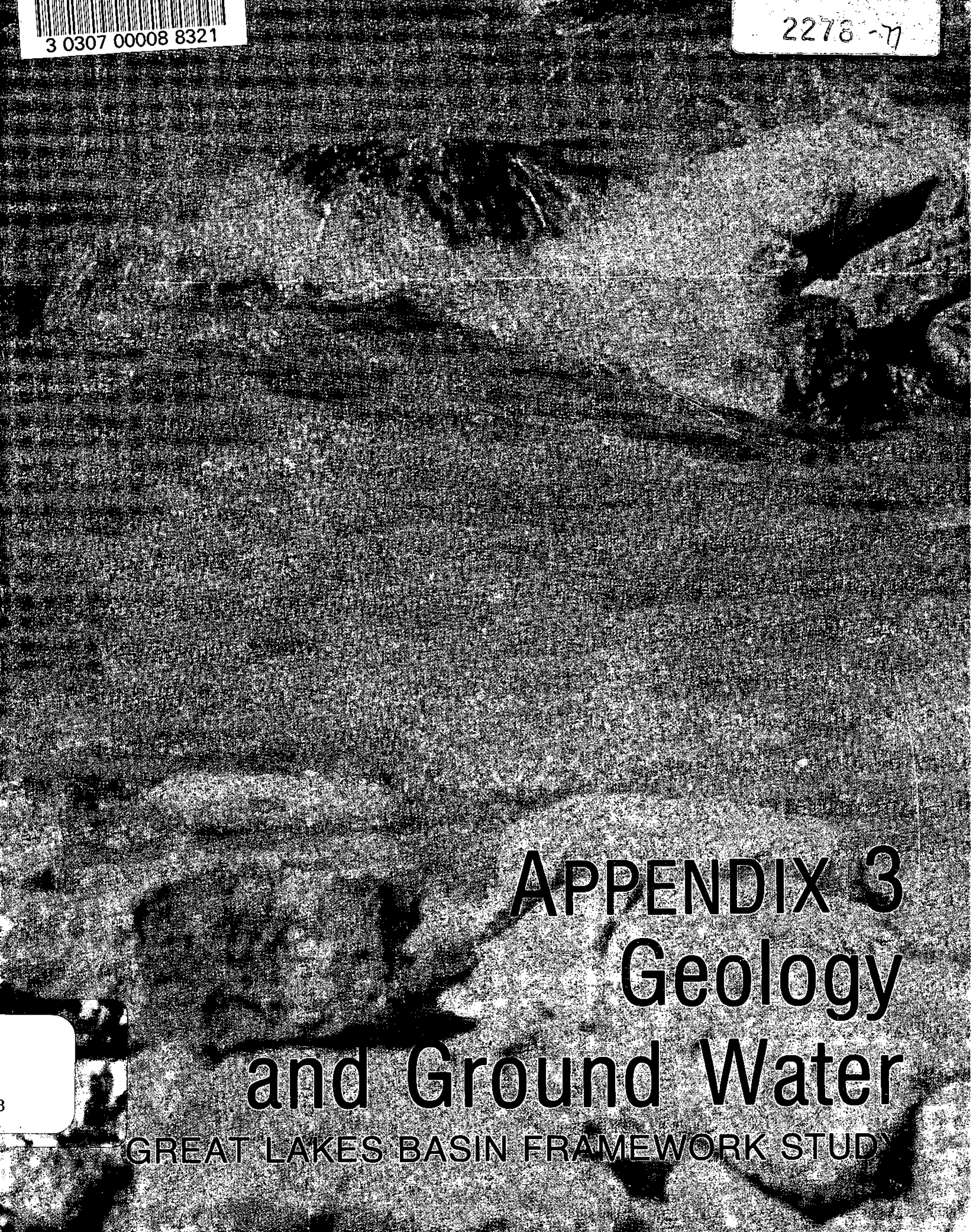

APPENDIX 3
Geology and Ground Water

GREAT LAKES BASIN FRAMEWORK STUDY

Great Lakes Basin Framework Study

APPENDIX 3

GEOLOGY AND GROUND WATER

GREAT LAKES BASIN COMMISSION

Prepared by Geology and Ground Water Work Group

Sponsored by United States Geological Survey

Published by the Public Information Office, Great Lakes Basin Commission, 3475 Plymouth Road, P.O. Box 999, Ann Arbor, Michigan 48106. Printed in 1975.
Cover photo by Kristine Moore Meves.

This appendix to the *Report* of the *Great Lakes Basin Framework Study* was prepared at field level under the auspices of the Great Lakes Basin Commission to provide data for use in the conduct of the Study and preparation of the *Report*. The conclusions and recommendations herein are those of the group preparing the appendix and not necessarily those of the Basin Commission. The recommendations of the Great Lakes Basin Commission are included in the *Report*.

OUTLINE

SYNOPSIS

The Great Lakes Basin is underlain almost entirely by a thick succession of sedimentary rocks. The major structures include the large Michigan basin and a long, narrow structural platform, extending from Indiana to the St. Lawrence Valley. Crystalline rocks extrude in the western Lake Superior and Adirondack regions and form a buried structural high separating the sedimentary basin and platform structures.

Glacial and alluvial deposits cover the bedrock. These deposits are as much as 1,100 feet thick, with the thickest deposits generally occurring in Michigan and locally in buried bedrock valleys of New York and Wisconsin. The deposits are thin or nonexistent on bedrock surface in the southern part of the Basin and in bedrock "highs" of Minnesota, New York, and Wisconsin. The deposits range in composition from clay and silt, through sand and gravel, to boulders which are well sorted or a heterogeneous mixture. The clay and silt deposits represent the former extent of lakes during deglaciation and generally border the present Great Lakes. The sand and gravel deposits were formed by glacial meltwater streams that sorted the glacial materials. The size and extent of these deposits are dependent upon the longevity of the meltwater stream. The glacial till is a heterogeneous mixture deposited by the ice with little or no sorting action by meltwater.

Ground water is present everywhere throughout the Basin, but in limited quantities in areas where the basement rock is at or near the surface. The most productive aquifers, with well yields as much as 2,500 gpm, occur in unconsolidated, well-sorted sand and gravel deposits, especially where natural recharge from streams or precipitation can occur readily. The deposits are most widespread in western and central Michigan, northeastern Indiana, the western part of the Wisconsin area, and locally in the remaining areas.

Bedrock aquifers also vary in their productivity throughout the Basin, but they are more widespread, continuous, and generally more predictable in their potential than unconsolidated aquifers. Carbonate (limestone and dolomite) aquifers constitute the most common bedrock aquifers in the Basin. They occur along the northern and western shore of Lake Michigan, from Illinois to Cleveland, and along the southern shore of Lake Ontario. The carbonates are most productive, with well yields as much as 1,000 gpm, where they extrude or are overlain by unconsolidated deposits. Solution processes have developed good permeability in these areas. Sandstone aquifers are the next most common bedrock aquifers. A thick sequence of productive sandstone units (well yields as much as 1,300 gpm) is present along the western and northern part of the Lake Michigan basin. Such productive units with well yields as much as 500 gpm are also present in parts of Michigan and in Ohio, Pennsylvania, and New York. As aquifers, shale beds are the least productive sedimentary unit. Shales are abundant in the southern part of the Great Lakes Basin from Indiana to the Adirondack Mountains.

Chemical quality of ground water in the Basin is generally good but varies considerably from area to area, depending on the type of aquifer and its depth. Hardness, iron content, and salinity are the most common problems in developing a ground-water source. Hard to very hard water generally is present in the carbonate aquifers, in many sandstone aquifers, and in aquifers in unconsolidated deposits that contain carbonate sediments. Excessive iron is very common in many of the sand and gravel and sandstone aquifers. A low iron content is common where the recharge source is relatively close or recharge is rapid. Saline, mineralized, or brackish water containing more than 1,000 mg/l of dissolved solids is present in deep bedrock throughout the Basin. In many areas, highly mineralized water is present at shallow or relatively shallow depths of 75 to 200 feet. This mineralized water has been in contact with the rocks for a long time or has moved through an easily dissolved rock, such as gypsum, and has accumulated excessive minerals. Highly mineralized water is seldom present in surficial unconsolidated sediments, except locally in New York, Pennsylvania, and Michigan. In these situations, the mineralized water usually has migrated upward from bedrock sources.

The most critical region for highly mineralized water is the Saginaw Bay area of Michigan, where saline water is present in most bedrock aquifers and even in much of the unconsolidated sediments. Saline water is present in relatively shallow (less than 300 feet) bedrock aquifers in the region from Gary, Indiana, to Oneida Lake, New York. Elsewhere, central Michigan, parts of upper Michigan, and the western Lake Superior area have saline-water aquifers at relatively shallow depths. Most of these areas have freshwater aquifers present in overlying sand and gravel deposits.

Natural ground-water discharge or runoff was used to estimate basin yield as a means of determining the ground-water potential of the Basin. Ground-water runoff with any evapotranspiration that can be salvaged represents the "perennial yield" of a basin. The greatest ground-water potential based on runoff lies in north-central Michigan and in the Adirondack Mountains. In these areas, and locally elsewhere, thick sand and gravel deposits with appreciable available recharge make very productive aquifers. The areas with the least yield are present along parts of the western shores of Lake Michigan and Lake Superior, and along the southern shores of Lakes Huron, Erie, and Ontario.

Problems in developing the ground-water resources are related to both natural and man-made conditions. Natural problems are those of poor quality water and low-yielding aquifers. Man-made problems are those of pollution and overdevelopment—or improper development—of ground-water resources.

Overdevelopment is caused by continuously withdrawing water in excess of recharge to the local system. The effect of overdevelopment is a continual lowering of water levels with resulting increases in pumping costs. The Chicago-Milwaukee area is a good example. Projections of the practical sustained yield have been made. New water supplies for those who can no longer afford the increasing pumpage costs have been planned. In addition, increased ground-water withdrawals from new developments penalize existing users by further lowering the water level. Water rights and management decisions need urgent consideration to develop the regional ground-water resource properly.

Local pollution of shallow ground-water supplies is common, but current disposal restrictions will hopefully reverse this trend. Pollution of deeper aquifers is rare, but improper well construction and the use of deep waste-disposal wells may permit migration of wastes to deep aquifers. Improper well design in multi-aquifer areas, especially where a poor-quality water zone is present, has been a problem in some areas. Deep disposal of toxic wastes is rapidly coming under State control. Instances of shallow disposal or disposal in brackish-water zones need evaluation as to displacement of water or migration of the wastes.

Unplanned ground-water development has caused problems. For example, construction of wells near streams to obtain the highest sustained yield can decrease streamflow during low-flow periods. The aesthetic and dilution considerations of maintaining flowing streams may outweigh the value of higher ground-water yields. Wetlands may be destroyed by ground-water withdrawals, destroying wildlife and aesthetic features. Finally, control of ground-water use can be one factor in curtailing the urban sprawl occurring in metropolitan areas.

FOREWORD

This appendix was written by Roger M. Waller and William B. Allen and reviewed by members of the Geology and Ground Water Work Group. Work began in September 1968 and was completed in June 1971. Material used was compiled from reports published by numerous State and Federal agencies and from the files of the U.S. Geological Survey. The task of the Survey was to describe pertinent geology, and to appraise the availability of ground water and its potential for development within the Great Lakes Basin.

Geologic names used in this report were determined from several sources and may not necessarily follow the usage of the U.S. Geological Survey.

Selected representatives from State agencies and universities were appointed to the Geology and Ground Water Work Group to act as technical advisors in planning, writing, and reviewing this report. These representatives were:

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This appendix could not have been completed without the assistance and advice of the district offices of the Geological Survey. The following district chiefs and their staffs provided published reports, maps, and data from their respective States and technical review of respective parts of this report:

Illinois—W. D. Mitchell

Indiana—M. D. Hale

Michigan—A. D. Ash and R. E. Cummings

Minnesota—C. R. Collier

New York—R. J. Dingman

Ohio—J. J. Molloy

Pennsylvania—N. H. Beamer

Wisconsin—C. L. R. Holt, Jr.

