

Determination of the 10,000 mg/1 TDS Surface Within the Bedrock Aquifers of Indiana

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Introduction

Evaluation of the total dissolved solids (TDS) content of bedrock aquifers in Indiana indicates that the 10,000 mg/1 (ppm) TDS interface is a regionally mappable aquifer parameter. The position of this surface where the salinity of the ground water equals 10,000 mg/1 TDS is controlled by the hydrologic framework of the region, which includes the regional and localized geologic structure, the lateral and vertical permeability distribution, and the patterns of ground water flow under the influence of hydrologic boundary conditions.

Although water that contains 10,000 mg/1 TDS is considered brackish (1), this concentration of total dissolved solids was established by the U.S. Environmental Protection Agency as a maximum for potentially potable water. Determination of the 10,000 mg/1 TDS surface is therefore important to petroleum-producing industries, steel-manufacturing industries, and users of potable water from deep bedrock aquifers.

Salinity Determination

In order that the general patterns of salinity distribution in deep bedrock aquifers throughout the state be established, approximately three hundred records of subsurface borings were examined. Most of these records were composed of geophysical logs, drill stem test results, driller's records, and rock samples (drill cuttings). Much data were from oil and gas investigations. Additional data were derived from stratigraphic test holes, mineral exploration borings, and underground storage operations.

Although in reality the surface is probably a transition zone between brackish and saline water (1), for mapping purposes the position within the stratigraphic column where the salinity of the formation water is equal to 10,000 mg/1 TDS is considered to be a point on this surface. Three methods were utilized to determine the hydrostratigraphic position of the 10,000 mg/1 TDS surface: direct salinity measurement, interpretation of geophysical logs, and qualitative analysis of formation water.

The most reliable means of determining the TDS content of a given hydrostratigraphic unit is direct measurement coupled with laboratory analysis (2). Water samples from deep aquifers may be recovered from drill stem tests, swab and pumping tests, and cable-tool bailers. Samples analyzed in the laboratory yield a more complete and accurate determination of anion and cation concentrations responsible for TDS values. Documentation of the various major ionic components also allows for greater confidence in the determination of TDS levels. On-site electrical conductance tests provide a check on the laboratory analyses. A laboratory gravimetric determination of the bulk TDS value is possible but lacks the accuracy of a major ion analysis.

The second method of determining the salinity of these waters is by interpretive calculation from geophysical logs. Log calculations entail a series of assumptions, some of which are practically and economically documentable. The assumptions are:

NaCl is the sole source of dissolved solids, the temperature of the formation can be accurately established, and the petrophysical properties of porosity, permeability, and pore throat tortuosity and cementation are known. There were three different methods of log calculation used in this study: 1) the static spontaneous potential (SSP) method, 2) the resistivity-porosity ($R_t\text{-}\phi$) method, and 3) the "quick-look" method. The applications of the first two methods to salinity determination of sub-surface brines in the Indiana part of the Illinois Basin were investigated by Geoscience Research Associates and Purdue University (3).

The static spontaneous potential (SSP) method is the most widely utilized and possibly the most accurate of the calculation methods (4). The basic relationship is:

$$R_w = R_{mf}^{10^{\frac{T}{a}}}$$

where: R_w = resistivity of the formation water
 R_{mf} = resistivity of the mud filtrate
 T_a = $SP/.11(460 + T)$ = coefficient proportional
to the absolute temperature
SP = deflection of spontaneous potential log
T = temperature in °F

The SSP method is applicable only where a thick porous sand section lies within a shale (i.e. a clean sand/shale sequence). The method cannot be applied in a massive carbonate section where there is minimal SP deflection. The log must be run in a well drilled with freshwater-based mud. A SP/R_{mf} /temperature nomograph is commonly utilized to obtain a value for R_w (5). The R_w is then converted to the equivalent concentration of Cl^- in a temperature dependent chart (5).

