Geohydrology and Simulations of Ground-Water Flow at Verona Well Field, Battle Creek, Michigan, 1988

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CONVERSION FACTORS

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
gallon (gal)	3.785	liter
gallon per minute (gal/min)	0.06308	liter per second
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square foot per day (ft^2/d)	0.09290	square meter per day

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:

°C = 5/9 (°F - 32).

VERTICAL DATUM

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

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Abstract

Public water supply for the city of Battle Creek, Mich. is withdrawn from the Marshall Sandstone through wells at the Verona well field. Analysis of borehole acoustic televiewer, gamma, and single-point-resistance logs from wells in Bailey Park, near the well field, indicates 12 fracture zones in the Marshall Sandstone. Further interpretation of flowmeter and temperature logs from the same wells indicates that the fracture zones are locally interconnected but appear to remain isolated over a lateral distance of 3,000 feet.

Organic chemicals were detected in water samples collected from water-supply wells in the Verona well field in 1981. In 1985, six water-supply wells were converted to purge wells to intercept organic chemicals and divert them from the remaining water-supply wells. Removal of these wells from service resulted in a water-supply shortage. A proposal in which an alternative purge system could be installed so that wells that are out of service may be reactivated was examined. A ground-water-flow model developed for this study indicates that, under the current purge configuration, most water from contaminant-source areas either is captured by purge wells or flows to the Battle Creek River. Some water, however, is captured by three water-supply wells. Model simulations indicate that with the addition of eight purge wells, the well field would be protected from contamination, most water from the contaminant-source areas would be captured by the purge system, and only a small portion would flow to the Battle Creek River.

In an effort to augment the city's water supply, the potential for expansion of the Verona well field to the northeast also was investigated. Because of the addition of three municipal wells northeast of the well field, some water from the site of a gasoline spill may be captured by two water-supply wells. Ground water in the area northeast of Verona well field contains significantly lower concentrations of iron, manganese, and calcium carbonate than does water in the existing well field area. However, the Marshall Sandstone in this area has significantly lower transmissivities than those within Verona well field.

INTRODUCTION

The city of Battle Creek is in Calhoun County in the southwestern part of Michigan's Lower Peninsula (fig. 1). Wells completed in the Mississippian Marshall Sandstone at the city's Verona well field (fig. 2) supply water for domestic and industrial use. Well yields at Verona well field are affected by the degree and interconnections of fractures in sandstone. Verona well field consisted of 20 water-supply wells as of July 1990. Supply wells are on both sides of Battle Creek River at the northeastern edge of the city; well depths range from 110 to 157.5 ft, and yields range from 300 to 1,400 gal/min. The average demand for water in 1990 was about 10,500 gal/min. Projected annual average water demand on the well field for the year 2010 is about 12,100 gal/min (Black & Veatch Engineers-Architects, 1987). This demand will require additional water-supply wells.

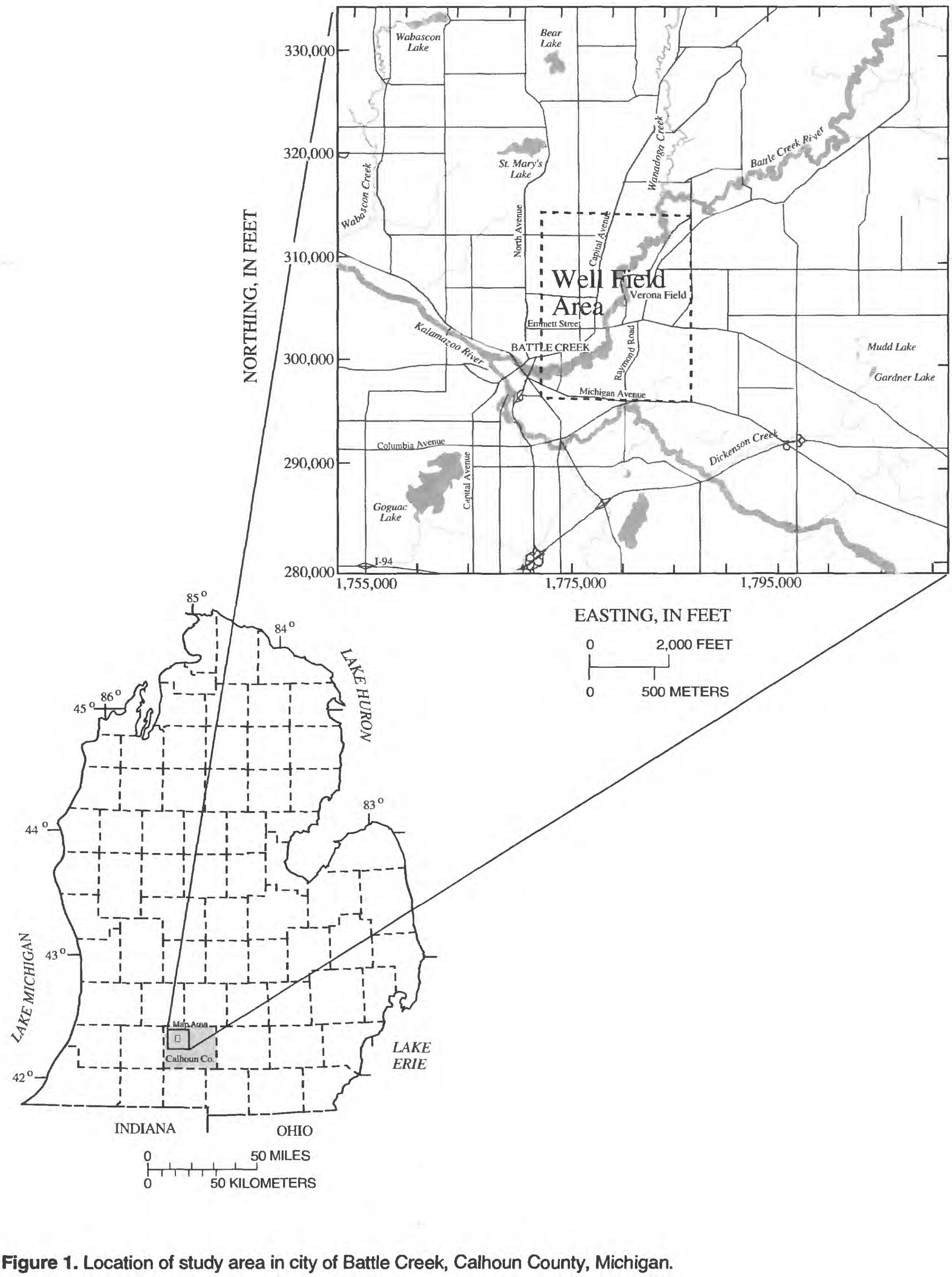


Figure 1. Location of study area in city of Battle Creek, Calhoun County, Michigan.

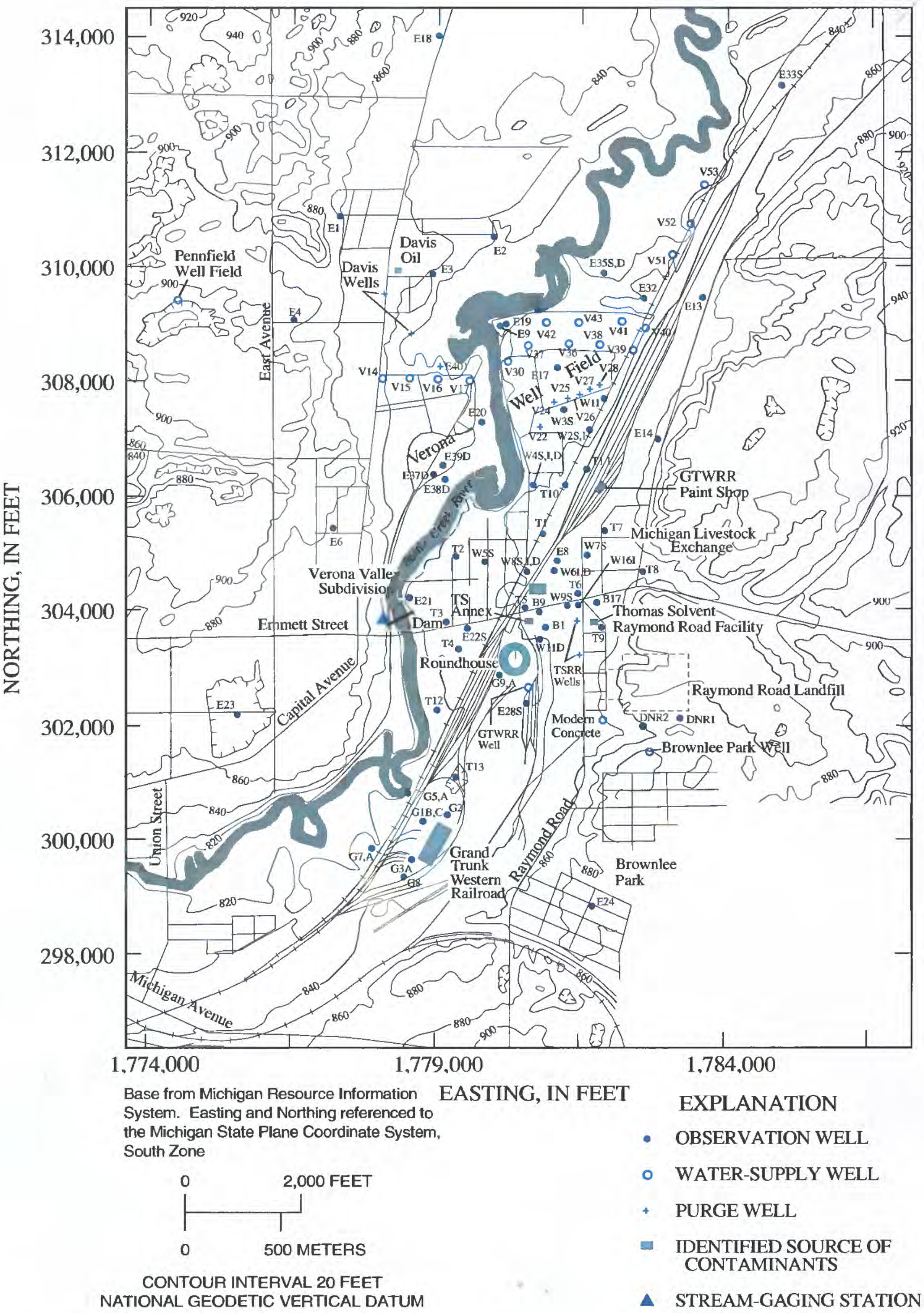


Figure 2. Physical features and well locations in study area, Battle Creek, Michigan.

Volatile organic compounds (VOCs) were detected in some wells in the Verona well field in 1981. The U.S. Geological Survey (USGS) did a study during 1981-84, in cooperation with the City of Battle Creek, to determine the geohydrology of the area, and to examine effects of pumping on ground-water flow, feasibility and effect of installing new wells, and pumping conditions needed to provide a sufficient supply of potable water. In addition, studies by the U.S. Environmental Protection Agency (USEPA) and the State of Michigan identified ground-water contamination and provided recommendations for remedial action under USEPA's Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) program (CH2M-Hill, 1990a). In 1985, six water-supply wells were converted to purge wells to intercept contaminated water before it could reach the northeastern part of the well field. South of the purge wells, the USEPA took action to remove contaminants at the source of the main contaminant plumes. Six other supply wells in the area were abandoned. The removal of water-supply wells from service resulted in a water-supply shortage.

Table 1. Selected data for observation wells installed by the U.S. Geological Survey since 1983, Battle Creek, Michigan

[Well: D, deep; I, intermediate]

Well	Well depth (feet below land surface)	Depth to bottom of casing (feet below land surface)	Distance of measuring point above land surface (feet)	Altitude of measuring point (feet above sea level)
E37D	162	21	3.0	833.32
E38D	162	24	3.0	831.27
E39D	162	26	3.0	832.67
E40I	101	41	3.0	[1]835.00
E41D	182	104	3.0	[1]858.00
E42D	182	104	3.0	[1]858.00
E43D	190	103	3.0	[1]860.00
E44D	142	114	1.5	[1]835.00
E45D	122	80	0.6	[1]820.00

[1]Altitude is estimated.

In 1986, 1,900 gal of gasoline were spilled at the Davis Oil site upgradient from water-supply wells in the northwestern part of Verona well field (Kraus and Kriscunas, 1988). Contaminants are likely moving toward supply wells and could affect the water supply.

The USGS, in cooperation with the Michigan Department of Natural Resources and the city of Battle Creek, began a study in 1989 to:

1. Collect and analyze additional data on secondary porosity and permeability of the Marshall Sandstone to aid in refining a ground-water-flow model prepared as part of the earlier USGS study;
2. Evaluate the feasibility and potential effects of relocating the present purge system;
3. Determine rate and direction of ground-water flow in the area of gasoline contamination; and
4. Re-evaluate the effects of ground-water withdrawals on ground-water flow and evaluate the effects of any increased pumpage on ground-water flow at Verona well field.

This report describes the results of this study.

Study Methods

Data were collected from an area that extends beyond the immediate vicinity of the well field (fig. 2) to allow a more accurate evaluation of ground-water-flow conditions at the well field. Geologic and hydrologic data, including production statistics and well records from city and State agencies and the USGS, were compiled and evaluated. Nine observation wells were drilled to depths ranging from 101 to 190 ft (table 1). Rock and soil samples were collected and examined during drilling. Borehole-geophysical measurements, which included acoustic televiewer, resistivity, natural-gamma, flowmeter, and caliper logs, were made in observation wells E37D, E38D, and E39D. Lithologic and geophysical data were used to examine secondary porosity and permeability.

Hydrologic data were collected and evaluated for the study. Water levels in observation wells CH136I and CH104 were recorded continuously from

December 12 through 14, 1989. Continuous water-level and pumping records were examined to study the effects of pumping on ground-water flow. Aquifer tests were done at wells E37D and E41D. Streamflows of Wanadoga Creek and Battle Creek River (fig. 2), a tributary to Battle Creek River about 2 mi north of the well field, were measured five times during 1989 and 1990. A ground-water-flow model developed by Grannemann and Twenter (1985) was modified to incorporate these new data. The ground-water-flow model was then used to evaluate relocation of the purge system, re-evaluate the effects of ground-water withdrawals on ground-water flow, and evaluate the effects of increased pumpage on ground-water flow.

Water samples from five wells were analyzed for VOCs. These analyses were done to determine whether a contaminant plume from the fuel spill northwest of the well field had reached these wells. Chemical and physical characteristics of water from three depths in well E37D were analyzed to examine secondary porosity and permeability. Finally, chemical and physical characteristics of water from observation wells E37D, E38D, and E42D were analyzed to compare the quality of water northeast of the well field with water within Verona well field for suitability of expansion of the well field in that direction.

Previous Studies

Ground-water flow and hydrogeology of the Verona well field area were described by Vanlier (1966) and Grannemann and Twenter (1985). Descriptions of ground-water contamination and remedial measures related to contamination are documented in reports by contractors for the USEPA (Ecology and Environment, 1982; Warzyn Engineering Co., 1985; CH2M-Hill, 1988, 1989a, 1989b, 1990a, 1990b). Investigation of the gasoline spill is documented in Kraus and Kriscunas (1988). Well and aquifer conditions at four water-supply wells at Verona well field were evaluated by Layne-Northern Company (1988, 1989).

Acknowledgments

Employees of the city of Battle Creek, particularly Mr. John F. O'Brien and Mr. David Rich, have been helpful not only in providing information about the Verona well field but also by assisting in other phases of the study. Permission to drill wells on property owned by Pennfield Township is gratefully acknowledged. Information and water-quality analyses from the Michigan Departments of Public Health and Natural Resources have been helpful in many aspects of the study. Cooperative work with contractors for USEPA and the city of Battle Creek have made valuable contributions to the study.

PHYSICAL SETTING

The valley of Battle Creek River is 1 mi wide at Verona well field and ranges in altitude from 820 to 840 ft (fig. 2). Upstream from the well field, 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 Street ponds the river at an altitude of about 824 ft for a 1.5-mile reach that passes through the well field (fig. 2). North of the well field, no commercial or industrial developments are within the study area. South of the field are eight large and several small companies. A railroad complex, including a switching yard, lies along the east side of the well field, and the Raymond Road 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 area of commercial and industrial development.

Sources and Pumpage of Water

Water for municipal supply and most commercial and industrial use is pumped from wells completed in the Marshall Sandstone. Most wells are 100 to 157.5 ft deep, and large-diameter wells can yield as much as 1,400 gal/min.

Table 2. Selected data for water-supply and purge wells in the Verona well field, Battle Creek, Michigan

[Well: *, purge well; x, abandoned well. Pump capacity: N, not operational. --, no data]

Well	Altitude of land surface (feet above sea level)	Well depth (feet below land surface)	Depth to bottom of casing (feet below land surface)	Nominal diameter of casing (inches)	Altitude of top of bedrock (feet above sea level)	Pump capacity (gallons per minute)	Year drilled
V14	840	129	39	12	802	1,000	1939
V15	836	141	--	12	804	1,000	1939
V16	834	134	--	12	812	750	1939
V17	831	133	33	12	824	N	1939
V22*	833	113	77	10	793	750	1919
V24*	835	118	41	8	823	300	1926
V25*	835	115	36	8	823	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
V31x	837	125	76	16	784	1,000	1948
V32x	838	120	57	16	794	1,000	1948
V33x	837	150	49	16	792	1,000	1948
V34x	840	140	67	16	792	1,000	1948
V35x	840	132	59	16	805	1,000	1948
V36	840	147	44	16	825	1,000	1957
V37	832	145	44	16	817	1,000	1957
V38	838	152	--	16	823	1,000	1959
V40	842	148	42	16	812	1,000	1962
V41	840	147	44	16	812	1,000	1962
V42	833	150	--	16	--	1,000	1968
V43	835	148	26	16	827	1,000	1976
V51	835	148	95	16	--	1,400	1984
V52	825	149	105	16	--	1,400	1984
V53	825	154	105	16	--	1,400	1984

Municipal supply wells for the city of Battle Creek range in depth from 110 to 157.5 ft (table 2). Sixteen of these wells consistently produce about 1,000 gal/min. Average pumpage from the entire Verona well field was 5,000 gal/min during 1970-81; 8,300 gal/min during 1982; and 6,650 gal/min during 1983. Pumpage was 12,000 to 14,000 gal/min during periods of peak production.

Contamination of Ground Water

In 1981, VOCs were detected in water from eight municipal wells and 74 private wells in the Verona Valley subdivision. Results of subsequent sampling during the next 2 years indicated that 15 of 30 city wells produced water with detectable concentrations of VOCs. In autumn 1983, the USEPA began an investigation of the extent and potential sources of contamination. The investigation identified a contaminant plume in the well field in which the concentrations of VOCs were as high as 100 µg/L. On the basis of analyses of ground-water samples during a 2-year period, the investigators concluded that the plume was moving north and northwest. The investigation also revealed three sources of contamination: Thomas Solvent Raymond Road facility (TSRR), Thomas Solvent Annex (TS Annex), and Grand Trunk Western Railroad Car Department Paint Shop (GTWRR) (CH2M-Hill, 1990b).

In 1984, as part of initial remedial action, six municipal wells (V22 and V24–V28) were converted to purge wells to prevent further migration of the contaminant plume toward production wells. In 1986, nine purge wells were installed and began operation at the TSRR site (fig. 2). Soil-vapor extraction commenced at this site in 1987.

GEOLOGY

Stratigraphic units underlying Verona well field, listed in ascending order, are the Coldwater Shale, the Marshall Sandstone, and glacial and alluvial deposits. The Coldwater Shale and Marshall Sandstone are of Mississippian age; glacial deposits are of Pleistocene age, and alluvial deposits are of Holocene age. The areal distribution of glacial and alluvial deposits near Battle Creek is shown in figure 3. Detailed descriptions of the geology of the area are in Grannemann and Twenter (1985).

The Coldwater Shale does not crop out in the study area, but it underlies and, in some areas, grades upward into basal beds of the Marshall Sandstone. Thickness of the Coldwater Shale ranges from 500 to 1,100 ft (Newcombe, 1933; Monnett, 1948; Cohee, 1965).

