PLAN OF STUDY FOR THE REGIONAL AQUIFER SYSTEMS ANALYSIS OF THE MICHIGAN BASIN

By R. J. Mandle

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For those readers who prefer metric (International System) units rather than the inch-pound units used in this report, the following conversion factors may be used:

Multiply inch-pound unit	by	To obtain metric unit
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.591	square kilometer (km^2)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

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ABSTRACT

Quaternary glacial deposits and Pennsylvanian and Mississippian sandstones--the Saginaw Formation and Marshall Sandstone--are the major aquifers in the Michigan basin. These aquifers supply approximately 188 million gallons per day to municipalities in the 29,000-square-mile study area. The most significant problems related to ground-water supplies are the identification of potable sources of ground water in large quantities and the migration of saline ground water toward pumping centers. Saline water underlies the entire Lower Peninsula of Michigan at indeterminate depth in the deeper parts of the Saginaw Formation and Marshall Sandstone in the center of the Michigan basin. In places, saline water is present in glacial deposits. Overdraft has resulted in severe drawdown in the Lansing area and the abandonment of wells near Flint because of saline-water encroachment. Increased demand on the ground-water resources of the study area are expected to cause further problems.

In 1985, the U. S. Geological Survey began a 5-year study to define the hydrogeologic framework, describe the geochemistry of ground water in the glacial and bedrock aquifers, and analyze regional ground-water-flow patterns. The scope, plan of study, organization and work elements are described in this report.

INTRODUCTION

Description of Study Area

The Michigan basin Regional Aquifer System Analysis (RASA) study area covers about 29,000 mi^2 (square miles) of the Lower Peninsula of Michigan. The study is limited to Mississippian and younger consolidated sedimentary rocks and unconsolidated sediments in the Michigan basin--an intracratonic structural bedrock depression. This includes the Marshall Sandstone (Mississippian), Saginaw Formation (Pennsylvanian) and Pleistocene and Holocene deposits. The outermost boundary for this study has been defined as the contact between the Mississippian Coldwater Shale and the overlying Marshall Sandstone (fig. 1). The Saginaw Formation is stratigraphically above the Marshall Sandstone. Glacial deposits, which overlie nearly all of the study area, range from a few inches to about 1,000 ft in thickness.

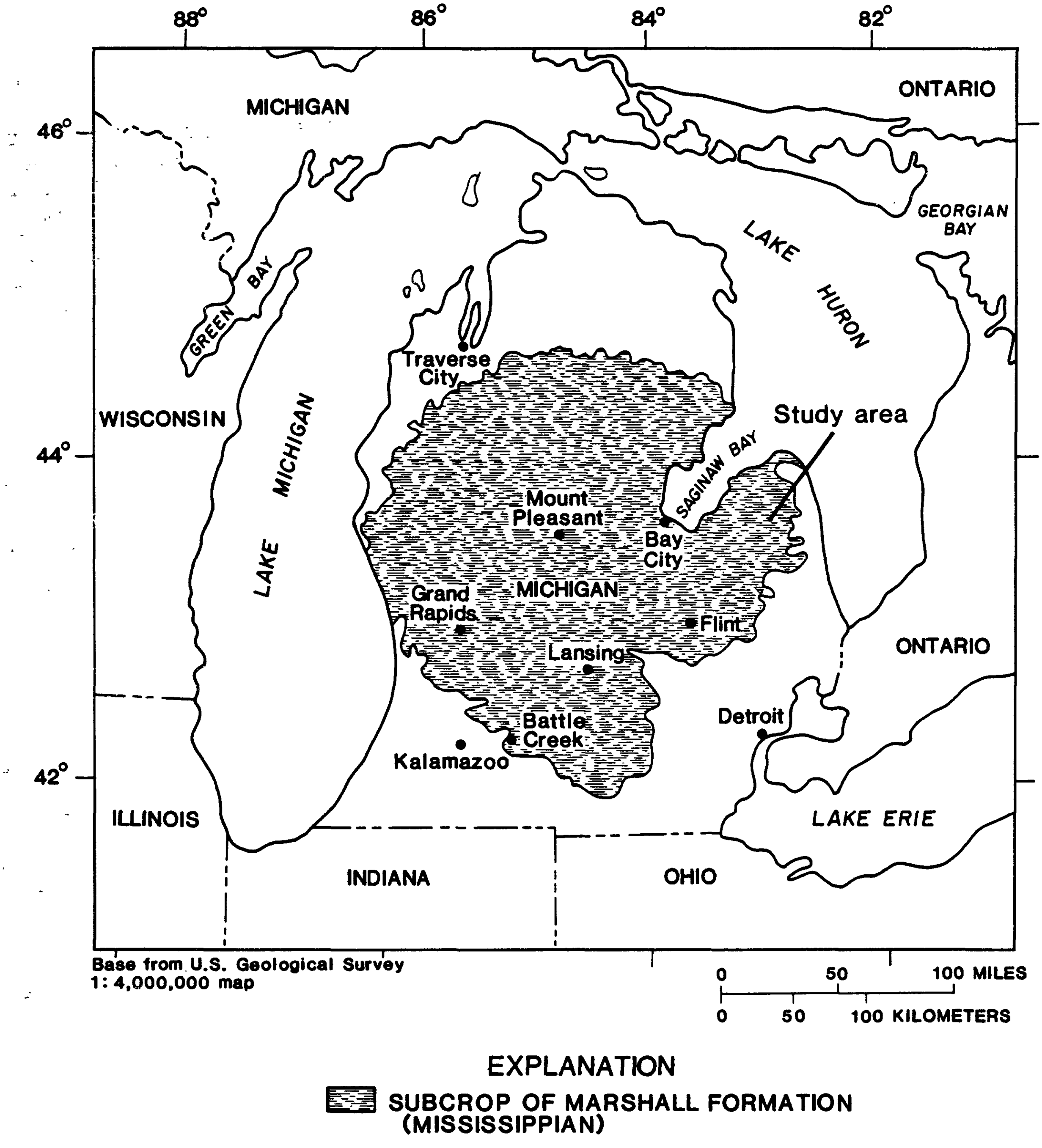

Figure 1.--Michigan Basin Regional Aquifer System Analysis study area.