Special thanks go to the above and to the work group members for their help in supplying data, for delineating problems in water development in their areas, and for their technical review of this report.

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INTRODUCTION

Purpose and Scope

An appraisal of geologic and ground-water data is needed to indicate areas of ground-water availability; potential for ground-water development; current and projected ground-water and related land-resource problems; and approaches for appropriate solutions to problems.

This appendix discusses the part of the Great Lakes Basin that is located within the United States. Data are presented in such a manner as to allow both Basin and river basin group planners to appraise the ground-water resources of the Basin; to indicate the potentials for management by public water-action agencies; and to identify deficiencies in knowledge and hydrologic factors that need to be considered in present and future water-resource development plans.

Compilation of this report entailed the analysis and appraisal of the existing data on geologic and ground-water conditions within the United States part of the Basin. No systematic or uniform coverage of the ground-water conditions in the Basin had previously been made. The data were used to describe the general geologic framework and ground-water situation throughout the Basin, major problems of quantity and chemical quality of ground water, and factors to be considered in the conjunctive and beneficial use of the Basin's entire water resources. Emphasis is on major aquifer systems because domestic-type supplies are available almost everywhere. Problems of insufficient data, technological lag, and legal or administrative conflicts pertaining to ground water are also presented. Ways and means to provide answers to the problems are discussed.

Most of the States within the Basin have begun to reappraise their water resources by drainage basins rather than by political boundaries. This progressive move permits more complete evaluation of the hydrologic system. Those concerned with use and management of water resources are gaining better understanding of ways to meet their water needs. Systematic appraisal of all smaller basins permits an integrated appraisal of the entire major basin or region. The division of the Great Lakes Basin into 15 river basin group areas by drainage divides permitted the presentation of ground-water data in usable segments.

Data analyzed from the various studies in each State are presented in five plan area sections. These sections cover the five Great Lakes basins in as great detail as available data and time permitted. Each section is designed to be usable as a separate report covering that particular area. Most of the data are presented on 15 river basin group base maps with State boundaries delineated to enable the user to extract needed information and still be aware of geographically unbound limits of the ground-water conditions. Discussions by river basin groups are presented at the end of each plan area section.

Information presented in the first section on the entire Great Lakes Basin gives gross aspects of the geology and ground water in the Basin as a whole, to enable the planner to gain a quick appraisal of Basinwide ground-water conditions. The Lake basin sections and their division into river basin groups provide specific ground-water details of a particular Lake basin or of a local condition.

Each river basin group discussion has tables and maps showing major aquifer systems, probable well yields from each system, boundaries of mineralized water zones, and an estimated total ground-water yield. The typical range of selected chemical constituents in ground water from each aquifer system is presented in tables. The accompanying text discusses future ground-water development and the status and needs of ground-water information.

Basin Reference Material

The basic framework needed for understanding the ground-water resources of any basin lies in the geologic environment of the basin and a knowledge of the principles of ground-water hydrology. Reports included in the Bibliography help provide a framework for this report and background material for the reader. Geologic data for the Canadian part of the Basin were readily available and also are included on the geologic maps to present a Basinwide framework for the planner. Reports used in compiling this appendix have been cited where specific references were made. The cited reports are included in the List of References.

Many of the referenced reports relate to detailed local studies of aquifers by county areas, but areal and Statewide summaries and reconnaissances of widely varied scope have been made. Summaries of a Basinwide nature are included in various national summaries. Recent framework studies similar to this appendix have been done on adjacent regions (Upper Mississippi and Ohio River basins, and Appalachia) and provide correlative information on mutual ground-water conditions. Reports including summaries that are useful in appraising ground-water conditions in the entire Basin are also listed in the List of References or Bibliography.

Numerous reports and unpublished data in the files of State or Federal surveys were used in compiling information on the river basin groups. Each Lake basin section has a map showing the coverage of published ground-water reports.

Scope of the reports ranges from general Statewide summaries to detailed local aquifer studies. Many of these reports could be useful in planning water-resources development. For purposes of this appendix regarding Basinwide planning, the scope of the reports has been divided as follows:

(1) Statewide or large Basinwide summaries giving the general occurrence of ground water

(2) general reconnaissance reports on a county or basin giving the occurrence, well yields, chemical quality, and problems of the ground-water resource

(3) detailed reconnaissance reports on a county or basin including the above information and describing the hydrologic system as well as presenting general quantitative data

(4) comprehensive reports on small areas presenting the above information, quantitative data on the relationship between ground and surface water in the solution of problems, and data on perennial or long-term ground-water yield

Section 1

PHYSIOGRAPHIC AND HYDROGEOLOGIC SETTING

1.1 Geologic Framework

1.1.1 Physiography

The Great Lakes Basin lies principally within the two major physiographic provinces (Figure 3–1), the Superior Upland and the Central Lowland.[12] Small parts of the Basin in New York and along the south side of Lake Erie lie in the St. Lawrence Valley, Adirondack, and Appalachian Plateaus provinces. The land area covers 118,000 square miles or approximately 60 percent of the U.S. part of the Great Lakes Basin, including the Lake surfaces.

The Superior Upland consists of a glaciated peneplain whose base is mostly crystalline rock. The Central Lowland is characterized by a generally flat lowland and lacustrine plain. The southeastern border of the Basin is formed by the Southern New York and Mohawk sections of the Appalachian Plateaus province. The area is a maturely dissected and glaciated plateau of varied relief and prominent escarpments. At the mouth of the Basin several tributary streams drain the subdued glaciated mountains of the Adirondack province. The Basin outlet is through the wide St. Lawrence Valley province, which consists of a young marine plain with local rock hills.

The entire Great Lakes Region was subjected to four major phases of glaciation during the Pleistocene era. Glacial deposits as much as 1,100 feet thick overlie the bedrock surface. Postglacial streams have partly reworked the glacial drift and deposited alluvium in the modern stream channels. The variety of glacial deposits has resulted in an imperfect drainage system with hundreds of thousands of lakes, ponds, marshes, and bogs. The topography and materials of the glacial deposits control the rate of recharge to the ground water. Postglacial alluvium along most of the streams is too small to be distinguished in Figure 3–2, a map of the glacial deposits.

Glaciation has formed the relief and in part controls the drainage pattern. The major legacy of the Pleistocene glaciation is the formation of the Great Lakes. The greatest relief in the Basin is in the Adirondack Mountains, where many mountain peaks are more than 2,000 feet. Santanoni Peak reaches 4,621 feet above mean sea level. In most of the Basin the land surface is less than 1,000 feet above mean sea level. The highest point in the headwaters area of Lake Superior is 2,301 feet at Eagle Mountain in Cook County, Minnesota. The elevation of the St. Lawrence River outlet is approximately 150 feet.

The Great Lakes Basin is unique in that approximately one-third of its area is water surface and there are no dominant tributary systems. Some dozen tributary river basins each have approximately 6,000 square miles of drainage area, whereas the remainder vary from a few to several hundred square miles and drain directly into one of the major Lakes. Water resources of some of the larger river basin groups have been studied in detail.

The bedrock succession of the Great Lakes Region consists of a series of sedimentary formations which overlie a basement of Precambrian rocks (Figure 3–3). Major structural features of the bedrock include the deep sedimentary basin centered under Michigan, a shallow sedimentary platform bordering the Appalachian trough in the Lake Erie-Ontario region, and a basement high that extends southeastward between the Michigan basin and the Appalachian trough. Basement rocks are exposed in uplands that extend from Minnesota eastward along the northern limits of the Great Lakes Basin into the Adirondack Mountains.

1.1.2 Unconsolidated Sediments

Unconsolidated sediments that mantle the bedrock surface of the Great Lakes Basin consist of glacial drift and alluvium. These deposits vary greatly in their water-bearing properties as well as in their land-use capabilities. Postglacial streams have reworked the glacial deposits and transported the material toward the Lakes. These reworked glacial deposits are alluvium, but in this appendix they are classed with the glacial drift because they are generally confined to narrow stream flood plains.

Meinzer's[34] description of the glacial drift and its water-bearing potential is so complete that his words need little reworking:

> The glacial drift consists chiefly of till, [unsorted material], deposited directly by the glaciers or great continental ice sheets; [outwash] deposited by streams issuing from the ice; stratified beds laid down in glacial lakes; and loess and dune sand, consisting largely of glacial materials picked up and redeposited by the wind.
>
> The bulk of the material is till. As it is [unsorted], it has low porosity and does not yield water freely. It varies greatly, however, in its water-yielding capacity [depending on whether] it is composed predominantly of coarse or fine material. It supplies a large number of shallow dug wells throughout the drift-covered area . . . The yield of these wells is generally small but commonly adequate for domestic use. The water of many of the wells is polluted by household and barnyard wastes and by near-by privies.
>
> The gravelly and sandy deposits made by the streams that issued from the ice are the great water bearers of the glacial drift. They yield copious supplies to many drilled and driven wells and are largely drawn upon for public, industrial, and live-stock uses, for which the yields from the till are inadequate. These . . . deposits consist largely of gravel but also include much sand. They occur in abundant irregular lenses and stringers of gravel and sand intimately intermingled with the till; in outwash aprons that extend out from the moraines, where the edges of the ice sheets once stood pouring out great debris-laden floods; and in valley trains, consisting of glacial debris deposited for many miles along the streams that headed in the ice sheets.
>
> The irregular lenses and stringers intermingled with the till in many places consist of imperfectly [sorted] gravel or sand, and, as a rule, they are not very thick or continuous. One or more of these water-bearing beds is, however, commonly encountered by drilled wells, and they generally yield reliable and rather large supplies under good pressure and protected from pollution to some extent by overlying drift. They furnish water to many successful wells throughout the glaciated area . . . for live-stock and general farm supplies, for industrial supplies, and for public supplies of villages and small cities.
>
> The outwash aprons and valley trains are generally large deposits of coarse and well [sorted] gravel or sand that yield water very freely and in large quantities. They occur abundantly in the glaciated area and for many miles along nearly all the streams that rise in that area. . . .
>
> The glacial drift is not all of the same age but consists of at least five sheets of different ages, superimposed upon one another like the successive formations of older rocks. Between the successive drift sheets are old soils and various stream and wind deposits. The most important of these deposits with respect to water supplies are beds of gravel laid down by the streams from the melting ice as the ice front retreated or by the streams from the advancing ice which later deposited the drift sheet that covers the gravel. Thus, the base of the lowest drift and the horizons between successive drift sheets are in many places the most productive water horizons.

Till occurs in two common types of land forms, end moraines and ground moraines. The former show up as conspicuous lobate forms on detailed surficial geologic maps (see isolated examples on Figure 3–2). Ground moraine deposits are generally an irregular thin veneer of till. Material in the end or terminal moraines can vary greatly from fine to coarse sediment and is generally poorly sorted. Sandy moraines can have significant water-bearing potential. In addition to the importance of till deposits as a source of small water supplies and ground-water recharge, till is significant in land-use practices. Construction that involves cutting even moderate slopes on most morainal hills can lead to slope failures when the material becomes water saturated. It behooves land-use planners to become aware of slope stability in such areas.

Till deposits are the most widespread of the glacial drift. In addition to being exposed in the areas shown on Figure 3–2, they commonly occur beneath other types of deposits. In much of the southern part of the Basin the ground moraine is relatively thin. The ground moraine deposits of fine-grained till commonly create perched water tables and vast areas of wetlands. These wetlands are very significant in the hydrology and land-use aspects of the Basin. Their relation to hydrology is discussed in the Lake basin sections of this report.

