

Approximate Location of the 10,000-Milligram-Per-Liter Dissolved-Solids Boundary in the Silurian and Devonian Carbonate-Rock Aquifer, Southwestern and Northern Indiana

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INTRODUCTION

The boundary between ground water with a dissolved-solids concentration greater than 10,000 mg/L (milligrams per liter) and ground water with a dissolved-solids concentration less than 10,000 mg/L in the Silurian and Devonian carbonate-rock aquifer in southwestern and northern Indiana has been used to establish one boundary for the Midwestern Basins and Arches regional ground-water-flow system. This boundary defines an internal "limit" for the Silurian and Devonian carbonate aquifers in Indiana where the mathematical simulation of ground-water flow must account for differences in fluid density. Additionally, a dissolved-solids concentration of 10,000 mg/L is a maximum limit for potential potability as recommended by the U.S. Environmental Protection Agency (1984). The boundary also has implications for the petroleum industry in deep parts of the Illinois Basin because the migration of hydrocarbons may be related to the presence and flow of connate saline water.

In 1988, the Midwestern Basins and Arches Regional Aquifer-System Analysis was initiated as part of the U.S. Geological Survey's Regional Aquifer-Systems Analysis (RASA) program (Sun, 1984). The objectives of the Midwestern Basins and Arches RASA project were to define the geology, hydrology, and geochemistry of the regional ground-water-flow system in the surficial and the Silurian and Devonian carbonate-rock aquifers (Bugliosi, 1990). The Silurian and Devonian carbonate-rock aquifer in southwestern

and northern Indiana has no distinct hydrogeologic boundary; therefore, the 10,000-mg/L dissolved-solids boundary defines one physical boundary condition that can be applied in ground-water-flow modeling.

Purpose and Scope

This report presents dissolved-solids data and identifies the approximate location of the 10,000-mg/L dissolved-solids boundary in the Silurian and Devonian carbonate-rock aquifer in southwestern and northern Indiana. This boundary is a three-dimensional transition zone between areas within the Silurian and Devonian carbonate-rock aquifer where ground water is likely to have a dissolved-solids concentration of either less than or greater than 10,000 mg/L. The 10,000-mg/L dissolved-solids boundary is mapped as a line for presentation purposes; however, the boundary is actually a diffuse zone where the dissolved-solids concentration changes from less than to greater than 10,000 mg/L. Rupp and Pennington (1987) show a generalized map for several deep aquifers containing the 10,000-mg/L dissolved-solids boundary across Indiana. Their study noted a fair correlation between regional structure and the position of the 10,000-mg/L dissolved-solids boundary within stratigraphic units.

The application of dissolved-solids concentrations to define the boundary between fresher water (dissolved-solids concentration less than 10,000 mg/L) and more saline water (dissolved-solids concentration greater than 10,000 mg/L) was used where the hydrologic boundaries in the Silurian and Devonian

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carbonate-rock aquifer were not distinct, such as on the lateral margins of the structural basins (fig. 1). Dissolved-solids concentrations were computed from geophysical information for areas where water-quality data were insufficient. Water wells in these areas are rarely drilled into the Silurian and Devonian carbonate-rock aquifer because potable ground water is more easily obtained from the overlying surficial aquifers or from overlying bedrock aquifers of Pennsylvanian and Mississippian age. Consequently, water-quality analyses for the carbonate-rock aquifer are scant in these areas of Indiana. Borehole-geophysical logs from oil and gas wells drilled in the study area were used to calculate dissolved-solids concentrations based on methods developed primarily by the petroleum industry.

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INTERPRETIVE BOREHOLE GEOPHYSICAL METHODS

The petroleum industry has developed methods to calculate the electrical resistivity of formation water, R_w , from geophysical logs (Asquith and Gibson, 1983). Three geophysical methods—resistivity-porosity, static-spontaneous-potential, and mud-filtrate resistivity (also called the “quick-look” method in the petroleum industry)—were used to calculate R_w 's for the Silurian and Devonian carbonate-rock aquifer in Indiana where water-quality data were insufficient. Each geophysical method yields R_w 's from which dissolved-solids concentrations can be extrapolated. The calculated R_w is a function of the concentration of dissolved ions, the ion species, and the formation temperature.

The estimate of dissolved-solids concentration is extrapolated from R_w on the basis of nomographs and is reported as a sodium chloride equivalent. All dissolved-solids concentrations calculated by application of geophysical methods are based on a sodium chloride equivalent. Chemical analyses of ground

water from deep wells in Indiana indicate that the dominant ions in water with dissolved-solids concentrations of about 10,000 mg/L are sodium and chloride. Because sodium and chloride are the dominant ions, the effects of other ions are minor, particularly at dissolved-solids concentrations of 10,000 mg/L and greater. Other ions, such as sulfate and bicarbonate, can be more important in waters in Indiana that are not dominated by sodium and chloride, particularly at dissolved-solids concentrations of 2,000 mg/L or less. Typically, sodium-chloride-equivalent dissolved-solids concentrations were only 1 to 2 percent less than the actual sodium chloride dissolved-solids concentrations for the Devonian ground water examined in this study, this minimal difference indicating that sodium and chloride are the dominant ions. Geosciences Research Associates, Inc., and the Department of Geosciences, Purdue University (1984), also concluded that sodium and chloride are the dominant ions in ground water in southwestern Indiana with dissolved-solids concentrations near 10,000 mg/L and greater.