Marshall Sandstone

The Marshall Sandstone, which conformably overlies the Coldwater Shale (Harrell and others, 1990), consists of a lower unit and an upper unit. A geohydrologic column of the Marshall Sandstone underlying Verona well field area is shown in figure 4. Lithology of the Marshall Sandstone and glacial deposits penetrated by wells installed since 1983 by the USGS is given in table 3.

Lithology and Thickness

The lower unit of the Marshall Sandstone, informally known as the lower part of the Marshall Sandstone, in the Battle Creek area ranges from 5 to 50 ft in thickness and is a very fine to fine-grained silty sandstone. The upper unit of the sandstone, informally known as the upper part of the Marshall Sandstone, ranges in thickness from 0 to 160 ft and is a fine- to medium-grained sandstone interbedded with siltstone and shale. The Marshall Sandstone crops out in a small area at the east foot of the dam on the Battle Creek River near Emmett Street (fig. 2).

Major lithologic units of the Marshall Sandstone shown in figure 4 can be identified on gamma logs for wells; logs for three wells are shown in figure 5. The principal marker beds in the geohydrologic column are the upper siltstone and shale (Grannemann and Twenter, 1985).

Description of Fractures

Fractures in wells E37D, E38D, and E39D, which are about 3,000 ft from water-supply wells in the Verona well field, were studied to determine whether an extensive fracture system that may affect ground-water flow underlies the Battle Creek area. More specifically, this study was done to characterize hydraulic conductivity and secondary permeability and to determine if fractures are related to stratigraphy and (or) structural features in the Marshall Sandstone.

A suite of borehole geophysical logs of wells was used to determine if fractures are present in the Marshall Sandstone underlying Verona well field area. Acoustic televiewer, caliper, natural-gamma, and single-point-resistance logs were used to characterize fractures and lithology. Thermal-pulse-flowmeter (TPFM), single-point-resistance, and temperature logs were used to define fracture flow.

Fractures that intersect the borehole were identified on acoustic televiewer logs. Twelve fracture zones, within sections labeled A through L (fig. 6), were identified on televiewer logs from wells E37D, E38D, and E39D. The fracture zones are at approximately the same altitude in each well (fig. 6). The caliper log, which provides a continuous record of borehole diameter, consistently shows an increase in diameter at these fracture zones (fig. 7).

Relations of Lithology and Fractures

Drillers' lithologic logs from wells E37D, E38D, and E39D (table 3) indicate that fracture zones seem to be associated with the sandstone units. Natural-gamma and single-point-resistance logs from the three wells were used to further examine the relationship between lithology and fractures. The gamma response in logs from all three wells is similar. The gamma response among the 12 fracture zones (fig. 7) ranges from an increased response in zones A, C, G, and J to a decreased response in zones I and K to a variable response in zone L to a relatively constant response in zones B, D, E, F, H. Gamma logs respond to radioactive decay of potassium, uranium, and thorium. Fine-grained detrital sediments, siltstone, and shale that contain abundant clay tend to contain more radiogenic minerals than the quartz sand or carbonate rocks. Therefore the gamma log from zones A, C, G, and J may be responding to a lithologic change from sandstone to siltstone, to clay lining the fractures, or to both.

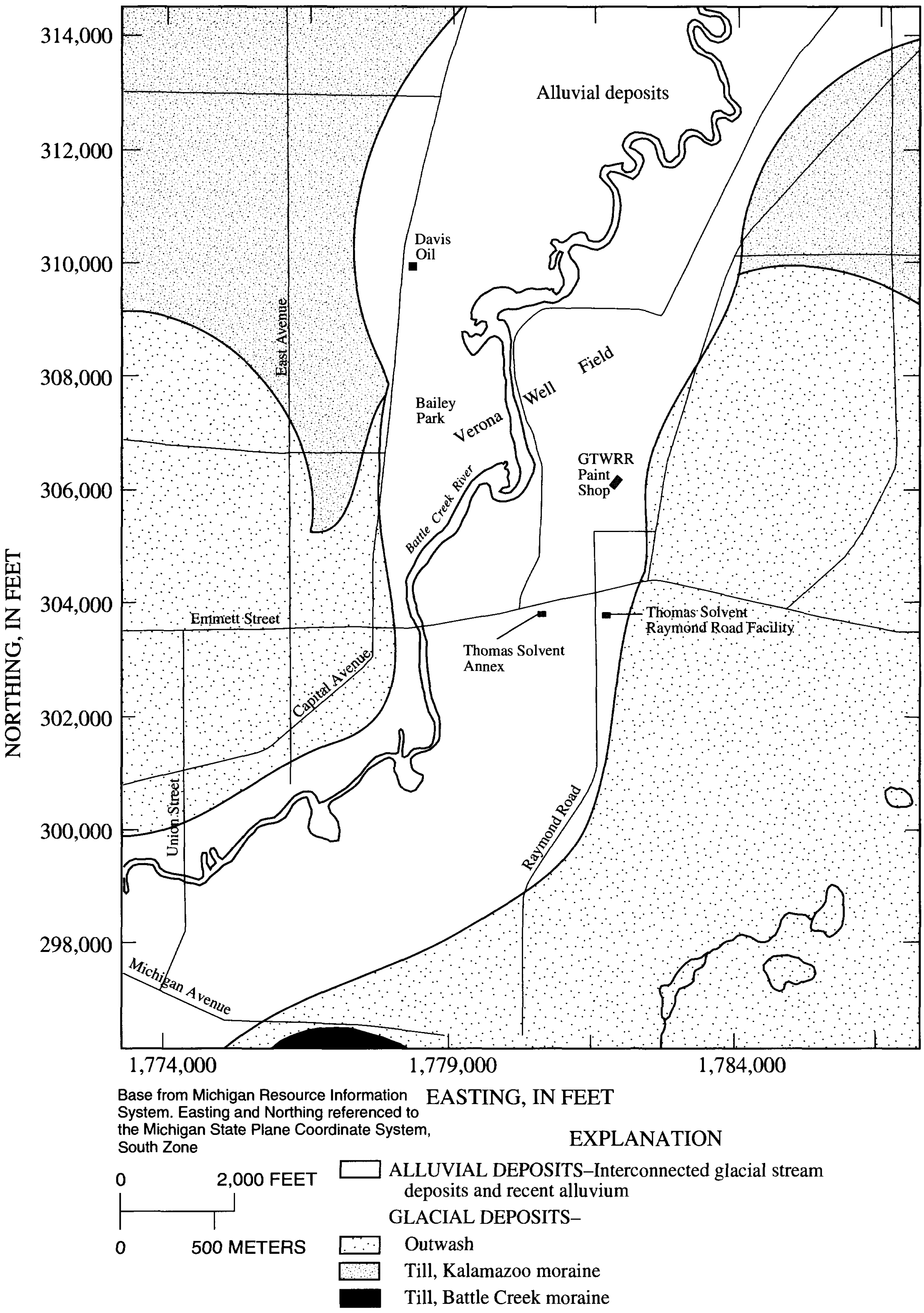


Figure 3. Areal distribution of glacial and alluvial deposits near Battle Creek, Michigan (from Grannemann and Twenter, 1985).

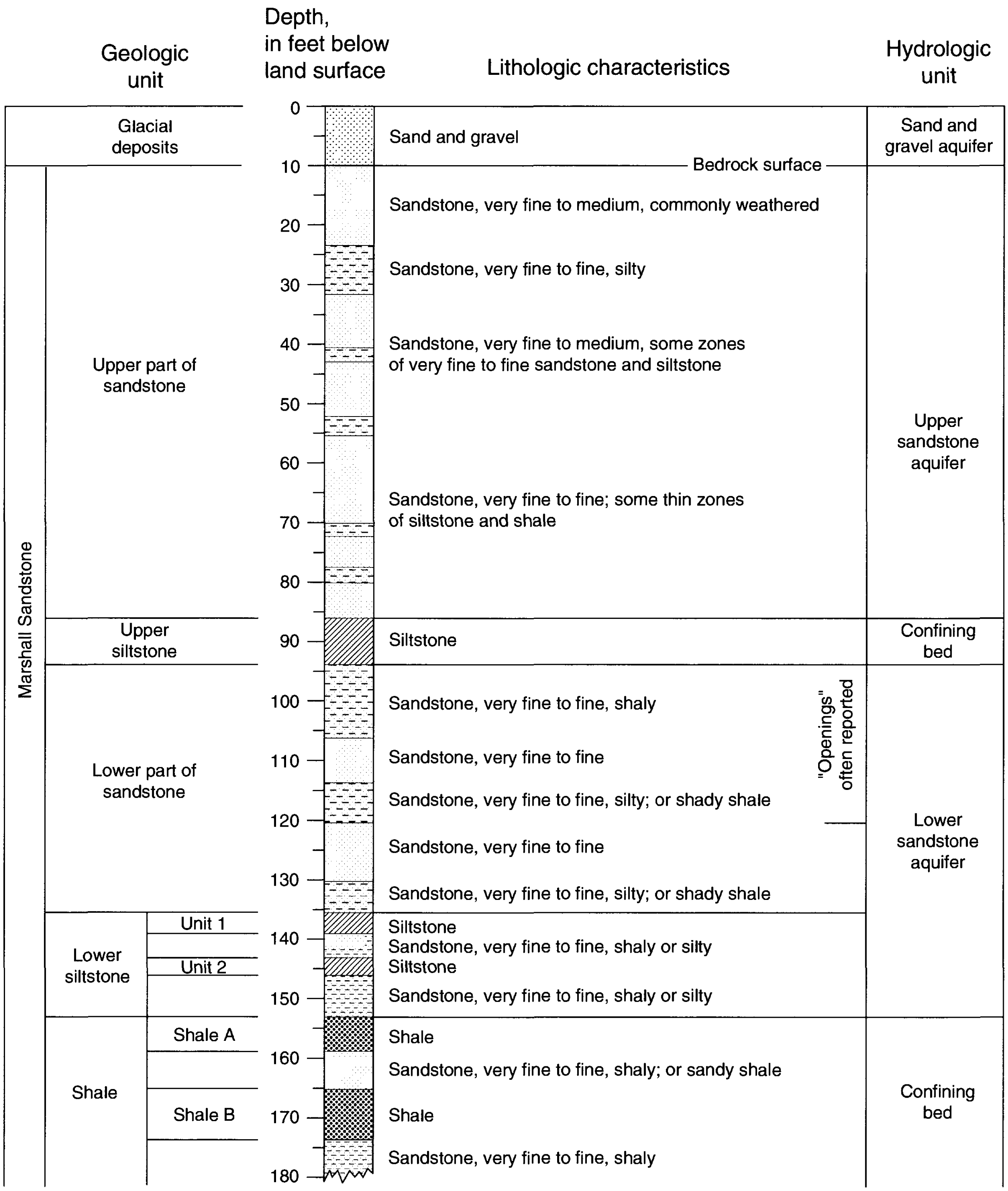


Figure 4. Type geohydrologic column of Marshall Sandstone in Verona well field area, Battle Creek, Michigan (from Grannemann and Twenter, 1985).

Table 3. Lithologic description of rocks and soils in boreholes drilled by the U.S. Geological Survey since 1983, Battle Creek, Michigan

Description of material	Depth (feet) From	Depth (feet) To
Well E37D		
Glacial deposits		
Sand (very fine to fine, rounded, ochre to tan) and silt (tan to ochre) with traces of gravel very fine, rounded, tan)	0	5
Marshall Sandstone		
Sandstone (very fine to fine, rounded, gray)	5	59
Siltstone (gray)	59	60
Sandstone (very fine to fine, rounded, gray)	60	79
Siltstone (light gray) fractured zone	79	81
Sandstone (very fine to fine, rounded, gray)	81	99
Fractured zone with oxidized material	99	101
Sandstone (very fine to fine, rounded, gray)	101	119
Shale or siltstone (dark gray)	119	120
Sandstone (very fine, rounded, gray)	120	127
Siltstone (gray)	127	130
Sandstone (very fine, rounded, gray)	130	147
Siltstone (gray)	147	150
Sandstone (very fine, rounded, gray)	150	158
Siltstone (gray)	158	162
Well E38D		
Glacial deposits		
Sand (very fine to fine, rounded, ochre to tan) and silt (ochre to tan)	0	8
Marshall Sandstone		
Sandstone (very fine to fine, rounded, gray)	8	18
Shale (gray to black)	18	20
Siltstone (gray)	20	22
Sandstone (very fine to fine, rounded, gray)	22	42
Sandstone (very fine, rounded, gray) and siltstone (gray) and shale (gray), layered	42	56
Sandstone (very fine to fine, rounded, gray)	56	120
Shale and siltstone (gray)	120	121
Sandstone (very fine to fine, rounded, gray)	121	125
Sandstone (very fine, rounded, gray) and siltstone (gray), possibly some thin limestone	125	148
Chert and limestone	148	149
Sandstone (very fine, rounded, gray) and siltstone (gray) and shale (gray-black), layered	149	157
Shale (gray) and siltstone (gray)	157	162
Well E39D		
Glacial deposits		
Sand (medium to coarse, rounded, tan) and gravel (medium, subrounded, tan)	0	8
Marshall Sandstone		
Sandstone (very fine to fine, rounded, gray)	8	18
Shale (black) or clay	18	19
Sandstone (very fine to fine, rounded, gray) and siltstone (gray)	18	23
Sandstone (very fine to fine, rounded, gray)	23	40
Siltstone (light gray to tan), shale, or clay	40	41
Sandstone (very fine to fine, rounded, gray)	41	60
Siltstone (light gray to tan), shale, or clay	60	62
Sandstone (very fine to fine, rounded, gray)	62	70
Siltstone (light gray) or shale (gray) or clay filling (light gray to tan)	70	71
No record	71	100
Fractured zone	100	102
Sandstone (very fine to fine, rounded, gray)	102	110
Oxidized zone with chert and sandstone (very fine to fine, rounded, red)	110	111
Sandstone (very fine to fine, rounded, gray)	111	120
Shale (dark gray)	120	122
Sandstone (very fine, rounded, gray)	122	130
Siltstone (light gray)	130	132
Well E40I		
Glacial deposits		
Marshall Sandstone		
Sandstone (very fine to fine, rounded, gray)	41	100
Well E41D		
Glacial deposits		
Sand (coarse, subangular, tan to gray) and gravel (subrounded, tan to gray)	0	57
Sand (coarse to very coarse, subangular, tan to gray) and gravel (coarser, subangular to rounded, tan to gray)	57	65
Till silt (gray) and sand	65	96
Marshall Sandstone		
Weathered bedrock	96	103
Sandstone (very fine to fine, rounded, gray)	103	112
Sandstone (very fine to fine, rounded, yellow)	112	115
Fracture zone	115	150
Sandstone (very fine to fine, rounded, gray)	150	175
Shale (dark gray)	175	182

Table 3. Lithologic description of rocks and soils in boreholes drilled by the U.S. Geological Survey since 1983, Battle Creek, Michigan—*Continued*

Description of material	Depth (feet) From	Depth (feet) To
Well E42D		
Glacial deposits		
Sand (coarse to very coarse, subangular, tan to gray) and gravel (coarser, subangular to subrounded, tan to gray)	0 -	66
Till, silt (gray) and sand	66 -	96
Marshall Sandstone		
Weathered bedrock	96 -	102
Sandstone (very fine to fine, rounded, gray)	102 -	175
Very hard drilling, possible chert nodule	175	--
Well E43D		
Glacial deposits		
Sand (coarse, subrounded, tan to gray) and gravel (coarse, subrounded, tan to gray)	0 -	57
Sand (coarse to very coarse, subrounded, tan to gray) and gravel (coarse, subangular to subrounded, tan to gray)	57 -	65
Silt (gray) and sand (fine to medium)	65 -	96
Marshall Sandstone		
Weathered sandstone (fine to medium, rounded, gray-brown)	96 -	103
Sandstone (very fine to fine, rounded, gray)	103 -	170
Siltstone (gray)	170 -	175
Sandstone (very fine, rounded, gray) and siltstone (gray)	175 -	177
Shale (dark gray)	177 -	190
Well E44D		
Peat and muck (black)	0 -	5
Glacial deposits		
Sand (medium to coarse, angular to subangular, tan) and gravel (fine to medium, angular)	5 -	65
Well E44D—*Continued*		
Glacial deposits—*Continued*		
Sand (medium to very coarse, subrounded) and gravel (coarse, subrounded)	65 -	81
Clay (gray) and silt (gray) and sand (very fine, rounded, tan) till	81 -	100
Boulder, sand and gravel	100 -	102
Clay (gray) and silt (gray) and sand (very fine, rounded, tan)	102 -	111
Marshall Sandstone		
Sandstone (very fine to fine, rounded, gray)	111 -	114
Sandstone (very fine, rounded, gray)	114 -	120
Siltstone (gray) and shale (gray), layered	120 -	143
Well E45D		
Peat and muck (black)	0 -	5
Glacial deposits		
Sand (medium to coarse) and gravel	5 -	42
Sand and gravel	42 -	60
Till (sandy, silty clay)	60 -	67
Marshall Sandstone		
Weathered rock with some clay	67 -	80
Sandstone (very fine to fine, rounded, gray)	80 -	97
Siltstone (gray)	97 -	101
Sandstone (very fine, rounded, gray)	101 -	105
Siltstone (gray)	105 -	110
Sandstone (very fine, rounded, gray)	110 -	112
Siltstone (gray)	112 -	115
Shale (gray)	115 -	122

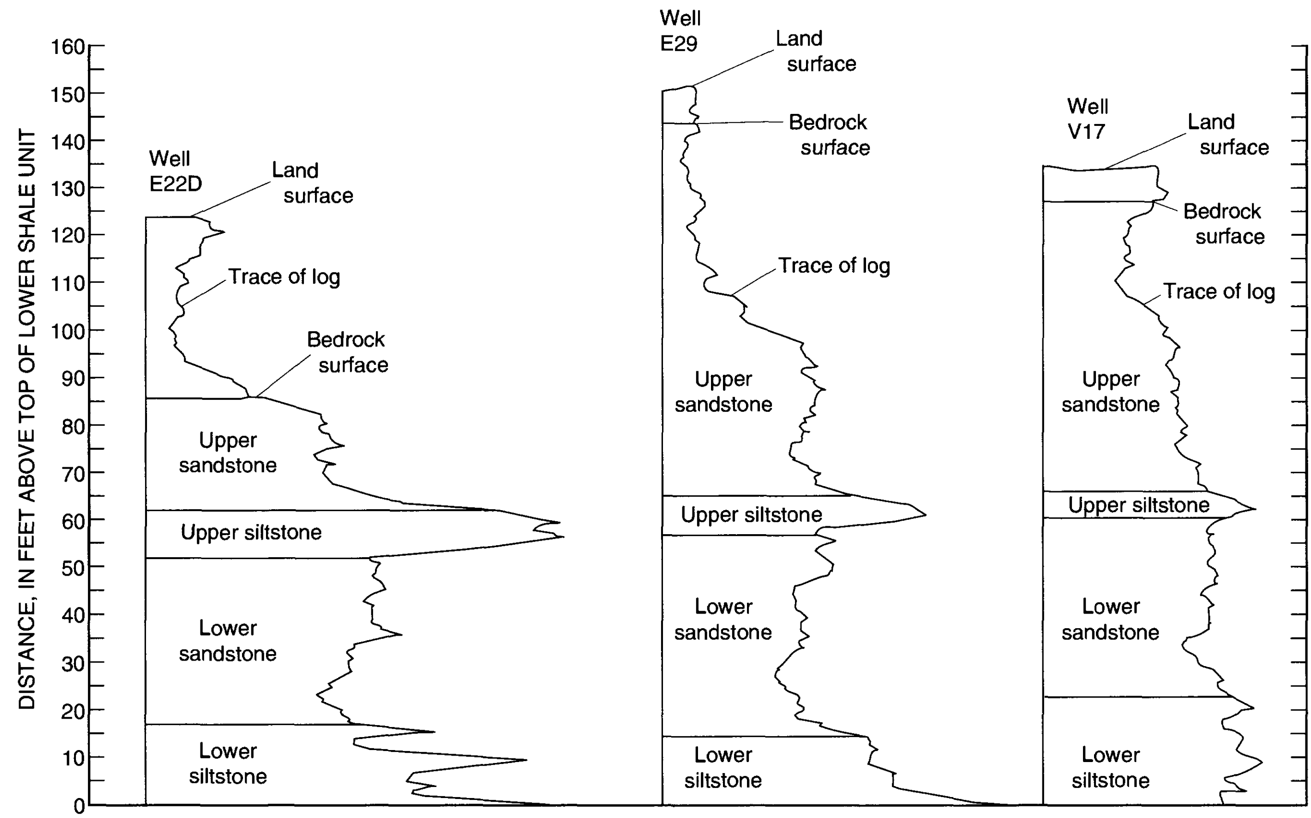


Figure 5. Units of Marshall Sandstone identified on natural-gamma logs of wells E22D, E29, and V17, Verona well field area, Battle Creek, Michigan (from Grannemann and Twenter, 1985).