Highly mineralized water is found in the deeper parts of the Marshall Sandstone and Saginaw Formation. In these areas, the total dissolved-solids content of water from the Marshall Sandstone is about 300,000 mg/L (milligrams per liter) and that from the Saginaw Formation may exceed 200,000 mg/L (Western Michigan University, 1981, table 7). In low-lying areas, such as the Saginaw Lowland (and to a lesser extent, the Michigan and Erie Lowlands), saline water is found in shallow bedrock (Twenter, 1966) and is locally present in the overlying glacial deposits.

Problem

Ground water has increasingly become an important source of water in Michigan. In 1978, use of ground water for public supply in the State totaled 215 Mgal/d (million gallons per day)(Bedell, 1982, p.2). Of this, about 82 Mgal/d was from the Saginaw and Marshall Formations. Another 106 Mgal/d was pumped from the glacial deposits in the study area.

The Marshall Sandstone and Saginaw Formation contain sandstone aquifers that are the major source of ground water for about 70 communities with a composite population of about 500,000. In the Lansing-East Lansing area, where the Saginaw Formation is the principal ground-water source, a cone of depression extending over 100 square miles has developed (Vanlier, and others, 1973); water levels near the center of the cone are as much as 160 ft below the prepumping level. In the Flint area, where both the Saginaw Formation and Marshall Sandstone were used for public supplies, heavy pumping caused migration of water with high chloride concentration to the pumping center (Wiitala, and others, 1963); this was a major cause for the abandonment of the well fields.

Increased demand for ground water in Michigan is anticipated because of population growth, irrigation, and industrial development. To protect the fresh ground-water resources of Michigan, an understanding of the occurrence of saline water and the relation between saline and freshwater, as well as between saline water and past and present ground-water-flow patterns is necessary.

Purpose and Scope

The purpose of this report is to outline a plan of study to describe and define the geohydrologic system in the sedimentary rocks and glacial deposits in the Michigan basin study area. Study plans include a geologic description of the Mississippian and younger sedimentary rocks, delineation of the freshwater-saline water interface, detailed discussion of the geochemistry of ground water and distribution of major ions in ground water, and a quantitative description of past and present ground-water-flow systems.

This study is one of several ongoing Regional Aquifer Systems Analysis (RASA) studies being conducted throughout the United States by the U. S. Geological Survey. These RASA studies cover large areas that coincide with geologic or hydrologic boundaries, rather than being confined by political or cultural boundaries. The purpose of these studies is to provide an understanding and assessment of the ground-water resources over these large geographic areas throughout the United States (Bennett, 1979).

GEOLOGIC SETTING

The Michigan basin RASA study area is contained entirely within the Michigan basin in the Lower Peninsula of Michigan. The Michigan basin is a circular structural basin that includes the Lower Peninsula and parts of Wisconsin, Illinois, Indiana, Ohio, and Ontario, Canada (fig. 2). It is bounded by the Canadian shield on the north, by the Wisconsin dome and Wisconsin arch on the northwest and west; by the Kankakee arch on the southwest; and by the Algonquin and Findlay arches on the east and southeast (Cohee,1965, p.211). The center of the basin is located to the west of Saginaw Bay (Dorr and Eschman, 1970, p.87).

Paleozoic and younger sedimentary rocks, estimated to be almost 14,000 ft thick (Cohee and others, 1951, p.1), overlie Precambrian crystalline rocks in the Michigan basin. These include Cambrian through Pennsylvanian sedimentary rocks. Upper Jurassic red beds are found in the center of the basin. Part of the Mesozoic sequence including the Triassic, Lower and Middle Jurassic and Cretaceous strata, is missing. The entire sequence of Paleozoic through Mesozoic rocks is mantled by glacial drift deposited during Wisconsin and probably earlier glaciation. These glacial and Holocene deposits are the only Cenozoic sediments found in the Michigan basin. Mississippian and younger sedimentary rocks found in the Michigan basin are the only rocks of interest in this study. These sedimentary rocks and their stratigraphic relations are shown in figure 3.

Bedrock Geology

A very thick Upper Devonian through Lower Mississippian clastic sequence marks the base of the rocks of interest in this study. Upper Devonian and Lower Mississippian black shale (Antrim Shale) and transitional, Devonian gray and gray-green shales and sandstones, called the Ellsworth Shale (western side of State) and the Bedford Shale, Berea Sandstone and Sunbury Shale (eastern side of State) reach thicknesses of about 1,300 feet in the subsurface (Dorr and Eschman, 1970, p.85). The overlying Mississippian Coldwater Shale also is very thick. In western Michigan it ranges from 500 to 800 ft in thickness and, in eastern Michigan, it is more than 1,100 ft thick. It consists of gray and bluish-gray shale, some limestone and dolomite on the