An additional assumption in calculating R_w from geophysical logs is the formation temperature (T_f). All calculated values of R_w are made at a specific temperature and are converted to dissolved-solids concentration on the basis of nomographs (Schlumberger Well Services², 1986, p. 5). The natural geothermal gradient in Indiana increases with depth in a borehole. Formation temperature can be estimated from the bottom-of-hole temperatures listed on log headers and by assuming a linear increase in temperature with depth. A shallow (10-foot (3-meter) deep) ambient subsurface temperature of 55° Fahrenheit (12.8° Celsius) was used as the temperature for the top of each borehole.

Dissolved-solids concentrations were calculated by use of each of the three geophysical methods for 13 data sets. Results were compared by regression analysis to water-quality data from the same well or a nearby well producing from a similar geologic unit (Schnoebelen and others, 1995). In general, the resistivity-porosity method produced dissolved-solids concentrations that most closely matched measured concentrations. Therefore, dissolved-solids concentrations calculated with the resistivity-porosity method were used most often to delineate the 10,000-mg/L

² Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

dissolved-solids boundary. The static-spontaneous-potential (SSP) method was applied in a few cases where modern (post-1970) porosity logs that are necessary for the resistivity-porosity method were not available. Dissolved-solids concentrations calculated based on the mud-filtrate resistivity method did not match water-quality data closely and were not used in determining the 10,000-mg/L dissolved-solids boundary. Schnoebelen and others (1995) has a detailed description of the methodology and statistical analysis of the geophysical methods used to define the 10,000-mg/L dissolved-solids boundary.

Criteria for Data Selection

Certain criteria were used for selecting specific intervals on geophysical logs to derive data for the calculation of R_w . Typically, a 10-foot (3-meter) interval from the geophysical log was chosen; porosity was to be greater than 8 percent, and no shale content was evident from the log. Some zones with indicated porosities of 5 to 8 percent were used if they were the only data available in the area. Additional criteria were that (1) the borehole annulus had to be uniform in size, (2) zones of interest had to be permeable, and (3) aquifers had to be water saturated (no oil and gas). The mud-filtrate resistivity value, R_{mf} , from the log header was used; otherwise, R_{mf} was calculated from the resistivity of the mud, R_m . Geophysical methods used and the inherent assumptions for each method are described in detail by Jorgensen (1989), Schlumberger Well Services (1989), and Asquith and Gibson (1983).

Resistivity-Porosity Method

The resistivity-porosity method was applied most often when modern (post-1970) porosity logs were available. In this method the following equations are used to calculate resistivity as

$$R_w = R_t/F \quad (1)$$

and

$$F = a/\phi^m, \quad (2)$$

where

- R_w is the resistivity of the formation water at formation temperature, in ohm-meters;
- R_t is true resistivity (deep) of the formation, in ohm meters, measured beyond the effect of mud-filtrate invasion of the formation;

- F is the formation factor;
- a is an empirically derived tortuosity coefficient;
- ϕ is porosity; and
- m is an empirically derived cementation exponent.

An average porosity was usually derived from a crossplot of density and neutron porosity (Schlumberger Well Services, 1989, p. 26–33). The tortuosity coefficient is assumed to be 1.0 for carbonates and in this study. A cementation exponent (m) of 2.0 is commonly assumed for carbonates (Schlumberger Well Services 1989, p. 8.1). A value of 2.0 was used in this study and confirmed in core analysis (Schnoebelen and others, 1995).

Static-Spontaneous-Potential Method

In the SSP method, data from the spontaneous-potential (SP) log are used. The equation used to calculate resistivity is

$$R_{we} = R_{mfe}/10^{(ssp/-k)}, \quad (3)$$

where

- R_{we} is equivalent formation water resistivity at the formation temperature, in ohm-meters;
- R_{mfe} is equivalent mud-filtrate resistivity at the formation temperature, in ohm-meters;
- ssp is the deflection (signed + or -), in millivolts, from a referenced shale baseline; and
- k is a constant approximated by $61 + 0.133(T_f)$.

R_{mfe} is calculated from the resistivity of the mud filtrate, R_{mf} (Schlumberger Well Services, 1989, p. 4.2), R_w is calculated from R_{we} (Schlumberger Well Services, 1986, p. 3), and T_f is the formation temperature, in degrees Fahrenheit. The shale baseline picked for this method was from geophysical logs that represented the Upper Devonian shale section. The selection of this line is somewhat arbitrary and can have a large effect on dissolved-solids concentrations calculated on the basis of the SSP method.

Mud-Filtrate-Resistivity Method

The mud-filtrate-resistivity method (commonly called the “quick-look method” in the petroleum industry) was found to give the least accurate results when compared with known dissolved-solids

concentrations; thus, it was not used to define any dissolved-solids concentrations for the purpose of delineating the 10,000-mg/L dissolved-solids boundary. The equation used for this method is

$$R_w = (R_{mf})(R_t/R_{x0}), \quad (4)$$

where

- R_w is the resistivity of the formation water at formation temperature, in ohm-meters;
- R_{mf} is resistivity of the mud filtrate at formation temperature, in ohm-meters;
- R_t is the resistivity of water-saturated formation, in ohm-meters; and
- R_{x0} is the resistivity of the flushed zone directly near the borehole, in ohm-meters.

