GEOPHYSICAL ASSESSMENT OF THE HYDRAULIC CONNECTION BETWEEN LAKE MICHIGAN AND THE AQUIFERS ON ITS WESTERN BOUNDARY

FINAL REPORT TO SEA GRANT

BY

MARY P. ANDERSON, UW-MADISON
DOUGLAS S. CHERKAUER, UW-MILWAUKEE
ROBERT W. TAYLOR, UW-MILWAUKEE
(P.I.'s listed alphabetically)

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SUMMARY

Waste disposal activities coupled with heavy water usage along the Great Lakes make it imperative that the degree of interconnection between the Lakes and associated aquifers be quantified. The lakebed forms the interface between groundwater and surface water systems. We applied geophysical methods to determine the hydraulic properties of the lakebed along the western shoreline of Lake Michigan.

A geophysical system was designed to operate automatically on shipboard. The geophysical system collects resistivity, seismic and induced polarization data. The seismic data allow us to estimate the thickness of the lake sediments and the resistivity data allow us to measure the electrical properties of the sediment from which hydraulic conductivities can be estimated for use in standard hydrogeologic analysis.

Hydrogeologic field investigations were done onshore at four type sites: Peninsula Park (Door County), Point Beach State Forest (Manitowoc County), Mequon (Ozaukee County) and Wind Point (Racine County). At these four primary type sites detailed hydrogeologic information was collected both on and offshore. In addition two other type sites (Haven, Sheyboygan County; Milwaukee Harbor) were studied less intensively. Hydrogeologic and geophysical data were analyzed with the aid of computer models designed to simulate groundwater flow. These analyses yielded estimates of the flux of water between the lake and associated aquifers at our four primary type sites as well as an estimate of the composite flux to Lake Michigan from the aquifers along its western shoreline. This composite flux rate estimate ranges from 1.5 to 2.2×10^5 m^3/day.

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INTRODUCTION

It is generally recognized that the interaction between lakes and aquifers is an important aspect of the hydrologic system that must be assessed in order to evaluate water resources. In Wisconsin, as well as in other states around the Great Lakes, work on groundwater-lake interaction has concentrated on the investigation of small, inland lakes. Heavy population growth on the shores of Lake Michigan and the associated heavy usage of water make it imperative that we determine the interconnection between the Lake and its contributing aquifers. Our study has made a start toward this objective by developing a geophysical technique which provides an inexpensive, fast and easy means of obtaining continuous data on the hydraulic properties of the materials connecting the Lake and the surrounding aquifers.

In all studies dealing with groundwater-surface water interaction, the information that is most crucial and yet most difficult to obtain, concerns the hydraulic properties of the geologic materials which serve as the connection between groundwater and the surface water systems. The extensive drilling programs necessary to obtain this type of information are expensive and generally provide only discontinuous stratigraphic data. Moreover, such drilling is particularly difficult offshore in lakes. In this project, we applied geophysical methods to the problem of determining hydraulic properties of lakebed sediments. We also conducted standard hydrogeologic investigations at four sites onshore. The techniques we use are not new in themselves, but prior to our study they had never been used in combination in this type of setting. For example, Cartwright _et al_. (1979) measured hydraulic gradients in the lakebed along the western shoreline of Lake Michigan, but were unable to extrapolate their point data. We believe our method will overcome this problem as well as others that have been encountered and will ultimately provide a rapid and accurate means of assessing the hydraulic connection between lakes and aquifers. Such information will be of direct benefit to those concerned with the wise management of water resources in the Great Lakes area.

METHODOLOGY

A. Hydrogeology

Research by Winter (1976, 1978, 1981a, 1981b, 1983), McBride and Pfannkuch (1975) and Munter and Anderson (1981), among others, has shown that the most important hydrogeologic factors affecting the interaction between groundwater and lakes are the hydraulic properties of aquifers adjacent to the lake, the thickness and hydraulic properties of materials between the aquifers and the lake (e.g., lakebed sediments) and the hydraulic gradient between the two water bodies. Thus, in order to estimate the flux of water between Lake Michigan and adjacent aquifers, one must quantify these hydrogeologic factors along the lakeshore.

In eastern Wisconsin, the geology of interest consists of a dolomite aquifer of Silurian and Devonian age, overlain by unconsolidated glacial drift of Pleistocene age and recent lacustrine deposits. The dolomite aquifer is the principal source of domestic well water along the lakeshore and is also the primary source of groundwater entering the lake. This geologic unit is part of the Michigan Basin structure; it dips eastward in southern Wisconsin and ESE in Door County. Its surface is a pre-glacial erosional surface, which consists of a series of buried valleys and ridges. The highest hydraulic conductivities occur in the highest and lowest stratigraphic portions of the unit (Hensel, 1984), while the middle portions are massive and less permeable. Toward the northern part of the study area and in bedrock valleys in the south, the uppermost parts of the dolomite have often been eroded away leaving a less permeable rock.

The glacial materials are predominantly clay-rich tills, but may contain substantial amounts of sand and gravel outwash or ice contact deposits. The modern lake deposits are also highly varied, but fine-grained materials are abundant. Thicknesses of the total column of unconsolidated sediments range from zero to over 200 feet.

Concept of Type Sites

Four hydrogeologic variables stand out as most important to the flux of water between the lake and the aquifer. They are the hydraulic conductivities of the dolomite aquifer and the unconsolidated materials, the thickness of the unconsolidated materials beneath the lake and the hydraulic gradient. All vary spatially and hydraulic gradient may vary temporally as well. The geology of any reach of shoreline can be characterized by some combination of hydraulic conductivities of dolomite aquifer and unconsolidated material, and thickness of unconsolidated material. These factors can be categorized within a matrix as shown in Table 1. Absolute hydraulic conductivities for the dolomite aquifer are generally not available so relative approximations are used in Table 1. The dolomite is subdivided into high ($> 10^{-5}$ m/sec) and low ($< 10^{-6}$ m/sec) permeabilities based on the stratigraphic position of the aquifer surfaces. If the top of the aquifer is in the upper 200 feet or lower 250 feet, the zone is classified as having high permeability. Hydraulic conductivity of the unconsolidated sediments was estimated from grain size distribution (lithology).

TABLE 1. Matrix of possible combination of important geologic conditions along the Lake Michigan shoreline

THICKNESS OF UNCONSOLIDATED MATERIALS	RELATIVE PERMEABILITY OF DOLOMITE AQUIFER	LITHOLOGY OF UNCONSOLIDATED MATERIALS				
		NO CLAY	SAND>CLAY	SAND≈CLAY	SAND<CLAY	100 % CLAY
LESS THAN 10 FEET	HIGH	*	*		PENINSULA	
	LOW	*	*			
LESS THAN 30 FEET	HIGH	*	*			HAVEN
	LOW	*	*	WIND POINT		
30 to 80 FEET	HIGH	*	*			MEQUON
	LOW	*	*			
GREATER THAN 80 FEET	HIGH	*	*	POINT BEACH		
	LOW	*	*			MILWAUKEE

*Rare combinations in Lake Michigan in Wisconsin.

It is assumed that as clay content increases, hydraulic conductivity decreases. Such an assumption is only approximately valid, but should be adequate for our purposes.

It is rare to find locations where the unconsolidated material on the lakebed of western Lake Michigan is dominantly sand. Hence, it is reasonable to reduce the matrix in Table 1 to the 24 categories in the three right-hand columns. A single location cannot be chosen that is representative of all the important geologic conditions along the shore. Therefore, we selected six "type areas" for more intensive study in hope of capturing key hydrogeologic settings. These sites are: Peninsula State Park, Door County; Point Beach State Forest, Manitowoc County; Haven, Sheboygan County; Mequon, Ozaukee County; Milwaukee Harbor, Milwaukee County; and Wind Point, Racine County (Figure 1). Each of the six was selected as being typical or representative of portions of the total shoreline. Their locations within the matrix are shown in Table 1 and the portions of the shoreline which they represent are cumulated in Table 2. Together the six sites have conditions representative of 84% of the shoreline, although Milwaukee Harbor and Wind Point conditions are less typical (Table 2) than we had originally anticipated.

