Determination of the Hydrogeologic Properties of Lakebeds Using Offshore Geophysical Surveys

by Kenneth R. Bradbury[a] and Robert W. Taylor[b]

ABSTRACT

Studies of the relationships between ground-water systems and surface-water systems (lakes) generally require knowledge of the hydrogeologic properties of lakebed materials. Direct measurement of these properties may be prohibitively expensive or difficult in an offshore environment. A correlation between longitudinal conductance, a geoelectric parameter, and lakebed leakance (vertical hydraulic conductivity divided by thickness) may provide a rapid and inexpensive method for estimating lakebed hydrogeological properties using data collected by offshore seismic and electrical surveys. A test of the method at three study sites in Lake Michigan shows a positive linear relationship between the logarithm of longitudinal conductance and the logarithm of lakebed leakance at the three sites.

INTRODUCTION

Recent concerns about the management of lakes (Winter, 1981) and the relationships between lakes and nearby ground-water supplies (Cherkauer and Zvibleman, 1981) show a need for methods to rapidly determine the hydrogeologic properties of lakebed materials. Because they are submerged, direct study of lakebed materials is often excessively difficult and/or prohibitively expensive. As a result, indirect geophysical methods appear particularly attractive for defining lakebed properties. A geophysical method which appears ideally suited to the problem is the use of longitudinal conductance to predict the vertical hydraulic conductivity of lakebed sediments. Henriet (1976) appears to have first suggested the method. Goodell (1981) described the theory and assumptions involved in the longitudinal conductance method and presented geophysical data showing the variation of longitudinal conductance in sediments beneath Lake Michigan.

In this paper, geophysical and hydrogeologic data were combined at three field sites in Wisconsin in an attempt to evaluate the utility of the method in studies of lake-aquifer relationships. This work is part of a continuing project, and the results are not final or conclusive. Nevertheless, these methods offer encouragement for future work on the rapid evaluation of hydrogeologic properties of lakebeds using geophysical techniques.

THEORY

The use of surface or borehole electrical measurements to determine the porosity of a material generally employs the formation factor, F, defined (Archie, 1942) as:

$$F = \frac{\rho_b}{\rho_w} \qquad (1)$$

where ρ_b is the bulk electrical resistivity of the saturated material, and ρ_w is the resistivity of the pore water. Equation (1) provides a means for the electrical determination of F. Porosity, ϕ, of the material is then found through another equation,

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generally of the form (Archie, 1942):

$$F = \frac{a}{\phi^n} \qquad (2)$$

where a and n are empirically determined constants of approximate magnitude 1 and 2, respectively. The porosity determined through equations (1) and (2) may then, under rather restrictive conditions, be related to hydraulic conductivity (Heigold and others, 1979; Urish, 1981).

Croft (1971) applied these relationships to borehole logging, and obtained good correlation with hydraulic conductivity obtained from pumping tests. Kelly (1977), Heigold and others (1979), and Kosinski and Kelly (1981) used resistivities obtained from vertical electrical soundings to correlate with pumping test data. Urish (1981) showed that apparent formation factors should be positively correlated with hydraulic conductivity in granular fresh-water aquifers. Unfortunately, the results of Kelly (1977) and Heigold and others (1979) are contradictory, possibly due to the influence of matrix conduction on the interpreted formation factor. In addition, Thompson (1981) reported both positive and negative relationships between electrical resistivity and hydraulic conductivity of unconsolidated materials in southeastern Wisconsin, and Leonard-Mayer and Taylor (1982) criticized the use of formation factor in determining aquifer properties. Barker and Worthington (1983) and Worthington (1977) studied sandstone cores in an attempt to better define formation factor in the presence of fresh-water pore fluids.

The above studies applied the formation factor/porosity technique to the evaluation of *aquifers*. In lake-aquifer interaction studies, however, the interest is in evaluating the hydrogeologic properties of an aquitard, composed of lakebed materials. Because aquitards normally contain clay minerals, and because clay minerals in the presence of water are electrically conductive (Zohdy, 1974), the assumption of a nonconducting matrix, implicit in equation (1), breaks down. Thus, the electrical evaluation of lake bottom hydrogeological characteristics would benefit from an alternative method of interpretation.

Henriet (1976) proposed a method for the determination of hydraulic conductivity which utilized measured electrical longitudinal conductance and is ideally suited to the study of lake bottom sediments. For a layered sequence of sediments, Figure 1, the unit longitudinal conductance, S, is defined as:

$$S = \sum_{i=1}^{n} \frac{b_i}{\rho_i} \qquad (3)$$

where b_i is thickness of the i^{th} layer, and ρ_i is the resistivity of that layer.