Another type of sediment included in the glacial drift is the lake deposits. The vast lakes that formed in front of the receding glaciers were sites of widespread deposition of clay, silt, and fine sand. Lake deposits generally occur on the borders of the present Great Lakes and extend into the contiguous lowlands (Figure 3–2). Their occurrence attests to the former extent of the large preglacial lakes. Lake deposits generally are not significant for ground-water supplies because most of the sediments are too fine to transmit water readily. Consequently, the deposits inhibit recharge to underlying formations and may create extensive water-logged areas with attendant excessive evapotranspiration losses. Lake deposits probably are of most critical significance in land-use developments involving cuts and fills, where excessive moisture causes slope instability. Glacial lake clays are particularly well known for their instability under imposed stresses.

Deposits of outwash sand, gravel, and alluvium are principally located in Michigan (Figure 3–2). Here the deposits have been spread over and between the morainal ridges in varying thicknesses. This region was primarily an interlobate area during much of the retreat of the last glaciation. With the area bounded on three sides by melting ice, numerous streams were available to sort and deposit the sediments.

Local outwash deposits and alluvium occur along most present-day streams throughout the Basin, but the area of the deposits is generally too small to show on the map scale of Figure 3–2. In addition, buried outwash from previous glaciations has been discovered in most of the States. Their small size and the lack of complete boundary delineation preclude plotting on Figure 3–2, but they are generally located in the bedrock valleys. Basin reports include descriptions of local buried deposits where they are significant in the areal ground-water situation.

Ice-contact stratified drift deposits of sand and gravel shown on Figure 3–2 occur principally in Wisconsin, with minor deposits in the other States. These deposits are similar to the outwash deposits in their composition but they generally are less well sorted. They commonly occur as isolated hills or ridges and thus lose their significance as major water-bearing deposits. Some of the units mapped as linear moraines in Wisconsin and elsewhere may actually be ice-contact deposits.

1.1.3 Bedrock Formations

General characteristics of the bedrock systems within the Basin and a general discussion of the water-bearing potential of each follows. Systems are described in chronological order from the bottom upwards (see geologic column, Figure 3–3).

The Precambrian system that underlies the entire Basin consists of an igneous and metamorphic crystalline complex, mainly granite, gneiss, schist, and a lesser amount of sedimentary rocks. The rocks are exposed or tapped by wells in two general areas, the Adirondacks of New York; and the Lake Superior highlands of northern Wisconsin, the Upper Peninsula of Michigan, and Minnesota (Figure 3–3).

Precambrian rocks generally provide small water yields for domestic, rural, and small industry use where no other supplies are available. Water is obtained from permeable zones consisting of fractures or, in some instances, weathered zones within the upper 100 feet of rock. Locally, several gallons per minute of water are reported. Several hundred gpm may be available to wells, particularly in the sandstones in northern Wisconsin. In general, however, the Precambrian must be considered only for yields less than 10 gpm. Under the thick cover of sedimentary rocks throughout most of the Basin, saline water is probably present in the basement complex. Recharge to the rocks occurs directly to the exposed rocks, through overlying sedimentary rocks, or through the surficial cover of glacial deposits.

Formations of Cambrian age consist predominantly of well-sorted, fine- to medium-grained sandstone up to a few thousand feet thick. Within the Basin the sandstone crops out only in Wisconsin, the Upper Peninsula of Michigan, and in a small region in New York (Figure 3–3). The upper formations are continuous through much of the U.S. part of the Basin. However, depth of occurrence and salinity of the water are too great for most uses in this area.

Sandstones are an excellent source of water in Illinois, Wisconsin, upper Michigan, and New York in and near their outcrop areas. Down the dip of the formations the waters become saline. In the Illinois, Wisconsin, and Michigan area, the Cambrian section is hydraulically connected to overlying Ordovician units that together may yield more than 1,000 gpm to wells. In New York only one or two thin sandstone units of the upper Cambrian series are present. They produce moderate yields to wells.

Principal recharge to the Cambrian aquifers occurs in their outcrop areas beneath the unconsolidated sediments. Appreciable recharge also occurs through the overlying Ordovician rocks, particularly where they are exposed (Figure 3–3).

Rocks of the Ordovician system consist of shale, carbonate, and sandstone more than 1,000 feet thick in places. The formations occur over much of the Basin but crop out only in a narrow band in eastern Wisconsin, the Upper Peninsula of Michigan, and in northwestern New York (Figure 3–3). The sandstone formation (St. Peter) is generally present in much of Wisconsin and Illinois. It is a significant aquifer. The sandstone is composed of well-rounded grains that are poorly cemented. Many wells in Wisconsin and a few in Illinois may obtain more than 500 gpm of water from this formation. As noted earlier, in these States the Ordovician aquifers are hydraulically connected to the underlying Cambrian sandstones. The St. Peter sandstone contains highly mineralized water in the southern part of the Great Lakes Basin. It is not present in New York.

The carbonate formations yield moderate to small supplies of fresh water west of Lake Michigan and in the outcrop area west of the Adirondack Mountains in New York. Elsewhere the aquifer contains saline water. The shale formations are generally not considered water bearing, although domestic supplies can be obtained in outcrop or shallow-depth areas west of Lake Michigan, in Ohio, and in north-central New York.

Recharge to the Ordovician aquifers principally occurs where the formations crop out beneath the glacial deposits (Figure 3–3).

The Silurian system, consisting primarily of carbonate rocks, has a maximum thickness of more than 3,000 feet. Formations crop out extensively around the lower four Lakes and continue beneath the intervening areas (Figure 3–3). Best known exposure of this type is at Niagara Falls where these rocks form the crest of the falls.

Silurian limestones or dolomites yield as much as 500 gpm of water to wells west and south of Lake Michigan. Eastward the aquifer becomes too saline for use where it extends beneath a thick sequence of salt beds. From Michigan eastward into New York an Upper Silurian Series of carbonate and sandstone beds provide moderate to high well yields in its upper zones. Recharge to the Silurian aquifers occurs in their outcrop areas (Figure 3–3) and locally from the overlying Devonian formations.

The Devonian system crops out around most of the borders of the Lower Peninsula of Michigan and Lake Erie and extends along southern New York. These rocks probably form much of the lake beds of Lakes Erie, Huron, and Michigan (Figure 3–3). The system consists of primarily shale in the west, limestone in the central parts, and increasingly more sandstones in New York. Thickness ranges from slightly more than 100 feet in the small outcrop area in Wisconsin, to more than 1,000 feet in Michigan, to several thousand feet in New York and Pennsylvania where it forms the divide at the southern boundary of the Basin.

Shale yields small water supplies to wells. Limestone yields moderate supplies in northern and southeastern Michigan, Indiana, and Ohio. Both units yield saline water to deeper wells. In New York and Pennsylvania the sandstone beds produce moderate well yields. Recharge occurs directly in the outcrop area (Figure 3–3) and through the overlying Mississippian beds.

The Mississippian system occurs in much of the Lower Peninsula of Michigan, in Indiana, and in small areas in northwest and north-central Ohio (Figure 3–3). Rocks mainly consist of sandstone, shale, and some limestone in thicknesses of more than 1,000 feet. The thick Marshall sandstone in Michigan has well yields of potable water in amounts as much as 1,800 gpm. Sandstone aquifers in north-central Ohio yield moderate supplies. Those in northern Indiana yield only small supplies of water.

Saline water is present in the Mississippian aquifers locally, and generally where it is overlain by Pennsylvanian rocks. Recharge occurs directly in the outcrop area (Figure 3–3).

The youngest and smallest areal occurrence of bedrock significant to ground-water occurrence is the shales and sandstone of the Lower Pennsylvanian Series. The unit occurs in central Michigan and near Akron, Ohio (Figure 3–3). The Pennsylvanian Saginaw sandstone aquifer has high well yields and contains saline water in parts of Michigan where it is confined by overlying bedrock. In Ohio, however, the Pennsylvanian Sharon sandstone provides moderate well yields of good quality water. Recharge is principally from overlying drift in the marginal parts of the outcrop area shown in Figure 3–3.

Jurassic rocks have recently been mapped in central Michigan[25] but are not shown on Figure 3–3. Outcrops of Cretaceous rock occur in mine pits on the Mesabi Iron Range, but they are insignificant with respect to Basin hydrology.

1.2 Ground-Water Hydrology

1.2.1 General

Preceding sections described the general water-bearing properties of the permeable parts of the Basin's bedrock and unconsolidated sediments. Sand and gravel beds within the unconsolidated sediments are the most permeable portion and form the principal aquifers. Throughout this report unconsolidated aquifers, glacial-deposit aquifers, and sand and gravel aquifers are used interchangeably and refer to the same condition. It was noted that ground water is present throughout the Basin. Water filters into the ground wherever the soil interstices permit. This ground water is derived directly from precipitation, or indirectly from surface bodies of water. Recharge to the aquifers beneath the soil zone occurs after surface evaporation, transpiration needs, and soil-moisture deficiencies are satisfied. Recharge to the surficial deposits by such infiltration occurs throughout the Basin.

Underlying bedrock aquifers can receive recharge in this manner also, but because they are usually mantled by the surficial deposits in this region, recharge occurs only if the soil zone water needs are met. Bedrock aquifers can also be recharged through stream beds that traverse their outcrop areas and through swamps and lakes. In some instances this type of recharge occurs to the surficial deposits, but in humid climates like the Great Lakes Region's, streams act as drains for the water table and recharge occurs through them only in rare instances where the water table lies below stream level.

Most recharge occurs as a result of water percolating to the water table during the spring snowmelt period. During the summer, the amount of water lost from evapotranspiration usually exceeds the amount of water retained from rainfall and little or no recharge occurs. Ground-water recharge resumes in the fall after evapotranspiration losses are reduced and may continue through part of the winter. However, severe winter conditions that result in extensive frost penetration, most prevalent in the northern part of the Basin, inhibit winter ground-water recharge. In places where the sand and gravel aquifers are confined, the recharge potential is lower because recharge has to occur through the confining layer. Thus, unconsolidated sediments in the Basin are not only significant for containing aquifers, but act as the recharge medium for bedrock aquifers. Recharge to many of the bedrock aquifers normally occurs in their outcrop area (although it may still be under the surficial deposit cover) as shown on the bedrock geology map (Figure 3–3). However, recharge also occurs downward through overlying formations by infiltration through fractures, permeable zones, and uncased wells as long as there is the proper head differential in the respective water levels.

Induced recharge from surface bodies of water, particularly streams, is of utmost importance in extensive development of unconsolidated aquifers. Pumping of wells located near streams reverses the water-table gradient so that water moves from the stream toward the well. Well yields are thus sustained and are generally higher because of availability of the constant head of the stream. However, reduced streamflow from pumpage can be detrimental to aquatic life and aesthetic values and must be evaluated.

The water-yielding potential of an aquifer is limited by available recharge and by the least permeable layer between the recharge area and the aquifer. Natural recharge is water that exceeds evapotranspiration and soil moisture needs and does not run off. Annual recharge is affected by variations in plant cover, soil conditions, and climatic conditions. Extensive wetlands, present in much of the ground-moraine and lake-deposit areas, store and evapotranspire much water. Drainage practices decrease the evapotranspiration loss and create additional farm land, but with consequent loss of wetlands for wildlife habitat.

Discharge of ground water in surficial aquifers occurs principally to streams, lakes, and ponds that intersect the water table. Discharge of bedrock aquifers occurs where the aquifers are near the surface, but movement may be somewhat different in deeper formations. Ground water moves from areas of recharge (high head) to areas of discharge (lower head). Wherever fresh water is found at appreciable depths, water must be moving out of the aquifer through relatively pervious rock or fractures. In this manner fresh water displaces the highly mineralized water present in some sedimentary formations in the Basin to depths greater than present sea level. The five Lakes are natural discharge areas for ground water from bedrock as well as surficial aquifers in their river basins. These surficial aquifers discharge primarily through the base flow of streams. Consequently, ground water makes an appreciable contribution to the Great Lakes. Most of it is included in the streamflow. A rough calculation of the ground-water seepage directly into the Lakes in the first few feet of rock beneath the entire lakeshores where most of the seepage would occur gives a value of only approximately 2,000 cfs (cubic feet per second).

