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Groundwater Flux into a Portion of Eastern Lake Michigan

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ABSTRACT. *One of the world's most precious resources is groundwater. Groundwater flow in the Great Lakes region is estimated to be 111.7 million* m^3 day^{-1}*. Not only is groundwater's value in the Great Lakes region attributed to its consumptive quality, but groundwater is also important to the hydrologic cycle in the region. The objective of this study is to quantify the volume of groundwater by applying two methods. In the past, groundwater volumes were quantified by computing the baseflow component of streamflow. This study compares the past method of computing groundwater flow with results obtained from a three-dimensional finite-difference model.*

A three river basin area on the eastern shore of Lake Michigan was chosen for this comparison. The results showed that traditionally computed groundwater flow (baseflow) is three orders of magnitude smaller than modeled flow.

INDEX WORDS: *Groundwater, Lake Michigan, hydrology.*

INTRODUCTION

One of the world's most precious natural resources is fresh water. The state of Michigan is bordered by four freshwater Great Lakes. Some of the variables that comprise the water balance of these lakes, such as precipitation, runoff, temperature, and water levels, have been studied, modeled, and quantified. One variable that is part of the lakes' water balance has been studied and modeled, but not quantified; that variable, groundwater, is the subject of this research.

Of the world's fresh water, 30% is accounted for in groundwater, 0.3% in freshwater lakes, and 69% (unavailable) in polar ice caps. Groundwater flow in the Great Lakes region is estimated to be 111.7 million m^3 day^{-1} (Great Lakes Basin Commission 1975).

Quantifying groundwater flux to Lake Michigan is not only important for predicting water levels, but is also important for predicting advective and dispersive flows of agricultural, industrial, and urban generated pollutants that infiltrate aquifers and are carried into the Great Lakes of North America.

This study will focus on quantifying the groundwater flux into a portion of eastern Lake Michigan. Two different methods will be used to compute groundwater flows. First, groundwater flow will be estimated by computing baseflow. Baseflow is the groundwater component of a streamflow hydrograph and through various methods can be separated from surface runoff, overland, and subsurface flows. And, second, groundwater flow will be estimated using a physically based model in which the aquifer system is considered. These methods will be compared.

STATEMENT OF OBJECTIVES

The overall objective of this study is to evaluate the hypothesis that traditional methods of computing groundwater flows by separating baseflows from streamflows underestimate groundwater flows. This overall objective will be accomplished by:

1. Identifying aquifers that contribute groundwater to eastern Lake Michigan.
2. Quantifying the baseflow contribution from rivers in that region.
3. Quantifying groundwater flux into eastern Lake Michigan.
4. Comparing groundwater flux from the two methods with previous studies.

LITERATURE REVIEW

In order to predict groundwater flow into Lake Michigan, contributing aquifers and their physical characteristics must be identified. Michigan's bedrock aquifers have been identified to a great extent by past researchers (Hough 1958, Great Lakes Basin Commission 1975, Mandle 1986). Although these bedrock aquifers, particularly the Marshall Sandstone, have been studied extensively for saline water content (Westjohn 1986) because of its association to oil and gas, they haven't been extensively studied for their contribution to Lake Michigan's water balance. Similarly, the Quaternary aquifer (unconsolidated sediments) which overlies the bedrock aquifers (Great Lakes Basin Commission 1975) hasn't been studied extensively because of its diverse hydraulic characteristics (Olcott 1992).

In contrast to aquifer characteristics, streamflow characteristics have been studied extensively, and several methods have been developed to separate streamflow into baseflow and stormflow. Baseflow has been successfully calculated by two different methods: 1) the stormflow analysis (Brooks *et al.* 1991) where baseflow is separated from runoff through the analysis of a stormflow hydrograph, and 2) the recession constant method (Mayboom 1961) where a time-series of streamflow is plotted on a semilogarithmic paper, and baseflows and recharge are derived from a recession curve.

Groundwater flow has been modeled using physically based mathematical models in which flows through a porous media are estimated (Cherkauer *et al.* 1992, Cherkauer and Hensel 1986, Cherkauer and Zager 1989, Fleck and McDonald 1978, McDonald and Harbaugh 1988). This study will use the computer model MODFLOW developed by McDonald and Harbaugh (1988) to predict groundwater flux into Lake Michigan.

Once groundwater flows are estimated from the two methods, they will be compared to previously derived values for Lake Michigan (Cherkauer and Hensel 1986, Great Lakes Basin Commission 1975, Cartwright *et al.* 1979, Bergstrom and Henson 1962).

BACKGROUND

Geologic Setting

Lake Michigan's geologic past can be summarized in two major episodes. The first episode was during the Paleozoic when sediment was deposited in marine water at various times when the continent became flooded by the oceans (Hough 1958). These deposits, which overlie Precambrian crystalline rock, filled the sunken Michigan basin and are in some areas up to 4,000 meters thick (Mandle 1986). Deposited between 185 and 520 million years ago, this Paleozoic rock consists mainly of limestone, sandstone, dolomite and shale. These sediments have since been consolidated but not otherwise strongly altered (Hough 1958).

The second major geologic episode that helped form the Michigan basin was during the Pleistocene epoch, particularly the Wisconsin glaciation, which occurred over 14,000 years before present (Mandle 1986). During this glaciation, previously laid bedrock surfaces were scoured, the Great Lakes were formed, and the present day unconsolidated sediment landforms were created (Hough 1958).

Unconsolidated sediments that overlie bedrock deposits consist of soils and parent materials that were deposited during the Pleistocene glaciation. These unconsolidated sediments, which are mostly drift, alluvial, and lacustrine deposits, vary greatly in their water bearing capacity (Great Lakes Basin Commission 1975). For the purpose of this study, however, these unconsolidated sediments will be referred to collectively as the Quaternary aquifer.