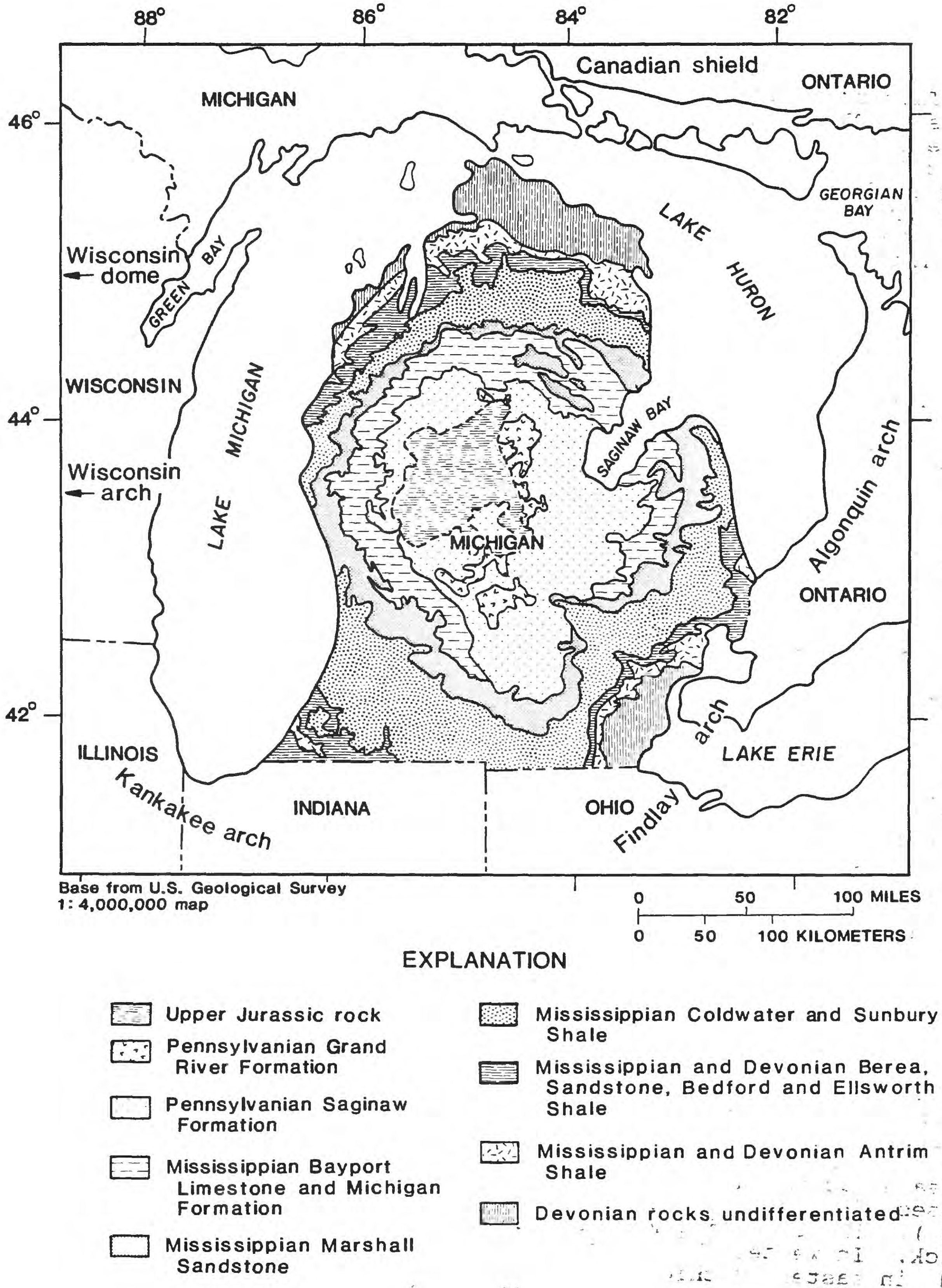

Figure 2.--General bedrock geology and regional structural features.
(From H. M. Martin, 1955)

Era	Period	Epoch	Glaciation
Cenozoic	Quaternary	Holocene	
		Pleistocene	Wisconsin Illinoian Kansan Nebraskan

Geologic time			Rock-Stratigraphic		
Era	Period	Epoch	Group	Formation	Member
Mesozoic	Jurassic	Late		Upper Jurassic Rocks	
Paleozoic	Pennsylvanian	Middle		Grand River Formation	Ionia, Eaton, and Woodville Sandstone[1]
		Early		Saginaw Formation	Verne Limestone[2]
				Parma Formation	
	Mississippian	Late	Grand Rapids	Bayport Limestone	
				Michigan Formation	
		Early		Marshall Sandstone	Napoleon Sandstone Member
				Coldwater Shale	
				Sunbury Shale, Becea Sandstone > Eastern Michigan	
	Mississippian and Devonian			Ellsworth Shale > Western Michigan Bedford Shale > Eastern Michigan	
	Devonian	Late		Antrim Shale	

Modified from Michigan Department of Conservation, 1964

[1] Designated members of the Saginaw Formation by Cohee (1951, p.5)

[2] From Kelly (1936)

Figure 3.--Diagram showing glaciation of the Quaternary and Post-Devonian Formations in the Michigan basin.

western side of the State, and siltstone and sandstone on the eastern side of the State (Monnett, 1948, pp.636-639; Cohee and others, 1951, p.3). The upper part of the Coldwater Shale is silty and sandy in eastern Michigan.

The Marshall Sandstone, which overlies the Coldwater Shale, is a very-fine-to fine-grained sandstone with some siltstone. Over large areas, it is predominately red but may be gray locally. The thickness of the Marshall Sandstone is about 200 to 300 ft in the western and southern Lower Peninsula (Cohee and others, 1951, p.3). Generally, it is difficult to determine the thickness of the Marshall Sandstone; in the center of the Michigan basin, the Marshall interfingers with rocks of the Michigan Formation. It is also difficult to distinguish between siltstone and sandstone at the base of the Marshall with those of the underlying Coldwater Shale.

The Upper Mississippian Michigan Formation overlies the Marshall Sandstone. It is a marine deposit consisting of gray, dark-gray and greenish-gray shale, anhydrite, gypsum, dolomite, limestone and some sandstone. The Michigan Formation thickens from less than 100 ft in the southern part of the study area to about 500 ft in the northern part.

The Upper Mississippian Bayport Limestone, which overlies the Michigan Formation, consists of light buff and brown cherty limestone and sandstone. In many places, the Bayport Limestone is composed of sandstone with interfingering limestone (Cohee and others, 1951, p.3). Thickness of the Bayport Limestone is highly variable as a result of irregular erosion on its surface. In some areas, such as near Saginaw Bay or the central part of the Michigan basin, the Bayport has been completely eroded (Cohee and others, 1951, p.3). In these areas, the Pennsylvanian rocks lie directly on the Michigan Formation or the Coldwater Shale (Cohee and others, 1951, fig. 16). The maximum thickness of the Bayport Limestone is less than 100 ft.

During Late Mississippian time, the Michigan basin was uplifted and parts of the Upper Mississippian and older deposits were eroded. This uplifting may have occurred as a result of reactivation of faults in the Precambrian basement rocks (Cohee, 1965, p.216). Pennsylvanian sedimentary rocks were deposited on this erosional surface.

A white quartz sandstone--the Parma Sandstone--forms the base of the Pennsylvanian. In some locations it is interbedded with siltstone, and in other areas, is replaced by shaley siltstone (Winchell, 1861, p.115; Kelly, 1936, p.136; Vugrinovich, 1984, p.9). It is a lenticular sandstone that generally is less than 100 ft thick and may be absent in some locations (Cohee and others, 1951, p.3).

A complex, repeated sequence of alluvial, deltaic and shallow marine sediments overlies the Parma Sandstone. The separation of these Pennsylvanian rocks into the Saginaw and Grand River Formations is preferred by the U. S. Geological Survey (Wanless and Shideler, 1975, p.68). Other authors, Cohee and others (1951) and Vugrinovich (1984) have proposed alternative groupings of the Pennsylvanian deposits and rocks.