The second means of log calculation, termed the resistivity-porosity ($R_t\text{-}\phi$) method (5), is often used in thick massive carbonate sections when no SP curve is available. The method is also applicable for use in sections that contain thin discontinuous porosity breaks. The basic relationship is:

$$R_w = R_t/F \text{ and } F = a/\phi^m$$

where: F = formation factor
R = resistivity of the formation
a = empirically derived tortuosity coefficient
 ϕ = porosity
m = empirically derived cementation exponent

F is determined most commonly by using the log-derived value for porosity and applying assumed values for cementation and pore-throat geometry based on lithologic interpretations. Actual values for a and m must be derived from laboratory analysis of cores. When values are not determined by laboratory analysis, values of 1 and 2.15 are usually assigned to these variables. Although a value for ϕ can be obtained from geophysical logs, there remains some question because of lithologic effects. As with the SSP method, a nomograph is used to derive a value for F from log-measured ϕ values, which is then divided into a log-measured value for R_t . R_w is again converted to equivalent Cl^- concentration in a temperature dependent chart.

The final log calculation method, the "quick-look," is a semi-quantitative method used when neither of the two previously described methods can be utilized but a resistivity log with deep (R_t) and shallow (R_{xo}) curves is available. This method basically compares the resistivity of the drilling mud with the resistivity of the formation water (4). From this comparison, an approximate value of R_w is obtained and converted to equivalent Cl^- concentration as in the first two methods. The relationship is:

$$R_w = R_{mf} (R_t/R_{x0})$$

where: R_{x0} = resistivity of the formation completely saturated with mud filtrate

Within the study area, the predominant type of log calculation utilized was the SSP method. Because some deep tests in northern Indiana lacked SP curves or contained the 10,000 mg/l TDS interface within the Knox carbonate section, the $R_t\phi$ method had to be used. The "quick-look" method was used most often in older tests in northern and eastern Indiana. All three methods were utilized in wells that had analyzed recovered fluids to cross-check the reported TDS values.

The third means of salinity determination is qualitative analysis of produced waters. If data are not available from laboratory-analyzed water samples or geophysical logs, an on-site comparison of recovered waters with waters of known salinity concentration is often helpful. The waters are qualitatively described in reference to taste, smell, and appearance. Comparison of this type of data in areas of low sample coverage can be meaningful for establishing basic salinity distribution in the rock column.