Wells drilled into the Quaternary aquifer yield over 2,724 m^3 day^{-1} (Great Lakes Basin Commission 1975). A report from the Great Lakes Basin Commission (1975) details two major areas of thick sand and gravel aquifers; these are the Manistee-Muskegon river basin groups. Wells in these groups yield 5,400 to 13,600 m^3 day^{-1}.

Overall, soils in the Quaternary aquifer are classified as spodosols in the northeastern lower peninsula and alfisols in the southern lower peninsula (Brady 1990). Spodosols are mineral soils that are formed on coarse textured acidic parent material. Forests are the natural vegetation under which most of these soils have developed. Alfisols, on the other hand, usually contain clays and are very productive agricultural soils.

The study area consists of hummocky landforms of either glacial drift deposits with textures of sandy clay loam, sandy loam or loamy sand, or ground moraines of medium textured till. These landforms are scattered throughout three river basins that have lacustrine river bed deposits of sand and gravel. These deposits are pale brown to pale reddish-brown fine to medium sand, often including beds of gravel (Farrand 1982).

Vegetation and topography associated with these soils can be divided into five major districts (Albert *et al.* 1986): the Allegan District, which lies in the extreme southwestern Lower Peninsula, the Ionia District which lies in south-central lower Michigan, the Highplains District which lies in the interior highland area of northern-lower Michigan, the Newaygo District which lies in west-central Lower Michigan, and the Manistee District which lies along the western coast of the state in the north-central part of Lower Michigan. Elevations in these districts range from 176.7 m (Lake Michigan's elevation) in the Manistee and Allegan districts to 526.0 m in the Highplaines district. Vegetation in these districts is mostly forested woodlands. Beech and sugar maple forests occur on richer alfisols of the Allegan and Ionia districts, whereas oaks and pines occur on the well-drained, coarse-textured spodosols of the Manistee, Highplains, and Newaygo districts.

Hydrologic Setting

The Michigan basin, resembling the shape of an inverted cone in the northern Lower Peninsula, is hydrologically divided down the middle of the state by rivers flowing either into Lake Michigan or Lake Huron. Three rivers flow through the study site: the Grand, Muskegon, and White rivers. These rivers, which drain the site, flow from highland elevations down to Lake Michigan. Since this study area is analyzed as a single unit and not three separate river basins, hydrologic parameters such as precipitation, runoff, and streamflow have been arealy weighted over the basins to produce one value for each parameter (Table 1).

Parameters listed in Table 1 are not only components of the hydrologic cycle, but also contribute to the water balance of Lake Michigan. Lake levels are measured by the United States Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service. Over-basin precipitation was obtained by Thiessen weighted (arealy averaging) precipitation stations to obtain one value for the basin (Croley and Hartmann 1984). Over-basin runoff, which includes streamflows, was also obtained from the Great Lakes Basin Runoff Model (Croley and Hartmann 1985). Comparatively, runoff accounts for 27% of precipitation that falls on the three-basin area.

TABLE 1. Average hydrologic parameters of the study area.

Precipitation (m^3s^{-1})	Runoff (m^3s^{-1})	Lake Michigan Water Level (m)	Combined Streamflow (m^3s^{-1})
694.4	188.9	177.0	207.1

METHODS AND ANALYSIS

Statistical Model Physical Aspects and Use

The mathematical model chosen for this study, MODFLOW (McDonald and Harbaugh 1988), is a three-dimensional finite-difference model which solves Darcy's Law (Equation 1).

$$Q = k_v A \frac{\Delta H}{L} \tag{1}$$

Where:
Q = rate of flow ($cm^3\ s^{-1}$);
K_v = hydraulic conductivity ($cm\ s^{-1}$);
A = cross-sectional area (cm^2);
ΔH = change in piezometric head (cm); and,
L = length of the soil column (cm).

Darcy's Law (Brooks *et al.* 1991), which approximates the rate of flow through a porous media, is based upon the continuity equation, where the difference between inflow and outflow within a system is equal to the change of storage in that system. This one-dimensional equation is applied three-dimensionally in MODFLOW using a finite-difference method (McDonald and Harbaugh 1988).

Since this model was designed as a series of independent subroutines or modules, it allows the user to statistically construct or design a hydrologic system which mathematically represents an aquifer through customized input parameters. Physical parameters such as the number of aquifer layers, aquifer withdrawals and recharges, location and extent of recharge boundaries, river and lake interactions, evapotranspiration rates, vertical and horizontal hydraulic conductivities, and storage coefficients allow the user to customize the model to a particular aquifer system.

Since groundwater flows are computed in MODFLOW three-dimensionally, data inputs must be in a spatial, three-dimensional format. This format includes areal extent of the aquifers (Fig. 1), in which each cell contains a hydrologic parameter, and vertical extent defined by the number of layers, and their thicknesses. Hydrologic parameters were input on a 5 km^2 grid spacing. A total grid of 31-by-31 was used because it covered the entire three-river-basin area as well as the sub-surface hydrologic divide (Figure 1).