These sediments--river channel and floodplain deposits, shallow marine limestone, swamp and swamp-laid coals--represent several cycles of deposition, alternating between continental and shallow marine environments (Kelly, 1936). The different lithologic units are lenticular and discontinuous and have highly variable thickness. The sandstones commonly contain abundant fossilized plant fragments and river-channel deposits. Shales may be light gray to dark gray. The light-gray shales often contain siltstone and plant fossils. The dark- gray shales contain siltstone, plant fossils, and marine invertebrates. Coal seams are common and range in thickness from several inches to less than 10 ft (Cohee and others, 1950, pp.3-4). The Verne Limestone member (Kelly, 1936) of the Saginaw Formation represents a shallow marine deposit.

The Grand River Formation consists mainly of massive, cross-bedded, coarse-grained sandstones, that contain very little mica, and that commonly are iron-stained on fresh fracture (Kelly, 1936, p.207). These are the Ionia, Eaton and Woodville Sandstone Members. Mapping these sandstones over extensive areas is very difficult because they were deposited in fluvial channels and are highly discontinuous. The Ionia, Eaton, and Woodville Sandstone Members are considered members of the Saginaw Formation by Cohee (1951, p.5).

During the Paleozoic Era, the Michigan basin subsided and sedimentary rocks accumulated in the basin. After deposition of Pennsylvanian rocks, the Michigan basin was uplifted. The Paleozoic sedimentary rocks in the basin were then eroded for most of the Mesozoic and Cenozoic Eras--a period of approximately 200 million years. Sediments accumulated in the area only briefly during Late Jurassic and late Cenozoic time. Upper Jurassic red beds were deposited on the erosional surface of the Paleozoic rocks. These are the only Mesozoic rocks found in the Michigan basin. These rocks, which overlie Mississippian and Pennsylvanian rocks, consist mainly of sandstone, shale, and clay, with some limestone and gypsum. Variable thickness and distribution of these rocks suggests that they were deposited in erosional depressions on the Paleozoic bedrock surface (Cohee, 1965, p. 220). The thickness generally ranges from 0 to about 100 ft. Locally these deposits reach thicknesses of 300 to 400 ft (Cohee, 1965, p. 220).

Glacial Geology

The Pleistocene epoch in North America lasted almost 2,000,000 years. It was characterized by four glaciations, during which large areas of Canada and the United States were scoured and covered by thick ice sheets. Approximately 10,000 years ago, ice of the last glaciation receded from Michigan (Broecker and Farrand, 1963, p. 800).

During each glaciation, the physiography of the Michigan basin was greatly altered by scouring of the bedrock surface; this scouring ultimatley lead to the formation of the Great Lakes.

The eroded bedrock surface, developed during the Mesozoic and early Cenozoic Eras, apparently included a surface-drainage network that probably was located in large valleys in the general vicinity of the present Great Lakes (Hough, 1958, pp. 86-89). These valleys tended to be located in areas where less resistant Devonian and Silurian shales cropped out. Initially, the preglacial valleys probably exerted only a slight influence on the directions of ice sheet movement. However, with subsequent ice advances, the preglacial valleys became more pronounced as glaciers scoured the bedrock surface. The preglacial valleys and the surrounding more resistant bedrock uplands created pathways for subsequent glacial ice advances and are the probable reason for the highly lobate character of late Wisconsin ice advances (Horberg and Anderson, 1956, pp.102-103; Hough, 1958, p. 113; and, Eschman, 1985, p.162).

There is evidence only for the last ice advance--the Wisconsin--in Michigan; the three earlier ice advances--the Illinois, Kansas, and Nebraska--have not been positively identified. Because Illinoian and Kansan deposits have been identified in Ohio and Indiana, there is reason to believe that Michigan may have been covered by these two earlier ice advances. Subsequent Wisconsin ice advances probably eroded and reworked older Illinoian and Kansan deposits. These were probably incorporated into younger Wisconsin deposits.

The Wisconsin Stage dates from 110,000 to 10,000 years before present (BP). The glacial features found in Michigan are the result of ice advances during late Wisconsin time. Glacial events of the early Wisconsin (110,000 to 55,000 years BP) are unknown in Michigan because deposits from that time are not well exposed or have been reworked by late Wisconsin ice advances. Interglacial sediments found in Michigan and Canada seem to indicate that, during most of the middle Wisconsin time (55,000 to 24,000 years BP), Michigan was relatively ice free (Eschman, 1985, p. 164).

The late Wisconsin (24,000 to 10,000 years BP) was the time that most of the glacial landforms of Michigan were formed. The four substages of late Wisconsin time in this area are the Nissouri (21,000 years BP), Port Bruce (15,500 years BP), Port Huron (13,000 years BP) and Greatlakean (11,500 years BP) (Eschman, 1985; Fullerton, 1980). The maximum ice advance for each of these substages is shown on figure 4, (adapted from Eschman, 1985). The oldest substage, Nissouri, advanced the farthest. Ice advanced into Indiana and Ohio, completely covering the Lower Peninsula. Each successively younger ice advance did not move as far south as the previous one. The final substage of the late Wisconsin, the Greatlakean Substage, only advanced to the tip of the Lower Peninsula.