This method was not considered to work well because R_{x0} and R_t values were often similar. This similarity can occur if the driller uses a freshwater-based drilling mud (which is common in southern Indiana) and if the invasion of drilling mud into the formation is deep and a shallow flushed zone does not develop nearest the borehole.

THE 10,000-MILLIGRAM-PER-LITER DISSOLVED-SOLIDS BOUNDARY

The position of the 10,000-mg/L dissolved-solids boundary (fig. 2) was interpolated from available water-quality data and dissolved-solids concentrations that were calculated by either the resistivity-porosity or the static-spontaneous-potential geophysical methods. Data used to evaluate the position of the 10,000-mg/L dissolved-solids boundary are listed in table 1 (at back of pamphlet). In northern Indiana, the boundary is somewhat coincident with the contact between the Traverse Formation and the Antrim Shale within the Devonian carbonate bedrock (fig. 3). In the western and southern parts of Indiana, the 10,000-mg/L dissolved-solids boundary is west of the contact between the Muscatatuck Group limestone and the New Albany shale units within the upper part of the Devonian carbonate bedrock and extends downdip into the Illinois structural basin. The 10,000-mg/L dissolved-solids boundary lies predominantly within the upper part of the Devonian carbonate strata of the Silurian and Devonian carbonate-rock aquifer but was also calculated within Silurian units where data was available (for example, site numbers 105, 107, 108, 133, and 142 in fig. 2 and table 1).

Anomalous areas were found in the southwestern part of Indiana (Martin, Daviess, Lawrence, and

Dubois Counties). The anomalously high dissolved-solids concentrations in ground water in Devonian bedrock from some wells in Lawrence and Martin Counties (sites 141 and 103) may be from trapped connate water that is more saline or that has not been flushed by Pleistocene meltwater or more recent recharge. Higher dissolved-solids concentrations in the Devonian carbonate-rock aquifer may represent older ground water trapped in isolated "pockets" within the relatively low-permeability bedrock of Devonian age. The range of different porosities and permeabilities in the Devonian carbonates that could lead to poor vertical communication between zones of similar porosity is discussed by Noel (1979, p. 22–23) for the Plummer field, Greene County, Indiana. The Silurian section is also known to display complex porosities and permeabilities. Strontium isotope work by Stueber and others (1987) in the Silurian reservoir at the Tilden field in the Illinois Basin indicate that wells may be tapping zones of porosity that have been isolated for a considerable period of time. Clearly, the complex nature of the hydraulic properties of Devonian and Silurian carbonates affects the distribution of fluids for the Plummer and Tilden fields, and similar conditions are probably present elsewhere in the study area. The more porous and permeable sections of Devonian and Silurian carbonate bedrock may reflect increased flushing by fresher water, whereas the isolated "pockets" were not affected.

Lower dissolved-solids concentrations were calculated for the Silurian section from borehole geophysical logs in Martin, Daviess, Lawrence, and Dubois Counties (site numbers 105, 107, 108, 133, and 142) than in water from boreholes in the overlying Devonian carbonates. Two hypotheses may explain the occurrence of denser saline water (more than 10,000 mg/L dissolved solids) above less dense, less saline water (less than 10,000 mg/L dissolved solids). The first hypothesis is that Silurian carbonate bedrock generally has a greater porosity than rock of Devonian age in this area; therefore, movement of Pleistocene or recent ground water may have preferentially moved into the Silurian bedrock. Similarly, Rupp and Pennington (1987) indicate that variable horizontal permeabilities within the carbonate-rock aquifer may affect the preferential movement of fresher water laterally and downdip beneath Devonian carbonates into the underlying Silurian carbonates in southwestern Indiana.

The second hypothesis is that bedding displacements produced by movement of the Mt. Carmel Fault (fig. 2) may have contributed to anomalous (lower) dissolved-solids concentrations than expected near the fault area. The fault area may provide preferential paths for the mixing of saline water with freshwater.

Geochemical and isotope work by Stueber and Walter (1993) in the Illinois Basin indicate that the salinities of the Silurian-Devonian waters are the result of mixing with remnant evaporated seawater and meteoric water. They discuss that the original marine waters have not been completely expelled and replaced by meteoric water. Geochemistry and isotope work for Upper Devonian carbonates in the Michigan Basin (Wilson and Long, 1993) also indicates that Devonian brines are a mixture of seawater brine diluted with meteoric-derived water. They show that dilution from meteoric water predominantly occurred along the basin margin. A mixture of more saline and meteoric water in the Indiana Devonian-Silurian section would be possible, resulting in anomalous areas related to the depositional and ground-water flow history and the local variability in porosities/permeabilities. Clearly, more research using geochemistry and isotopes is needed in these anomalous areas to explain the flow of saline Silurian-Devonian water into the Illinois and Michigan Basins.

SUMMARY AND CONCLUSIONS

The 10,000-mg/L dissolved-solids boundary in the Silurian and Devonian carbonate-rock aquifer in southwestern and northern Indiana defines a limit where the mathematical simulation of ground-water flow may need to account for differences in fluid density. This boundary also defines a maximum limit for potentially potable water as recommended by the U.S. Environmental Protection Agency (1984). Defining the boundary would also be important for the petroleum industry in deeper parts of the Illinois Basin because the migration of hydrocarbons may be related to the presence and flow of connate saline water.