Shifted single-point resistance logs show a decrease at all fracture zones except A and J (fig. 6). Single-point-resistance logs measure the electrical resistance of any geologic medium. Electrical resistance is affected by composition of the rock and any fluid in the rock. A shifted single-point resistance log shows only changes that can be attributed to changes in the resistivity of the rock. Either an increase in the gamma response or a decrease in the resistivity response indicates a possible increase in the clay mineral content of the rock because of the more radioactive nature of clay minerals as well as their more conductive electrical properties. Therefore, the deposits at zones A and J may be siltstone or shale units or areas of clay-lined fractures. Fracture zones E, G, and J are associated with siltstone or shale units identified in the driller's log (table 3). Fracture zones A, B, C, D, F, H, and I do not appear to be associated with lithologic changes noted on the driller's log. Fracture zones A and C may show an increased gamma response because of clay lining of fractures. As explained later under the section "Fractures and Ground-Water Flow," this conclusion for fracture zones A and C is consistent with a limited amount or lack of fluid flow.

Glacial and Alluvial Deposits

Unconsolidated glacial and alluvial materials overlie the Marshall Sandstone in most of the study area. These materials were deposited by glacial ice and glacial meltwater streams more than 12,000 years ago or by streams of more recent age. The areal distribution of these materials which consist of till, outwash, and channel deposits is shown in figure 3.

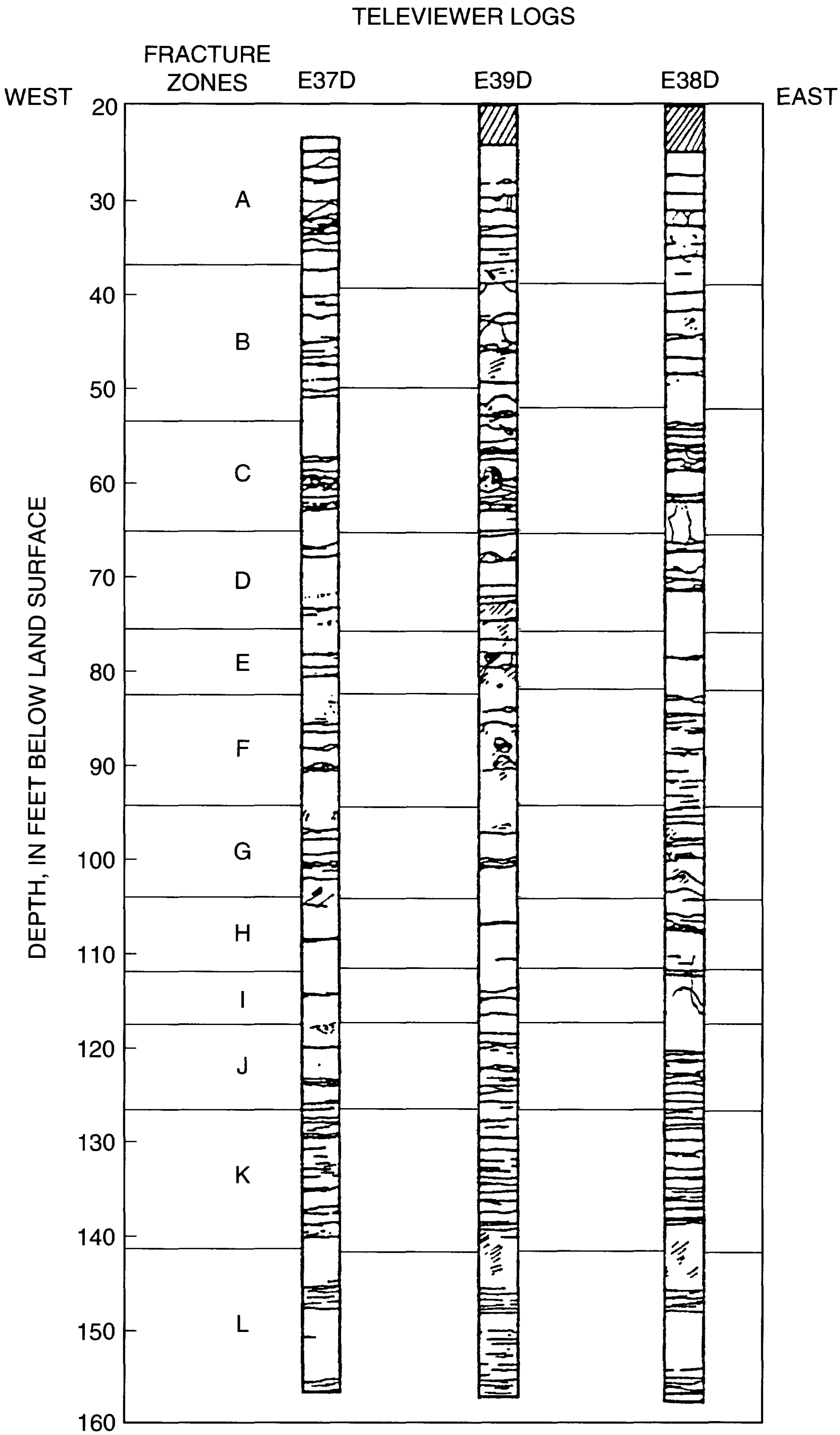


Figure 6. Acoustic-televiewer logs for wells E37D, E38D, and E39D showing fracture zones A through L, Verona well field area, Battle Creek, Michigan (from Paillet, 1991).

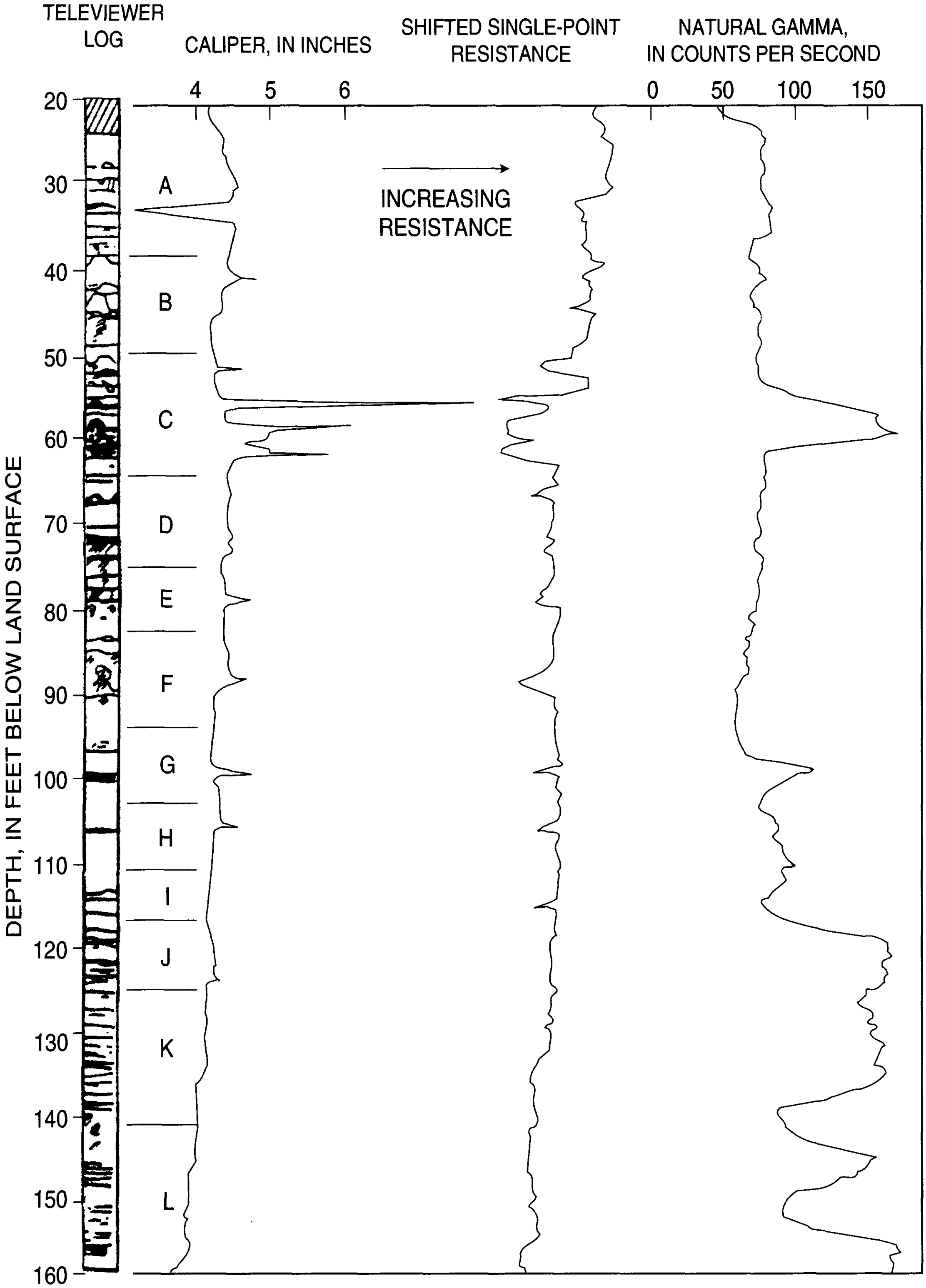


Figure 7. Acoustic-televiewer, caliper, single-point-resistance, and natural-gamma logs for well E39D, Verona well field area, Battle Creek, Michigan (from Paillet, 1991).

HYDROLOGY

Annual precipitation in the Battle Creek area averages 29 in. (National Oceanic and Atmospheric Administration, 1989). Of this, about one-third recharges the aquifer system; the remainder flows to streams and lakes or is lost from the area by evapotranspiration (Grannemann and Twenter, 1985). Two major rivers, the Battle Creek and the Kalamazoo Rivers, flow through the study area; these rivers have numerous tributaries. Numerous small lakes also are present.

Surface Water

Since 1934, a gaging station on Battle Creek River at the dam near Emmett Street (fig. 2) has been operated by the USGS. Average annual streamflow at the station is 204 ft^3/s. Daily mean streamflow during October 1989–September 1990 ranged from 67 ft^3/s on September 3 and 4 to 1,670 ft^3/s on March 13; monthly mean streamflow during this 12-month period ranged from 96.4 ft^3/s in August to 578 ft^3/s in March (Blumer and others, 1991).

Ground Water

Ground water is the source of municipal, commercial, and industrial supplies in the Battle Creek area. The Marshall Sandstone is the principal aquifer; water from glacial deposits also is tapped for domestic use.

Recharge

Recharge from precipitation in the drainage area between Bellevue and Battle Creek has been estimated at 12 in/yr (Grannemann and Twenter, 1985). This value includes loss from the Battle Creek River to ground water at Verona well field, estimated at 2.5 ft^3/s. A recharge of 8 in/yr from precipitation was estimated for the drainage area of Wanadoga Creek, about 1.5 mi north of Verona well field.

Water Levels and Potentiometric Surface

Water levels measured in observation wells completed in the glacial and alluvial aquifer and Marshall Sandstone aquifer in August 1988 (table 4) were used in combination with lake and stream elevations to prepare potentiometric-surface maps for the study area. Most water levels in wells used to prepare the potentiometric-surface maps reflect water-table conditions even though some wells are cased into the upper sandstone aquifer (fig. 4). A potentiometric-surface map for the glacial and alluvial aquifer is shown in figure 8; a similar map for the Verona well field area is shown in figure 9. In most of the study area, ground water flows toward and discharges to Battle Creek and Kalamazoo Rivers and their tributaries or is withdrawn by wells. In some areas, particularly near Verona well field, aquifers are recharged by streams (Grannemann and Twenter, 1985).

Hydraulic Properties of Aquifers

Porosity and permeability are the primary factors affecting movement and storage of water in aquifers. Porosity and permeability are typically enhanced by fractures, such as those present in the Marshall Sandstone. Hydraulic properties of the aquifers in the Battle Creek area have been determined by use of aquifer tests and grain-size analyses in previous studies and during this study.

Data from Previous Studies

Previous studies have shown that aquifers underlying the Verona well field have higher transmissivities than those in peripheral areas. This may be due to the large diameters of municipal water-supply wells, which allow for more effective development of the aquifer than is possible with small domestic wells. Most high-production capacities of wells open to the sandstone aquifers seem to be related to fractures. Transmissivities for the lower part of the Marshall Sandstone range from 3,000 to 27,000 ft^2/d based on a constant hydraulic conductivity of 150 ft/d and thicknesses ranging from 5 to 50 ft. Transmissivities for the upper part of the Marshall Sandstone range from 0 to 15,000 ft^2/d based on a constant hydraulic conductivity of 550 ft/d and thicknesses ranging from 0 to 100 ft (Grannemann and Twenter, 1985).

Hydraulic conductivities of glacial deposits were estimated by Grannemann and Twenter (1985). These conductivities were based on grain-size analysis and conductivities of similar deposits in Michigan. A horizontal hydraulic conductivity of 110 ft/d was estimated for channel deposits, 70 ft/d for outwash, and 15 ft/d for till.

Table 4. Water levels in and characteristics of observation wells used for model calibration, Battle Creek, Michigan, August 23, 1988

[Well: D, deep; I, intermediate; S, shallow. See figure 2 for location of wells. --, not measured or not recorded; <, actual value is less than value shown]

Well	Well depth (feet below land surface)	Depth to bottom of casing (feet below land surface)	Altitude of measuring point (feet above sea level)	Distance of measuring point above land surface (feet)	Altitude of bedrock (feet above sea level)	Altitude of potentiometric surface (feet above sea level)
Wells Installed by U.S. Geological Survey						
E1	57.0	[1]51.7	865.42	2.3	815	826.26
E2	28.5	26.6	829.66	.9	802	829.66
E3	27.5	23.4	830.73	3.6	800	822.28
E4	81.0	[1]70.0	883.16	2.0	803	823.27
E6	60.0	44.7	875.33	.3	828	822.24
E8	31.0	[1]28.9	847.89	2.6	<814	823.48
E9	17.0	15.1	831.48	.9	816	821.89
E10	35.0	[1]30.0	835.92	2.0	824	818.14
E13	54.0	53.2	856.94	3.8	801	817.37
E14	70.0	[1]62.8	878.79	2.2	832	818.37
E17	32.0	[1]27.8	835.84	1.7	830	816.65
E18	24.0	17.4	848.92	3.6	834	830.52
E19	34.0	24.6	831.86	1.4	819	821.94
E20	21.0	13.5	830.44	2.5	820	821.54
E21	25.0	16.6	831.41	1.4	815	822.91
E22S	14.0	[1]10.1	840.21	3.4	--	824.27
E23	155.0	77.4	849.04	3.6	805	824.53
E24	163.0	98.0	890.42	2.5	821	849.03
E28S	10.0	[1]6.8	840.98	3.2	--	828.11
E32	60.0	36.4	844.39	1.6	818	816.70
E33S	18.0	[1]15.3	845.53	2.7	--	845.53
E35S	22.0	[1]17.1	833.80	2.9	--	822.16
E35D	81.0	49.5	833.36	2.5	795	820.43
Wells Installed by Ecology and Environment, Inc.						
T1	39.0	28.0	845.90	--	815.90	822.41
T2	39.0	25.0	838.38	--	816.38	823.12
T3	39.0	35.0	833.43	--	798.43	823.46
T4	39.0	35.0	835.47	--	800.47	824.68
T5	39.0	25.0	843.28	--	818.28	825.77
T6	39.0	39.0	846.45	--	807.45	825.75
T7	39.0	30.0	845.84	--	820.84	821.91
T8	39.0	25.0	851.78	--	826.78	828.18
T9	39.0	15.0	855.08	--	841.58	831.95
T10	39.0	35.0	841.53	--	<802.53	820.76
T11	39.0	30.0	839.39	--	<800.39	819.58
T12	39.0	38.5	831.87	--	<792.87	817.72
T13	39.0	30.0	829.62	--	<790.62	818.32

Table 4. Water levels in and characteristics of observation wells used for model calibration, Battle Creek, Michigan, August 23, 1988—*Continued*

Well	Well depth (feet below land surface)	Depth to bottom of casing (feet below land surface)	Altitude of measuring point (feet ebove see level)	Distance of measuring point above lend surface (feet)	Altitude of bedrock (feet above sea level)	Altitude of potentiometric surface (feet above sea level)
Wells Installed by Environmental Data, Inc.						
G1B	37.0	33.0	--	--	--	817.49
G1C	110.0	87.0	832.10	--	748.00	816.68
G2	22.0	18.0	--	--	--	818.07
G3A	28.0	24.0	--	--	--	817.33
G5	35.9	32.0	--	--	--	816.91
G5A	140.0	95.2	825.60	--	732.00	817.71
G7	38.1	34.2	--	--	--	815.82
G7A	120.0	74.5	826.50	--	772.00	814.96
G8	23.5	19.6	--	--	--	818.50
G9	14.9	11.0	--	--	--	825.69
G9A	45.0	36.9	836.80	--	825.00	826.63
Wells Installed by Warzyn Engineering, Inc.						
B1	25.9	--	--	--	--	826.63
B9	26.3	--	--	--	--	825.66
B17	36.0	--	--	--	--	828.17
Wells Installed by Michigan Department of Natural Resources						
DNR1	46.0	--	--	--	--	844.48
DNR2	58.0	--	--	--	--	839.75
Wells Installed by Warzyn Engineering, Inc.						
W1I	70.0	--	--	--	--	816.44
W2S	40.0	--	--	--	--	818.08
W2I	70.0	--	--	--	--	818.05
W3S	40.0	--	--	--	--	814.72
W4S	40.0	--	--	--	--	821.16
W4I	70.0	--	--	--	--	821.05
W4D	140.0	--	--	--	--	820.99
W5S	40.0	--	--	--	--	822.81
W6I	70.0	--	--	--	--	822.72
W6D	140.0	--	--	--	--	822.86
W7S	40.0	--	--	--	--	824.54
W8S	40.0	--	--	--	--	823.08
W8I	70.0	--	--	--	--	822.81
W8D	140.0	--	--	--	--	823.55
W9S	40.0	--	--	--	--	826.08
W11D	140.0	--	--	--	--	826.59
W16I	70.0	--	--	--	--	825.98

[1]Screened well.