Multi-aquifers in an area can provide large supplies of water. Probable yield, well depth, and quality of water in each aquifer can be evaluated so that a well or wells can be constructed to obtain desired quantity and quality. Although theoretically one well tapping all hydrologically separated bedrock aquifers should yield the total aggregate of a well in each aquifer, actual yield is somewhat less than aggregate. The ground-water planner of the future should consider all aspects of a multi-aquifer system and guide development to make the best use of the system, e.g., prevention of unnecessary drawdowns or interchange of aquifer waters of differeing chemical quality.

Bedrock aquifers, although widespread throughout the Basin, differ in areal extent, thickness, yield to wells, and quality of water yielded. Each major aquifer system in each of the five Lake basins is presented on separate river basin group maps and discussed separately in the basin sections. Chemical quality data concerning representative aquifer waters are presented in tables by aquifer, State, and river basin group.

1.2.2 Water Quality Characteristics

Generally, mineral content of ground water increases with the length of time the water is in contact with rocks. As water infiltrates the ground and moves toward discharge points, it usually undergoes changes in mineral content. The farther water travels and the greater the solubility of the rock material through which it passes, the greater chance it has of becoming highly mineralized. For example, water passing through salt beds that contain easily soluble sodium chloride readily becomes highly saline.

Some mineralized water originated in seawater inundation during the Ice Age. Such an inundation is known to have occurred in the St. Lawrence Valley in the area where Lake Ontario is now. Much of this seawater has probably been flushed out of the Basin.

Chemical quality of ground water in the Great Lakes Basin is variable. In most of the Basin at least one bedrock aquifer contains water with a satisfactory level of dissolved solids, usually less than 1,000 mg/l (equal to 1,000 parts per million). However, this water commonly has undesirable hardness. Mineral content of water generally increases with depth and with the dip of the formation. High iron content in water from sandstone aquifers is a general problem in the Wisconsin-Illinois area. Iron content higher than 0.3 mg/l is considered undesirable.[67] Water quality in unconsolidated aquifers varies considerably from place to place because of differences in sediment types and recharge conditions. Generally, waters of unconsolidated aquifers are softer than average bedrock water, but in some areas the situation is reversed. High iron content also is a problem in most shallow aquifers.

Highly mineralized ground water occurs at depth throughout the Basin. Feth and others[14] have compiled a map of the United States showing deepest to shallowest ground water containing various contents of minerals. That part of their map covering the Great Lakes Basin is shown with modifications for this study in Figure 3–4. Mineralized water is divided into three ranges: 1,000 to 3,000 mg/l; 3,000 to 10,000 mg/l; and 10,000 to 35,000 mg/l. It was noted by Feth and others[14] that 1,000 mg/l ". . . departs from the limit on dissolved solids content, 500 [mg/l] recommended by the U.S. Public Health Service[67] for water to be used in public supplies" because they ". . . recognized that persons become accustomed to higher concentrations and use water for domestic supply containing more than 1,000 (mg/l), and locally more than 2,000 (mg/l) of dissolved solids where less mineralized water is not available." Mapping of mineralized water also lends itself to distinguishing areas where demineralization processes may become economically feasible for moderately mineralized waters. In this report water containing more than 1,000 mg/l is termed saline or mineralized and a qualifying adjective such as moderate or high is frequently used with it.

In basin sections of this report, known saline zones of each aquifer system are delineated. Some maps show areas where fresh water is available beneath saline aquifers and the text points out potential as well as current problems of contamination from improperly constructed wells in such areas. In areas where saline water is relatively close to the surface, it is difficult to portray the zone without presenting the three-dimensional picture. Fresh water is generally present above saline water and the depth of the saline zone varies with topography and the character of the rock. Saline zones are not depicted on the aquifer maps in areas where the average freshwater well does not extend down to the saline water.

1.2.3 Development Potential

Several major aquifer systems in the Great Lakes Basin are very productive in terms of industrial and municipal water supplies.

Available streamflow data offered the best means to determine overall and comparative ground-water potential within the Great Lakes Basin. Base flow of unregulated streams represents outflow of the ground-water system of an area. Surface-water data are presented in Appendix 2, *Surface Water Hydrology,* but data pertinent to base flow or ground-water outflow are used here.

Areas underlain by good aquifers, as indicated by their yield as runoff, are shown in Figure 3–5. Nearly half the Basin's land area is underlain by aquifers that yield more than a quarter million gallons per day per square mile. Well yields can range upward to as much as 5,000 gpm within these areas. More prolific areas are denoted as those areas yielding more than 0.50 mgd per square mile. In general, the Basin's ground-water resources are among the largest in the nation.

The use of 50 gpm as a minimum "high" well yield value in the tables of this appendix is arbitrary. Other studies use either 40 gpm, because it is equivalent to a convenient unit of flow of approximately 0.1 cfs, or 70 gpm, because it is equivalent to 100,000 gpd (gallons per day). In compiling data from various areas for such a large region as the Great Lakes Basin, it is apparent that well-yield descriptions vary considerably. "Small" yields may mean less than 5 gpm in one area, and in another area yields less than 100 gpm may be considered small.

Areas adjacent to Lake Superior and the Adirondack region of New York have low yields because the underlying bedrock is Precambrian crystalline complex. Elsewhere in New York, Pennsylvania, and Ohio sedimentary bedrock formations are also low-yielding aquifers.

The estimated ground-water yield map, Figure 3–5, is suitable for depicting areas of high potential, but the potential user should also consider whether or not existing pumpage is exceeding or nearly exceeding the perennial yield of that area. Such areas are those where water levels have been declining for several years because the aquifers probably are being overdeveloped. Areas are noted on maps in the basin sections. Such notation implies that additional bedrock wells developed in that area would compound pumping effects and add to ground-water depletion. Immediately adjacent areas might also be considered poor areas to develop wells because they would impose their drawdown effects on the existing area.

Detailed local investigations have resulted in estimates of annual recharge to the ground-water system. Estimates of recharge ranging from less than 1 to 10 inches per year, covering different areas or different years, show the problems of trying to establish areal values of potential recharge. Studies have shown, however, that most recharge occurs during the March to June period when snowmelt and spring rains far exceed minimal evapotranspiration demands. Recharge occurs during the summer growing season only when above normal precipitation occurs or when rainfall is intense or prolonged. During the dormant fall-winter season recharge is inhibited by frost conditions, and may not occur if moisture is locked in the snow pack. Fall-winter recharge is more significant in the southern part of the Basin, where frost conditions and snow pack do not develop as extensively as in the northern portions.

Development plans for using water-table aquifers far removed from stream recharge require an appraisal of annual recharge and potential recharge under development conditions, as well as the feasibility of capturing the discharge that leaves the area. Recharge value puts an upper limit on maximum sustained ground-water development possible by capturing all discharge and without removing water from storage. One inch of annual recharge, for example, amounts to approximately 17 million gallons per year per square mile, enough water to supply 465 people 1000 gpd for an entire year. Even low annual recharge to a water-table aquifer can supply a lot of water to an area.

Unconsolidated sand and gravel aquifers of the Great Lakes Basin offer high potential for induced recharge to large production wells. Principal areas where induced recharge is feasible often occur along streams. Yields of 1,000 to 2,000 gpm are possible in many of these situations. These sites are too small to show on the map, but practically every stream in the Basin has this potential where it flows through medium to coarse unconsolidated material. These shallow sand and gravel aquifers are good sources for future development. In addition to induced recharge, these aquifers lend themselves to artificial recharge during periods when excess surface water is available.

Natural discharge of ground water occurs principally by transpiration during the growing season and by seepage or outflow to surface water. Base flow discharge of streams, therefore, gives a measure of the natural ground-water outflow of an area. Where geologic conditions are favorable for storing natural recharge and delayed release of ground water, base flow will be much higher than in areas lacking storage potential. In this region stream discharge consists entirely of ground water at least 90 percent of the time.

Cumulative-frequency curves showing the percent of time specified discharges were equaled or exceeded are called flow-duration curves. In streams in this region total average annual runoff, including runoff from precipitation, is generally near the 30 percent point of the flow-duration curve. Average annual ground-water runoff value should lie between the 30 and 90 percent points, depending in part on geologic conditions.

The slope of the duration curve gives a clue to the proportion of ground-water contribution. The flatter the slope as it approaches the 100 percent point, the greater the storage and generally the greater the ground-water contribution. Upstream conditions, such as large surface-water bodies maintaining a high base flow, or man-induced conditions, have to be evaluated. For those duration curves that have a relatively straight slope in this segment, a reasonable estimate of the average annual ground-water runoff can be obtained.

In recent years, a point within the 60 to 70 percent range has been considered a representative conservative value for average annual ground-water runoff (see references 66 and 76). Ground-water yields computed for this and other studies using varied methods compare favorably with this range (Tables 3-6, 3-12, and 3-15). The smaller the storage and release capabilities in the Basin aquifers, the closer the average value will be to 90 percent. For the purpose of this appendix, 70 percent flow-duration values were chosen. This is both a conservative value for dependable ground-water discharge and a measure of the potential ground-water yield of a lake basin.

Ground-water runoff value determined for a lake basin from flow-duration data is useful in comparing adjacent basins. For correlative purposes, discharge at any point can be correlated with the size of surface drainage area and compared with that of another basin with a comparable period of flow record.

The 70 percent value represents the estimated ground-water potential of shallow and deep bedrock aquifers. Bedrock aquifers usually have a much lower water transmitting capacity than sand and gravel aquifers and receive their recharge from the shallow aquifers. Deep aquifer ground-water potential can best be considered as storage. No attempt is made to determine the vast amount of water in storage, which in some instances could provide water for years without any recharge.

Values estimated for the ground-water potential of each planning subarea in the Basin, based on the 70 percent flow duration, are shown in tables in each basin section. The estimated totals for each Lake basin and the total for the Great Lakes Basin are given below:

Basin	Yield (mgd)
Lake Superior	4,240
Lake Michigan	11,710
Lake Huron	3,215
Lake Erie	1,900
Lake Ontario	4,910
Total	25,975

Values generally show a good correlation with well yields and surficial geology. Higher discharges lie within the higher well-yield areas. Where comprehensive studies have determined ground-water potentials, their yield values are inserted for comparison.

Estimated ground-water yield from flow-duration data gives the planner a preliminary estimate of the minimum amount of ground water available annually. Average annual ground-water runoff is usually greater than the 70 percent duration value. Where reliable flow-duration curves are available and represent ground-water drainage area, values up to 60 percent may be used as the minimum ground-water potential of an area. The flatter the curve toward the 100 percent end, the greater the ground-water contribution. For example, the 60 percent value for the Great Lakes Basin total is approximately 36,000 mgd.

The planner must realize, however, that yield values determined by this method are only generalizations. Perennial yield can only be based on information concerning potential location of well development and type of pumpage operations. Potential yield is ground water that can be captured before discharging out of the Basin and recharge that can be obtained by lowering the water level and reducing evapotranspiration losses. Therefore, perennial yield depends upon the conditions imposed by man. The planner must also realize that additional ground water is available in other ways. Recycled water may be reused by down-gradient users. Water may temporarily be drawn from storage in thick aquifers. Excess waters may be artificially recharged. On the negative side, a natural base flow in most streams is desired for aesthetic reasons. Consuming uses of ground water will reduce the flow of the streams. Nonconsumed water is usually put back into the hydrologic system as effluent and would help to maintain base flow. However, unless the effluent is highly treated, water quality would be degraded. Withdrawals from aquifers can also create storage space that helps reduce flood peaks by storing water during periods of high runoff. Combined use of ground and surface waters can even out the amount available during wet and dry spells.

1.2.4 Regional Problems

Although the Great Lakes Basin has some of the most productive aquifers in the United States and good annual recharge capability, problems related to natural as well as man-made conditions are present. Natural conditions are known for the most part and man has adapted somewhat to the problems they create. Major natural problems are low-yielding aquifers or high salinity water. These were already noted in the discussions and maps on aquifers and their capabilities (Figures 3–4 and 3–5).