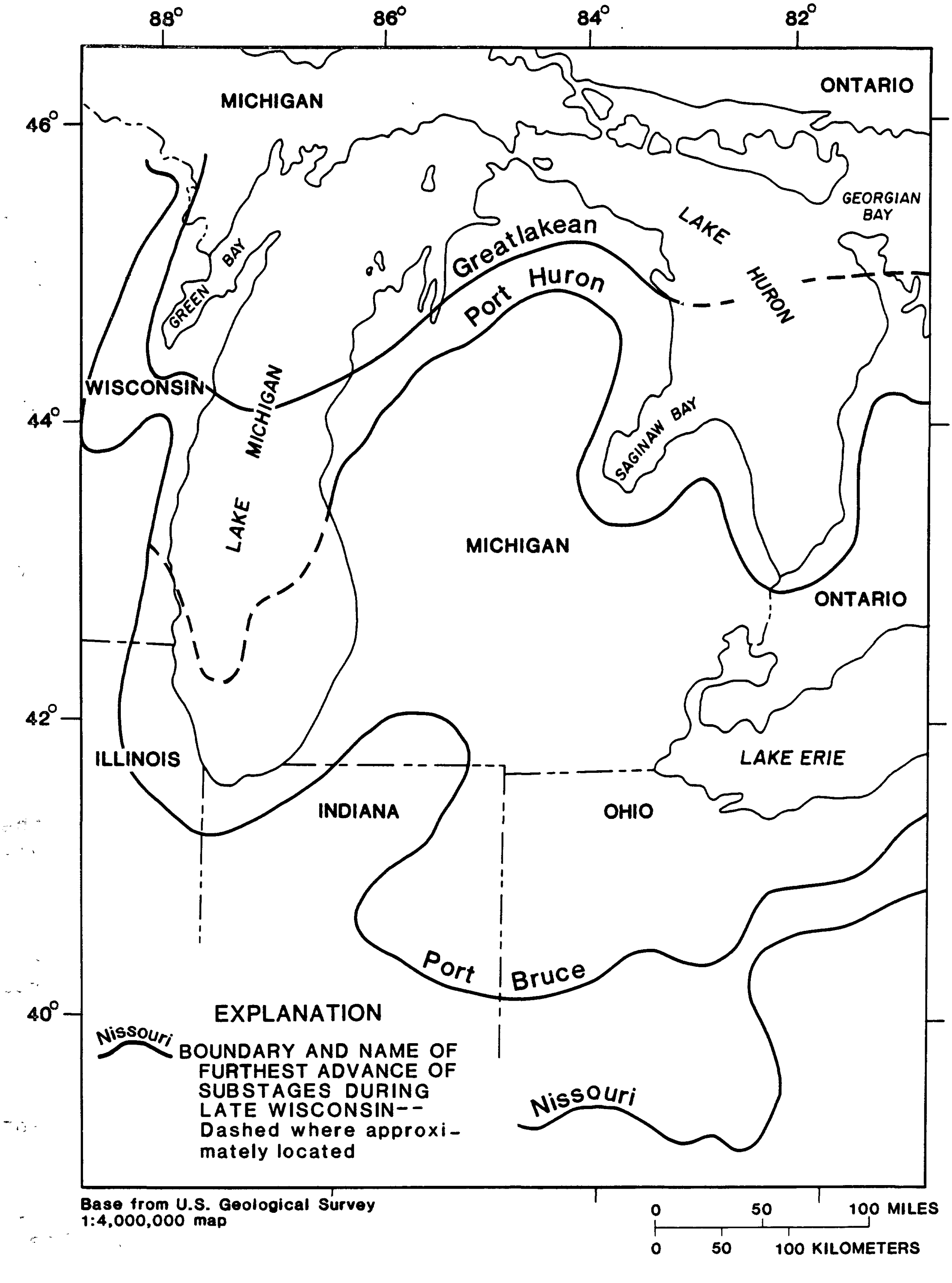

Figure 4.--The four ice advances during the late Wisconsin in the Great Lakes Region. (From Eschman, 1985)

HYDROLOGIC SETTING

The Lower Peninsula of Michigan is surrounded by three of the Great Lakes, Michigan, Huron and Erie. Lake Michigan borders the Lower Peninsula on the western side, Lake Huron on the eastern and northeastern sides and Lake Erie on the southeastern side. A surface-water drainage divide runs north to south dividing the penninsula approximately in half. Rivers on the western half of the penninsula drain into Lake Michigan; those on the eastern half drain into Lake Huron and Lake Erie. This divide is formed, in part, by interlobate and end-moraine deposits.

The main aquifers in the study area are the glacial deposits, the Saginaw Formation, and the Marshall Sandstone. Other consolidated bedrock may yield moderate quantities of ground water where these units subcrop beneath the glacial deposits and are locally fractured. Presumably, ground-water-flow-directions in all aquifers are similar to surface-water drainage patterns.

The rock sequence of Lower Mississippian Coldwater Shale to Lower Mississippian and Upper Devonian Antrim Shale form a very thick lower confining unit for the glacial, Saginaw, and Marshall aquifers. Vertical movement of ground water through this thick sequence (perhaps greater than 1,000 ft thick) would be restricted except in faulted and fractured areas.

Paleo-Ground-Water-Flow Patterns

Surface-water and ground-water-flow patterns were different during the Pleistocene than they are today. As ice sheets covered the Lower Peninsula, glacial meltwater at the base of these ice sheets was under high pressure because of the thick ice overburden. This pressure may have facilitated recharge of the glacial drift and bedrock aquifers in these areas. The hypothesized paleo-recharge areas coincide with the location of the Michigan, Saginaw, and Erie lobes. Presently, these are presumed areas of ground-water discharge. With every advance and retreat of the ice sheets, changes probably occurred in the location of ground-water recharge and discharge areas.

Concurrent with, or between, ice advances, proglacial lakes formed in the general location of the present-day Lake Michigan, Huron, and Erie basins. Evidence of former lake stages are Pleistocene sand-and-gravel beach deposits located inland from present lake shores. These beach deposits show that, at different times in the past, glacial lake levels were much higher than at present. During the different Wisconsin stages and interstages, the extent of each of the proglacial lakes fluctuated, and the location of surface-water outlets changed as the ice sheets advanced and retreated. The extent and levels of late Wisconsin proglacial lakes in the Lake Michigan, Huron, and Erie basins have been quite different from the extent and levels of present lakes. Late Wisconsin lake levels ranged from 230 to 640 ft, 230 to 730 ft, and about 573 to 800 ft above sea level in the Lake Michigan, Huron, and Erie basins, respectively. Streams that graded to these lake levels produced different directions of regional surface-water runoff quite unlike present conditions. These phenomena were relatively recent (25,000 to 10,000 years BP), so that their effect on the ground-water-flow system may be discernable--perhaps by analysis of present-day ground-water chemistry.