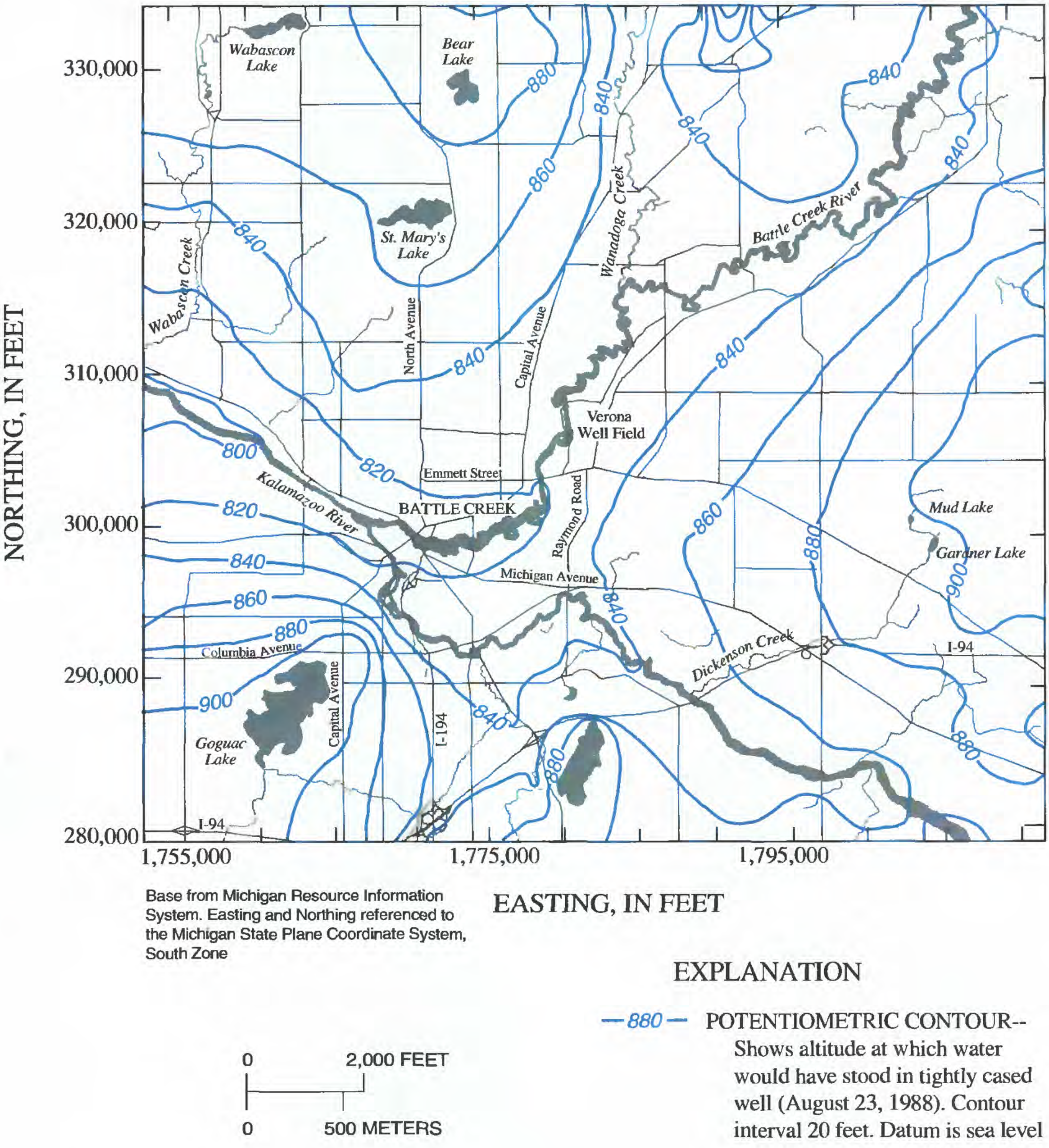


Figure 8. Generalized potentiometric surface of the glacial and alluvial aquifer near Battle Creek, Michigan, August 23, 1988.

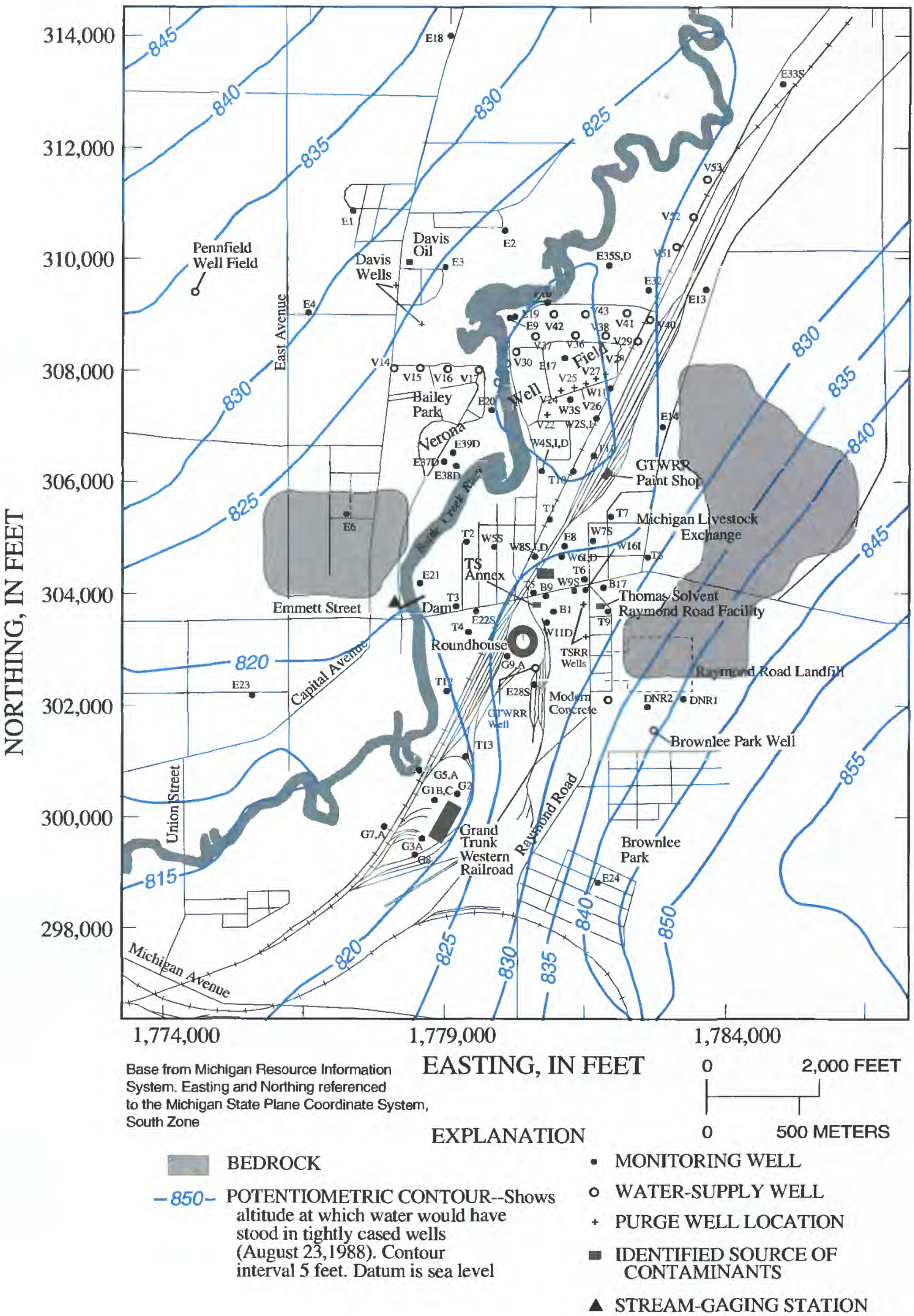


Figure 9. Localized potentiometric surface of the glacial and alluvial aquifer near Battle Creek, Michigan, August 23, 1988.

Aquifer Tests Conducted During This Study

Two aquifer tests were done by the USGS to determine hydraulic properties of the Marshall Sandstone in the study area. Wells E37D, E38D, and E39D (located within the Verona well field) were used for one test, and E41D, E42D, and E43D (located northeast of Verona well field) were used for the other (table 5). Because both sets of wells are open to the upper and lower parts of the Marshall Sandstone, the hydraulic characteristics estimated from results of the aquifer tests average the contributions of the combined parts of the Marshall. A graph of measured drawdown and time in observation well E39D during the aquifer test in which well E38D was pumped is shown in figure 10. A Theis type curve (Theis, 1935) is matched to the measured data. Hydraulic conductivities and transmissivities estimated for the aquifer test in which well E39D was pumped are nearly 10 times higher than those estimated for the aquifer test in which well E42D was pumped. These results indicate that hydraulic conductivity and transmissivity are higher within the Verona well field than to the northeast.

Table 5. Results of aquifer tests, Verona well field, Battle Creek, Michigan

[All wells are open to the upper and lower parts of the Marshall Sandstone]

Well	Transmissivity (feet squared per day)	Thickness (feet)	Hydraulic conductivity (feet per day)	Storage coefficient
		Pumped well, E38D		
E37D	64,400	133	490	7×10^{-4}
E39D	56,200	133	420	1×10^{-3}
		Pumped well, E42D		
E41D	4,200	79	53	3×10^{-4}
E43D	4,200	75	56	4×10^{-4}

Fractures and Ground-Water Flow

Ground water flows preferentially along fractures in the Marshall Sandstone. This interpretation is based on examination of geophysical logs of wells E37D, E38D, and E39D.

For this study, a thermal-pulse flowmeter was used by F.L. Paillet (USGS borehole geophysical unit) to record logs under static and pumping conditions.

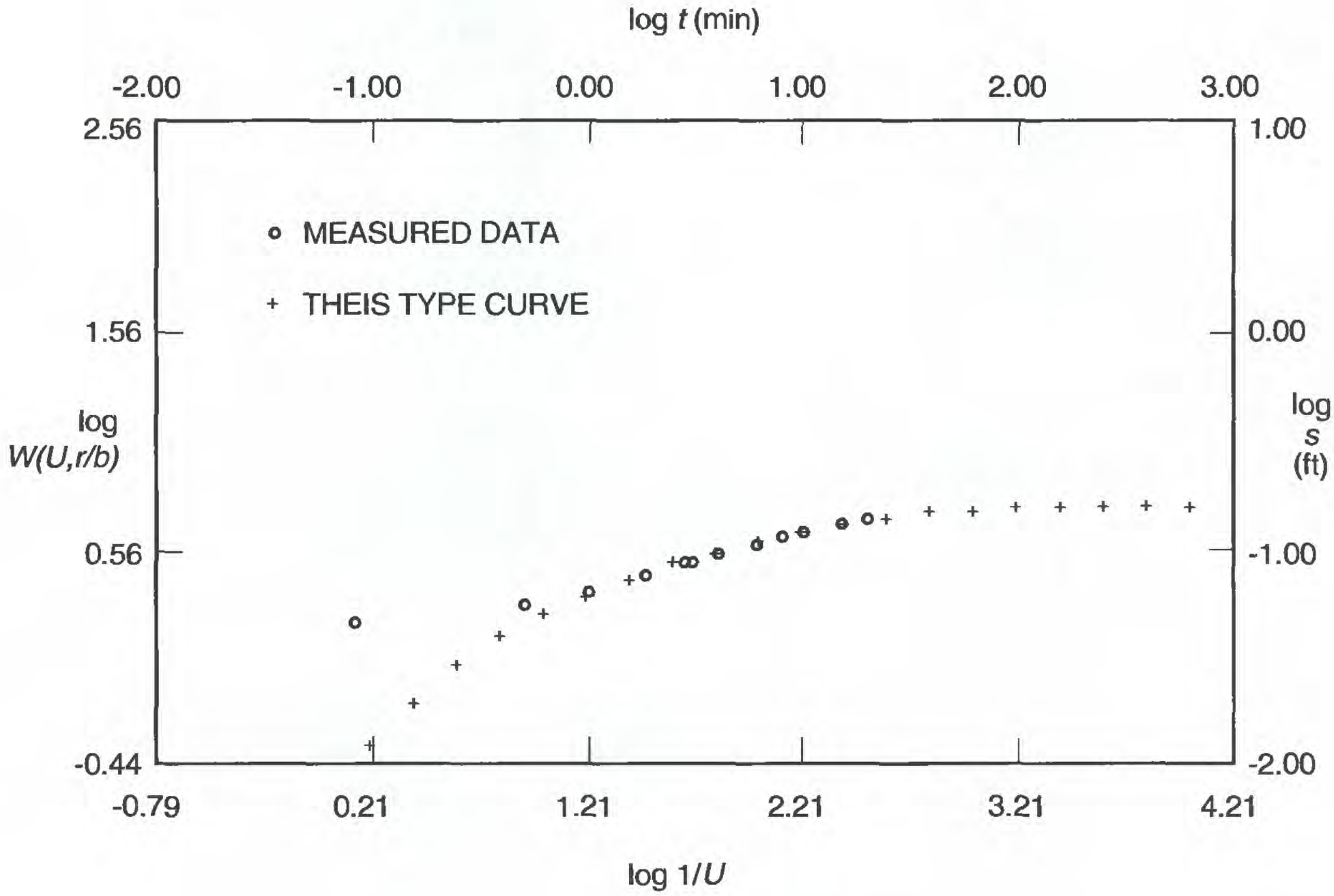


Figure 10. Drawdown in well E39D during aquifer test and Theis type curve, Verona well field area, Battle Creek, Michigan.

Flowmeter logs measure vertical flow of ground water within the borehole. Lateral flow also affects the flowmeter log (Keys, 1988). Under static conditions, flowmeter logs were recorded in wells E37D, E38D, and E39D. Under pumping conditions, well E38D was pumped and flowmeter logs were recorded in wells E37D and E39D. Paillet's analysis (1991) follows:

> The temperature and single-point resistance logs obtained in the three observation boreholes (wells E37D, E38D, and E39D) indicated that pumping in the municipal well field (Verona well field) produced hydraulic head differences between individual subhorizontal openings (indicated in figure 6 in this report). These hydraulic-head differences produced flows which resulted in a variation of the salinity of borehole fluid indicated by the resistance log, and isothermal intervals indicated on the temperature log. For example, the resistance log indicates an abrupt change in borehole fluid salinity in the interval from 110 to 115 ft in depth in borehole E39D (fig. 11A, in this report). The temperature log for this borehole is isothermal over the interval from 115 to 70 ft, and shows an unexpected decrease in temperature with depth below 120 ft. If flowmeter logs were not available, the temperature and resistance logs alone would indicate major inflow near 70 ft and major outflow near 115 ft, with other small inflows and outflows indicated by the irregular temperature log at other depths along the borehole.
>
> TPFM (thermal-pulse flowmeter) measurements made in borehole E39D before pumping from one of the other observation boreholes confirm the suspected pattern of flow (fig. 11B, in this report). However, the details of the flow distribution are somewhat more complicated than inferred from the character of the resistance and temperature logs alone. The TPFM data indicate inflow at several depths, and both above and below the major contact in borehole fluid salinity. The TPFM did not give repeatable flow measurements in the interval between 55 and 80 ft in depth, so the increase in flow between reliable measurements at 45 and 92 ft in depth has been lumped into a single increase in borehole flow near the depth associated with the top of the isothermal interval on the temperature log. This instability in TPFM readings in the interval from 50 to 80 ft was later identified as the result of thermal convection in the borehole. The convection was driven by the entrance of relatively warm water between 60 and 90 ft in depth. Although the hydraulic-head differences between zones caused the average flow in the borehole to flow downward from these depths, the buoyancy of the warm water entering the borehole apparently produced convective overturning superimposed on this flow regime. This convective flow is assumed to have caused the observed instability in TPFM readings in the interval where convective flow was occurring. This explanation is supported by the stability of TPFM measurements in the same interval when the net downward flow was reversed by pumping from one of the adjacent observation boreholes.
>
> The changes in vertical flow induced in borehole E39D by pumping at about 80 gal/min from borehole E38D are also indicated in figure 11*B*. The changes in vertical flow associated with this local pumping were almost instantaneous, so that transients were not measured. The local pumping reversed the flow in the upper part of the borehole, although the major inflow still occurred from fracture zone D. The flow reversal is attributed to the effects of a hydraulically conductive connection in the upper levels of the formation that transmitted the decreases in hydraulic-head induced by pumping in borehole E38D to borehole E39D. Closely spaced, repeated TPFM measurements indicated that a single, well defined fracture set in zone D is the source of the inflow. The major cross-connection between boreholes E39D and E38D is provided by fractures or solution openings in zones A and B. The local pumping apparently transmitted a lower hydraulic head to borehole E39D, resulting in reduction or reversal of downward flow, and accentuation of upward flow in the deeper zone.
>
> The significant hydraulic-head differences that occur at several thousand feet from the municipal well field indicate that the subhorizontal solution openings or fractures project over large lateral distances, and are poorly connected to other such horizontal permeability zones. The changes in vertical flows induced in borehole E39D and E37D during local pumping from borehole E38D indicates that at least some of the other solution openings indicated by the BHTV (acoustic borehole televiewer) logs (fig. 6) are as permeable as those that appear hydraulically connected to the municipal well field. However, figure 6 indicates the significant differences in appearance of individual solution openings over the relatively small distances separating the observation boreholes. The secondary permeability system model that seems best suited to this situation is one of individual solution openings that are locally variable in hydraulic aperture and probably somewhat interconnected within beds from 5 to 20 ft thick. At the same time, these locally interconnected and variable flow paths appear to remain isolated from each other within lithologic sub-units over lateral distances of several thousand feet. The data also indicate that the deeper openings are more continuous than the other apparently larger openings in the overlying sandstone, because the deeper fractures near the contact between sandstones and shale transmit the effects of the well field pumping to the observation boreholes even though the production wells are screened in the overlying sandstones.

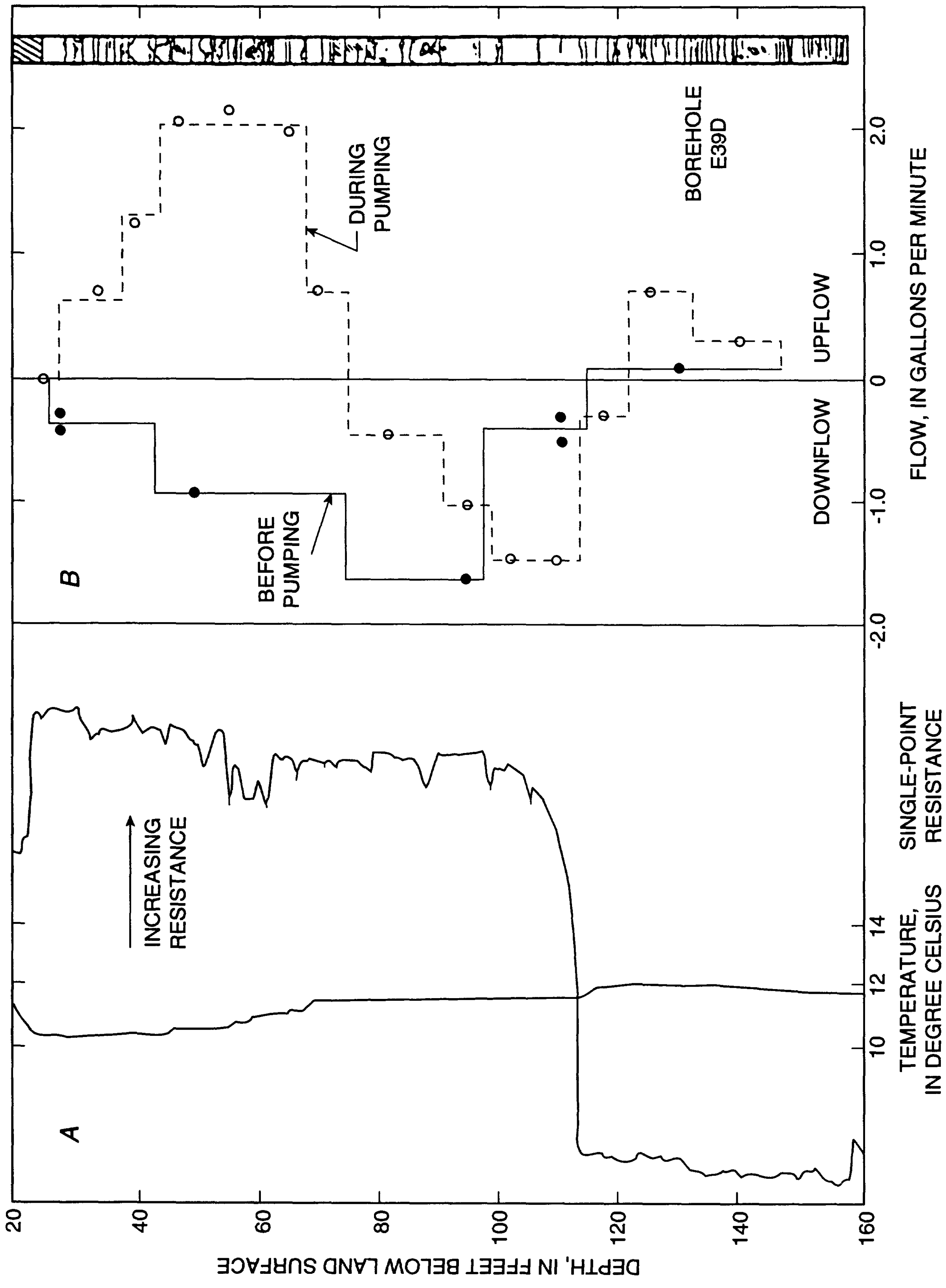


Figure 11. Temperature, single-point resistance, and flowmeter logs for well E39D, Verona well field area, Battle Creek, Michigan (from Paillet, 1991).