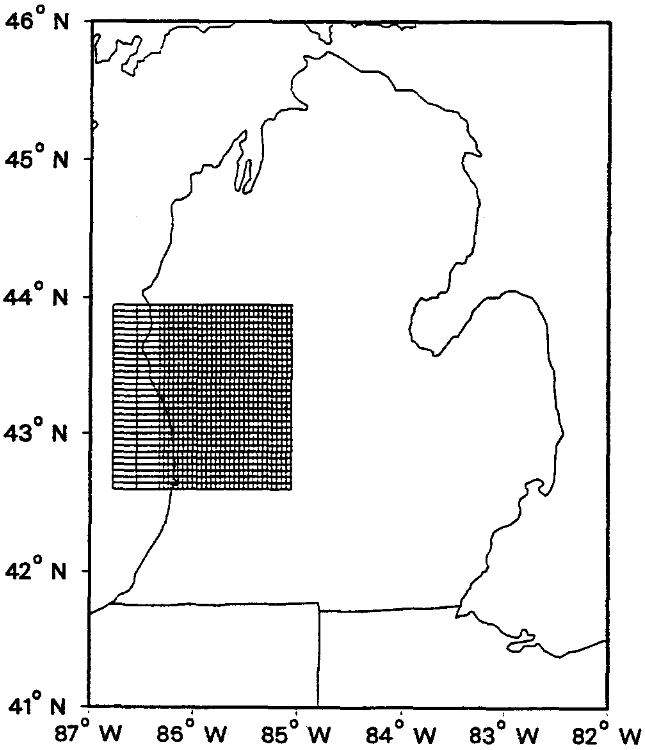

FIG. 1. The study area showing the grid used for MODFLOW model.

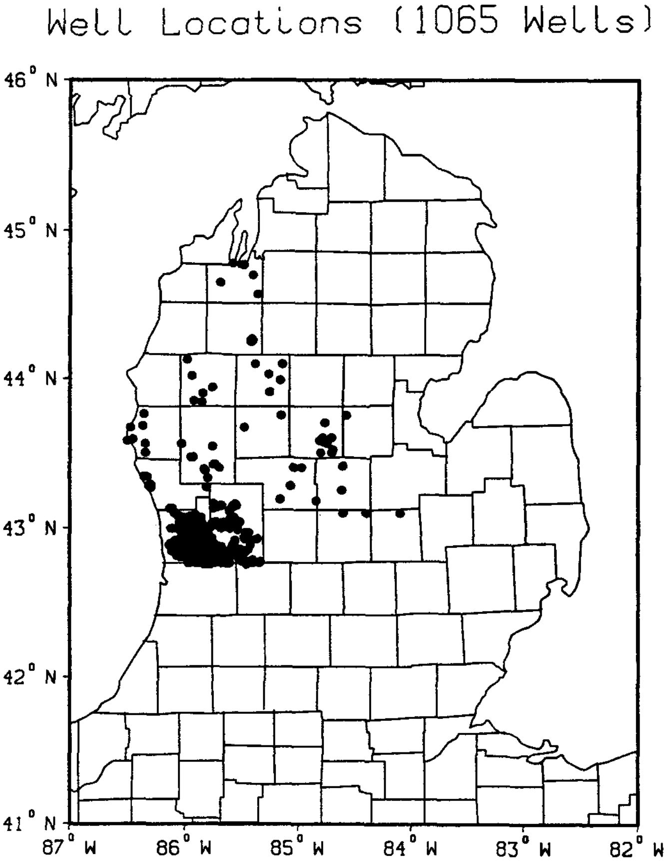

FIG. 2. Well locations.

SITE LOCATION

The study site, shown in Figure 1, is located in central-western Michigan along the eastern coastline of Lake Michigan and extends latitudinally from 42.33° to 44.0° North and longitudinally from 87° to 85° West. This site, a good candidate for groundwater studies, was chosen for three reasons: 1) it is an area where two aquifers contribute to Lake Michigan; 2) two larger rivers, the Grand and Muskegon rivers, and one smaller river, the White River, contribute baseflow to Lake Michigan; and, 3) an enormous amount of well data is available for this region.

WELL DATA AND LOCATION

Data archived by the Michigan Department of Natural Resources, Geological Survey Division (Michigan Department of Natural Resources 1992) were used to compute aquifer thicknesses, boundaries, lithologic sequences, transmissivities and hydraulic conductivities. Figure 2 shows the location of 1,065 wells spanning a 16 county area, with the majority concentrated at 43° N near Muskegon county.

Ninty-nine of these wells are classified as Type-1 wells. Type-1 wells are usually deeper municipal wells with stricter well-log reporting requirements, compared to wells drilled for private use or oil and gas.

RESULTS

Information required as input to MODFLOW resulted from a detailed analysis of 1,065 well logs. Detailed information such as depths to stratigraphic layers, aquifers' elevations, piezometric heads, aquifers' thicknesses, transmissivities, and hydraulic conductivities were derived from these logs.

Stratigraphic Sequence

A representative cross sectional area was created to illustrate the stratigraphic sequence of these subsurface aquifers. The cross sectional line (AB) depicted in Figure 3 shows the area at 43.5° North latitude and that spans from 84.7 to 86.5° West longitude.

Of the 1,065 wells, 110 were within 0.5 degrees of this cross-sectional area. Of the 110 wells, 13 were selected because they met the following criteria: 1) they penetrated both aquifer layers; and 2) they were stratigraphically consistent to adjacent wells. These wells are listed in Table 2.

Using these wells' lithological descriptions, depths to the different stratigraphic layers were obtained, and a stratigraphic sequence constructed (Fig. 4); this sequence agrees with one constructed by Westjohn (1986) in a nearby region.