For a three-layer (water, sediment, and bedrock) geoelectric section characterizing lakes, the bedrock can be considered an insulator and the summation of equation (3) is terminated by the high resistivity of the bedrock. Under the condition of a highly resistive bedrock, the longitudinal conductance is uniquely and easily determined by graphical methods (Zohdy, 1974) and is generally considered the electrical parameter which can be determined with the highest precision (Keller and Frischknecht, 1966). Thus, longitudinal conductance provides a single number which relates to the electrical properties of multilayered lake sediments and which can be rapidly and reliably determined from field data.

For a layered sequence of sediments (Figure 1) the composite vertical hydraulic conductivity, $\bar{K}$, is defined as:

$$\bar{K} = \frac{\sum_{i=1}^{n} b_i}{\sum_{i=1}^{n} \frac{b_i}{K_i}} \qquad (4)$$

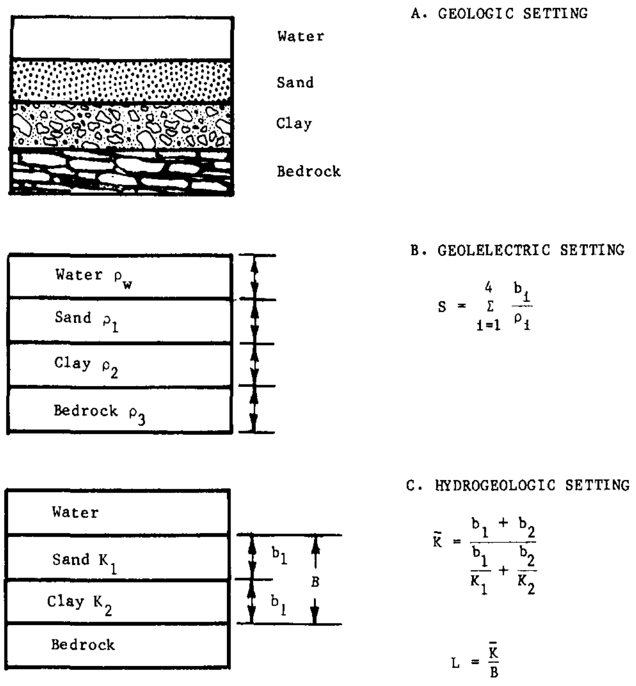

Fig. 1. Relationships between geology, geoelectric parameters, and hydrogeologic parameters for a typical lakebed setting.

where K_i is the hydraulic conductivity of the i^{th} layer.

Dividing the composite vertical hydraulic conductivity by the total thickness, B, of the unconsolidated materials gives the leakance, L (Pfannkuch, 1969), also called hydraulic conductance by some authors (Cooley, 1977). Thus,

$$L = \frac{\bar{K}}{B} = \{ \sum_{i=1}^{n} \frac{b_i}{K_i} \}^{-1} \qquad (5)$$

If it is now assumed that over a limited range, K_i and ρ_i are linearly related through clay content of the sediments, then:

$$L = \frac{C_o}{S} \qquad (6)$$

where C_o is the constant of proportionality between ρ_i and K_i which must be empirically determined for a given area.

The material properties which determine resistivity of lake sediments include porosity, water content, water quality, and the presence of clay minerals (Zohdy, 1974). Because the lake bottom sediments are saturated, and water quality does not generally exhibit strong lateral variations, sediment resistivities should be related to porosity and to the presence of clay minerals. Both these properties also influence lakebed hydraulic conductivities. Thus, from a qualitative standpoint the above assumption of linearity is not necessary, and it should be possible to empirically establish a relationship between lakebed resistivities, as measured by the longitudinal conductance, and lakebed leakance. The following section describes field tests of this hypothesis.

The use of longitudinal conductance in place of formation factor or actual layer resistivities provides several practical advantages. Given the assumption of a highly resistive bedrock, the longitudinal conductance can be determined from a single electrical measurement and does not require a complete electrical sounding curve. The inversion of electrical soundings is not necessary and the resulting conductance is unique. Thus, the use of electrical conductance minimizes the need for electrical data and also minimizes the necessary computations.