Type Sites Investigations

Detailed hydrogeologic information was assembled for all six type areas. The hydrogeologic information was combined with geophysical data and analyses based on groundwater modeling techniques to estimate existing groundwater fluxes. Two of the areas, Haven and Milwaukee Harbor, had been studied by other investigators. Relevant data were summarized by Yelderman (1980) for the Haven site and by the Milwaukee Metropolitan Sewerage District (MMSD,

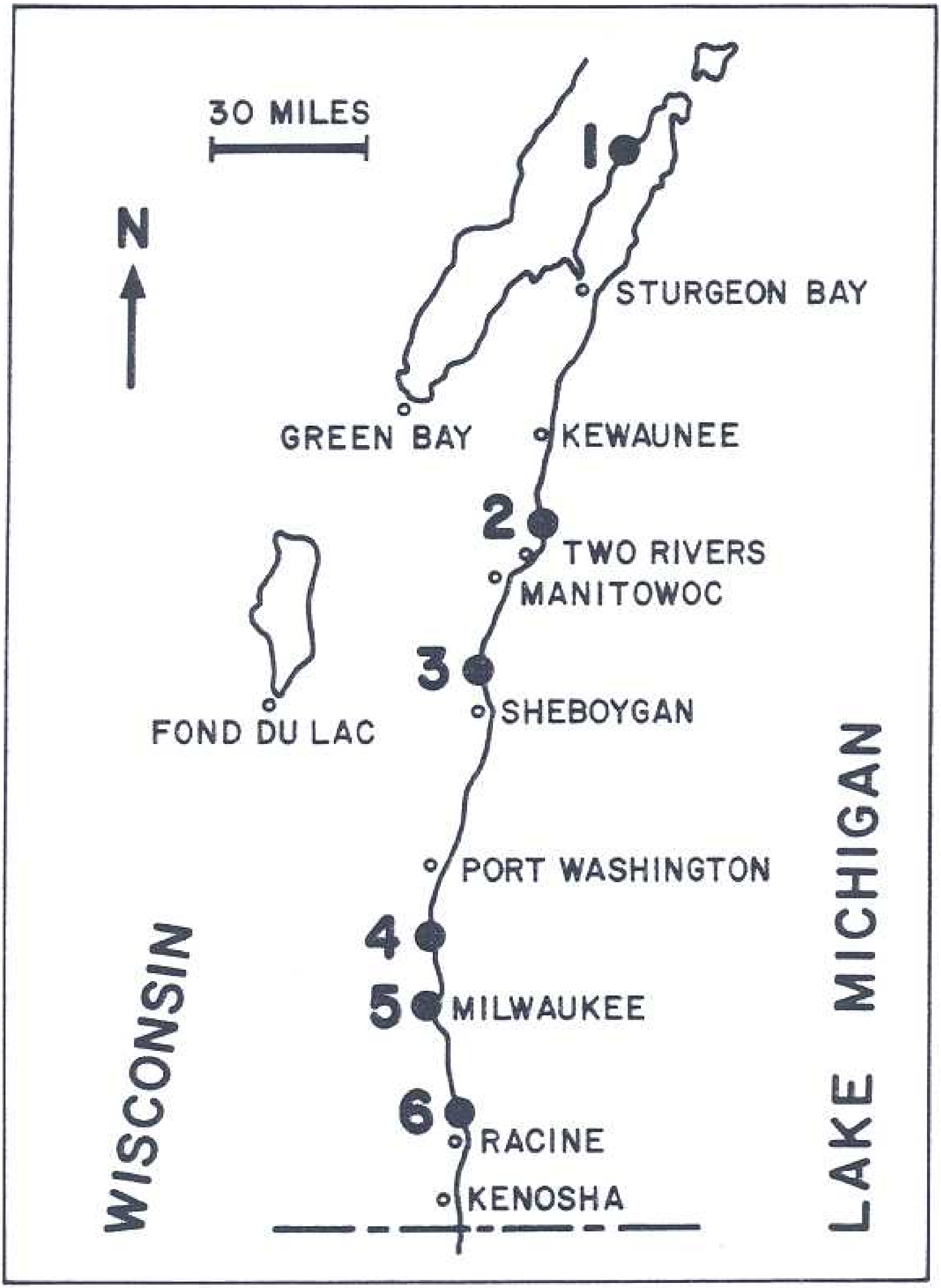

FIGURE 1. Locations of type sites

TABLE 2

Distribution of type area geologic conditions along the Lake Michigan shoreline in Wisconsin

Type Conditions	Portion of shoreline having type geology	
	Mileage	Percentage
Peninsula Park	71.7	25
Point Beach	37.0	13
Haven	34.6	12
Mequon	78.3	27
Milwaukee Harbor	6.9	2
Wind Point	15.4	5
Other*	47.7	16

*Portions of the shoreline having geologic conditions unlike any of the type areas.

1981) for the Milwaukee Harbor site. We used the existing data bases at these two sites.

We conducted independent field hydrogeologic studies at the remaining four areas. At each site, we assembled well logs from existing wells to obtain information about the underlying geology and the hydraulic properties of the various materials. At all these sites except Mequon it was necessary to augment the existing well network by installing piezometers. Water levels were measured in wells and piezometers and were used to construct water table maps from which flow directions can be inferred. Groundwater samples were also collected at each site and chemically analyzed to ascertain whether lake water was present in the aquifer. In addition to the onshore work described above, we ran electrical and seismic surveys offshore from each of the four sites to obtain information on the thickness and properties of the lakebed sediments. We also collected sediment samples and measured their hydraulic conductivities in the laboratory.

Detailed hydrogeological descriptions at our four primary type sites are given by Bradbury (1981, 1982a), for Peninsula State Park; Morrison (1980), for Point Beach; Bues (1983) for Mequon; and Thompson (1980) for Wind Point. Brief synopses of the hydrogeologic conditions of all six sites are given below and are presented schematically for our four primary sites in Figure 2.

At Peninsula State Park, the lower (and high permeability) portions of the dolomite are exposed. The dolomite is overlain by thin layers of both clay, and sand and gravel but clay is more abundant than sand. Groundwater flow is toward Green Bay. The thin lakebed sediments with exposures of bedrock allow for relatively large groundwater influxes to the lake.