Stratigraphically, beneath the Quaternary aquifer lies the first bedrock formation, a Mesozoic confining unit known as the Jurassic Red Beds. These beds are composed of gypsiferous shales and red sandstones. Beneath this confining unit is a Paleozoic water bearing aquifer, the Pennsylvanian Saginaw Formation (Milstien 1987). Since this formation does not contribute to the water balance of Lake Michigan, it was not modeled in this study. Another confining unit underlies the Saginaw Formation. This unit, Mississippian in age, is known as the Grand Rapids Group and consist of two units: the Bayport and Michigan Formations. Confined by the Michigan and Bayport Formations (which is depicted as one confining unit), the Marshall Sandstone (also Mississippian) is modeled in this study since it contributes to the water balance of Lake Michigan. The Marshall, which overlies the Coldwater Shale Formation, is composed of sandstone, siltstone, and shale and is most productive where unconfined. Wells drilled in this aquifer are usually 15-152 meters deep, yielding 100-1,800 gpm (Great Lakes Basin Commission 1975).

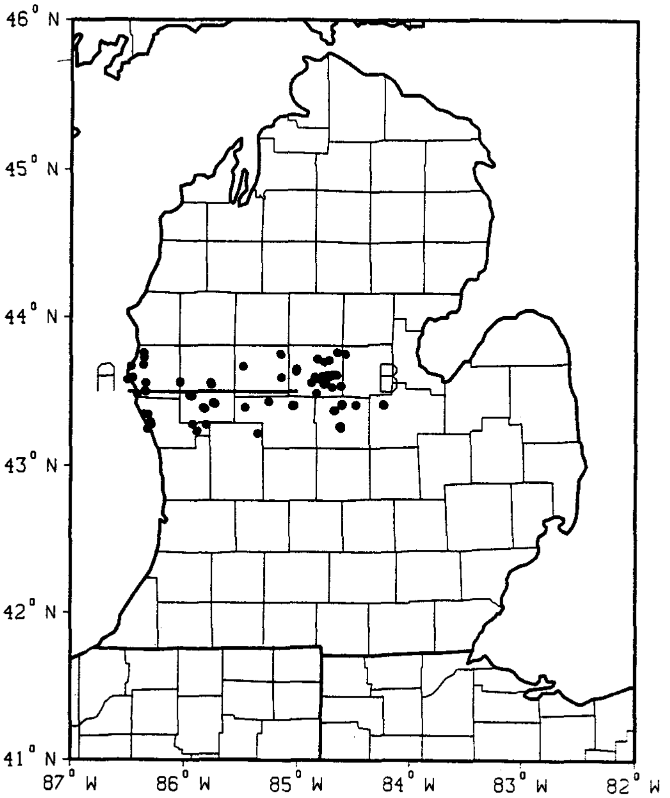

FIG. 3. Cross-section well locations.

Aquifer Hydrology

Hydrologic parameters required to model the aquifer system are hydraulic conductivity, transmissivity, piezometric (well) heads, vertical conductance, recharge and withdrawal values. Fleck and McDonald (1978) calculated the vertical conductance for the confining unit over the Marshall Sandstone at .004 $m^2\ d^{-1}$. This value was used where the unit is confined. Hydraulic conductivities for the Quaternary aquifer was obtained by first computing transmissivities from wells' step-drawdown data (Domenico and Schwartz 1990), then applying the relationship in Equation 2. The Marshall Sandstone's transmissivity values were obtained by multiplying previously measured hydraulic conductivities (Westjohn *et al.* 1990) by the layer thicknesses (Equation 2).

$$T = K \times B \tag{2}$$

Where: T = Transmissivity
K = Hydraulic Conductivity
B = Layer Thickness

Withdrawal rates from discharging wells in the study area were obtained from measured rates reported in Baltusis *et al.* (1992). Recharge, the flow of water into an aquifer, was estimated with a method detailed in Mayboom (1961). Recharge was estimated by plotting stream discharges versus time on a semilogarithmic paper. This plot yields a straight line, the slope of which is the recession constant, or the rate at which groundwater is discharged (Domenico and Schwartz 1990). Once the recession constant is known, then recharge and baseflow can also be graphically separated from the time-series. These estimates are listed in Table 3.

TABLE 2. Wells used to create cross-sections.

No.	Well No.	County	Latitude	Longitude	Elev (M)
1	61111716003	Muskegon	43.34	86.35	191
2	61111715002	Muskegon	43.34	86.32	194
3	61101702006	Muskegon	43.28	86.29	189
4	61101402002	Muskegon	43.28	85.93	216
5	62121335021	Newaygo	43.39	85.83	191
6	41091231006	Kent	43.12	85.77	269
7	62121221002	Newaygo	43.42	85.75	216
8	62121221019	Newaygo	43.42	85.74	216
9	41061112022	Kent	42.92	85.56	244
10	41050929012	Kent	42.79	85.41	233
11	41050926003	Kent	42.78	85.34	228
12	37140420017	Isabella	43.59	84.81	233
13	37140427014	Isabella	43.59	87.77	240

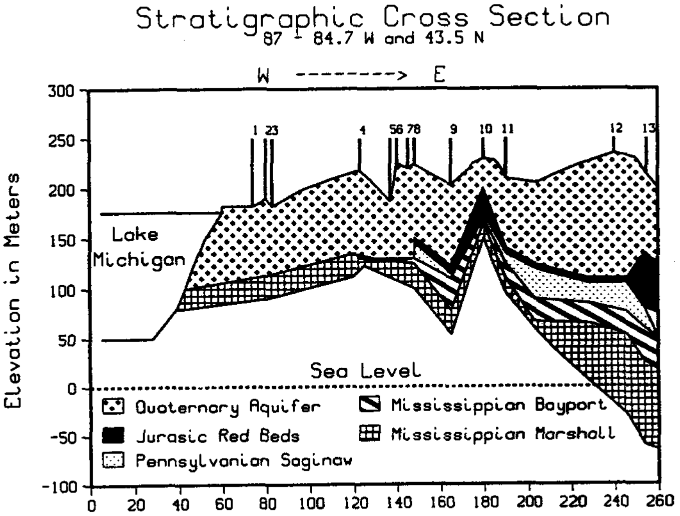

FIG. 4. Stratigraphic sequence along line A-B in Figure 3.