The man-made problem of aquifer contamination, although a local problem, occurs throughout the Basin. Indiscriminate disposal of wastes easily contaminates aquifers through recharge areas, or indirectly through induced recharge from surface waters. In addition, multi-aquifer wells have permitted interflow of waters of variable quality from different aquifers. Where a saline aquifer is penetrated, the resulting contamination of the freshwater aquifer is especially disastrous if the aquifer is used locally.

Shallow sand and gravel aquifers also raise problems that should be considered in potential development. Shallow aquifers are easily subject to pollution from wastes dumped on land or into streams. Extensive use of aquifers adjacent to streams will seriously deplete base flow and add to low-flow pollution problems. Ideally, nonconsumed water, returned to the stream as "fully" treated effluent, will not appreciably add to the pollution problem.

Septic tanks, leaching fields, disposal wells, land fills, spillage, and leakage may all add waste contaminants to sand and gravel aquifers and to permeable bedrock formations near the land surface. Prolific sand and gravel aquifers in much of Michigan and parts of Wisconsin are affected by extensive waste disposal in heavily populated areas. Limestone and dolomite aquifers that occur beneath a thin surficial-deposit cover, such as the Silurian-Devonian aquifer, are most susceptible to pollution because of their open-fracture and solution-joint systems. The Door Peninsula area of Wisconsin is a good example and is currently under study for possible remedies. Seepage of wastes into the shallow unconfined part of bedrock aquifers can easily occur. Aquifer maps show the unconfined areas, where pollution potential is greater.

Deep-well disposal or storage of wastes, including toxic wastes from industries, is becoming more common. One major accident of a disposal system already has occurred within the Great Lakes Basin. Until recently, the States have not had stringent control over these disposal sites. Most have just begun maintaining records and controlling such practices. Piper[47] recently advanced the need for a national body to delineate sites for injection and to maintain records of waste storage. In this appendix, 31 known sites of well disposal are plotted on the respective aquifer maps pertaining to zone of disposal and reported depth. Most disposal wells are deep and in highly saline formations, but some are relatively shallow. While migration of toxins is of prime concern in well disposal, use of brackish-water zones now seems imprudent because technology is making demineralization of brakish waters economically feasible.

Management should consider that random surface disposal of any wastes is likely to affect some shallow aquifer. Sites should be chosen to eliminate as much contamination as possible. Proposals for land-development areas should consider the protection of underlying aquifers. Public sewerage systems may prevent pollution of an aquifer suitable for individual or community-wide water systems. The cost of obtaining or treating a water supply may be greatly increased if septic tanks are permitted in unsuitable areas. It is imperative that any housing, commercial, or industrial development that creates substantial wastes be required to treat the effluent. Disposal in or near shallow aquifers requires complete treatment to prevent undesirable contaminants from entering the aquifers. Septic tanks may not be suitable for lot-sized developments in areas of thin surficial deposits. Such areas of thin drift or bedrock outcrops occur locally in the western and northern shores of Lake Michigan, in Precambrian areas of the Upper Peninsula of Michigan, and in northern Wisconsin.

Ground-water overdevelopment is a problem affecting part of the Lake Michigan basin. Extensive ground-water withdrawals in the Chicago area, coupled with heavy pumpage in the Milwaukee area, have been lowering the water level of the deep sandstone aquifer. Increasing pumping costs and pump maintenance are affecting a steadily increasing region involving the two States. Restrictions on increased use of Lake Michigan water and increasing economic loss to ground-water users make it imperative that a water-supply solution be worked out in this large metropolitan area.

1.2.5 Cost of Developing Ground Water

The cost of developing a ground-water supply in an area must be evaluated in conjunction with costs of developing other sources of water. In contrast with surface-water development, ground-water development varies considerably from area to area both in initial capital and in annual operating costs which are dependent upon the type of aquifer and physical characteristics of the well or wells needed to extract the necessary quantity of water.

Data on aquifer systems, well depths, and well yields compiled for individual river basin groups were used in applying standard cost indexes to the cost of developing the necessary wells to produce 1 mgd. The data were used further to estimate the annual cost of pumping 1 mgd. These data have been adapted from Illinois studies as shown in Gibb and Sanderson.[18] Costs of developing a ground-water supply have been summarized in Figure 3–6 for each basin. Major assumptions have been included. Even with the assumptions and averages used in this compilation, it can be seen that costs vary considerably by area and type of aquifer. In general, unconsolidated-sediment wells cost less to develop and operate because of higher yields and smaller pumping lifts.

As shown on the graph, unconsolidated-aquifer well and pumping costs are slightly higher than they should be. In many areas wells in sand and gravel are capable of 500 gpm. To obtain 1 mgd (approximately 700 gpm) for comparative purposes, the cost of an extra well of the same capacity was added. It was too complicated and detailed for this framework study to adjust costs to accommodate selection of a proper-sized well to get the extra 200 gpm. In contrast, bedrock wells generally have lower yields. It was practicable to select the approximate number of wells needed to provide 1 mgd.

1.3 Ground-Water Management

1.3.1 General

Management has a responsibility to be aware of the nature of the hydrologic system to make best use of water resources. Guidance and control of urban and industrial growth can forestall the necessity of extensive and expensive water developments, as well as transportation, pollution and other problems. Limitation on available water supply can lead to the curtailment of metropolitan expansion and may be a prime factor in developing satellite communities with green belts and rural areas interspersed with urban and industrial complexes. Public awareness of the ultimate effects of unplanned expansion can create support for management decisions that could produce the most beneficial long-term use of water resources.

1.3.2 Water Rights

Rights to ground water have not been a common legal consideration in the water-rich Great Lakes Basin. However, in areas of overdraft the rights of land (well) owners are beginning to be questioned. Economic considerations, rather than water shortages, are the causes of concern. According to Thomas,[57] public opinion used to favor "mining" of ground water rather than conserving its use over an indefinite period, but recent awareness of man's environment may be changing this opinion. Thomas also reviewed existing water laws and concepts with respect to more effective management of the nation's water resources.[59] Appendixes F20, *Federal Laws, Policies, and Institutional Arrangements*, and S20, *State Laws, Policies, and Institutional Arrangements*, cover details of water rights and regulations in the Basin.

Water rights by land ownership usually imply a reasonable use of water. However, a major user of water, such as an industry or a municipality, can create an overdraft in an area outside its land boundaries. Continuing overdraft necessitates increased pumping lifts, increased costs, periodic extension of pump columns, and larger pumping units. Capital investments in ground-water development are damaged by these unforeseen costs.

Use of wells in heavily pumped areas may become uneconomical because of pumping lifts and because water supplies may be imported from other areas. This could be to the disadvantage of other areas. Lowering the water levels in numerous domestic wells in one aquifer or in an overlying aquifer that loses its water to the underlying aquifer causes a serious financial loss to individuals. Draining lands by ditching can seriously affect shallow rural and domestic water supplies. Similar effects can be created by the hard surfacing of the land surface that takes place in urbanization. Recharge is decreased and runoff is increased.

A plan is needed to use the water in the best manner while minimizing undesirable effects. In some cases there may be justification in limiting new withdrawals where increased pumping costs, endangered investments, increased urban growth, or decreased use of existing installations are created. Reservation of shallow, low-producing aquifers for domestic and rural use can solve some problems.

Another aspect of overdevelopment is the decrease in ground-water contribution to stream flow. Bedrock aquifers contribute to some streams, but most base flow in this Region comes from unconsolidated aquifers. Development of unconsolidated aquifers to their fullest capabilities can decrease streamflow by two principal means: decreasing ground-water outflow; and increasing recharge, which results in less surface-water runoff. Use of all annual recharge would eventually diminish ground-water outflow to streams from both unconsolidated and bedrock aquifers. Streams could become intermittent, flowing only in response to runoff from precipitation. Sewage effluent would still provide a base flow, but under present conditions water quality would be poorer.

It must be decided whether sustained flow in a stream is desirable. The demand for adequate flow of high quality water in most streams is increasing with recreational demands. Many cases of overdraft or stream depletion and subsequent litigation have occurred in the western States. Management cannot develop aquifers to their limits, divert the effluents, and still retain "normal" flow in every stream.

Adequate knowledge of an aquifer system can provide managers with alternatives such as nonuse of shallow aquifers or overdevelopment of deeper aquifers; overdraft from aquifers that yield water of good quality, or nonuse of aquifers that yield water of poorer quality; areally concentrated well development, or adequate spacing of wells; a water supply drawn from one source, or seasonal or combined use of ground water and surface water; or the high per capita use of unmetered water or the lower per capita use of metered water.

Section 2

LAKE SUPERIOR BASIN

2.1 General

The Lake Superior basin has poor to fair potential for ground-water supplies, but locally there are good aquifers. The best aquifers are in sand and gravel deposits, especially in the east end of the Upper Peninsula of Michigan, in the headwaters of the St. Louis River system of Minnesota, and in the headwater areas of Wisconsin. Sedimentary rocks in the eastern part also have good aquifers. Elsewhere bedrock is dominantly Precambrian igneous, metamorphic, and sedimentary rock with a 25- to 400-foot thick glacial-drift cover.

The major ground-water problem is low yields. Highly mineralized water occurs in a few areas, particularly in the Superior Slope and Apostle Islands complexes, the Keweenaw Peninsula area, and the headwaters of the Tahquamenon complex. Relatively sparse populations, seasonal vacation use, and the fact that industry is developed only locally limit man-made pollution problems.

2.2 Physiography and Drainage

The land part of the Lake Superior basin within the United States (Figure 3–7) consists of 16,986 square miles, approximately one-half of the entire Lake surface area. Most streams draining the United States part have relatively small drainage basins. The largest, the St. Louis River basin, drains more than 3,600 square miles.

Most of the Lake Superior basin lies within the Superior Uplands province (Figure 3–1). Part of the basin at the eastern end of Michigan's Upper Peninsula is included in the Central Lowland physiographic province. The basin is characterized by its rugged uplands and a rock escarpment bordering parts of the lakeshore. A maximum altitude of 2,301 feet occurs at Eagle Mountain near Grand Marais, Minnesota, but 1,800- to 2,000-foot altitudes are common in much of this area. The approximate mean elevation of Lake Superior is 602 feet. In Minnesota, an upland glacial-lake plain is drained by the St. Louis River. Other glacial-lake lowlands cover much of the Wisconsin part of the basin and parts of the eastern end of the basin.

Approximately two-thirds of the basin is underlain by Precambrian igneous, sedimentary, and metamorphic rocks. Precambrian and Paleozoic rocks form topographic highlands and ridges, which were eroded primarily in preglacial times and less so by relatively recent continental glaciation. Mesozoic rocks crop out in iron mines of the Mesabi district.

The small area of Paleozoic sedimentary rocks within the eastern part of the basin is shown in Figure 3–11. The relationship of the Paleozoic and Precambrian rocks is shown in the geologic section. Sandstone and carbonate rocks were deposited on the surface of Precambrian rocks that form the northern edge of the Michigan sedimentary basin. As many as 2,000 feet of these sedimentary rocks remain after erosion has removed overlying rocks and worn down the updip edges of what remains.

Most basin bedrock is covered with sediments of almost entirely glacial drift, and many bedrock valleys have been partially or wholly filled. Lakes and swamps resulted from glaciation. Glacial deposits, shown in Figures 3–8 and 3–10, consist primarily of lake deposits and till. Well-sorted outwash and ice-contact sediments are less common. Thickness of the deposits is highly variable, but the maximum known thickness (550 feet at Superior) is not as great as in other Great Lakes basins. Bedrock exposures are common, particularly in the Superior north shore, Apostle Islands, Porcupine Mountains, Keweenaw Peninsula, and Huron Mountain areas.

Most of the basin has a stand of second growth forests after being partly logged and burned during the late 19th and early 20th centuries.

