coarse, tan) and gravel (fine, brown)	8-10
E28D	Fill (topsoil and bricks)	0-8
	Glacial deposits:	
	Sand (very fine to coarse, tan) and gravel (fine to medium, multicolored; coal fragments, 21-28 ft)	8-28
	Clay (dark gray), silt (gray), and sand (very fine to fine, tan)	28-32
	Sand (fine to very coarse, multicolored) and gravel (fine to coarse, multicolored)	32-42
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (silty, very fine to fine, gray)	42-46
	Sandstone (very fine to medium, gray)	46-53
	Upper siltstone:	
	Siltstone (shaly and sandy, gray)	53-65
E28D (cont.)	Marshall Formation	
	Lower sandstone:	
	Sandstone (very fine to fine, gray)	65-68
	Sandstone (shaly, very fine to fine, gray)	68-73
	Sandstone (very fine to fine, gray)	73-78
	Sandstone (silty, very fine to fine, gray)	78-86
	Sandstone (very fine to fine, gray)	86-98
	Lower siltstone:	
	Siltstone (shaly, gray)	98-101
	Sandstone (silty, very fine to fine, gray)	101-104
	Siltstone (shaly, gray)	104-109
	Sandstone (shaly and silty, very fine to fine, gray)	109-116
	Shale:	
	Shale (gray)	116-120
	Shale (sandy and silty, gray)	120-122
	Shale (dark gray)	122-130
E29	Glacial deposits:	
	Sand (fine to coarse, yellow) and gravel (fine to cobbles, multicolored) with traces of silt (yellow) and clay (yellow)	0-8
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to medium, yellow)	8-21
	Sandstone (silty, very fine to fine, yellow)	21-29
	Sandstone (very fine to medium, gray)	29-38
	Sandstone (silty, very fine to medium, gray)	38-41
	Sandstone (very fine to medium, gray)	41-53
	Sandstone (very fine to fine, gray)	53-86
	Upper siltstone:	
	Siltstone (shaly, gray)	86-94
	Lower sandstone:	
	Sandstone (shaly, very fine, gray)	94-104
	Sandstone (very fine to fine, gray)	104-110
	Sandstone (very fine to fine, gray) with thin layers of siltstone (gray)	110-118
	Sandstone (very fine to fine, gray)	118-128
	Sandstone (shaly, very fine, gray)	128-132
	Sandstone (very fine to fine, gray)	132-137
	Lower siltstone:	
	Siltstone (shaly, gray)	137-142
	Sandstone (shaly, very fine,gray)	142-144
	Siltstone (shaly, gray)	144-146
	Sandstone (shaly, very fine, gray)	146-152
	Shale:	
	Shale (gray)	152-156

Table 3.--Description of rocks and soils from wells drilled by U.S. Geological Survey--Continued