Water samples were collected from well E37D at depths of 40, 95, and 125 ft by use of a depth-discrete sampler. Specific conductance and pH measurements of the water were made. Samples were analyzed for dissolved constituents as described in table 6 and in the section "Water Quality." A significant increase in concentration of dissolved solids (residue at 180°C) was noted in water sampled from 125 ft in comparison to water sampled from 40 and 95 ft. This observation supports the above interpretation of the decrease in the resistance log below 115 ft. An increase in concentration of dissolved solids in water decreases the resistivity of that water and therefore, as indicated by the specific conductance reading, increases the conductivity.

Velocity of Flow

Average velocity of ground-water flow depends on the gradient of the potentiometric surface, hydraulic conductivity, and effective porosity of the aquifer according to the following equation (Lohman, 1979, p. 10):

$$\vartheta = \frac{K\frac{dh}{dl}}{\theta}, \quad (1)$$

where:

ϑ is average velocity, in feet per day;

K is hydraulic conductivity, in feet per day;

$\frac{dh}{dl}$ is gradient of the potentiometric surface, in feet per feet; and

θ is effective porosity, dimensionless.

Along parts of the margin of the Battle Creek River flood plain, the gradient of the potentiometric surface in the glacial and alluvial aquifer is high. The highest gradients are associated with till of the Kalamazoo and Battle Creek moraines, where hydraulic conductivities are estimated to be 30 ft/d. Velocity of flow in this area is estimated to be 2.7 ft/d.

Within the flood plain, the gradient is lower and hydraulic conductivity is estimated to be 110 ft/d (Grannemann and Twenter, 1985). The average velocity in August 1988 between the Emmett Street-Raymond Road intersection and pumped wells V38–V43 in the well field was calculated to be 1.2 ft/d. The highest velocity, 2.4 ft/d, was at the intersection; velocities elsewhere were 0.9 ft/d near the river and 0.6 ft/d in the southern part of the well field. An effective porosity of 0.25 (David B. Westjohn, U.S. Geological Survey, oral comm., 1990) and gradients from figure 9 were used for all calculations.

Ground-water-flow velocities were calculated for the sandstone aquifers; these velocities, however, are less accurate than those for the overlying aquifer because a value for effective porosity of the fractured bedrock cannot be determined accurately. For these calculations, a porosity of 0.3 was used. This value is greater than that of the matrix porosities for the Marshall Sandstone, which were determined by Westjohn and others (1990) to be 0.18 to 0.25. This value was increased over the matrix porosity because of the fractures but should be considered a minimum effective porosity. Primary hydraulic conductivity of this unit was determined to be less than 1 ft/d on the basis of laboratory tests of core from well W6D (Westjohn and others, 1990). Because of fracturing, a horizontal hydraulic conductivity of 150 ft/d was used for the upper sandstone aquifer. If a gradient of 0.0045 is assumed for the potentiometric surface, then an average velocity of flow of 2.25 ft/d for the upper sandstone aquifer results. Fractures in the lower sandstone aquifer are more productive than in the upper sandstone aquifer such that an estimate of effective porosity would be unreliable. Therefore a flow velocity is not calculated for the lower sandstone aquifer.

Water Quality

Water from wells E38D, E40I, E42D, H, and Bailey Park was analyzed for VOCs. Four of these wells are in Bailey Park, just west of Verona well field; well E42D is about 1.5 mi northeast of Verona well field (fig. 2). Concentrations of VOCs in water from four of the five wells sampled were less than the detection limits. Water from well E40I (1/3/90) contained 0.30 μg/L of 1,2-dichloroethane, the only compound detected. These data indicate that a hydrocarbon plume from the Davis Oil spill site had not reached these wells at the time of sampling.

Chemical and physical characteristics of water for wells E37D, E38D, and E42D are given in table 6. Well E37D is 95 ft southwest of well E38D in Bailey Park (fig. 2). Water samples were collected from depths of 40, 95, and 125 ft in well E37D. Concentrations of all constituents, with the exception of alkalinity and dissolved sulfate, increased with depth.

Table 6. Chemical and physical characteristics of water from wells E37D, E38D, and E42D near Verona well field, Battle Creek, Michigan

[<, actual value is less than value shown. °C, degrees Celsius; µS/cm, microsiemen per centimeter at 25°C; --, not determined]

Constituent or property	E37D (8/8/89)			E38D (12/6/89)	E42D (12/6/89)
	40 feet	95 feet	125 feet		
Properties					
Specific conductance (µS/cm)	626	872	7,050	973	497
pH (standard units)	6.9	7.5	8.0	7.3	7.5
Temperature (°C)	--	--	--	11.0	10.5
Color (platinum-cobalt units)	--	--	--	3	3
Turbidity (FTU)	--	--	--	4.3	1.5
Major constituents, in milligrams per liter					
Hardness, total (as $CaCO_3$)	--	--	--	440	270
Calcium, dissolved	62	92	140	120	72
Magnesium, dissolved	19	30	44	34	21
Sodium, dissolved	13	24	1,200	32	2.8
Potassium, dissolved	1.4	1.3	12	1.3	.70
Sulfate, dissolved	270	170	9.0	95	39
Alkalinity (as $CaCO_3$)	14	192	115	287	235
Chloride, dissolved	21	64	2,300	89	2.9
Fluoride, dissolved	--	--	--	.10	.10
Silica, dissolved	--	--	--	13	15
Solids, residue at 180°C, dissolved	427	557	3,780	567	274
Solids, sum of constituents, dissolved	--	--	--	558	285
Cyanide, total	--	--	--	<.010	<.010
Trace constituents, in micrograms per liter					
Aluminum, total recoverable	--	--	--	<10	<10
Arsenic, total	--	--	--	<1	2
Barium, total recoverable	--	--	--	<100	<100
Beryllium, total recoverable	--	--	--	<10	<10
Boron, total recoverable	--	--	--	50	20
Cadmium, total recoverable	--	--	--	<1	<1
Chromium, total recoverable	--	--	--	<1	<1
Cobalt, total recoverable	--	--	--	1	<1
Copper, total recoverable	--	--	--	1	2
Iron, dissolved	--	--	--	1,200	480
Iron, total recoverable	--	--	--	1,500	540
Lead, total recoverable	--	--	--	2	2
Lithium, total recoverable	--	--	--	<10	<10
Manganese, dissolved	--	--	--	120	46
Manganese, total recoverable	--	--	--	130	50
Mercury, total recoverable	--	--	--	<.10	<.10
Molybdenum, total recoverable	--	--	--	<1	1
Nickel, total recoverable	--	--	--	2	<1
Selenium, total	--	--	--	<1	<1
Silver, total recoverable	--	--	--	<1	<1
Strontium, total recoverable	--	--	--	110	60
Zinc, total recoverable	--	--	--	30	130

Alkalinity increased then decreased and concentrations of dissolved sulfate decreased with depth. A large increase in the concentration of dissolved solids was detected between 95 and 125 ft. This indicates inflow of water with high concentrations of dissolved solids at depth. Specific conductance and pH also increase with depth.

Concentrations of most dissolved constituents in ground water from well E42D (representing water northeast of the well field, an area of possible well field expansion) and from well E38D (representing water near or within the well field) were about the same (table 6). The concentrations of calcium carbonate (hardness), dissolved and total recoverable iron, and dissolved and total recoverable manganese are significantly higher in the well field than to the northeast.

Conceptual Model of Ground-Water-Flow System

A conceptual model of a ground-water-flow system is typically developed to organize data and to form the basis for preparation of a numerical model. A realistic conceptual model is an essential prerequisite for a numerical model that will realistically represent ground-water flow.

The conceptual model for this study is the same as that developed by Grannemann and Twenter (1985) for the Battle Creek area. The model consists of three layers representing glacial and alluvial deposits and the upper and lower parts of the Marshall Sandstone. Horizontal hydraulic conductivity of glacial and alluvial deposits is zoned laterally according to type of glacial material. Horizontal hydraulic conductivities of 15 ft/d for till, 70 ft/d for outwash deposits, and 110 ft/d for channel deposits (fig. 12) are based on those used by Grannemann and Twenter (1985). A horizontal hydraulic conductivity of 30 ft/d is used where till and outwash are interbedded. A horizontal hydraulic conductivity of 40 ft/d is used where channel deposits overlie outwash areas.

Laminar flow through a medium with systematic primary porosity and permeability is assumed in ground-water-flow simulation. Even though porosity and permeability of the upper and lower parts of the Marshall Sandstone are enhanced by fractures, the flow in the fractured system is considered to be similar enough to flow in a system with primary porosity and permeability that it can be modeled on the basis of the ground-water-flow (Darcy) equation. The upper and lower parts of the Marshall Sandstone are considered to be laterally homogeneous and isotropic. Initially, horizontal hydraulic conductivities of 150 ft/d were assumed for the upper part of the sandstone and 550 ft/d for the lower part of the sandstone. The upper part of the sandstone pinches out to the west and southwest of the study area.

Processes that recharge the aquifer system include precipitation and leakage from streams. Recharge is assumed to be a function of lithology, location of urban areas, and amount of precipitation. In the areas of outwash and channel deposits, recharge from precipitation is estimated to be 13 in/yr. In urbanized areas and areas covered with till, recharge from precipitation is estimated to be 8 and 10 in/yr, respectively. Recharge from river leakage occurs locally where pumping from water-supply wells near the Battle Creek River induce infiltration of water from the river (Grannemann and Twenter, 1985).

Discharge of the system is through pumpage from Verona well field, Columbia well field, other surrounding wells, and leakage to rivers. In areas where the water table is near land surface, discharge also occurs as evapotranspiration, but these areas are not extensive; therefore, evapotranspiration is considered negligible in the conceptual model.

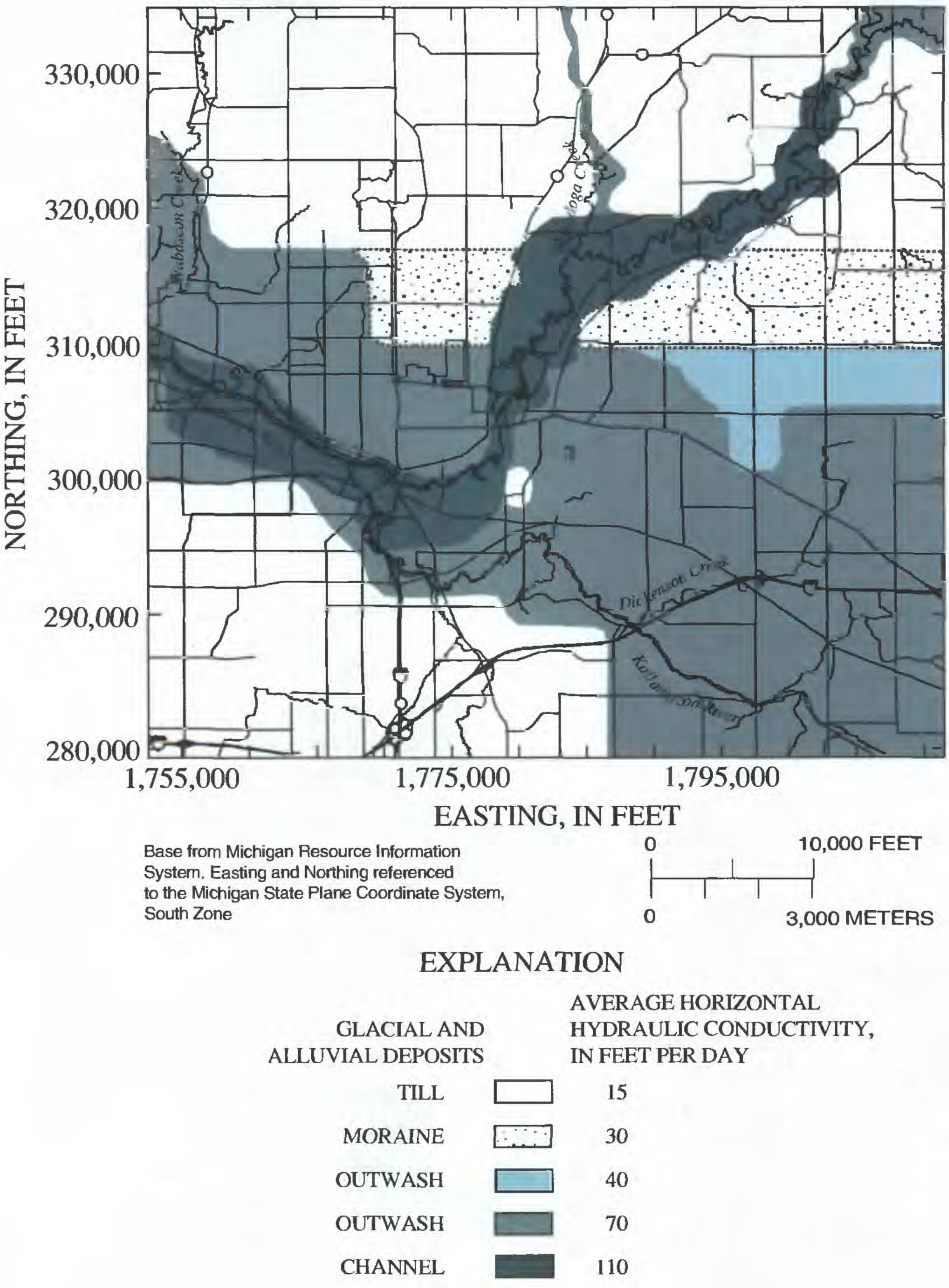


Figure 12. Horizontal hydraulic conductivities of glacial and alluvial deposits, Battle Creek, Michigan.

SIMULATIONS OF GROUND-WATER FLOW

Simulation of ground-water flow can be achieved through a numerical model. For this study, ground-water flow was simulated to evaluate the feasibility and potential effects of relocating the present purge system, to determine the rate and direction of ground-water flow in the area of gasoline contamination, and to re-evaluate the effects of ground-water withdrawals on ground-water flow and evaluate the effects of any increased pumpage on ground-water flow at Verona well field.

Development of Numerical Model

The USGS three-dimensional finite-difference ground-water-flow model, MODFLOW (McDonald and Harbaugh, 1983), was used to simulate ground-water flow in the study area. A post-processing program to MODFLOW, MODPATH, was used to aid in analyzing modeling scenarios. MODPATH is a three-dimensional particle-tracking program (Pollock, 1994).

The numerical model of ground-water flow is constructed on the basis of data sets and parameters created from the conceptual model. These values are used with a partial differential equation that combines Darcy's law and a water-balance equation (Anderson and Woessner, 1992) to describe three-dimensional flow of ground water of constant density through porous earth material. The equation can be written as (McDonald and Harbaugh, 1988):

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right)-W = S_s\frac{\partial h}{\partial t}, \quad (2)$$

where:

K_x, K_y, and K_z are the hydraulic conductivities along the *x*-, *y*-, and *z*-coordinate axes, in feet per day;

h is the hydraulic head, in feet;

W is a general source/sink term that defines the volume of flow to and from the system per unit volume of aquifer per unit time;

S_s is specific storage; and

t is time, in days.

Output from MODFLOW is used in MODPATH to compute paths for imaginary particles of water moving through the simulated ground-water-flow system. Traveltimes of particles moving through the system also are calculated. MODPATH was used to determine the flow paths of particles originating at the sources of contamination. All identified sources of contamination are considered to originate in the glacial and alluvial aquifer. Recharge locations for the most recently installed water-supply wells in Verona well field (V51, V52, and V53) also are determined.

Assumptions

The following assumptions and simplifications were incorporated into the ground-water-flow model:

1. Fracture flow in the upper and lower parts of the Marshall Sandstone is similar enough to flow in a system having primary porosity and permeability that the ground-water-flow (Darcy) equation can be used.
2. Hydraulic conductivities of the upper and lower parts of the Marshall Sandstone are laterally homogeneous and isotropic.
3. All rivers and lakes have a bed thickness of 3 ft.
4. Where the upper part of the Marshall Sandstone pinches out, the sandstone is 1 ft thick. This assumption allows for simulation of flow between the glacial and alluvial aquifer and the lower part of the Marshall Sandstone in this area.
5. The system is in steady state based on the length of time that wells have been pumped in the well field.

Discretization

The aquifer system is spatially discretized with a grid of blocks called cells. The ground-water-flow model is composed of 5,160 cells. Three layers of cells in the model represent aquifers in the glacial and alluvial deposits (layer 1), the upper part of the Marshall Sandstone (layer 2), and the lower part of the Marshall Sandstone (layer 3), in descending order. Each layer has 40 rows and 43 columns of cells.

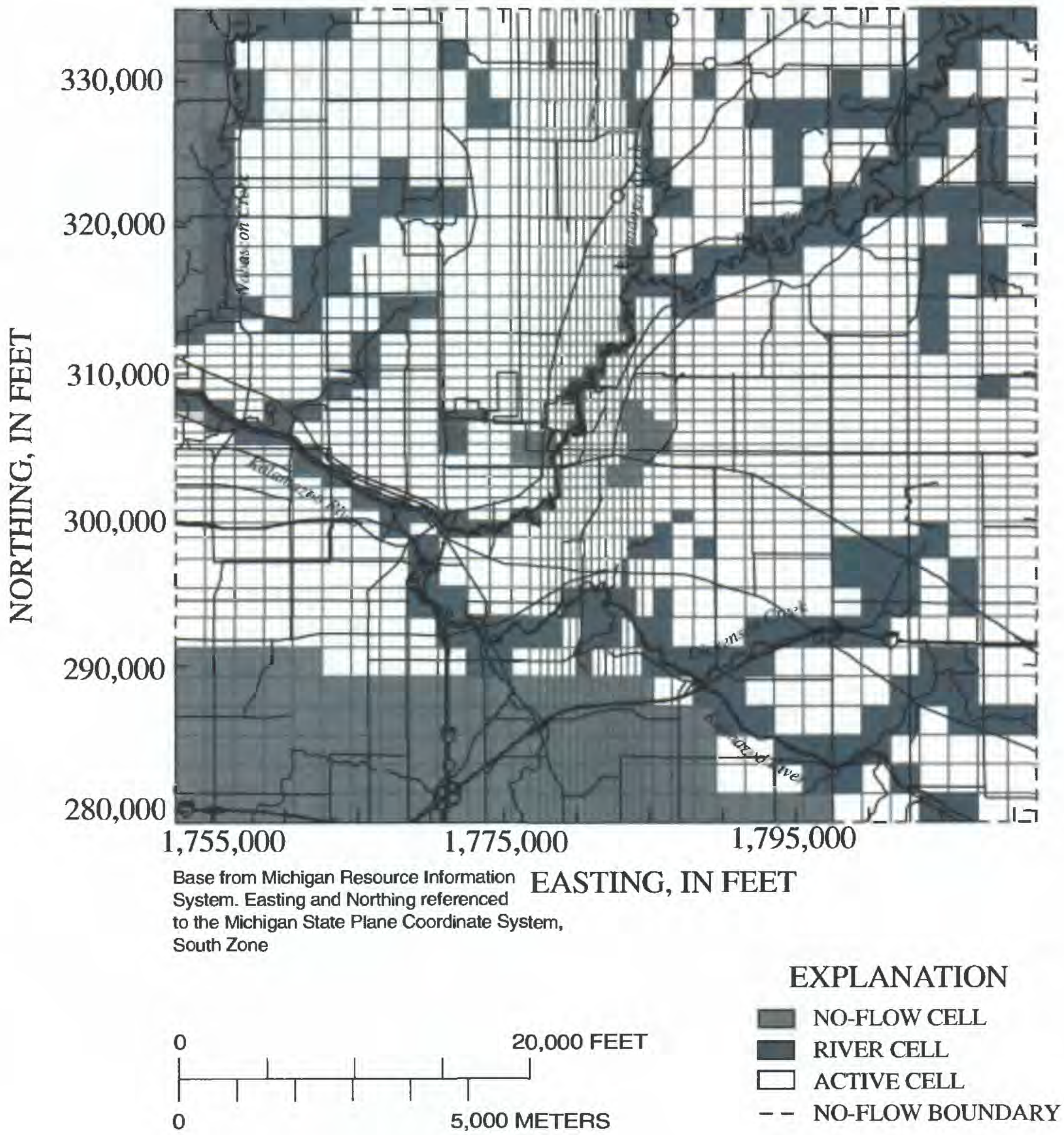


Figure 13. Boundaries and grid spacing used in layer 1 (glacial and alluvial aquifer) of the numerical model, Battle Creek, Michigan.