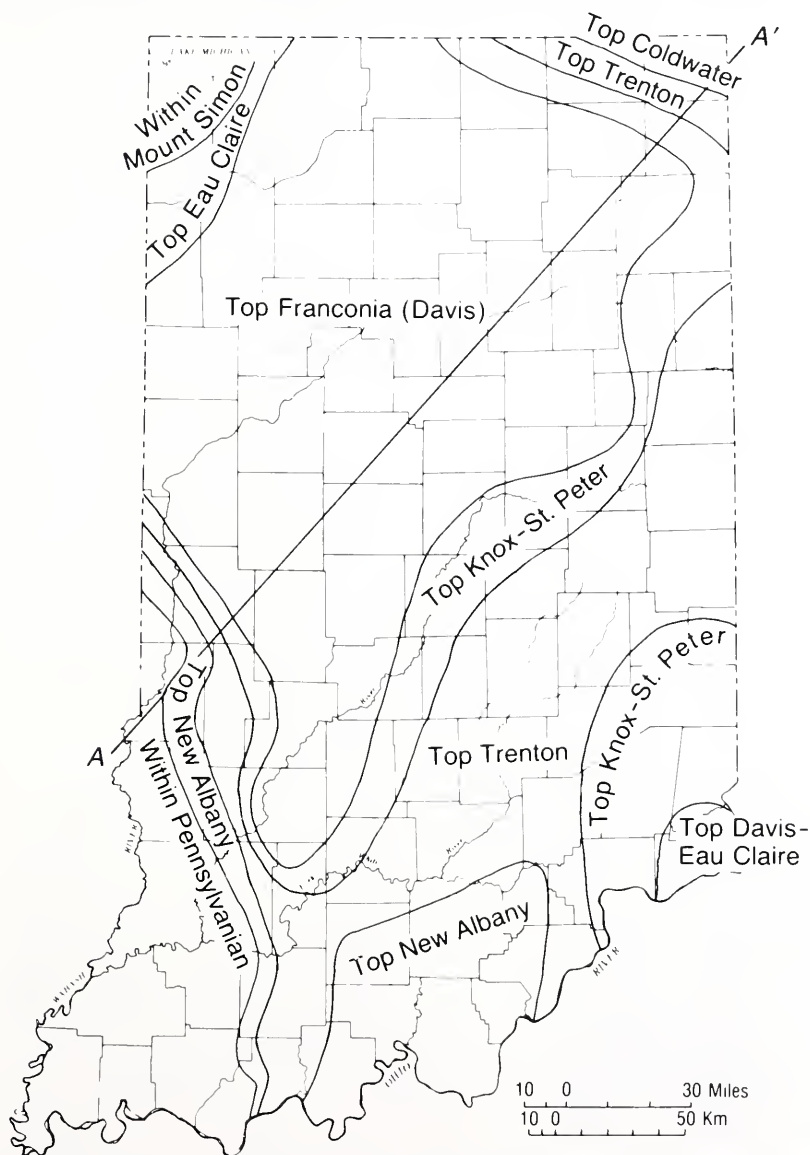


FIGURE 1. Map of Indiana showing hydrostratigraphic units in which the 10,000 mg/l TDS surface is located. A-A' is the line of cross section shown in Figure 4.

Mapping of the 10,000 mg/1 TDS Surface

Data derived from the various sources of formation water salinities were combined to form a map of Indiana showing the hydrostratigraphic units in which the 10,000 mg/1 TDS surface lies (Figure 1). The hydrostratigraphic units identified in this study were derived by dividing the lithostratigraphic column into aquifers, intermediate-quality aquifers, and aquitards or confining units (Figure 2). The 10,000 mg/1 TDS surface was designated as the top of the uppermost units that contained waters of greater than 10,000 mg/1 TDS. If the aquifer that contained these higher salinity waters was overlain by a non-reservoir rock unit of very low permeability (such as the Franconia Formation or the New Albany Shale), the surface was positioned at the top of the overlying impermeable unit. Although some units are of poor aquifer quality (such as the Ancell and Black River Groups), small discontinuous porosity breaks within them can contain water of less than 10,000 mg/1 TDS and are therefore classified as within the potentially potable ground water system. For these units, the 10,000 mg/1 TDS surface is placed at the base of the intermediate-quality aquifer or therefore at the top of the underlying aquifer bearing saline water (e.g. the Knox-St. Peter aquifer) (Figure 2).