2.3 Ground-Water Conditions

Ground water is present throughout the Lake Superior basin, but varies greatly in quantity between areas. Dominance of dense crystalline bedrock, glacial till, and lake deposits limits the occurrence of high-yielding, permeable aquifers. Aquifers that produce moderate to high yields are locally present in three major types of rocks: sand and gravel, carbonates, and sandstones. There are few areas where large-producing wells can be drilled. Their whereabouts need to be delineated in future studies. Wells that yield adequate water for domestic supplies can be constructed nearly everywhere.

2.3.1 Unconsolidated Aquifers

Aquifers in unconsolidated sediments (glacial drift and alluvium) primarily occur in well-sorted sand or gravel beds where recharge occurs freely. Areas where glacial streams deposited outwash and ice-contact material, and where postglacial streams have reworked the sediments have the best potential for ground water. Surficial deposits and availability of ground water in them, as expressed in well yields, are shown in Figures 3–8 and 3–10 for River Basin Groups 1.1 and 1.2, respectively. Higher yielding areas are generally associated with sand and gravel deposits. High yields may be possible where lake deposits are indicated because of the presence of buried outwash deposits. Dominance of till and other thin glacial drift in the basin is reflected in the vast areas with well yields less than 10 gpm.

A summary of characteristics of unconsolidated aquifers by river basin groups and States is included in Table 3–1. The thickness of sediments containing one or more aquifers ranges up to 550 feet, with the Wisconsin area (except for Superior) having the thinnest section. Well depths are usually between 15 and 200 feet. High yields range from 50 to 500 gpm. The scale of the ground-water maps cannot show smaller areas where large yields are possible. However, many stream valleys, except those in the Superior Slope area, have sand or gravel in some reaches, and high yields are obtainable by inducement of stream recharge.

Chemical quality of ground water from unconsolidated deposits in the Lake Superior basin is generally good, owing principally to the crystalline-rock origin of much of the sediments. Table 3–2 shows the range of some principal chemical constituents. Dissolved-solids content usually ranges from 30 to 400 mg/l. Water may be hard, particularly in the eastern part of Michigan and the western part of the St. Louis River basin, where sediments contain much carbonate material. Iron contents as high as 10 mg/l have been determined and are a significant detriment. High sulfate and chloride contents in unconsolidated aquifers are associated with ground water that has migrated from underlying bedrock aquifers.

Recharge to sand and gravel aquifers occurs from percolation directly into the sediments. Most recharge occurs in spring from snowmelt and in fall from rains, when evapotranspiration losses are low. Summer evapotranspiration usually exceeds available moisture and the water table gradually recedes. A continuous recession of the water table usually occurs in winter as ground water is discharged to streams and lakes. Recharge can occur during winter only in the absence of heavy frost conditions.

Hydrographs of typical water-level fluctuations are shown in Figures 3–8 and 3–10. Long-term hydrographs in Figure 3–8 show how the water table fluctuates in response to climatic variations. Well numbers for hydrographs here and throughout the appendix are local numbers used by water agencies and are based on county designations.

2.3.2 Bedrock Aquifers

Significant bedrock aquifers occur only in certain areas of the Lake Superior basin. Sedimentary Paleozoic formations in the eastern part of the basin, and sedimentary Precambrian units in western Michigan and in the Mesabi Range of Minnesota contain higher producing aquifers. Bedrock units and areas of saline ground water are shown in Figures 3–9 and 3–11.

Bedrock units making up a major aquifer system are delineated in Table 3–1. The fresh-water portion of the aquifers is sometimes 500 feet thick, and well yields of 50 to 500 gpm are obtained. The few available chemical ayalyses of bedrock water (Table 3–2) show that the water is very hard, 200–250 mg/l. Its sulfate content generally ranges from 20–200 mg/l.

A small area of carbonate rocks of late Ordovician and Silurian age occurs in the eastern end of the basin (Figure 3–11). Although areal extent of the unit is small, the rocks have high ground-water potential. The aquifer system occurs in the near-surface part of the carbonates where solution activity has created high permeability. The few chemical analyses of the water indicate that it is of good quality but hard (Table 3–2). The rocks receive recharge directly where they are exposed and indirectly through overlying glacial drift. Saline water is encountered at relatively shallow depth in the carbonates. Saline springs, as well as freshwater springs, seep out of the bases of escarpments in the area.

Units of Precambrian, Cambrian, and Ordovician rocks form the most significant bedrock aquifer system in Lake Superior basin. The system is present only in River Basin Group 1.2. The aquifer system consists of sandstone beds. There are some carbonates in the upper part of the system in the eastern part of the basin, within a rock sequence that reaches as much as 1,600 feet in thickness. The lowermost sandstone, considered partially Precambrian, is the only part of the system west of Marquette. The relationship of the aquifer to the rock sequence is shown in Figure 3–11.

The aquifer system has high well yields, in the 50- to 500-gpm range. Wells range from 20 to 500 feet deep (Table 3–1). Chemical quality, particularly sulfate and chloride content, is generally related to depth; the deeper the well, the greater the mineral content. Saline water is present at relatively shallow depth in two major areas in the basin (Figure 3–11). In the eastern part the lower portion of the aquifer system contains fresh water beneath highly saline waters occurring in the upper parts of the aquifer and overlying Silurian and Ordovician systems (geologic section, Figure 3–11). Salinity here is believed derived from leaching of evaporate beds in the system. Recharge to aquifer systems occurs principally through the glacial-drift cover. Position of the ground-water divide is not known, but it is probably close to the surface-water divide. Most of the natural discharge probably drains into Lake Superior.

Precambrian rocks contain significant aquifers only in Minnesota's Mesabi district and locally in Wisconsin. In the Mesabi district, a sedimentary formation that produced extensive iron deposits has been so altered by weathering, that its porosity and permeability have been greatly increased.[6] Well yields of 100 to 200 gpm are generally obtained, but yields as high as 1,000 gpm are reported. In Wisconsin and southeastern Carlton County, Minnesota, coarse red Precambrian sandstone yields moderate supplies of hard water from shallow to medium depth wells. Elsewhere Precambrian metamorphic and volcanic rocks are only capable of producing yields for domestic and small industrial wells. Locally along the north shore volcanic rocks are very porous and yield moderate amounts of water to wells. Well depths in Precambrian aquifers range from 5 to 600 feet.

Chemical quality of water from all Precambrian aquifers varies locally with hardness. Iron and chloride contents present problems in some areas (Table 3–2). Generally, the deeper the well, the poorer the quality of water encountered. The north shore of Lake Superior, much of the Wisconsin area, and an area in Michigan (Figures 3–9 and 3–11) reportedly have areas of saline water, especially in wells drilled deeper than 200 or 300 feet. Wells close to the Lake Superior shore commonly encounter saline water at 100 feet or less.

Recharge to aquifers occurs through outcrops and glacial drift. A hydrograph of water levels in a Precambrian well shows normal seasonal and climatic responses to precipitation (Figure 3–11).

2.4 Ground-Water Potential

An estimate of ground-water yield, based on flow-duration data as discussed in Section 1, was made for the basin. Flow-duration data for the 70 percent value were used in correlation with the map of unconsolidated deposits to compile Figure 3–12. Areal coverage of stations for flow-duration analysis is poor except for the Bad River to Keweenaw Bay region. Table 3–3 shows estimated ground-water yield by river basin groups and by States within the basin for use in regional planning. The appraisal of ground-water potential based on relatively sparse 70 percent flow-duration data provides only a first approximation. The user should also consider additional potential in normal reuse of ground water as it migrates from one area to the next, practicality of inducement of surface-water recharge, and planned temporary withdrawal from storage of water from aquifers.

Flow-duration data indicate that several areas have high potential for major ground-water supplies (Figure 3–12). Parts of Wisconsin show the highest yield, and the Sturgeon and Ontonagon river basins of Michigan show good yields. High yield may be related to surface-water storage in the form of lakes or swamps. Knowledge of basin characteristics is needed to relate to flow-duration data. Delineation of sand and gravel deposits and their thicknesses within these areas would pinpoint potential sources of major ground-water supplies. Presence of buried aquifers beneath lake sediments indicates a high potential, even though flow-duration data do not show a high yield, and recharge capabilities are limited. Sand and gravel aquifers in the extreme eastern part of the basin, as well as the Cambrian-Ordovician aquifer, reportedly have the highest well yields in the basin. Because this area is densely populated, more well data are available than for less populated areas.

2.5 Problems, Needs, and Management Considerations

2.5.1 General

Lake Superior basin does not have an unlimited ground-water resource, so areas not adjacent to surface-water resources can be considered problematic from the standpoint of future growth and development. However, surface-water resources here are relatively untapped and population density is the lowest in the Great Lakes Basin, less than 2.5 people per square mile. Much of the Lake Superior basin serves as a recreational haven for the upper Great Lakes population. Emphasis on this type of development fits natural conditions of the area. There may be merit in discouraging urbanization in natural problem areas. For example, low water yielding and impervious rock terrain can cause problems in obtaining an adequate water supply and in subsurface disposal of wastes.

Some of man's current activities can cause serious problems in natural conditions. Contamination of aquifers presents the most serious problem. Thin glacial drift throughout much of the basin and an area of highly permeable carbonate rock exposed in the eastern part are areas susceptible to contamination of aquifers by poor waste-disposal practices. Only a few instances of pollution have been noted to date, principally because of present low population densities. Disposal of mining and wood-processing wastes creates another potential for pollution (e.g., mercury pollution from wood processing). Antipollution laws are beginning to control disposal practices. With a thorough knowledge of the hydrologic system of an area, there is no reason that compatible use of all natural resources cannot be accomplished. The two river basin groups are discussed separately as to specific problems, needs, and management considerations.

2.5.2 River Basin Group 1.1

Low well yields and local areas of poor water quality are problems in this area. Moderate to small well yields are considered possible in parts of the St. Louis River basin. Somewhat larger yields are found in parts of the Apostle Islands Complex, but only small supplies are available in the remaining area. The former mining area in the Gogebic Iron Range in the Montreal River area has special ground-water supply problems. Sand and gravel units in glacial drift, particularly adjacent to streams, and the Biwabik-Iron Formation in the Mesabi Range offer best potential. Supply problems may be largely eliminated through detailed site studies in areas of concern.

Chemical quality of ground water varies considerably. Generally sand and gravel aquifers yield good quality water, but iron is a common problem. Bedrock aquifers yield soft to hard water with saline water locally at depths greater than 200 feet in the north shore area and at shallower depths along the western parts of the south shore area.

Ground-water pollution is not a problem at present. There is waste-pollution potential in the Duluth area, but waste-treatment facilities are being improved.

Ground-water management has no specific regional problems. The populated Duluth-Superior and Ashland areas withdraw water from Lake Superior. The Mesabi Range area has moderate to large ground-water supplies from sand and gravel and small yields from bedrock aquifers. Quality control by regulation of waste-disposal practices needs constant supervision. Land-use practices such as recreation and forestry management that require low population density may offer best use of the land.

General and detailed reconnaissance studies have been made for parts of the basin (Figure 3-7) and a general reconnaissance is now under way for the Wisconsin area. These reports are probably adequate for preliminary regional appraisals. A special study is being made on use of abandoned mines in the Gogebic Range for ground-water supplies. Small areal comprehensive studies will be needed for projected land development in inland areas where surface-water supplies are not adequate. Intensive studies will be required to determine occurrence of aquifers and their long-range yield. Better regional appraisals of ground-water potential could be made if more stream-gaging sites were established to obtain low-flow data. The existing network is very sparse and should be expanded to facilitate water resource appraisals of smaller areas. The observation-well network for bedrock aquifers is very sparse. In areas of highest potential for future population growth and increased ground-water use, additional wells for observation of water levels would aid in evaluating changes in storage from future ground-water development.