FIELD STUDIES

Description of Field Sites

During 1981 and 1982, extensive offshore electrical surveys were conducted at three field sites where hydrogeologic investigations were already underway. The sites are located along the Lake Michigan shore of eastern Wisconsin (Figure 2) and were chosen to represent differing hydrogeologic environments. At the more northerly Peninsula Site (Figure 2), a fractured Silurian dolomite aquifer lies beneath Green Bay. A layer of unconsolidated materials consisting of glacial tills, lake clays, and recent sediments ranging from absent to over 60 ft thick separates the aquifer from the bay. Because these unconsolidated

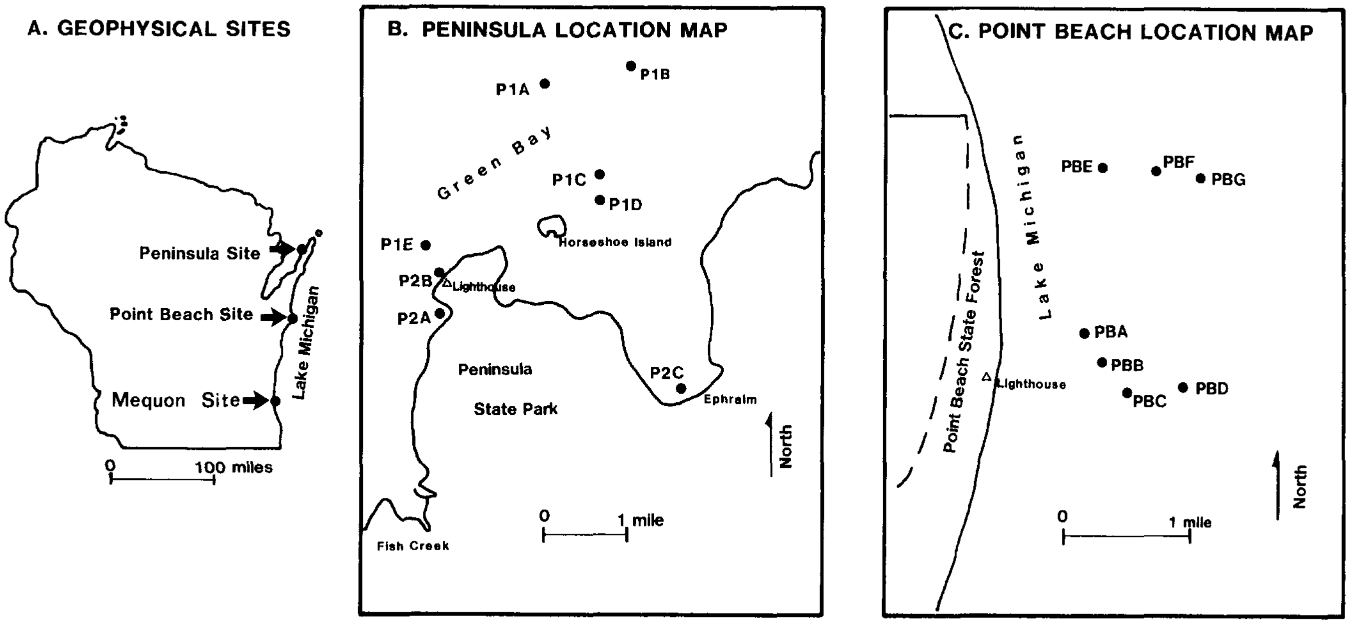

Fig. 2. Geophysical survey locations.

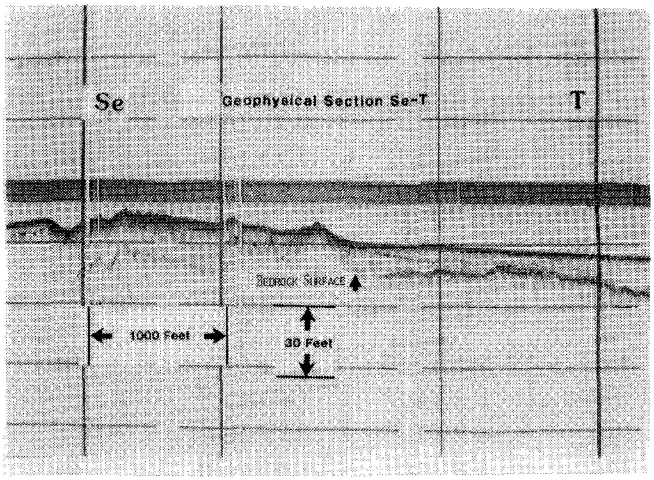

Fig. 3. Example of high resolution acoustic profile obtained offshore of the Peninsula site.

materials have lower hydraulic conductivities than the dolomite aquifer beneath them, they act as an aquitard which restricts ground-water flow from the aquifer into the bay (Bradbury, 1982).