Estimated dissolved-solids concentrations calculated on the basis of three borehole geophysical methods (resistivity porosity, static spontaneous potential, and mud filtrate resistivity) were evaluated. Water-quality data and dissolved-solids concentrations calculated on the basis of two borehole-geophysical methods (resistivity porosity and static spontaneous potential) were then used to establish dissolved-solids

concentrations of ground water at selected sites. The mud-filtrate-resistivity method was not used to define the 10,000 mg/L boundary. The mud-filtrate-resistivity method did not work well and appears limited because of the low contrast between the resistivity of the drilling mud and pore fluid in the study area. This can be caused by deep invasion of the drilling mud and (or) by use of freshwater-based drilling muds, which are often similar to pore fluid in ionic content.

A line representing the 10,000-mg/L dissolved-solids boundary in the northern part of Indiana is north of the contact between Devonian limestone and shale units and south and west of this contact in southern and western Indiana. In general, the formation water in the carbonate-bedrock aquifer becomes more saline downdip, and northward into the Michigan Basin in northern Indiana and southwestward into the Illinois Basin in southwestern Indiana.

The dissolved-solids concentration of ground water normally increases with depth from land surface. However, dissolved-solids concentrations of ground water from some of the boreholes in Devonian strata in Martin, Daviess, Lawrence, and Dubois Counties were higher than dissolved-solids concentrations of ground water in the underlying Silurian bedrock. The higher dissolved-solids concentrations in aquifers that are stratigraphically above aquifers with lower dissolved-solids concentrations may represent older water in isolated "pockets" of the bedrock of Devonian age positioned above Silurian strata that have been significantly diluted by Pleistocene-age or recent ground-water recharge.

The anomalously high dissolved-solids concentrations in ground water in Devonian bedrock from some boreholes in Martin and Lawrence Counties may be from trapped connate water that is more saline or that has not been flushed by Pleistocene meltwater or more recent recharge. More porous and permeable sections of Devonian and Silurian carbonate bedrock possibly indicate increased flushing by fresher water.

Water with dissolved-solids concentrations lower than expected (when following the trend downdip) in southwestern Indiana also may be due to proximity to the Mt. Carmel Fault and ground-water flow through localized zones of high horizontal permeability within the Silurian and Devonian carbonate-rock aquifer. A lack of data for Devonian aquifers in these anomalous areas precludes making any definite conclusions. Clearly, more research focused on these anomalous areas is needed.

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Table 1. Well data and dissolved-solids concentrations of ground water in wells used to approximate the location of the 10,000-milligram-per-liter dissolved-solids boundary in the Silurian and Devonian carbonate-rock aquifer, southwestern and northern Indiana

[Land-surface altitude measured in reference to sea level; well depth, top, and bottom of interval measured from land surface; ft, feet; mg/L, milligrams per liter; SSP, static-spontaneous-potential method; Res/Por, resistivity-porosity method; Mud/Res, mud-filtrate-resistivity method; Dev/Sil, undifferentiated Devonian-Silurian; Sil/Ord, undifferentiated Silurian-Ordovician; --, not available or not calculated]

County	Site number	Land-surface altitude (ft)	Total well depth (ft)	Top of interval (ft)	Bottom of interval (ft)	Age of geologic unit	Dissolved-solids concentration, by source				
							Water-quality analyses		Geophysical analyses		
							Keller ¹ (mg/L)	Other ² (mg/L)	Res/Por (mg/L)	SSP (mg/L)	Mud/Res (mg/L)
Bartholomew	154	635	1,700	180	182	Silurian	1,100	--	--	--	--
Benton	26	772	1,370	322	330	Devonian	--	--	4,500	--	--
Clark	155	622	276	256	259	Devonian	--	--	70,000	--	--
Clay	59	664	1,407	1,377	1,381	Devonian	--	3,500	--	--	--
Clay	60	658	1,391	1,376	1,381	Devonian	4,000	--	--	--	--
Clay	61	635	1,588	1,566	1,570	Devonian	3,740	--	--	--	--
Clay	62	631	1,339	1,336	1,339	Devonian	--	2,840	--	--	--
Clay	63	622	1,458	1,315	1,321	Devonian	--	3,020	--	--	--
Clay	64	558	1,802	1,714	1,722	Devonian	--	--	3,400	11,000	3,400
Clay	65	586	1,379	1,374	1,379	Devonian	--	3,310	--	--	--
Clay	66	595	6,751	1,620	1,630	Devonian	--	--	4,500	--	--
Clay	67	550	1,964	1,812	1,820	Devonian	--	--	9,400	--	--
Clay	156	607	1,505	1,324	1,333	Devonian	--	--	3,200	15,000	4,700
Clay	157	567	1,950	1,848	1,858	Devonian	--	--	9,500	15,000	6,400
Crawford	137	738	1,995	1,774	1,784	Devonian	--	--	100,000	--	--
Crawford	138	738	1,830	1,714	1,724	Devonian	--	--	90,000	--	--
Daviess	95	548	2,462	1,748	1,758	Devonian	--	--	10,100	--	--
Daviess	96	479	2,659	1,836	1,856	Devonian	--	--	10,000	--	--
Daviess	96	479	2,659	1,950	1,962	Silurian	--	--	15,500	--	--
Daviess	97	524	2,010	1,874	1,884	Devonian	--	--	15,500	--	--
Daviess	98	487	2,600	2,360	2,372	Devonian	--	--	35,500	--	--
De Kalb	4	878	2,117	446	456	Devonian	--	--	--	4,700	--
Dubois	113	563	3,100	1,780	1,788	Devonian	--	--	3,700	--	--
Dubois	113	563	3,100	2,416	2,430	Silurian	--	--	12,500	--	--
Dubois	114	531	2,400	2,046	2,054	Devonian	--	--	35,000	--	--
Dubois	114	531	2,400	2,306	2,318	Silurian	--	--	35,000	--	--
Dubois	115	471	2,400	2,302	2,310	Silurian	--	--	35,000	--	--
Dubois	116	665	2,488	2,026	2,036	Devonian	--	--	38,000	--	--
Dubois	116	665	2,488	2,400	2,414	Silurian	--	--	30,500	--	--
Dubois	117	517	2,480	2,460	2,462	Devonian	--	--	42,000	--	--
Dubois	118	468	2,429	2,394	2,402	Devonian	--	--	46,000	--	--
Dubois	119	514	3,170	2,532	2,552	Devonian	--	120,000	--	--	--
Dubois	120	442	3,700	2,310	2,318	Devonian	--	--	54,500	--	--
Dubois	120	442	3,700	2,626	2,636	Silurian	--	--	54,000	--	--