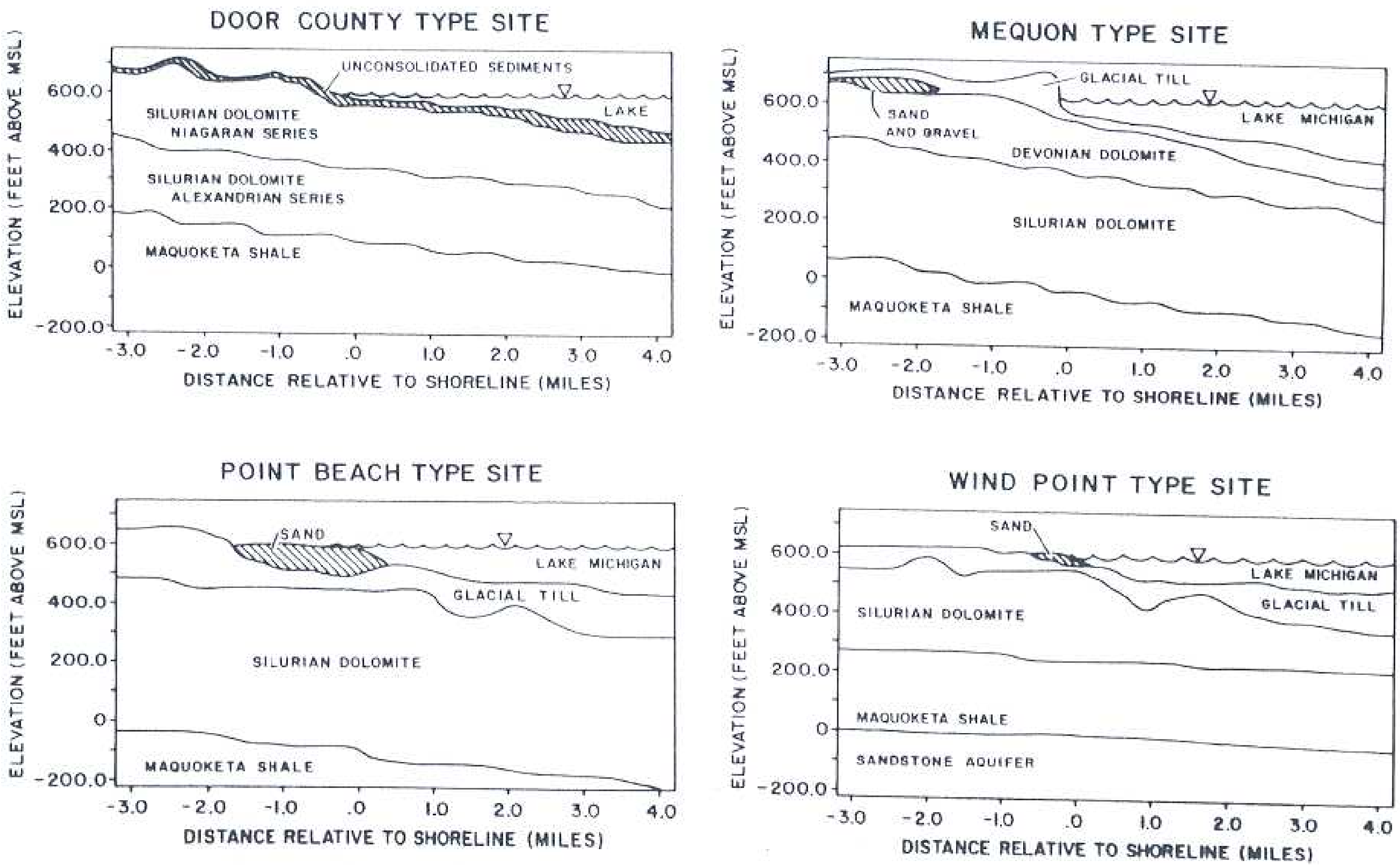

FIGURE 2. Cross sections showing hydrostratigraphic units at the four primary type sites

The Point Beach site is somewhat anomalous among the type sites. Here the dolomite aquifer is hydraulically separated from the lake by glacial tills over 100 feet thick. Groundwater flows to the lake from a 50-80 feet thick sand aquifer. Groundwater discharge occurs up to a half mile offshore through thick sandy sediments which are limited in areal extent.

The work done at the Haven site provided excellent geological information but less thorough hydrologic analysis. The geology at the site is dolomite overlain by thin sediments which are almost exclusively clay. In addition, the top of the dolomite is composed of relatively high permeability brecciated or vuggy material. The presence of high permeability material coupled with the high lakeward gradients resulting from the 50 foot high bluff allows a moderate influx of groundwater to the lake despite the clayey lakebed.

Heavy pumpage of groundwater at Mequon has lowered groundwater levels below the lake surface inducing lake water to enter the aquifer. The dolomite surface in Mequon consists of a series of ridges and valleys where the ridges form the high permeability portions of the unit. In the valleys, the upper dolomite has been eroded away and the lower permeability middle dolomite remains directly beneath the glacial deposits. Onshore sediment thicknesses exceed 100 feet, but offshore thicknesses are much less. Clay dominates in all areas. Flow is induced from the lake to the aquifer in Mequon in areas of landward hydraulic gradients where thin sediments containing some sand overlie bedrock ridges (Cherkauer and Zvibleman, 1981).

At the Milwaukee Harbor site, pumpage has caused strong landward gradients. However, there is no induced recharge here because of the geologic differences between Milwaukee and Mequon. At the Milwaukee Harbor site the bedrock surface is an exceptionally deep bedrock valley which cuts into low permeability dolomite. The valley is also filled by over 200 feet of glacial sediments (predominantly clay) which act to minimize groundwater/lake interactions.

The Wind Point site has dolomite near the surface on land, overlain by both sand and clay in almost equal proportions. Offshore the sediment thicknesses are highly varied although the sand/clay mix remains roughly constant. Near the Point itself, dolomite is exposed in the lakebed. Hydraulic gradients are predominantly landward and there is substantial induced recharge where thin sediments occur nearshore. Figure 2 shows the hydrostratigraphy south of Wind Point. North of the Point, the sand body is located farther offshore over the rise in the dolomite bedrock shown in the figure.

Two sites, Mequon and Peninsula Park, proved to be representative of more than half the shoreline (Table 2). They were given special attention in all three phases of investigation (hydrogeologic, geophysical, and modeling). At Peninsula Park, cores were taken offshore and piezometers were installed in the lakebed through the winter ice (Bradbury, 1981; Hassler, 1984). These cores enabled us to measure hydraulic conductivities in the laboratory while the piezometers provided field-measured permeabilities and the offshore hydraulic heads needed for modeling. At Mequon, there is no stable ice platform and the lakebed is too hard for piezometer installation; we used scuba divers to install seepage meters on the lakebed. These devices allowed us to map the magnitude and direction of the lake flux.

B. Geophysics

Basic Approach

A primary objective of this project was to develop the geophysical procedures and instrumentation necessary to determine the hydraulic conductivity of lake bottom sediments on the basis of shipboard geophysical measurements. Electrical measurements have been the dominant geophysical method employed in land based hydrological studies but application in marine-like environments has been limited. Land-based electrical measurements are generally degraded by strong lateral changes in surface resistivity, surface relief, nonplanar saturation surfaces and time variant surface resistivity. These conditions are either minimized or eliminated underwater and, thus, marine conditions should enhance the utility of electrical measurements. In addition, unlike land-based surveys, marine data may be obtained on a continuous basis allowing greater data density in comparison to land surveys.

Conventional, electrical depth soundings (EDS) were employed to determine the hydraulic conductivity of lake bottom sediments, initially following an approach developed by Henriet (1976) who demonstrated that hydraulic conductivity could be related to electrical longitudinal conductance, provided that an independent measure of sediment thickness was available. Sediment thickness is easily obtained under marine conditions by use of an acoustic sub-bottom profiler to obtain seismic reflection measurements. Bradbury and Taylor (1984) modified the approach of Henriet (1976) to demonstrate that under the same conditions, longitudinal conductance could be related to hydraulic leakance (hydraulic conductivity divided by thickness). The results of this project were used to demonstrate empirically the validity of the theoretical relationship established by Bradbury and Taylor (1984).

The theoretical developments of both Henriet (1976) and Bradbury and Taylor (1984) require assumptions which are unlikely to be true under actual field conditions. In an attempt to relax these assumptions, electrical induced polarization (IP) measurements were also taken. While the use of IP measurements in hydrological studies has been suggested (e.g., Mohamed, 1970) field applications are limited and the data resulting from this study appear to constitute the largest hydrologically oriented IP data base in existence.

In summary, resistivity and IP measurements were interpreted to yield leakance of the bottom sediments and their lithology. Sediment thickness, as determined by seismic reflections, was used to transform leakance into hydraulic conductivity. All measurements were made on an essentially continuous basis, allowing spatial maps of leakance and relative hydraulic conductivity to be constructed for each of the four primary study sites.

Instrumentation

The objective of the instrumentation development was to produce a shipboard system which would produce continuous electrical depth soundings while simultaneously acquiring seismic reflection data and tracking ship location. A schematic diagram of the final system is shown in Figure 3. The system is fully automated and utilizes a microcomputer for real time data reduction and storage.