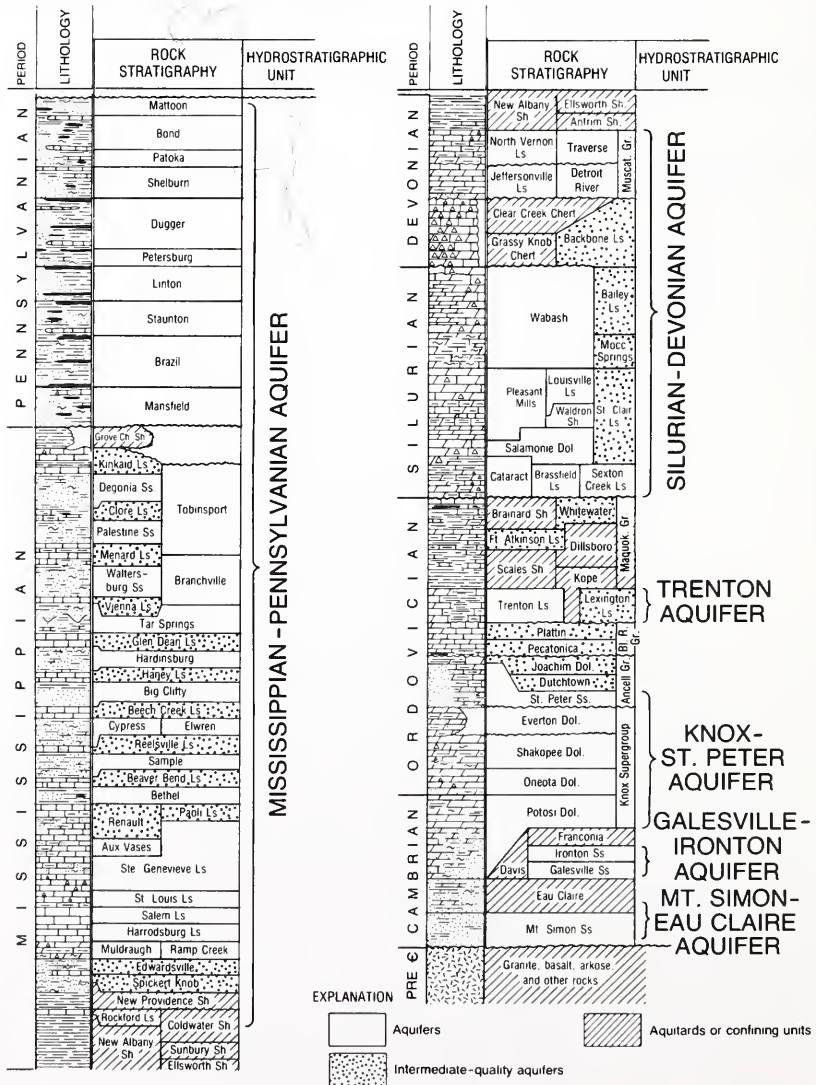


FIGURE 2. Generalized stratigraphic column for Indiana showing hydrostratigraphic units.

The factors that affect the geometry of this salinity transition surfaces are regional and localized structures, lateral and vertical permeability distribution, and recharge sources and flow gradients of aquifers. In a homogeneous porous medium with no external effects, the shape of the isosalinity surface will subparallel the topographic surface. The map of the 10,000 mg/l TDS surface indicates significant influence from the above mentioned factors.

Structural influence on the salinity surface is dominated by the large regional low-amplitude Cincinnati and Kankakee Arches which divides the state into the Michigan Basin to the northeast and the Illinois Basin to the southwest (Figure 3). Because older sediments are structurally higher along the arch, the 10,000 mg/l TDS surface occupies a lower hydrostratigraphic position along the axial trend. Smaller scale features such as faulting and fracture systems, may significantly affect the distribution of salinity in aquifers, most notably the Knox-St. Peter and Silurian-Devonian aquifers (Figure 4).