The width and length of the rows and columns ranges from 500 to 2,000 ft. The closest spacing is concentrated at and near Verona well field (fig. 13).

The thickness of the glacial and alluvial aquifer (layer 1) is the saturated thickness of the glacial and alluvial deposits. Layer 1 is modeled as unconfined. Thickness of the upper part of the Marshall Sandstone (layer 2) varied because the bedrock surface is erosional. The lower part of the Marshall Sandstone (layer 3) is modeled with a uniform thickness of 50 ft. Layers 2 and 3 are modeled as confined aquifers.

Boundaries

Hydrogeologic boundaries can be represented with the following conditions: no-flow, constant-head, or variable-head. No-flow and variable-head boundaries are used in the numerical model developed for this study.

Boundaries of the numerical model (fig. 13) developed for this study generally coincide with those for the ground-water-flow model previously developed (Grannemann and Twenter, 1985). These boundaries follow surface-water features and ground-water divides in the glacial and alluvial aquifer.

External boundaries are identical in type and location in all three layers except where streams intersect them. Where this occurs, the lower 2 layers have no-flow boundaries. Cells along most of the south and southwest boundaries, south of the Kalamazoo River (fig. 13), are no-flow cells. No-flow cells are also located along the west boundary, west of Wabascon Creek (fig. 13). All of these cells follow ground-water divides. Various combinations of constant-head and variable-head boundaries along the remaining external boundaries were tried during model construction. Varying boundaries as to constant-head cells and variable-head cells, however, had little effect on model-generated heads.

With regard to differences between model-generated flows and field-measured or estimated flows, little variation also is expected with changes in cell type along boundaries. Estimates of flow were made for seven streams. When model boundaries were varied between constant-head and variable-head, residual flow varied. Two streams account for most of this variation. Parts of these two streams are along the edges of the model grid. By changing the boundaries, one could expect to change flows in these streams. Variation of boundaries from constant head to variable head has little to no effect on streams internal to the model and near the well field. Therefore, the remaining boundaries were simulated as variable-head cells.

Boundaries internal to the model include river cells and no-flow cells. The river cells represent the locations of rivers and lakes and are limited to layer 1. The no-flow cells also occur in layer 1 and represent bedrock highs where the water table is in bedrock (layer 2) (fig. 13).

Hydraulic Properties

Hydraulic conductivity describes the rate at which a unit volume of water is transmitted through a cross section of unit area per unit time. As described previously for the conceptual model, the glacial and alluvial aquifer is zoned according to type of material. In the ground-water-flow model, these zones are defined by groupings of layer 1 cells. Each group of cells is assigned a horizontal hydraulic conductivity according to the material type it represents; 15 ft/d for till, 70 ft/d for outwash deposits, and 110 ft/d for channel deposits.

Layers 2 and 3 cells are assigned horizontal hydraulic conductivities of 150 and 300 ft/d, respectively. These conductivities are applied equally over each layer. Vertical leakance from layer 1 to layer 2 and from layer 2 to layer 3 is modeled with a value of 0.004/d. Riverbeds and lakebeds are modeled with a hydraulic conductivity of 4 ft/d. Cells representing rivers and lakes are limited to layer 1.

Hydrologic Stresses

Lateral zoning of recharge from precipitation is based on the location of outwash, channel, and till deposits and on the location of urban areas, as described in the conceptual model. Groupings of cells in layer 1 represent these land covers. At bedrock highs, the water table is in layer 2 cells (fig. 9), and recharge is applied to the layer 2 cells. Recharge also results from infiltration of water from the Battle Creek River induced by pumping of water-supply wells in Verona well field. The rate of surface-water infiltration is estimated to be 2.5 ft^3/s.

Discharge in the model is by pumping from wells and ground-water flow to rivers and lakes. Pumping in Verona well field is simulated as being from model layers 2 and 3. For the simulation under August 1988 conditions, Verona well field pumping rate was modeled at 10,100 gal/min; of this amount, about 1,200 gal/min is pumped from purge wells (V22, V24, V25, V26, V27, and V28).

Calibration of Numerical Model

Calibration of a numerical flow model refers to a demonstration that measured hydraulic heads and flows can be simulated by the model. Calibration is accomplished by finding a non-unique set of parameters, boundary conditions, and stresses that produce simulated heads and flows that match measured values within a preestablished range of error (Anderson and Woessner, 1992). The preestablished range of error is based on the range of measured values.

Steady-state calibration was achieved by adjusting individual model input parameters within maximum and minimum limits (table 7) and observing the changes in head and flow. When simulated heads matched measured heads (table 8) and simulated flows matched measured flows, especially loss (infiltration) of water from the Battle Creek River to the well field, the model was considered calibrated. Certain water-level measurements were considered to be more critical to match than others—those farthest from stresses, because they are the most stable, and those in layer 2 near the river, so that loss from the river to the well field would be accurately simulated. The range in historical head data served as the range of error for simulated heads.

Calibration of the model under August 1988 pumping conditions resulted in an increase in the vertical leakance of the till from 1.8×10^{-5} to 1.8×10^{-4}/d and a decrease in the horizontal hydraulic conductivity of the lower part of the Marshall Sandstone from 550 to 300 ft/d. All other parameters remained as described in the section "Conceptual Model."

Comparison With Previous Model

Input files to the current ground-water-flow model were rediscretized on the basis of the model developed by Grannemann and Twenter (1985). Their model consists of 3 layers, 99 rows, and 116 columns, whereas the model developed for this study consists of 3 layers, 40 rows, and 43 columns. The models are referred to hereafter as "99×116" and "40×43" models, respectively. Model boundaries and types are similar in the two models, but river cells were redigitized for the 40×43 model. Layer 1 in the areas where the water table is within bedrock are represented by no-flow cells in the 40×43 model. In the 99×116 model, the same area is represented by variable-head cells.

Table 7. Model parameters and adjustments during calibration of numerical model, Battle Creek, Michigan

Model layer	Starting value	Minimum	Maximum	Final
Horizontal Hydraulic Conductivity (feet per day)				
Layer 1 - till	15	11.25	18.75	15
Layer 1 - outwash	70	52.5	87.5	70
Layer 1 - channel deposits	110	82.5	137.5	110
Layer 2 (upper Marshall Sandstone aquifer)	150	75	350	150
Layer 3 (lower Marshall Sandstone aquifer)	550	300	750	300
Vertical Leakance (per day)				
Layers 1, 2 - till	1.8×10^{-5}	1.8×10^{-6}	1.8×10^{-4}	1.8×10^{-4}
Layers 1, 2 - outwash	4.0×10^{-5}	4.0×10^{-6}	4.0×10^{-4}	4.0×10^{-5}
Layers 1, 2 - channel deposits	2.5×10^{-2}	2.5×10^{-3}	2.5×10^{-1}	2.5×10^{-2}
Layers 2, 3	1.2×10^{-2}	1.2×10^{-3}	1.2×10^{-1}	1.2×10^{-2}
Riverbed and Lakebed Conductivity (feet per day)				
Layer 1 only	4	0.4	40	4

Table 8. Measured and simulated hydraulic heads for August 1988, Battle Creek, Michigan

Well	Cell (row, column)	Hydraulic head (feet above sea level)		Measured head minus simulated head (ifeet)
		Measured	Simulated	
Model Layer 1, Glacial and Alluvial Aquifer				
B1	21, 25	826.63	827.42	-0.79
B9	21, 24	825.66	826.03	-.37
B17	23, 24	828.17	826.53	1.64
DNR1	26, 27	844.48	838.93	5.55
DNR2	25, 27	839.75	839.02	.73
E3	18, 17	822.28	823.52	-1.24
E8	22, 23	823.48	824.93	-1.45
E22S	19, 24	824.27	824.44	-.17
E28S	21, 26	828.11	829.17	-1.06
E33S	29, 12	825.53	826.20	-.67
E35S	23, 16	822.16	824.23	-2.07
G1B	18, 29	817.49	822.97	-5.48
G2	19, 29	818.07	827.47	-9.40
G3A	17, 30	817.33	823.71	-6.38
G5	17, 28	816.91	819.09	-2.18
G7	16, 29	815.82	819.47	-3.65
G8	17, 30	818.50	823.71	-5.21
G9	20, 26	825.69	826.58	-.89
T1	22, 22	822.41	822.80	-.39
T2	18, 23	823.12	823.27	-.15
T3	18, 24	823.46	823.50	.04
T4	19, 25	824.68	824.12	.56
T5	21, 24	825.77	826.03	-.26
T6	23, 24	825.75	826.53	-.78
T7	24, 22	821.91	823.34	-1.43
T8	25, 23	828.18	826.98	1.20
T9	24, 24	831.95	826.91	5.04
T10	22, 21	820.76	821.46	-.70
T11	23, 21	819.58	821.45	-1.87
T12	18, 26	817.72	821.32	-3.60
T13	19, 28	818.32	823.87	-5.55
W2S	23, 20	818.08	819.64	-1.56
W3S	22, 20	814.72	819.39	-4.67
W4S	21, 22	821.16	822.86	-1.70
W5S	19, 23	822.81	824.17	-1.36
W7S		824.54	825.25	-.71
W8S	21, 23	823.08	824.77	-1.69
W9S	22, 24	826.08	826.45	-.37
P1	20, 17	824.64	824.42	.22
P3	21, 17	824.54	824.37	.17
Model Layer 2, Upper Part of the Marshall Sandstone Aquifer				
E1	15, 15	826.26	825.59	0.67
E2	20, 16	822.83	823.38	-.55
E4	13, 18	823.27	824.16	-.89
E6	14, 22	822.24	822.79	-.55
E9	21, 18	821.89	819.34	2.55
E10	22, 17	818.14	821.06	-2.92
E13	27, 17	817.37	820.89	-3.52
E14	25, 20	818.31	820.75	-2.44
E17	22, 19	816.65	817.08	-.43
E18	18, 12	830.52	827.87	2.65
E19	20, 18	821.94	821.63	.31
E20	19, 20	821.54	821.54	.00
E21	17, 24	822.91	822.84	.07
E32	25, 17	816.70	818.27	-1.57
E35D	23, 16	820.43	821.97	-1.54
G9A	20, 26	826.63	823.21	3.42
W1I	24, 19	816.44	817.29	-.85
W2I	23, 20	818.05	819.34	-1.29
W4I	21, 22	821.05	822.57	-1.52
W6I	22, 23	822.72	822.89	-.17
W8I	21, 23	822.81	822.84	-.03
W16I	22, 24	825.98	822.41	3.57
Model Layer 3, Lower Part of the Marshall Sandstone Aquifer				
E23	13, 27	824.53	821.71	2.82
E24	23, 30	849.03	828.76	20.27
G1C	18, 29	816.68	825.40	-8.72
G5A	17, 28	817.71	823.70	-5.99
G7A	16, 29	814.96	823.89	-8.93
W4D	21, 22	820.99	822.11	-1.12
W6D	22, 23	822.86	823.15	-.29
W8D	21, 23	823.55	822.93	.62
W11D	21, 25	826.59	824.12	2.47

The two models were run with identical stresses, and the results were compared. Stress and measured data used to calibrate the 99×116 model were used in the model comparison. Comparison of resultant hydraulic heads at measurement points for summer 1983 data indicates a close correlation between the two models (table 9). The average difference in hydraulic head at measurement points in layer 1 between models is 2.0 ft. By eliminating observation well E12 (where head difference between models is 23.0 ft), the average head difference decreases to 1.2 ft. Observation well E12 is located adjacent to no-flow cells representing the bedrock high. The large head difference my be the result of a boundary effect. The average difference in head at measurement points in layer 2 is 1.6 ft. The average difference in head at measurement points in layer 3 is 0.9 ft.

A close correlation between hydraulic heads at measurement points for winter 1984 data also is expected. The average difference between the models for heads at measurement points in layer 1 is 2.8 ft. The average head difference is 3.1 ft for layer 2 and 1.5 ft for layer 3. These values do not correlate as closely as those for summer 1983 data, but the differences are still within reason. Rediscretization of the 99×116 model did not significantly affect model results. The addition of no-flow cells, to the 40×43 model, in the areas where the water table is within bedrock showed a significant change in simulated water level in only one observation well.

Sensitivity Analysis

Sensitivity analysis is done to quantify the uncertainty in the calibrated model caused by uncertainty in the estimates of aquifer parameters, stresses, and boundary conditions (Anderson and Woessner, 1992). During a sensitivity analysis, calibrated parameters are systematically changed within established limits. The magnitude of change in hydraulic heads from the calibrated-model solution is a measure of the sensitivity of the model to variations in the value of that particular parameter. The results of the sensitivity analysis are reported as the effects of the parameter change on the average measure of error selected as the calibration criterion. The effect of changes in parameter values on streamflow also can be examined in the sensitivity analysis. The results of the sensitivity analysis on hydraulic heads for the calibrated model are summarized in table 10. The model is shown to be most sensitive to recharge and vertical leakance of outwash and upper part of the Marshall Sandstone. A 50-percent increase in recharge results in a 0.95-foot increase (for layer 1) and a 0.5-foot increase (for layers 1 and 2) in the average residual for hydraulic heads at observation wells. With respect to hydraulic heads, the model is relatively insensitive to other parameters. For example the model is the next most sensitive to horizontal hydraulic conductivity of layer 3. A 50-percent increase in horizontal hydraulic conductivity of layer 3 results in a 0.12-foot increase in the average residual for hydraulic heads at observation wells.

The results of the sensitivity analysis on streamflow for the calibrated model are summarized in table 11. Similar to the results of the sensitivity analysis on hydraulic heads, the parameter having the greatest effect on streamflow is recharge. A 50-percent increase in recharge results in an increase in streamflow of 0.239 ft^3/s. With respect to streamflow, the model is relatively insensitive to most parameters except vertical leakance of outwash deposits to the upper part of the Marshall Sandstone.

Analysis of Alternatives for Well Field Operations

A calibrated ground-water-flow model can be used as a tool to evaluate/analyze the potential effects of changes in stress on the ground-water-flow system. The model prepared for this study was used in combination with the particle-tracking program MODPATH to evaluate the feasibility of relocating the present purge system, to reevaluate the effects of current and increased ground-water withdrawals on ground-water flow, and to estimate the rate and direction of ground-water flow northwest of Verona well field.

Table 9. Measured and simulated hydraulic heads for summer 1983 and winter 1984 stresses, Battle Creek, Michigan

[99 x 116, 99 rows by 116 columns; 40 x 43, 40 rows by 43 columns; --, no data]

Well	Heads, summer 1983			Heads, winter 1984		
	Measured	99 x 116 model simulated	40 x 43 model simulated	Measured	99 x 116 model simulated	40 x 43 model simulated
Model Layer 1, Glacial and Alluvial Aquifer						
E2	823.34	823.1	823.3	823.91	824.0	823.7
E3	824.85	823.6	822.7	825.17	824.3	822.8
E8	825.26	827.9	824.3	826.59	829.4	826.0
E11	823.35	827.0	824.9	824.79	828.8	826.2
E12	867.84	862.8	839.8	867.29	863.5	840.0
E22S	824.97	824.4	823.7	826.40	825.3	824.4
E28S	829.38	830.3	829.9	830.37	830.9	830.4
E31	--	--	--	825.06	823.7	825.2
E33S	825.18	829.1	826.7	825.94	830.2	827.2
T1	823.84	826.0	821.6	825.40	827.6	824.0
T2	823.71	823.6	822.4	824.91	824.4	823.1
T3	823.86	822.6	822.1	825.42	823.4	822.8
T4	825.34	822.9	823.1	826.83	823.7	823.7
T5	827.46	827.6	826.5	828.55	828.7	827.5
T6	829.20	829.9	828.7	828.30	831.2	829.6
T7	823.92	827.6	--	825.82	829.8	--
T8	830.40	833.8	--	831.03	835.2	--
T9	834.59	831.3	--	835.04	832.4	--
T10	822.26	822.2	820.5	824.51	825.2	823.4
T11	821.26	821.7	820.2	823.94	825.3	823.5
T12	817.74	820.6	820.7	818.51	820.9	821.1
T13	818.70	822.0	823.7	819.20	822.2	824.0
T14	820.81	830.1	827.6	821.46	830.6	827.9
T15	835.47	834.5	833.4	835.78	835.0	833.9
T16	828.57	830.3	830.1	829.63	831.1	830.8
G1,A,B	818.23	821.0	822.5	818.69	821.3	822.7
G2,A	818.87	825.2	827.6	819.22	825.6	827.9
G3,A	818.08	821.9	822.0	818.61	822.4	822.3
G4,A	817.91	819.5	819.7	818.42	819.7	819.8
G5	817.30	819.0	818.8	817.87	819.2	818.9
G7	816.68	819.2	818.7	817.64	819.4	818.8
G8	817.91	823.7	822.0	818.82	824.2	822.3
G9	827.56	827.3	826.9	828.68	828.1	827.4
M	823.85	823.4	822.4	825.21	824.3	823.1
Model Layer 2, Upper Part of the Marshall Sandstone Aquifer						
E1	828.22	821.8	823.0	829.48	822.8	823.1
E4	823.50	820.3	820.9	824.40	820.8	820.7
E5	819.62	817.0	818.9	818.90	817.6	817.8
E6	822.88	819.8	820.2	824.26	820.9	820.3

Table 9. Measured and simulated hydraulic heads for summer 1983 and winter 1984 stresses, Battle Creek, Michigan—*Continued*

Well	Heads, summer 1983			Heads, winter 1984		
	Measured	99 x 116 model simulated	40 x 43 model simulated	Measured	99 x 116 model simulated	40 x 43 model simulated
Model Layer 2, Upper Part of the Marshall Sandstone Aquifer—*Continued*						
E7	837.86	824.4	825.6	838.35	826.9	827.3
E9	821.73	816.1	815.6	822.37	819.1	819.2
E10	816.92	815.0	820.3	818.66	819.6	822.1
E13	820.13	821.4	822.9	823.13	825.6	825.8
E14	820.58	820.1	820.0	823.59	824.5	824.2
E15	823.38	819.3	820.4	824.11	820.3	820.4
E16	820.22	816.5	817.7	823.35	821.6	822.3
E17	817.56	813.5	815.5	820.93	819.4	821.1
E18	832.65	825.3	825.1	832.31	826.6	825.5
E19	821.76	815.8	819.9	822.35	818.9	821.2
E20	821.72	816.9	819.6	822.29	819.9	820.8
E21	823.31	820.5	821.7	824.59	821.9	822.2
E32	819.26	817.0	819.5	822.67	822.6	823.0
G9A	827.55	821.9	822.3	828.70	823.9	823.5
R	825.26	820.5	821.9	825.74	821.5	821.7
Model Layer 3, Lower Part of the Marshall Sandstone Aquifer						
E22D	824.38	821.1	821.3	826.02	823.0	822.5
E23	825.63	819.6	819.0	825.48	820.5	819.3
E24	850.36	825.9	827.1	816.58	827.5	829.1
E25	815.02	817.9	815.7	816.58	818.6	816.0
E26	816.63	822.2	821.7	819.64	823.1	822.2
E27	822.70	818.9	821.1	824.02	823.3	823.4
E28D	828.06	822.4	822.7	829.14	824.3	823.9
E29	839.97	824.6	824.4	840.42	827.3	826.5
E30	846.22	824.6	824.5	846.18	826.3	825.5
E33D	825.67	826.8	826.2	826.45	828.5	826.9
E34	821.94	822.2	823.7	823.75	825.5	825.4
E35D	822.98	817.8	820.3	824.12	822.2	822.0
E36	822.36	822.5	823.7	824.04	825.7	825.4
G1C	818.68	822.9	822.5	819.80	824.2	823.3
G5A	818.31	822.1	821.3	819.35	823.4	821.9
G6	822.94	822.8	822.8	824.98	824.3	823.7
G7A	816.02	821.4	820.9	817.16	822.5	821.4
G8A	818.37	822.4	822.0	819.76	823.6	822.6
S1	824.45	824.0	824.5	824.44	826.6	825.7
H	821.82	818.0	819.3	822.70	817.8	818.2
V01	819.32	814.6	816.7	822.27	819.8	821.1