Ship location was determined by means of a Mini Ranger with an accuracy of ± 3m at three second intervals. Seismic profiles were obtained using an Edo, 3.5 KHz, sub-bottom profiler operated at 0.25 second intervals. Penetration

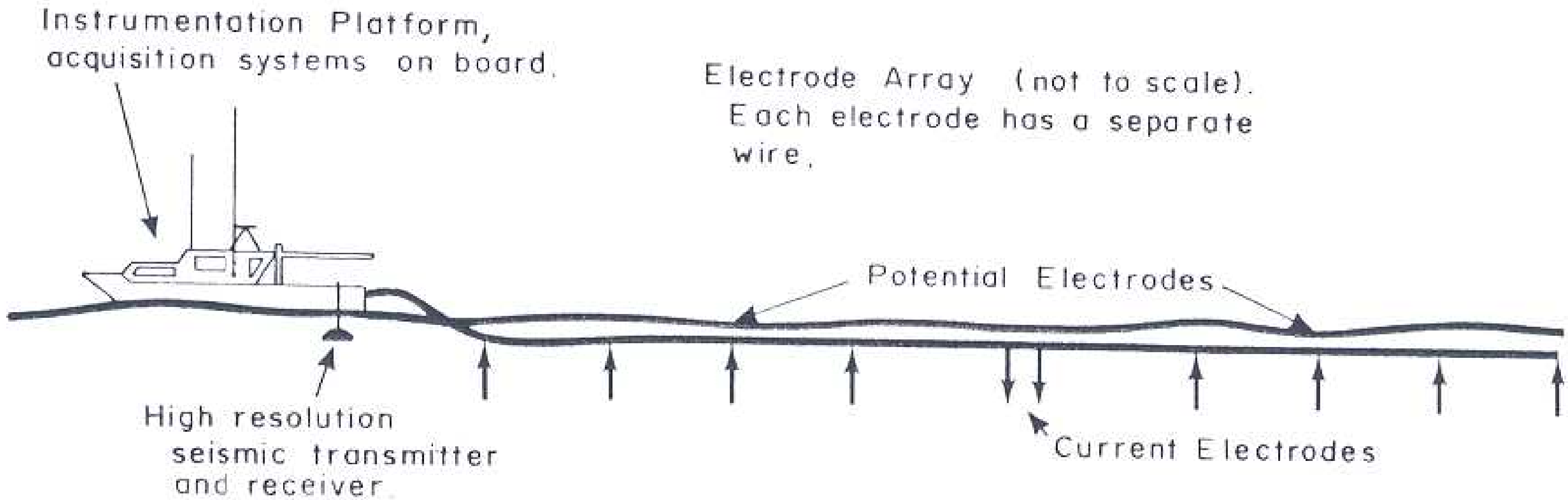

Figure 3. Schematic drawing of the instrumentation platform with the geophysical systems deployed. Position of ship is fixed by radar transponders.

of the Edo system was approximately 20 m. In areas of greater sediment thickness a DelNorte 1 Kjoule sparker was employed. The sparker yielded penetration of approximately 100 m.

While the location tracking and seismic profiling systems were designed following standard marine procedures, the acquisition and electrical resistivity systems were developed specifically for this project. A theoretical analysis of cable parameters, such as the effect of cable length and tow depth on resolution and penetration, was done by Goodell (1981). On the basis of his study, a floating cable with a length of 330 m containing 21 electrode pairs was selected. A typical electrode within the cable is shown in Figure 4. Details of the cable design and construction are given by Bishea (1983).

The data acquisition, reduction and storage system was developed around a Digital Equipment Corporation PDP-11/03 minicomputer. A block diagram of the overall shipboard system is shown in Figure 5. Software for control of the PDP-11 was developed for this project by Winkelman (1981) and modified by Bishea (1983). The final software package allows the acquisition of the potential difference between 16 electrode pairs, calculates apparent resistivity, induced polarization and shelf potential for each of the three pairs, and stores the results on FLOPPY disk along with ship time and location. All of the above functions can be performed at six second intervals which yield essentially continuous electrical depth soundings with IP and SP values.

The finalized acquisition system yielded production rates of approximately 32 Km per eight hour day with a complete electrical sounding obtained at 10 m intervals. This rate is greatly in excess of any land crew production. A review of the open literature suggests that our system is the only fully automated marine resistivity system presently available in this country.

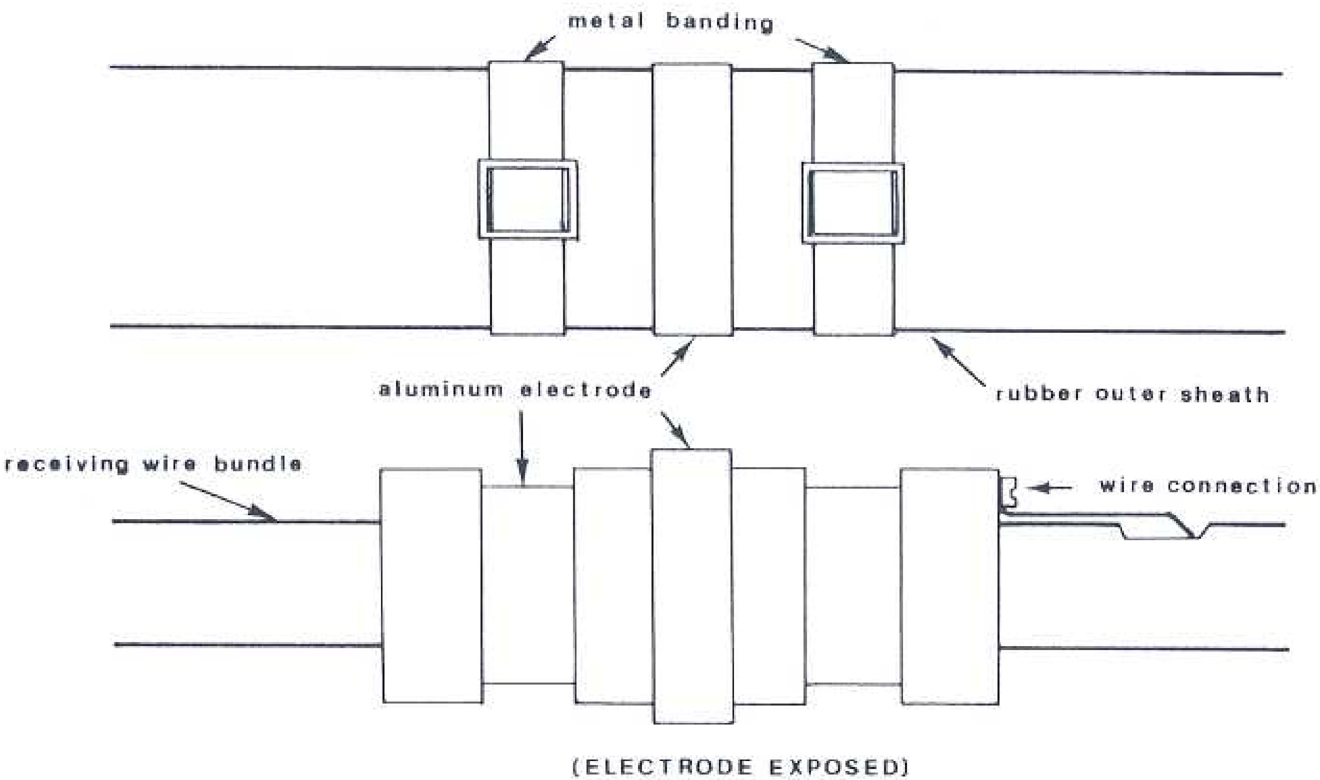

FIGURE 4. Diagram of a typical potential electrode on the IP cable. Transmitting wires and strain-relief cord are banded to the outside of the rubber protective sheath.