Table 1. Well data and dissolved-solids concentrations of ground water in wells used to approximate the location of the 10,000-milligram-per-liter dissolved-solids boundary in the Silurian and Devonian carbonate-rock aquifer, southwestern and northern Indiana—Continued

[Land-surface altitude measured in reference to sea level; well depth, top, and bottom of interval measured from land surface; ft, feet; mg/L, milligrams per liter; SSP, static-spontaneous-potential method; Res/Por, resistivity-porosity method; Mud/Res, mud-filtrate-resistivity method; Dev/Sil, undifferentiated Devonian-Silurian; Sil/Ord, undifferentiated Silurian-Ordovician; --, not available or not calculated]

County	Site number	Land-surface altitude (ft)	Total well depth (ft)	Top of interval (ft)	Bottom of interval (ft)	Age of geologic unit	Dissolved-solids concentration, by source				
							Water-quality analyses		Geophysical analyses		
							Keller ¹ (mg/L)	Other ² (mg/L)	Res/Por (mg/L)	SSP (mg/L)	Mud/Res (mg/L)
Dubois	120	442	3,700	2,582	2,590	Silurian	--	--	54,000	--	--
Dubois	121	461	2,900	2,774	2,782	Silurian	--	--	98,000	--	--
Dubois	122	503	2,457	2,086	2,092	Devonian	--	--	49,000	--	--
Dubois	122	503	2,457	2,290	2,300	Silurian	--	--	59,000	--	--
Dubois	123	739	2,451	2,016	2,022	Devonian	--	--	94,000	--	--
Dubois	123	739	2,451	2,134	2,142	Dev/Sil	--	--	115,000	--	--
Dubois	124	553	2,676	2,484	2,494	Silurian	--	--	70,000	--	--
Elkhart	9	760	1,000	290	292	Devonian	13,517	--	--	--	--
Elkhart	10	815	4,132	412	420	Devonian	--	--	11,500	--	--
Elkhart	10	815	4,132	666	676	Silurian	--	--	13,000	--	--
Fountain	28	591	865	600	602	Devonian	6,680	--	--	--	--
Fountain	29	495	1,116	1,057	1,059	Silurian	11,950	--	--	--	--
Greene	80	540	1,750	1,732	1,750	Devonian	9,399	--	--	--	--
Greene	81	563	1,528	1,485	1,528	Devonian	6,272	--	--	--	--
Greene	82	587	1,530	1,510	1,529	Devonian	4,997	--	--	--	--
Greene	83	557	3,214	1,580	1,610	Devonian	34,257	--	--	--	--
Greene	84	573	2,185	1,940	1,964	Devonian	--	--	--	22,000	6,200
Greene	85	580	1,785	1,735	1,755	Devonian	11,896	--	--	--	--
Greene	86	559	1,778	1,720	1,729	Devonian	7,761	--	--	--	--
Greene	87	563	1,834	1,739	1,756	Devonian	9,915	--	--	--	--
Greene	88	512	2,516	1,450	1,460	Devonian	--	--	8,200	--	--
Greene	89	576	2,704	1,648	1,674	Devonian	--	--	10,100	--	4,900
Greene	90	515	1,687	1,606	1,610	Devonian	15,730	--	--	--	--
Greene	91	537	1,690	1,628	1,634	Devonian	13,010	--	--	--	--
Greene	92	573	1,605	1,560	1,563	Devonian	--	6,480	--	--	--
Greene	92	573	1,605	1,517	1,521	Devonian	--	6,480	--	--	--
Greene	93	670	1,710	1,644	1,664	Devonian	--	--	11,000	--	--
Greene	94	478	2,000	1,914	1,928	Devonian	--	--	32,000	--	--
Harrison	139	662	1,759	986	994	Devonian	--	--	149,000	--	--
Harrison	139	662	1,759	1,114	1,126	Silurian	--	--	250,000	--	--
Jackson	153	535	2,169	402	410	Devonian	--	--	--	14,400	--
Knox	100	428	3,020	2,936	2,940	Devonian	--	--	185,000	--	--
Knox	101	411	3,510	3,308	3,415	Devonian	142,323	--	--	--	--
Knox	99	464	2,220	2,184	2,190	Devonian	--	--	27,500	--	--