Table 10. Results of sensitivity analysis on hydraulic heads of the numerical model, Battle Creek, Michigan

Hydraulic parameter			Average measured minus simulated hydraulic head (feet)	
Name	Value simulated	Percentage of change	Model layer 1 (glacial and alluvial aquifer)	Model layers 2 and 3 (upper and lower Marshall sandstone)
Recharge	19.5	50	3.03	3.17
(inches per year)	13.0	0	2.08	2.67
	6.5	-50	2.40	2.81
Riverbed conductivity	6.0	50	2.06	2.67
(feet per day)	4.0	0	2.08	2.67
	2.0	-50	2.16	2.69
Model Layer 1, Glacial and Alluvial Aquifer, Till				
Horizontal hydraulic conductivity	22.5	50	2.12	2.68
(feet per day)	15.0	0	2.08	2.67
	7.5	-50	2.05	2.66
Model Layer 1, Glacial and Alluvial Aquifer, Outwash				
Horizontal hydraulic conductivity	105.0	50	2.16	2.71
(feet per day)	70.0	0	2.08	2.67
	35.0	-50	2.20	2.64
Model Layer 1, Glacial and Alluvial Aquifer, Channel Deposits				
Horizontal hydraulic conductivity	165.0	50	1.87	2.70
(feet per day)	110.0	0	2.08	2.67
	55.0	-50	2.71	2.66
Model Layer 2, Upper Part of the Marshall Sandstone Aquifer				
Horizontal hydraulic conductivity	225.0	50	2.17	2.79
(feet per day)	150.0	0	2.08	2.67
	75.0	-50	1.96	2.65
Model Layer 3, Lower Part of the Marshall Sandstone Aquifer				
Horizontal hydraulic conductivity	450.0	50	1.95	2.53
(feet per day)	300.0	0	2.08	2.67
	150.0	-50	2.18	3.67
Model Layers 1 and 2, Glacial and Alluvial, Till and Upper Part of the Marshall Sandstone Aquifers				
Vertical leakance	2.7×10^{-4}	50	1.87	2.62
(per day)	1.8×10^{-4}	0	2.08	2.67
	0.9×10^{-4}	-50	1.92	2.86
Model Layers 1 and 2, Glacial and Alluvial, Outwash and Upper Part of the Marshall Sandstone Aquifers				
Vertical leakance	6.0×10^{-5}	50	1.89	2.56
(per day)	4.0×10^{-5}	0	2.08	2.67
	2.0×10^{-5}	-50	1.94	2.91
Model Layers 1 and 2, Glacial and Alluvial, Channel Deposits and Upper Part of the Marshall Sandstone Aquifers				
Vertical leakance	3.8×10^{-2}	50	1.88	2.61
(per day)	2.5×10^{-2}	0	2.08	2.67
	1.3×10^{-2}	-50	1.89	3.02
Model layers 2 and 3, Upper Part and Lower Part of the Marshall Sandstone Aquifers				
Vertical leakance	1.8×10^{-2}	50	1.88	2.63
(per day)	1.2×10^{-2}	0	2.08	2.67
	0.6×10^{-2}	-50	1.85	2.74

Table 11. Results of sensitivity analysis on streamflows simulated with the numerical model, Battle Creek, Michigan

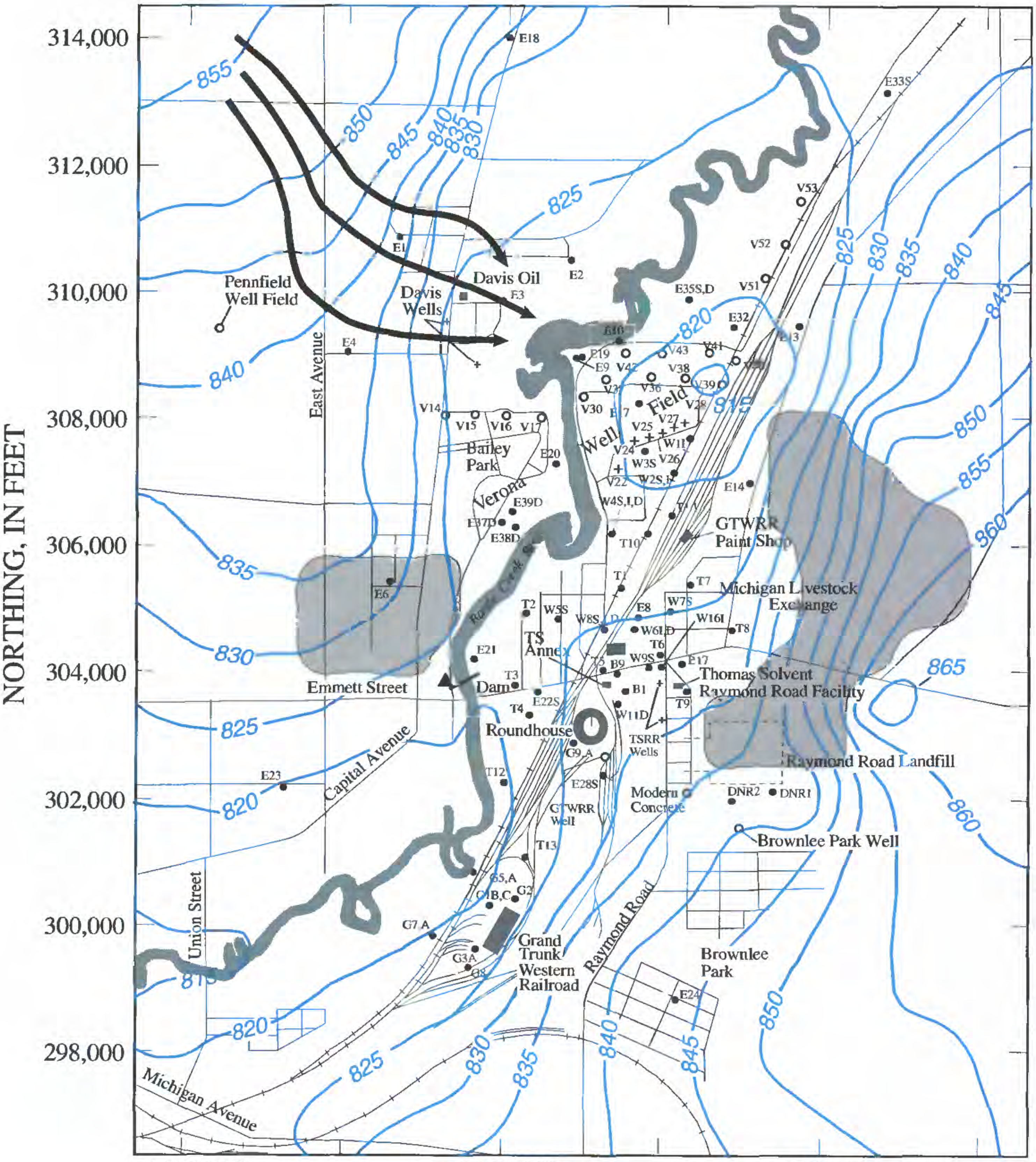
Hydraulic parameter			Average measured minus simulated streamflow (cubic feet per second)
Name	Value simulated	Percentage of change	
Recharger (inches per year)	19.5	50	0.967
	13.0	0	.728
	6.5	-50	1.689
Riverbed conductance (feet per day)	6.0	50	.744
	4.0	0	.728
	2.0	-50	.736
Model Layer 1, Glacial and Alluvial Aquifer, Till			
Horizontal hydraulic conductivity (feet per day)	22.5	50	.903
	15.0	0	.728
	7.5	-50	.879
Model Layer 1, Glacial and Alluvial Aquifer, Outwash			
Horizontal hydraulic conductivity (feet per day)	105.0	50	.865
	70.0	0	.728
	35.0	-50	.564
Model Layer 1, Glacial and Alluvial Aquifer, Channel Deposits			
Horizontal hydraulic conductivity (feet per day)	165.0	50	.740
	110.0	0	.728
	55.0	-50	.709
Model Layer 2, Upper Part of the Marshall Sandstone Aquifer			
Horizontal hydraulic conductivity (feet per day)	225.0	50	.771
	150.0	0	.728
	75.0	-50	.699
Model Layer 3, Lower Part of the Marshall Sandstone Aquifer			
Horizontal hydraulic conductivity (feet per day)	450.0	50	.826
	300.0	0	.728
	150.0	-50	.712
Model Layers 1 and 2, Glacial and Alluvial, Till and Upper Part of the Marshall Sandstone Aquifers			
Vertical leakance (per day)	2.7×10^{-4}	50	.852
	1.8×10^{-4}	0	.728
	0.9×10^{-4}	-50	.621
Model Layers 1 and 2, Glacial and Alluvial, Outwash and Upper Part of the Marshall Sandstone Aquifers			
Vertical leakance (per day)	6.0×10^{-5}	50	.129
	4.0×10^{-5}	0	.728
	2.0×10^{-5}	-50	.771
Model Layers 1 and 2, Glacial and Alluvial, Channel Deposits and Upper Part of the Marshall Sandstone Aquifers			
Vertical leakance (per day)	3.8×10^{-2}	50	.732
	2.5×10^{-2}	0	.728
	1.3×10^{-2}	-50	.717
Model Layers 2 and 3, Upper and Lower Parts of the Marshall Sandstone Aquifers			
Vertical leakance (per day)	1.8×10^{-2}	50	.731
	1.2×10^{-2}	0	.728
	0.6×10^{-2}	-50	.720

Simulation Using Extraction Wells for Purge System

Three simulations were run to determine the feasibility of relocating the present purge system while still protecting Verona well field from the identified sources of contamination. The current purge system configuration was simulated first. In this simulation, six purge wells (V22,V24, V25, V26, V27, and V28) form a line along the southeast edge of the well field (fig. 14). This simulation shows that water from the site of Thomas Solvent Raymond Road facility (TSRR) and Grand Trunk Western Railroad car department paint shop (GTWRR) flows vertically down to the upper part of the Marshall Sandstone and is captured by production wells V39 and V41 (fig. 14). Most water from the Thomas Solvents annex (TS annex) flows to the Battle Creek River, but a small part flows to the upper part of the Marshall Sandstone and to production wells V17, V39, and V41. Water at the Davis Oil site flows vertically from the glacial and alluvial aquifer to the upper part of the Marshall Sandstone. Thus this simulation indicates that the current purge system does not completely protect the well field from possible contamination.

A configuration of wells incorporating the current purge system plus eight additional purge wells south of the current purge wells (fig. 15) was simulated second. The eight purge wells (BW1 through BW8) pump from the upper part of the Marshall Sandstone. With these additional purge wells, water from TSRR and TS annex is captured in the upper part of the Marshall Sandstone by purge wells BW3 and BW4. A small part of water from TS annex flows to Battle Creek River. Water from GTWRR flows to the upper part of the Marshall Sandstone and is captured by purge wells V26, V27, and V28. Water from Davis Oil flows vertically from the glacial and alluvial aquifer to the upper part of the Marshall Sandstone. With this configuration of purge wells, the simulation results indicate that the well field is protected from contamination from the identified source areas.

The third simulation uses the eight purge wells (BW1 through BW8) just described. In this simulation however, the current purge system is turned off (fig. 16). Water from TSRR flows to the upper part of the Marshall Sandstone and is captured by purge wells BW3 and BW4. Most water from TS annex flows to the Battle Creek River, and the rest is captured in the upper part of the Marshall Sandstone by purge wells BW3 and BW4. Water from GTWRR flows to the upper part

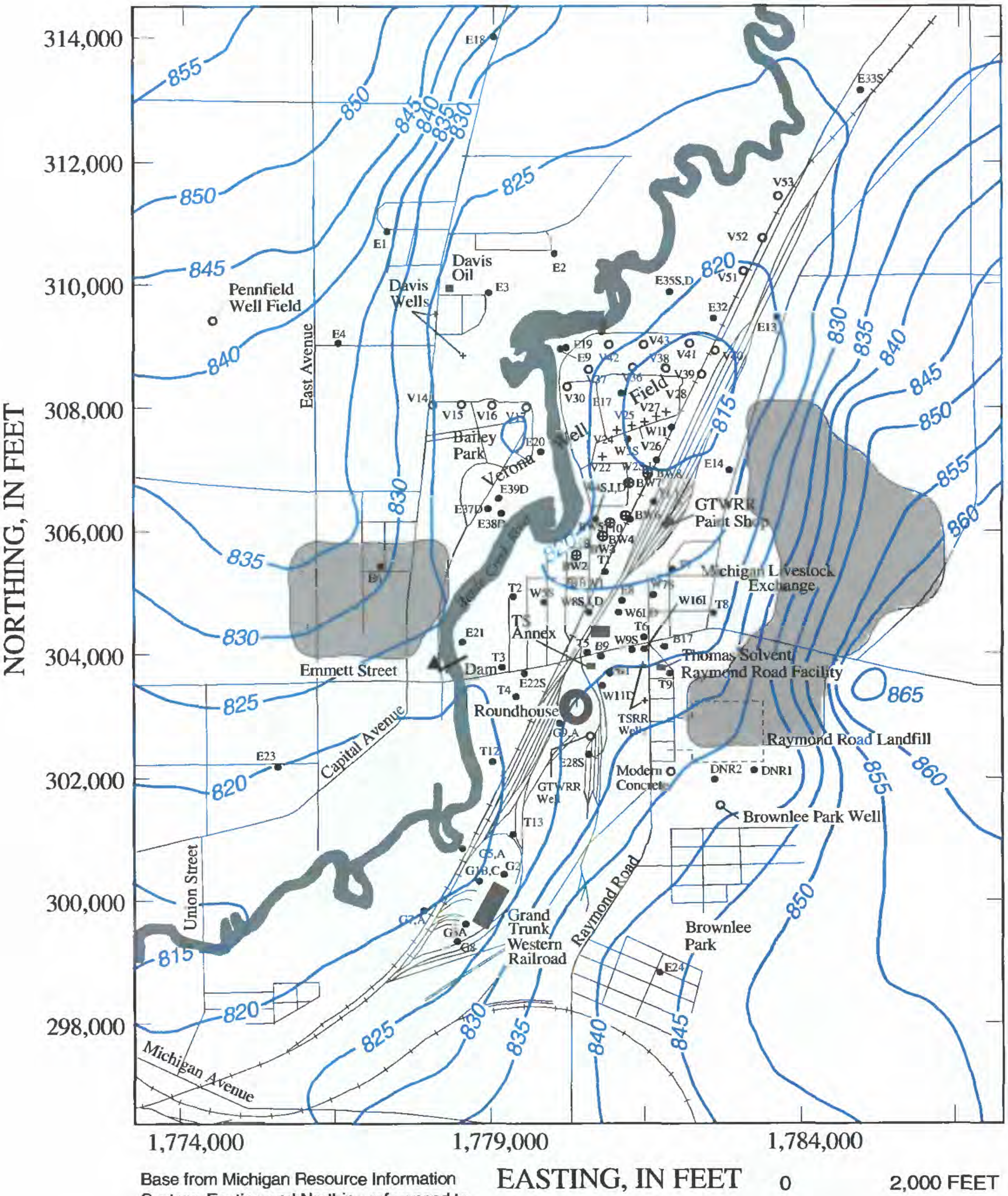


Base from Michigan Resource Information System. Easting and Northing referenced to the Michigan State Plane Coordinate System, South Zone

EXPLANATION

- BEDROCK
- —840— POTENTIOMETRIC CONTOUR -- Shows altitude at which water would have stood in tightly cased wells (August 23, 1988). Contour interval 5 feet. Datum is sea level
- DIRECTION OF FLOW
- • MONITORING WELL
- o WATER-SUPPLY WELL
- + PURGE WELL
- IDENTIFIED SOURCE OF CONTAMINANTS
- ▲ STREAM-GAGING STATION

Figure 14. Simulated potentiometric surface of glacial and alluvial aquifer for current purge-system configuration, Verona well field area, Battle Creek, Michigan.



Base from Michigan Resource Information System. Easting and Northing referenced to the Michigan State Plane Coordinate System, South Zone

0 2,000 FEET

0 500 METERS

EXPLANATION

- BEDROCK
- —850— POTENTIOMETRIC CONTOUR -- Shows altitude at which water would have stood in tightly cased wells (August 23, 1988). Contour interval 5 feet. Datum is sea level
- • MONITORING WELL
- o WATER-SUPPLY WELL
- \+ PURGE WELL
- ⊕ PROPOSED PURGE WELL
- ■ IDENTIFIED SOURCE OF CONTAMINANTS
- ▲ STREAM-GAGING STATION

Figure 15. Simulated potentiometric surface of glacial and alluvial aquifer for current purge system and eight additional purge wells, Verona well field area, Battle Creek, Michigan.

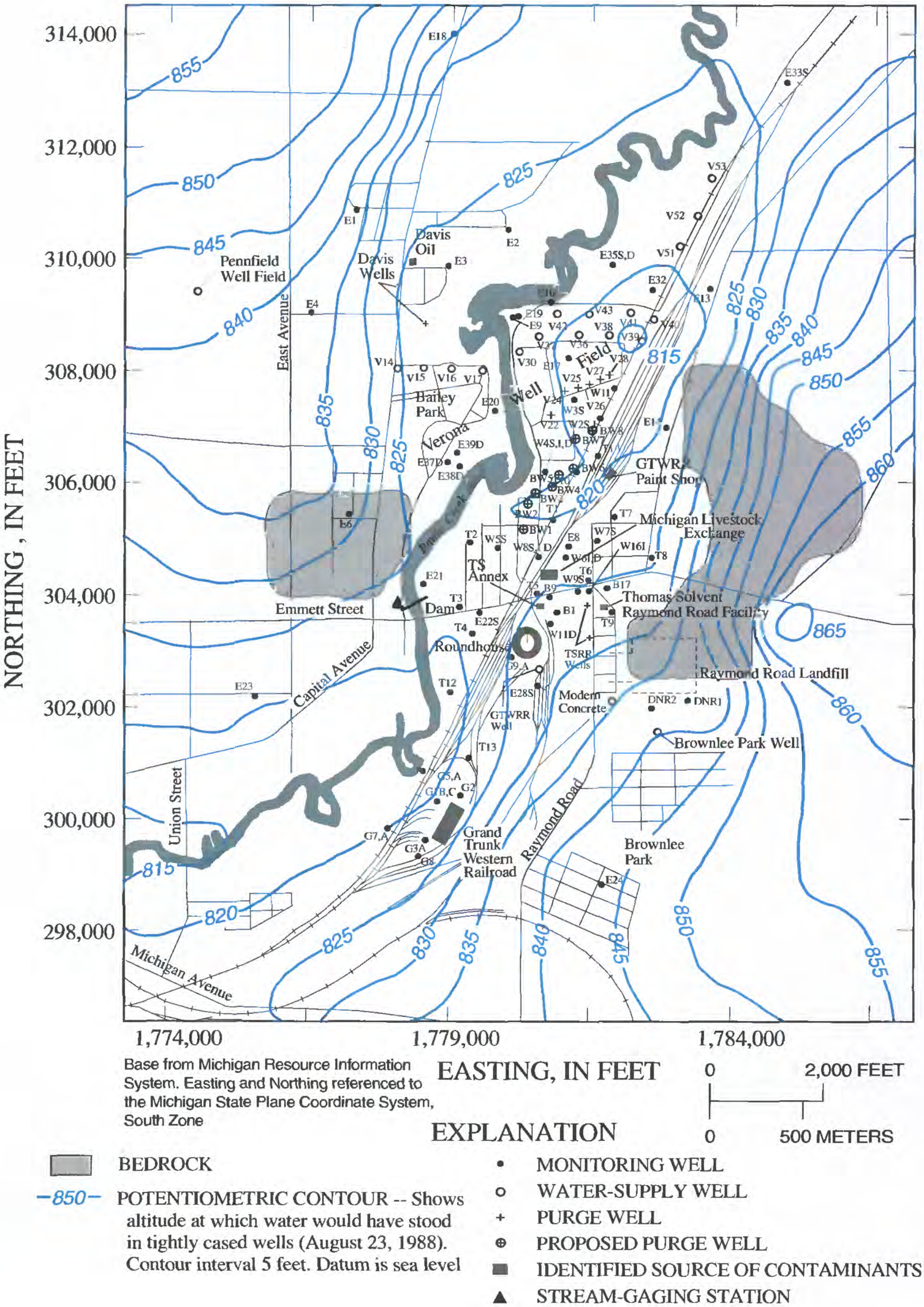


Figure 16. Simulated potentiometric surface of glacial and alluvial aquifer with eight purge wells, Verona well field area, Battle Creek, Michigan.

of the Marshall Sandstone and stops at the location of purge wells V26, V27, and V28, which are not pumping in this simulation. Most water from Davis Oil flows vertically to the upper part of the Marshall Sandstone. A small amount, however, flows to production wells V39 and V41. In the upper part of the Marshall Sandstone, the center of the cone of depression is raised by 4 ft and is much less steep than in the second simulation. In the lower part of the Marshall Sandstone, the cone of depression is increased by only 2 ft. The ground-water divide to the south of the cone of depression is slightly farther to the southwest. The simulation results indicate that this purge configuration protects the well field from contamination from the identified source locations to the south and east but not from the Davis Oil site.