Well number	Lithology	Depth feet
E30	Fill (mostly from foundary nearby)	0-12
	Glacial deposits:	
	Sand (medium to very coarse, multicolored) and gravel (fine to medium, multicolored)	12-17
	Peat (black) and clay (black)	17-21
	Silt (dark gray to black), sand (very fine, tan), peat (black), and clay (dark gray to black)	21-29
	Sand (very fine to very coarse, mostly tan) and gravel (fine, multicolored)	29-44
	Sand (very fine to fine, tan), silt (tan), and clay (tan to dark gray)	44-62
	Silt (gray to tan), sand (very fine to medium, tan), gravel (fine to medium, multicolored)	62-75
	Clay (gray to tan)	75-78
	Sand (very fine to medium, multicolored) with some silt (gray) and clay (gray)	78-81
	Clay (gray)	81-84
	Clay (gray), silt (gray), sand (very fine to fine, tan), and gravel (fine, multicolored)	84-91
	Marshall Formation:	
	Lower sandstone:	
	Sandstone (very fine to fine, gray)	91-102
	Sandstone (shaly, very fine, gray)	102-106
	Sandstone (very fine to fine, gray)	106-118
	Lower siltstone:	
	Siltstone (shaly, gray)	118-120
	Sandstone (silty, very fine, gray)	120-123
	Siltstone (shaly, gray)	123-128
	Sandstone (shaly, very fine, gray)	128-133
	Shale:	
	Shale (dark gray)	133-139
E31	Topsoil (dark brown)	0-2
	Glacial deposits:	
	Clay and organic matter (black)	2-4
	Sand (fine, tan)	4-5
	Sand (medium to coarse, tan)	5-6
	Sand (medium to coarse, tan) and some gravel (fine, multicolored)	6-10
E32	Glacial deposits:	
	Sand (very fine to medium, tan), silt (brown), and traces of gravel (fine, multicolored)	0-13
	Sand (fine to medium, tan)	13-25
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to medium, gray)	25-35
	Sandstone (silty, very fine to fine, gray)	35-37
	Sandstone (very fine to medium, gray)	37-60
E33S	Glacial deposits:	
	Sand (very fine to medium, tan) with some silt (tan) and clay (tan)	0-9
	Sand (fine to very coarse, tan) and gravel (fine, multicolored)	9-18
E33D	Glacial deposits:	
	Sand (very fine to medium, tan) with some silt (tan) and clay (tan)	0-9
	Sand (fine to very coarse, tan) and gravel (fine, multicolored)	9-21
	Sand (very fine to very coarse, tan) and gravel (fine to medium, multicolored) with traces of silt (brown) and clay; some coal fragments	21-34
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to medium, gray)	34-57
	Sandstone (silty, very fine to fine, gray)	57-63
	Sandstone (very fine to medium, gray)	63-70
	Siltstone (gray)	70-74
	Sandstone (very fine to fine, gray)	74-93
	Siltstone (gray)	93-95
	Sandstone (very fine to fine, gray)	95-106
	Upper siltstone:	
	Siltstone (shaly, gray)	106-111
	Lower sandstone:	
	Sandstone (shaly, very fine to fine, gray)	111-120
	Sandstone (very fine to fine, gray)	120-136
	Sandstone (very fine to fine, gray) with layers of siltstone (gray)	136-145
	Lower siltstone:	
	Siltstone (shaly, gray)	145-148
	Sandstone (shaly, very fine, gray)	148-150
	Siltstone (shaly, gray)	150-156
	Sandstone (shaly, very fine to fine, gray)	156-165
E33D (cont.)	Shale:	
	Shale (dark gray)	165-170
E34	Glacial deposits:	
	Sand (very fine to very coarse, tan) and gravel (fine to medium, multicolored; coal fragments 19-23 ft) with traces of silt (brown) and clay (gray-black)	0-30
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to medium, gray)	30-53
	Sandstone (silty, very fine to fine, gray)	53-56
	Sandstone (very fine to medium, gray)	56-62
	Sandstone (shaly, very fine to fine, gray)	62-71
	Sandstone (very fine to medium, gray)	71-76
	Upper siltstone:	
	Siltstone (sandy, brown to light gray)	76-82
	Lower sandstone:	
	Sandstone (very fine to fine, gray)	82-89
	Sandstone (shaly, very fine to fine, gray)	89-104
	Sandstone (very fine to fine, gray)	104-115
	Sandstone (shaly, very fine to fine)	115-117
	Sandstone (very fine to fine, gray)	117-125
	Lower siltstone:	
	Siltstone (shaly, gray)	125-129
	Sandstone (silty, very fine to fine, gray)	129-133
	Siltstone (shaly, gray)	133-136
	Sandstone (shaly, very fine to fine, gray)	136-146
	Shale:	
	Shale (dark gray)	146-155
E35S	Glacial deposits:	
	Sand (medium to coarse, tan) with traces of gravel (fine, multicolored)	0-7
	Sand (fine to very coarse, tan) and gravel (fine to medium, multicolored) with traces of silt (brown) and clay (brown to black)	7-11
	Sand (medium to very coarse, gray to brown) and gravel (fine to medium, multicolored; some coal fragments)	11-22
E35D	Glacial deposits:	
	Sand (medium to coarse, tan) with traces of gravel (fine, multicolored)	0-7
	Sand (fine to very coarse, tan) and gravel (fine to medium, multicolored) with traces of silt (brown) and clay (brown to black)	7-11

Table 3.--Description of rocks and soils from wells drilled by U.S. Geological Survey--Continued

Well number	Lithology	Depth feet
E35D (cont.)	Glacial deposits:	
	Sand (medium to very coarse, gray to brown) and gravel (fine to medium, multicolored; some coal fragments)	11-22
	Sand (very fine to coarse, gray to tan; some coal fragments)	22-30
	Sand (very fine to very coarse, tan to gray) fine gravel (fine to coarse with some cobbles, multicolored)	30-36
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to medium, gray)	36-50
	Sandstone (silty, very fine to fine, gray)	50-54
	Sandstone (very fine to fine, gray)	54-63
	Sandstone (shaly, very fine to fine, gray with traces of brown)	63-68
	Sandstone (very fine to medium, gray with traces of brown)	68-77
	Upper siltstone:	
	Sandstone (shaly, very fine to fine, gray)	77-81
E36	Glacial deposits:	
	Sand (fine to medium, tan) and gravel (fine, multicolored) with traces of silt (brown) and clay (brown)	0-11
	Peat (black) and clay (black)	11-14
	Sand (fine to very coarse, tan) and gravel (fine to coarse, multicolored) with several silty zones	14-34
	Sand (very fine to very coarse, tan), gravel (fine to coarse, multicolored), silt (gray), and clay (gray)	34-37
	Marshall Formation:	
	Upper sandstone:	
	Sandstone (very fine to medium, gray)	37-76
	Sandstone (silty, very fine, gray)	76-78
	Upper siltstone:	
	Siltstone (shaly, gray to brown)	78-80
	Lower sandstone:	
	Sandstone (very fine to fine, gray)	80-87
	Siltstone (shaly, gray)	87-92
	Sandstone (very fine to fine, gray)	92-103
	Sandstone (very fine to fine, gray) with siltstone (gray) in layers	103-112
	Sandstone (very fine to fine, gray)	112-125

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