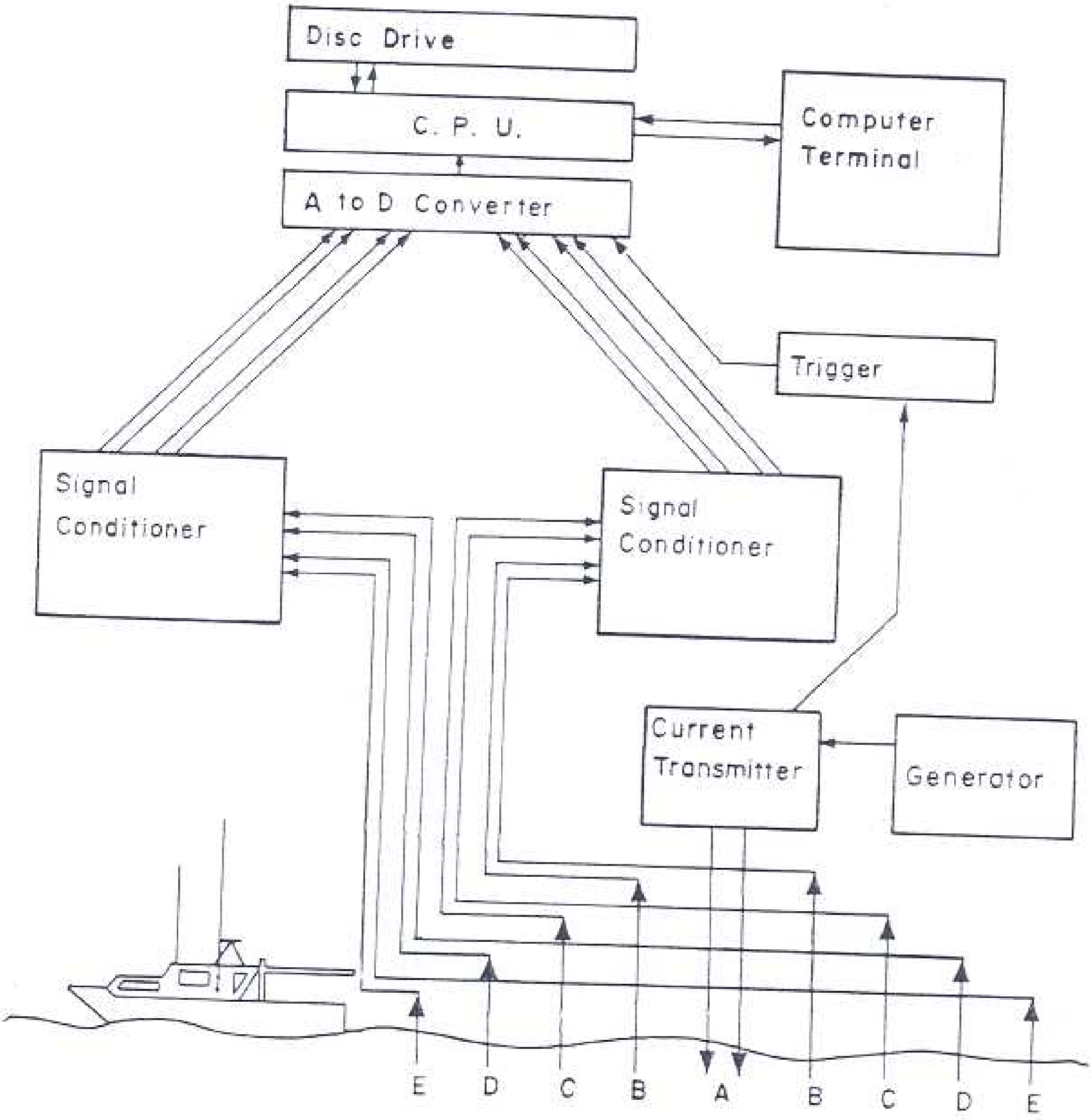

FIGURE 5. Schematic drawing of the electronic equipment used during a field survey (modified from Goodell, 1981); position of ship is fixed by radar transponders.

C. Computer Modeling

Groundwater flow models were used as an aid in quantifying seepage to Lake Michigan at our four primary type sites: Peninsula Park, Point Beach, Mequon, and Wind Point. Peninsula Park and Mequon were given special emphasis. Details of the modeling studies at these sites are given by Bradbury (1982) for Peninsula Park and by Rovey (1983) for Mequon. Bradbury (1982) used a three-dimensional flow model as well as a special purpose two-dimensional, areal-view parameter estimation model to simulate the groundwater system at Peninsula Park. Rovey (1983) used a two-dimensional areal-view model to simulate both flow and chemical transport at Mequon. Mequon site modeling is summarized in a later section of this report (see "Hydrologic Verification of the Geophysical Method").

Rumbaugh (1985) simulated the groundwater flow in representative cross sections at Point Beach, Mequon and Wind Point. He also selected a cross section studied by Sherrill (1978) which is representative of the general hydrogeologic conditions in Door County. (The flow pattern at Peninsula Park itself is three-dimensional in nature and cannot be simulated using a cross-sectional model.)

The hydrostratigraphic cross sections used by Rumbaugh (1985) are shown in Figure 2. The seepage rates estimated by Rumbaugh (1985), Bradbury (1982) and Rovey (1983) are summarized in Table 3. Note that estimates for the areal-view modeling done by Bradbury (1982) for Peninsula Park are higher than the estimate obtained from the cross-sectional model for the generalized Door County site and the estimate from Rovey's areal-view modeling of Mequon is smaller than Rambaugh's estimate. To help elucidate the reasons for these discrepancies, several simulations were performed with the cross-sectional models in order to test model sensitivity to changes in hydraulic gradient and lithology (e.g., the presence or absence of a sand lens at the Wind Point type site listed on Table 3). These sensitivity analyses show that the discharge rate to the Lake is moderately sensitive to changes in the magnitude of the hydraulic gradient but very sensitive to the presence or absence of high permeability units, such as sand lenses. The Peninsula Park site, as modeled by Bradbury (1983), includes exposures of high permeability bedrock that represent near shore reefs such as Horseshoe Reef. The cross section modeled by Rumbaugh (1985) does not include reefs. Bradbury (1983) estimated that roughly 0.5% of the nearshore groundwater discharge to Green Bay at Peninsula Park occurs through the reefs. Hence, discharge of water through the reefs may account for at least part of the discrepancy. The presence of relatively high permeability lakebed sediments off Peninsula Park (as compared to the generalized Door County site) also contributes to the difference. Areal heterogeneity in the lakebed sediments near Mequon account for the discrepancies at this site. These areal heterogeneities are discussed later in this report (See "Hydrologic Verification of the Geophysical Method").

The sensitivity studies point to the need for a regional modeling effort wherein it will be possible to consider site specific conditions in addition to type site conditions. Such an analysis is planned for future studies. However, a first step toward obtaining a composite estimate of the groundwater discharge to the Lake was accomplished by means of a modeling study performed by Hansel (1984). The results of his simulations are reported in a later section of this report (see "Application").

TABLE 3. Groundwater discharge rates (m^3/day/km of shoreline) to Lake Michigan calculated from modeling studies

	Rumbaugh (1985)	Bradbury (1982)	Rovey (1983)
Door County	4.7×10^2	$23.-41. \times 10^{2}$*	
Point Beach	7.3×10^2		
Mequon	6.7×10^2		4.1×10^2
Wind Point with sand unit present	2.0×10^2		
Wind Point without the sand unit	0.2×10^2		

* Peninsula Park site in Door County.
Discharge is to Green Bay.