TABLE 3. Calculated streamflow, baseflow, and recharge amounts (m^3 day^{-1}).

River	Streamflow (m^3)	Baseflow (m^3)	Recharge (m^3)
Grand	$4.69 * 10^4$	$7.75 * 10^2$	$2.11 * 10^3$
Muskegon	$2.38 * 10^4$	$9.99 * 10^2$	$2.88 * 10^3$
White	$4.91 * 10^3$	$5.15 * 10^1$	$1.13 * 10^3$
Total	$7.55 * 10^4$	$1.83 * 10^3$	$6.12 * 10^3$

Recharge was applied directly to the Quaternary aquifer, and where the Marshall Sandstone was unconfined, it was recharged by water that percolated through the overlying sediment. Illustrated in Figure 5 is the unconfined area where the Marshall Sandstone is recharged (diamonded area), similarly illustrated is the shaded confined area.

Piezometric surfaces for both aquifers were determined by identifying the stratigraphic sequence layers of wells that contained water. Descriptors such as "water bearing" or "water sand" were used to identify the aquifer's piezometric head.

Of the 1,065 wells, 92 contained the Marshall Sandstone's piezometric levels and 974 contained the Quaternary aquifer's piezometric levels. Once these levels were identified, they were structured into a grid, then contoured with CA-DISPLAY, a computer graphics package (Computer Associates International 1988). Figures 6 and 7 are plots of these surfaces.

The water table in the Quaternary aquifer reaches an elevation of 345 meters in the far northeastern corner of the study area (highland portion of the Michigan basin), and slopes first steeply, then somewhat gently toward Lake Michigan. This is more apparent by the surface piezometric plot in Figure 8.

Flows in the Quaternary aquifer are mostly toward Lake Michigan. However, flows are away from Lake Michigan east of the 85th degree longitude as illustrated in Figure 8.

In order to better illustrate flow direction in the Quaternary and Marshall aquifers, flow directions were calculated. These calculations were based upon the knowledge that water flows from a higher

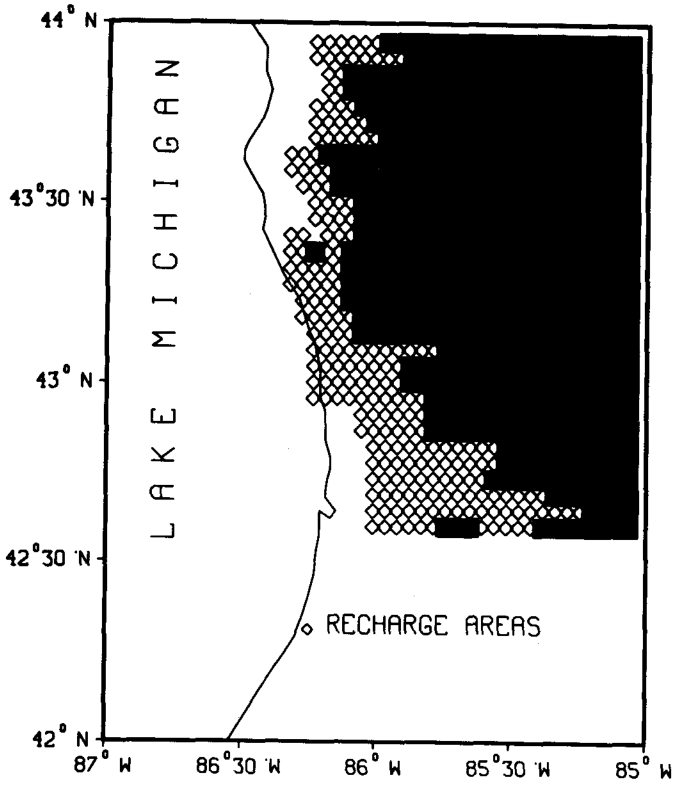

FIG. 5. Marshall Sandstone recharge area.

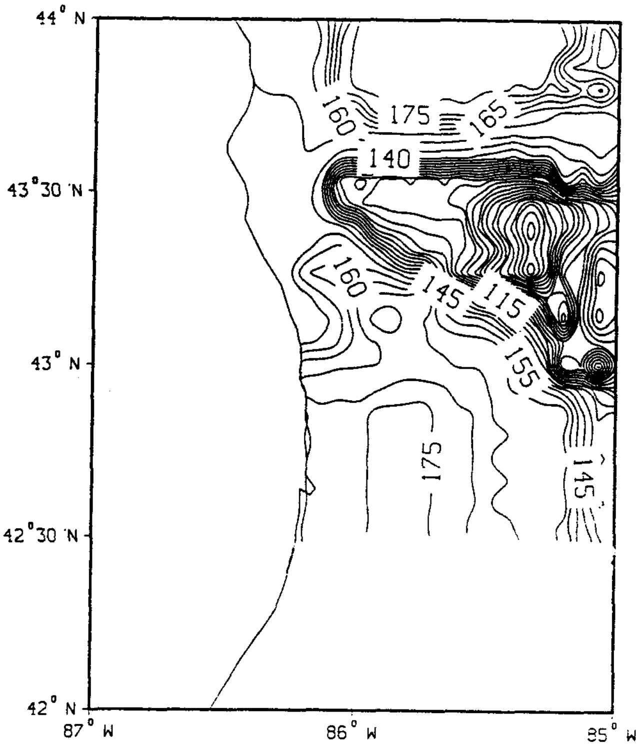

FIG. 7. Marshall Sandstone's piezometric contours.