Evaluation of Increased Ground-Water Production at Verona Well Field

August 1988 pumpage represents the addition of three wells (V51, V52, and V53) to the northeast of the well field. In comparison to summer 1983 pumpage, without these wells to the northeast, the cone of depression is deepened by about 2 ft and the cone of depression broadens to the northeast (figs. 17 and 18). All three wells draw water from areas northwest and southeast of the well field. The wells also draw water from the Battle Creek River immediately adjacent to the well field. Bear Lake to the northwest of the well field serves as a source of water to the wells, as do Gardner and Mud Lakes and surrounding swampy areas.

Ground-Water-Flow Rates and Directions Northwest of Verona Well Field

In the glacial and alluvial aquifer northwest of the Verona well field, under the current pumping and purging configuration, ground water flows to the southeast; as flow lines approach the Battle Creek River, they turn more easterly (fig. 14). Based on an effective porosity of 0.15, the velocity of ground-water flow at distance from the river is about 1.5 ft/d. As flow lines approach the Davis Oil area of contamination, ground-water flow increases to as much as about 5.3 ft/d. Flow rates then decrease to about 0.3 ft/d in the flood plain of the Battle Creek River due to a lower topographic gradient and finer grained sediments. Along these flow lines, the hydraulic conductivity ranges from 15 to 110 ft/d.

In the upper part of the Marshall Sandstone northwest of the Verona well field, ground water flows south to slightly southeast (fig. 19). Based on an effective porosity of 0.15 ft and a hydraulic conductivity of 150 ft/d, the velocity of ground-water flow in this area is about 1.5 ft/d.

In the lower part of the Marshall Sandstone northwest of the Verona well field, ground water flows south-southeast toward the well field (fig. 18). As flow lines approach the well field, the effect of pumping increases and flow lines are drawn in a more easterly direction. Based on an effective porosity of 0.15 and a hydraulic conductivity of 300 ft/d, the velocity of ground-water flow in this area is about 2.9 ft/d.

Expansion of Verona Well Field

Since publication of Grannemann and Twenter's report (1985), Verona well field has been expanded to the northeast by the addition of municipal wells V51, V52, and V53. The effect on the water table is observed by comparing head maps based on 1983 data (fig. 17), which were used in the previous study, and maps based on 1988 data (figs. 18 and 19) used in this study. The addition of the three wells to the northeast has deepened the cone of depression for the well field by about 2 ft. The cone of depression has broadened and the center has moved farther to the northeast.

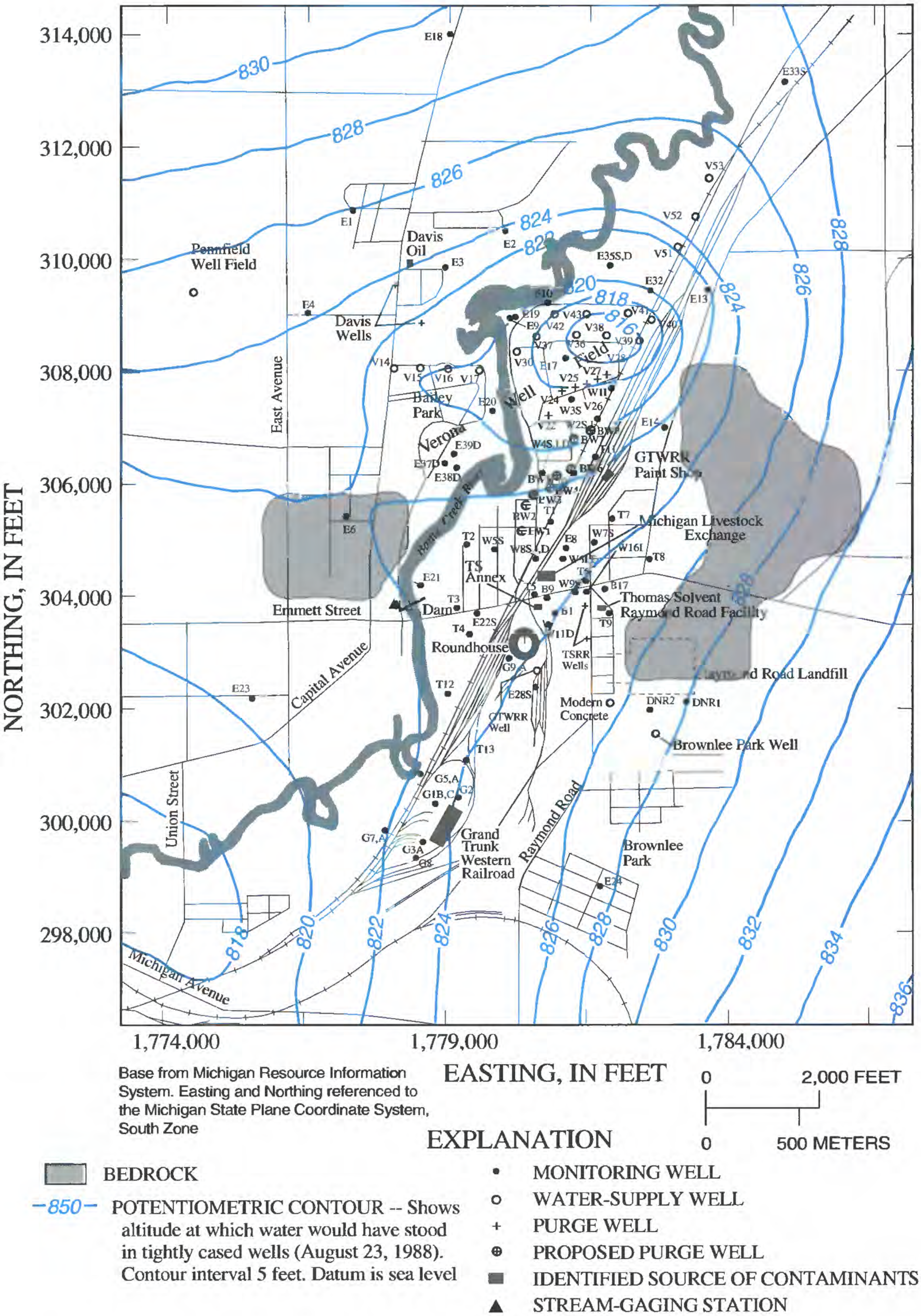
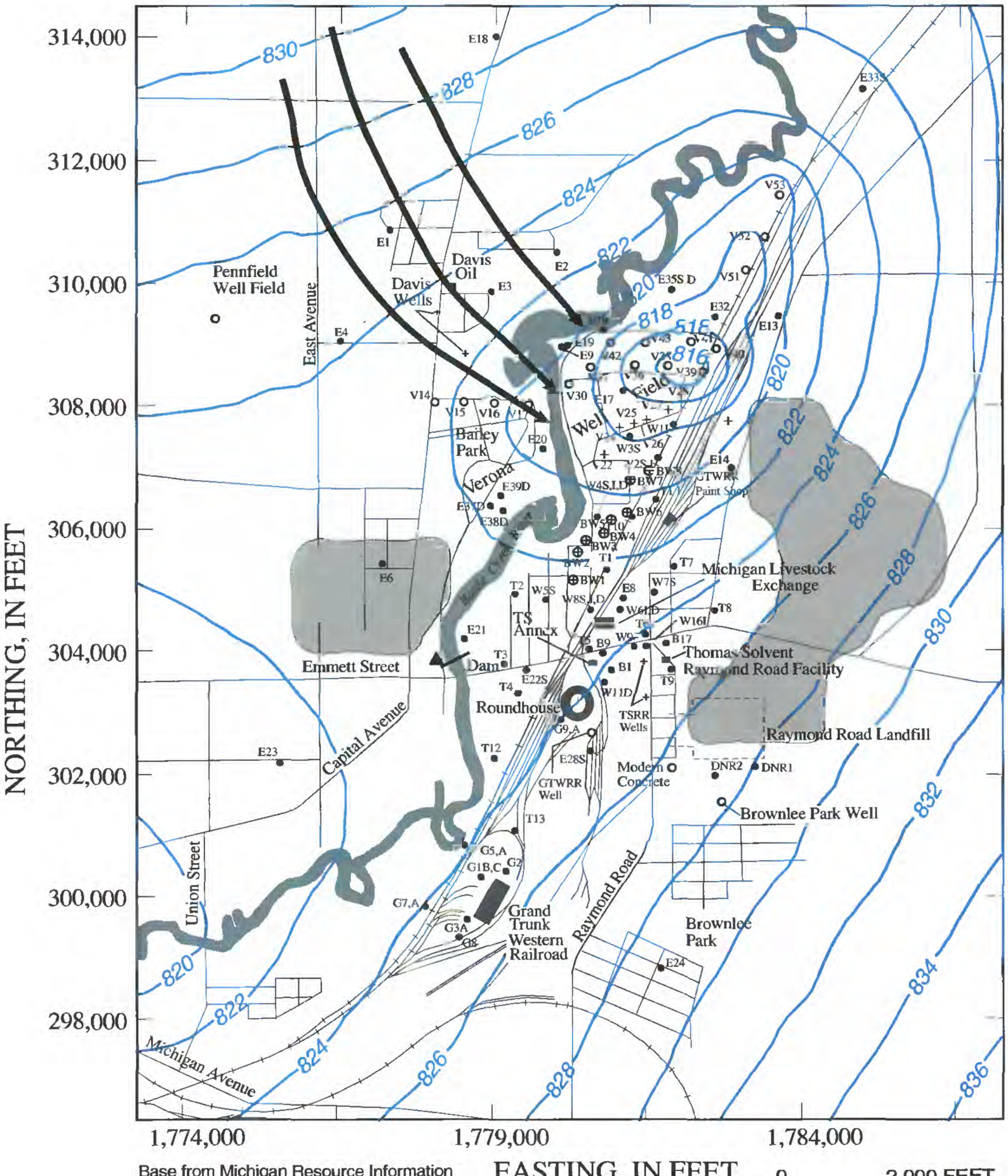


Figure 17. Simulated potentiometric surface of lower sandstone aquifer for summer 1983 data, Verona well field area, Battle Creek, Michigan.



Base from Michigan Resource Information System. Easting and Northing referenced to the Michigan State Plane Coordinate System, South Zone

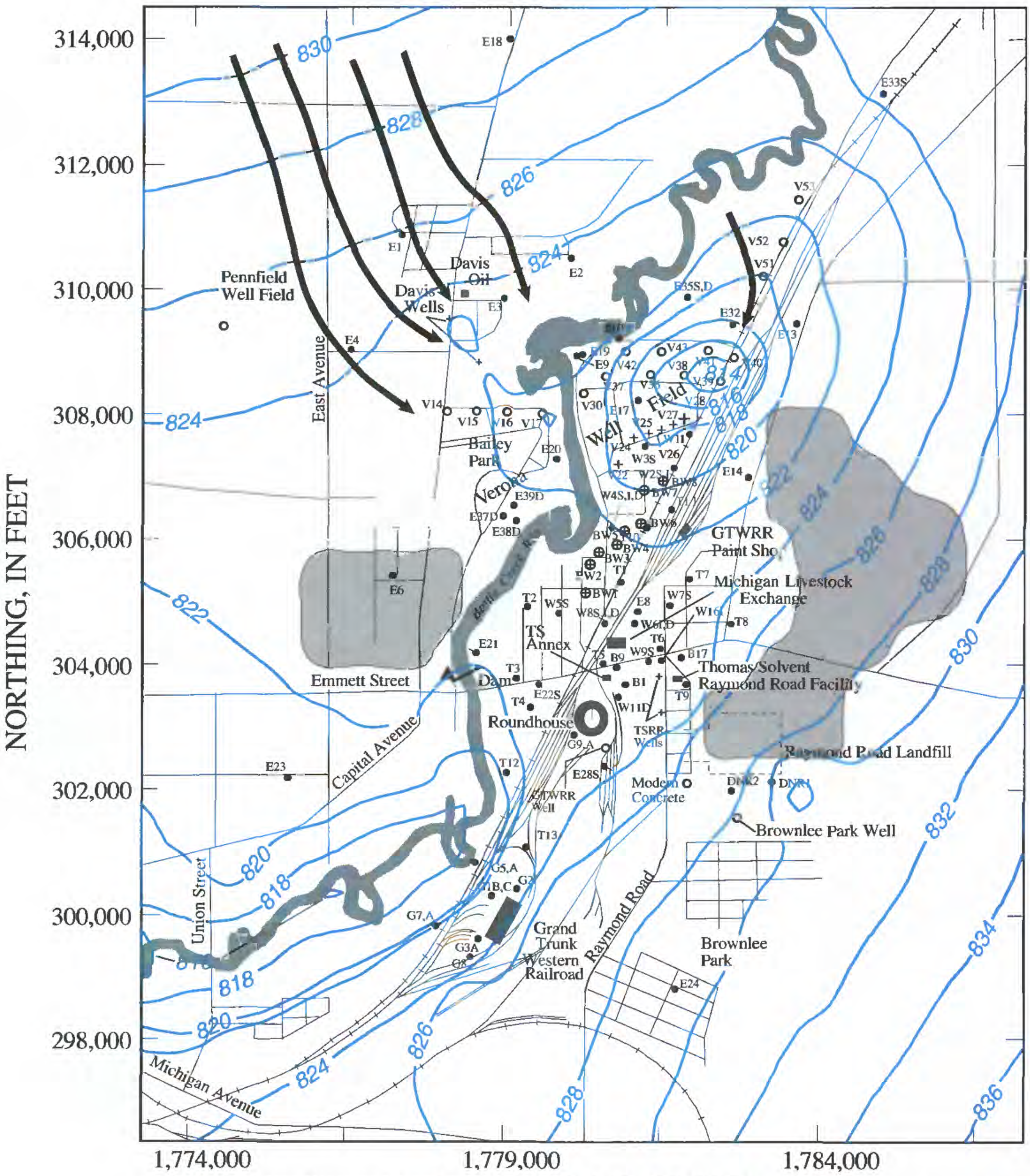
0 2,000 FEET

0 500 METERS

EXPLANATION

- BEDROCK
- 850 POTENTIOMETRIC CONTOUR -- Shows altitude at which water would have stood in tightly cased wells (August 23, 1988). Contour interval 5 feet. Datum is sea level
- DIRECTION OF FLOW
- MONITORING WELL
- WATER-SUPPLY WELL
- PURGE WELL
- PROPOSED PURGE WELL
- IDENTIFIED SOURCE OF CONTAMINANTS
- STREAM-GAGING STATION

Figure 18. Simulated potentiometric surface of lower sandstone aquifer with the addition of water-supply wells V51, V52, and V53, Verona well field area, Battle Creek, Michigan.



Base from Michigan Resource Information System. Easting and Northing referenced to the Michigan State Plane Coordinate System, South Zone

EASTING, IN FEET

0 2,000 FEET

0 500 METERS

EXPLANATION

BEDROCK

—850— POTENTIOMETRIC CONTOUR -- Shows altitude at which water would have stood in tightly cased wells (August 23, 1988). Contour interval 5 feet. Datum is sea level

DIRECTION OF FLOW

• MONITORING WELL

o WATER-SUPPLY WELL

+ PURGE WELL

⊕ PROPOSED PURGE WELL

■ IDENTIFIED SOURCE OF CONTAMINANTS

▲ STREAM-GAGING STATION

Figure 19. Changes in the potentiometric surface in the upper sandstone aquifer as a result of simulating pumping with the addition of wells northeast of the Verona well field, (wells V51, V52, and V53), Battle Creek, Michigan.

SUMMARY AND CONCLUSIONS

Verona well field is the primary source for the public water supply of Battle Creek, Mich. Wells in Verona well field are completed in the Marshall Sandstone. Volatile organic chemicals (VOCs) were detected in water samples collected from the water-supply wells in 1981. In 1985, six water-supply wells were converted to purge wells to intercept the VOCs from sources to the southeast of the well field. The removal of water-supply wells from service resulted in a water-supply shortage. In 1986, 1,900 gal of gasoline were spilled northwest of the well field. This spill could threaten supply wells on the west side of the well field. The USGS, in cooperation with the city of Battle Creek, did a study to determine the extent of secondary permeability of the Marshall Sandstone, evaluate the feasibility of relocating the present purge system, determine the rate and direction of ground-water flow in the area of gasoline contamination, reevaluate the effects of ground-water withdrawals on ground-water flow, and evaluate the possibility of expanding water-production capacity of Verona well field.

Secondary permeability was examined through the analysis of acoustic televiewer, gamma, and single-point resistance logs of wells in Bailey Park. Twelve fracture zones were identified in the Marshall Sandstone underlying Verona well field. Additional study of fracture zones using flowmeter and temperature logs defined a major inflow zone at a depth of about 70 ft and a major outflow zone at about 115 ft. The fracture zones are locally connected but appear to remain isolated over a lateral distance of 3,000 ft.

A numerical model of ground-water flow was developed based on a conceptual model of the study area surrounding and including the Verona well field area. The model describes a three layer system representing a glacial and alluvial aquifer and the upper and lower parts of the Marshall Sandstone aquifer. These aquifers are recharged by precipitation and leakage from rivers and streams. Discharge of these aquifers is through pumpage from Verona well field, Columbia well field, other surrounding wells, and leakage to rivers and streams. The numerical model or ground-water-flow model was used to examine ground-water flow from known source areas of VOCs under various purge system configurations, rate and direction of ground-water flow in the area of gasoline contamination, and effects of well field expansion on potentiometric surfaces of the aquifers.

The ground-water-flow model developed for this study shows that the current configuration of purge wells have not completely protected the well field from possible contamination by VOCs. Some water from source areas is captured by three production wells. The activation of a new purge system, consisting of eight wells south of the current system, allows virtually all water from the contaminant source areas to be captured. Expansion of the well field to the northeast may cause some water from the gasoline spill site to be drawn into 2 supply wells. Water quality in the area northeast of the well field is slightly better than that from within the well field based on lower concentrations of iron, manganese, and calcium carbonate. However, this area has significantly lower transmissivities than those within Verona well field.

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