Table 1. Well data and dissolved-solids concentrations of ground water in wells used to approximate the location of the 10,000-milligram-per-liter dissolved-solids boundary in the Silurian and Devonian carbonate-rock aquifer, southwestern and northern Indiana—Continued

[Land-surface altitude measured in reference to sea level; well depth, top, and bottom of interval measured from land surface; ft, feet; mg/L, milligrams per liter; SSP, static-spontaneous-potential method; Res/Por, resistivity-porosity method; Mud/Res, mud-filtrate-resistivity method; Dev/Sil, undifferentiated Devonian-Silurian; Sil/Ord, undifferentiated Silurian-Ordovician; --, not available or not calculated]

County	Site number	Land-surface altitude (ft)	Total well depth (ft)	Top of interval (ft)	Bottom of interval (ft)	Age of geologic unit	Dissolved-solids concentration, by source				
							Water-quality analyses		Geophysical analyses		
							Keller ¹ (mg/L)	Other ² (mg/L)	Res/Por (mg/L)	SSP (mg/L)	Mud/Res (mg/L)
La Grange	5	930	3,022	1,428	1,438	Silurian	--	--	60,000	--	--
La Grange	6	931	4,737	1,102	1,108	Devonian	--	--	80,000	--	--
La Grange	7	845	860	800	810	Devonian	--	--	55,000	--	--
Lake	23	715	660	183	194	Dev/Sil	--	625	--	--	--
Lake	24	640	660	54	76	Devonian	--	361	--	--	--
Lake	25	682	2,438	300	310	Silurian	--	--	--	2,200	--
La Porte	13	573	950	630	632	Silurian	11,580	--	--	--	--
La Porte	14	650	650	296	306	Devonian	--	--	--	800	--
La Porte	14	650	650	362	370	Devonian	--	--	--	900	--
La Porte	14	650	650	556	568	Silurian	--	--	--	10,500	--
La Porte	15	711	307	276	286	Devonian	17,600	--	--	--	--
La Porte	16	711	307	276	286	Devonian	8,810	--	--	--	--
La Porte	17	707	280	278	280	Devonian	12,100	--	--	--	--
La Porte	18	668	1,125	248	256	Dev/Sil	--	--	--	2,200	--
Lawrence	141	603	2,200	1,164	1,180	Devonian	--	--	22,000	--	--
Lawrence	142	562	2,500	850	854	Devonian	--	--	4,100	--	--
Lawrence	142	562	2,500	1,086	1,094	Silurian	--	--	3,700	--	--
Lawrence	143	659	2,502	852	860	Devonian	--	--	4,500	--	--
Lawrence	143	659	2,502	1,078	1,088	Silurian	--	--	6,600	--	--
Lawrence	144	503	2,656	760	768	Silurian	--	--	5,400	--	--
Lawrence	144	503	2,656	628	646	Devonian	--	--	5,400	13,500	1,700
Lawrence	162	743	882	794	800	Devonian	--	3,300	--	--	--
Lawrence	163	776	859	846	859	Devonian	--	3,516	--	--	--
Lawrence	164	577	716	672	676	Devonian	--	4,800	--	--	--
Marshall	12	789	4,082	320	328	Devonian	--	--	7,800	--	--
Martin	102	657	1,796	1,780	1,788	Devonian	--	--	3,700	--	--
Martin	103	707	3,050	1,824	1,836	Devonian	--	--	60,000	--	--
Martin	103	707	3,050	1,910	1,922	Devonian	--	--	60,000	--	--
Martin	104	639	3,050	2,132	2,288	Silurian	--	9,900	--	--	--
Martin	104	639	3,150	1,832	1,840	Devonian	--	--	18,500	31,000	11,500
Martin	105	536	5705	1,866	1,880	Devonian	--	--	21,000	--	10,000
Martin	105	536	5705	2,200	2,214	Silurian	--	--	4,500	--	5,000
Martin	106	565	3,135	1,874	1,890	Devonian	--	--	5,100	--	--
Martin	106	565	3,135	2,234	2,246	Silurian	--	--	7,000	--	--

Table 1. Well data and dissolved-solids concentrations of ground water in wells used to approximate the location of the 10,000-milligram-per-liter dissolved-solids boundary in the Silurian and Devonian carbonate-rock aquifer, southwestern and northern Indiana—Continued

[Land-surface altitude measured in reference to sea level; well depth, top, and bottom of interval measured from land surface; ft, feet; mg/L, milligrams per liter; SSP, static-spontaneous-potential method; Res/Por, resistivity-porosity method; Mud/Res, mud-filtrate-resistivity method; Dev/Sil, undifferentiated Devonian-Silurian; Sil/Ord, undifferentiated Silurian-Ordovician; --, not available or not calculated]