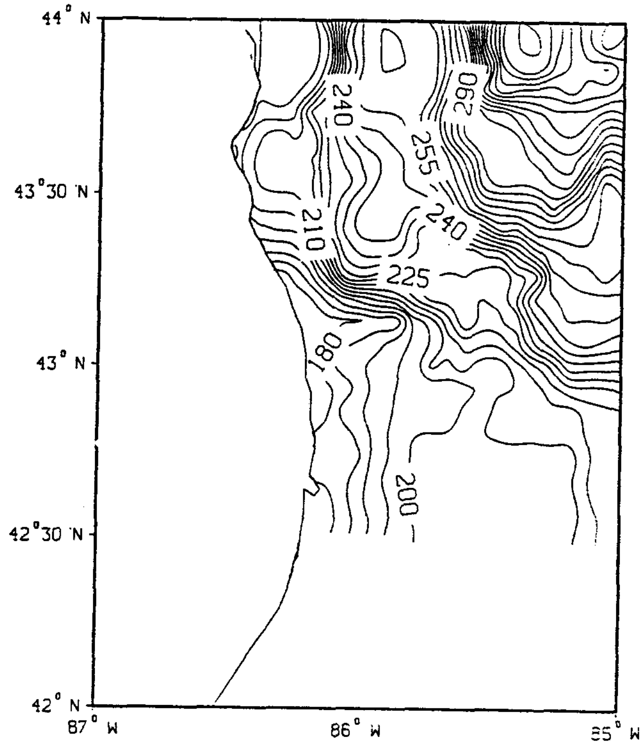

FIG. 6. Quaternary aquifer's piezometric contours.

elevation to a lower elevation. Using this knowledge, flow directions were calculated for each grid cell by identifying adjacent cells with a lesser elevation. In the case where adjacent cells' elevations were higher, no directions were calculated.

The Quaternary aquifer's flow directions are illustrated in Figure 9. Arrows located in the upper right hand corner of the study area illustrate flows from an upper elevation. Non-uniform arrows located just south of the 43.5° latitude illustrate flows through the hummocky glacial landscape. Although some of these flows are non-uniform toward Lake Michigan, the regional trend is toward the lake.

Compared to the Quaternary aquifer, the Marshall aquifer's piezometric head is much more complicated in this study area. Figure 10 is a piezometric surface plot derived from these surface contours. The Marshall Sandstone's surface contour plot shows the existence of an elevation high. This elevation high is similar to the elevation high in the Quaternary aquifer. In contrast to the elevation high is an additional topographic extreme, an elevation low that is located between 86th and 85th degrees longitude. This elevation low is consistent with a

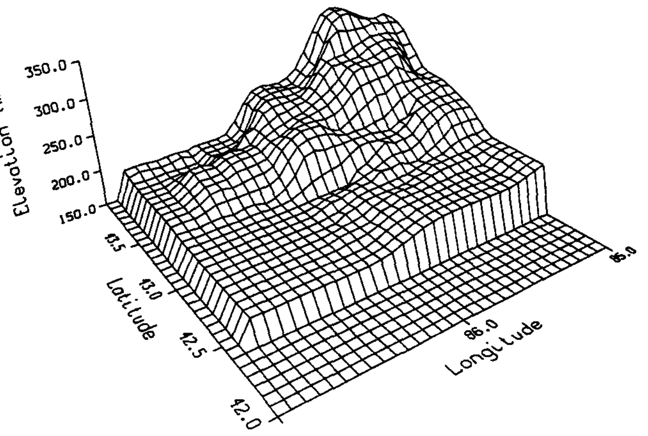

FIG. 8. Quaternary aquifer's piezometric surface.

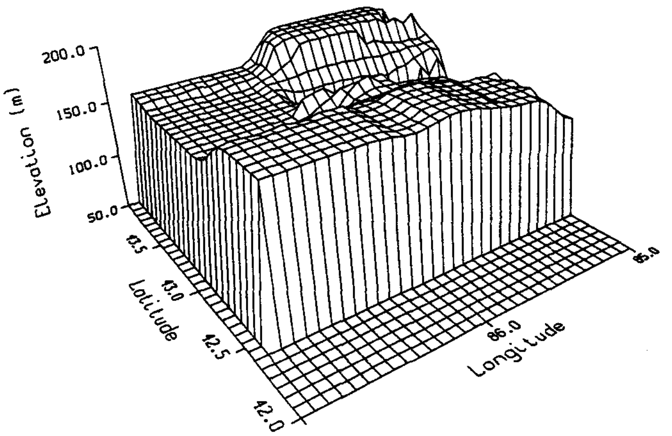

FIG. 10. Marshall Sandstone's piezometric surface.