2.5.3 River Basin Group 1.2

Much of the area within River Basin Group 1.2 has an indicated ground-water yield to wells of less than 10 gpm. The Tahquamenon Complex has the highest potential; wells capable of yielding 100 to 500 gpm are reported. These are principally from sandstone and carbonate aquifers of Precambrian to Ordovician age and from aquifers in glacial drift. On the basis of streamflow data (Figure 3–2), the Sturgeon and Ontonagon River basins indicate good potential for high ground-water yield.

Chemical quality of ground water is variable. Water in all types of aquifers can be hard to very hard and have an appreciable iron content. Bedrock aquifers contain saline water at relatively shallow depth in the Keweenaw Peninsula area and in shallow carbonates in the Tahquamenon Complex. In the latter area, however, deeper bedrock aquifers contain potable water.

High iron content in many aquifers is almost a basinwide problem. Only carbonate aquifers are free of this problem. Unconsolidated aquifers have water containing up to 10 mg/l iron (Table 3–2). Water treatment is the most practical solution in most cases. Wells located near a surface-water recharge source have better potential for obtaining iron-free water.

Pollution of shallow aquifers has occurred in Michigan from mining and wood-products wastes, and from sewage systems.[9] Michigan has applied more stringent waste-disposal regulations in recent years. Contamination of fresh-water zones by saline water from overlying Ordovician-Silurian aquifers (Figure 3–11) presents a potential problem depending upon well construction.

River Basin Group 1.2 has been covered by general studies, except for Baraga County[10] and parts of Marquette County, where studies are in progress. Several studies have been made on mining areas, but they have not specifically been on water problems related to mining developments. To provide a better regional evaluation of ground-water potential of the area, river basin studies of entire water resources should be made, with particular emphasis on potential yield of unconsolidated aquifers.

Management of ground water is probably most important in eastern counties. Here the high potential of ground water and coexistence of saline-water zones require wise development of the resource to prevent contamination. Much of the area lends itself to recreation and reforestation or other developments with small water-withdrawal requirements.

TABLE 3–1 General Stratigraphy and Major Aquifer Systems in the Lake Superior Basin

(Stratigraphy only carried down to lowermost major aquifer)

Era	System	Group	Formation	Thickness (ft.)	Major aquifers: Well yields[1] (gpm)	Major aquifers: Well depths[2] (ft.)	Remarks
RIVER BASIN GROUP 1.1 — Minnesota							
Cenozoic	Quaternary			0-300	100-500	20-150	Sand, gravel in drift.
Mesozoic	Cretaceous		Coleraine	0-100			Conglomerate, shale, and sand. Little water.
Precambrian	(Keweenawan)			0-2100+			Sandstone, shale, conglomerate and igneous rocks. Some water.
		Animikie	Virginia-Thomson	0-2000+			Slate and graywacke. Some water.
			Biwabik Iron	0-800	100-250	50-150	Slate, chert, and taconite. High yields in Mesabi district only.
Wisconsin							
Cenozoic	Quaternary			0-150[3]	100-200	20-80	Sand, gravel in drift.
Paleozoic(?)	Cambrian(?)	Bayfield		0-600	50-100	50-600	Sandstone.
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Precambrian	(Keweenawan)	Oronto					Sandstone, shale, and conglomerate.
RIVER BASIN GROUP 1.2 — Michigan							
Cenozoic	Quaternary			0-350	50-500	15-200	Sand, gravel in drift.
Paleozoic	Silurian		Engadine	0-500	50-100	25-500	Dolomite.
			Manistique				Dolomite.
			Burnt Bluff				Carbonates.
		Cataract		0-110			Dolomite and shale.
	Ordovician	Richmond		0-425			Limestone and shale.
			Collingwood				Shale; partial confining bed.
			Trenton	0-250			Limestone. Fresh water only in Alger Co.
			Black River				
		Prairie du Chien					Sandstone and dolomite.
	Cambrian		Trempealeau	0-1200	50-500	20-500	Sandstone.
			Munising				Sandstone.
------?------	--?------	----------	Jacobsville				Sandstone.
Precambrian							

[1]Range is that of typical high-capacity wells.

[2]Range is that of all wells.

[3]Depths to 550 feet at Superior.

TABLE 3–2 Chemical Quality Characteristics of the Major Aquifer Systems in the Lake Superior Basin

(Numerical ranges represent typical values and do not include unusually high or low values)

Aquifer system	Hardness (mg/l)	Sulfate (mg/l)	Chloride (mg/l)	Iron (mg/l)	Total dissolved solids (mg/l)	Temperature (°F)	Remarks
RIVER BASIN GROUP 1.1							
Minnesota							
Quaternary (Sand and gravel)	10-250	5-150	1-15	0.3-5	50-300	42-47	Manganese is a problem in Mesabi Range.
Precambrian (Biwabik Iron)	10-350	5-25	1-350	0.2-2.5	125-500	44-50	
Wisconsin							
Quaternary (Sand and gravel)	40-50	3-12	1-30	0-3	50-200	43-52	
Precambrian (Sandstone)	70-250	5-60	1-50	0-1	110-500	45-47	
RIVER BASIN GROUP 1.2							
Michigan							
Quaternary (Sand and gravel)	20-400	3-75	1-200	1-10	30-400	42-50	
Ordovician-Silurian	250-500	50-200	10-50	0.05	250-650	45	Only 1 iron and temperature value.
Cambrian-Ordovician	25-450	3-60	1-300	0-1	50-700	42-49	
Precambrian-Cambrian (Jacobsville)	10-500	5-100	1-500	0.05-7	50-1000	42-48	

TABLE 3–3 Estimated Ground-Water Yield from 70 Percent Flow-Duration Data in the Lake Superior Basin

Subbasin	Runoff at 70-percent duration (cfsm)	Subbasin yield (mgd)	State totals (mgd)	River Basin Group totals (mgd)
		RIVER BASIN GROUP 1.1		
		Minnesota	1,010	2,240
Superior Shore Complex	0.20	300		
St. Louis River	0.27	710		
		Wisconsin	1,230	
Apostle Islands Complex	0.60	770		
Bad River	0.50	340		
Montreal River Complex	0.60	120		
		RIVER BASIN GROUP 1.2		
		Michigan	2,000	2,000
Porcupine Mountains Complex	0.20	140		
Ontonagon River	0.52	450		
Keweenaw Peninsula Complex	0.40	350		
Sturgeon River	0.52	240		
Huron Mountains Complex	0.30	190		
Grand Marais Complex	0.40	310		
Tahquamenon River	0.47	250		
Sault Complex	0.40	70		
			Lake Basin total	4,240 mgd

Note: estimates based on flow-duration data for period of record (generally more than 10 years) at all gaging stations within the subbasin; extrapolations within drainage area and to ungaged areas based on surficial geology.

Section 3

LAKE MICHIGAN BASIN

3.1 General

The Lake Michigan basin has the greatest ground-water potential of any Great Lakes basin. Glacial drift contains many high-producing aquifers, particularly in the Lower Peninsula of Michigan. In addition the western shore of Lake Michigan is underlain by high-producing bedrock aquifers. However, sandstone aquifer in the Chicago-Milwaukee area is being "mined" by overpumping in northeast Illinois.

Areas of poor ground-water yield are relatively scarce and of small areal extent. They mainly occur in Precambrian areas of northern Wisconsin and Michigan's Upper Peninsula and in the Ottawa River in the Lower Peninsula of Michigan. Highly saline water is present at relatively shallow depths in bedrock formations of Michigan's Lower Peninsula and northern Indiana, but overlying aquifers in glacial drift provide good freshwater sources. Unwise test drilling and ground-water development practices could result in contamination of overlying aquifers due to this occurrence of saline water.

The problem of excessive lowering of water levels has occurred where pumpage has increased. The heavily pumped Chicago area and the Green Bay, Lansing, and Milwaukee areas are major places that have faced or will face this problem. The City of Green Bay alleviated its problem by switching to Lake Michigan water. However, increased industrial pumpage has again lowered ground-water levels, but the rate of lowering is not excessive at present. Milwaukee has slowed the lowering rate by increasing use of Lake Michigan water. Chicago area water levels continue to decline even with extensive use of Lake Michigan water. In 1966 it was estimated that Chicago area pumpage from the principal aquifer, the Cambrian-Ordovician, exceeded its "practical sustained yield" of 46 mgd by about 37 mgd.[51]

Reconnaissance studies have been made in much of the basin. Detailed studies of river basin groups are needed where problems exist. The basin needs a comprehensive integrated study of bedrock-aquifer systems from Green Bay, Wisconsin, to Gary, Indiana. Bedrock aquifers are hydraulically connected and reflect the demands of man's activities. Overlying glacial drift acts as a recharge medium and should be studied concurrently. The basinwide network of observation and chemical-quality wells needs to be reevaluated so that each aquifer unit is monitored separately. In this way the effects of increasing development of the ground-water system can be predicted and measured.

Contamination of aquifers has occurred from unrestricted drilling and well-construction practices in areas of saline or poor quality aquifers. Carbonate rocks under a thin surficial cover are particularly subject to pollution from waste disposal. Sealing and plugging of all abandoned wells and test holes is needed to stop interaquifer movement of water and resultant quality deterioration.

Heavily pumped areas need alternatives to existing practices. Restriction or metering of water use may reduce demand, and restrictions on new or additional pumping may be required. Allocation of aquifers to specific users on the basis of necessary water quality may decrease overdraft. Seasonal or continual use of Lake Michigan waters by all feasible users may reduce overpumping.

3.2 Physiography and Drainage

The Lake Michigan basin is the only Great Lakes basin that lies entirely within the United States. The basin, third largest in total area, covers 67,900 square miles and includes 44,330 square miles of land. The drainage area is the largest of the Great Lakes, more than twice that of the Lake Erie-St. Clair basin. Except in Illinois and Indiana, most streams have relatively large drainage areas contributing water to Lake Michigan (Figure 3–13). Here the drainage boundary parallels the shoreline and includes very little contributing land area. Illinois in particular has no significant stream system contributing to Lake Michigan. The Chicago River and subsidiary drainage system is now diverting water into the Mississippi basin via a canal system. The two major drainage systems within the Lake Michigan basin are the Fox River system in Wisconsin, containing 6,600 square miles, and the Grand River system in Michigan, containing 5,600 square miles.

The Lake Michigan basin lies entirely within the eastern lake section of the Central Lowland physiographic province. The basin is characterized by a maturely dissected glaciated terrain. Most of the Lower Peninsula of Michigan and southern Wisconsin has low rolling relief from morainal deposits. To the north, particularly in the Upper Peninsula of Michigan, bedrock crops out and forms more rugged relief. Elevations of a few isolated bedrock peaks in Wisconsin and the Upper Peninsula of Michigan exceed 1,900 feet, but most of the basin's land surface is less than 1,000 feet. The surface of Lake Michigan is at approximately 580 feet. A prominent escarpment, extending from Michigan's Garden Peninsula through Wisconsin's Door Peninsula to south of Lake Winnebago, is formed by the exposed crest of a dolomite formation.

Glacial deposits (Figures 3–14, 3–17, 3–21, and 3–24) cover the basin and create relief. The morainic system, particularly the end moraines, forms large lobate or arcuate ridges and dominates the basin landscape. Intermorainal areas are relatively flat and contain numerous bodies of water and wetlands. Lowlying flat areas of glacial lake origin rim much of Lake Michigan shores. In addition, the Fox River valley of Wisconsin, the Chicago area, and much of the Upper Peninsula of Michigan are underlain by vast areas of glacial lake beds.

Postglacial streams have reworked glacial material in most valleys and deposited alluvium as flood plains and low terraces. Larger streams have developed more extensive reaches and greater alluvial thickness, but it is not feasible to distinguish between alluvium and glacial outwash in the figures.