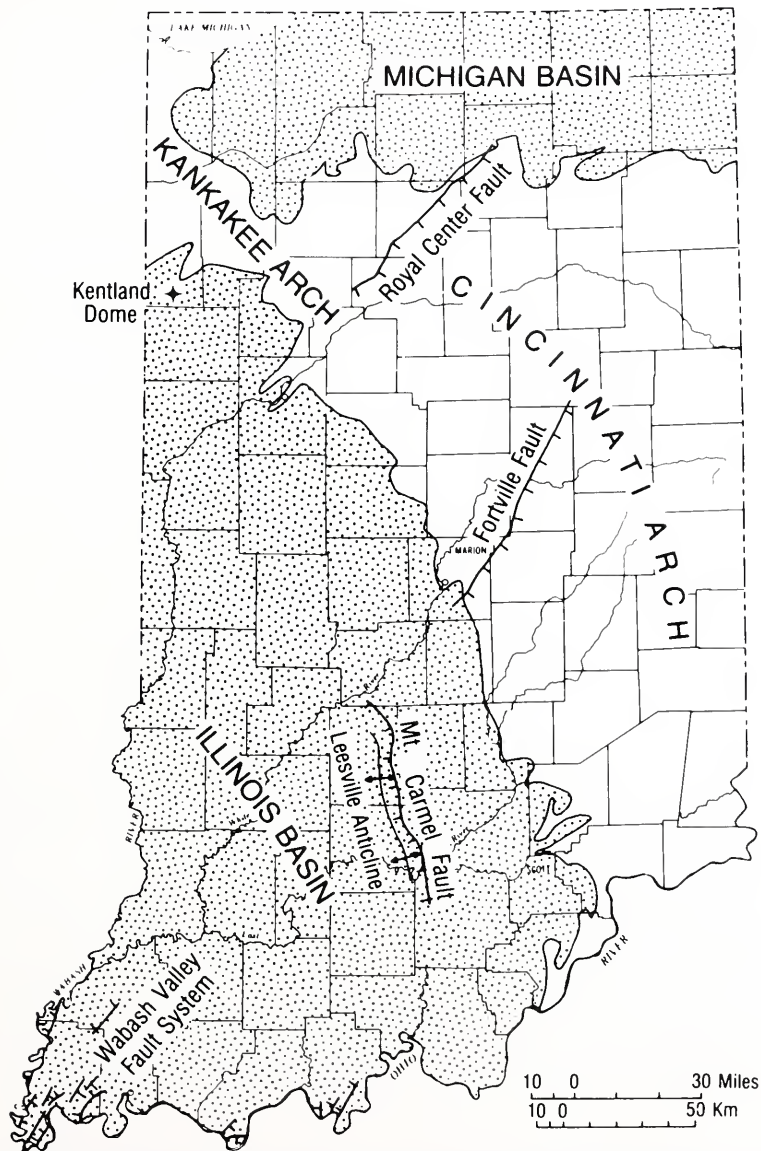


FIGURE 3. Map of Indiana showing major structural features. Basin margins are denoted by the erosional limit of the Muscatatuck Group.

Vertical and horizontal heterogeneities in the rock column are a major control on the distribution of fluid salinities in the subsurface (Figure 2). Because the subsurface strata of Indiana are not a homogeneous porous medium but are a series of interbedded aquifers and aquitards with varying horizontal and vertical hydraulic transmissivities, the 10,000 mg/l TDS surface "stairsteps" up the hydrostratigraphic column in an irregular manner (Figure 1). Horizontal variability in the permeability of various hydrostratigraphic units may be partially responsible for the different levels of fresh water infiltration in the Knox-St. Peter and Silurian-Devonian aquifers (Figure 4).