Regional Ground-Water Movement

On a regional scale, the water table conforms to the main features of the topography of the Lower Peninsula. The topographic features of this peninsula were formed by several major advances and retreats of glacial ice sheets. Figure 5 shows a generalized topographic map of the Lower Peninsula. Land-surface elevations higher than 800 ft are shaded and generally conform to the upland and lowland physiographic provinces described by Leverett (1899). In general, areas of high land surface elevation on the topographic map tend to be areas of highest ground-water altitudes, and low land surface elevation areas tend to be areas where ground-water altitudes are lowest. Generally, ground water moves from upland areas down gradient to lowland areas and discharges to Lakes Michigan, Huron, and Erie and to streams tributary to these lakes. This ground-water-flow pattern may result in movement of saline water from deeper parts of the bedrock aquifers to lowland areas. This would be particularly true for the Saginaw Lowlands, and to a lesser degree, in the Michigan and Erie Lowlands, and is confirmed by early reports of brine springs by Houghton(1839) and Winchell (1860). Lane (1899, pl. IV) mapped saline water in the Saginaw and Erie Lowlands, whereas Twenter (1966) mapped saline water in the Michigan Lowlands in addition to the Saginaw and Erie Lowlands.

At some locations, the presence of highly mineralized shallow ground water has been attributed to the many unplugged wells and to coal-mining activity that provide open conduits for upward ground-water migration. However, historic reports suggest that shallow ground water in these areas was highly mineralized before the first wells were drilled.

Regional Ground-Water Quality

The quality of ground water in the Michigan basin appears to be related to structure, mineralogy and assumed regional ground-water-flow patterns. Ground water in the glacial drift generally has a

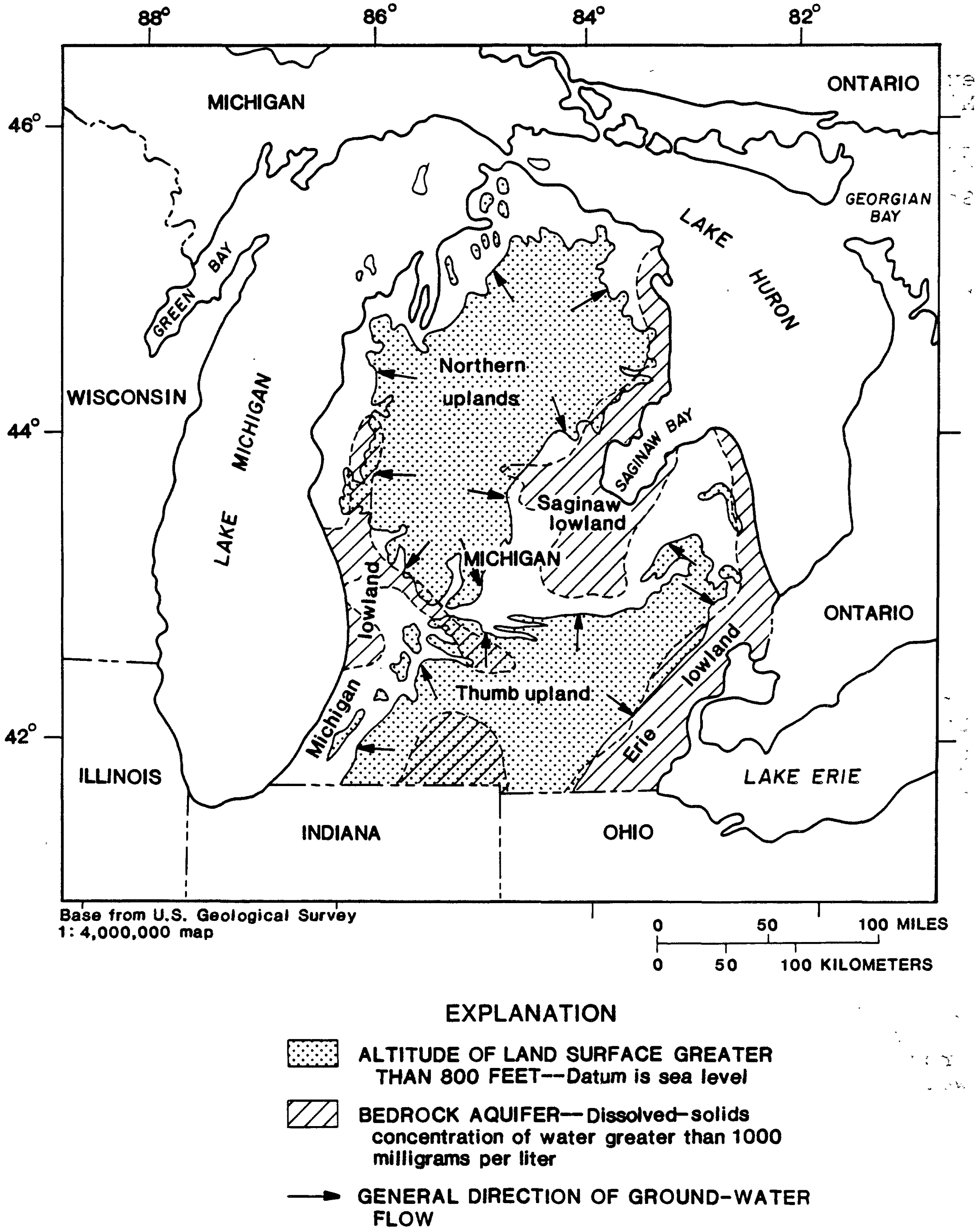

Figure 5.--Generalized topography, conceptual regional ground-water flow, and the location of saline water in the bedrock aquifers in the Michigan basin. (Dissolved-solids concentration from Twenter, 1966)

dissolved-solids content of less than 1,000 mg/L. In the Saginaw Lowlands, the total dissolved solids of ground water in the glacial deposits exceeds 1,000 mg/L. There are also reports of saline water in the glacial deposits in the Michigan Lowlands. Wood (1969, p. 48) found that, in the upper Grand River basin, ground-water from glacial deposits had higher dissolved solids than ground water from the underlying Saginaw Formation.

Ground water in the Marshall Sandstone and Saginaw Formation tend to be more saline at the center of the basin than at its margins. Total dissolved solids in ground water in the Marshall Sandstone in the central part of the basin is about 300,000 mg/L and for the Saginaw Formation, about 200,000 mg/L. Ground water in both aquifers has relatively low total dissolved solids near the basin margins, except in the Saginaw, Michigan, and Erie Lowlands. Few data from along the northern limbs of the basin are available for defining the ground-water quality of these aquifers. The area of the Saginaw Formation with ground water containing elevated concentrations of dissolved solids generally coincides with the area overlain by Jurassic rocks. The area of elevated concentrations of dissolved solids in the Marshall Sandstone approximately corresponds to areas where it is overlain by Pennsylvanian rocks. Wood (1969) and Long and Larson (1983) have proposed that ion filtration has resulted in the concentration of ions in ground water in both the Saginaw Formation and Marshall Sandstone. The saline water in shallow bedrock in the Saginaw, Michigan and Erie Lowlands is probably caused by upward movement of deeper saline ground water.