HYDROLOGIC VERIFICATION OF THE GEOPHYSICAL METHOD

General Approach

Verification of the geophysical method on Lake Michigan requires a site where the heterogeneities of the lakebed produce measurable differences in groundwater flow or chemistry which can then be compared spatially to the geophysically measured properties of the lakebed. The primary purpose of the geophysical method is to provide a continuous spatial distribution of lakebed hydraulics. For a verification experiment, sufficient field data are required to provide a check on the geophysical data. In small lakes, it would be possible to instrument the lakebed densely enough to measure the areal distribution of flow and hydraulic conductivity (e.g., Lee et al., 1980) and compare that information directly to the geophysically-derived hydraulic properties. In Lake Michigan, because of wave strength, water depth and monetary limits, we have been unsuccessful in setting up enough instrumentation on the lakebed to provide an adequate test. Therefore, we have chosen to perform the verification test in an area where pumping from wells onshore has caused lake water to enter aquifers and move landward.

The amount of lake water induced into an adjacent aquifer is dependent upon the hydraulic properties of the aquifer and of the sediments beneath the lake and upon the hydraulic gradients created by pumping (Cherkauer and Zvibleman, 1981). Of these variables, only the hydraulics of the lakebed cannot be measured on land from existing wells. Thus, the configuration of the lake water plumes in the aquifer can be treated as a spatially continuous distribution resulting from one unknown (lakebed properties) and several knowns.

Aquifer properties and observed heads in the aquifer were used to calibrate a finite difference model based on the code known as PLASM (Prickett & Lonnquist, 1971). The model was used to simulate groundwater flow assuming homogeneous lakebed properties. Then the flow model was coupled with a chemical mass transport model (Prickett et al., 1981) to simulate the movement of lake water plumes into the aquifer. This simulation is sensitive to variations in lakebed properties. Finally the geophysically-derived hydraulic conductivities of the lakebed were entered into the chemical mass transport model. The objective of this simulation was to produce a configuration of lake water plumes which matched the observed plumes. If this is accomplished, the geophysical data can be considered meaningful and the geophysical method is verified. The verification test is summarized below and is discussed in detail by Rovey (1983).

Site Hydrogeology

Our test site was at the Mequon type area where pumping from domestic and irrigation wells near the lake has drawn down the potentiometric surface in the dolomite aquifer below lake level (Figure 6) inducing lake water to flow into the aquifer. Because the lake is substantially lower in dissolved solids (200 mg/1 TDS) than the ambient groundwater (550 mg/1 TDS), the induced recharge forms plumes of water of low dissolved solids which are mappable beneath the test site (Figure 7).

The glacial drift at this site is predominantly clay, with lenses of coarser material ranging in size up to boulders. This heterogeneity plays a key role in influencing where lake water enters the aquifer. The dolomite