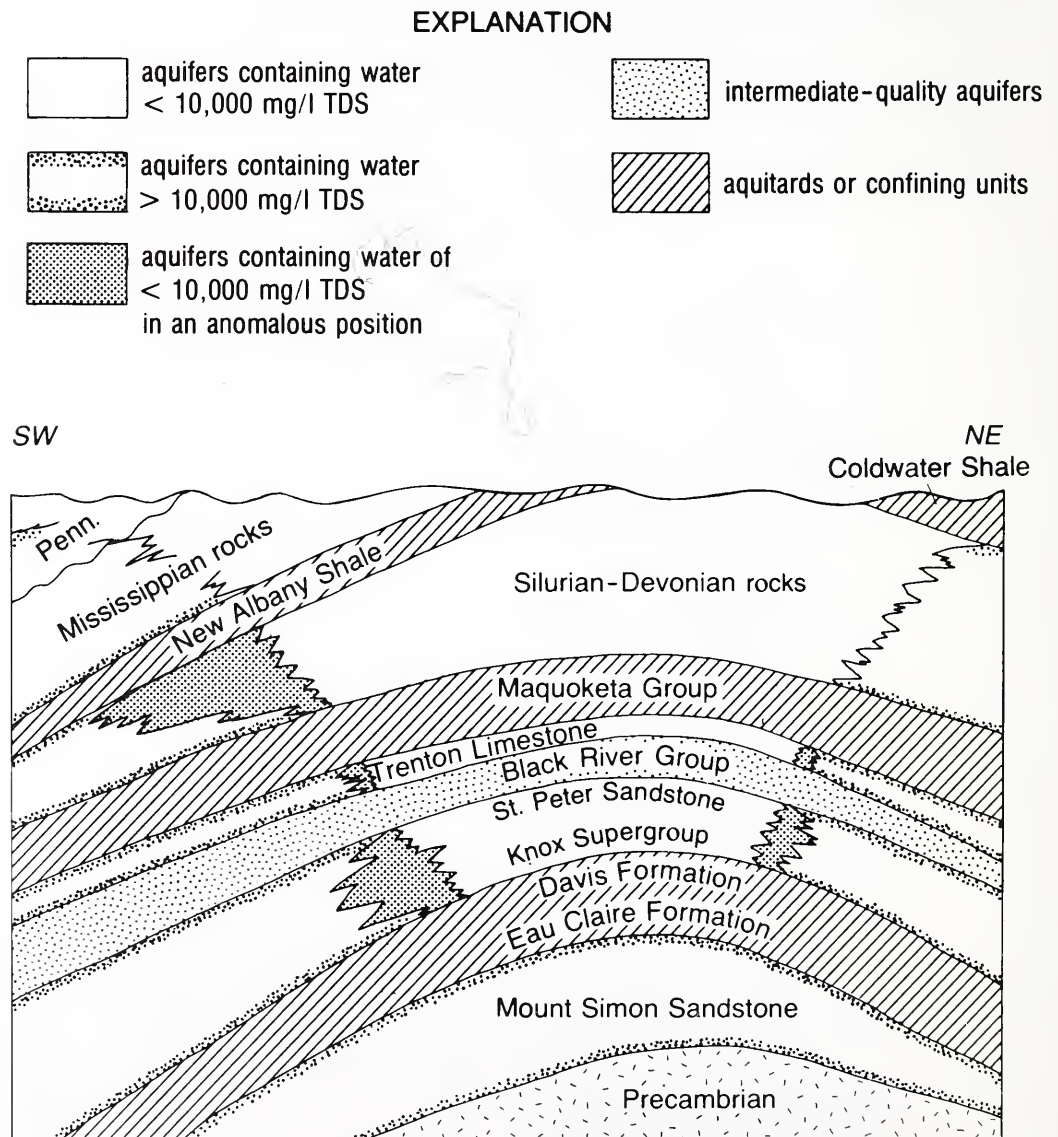


FIGURE 4. Diagrammatic southwest-northeast cross section showing the hydrostratigraphic position of the 10,000 mg/l TDS surface. Waters of less than 10,000 mg/l TDS plunge off of the axial trend of the Cincinnati Arch deep into the Illinois Basin.

The recharge and discharge areas of the aquifers also affect ground water flow and therefore the salinity distribution. Although most of the brackish and saline ground

water occurs in confined deep bedrock aquifers, the surface and near surface hydrologic framework also influences the salinity gradients. Large plumes of less than 10,000 mg/1 TDS ground water exist in the otherwise saline Knox-St. Peter and Silurian-Devonian aquifers. These plumes, which in some places underlie waters of greater than 10,000 mg/1 TDS (Figure 4), are potentially the result of increased recharge due to Quaternary glacial effects over large outcrop areas. Although some aspects of the direction and magnitude or regional flow in these bedrock aquifers have been established (6), the long-term effect on the salinity gradients has not been documented.

Summary

The final map (although generalized) shows the basic configuration of the 10,000 mg/1 TDS surface in Indiana. Local geologic circumstances will slightly modify this basic configuration as more data are acquired. There is a fair correlation between the regional structural patterns (Figure 3) and the position of the 10,000 mg/1 TDS within the hydrostratigraphic column (Figure 2). The structural influence on the position of the 10,000 mg/1 TDS surface in the hydrogeologic column is similar to the structural effect on the outcrop pattern of the stratigraphic units. Although the configuration basically conforms to regional structural fabric, significant deviations are evident. A notable deviation is the major southward-trending anomaly that shows fresher water occurring on the southwest side of the Cincinnati Arch deep in the hydrostratigraphic section. Anomalously fresh water is present in both the Knox-St. Peter and Silurian-Devonian aquifers within this area (Figure 1).

These plumes of fresh water may be the result of increased infiltration through fracture systems within the carbonate aquifers and (or) differential recharge that could have resulted from Quaternary glacial effects. With the addition of more tests in areas which have been historically non-productive of data from deep drill holes, an increased resolution of the geometry of the 10,000 mg/1 TDS surface will be possible. A clearer definition of the position of this surface will permit a more accurate assessment of the volume and distribution of Indiana's potentially potable ground water resource.

Literature Cited

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