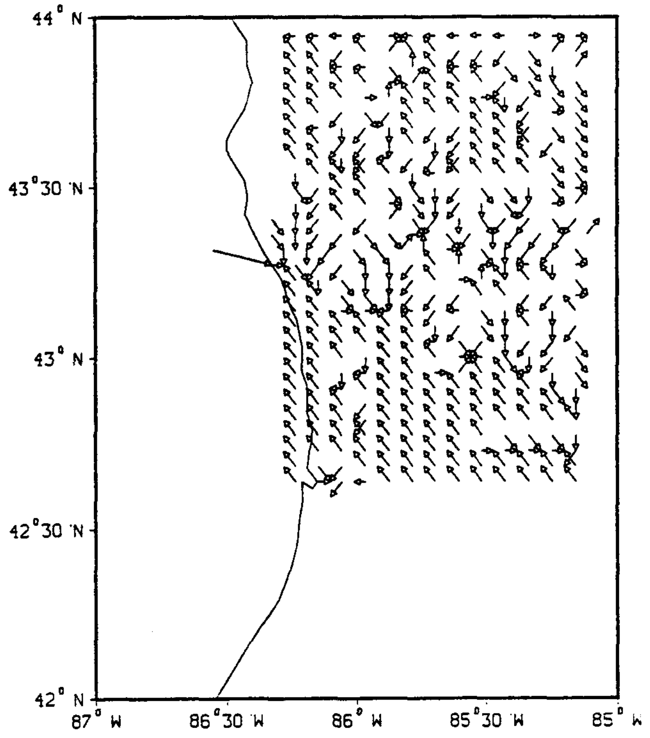

FIG. 9. Quaternary aquifer's flow directions.

surface mapped by the U.S.G.S. (Olcott 1992). Since the study area doesn't cover the entire Marshall Sandstone aquifer, it is difficult to determine what caused this elevation. Further study might reveal that it is a portion of a cone of depression. Although this surface has extreme elevational highs and lows, it eventually flattens out where it is in direct contact with Lake Michigan between 43 and approximately 43.5 degrees latitude.

Due to this complicated surface area, flow directions are also complicated (Fig. 11). Flow directions are mostly toward Lake Michigan, and where highs and lows exist flows become turbulent. As with the Quaternary aquifer, flows are in the direction of Lake Huron as the 85th longitude is approached.

Model Calibration Statistics

Once the aquifers' hydraulic characteristics were formatted for MODFLOW inputs, where each gridsquare contained a value, the model was executed until calibrated. Calibration was reached once the input heads for both layers reasonably matched the output heads at the end of the model's execution.

Once calibration was reached, the modeled outputs were statistically compared to the measured well heads. Figures 12 and 13 are the residuals of the measured heads minus the modeled heads for the Quaternary aquifer and the Marshall Sandstone, respectively. The open-circles in these figures are exact head match, where the difference between measured and modeled heads is zero. Similarly, the bars are differences between heads. The small variance in the residuals for the Quaternary aquifer is reflected in the computed root-mean-squared-error (rms) of .02 m. Variances in the Quaternary piezometric surface appear to correspond to areas of sharp head changes. Residuals of the Marshall Sandstone were slightly larger with a rms of .18 m. Variances of heads in the Marshall aquifer directly corresponds to the recharge area (Fig. 13), the area of major flux. As mentioned above, since vertical conductance values for the entire surface weren't exact, different values were incrementally applied to the model until the sandstone layer was calibrated. A more precise seepage value would have resulted in less variance in layer 2.

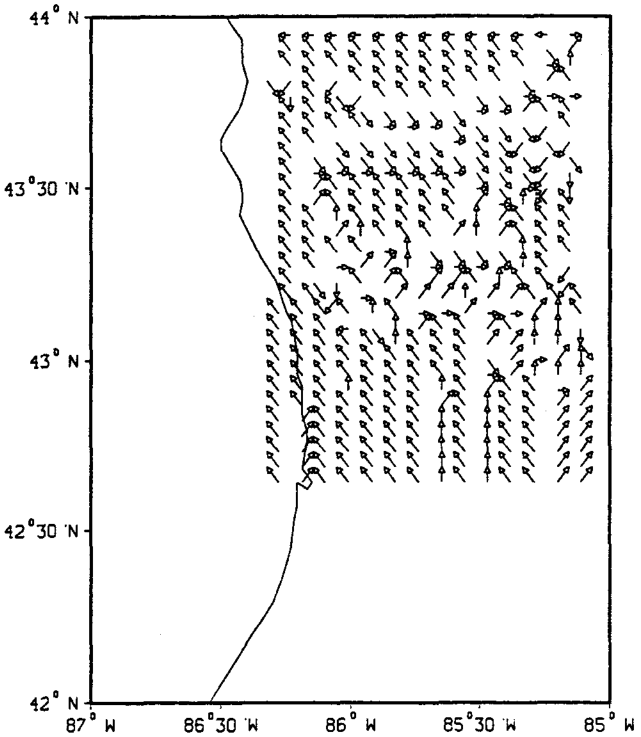

FIG. 11. Marshall Sandstone's flow directions.

DISCUSSION

Model Results

Aquifers in this region were modeled as two layers; the Quaternary upper layer which is modeled as an unconfined aquifer and is hydraulically connected to the Marshall Sandstone lower layer which is modeled as a confined aquifer. Boundaries of these two aquifers consist of a confining unit between the two layers, a constant head boundary where the aquifers are in contact with Lake Michigan, and variable heads elsewhere.

As discussed previously, flows into the aquifer were in the form of precipitation that infiltrated both layers. Flows out of the aquifers were in the form of discharging wells and flows into Lake Michigan which were represented as a constant head boundary. The results indicate that discharging