At the Point Beach site (Figure 2) a low hydraulic conductivity clay till, overlain by clean unconsolidated sands, covers the dolomite aquifer. Sediments are generally thicker than at the Peninsula Site, and range from about 60 to 130 ft thick (Morrison, 1983).

The Mequon site (Figure 2) is characterized by glacial material termed the Shorewood till by Lineback and Gross (1974). The till is a clay-rich deposit with sand, pebble and larger size particles present (Bues, 1983). The thickness of the till varies from 40 ft to 70 ft (Bishea, 1983).

Geophysical Data Collection

The electrical resistivity equipment used at the two sites consisted of a surface-towed 666-ft Schlumberger array with five different A spacings. A computer automated acquisition system provided electrical soundings at every 40 ft of lateral movement. In addition, a high resolution acoustic profiler provided a simultaneous record of water depth and sediment thickness, giving excellent resolution of sediment stratigraphy (Figure 3). The combined electrical and seismic systems are described by Goodell (1981), Taylor (1982), and Winkelman (1981).

Goodell (1981) summarized the geophysical data from the Peninsula and Point Beach surveys. He reported longitudinal conductance (S_{Sed}) values at five points offshore of the Peninsula area and produced a contour map of S values offshore of the Point Beach area in addition to constructing geophysical models at six points offshore at Point Beach (Figure 2). Goodell concluded that S_{Sed} values at Peninsula were only about half the values at Point Beach. The lack of hydrogeologic data available at the time limited his analysis of the relationships between S values and hydrogeological properties of bottom sediments.

Bishea (1983) conducted geophysical studies at the Mequon site (Figure 2) using the geophysical system described above. His effort provided a contour map of longitudinal conductance offshore of Mequon. Estimates of the hydraulic properties of sediments at Point Beach are provided by Morrison (1983). Bradbury (1982) provided estimates of hydraulic properties at Peninsula while Bues (1983) obtained hydraulic properties at Mequon. During March 1982, additional electrical surveys were carried out through winter ice at three sites off Peninsula Park (Figure 2). These sites were at areas where offshore drilling and sampling gave good control on the thicknesses and hydraulic properties of bottom sediments.

RESULTS

Table 1 summarizes the hydrogeologic and geophysical data collected at each of the geophysical sites in Figure 2. Water depths range from 9 to 66 ft, and sediment thicknesses range from 1 to 130 ft. Leakance factors range from 1.7×10^{-4} sec^{-1}, where bedrock is exposed at Peninsula, to 1.3×10^{-11} sec^{-1} for the thickest sediments at Point Beach. The values for longitudinal conductance, S, given in Table 1 have been corrected for the effect of the water layer and range from 0.02 to 0.9 mhos at the same two points mentioned above.

Figure 4 is a plot of log S_{Sed} values versus log leakance. Symbols on the figure indicate the four different geophysical surveys. Notice that data from the three study sites tend to cluster in different parts of the plot, and that some relationship between the two variables appears to exist. A regression line fitted to the data has the equation:

$$\text{Log } L = -10.5 - 3.87 \log (S) \qquad (7)$$

with correlation coefficient $R^2 = 0.65$. T-tests on the slope and intercept of the regression line show that both statistics are significant at greater than the 99% level with 17 degrees of freedom. Thus the fitted regression line explains 65% of the variation in the data, and there is very little likelihood that random error has caused the data distribution.

The clustering of data from each site suggests that the two sites are hydrogeologically different.

Table 1. Summary of Hydrogeologic and Geophysical Measurements (See Figure 1 for Site Locations)