Ground-Water Use

Municipalities in Michigan used an estimated 1,224 Mgal/d in 1978 (Bedell, 1982, p. 1). Of this, 80 percent or 976 Mgal/d was from the Great Lakes and 17 percent (215 Mgal/d) was from ground-water sources. The remaining 3 percent (33 Mgal/d) was from inland lakes and streams. Total ground-water use, including industrial and agricultural use, amounted to 530 Mgal/d in 1980 (Solley and others, 1980). They estimate municipal ground-water use to be 220 Mgal/d for 1980. Almost half of the municipal ground-water use (100 Mgal/d) is concentrated in south central Michigan.

Large quantities of ground water are available from the Saginaw Formation in Lansing and Marshall Sandstone in Jackson and Battle Creek. Municipal ground-water pumpage from the Mississippian and younger rocks in the study area, totaled 82 Mgal/d for 1978 (Bedell, 1982, Table 2). Even greater quantities of ground water are pumped from the glacial deposits. In the study area, this pumpage totaled 106 Mgal/d for 1978.

Over most of the State, relatively good quality water can be found. Finding potable ground water in large quantities and the migration of saline ground water toward pumping centers have been the most significant ground-water problems encountered. In the Saginaw, Michigan, and Erie Lowlands poor quality ground water has resulted in the conversion to water from the Great Lakes for public water supplies. In addition, migration of saline water to the well field for the city of Flint resulted in the eventual abandonment of wells in that city. Ground-water withdrawals have been great enough in the Lansing area that there has been as much as 160 ft of drawdown in the center of a cone of depression that has spread over 100 square miles.

PLAN OF STUDY

The objectives of the study are to:

(1) Describe the geologic, hydrologic, and chemical-quality characteristics of the Lower Mississippian Marshall Sandstone, the Pennsylvanian Saginaw Formation, and the Pleistocene glacial deposits in the central-part of the Michigan basin.

(2) Delineate the vertical and areal extent of saline water, and identify areas subject to saline-water contamination.

(3) Relate the chemistry of the ground water to ground-water-flow directions within the aquifers, and to bedrock and glacial drift mineralogy.

(4) Develop a regional ground-water-flow model to simulate present, and possibly, paleo-ground-water-flow directions.

(5) Develop a computer data base for the study.

(6) Evaluate hydrologic data through model simulation to suggest a feasible, effective network for monitoring future water-use, water levels, and changes in water quality.

Approach

The area covered by the Michigan basin RASA study is relatively large. It would not be feasible to collect all data required by this study. As a result, previously collected data will be relied upon wherever possible. The approach to the study will involve accumulating all existing hydrogeologic data and determine its reliability. All reliable data will be stored in a computer data base. This will allow easy manipulation, analysis, and display of these data, and provide a preliminary description of regional geology, and ground-water quality. Deficiencies in existing data will then be identified from an analysis of these data. Data collection programs will then be planned.

Definition of the Geohydrologic Framework

This study will rely entirely on previously collected data to define the geologic framework. These data will include geophysical and geologic logs and interpretative reports available from the Michigan Department of Natural Resources, Geologic Survey Division (DNR-GSD), theses and dissertations available from universities in the State, and geophysical logs available from the petroleum industry.

These data will be used to delineate aquifer and confining-layer boundaries, textural changes, and porosity variation within aquifer and confining layers. After evaluation and interpretation these data will be stored in a computer data base from which computer-generated maps of geologic structure, thickness, and texture maps and sections will be drawn.

Determination of Ground-Water Chemistry

Existing sources of ground-water-quality data will be reviewed. These data will be used to construct maps of different water-quality parameters or dissolved constituents in ground water. Sources of data that will be reviewed are the chemical analyses in the National WATer Data STOrage and REtrieval System (WATSTORE) and other published or unpublished analyses from technical files of the U.S. Geological Survey and various State agencies. Many of the analyses available from State agencies are incomplete and may not be suitable except to map trends in constituents such as total dissolved solids or chlorides. Therefore, these data will be evaluated for reliability of analysis, location, and formation sampled. After evaluation, the data will be added to a computer-data base from which computer-generated maps of appropriate water-quality parameters will be made for each aquifer.

A concerted effort is planned to gather as many ground-water samples as possible from existing wells to develop a reliable ground-water-quality data base for the central part of the Michigan basin. The design of a sampling network will depend on the distribution of available data and ground-water-flow directions generated with a preliminary flow model of the study area. New wells will then be sampled where data are lacking. Where unreliable analyses are available, wells will be resampled. Analysis of the samples will include parameters used for geochemical modeling. This will include, 1) Field analysis for alkalinity, specific conductance, dissolved oxygen, and pH, 2) Lab analysis for dissolved organic carbon (DOC), sulfate, sulfide, Mn, Mg, Fe, total dissolved solids, Sr, Br, Al, Si, Li, Ca, Na, K, Cl, B, As, Zn, and F, and 3) Analysis for stable isotopes of selected samples will occur at a later date.

The final data set will be used to map geochemical facies in each aquifer. If sufficient data are available, chemical-equilibrium and thermodynamic models will be used to evaluate the geochemistry of the ground-water system and, chemical-equilibrium modeling will be used to relate ground-water quality to mineralogy and ground-water-flow patterns. This, along with stable isotope data, will help delineate recharge and discharge areas in the ground-water-flow system and, possibly, identify influences of paleo-flow systems on the presently observed water quality of ground water in these aquifers.

Delineation of the Freshwater-Saline Water Transition Zone

Specific conductance and total dissolved-solids data from available data sources and from newly sampled wells will be used along with borehole-geophysical logs and surface-geophysical surveys to map the transition zone from fresh to saline water. This will be done by initially approximating its location from available electric logs and water-quality analyses. In areas where this transition zone cannot be well-defined, surface-geophysical techniques such as time-domain electromagnetic (TDEM) and direct current (DC) resistivity surveys will be made. Finally, ground-water samples will be collected at selected locations to confirm the location of the fresh-saline water transition zone.