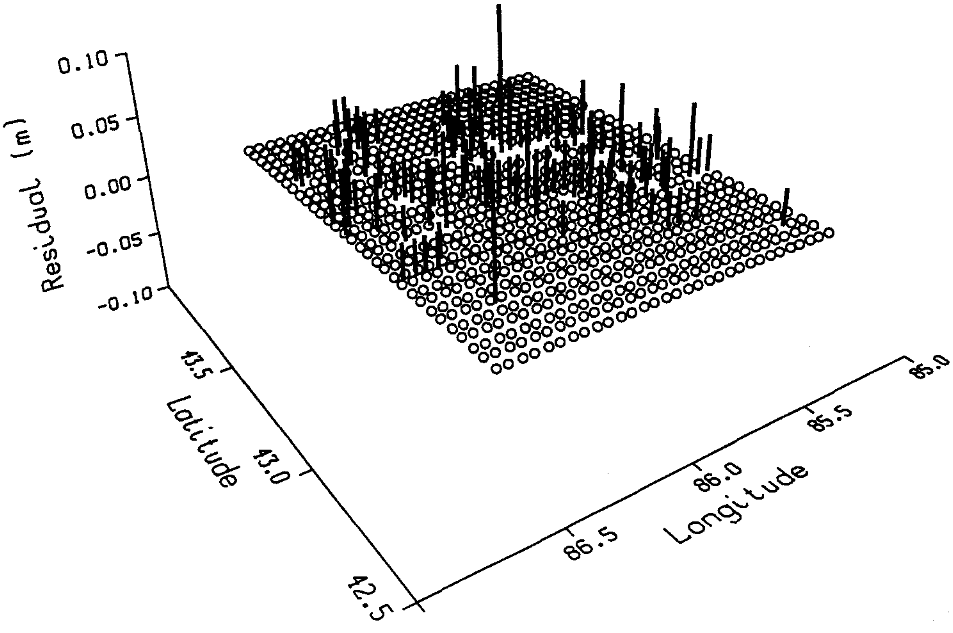

FIG. 12. Quaternary aquifer's residuals.

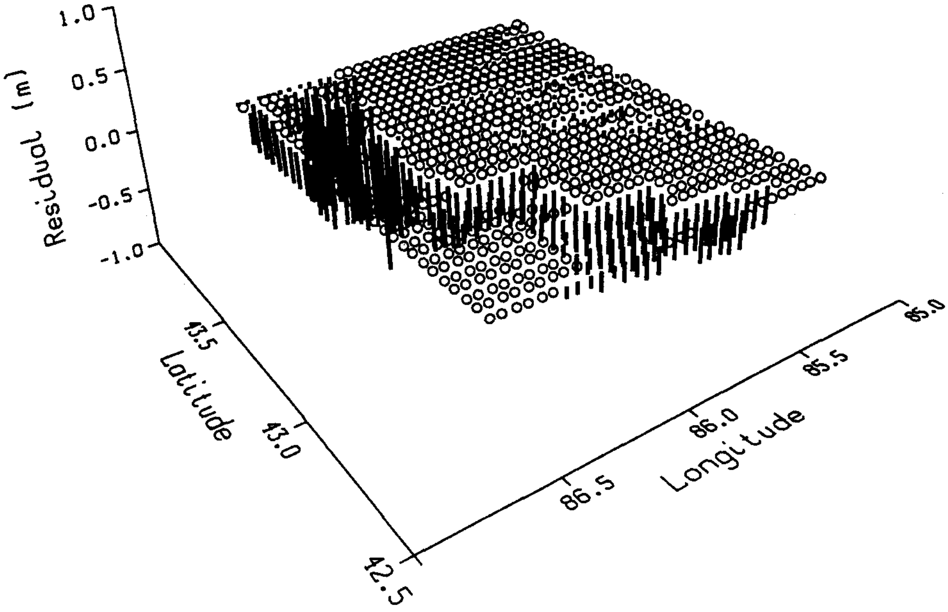

FIG. 13. Marshall Sandstone's residuals.

well flows accounted for 1.49 * 10^4 m^3 day^{-1}, and flows into Lake Michigan totaled 1.33 * 10^7 m^3 day^{-1}. In addition to the inflows and outflows, the combined volume of water stored within these two aquifers on a daily basis is 8.29 * 10^8 m^3. The model was developed under the assumption that flows to the area's tributaries would enter Lake Michigan, therefore these tributaries were considered part of the Quaternary aquifer.

The modeled volumetric groundwater flow into Lake Michigan was normalized to units of 553 m^3 day^{-1} km^{-1} in order to compare it to previously computed groundwater flow quantities. This normalized value was obtained by dividing the volumetric flow by the model's grid portion that was in direct contact with Lake Michigan's shoreline. In 1974 the Great Lakes Basin Commission estimated groundwater flux for the Lake Michigan basin at 19 m^3 day^{-1} km^{-1} using the 70% flow duration curve method. Using a water budget approach where precipitation, runoff, and evapotranspiration were assumed known, Bergstrom and Henson (1962) estimated groundwater as a residual resulting in a volume of 350 m^3 day^{-1} km^{-1}. Cartwright *et al.* (1979) made direct measurements of the hydraulic gradients in southern Lake Michigan and calculated groundwater flows of 8,300 m^3 day^{-1} km^{-1}. Using a digital simulation model Cherkauer and Hensel (1986) calculated flows at several areas along the Wisconsin shoreline and produced a range of groundwater flows from 580 to 880 m^3 day^{-1} km^{-1}. The wide range in groundwater estimates of 19-8,300 m^3 day^{-1} km^{-1} can be attributed to 1) different techniques used to obtain groundwater flows; and, 2) the location around and/or in Lake Michigan where these flows were obtained.

The study's overall objective is to compare traditionally computed groundwater flows (baseflows) with groundwater flows obtained from a physically based model (MODFLOW). Average daily baseflows are three orders of magnitude smaller than daily groundwater flows.

This value may be significant when considering contaminant transport to the lake. Contaminants that enter the lake at this rate, over a period of time, may cause eutrophication or other forms of pollution. This area requires further study.

CONCLUSIONS

This study suggests that groundwater flow into Lake Michigan is underestimated by simply quantifying baseflows, and that a physically based model will yield volumetric flows within the range calculated by other methods. This is GLERL contribution No. 907.

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