County	Site number	Land-surface altitude (ft)	Total well depth (ft)	Top of interval (ft)	Bottom of interval (ft)	Age of geologic unit	Dissolved-solids concentration, by source				
							Water-quality analyses		Geophysical analyses		
							Keller ¹ (mg/L)	Other ² (mg/L)	Res/Por (mg/L)	SSP (mg/L)	Mud/Res (mg/L)
Martin	107	449	2,003	1,848	1,864	Devonian	--	--	19,000	--	--
Martin	107	449	2,003	1,962	1,976	Silurian	--	--	17,000	--	--
Martin	108	458	2,856	1,612	1,626	Devonian	--	--	9,000	--	--
Martin	108	458	2,856	1,964	1,974	Silurian	--	--	8,000	--	--
Noble	8	917	2,201	470	550	Devonian	--	--	--	8,500	--
Orange	140	558	1,130	1,130	1,132	Devonian	--	19,900	--	--	--
Owen	68	565	1,150	³ 1,148	³ 1,150	Silurian	2,070	--	--	--	--
Owen	69	619	1,428	1,394	1,404	Devonian	--	--	2,800	--	--
Parke	30	496	1,686	1,200	1,202	Devonian	7,030	--	--	--	--
Parke	31	735	4,668	1,310	1,318	Devonian	--	--	2,200	--	--
Perry	135	748	3,534	2,030	2,032	Silurian	111,466	--	--	--	--
Perry	136	456	4,100	2,020	2,030	Silurian	--	--	56,000	--	--
Perry	136	456	4,100	1,794	1,802	Devonian	--	--	57,000	--	--
Pike	109	525	2,800	2,582	2,591	Devonian	--	--	31,000	--	--
Pike	110	506	3,050	2,368	2,380	Devonian	--	--	35,000	--	--
Pike	110	506	3,050	2,800	2,860	Dev/Sil	25,270	--	--	--	--
Pike	111	463	2,777	2,496	2,506	Devonian	--	--	25,000	26,000	5,500
Pike	111	463	2,777	2,634	2,646	Silurian	--	--	35,000	--	--
Pike	112	497	2,856	2,622	2,632	Devonian	--	--	145,000	--	--
Porter	20	616	864	840	842	Silurian	8,600	--	--	--	--
Porter	21	638	860	860	862	Sil/Ord	5,854	--	--	--	--
Porter	22	774	4,528	410	420	Devonian	--	--	2,700	--	--
Pulaski	19	689	1,200	205	207	Silurian	500	--	--	--	--
Scott	151	538	115	86	115	Devonian	30,200	--	--	--	--
Scott	152	534	128	88	128	Devonian	42,100	--	--	--	--
Spencer	126	495	2,904	2,454	2,464	Devonian	--	--	16,800	--	--
Spencer	126	495	2,904	2,492	2,502	Devonian	--	--	56,000	--	--
Spencer	127	405	4,486	2,054	2,056	Devonian	--	--	120,000	--	--
Spencer	127	405	4,486	1,963	1,967	Devonian	--	--	49,000	--	--
Spencer	128	450	2,775	2,542	2,552	Devonian	--	--	129,000	--	--
Spencer	129	451	2,552	2,400	2,410	Devonian	--	--	140,000	--	--
Spencer	129	451	2,552	2,530	2,540	Silurian	--	--	149,000	--	--
Spencer	130	449	2,335	2,250	2,260	Devonian	--	--	50,000	--	--
Spencer	131	425	2,750	2,628	2,634	Devonian	--	--	98,000	--	--

Table 1. Well data and dissolved-solids concentrations of ground water in wells used to approximate the location of the 10,000-milligram-per-liter dissolved-solids boundary in the Silurian and Devonian carbonate-rock aquifer, southwestern and northern Indiana—Continued

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County	Site number	Land-surface altitude (ft)	Total well depth (ft)	Top of interval (ft)	Bottom of interval (ft)	Age of geologic unit	Dissolved-solids concentration, by source				
							Water-quality analyses		Geophysical analyses		
							Keller ¹ (mg/L)	Other ² (mg/L)	Res/Por (mg/L)	SSP (mg/L)	Mud/Res (mg/L)
Spencer	131	425	2,750	2,682	2,690	Devonian	--	--	101,000	--	--
Spencer	132	510	3,150	2,864	2,872	Devonian	--	--	180,000	90,000	3,500
Spencer	132	510	3,150	2,894	2,904	Devonian	--	--	120,000	--	--
Spencer	133	450	2,964	2,352	2,362	Devonian	--	--	90,000	--	--
Spencer	133	450	2,964	2,710	2,720	Silurian	--	--	50,000	--	--
Spencer	134	478	2,801	2,771	2,783	Devonian	--	163,000	--	--	--
St. Joseph	11	836	2,103	548	556	Devonian	--	--	--	17,500	--
Steuben	1	1,058	3,363	1,194	1,200	Devonian	--	--	36,000	--	--
Steuben	2	1,050	3,340	1,674	1,682	Silurian	--	--	45,000	--	--
Steuben	2	1,050	3,340	1,176	1,186	Devonian	--	--	38,000	--	--
Steuben	3	988	3,126	918	928	Devonian	--	--	34,000	--	--
Sullivan	70	472	2,221	2,158	2,187	Devonian	29,142	--	--	--	--
Sullivan	71	509	2,281	2,242	2,246	Devonian	33,000	--	--	--	--
Sullivan	72	532	2,556	2,556	2,558	Silurian	59,473	--	--	--	--
Sullivan	73	516	2,229	2,089	2,116	Devonian	18,278	--	--	--	--
Sullivan	73	516	2,229	2,144	2,156	Devonian	17,535	--	--	--	--
Sullivan	74	524	2,039	2,021	2,025	Devonian	11,718	--	--	--	--
Sullivan	75	494	2,459	2,210	2,253	Devonian	--	--	60,500	60,000	9,500
Sullivan	76	501	2,409	2,386	2,401	Devonian	84,380	--	--	--	--
Sullivan	77	538	2,350	2,110	2,130	Devonian	--	--	7,900	10,500	3,200
Sullivan	78	526	2,351	2,072	2,092	Devonian	--	--	9,000	--	--
Sullivan	79	481	2,428	2,652	2,666	Devonian	--	--	70,000	--	--
Sullivan	158	524	2,320	2,292	2,302	Devonian	--	--	16,000	18,000	6,000
Sullivan	159	522	2,139	2,088	2,100	Devonian	--	--	9,000	10,000	6,500
Tippecanoe	27	553	230	217	219	Silurian	7,300	--	--	--	--
Vermillion	32	477	1,245	1,232	1,235	Devonian	7,700	--	--	--	--
Vermillion	33	620	1,463	1,370	1,380	Devonian	--	--	4,500	--	--
Vermillion	34	529	1,337	1,217	1,247	Devonian	6,040	--	--	--	--
Vermillion	160	591	1,494	1,382	1,392	Devonian	--	--	6,400	24,000	3,900
Vigo	35	503	1,617	1,537	1,541	Devonian	21,793	--	--	--	--
Vigo	36	505	1,793	1,783	1,793	Devonian	5,990	--	--	--	--
Vigo	37	490	1,865	1,800	1,802	Silurian	6,030	--	--	--	--
Vigo	38	562	1,671	1,645	1,669	Devonian	5,690	--	--	--	--
Vigo	38	562	1,671	1,652	1,670	Devonian	--	--	--	5,000	--