Analysis of the Ground-Water-Flow System

Analysis of regional ground-water-flow in either the Saginaw Formation or Marshall Sandstone will rely primarily on simulating plausible flow directions using a basin-wide ground-water-flow model. This model will depend on the geologic framework to define aquiferand confining-layer boundaries. The hydraulic properties of the different aquifers and confining layers will be assembled from data in technical files, interpretative reports from the U. S. Geological Survey, State agencies, theses or dissertations, and the literature.

Hydraulic-head data will be gathered from technical files of the U. S. Geological Survey and State agencies. These data will be used to approximate the potentiometric surface of each aquifer. Hydraulic-head data are available to depict regional-ground-water flow in the glacial-drift aquifer. Hydraulic-head data to construct a potentiometric-surface map for the bedrock aquifers are lacking over much of the study area. There are no bedrock-water wells over most of the northern half of the study area where glacial deposits are thick. In the center of the basin, where total dissolved solids of ground water from the bedrock aquifers are high, defining ground-water-flow patterns in these areas will have to account for variable ground-water density.

Fluid-pressure data for oil and gas wells and brine analyses will be obtained from The Michigan DNR-GSD, petroleum industry, or published sources. Relative density-total dissolved-solids relations and dynamic viscosity-temperature relations will be determined from available data or from the literature. These data will then be used to analyze ground-water-flow patterns with a ground-water-flow model that accounts for variable density and, possibly, solute transport.

This model will be used to test various hypotheses concerning the relationship of saline ground water to present and possibly past ground-water-flow patterns. Subregional models may be developed in areas where refinement of the regional model is needed, such as in the Lansing metropolitan area.

Developing a Project Data Base

All data gathered together for the study will be stored in a project-computer-data base. This data base will initially include all existing hydrologic, geologic and water-quality data that has been reviewed for its reliability. Data collected during the study will be added to the data base. The use of a computer-data base will allow rapid processing of data for statistical analysis or geochemical and ground-water-flow modeling. Data may also be readily displayed in graphs or on maps. After completion of this project, the data base will reside in the Michigan District office of the U. S. Geological Survey.

Reports

It is intended that the final results of the study be presented as a professional paper with four chapters, A through D. Chapter A will summarize the work done in the study. This will include a discussion of the hydrogeology of the Mississippian and younger Formations, the results of the simulation with the regional model and the geochemistry of ground water in these sediments. Ground-water-management problems and alternatives will be discussed.

Chapter B will discuss the hydrogeology of the Mississippian and younger Formations. This will be a complete discussion of the geologic framework, hydraulic characteristics of the aquifers and a discussion of freshwater-saline water relations in these aquifers. This report will include regional maps of the structure, thickness, texture, estimated transmissivity and potentiometric surface of each aquifer in the study. An estimated depth to saline water map will also be presented. Geologic-sections and fence diagrams will be included, if appropriate.

Chapter C will present a description of past and present ground-water flow with emphasis on the results of simulations with the regional ground-water-flow model.

Chapter D will describe the geochemistry of this ground-water-flow system. The relationship of ground-water quality to ground-water-flow patterns will be emphasized. Maps of regional distribution of selected ions will be presented. Changes to the natural-water quality of these aquifers by saline-water migration toward pumping centers will be discussed. Ground-water contamination due to other activities will not be included because the number of local contamination problems are beyond the resources of this study.

Throughout the study, preliminary hydrogeologic and water-quality maps and, if possible, model analysis of local-flow problems will be presented. Preparation of these preliminary reports will depend on the time and resources available. Journal articles or conference papers may be used to present certain work done during the study.

ORGANIZATION AND STAFFING

The project staff will be located in Lansing, Michigan, and will consist of a project chief, geochemist, hydrogeologist, and a geologist/geophysicist. Each staff member will be responsible for specific work elements (see figure 6).

The project chief will serve as project manager and, depending on qualifications of project staff members, lead ground-water modeler. He will be responsible for work elements 1, 5 and 8, and assist in work element 3. The geochemist will be responsible for overseeing the ground-water sampling program and interpretation of ground-water-quality analyses. He will be responsible for element 4 and will assist in elements 3d,6b and 8. The hydrogeologist will be responsible for collecting and analyzing geologic and hydrologic data needed for the project and to serve as an additional ground-water modeler on the project. This person will be responsible for work element 2 and will assist in elements 3 and 8. A geophysicist will be responsible for work element 6 and assist in element 2.

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     TASK                                                  +FY86     +FY87     +FY88     +FY89     +FY90

(1) Project planning and organization                      ---------R+

(2) Definition of geologic framework
    (a) Compilation of previous studies                         -----+----
    (b) Compilation of geologic and geophysical logs              ---+----
    (c) Preparation of geologic maps and sections                    +--------R+

(3) Definition of hydrologic setting
    (a) Compilation of previous studies                         -----+----
    (b) Compilation of water-level measurements                      +----
    (c) Compilation of aquifer test data                             +----
    (d) Water level measurement                                      +---------+---------
    (e) Preparation of potentiometric maps                           +---------+--------R+
    (f) Preparation of hydrogeologic setting chapter in
        final report                                                                        ----+-----R

(4) Geochemistry
    (a) Compilation of previous studies                         -----+----
    (b) Review of existing data                                 -----+----
    (c) Determine sampling strategy                                  +----
    (d) Collection of field samples                                  +---------+---------+
    (e) Preparation of major ion maps                                          +---------+---R
    (f) Preparation of isotope maps                                                   ---+---------R
    (g) Analysis of geochemical reactions                                                +---------
    (h) Preparation of geochemistry chapter in
        final report                                                                       -----+-----R

(5) Flow system analysis
    (a) Preliminary regional model development                       +--------R+
    (b) Sensitivity analysis and refinement of
        regional model                                                         +---------+----
    (c) Analysis of regional flow relationships                                       ---+-----R
    (d) Preparation of flow analysis chapter in
        final report                                                                       -----+-----R

(6) Saline-fresh water relationships
    (a) Compile geophysical logs                                  ----+
    (b) Compile water quality analyses                            ----+----
    (c) Use surface geophysical techniques to
        approximate transition from fresh to saline water            +--------
    (d) Test drilling                                                          +---------+
    (e) Preparation of saline water maps and sections                                    +--------R+

(7) Project data base development                                    +---------+---------+--------R+

(8) Summary Report                                                                                  ------R
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R denotes due date of first draft.
+ denotes beginning of fiscal year.

Figure 6.--Graph showing schedule of major work elements.

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