*Location**	*Water depth (ft)***	*Sediment thickness (ft)***	*Sediment type†*	*Water resistivity (ohm-ft)*	*K (ft/sec)*	*Leakance (sec^{-1})*	*S (mhos)●*
P1A	49	9	Clay	145	6.6×10^{-7}	7.3×10^{-8}	.14
P1B	66	9	Clay	145	6.6×10^{-7}	7.3×10^{-8}	.22
P1C	59	18	Clay	145	6.6×10^{-7}	3.7×10^{-8}	.36
P1D	63	18	Clay	145	6.6×10^{-7}	3.7×10^{-8}	.29
P1E	38	7	Clay	145	6.6×10^{-7}	9.4×10^{-8}	.22
P2A	9	14	Gravel over sandy clay	252	1.7×10^{-7}	1.2×10^{-8}	.05
P2B	12	1	Broken rock	252	1.7×10^{-4}	1.7×10^{-4}	.02
P2C	7	68	Clay	298	5.2×10^{-8}	7.6×10^{-10}	.20
PBA	20	60	Clay	150	1.9×10^{-9}	3.2×10^{-11}	.50
PBB	31	107	Clay	150	1.8×10^{-9}	1.6×10^{-11}	.50
PBC	40	130	Clay	150	1.7×10^{-9}	1.3×10^{-11}	.65
PBD	64	130	Clay	150	1.7×10^{-9}	1.3×10^{-11}	.43
PBE	33	80	Clay	150	1.8×10^{-9}	2.3×10^{-11}	.65
PBF	50	80	Clay	150	1.8×10^{-9}	2.3×10^{-11}	.43
PBG	60	98	Clay	150	1.8×10^{-9}	1.8×10^{-11}	.43
Mequon	–	45	–	130	2.2×10^{-8}	4.9×10^{-10}	.5
Mequon	–	60	–	130	1.8×10^{-9}	3×10^{-10}	.5
Mequon	–	65	–	130	1.5×10^{-7}	2.3×10^{-9}	.6
Mequon	–	65	–	130	2.2×10^{-8}	3.4×10^{-10}	.6

* Locations coded P1A-P1E are Peninsula sites from Goodell (1981). Sites P2A-P2C are Peninsula sites from the 1982 winter survey. Sites PBA-PBG are Point Beach sites from Goodell. Data at Mequon sites are from Bues (1983).

** Water depth and sediment thicknesses measured on high resolution acoustic profiles, except for sites P2A-P2C where thicknesses were measured by offshore sampling.

† Sediment type inferred from offshore samples and acoustic profiles.

● Longitudinal conductance, field values corrected for the thickness and resistivity of the water column.

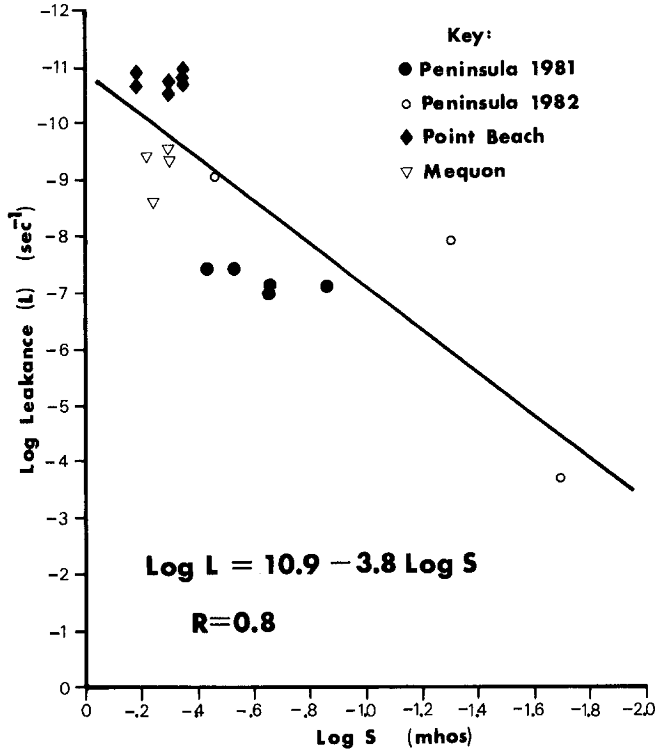

Fig. 4. Plot of log of leakance values versus log longitudinal conductance (s) at the study sites.

From Table 1, the sediments at Point Beach are thicker, and have lower hydraulic conductivities than the sediments at Peninsula, and the S_{Sed} values appear to reflect this trend. Although the data suggest that neither site offers a good lake-aquifer connection where clayey sediments are present, the low S_{Sed} value at the single site (P2B) where rock is exposed may indicate that the geophysical technique can detect areas of good lake-aquifer connection.

CONCLUSIONS

The limited offshore geophysical and hydrogeologic data presently available show that a statistically significant inverse relationship exists between the leakance and longitudinal electrical conductance, S, of sediments beneath Lake Michigan and Green Bay. Leakance is a measure of the potential for hydraulic connection; thus the S values may be used to spatially map the relative hydraulic connection between lakes and aquifers. Offshore geophysical surveys are relatively fast and inexpensive when compared with direct measurements of offshore lakebed properties. Therefore, offshore electrical surveys, combined with seismic reflection data, provide a promising tool for lake-aquifer studies.

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