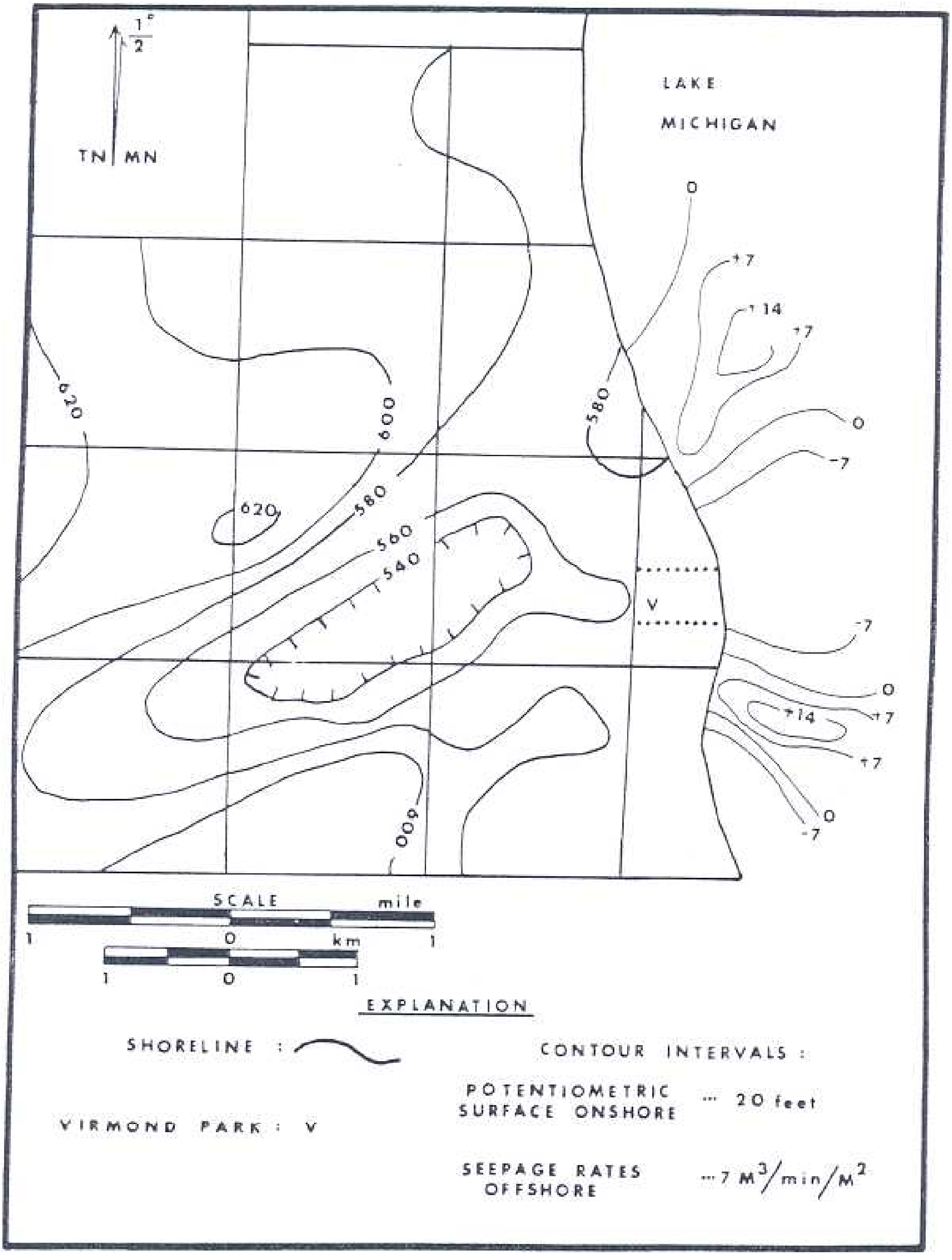

FIGURE 6. Potentiometric surface in the dolomite aquifer at Mequon

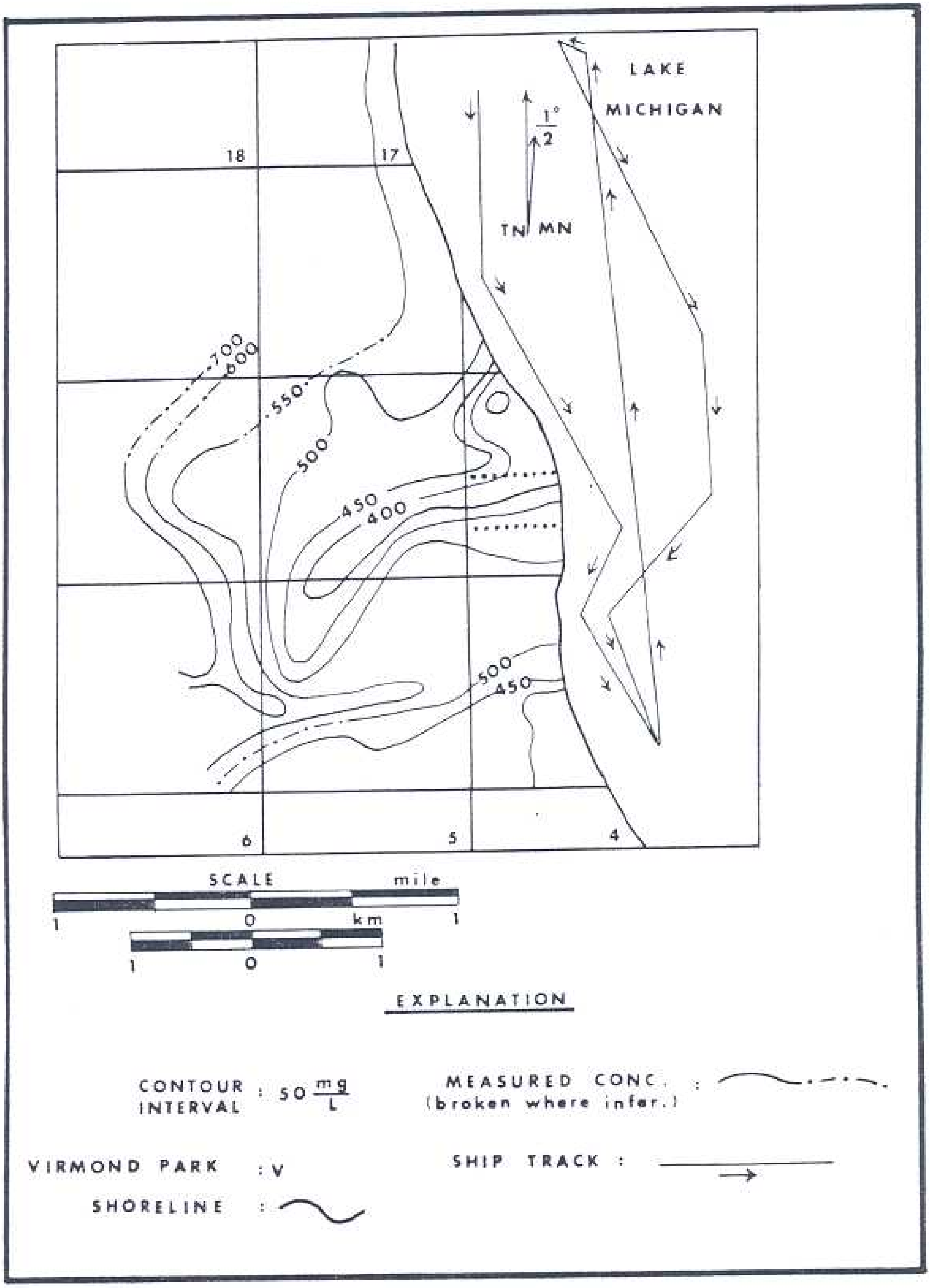

FIGURE 7. Plumes of low TDS lake water in the dolomite aquifer at Mequon

aquifer is anisotropic with the primary directions of hydraulic conductivity paralleling the two main fracture directions (ENE and NNW). At the Mequon site, the bottom 135 m of the aquifer has a hydraulic conductivity of 2×10^{-6} m/sec (Zvibleman, 1983), while the upper portions have substantially high permeability of $2\text{-}5 \times 10^{-5}$ m/sec (Rovey, 1983).

Seepage meters were installed by divers at 16 locations in the lakebed at water depths ranging from 2 to 7 meters. The direction and magnitude of seepage is controlled by both the hydraulic heads in the aquifer (Figure 6) and heterogeneities within the lakebed. Upward seepage was observed whenever landward heads exceeded lake level. The strongest downward seepage (near Virmond Park, Figure 6) occurs where the lakebed sediments are predominantly boulders.

Results

The distribution of relative hydraulic conductivity offshore of the study area was determined geophysically. Relative hydraulic conductivity is mapped in Figure 8; high values indicate areas with a high potential to transmit water. The large zone of sediment of high relative hydraulic conductivity offshore of Virmond Park (Figure 8) correlates well with the location of the main plume of lake water (Figure 7) as well as a zone of downward seepage as measured in seepage meters (Figure 6).

The groundwater flow model was calibrated for conditions in 1978 and then the calibration was verified against conditions in 1962. Since the flow model proved to be insensitive to lakebed hydraulic properties, the lakebed was assumed to be homogeneous and isotropic with a hydraulic conductivity of 9×10^{-9} m/sec.

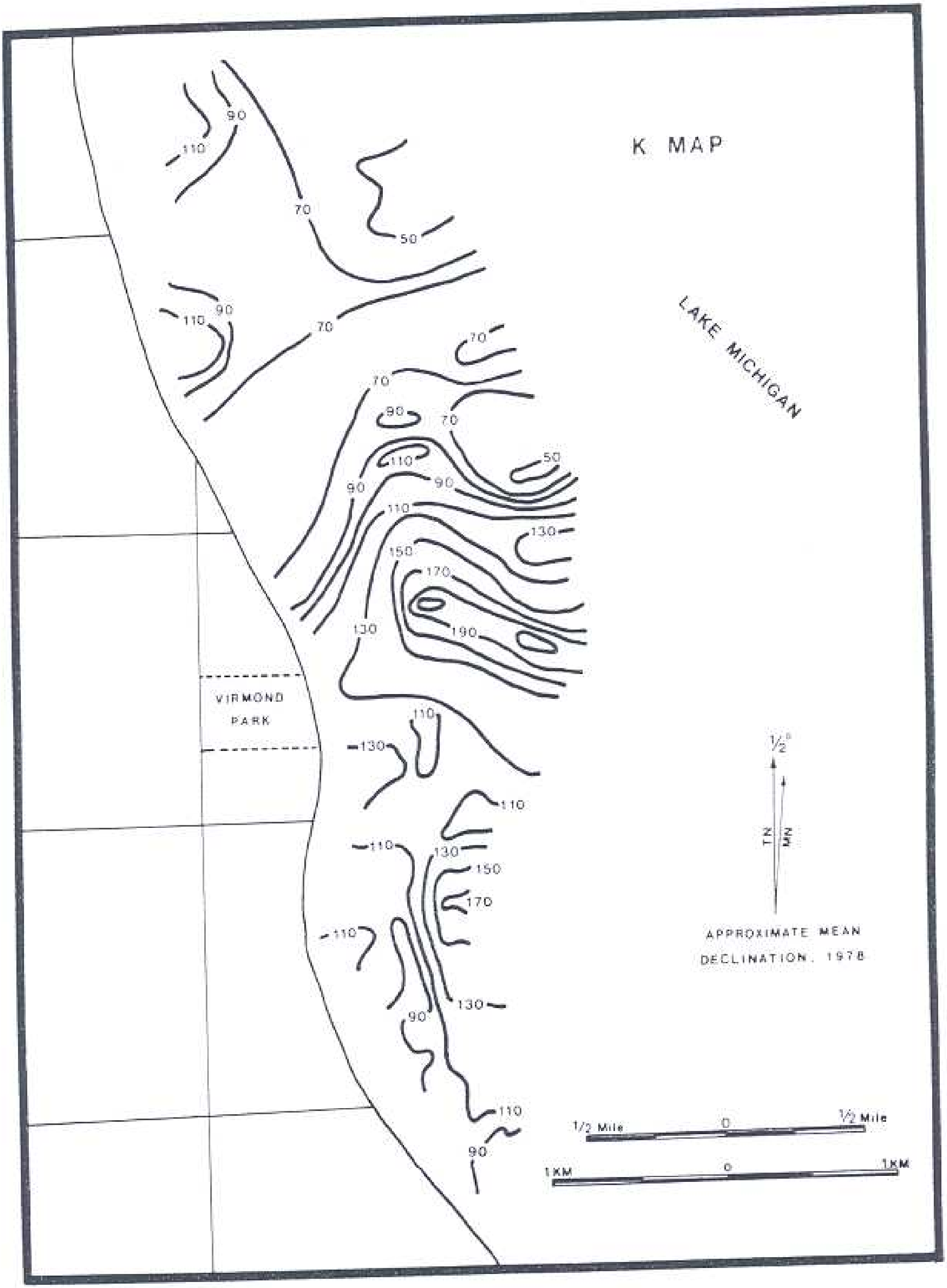

FIGURE 8. Map of relative hydraulic conductivity of lakebed sediments, determined geophysically

The dolomite aquifer was modeled as an anisotropic, two-layered medium. In both layers, the value of the conductivity along the ENE direction was twice that transverse to it. Calibrated conductivities in the lower layer (the bottom 135 m of the aquifer) were one tenth those in the upper part of the aquifer.