Table 1. Well data and dissolved-solids concentrations of ground water in wells used to approximate the location of the 10,000-milligram-per-liter dissolved-solids boundary in the Silurian and Devonian carbonate-rock aquifer, southwestern and northern Indiana—Continued

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County	Site number	Land-surface altitude (ft)	Total well depth (ft)	Top of interval (ft)	Bottom of interval (ft)	Age of geologic unit	Dissolved-solids concentration, by source				
							Water-quality analyses		Geophysical analyses		
							Keller ¹ (mg/L)	Other ² (mg/L)	Res/Por (mg/L)	SSP (mg/L)	Mud/Res (mg/L)
Vigo	39	568	1,697	1,670	1,682	Devonian	--	--	--	5,000	--
Vigo	40	559	1,860	1,712	1,740	Devonian	--	--	6,200	14,100	3,900
Vigo	41	563	1,702	³ 1,690	³ 1,700	Devonian	5,710	--	--	--	--
Vigo	42	490	1,691	1,684	1,687	Devonian	6,580	--	--	--	--
Vigo	43	499	1,762	1,681	1,704	Devonian	6,184	--	--	--	--
Vigo	44	500	1,700	1,688	1,691	Devonian	--	7,440	--	--	--
Vigo	45	505	1,702	1,675	1,702	Devonian	--	6,990	--	--	--
Vigo	46	523	1,885	1,782	1,810	Devonian	4,938	--	--	--	--
Vigo	47	607	1,720	1,621	1,641	Devonian	3,840	--	--	--	--
Vigo	48	610	3,200	2,004	2,020	Devonian	--	--	6,600	20,000	6,400
Vigo	49	635	1,920	1,897	1,900	Devonian	7,970	--	--	--	--
Vigo	50	583	2,130	1,920	1,935	Devonian	--	--	8,000	9,500	3,000
Vigo	51	579	2,450	2,310	2,321	Dev/Sil	--	--	15,000	7,200	3,500
Vigo	52	547	2,175	2,094	2,096	Devonian	15,898	--	--	--	--
Vigo	53	530	2,171	2,022	2,171	Devonian	14,010	--	--	--	--
Vigo	54	539	2,190	2,103	2,190	Devonian	13,538	--	--	--	--
Vigo	55	540	2,198	2,089	2,091	Devonian	18,117	--	--	--	--
Vigo	56	480	1,912	³ 1,840	³ 1,842	Dev/Sil	6,980	--	--	--	--
Vigo	57	492	1,835	³ 1,816	³ 1,833	Devonian	16,400	--	--	--	--
Vigo	58	536	2,300	2,162	2,192	Dev/Sil	--	--	12,500	32,000	7,100
Vigo	161	534	2,329	2,170	2,184	Devonian	--	--	14,000	38,000	8,000
Warrick	125	473	3,800	3,282	3,288	Silurian	--	--	250,000	--	--
Washington	145	521	638	631	638	Devonian	4,380	--	--	--	--
Washington	146	899	1,029	924	936	Devonian	--	--	112,000	--	--
Washington	147	860	2,735	1,014	1,022	Devonian	--	--	20,000	--	--
Washington	148	885	990	864	874	Devonian	--	--	140,000	--	--
Washington	149	957	975	872	880	Devonian	--	--	125,000	--	--
Washington	150	739	915	790	800	Devonian	--	--	62,000	--	--

¹Keller (1983) and Indiana Geological Survey brine data files.

²U.S. Geological Survey samples and sample records from independent petroleum operators.

³Approximate interval.