The flow model indicated that 2.3 x 10^2 m^3/day of lake water is entering the aquifer per km of shoreline (0.27 ft^3/sec/mile) in the study area. The amount measured directly via seepage meters was 2.1 x 10^2 m^3/day/km, while the amount calculated indirectly by assuming simple mixing of lake and aquifer waters to produce the observed water quality was 2.4 x 10^2 m^3/day/km.

Subsequent to this testing, the chemical mass transport model was coupled to the calibrated flow model. The coupled model was calibrated by assuming a homogeneous lakebed and adjusting the porosity of the dolomite until the simulated distribution of total dissolved solids most closely resembled the observed. Porosity is not used in the flow model and no other variables were changed at this stage of the calibration. In other words, the flow portion of the coupled model was not altered subsequent to its independent calibration.

The plumes modeled using homogeneous lakebed properties differed in several ways from observed conditions. See Rovey (1983) for details. These discrepancies between simulated and observed conditions can be attributed to the failure to account for the heterogeneous nature of the lakebed sediments. The next step in the modeling exercise was to take the geophysically-measured, longitudinal electrical conductances of the lakebed as converted to absolute hydraulic conductivities as described by Bradbury and Taylor (1984) and use these hydraulic conductivities in the coupled model. The resulting simulation

(Figure 9) produced very good correlation between the observed and modeled TDS concentrations. No other combination of heterogeneous lakebed hydraulic conductivities could be found which produced as good a match as in Figure 9.

In summary, entry of the geophysical data into the chemical mass transport model produced an excellent match with the field data. We feel this demonstrates that the geophysically-derived hydraulic conductivities are valid.

APPLICATION

The amount of groundwater entering Lake Michigan has been estimated by a variety of researchers including Bergstrom and Hansen (1962), Skinner and Borman (1973) and Cartwright et al. (1979). However, each study used different methods applied to different areas. The result is a range of flux estimates of about 2 orders of magnitude, from 110 to 8200 m^3/day/km of shoreline (Taylor and Cherkauer, 1984). Hensel (1984) used the information from this study to calculate an improved flux estimate. He took the fluxes Rumbaugh (1985) calculated for each primary type site (Table 3) and assumed that they occur for the entire portion of the shoreline having geology similar to that type area (Table 2). Rumbaugh (1985) did not model the Milwaukee and Haven sites because the hydrogeologic data available there did not allow for proper model calibration. Flux from the Milwaukee site was assumed to be negligible while flux from the Haven site was approximated as the average of the Peninsula and Mequon values. Fluxes for those areas which are not similar to any of the type areas (Table 2) were equated to those at Wind Point, the type site hydrogeologically closest to the unknown areas on the matrix (Table 1).

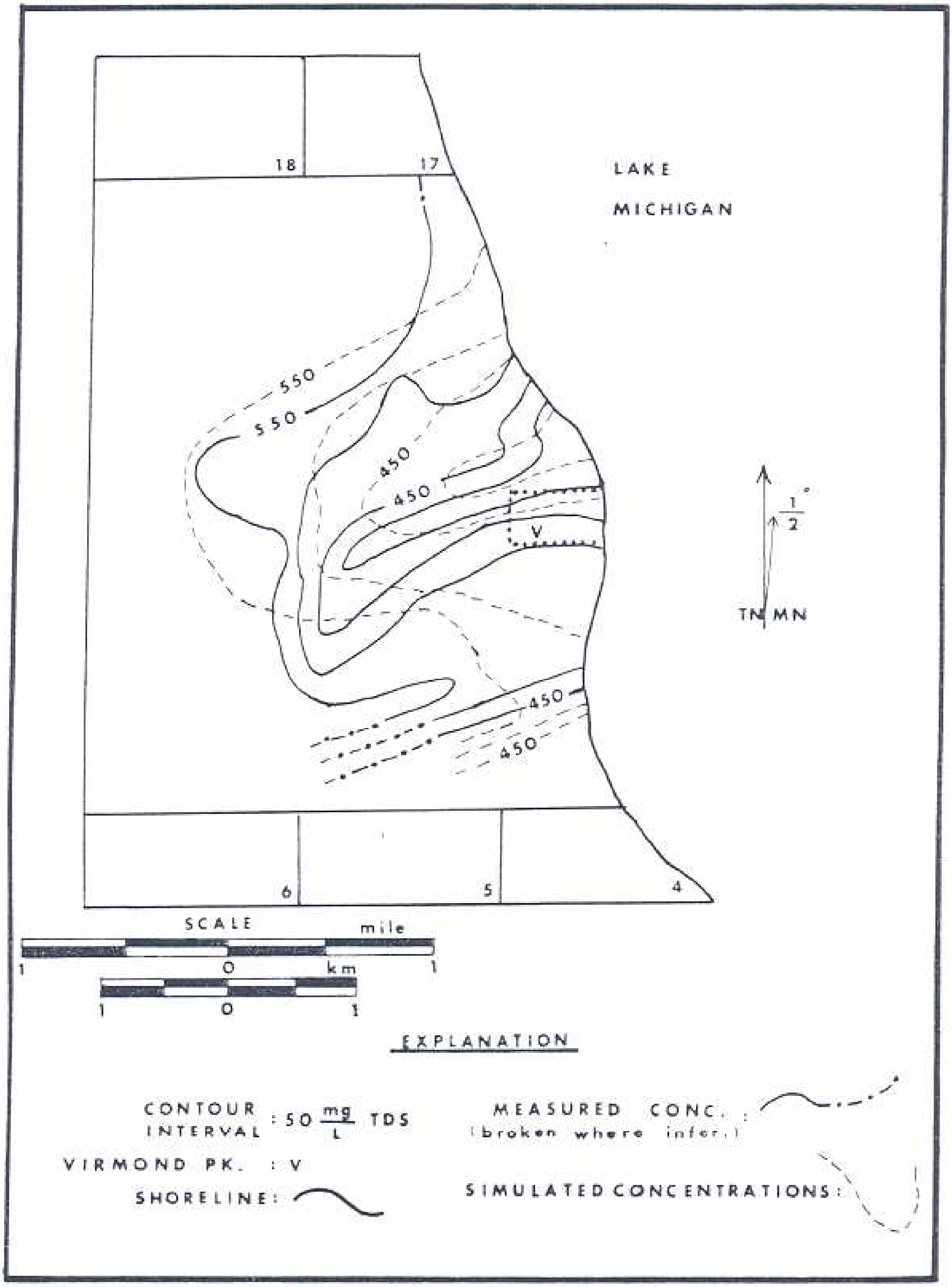

FIGURE 9. Comparison between simulated and observed TDS plumes

For the entire Wisconsin shoreline, Hensel (1984) calculated an influx of groundwater to Lake Michigan of 330-460 m^3/day/km of shoreline. Based on our evidence, the daily influx to the Lake from the Wisconsin side is between 1.5×10^5 and 2.2×10^5 m^3. (See Hensel (1984) for details of the calculation.) In comparison, Skinner and Borman (1973) estimated the daily surface runoff to Lake Michigan from the study area to be 5×10^6 m^3. While our flux calculation is based on a variety of hydrogeological assumptions which require further testing, we believe it is the most accurate estimate available.

POTENTIAL FUTURE USES

Application of our research will be of interest to both state and federal agencies, in particular the Wisconsin Department of Natural Resources, the Wisconsin Geological and Natural History Survey, the Illinois Water Survey, the Army Corps of Engineers and the IJC. Applications of our technique are possible in the general areas of: water supply, land use planning, mobilization of microcontaminants from lakebed sediments, lake water budget studies, inland lake hydrology, fisheries biology, and basic research in stratigraphic analysis. Details concerning these potential applications are given in the Appendix.

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