Bedrock underlying the Lake Michigan basin consists of thousands of feet of sedimentary rock lying in the western part of a deep structural basin in the basement igneous-metamorphic complex. These sedimentary rocks consist of sandstones, carbonates, shales, and evaporites of Cambrian through Jurassic age. The bedrock outcrop pattern, which underlies glacial drift in most of the Lake Michigan basin, is shown in Figure 3–3 with a generalized description of the rocks. Major aquifer systems are described in Table 3–4 and shown on figure maps.

3.3 Ground-Water Conditions

Ground water occurs in several formations throughout the basin. It is probable that more than one aquifer will be encountered at any well site. This multiplicity of aquifers, with their differences in thickness, well yield, and water quality, is discussed separately by aquifer system. Unconsolidated or sand and gravel aquifers and significant bedrock aquifers are also mapped individually. In addition, the basin has been divided into four river basin groups as a basis for planning. For each river basin group, therefore, ground-water conditions are presented separately by aquifers on maps and in tables, and are separately discussed in regard to specific problems and management considerations.

3.3.1 Unconsolidated Aquifers

Availability of water in glacial drift and alluvium varies considerably. More productive aquifers (well yields over 500 gpm) are likely to occur in thick sand and gravel deposits adjacent to streams. The poorest aquifers are more likely to be those in thin deposits or in the clayey or silty till and lake deposits. Table 3–4 includes a summary of hydrologic characteristics of wells in unconsolidated deposits in each river basin group.

Two major areas of thick sand and gravel aquifers are the Manistee-Muskegon river basin groups in Michigan (Figure 3–24), and the western slope of the Fox river basin group in Wisconsin (Figure 3–14). Parts of the St. Joseph and Kalamazoo basins in River Basin Group 2.3 (Figure 3–21) also are high yielding. Wells yielding from 1,000 to more than 2,500 gpm can be obtained in all of these areas.

Aquifers adjacent to the above areas are capable of producing well yields of 100 to 500 gpm. These areas have lesser yields because the saturated thickness of sediments is not as great and deposits are generally finer grained.

Smaller well yields (less than 100 gpm) indicated in the remaining areas are related either to less thickness of glacial deposits or to the predominance of fine-grained till or lake deposits. Along major streams in these areas, higher yields are possible from the alluvial sand and gravel.

Buried bedrock channels filled with unconsolidated sediments are present in many areas of the basin. They have not been mapped in detail nor has their ground-water potential been fully explored. Major valleys containing 300 to 400 feet or more of unconsolidated sediments are known to be present in the Fox, Grand, Kalamazoo, and St. Joseph River basins. These buried channels do not always contain ideal aquifer material, but the frequency of high well yields in buried valleys warrants their exploration where evidence shows they exist. Channels are of particular importance where overlying surface streams provide natural or induced recharge. In many areas buried-channel potential has not been explored because of adequate water supplies at shallower depth.

Chemical quality of water from sand and gravel aquifers ranges from good to poor. Normal ranges of constituents in numerous partial analyses for different areas are presented in Table 3–5. Dissolved solids are usually in the 100 to 2,000 mg/l range. Water is generally hard, ranging up to 1,000 mg/l, and its iron content is objectionable in much of the basin. Chloride and sulfate are generally less than 50 mg/l, except where bedrock water contaminates shallow unconsolidated aquifers. Several places in Michigan have contamination problems from salt, brine, or oil well leakage. Water in the sand and gravel aquifer can be classed in general as a calcium magnesium bicarbonate water.

Sand and gravel aquifers are recharged by water from precipitation, mainly from snowmelt at the spring thaw. Summer evapotranspiration losses generally exceed precipitation and available moisture in the ground, and consequently, recharge to the water table at this time is negligible. Fall recharge occurs as evapotranspiration losses diminish. Winter recharge from snowmelt or unseasonal rains depends upon ground-frost conditions. Extensive frost development inhibits recharge, so winter recharge is generally less significant in the northern parts of the basin.

The ground-water divide does not always coincide with the surface-drainage divide as shown on the maps. In some places, ground water moves into the basin from adjacent areas, while in other places it moves out. Detailed data are not available to delineate these divides.

3.3.2 Bedrock Aquifers

The Lake Michigan basin contains several major aquifer systems within bedrock formations. Sequences of rock formations and characteristics of the major aquifer systems are shown in Table 3–4 for each of the four river basin groups. Each system is discussed in descending sequence, from youngest to oldest, and its relationship to the other systems is noted.

The uppermost significant bedrock aquifer occurs in the Saginaw Formation of the Pennsylvania system. This formation occurs only in Michigan where it borders the eastern edge of Lake Michigan basin (Figures 3–22 and 3–25). It is partially confined by overlying rock. Along the northwestern part of the formation, beds of gypsiferous shales, red sandstones, and gypsum locally called Red Beds, overlie and partially confine the Saginaw Formation. The Red Beds, Jurassic in age, are thin and are not sources of ground water. In the central area of the Saginaw Formation is the Grand River Formation. Containing beds of red and brown sandstone and shale, it overlies and partially confines the Saginaw Formation. Only locally is the Grand River Formation thick or permeable enough to be an important source of water. Elsewhere, it is thin or cemented with iron oxide and is relatively impermeable.

The Saginaw Formation is composed of beds of sandstone, siltstone, shale, coal, and limestone. Hydrologic characteristics of the Saginaw Formation are summarized in Table 3–4. Where the formation is mantled confining bedrock, and many places elsewhere, it is 300 to 500 feet thick. At other places it is only a few feet thick. Where the formation is composed of sandstone, it will yield more than 700 gpm to properly constructed wells. Where it is mostly shale, it yields only a few gallons per minute. Large-capacity wells drawing water from the Saginaw Formation are generally 200 to 500 feet deep. Recharge to the aquifer occurs through the overlying glacial drift.

Chemical quality of water in the Saginaw Formation (Table 3–5) ranges from soft to very hard. It may contain objectionable amounts of dissolved iron. Many wells, especially in Eaton and Shiawassee Counties, yield water containing objectionable amounts of sulfates and chlorides. They apparently draw water from the lower part of the aquifer where coal and gypsum deposits are present. Figures 3–22 and 3–25 show areas where the mineral content of ground water is high and it is classed as saline water. Where the formation contains water of high chloride content, the aquifer is at shallow depth in a topographically low area, and is discharging water. Salty water has migrated upward into the Saginaw Formation through old coal borings. Extensive withdrawals of water from the aquifer can result in migration of saline water into the formation from lower saline formations.

In the Lake Michigan basin the next significant bedrock aquifer below the Saginaw Formation is the Marshall Formation of Mississippian age. Like the Saginaw, the Marshall occurs only in Michigan (Figures 3–23 and 3–26). It extends through a large part of the basin, but much of it yields saline water.

The Marshall Formation is composed of sandstone, siltstone, and shale. It is confined, except for a circular outer strip, by overlying Michigan and Bayport Formations, and is underlain by impermeable Coldwater shale (Figure 3–23). In the eastern part of the basin the Marshall Formation is 550 feet thick, whereas in the unconfined area it is relatively thin.

The Marshall Formation is most productive as an aquifer where it is not confined by the Michigan Formation, where it is directly overlain by glacial drift, or where streams are in direct contact with the aquifer. Productivity decreases markedly toward the thicker parts of the formation. Hydrologic characteristics of the formation are presented in Table 3–4. Wells are generally from 50 to 500 feet deep. Yields from large-capacity wells range from 100 to 1,800 gpm.

Where the Marshall Formation is mantled directly by glacial drift, the chemical quality of water is generally good. Water quality data are shown in Table 3–5. The water is commonly hard and may contain objectionable amounts of iron, but can be made satisfactory for most uses by treatment. Because the Michigan Formation contains salt and gypsum beds, it contributes to contamination of the underlying Marshall aquifer through leakage under differential-head situations. The aquifer becomes saline in its deeper or thicker parts because they lie principally under the confining Michigan Formation (Figures 3–23 and 3–26). Brine and salt contamination in Michigan is discussed more thoroughly in Subsection 3.5.5.

Recharge to the Marshall Formation occurs principally from water migrating through overlying glacial drift in unconfined areas. Stream recharge to the aquifer can be induced where the formation is in close proximity with streams, such as at Battle Creek. Large capacity wells installed at Battle Creek induce filtration of water from a stream through the glacial drift and into the Marshall Formation. Water-level fluctuations in an observation well in the Battle Creek area are shown to illustrate the seasonal (including pumpage effects) and long-term water-level trends (Figure 3–23).

A series of interbedded dolomite and shale with some limestone, sandstone, anhydrite, and salt beds of several formations and groups make up a complex Silurian-Devonian aquifer system extending over two-thirds of the Lake Michigan basin (Figures 3–15, 3–18, and 3–27). The system is confined by thick shale (Antrim and Ellsworth) in most of lower Michigan and Indiana. In the unconfined area of the Upper Peninsula of Michigan, most of Wisconsin, and parts of Indiana and Illinois, the Devonian units have been eroded away and only Silurian bedrock is present. The aquifer system is mainly dolomite west of Lake Michigan. It changes to thin-bedded limestone with sandstone and shale beds to the east.

Aquifer hydrologic characteristics are included in Table 3–4. The aquifer system ranges in thickness from a few feet to 600 feet west of Lake Michigan, but reaches 1,800 feet in the Upper Peninsula of Michigan. Here some 450 feet of Ordovician carbonates are included in the aquifer system. Solution activity has produced extensive permeability in the upper parts of the formation, and well yields up to 1,000 gpm are reported. Solution activity is highly variable, however, as is common in carbonate rocks. High-producing wells tapping permeable zones may be adjacent to moderate or low producers tapping dense rock. The Devonian part of the system is most significant as an aquifer in its unconfined area in southern Michigan and Indiana where yields as high as 100 gpm are possible.

West of Lake Michigan the Silurian aquifer is encountered beneath the glacial drift at a few feet or at as much as several hundred feet. Recharge to the Silurian aquifer occurs through the glacial drift. Ground water moves toward streams draining the area and thence to Lake Michigan.

Natural discharge is being diverted toward pumping centers in the Milwaukee and Chicago areas because of increasing pumpage from the Silurian aquifer and loss of water downward into deeper, heavily pumped sandstone aquifers. Leakage occurs vertically through underlying shale beds because the head of the deeper aquifer has been reduced below that of the Silurian aquifer. Loss also occurs through wells uncased in both aquifers. For example, in 1950 in the Milwaukee area it was estimated[15] that 5.5 mgd was being lost to deeper aquifers, primarily through wells. In

1958, in the northeastern Illinois area of approximately 4,000 square miles, 8.4 mgd was leaking through the shale beds.[71] Increasing head differences and continued construction of multi-aquifer uncased wells will increase this loss from the Silurian aquifer and increase the recharge to the underlying sandstone aquifer.

As noted on Figures 3–18 and 3–27, much of the Silurian-Devonian aquifer system in the Lake Michigan basin contains saline water. Salinity generally increases down the dip of the formation. East of Lake Michigan in the Lower Peninsula of Michigan, only the uppermost part (Devonian) of the system contains fresh water (Figure 3–27). The saline zone is present only in small areas in Wisconsin. The areas in Manitowoc and Sheboygan Counties are based on only a few analyses, but the data imply that the Silurian water has a salinity of up to 3,000 mg/l along the lakeshore. In the Milwaukee area there is evidence of high salinity in the Silurian aquifer, but conclusions by investigators to date indicate that upward contamination from Maquoketa shale or from the deeper aquifer or multi-aquifer sampling may have caused the salinity.

Some areas, such as the Upper Peninsula of Michigan, have a high sulfate content believed related to gypsum or shale beds within the Silurian rocks. The upper Silurian rocks in the Lower Peninsula of Michigan contain extensive evaporite beds, and the western edge of these beds extends under Lake Michigan. Salt beds have not been noted in drilling in Wisconsin, but the western terminus of the beds may be fairly close to Wisconsin.[61] Saline Silurian-Devonian water may be related to these beds. Elsewhere, variability of the chemical quality of Silurian-Devonian water may be related to variations in rate and amount of vertical recharge and depth to the water table.

The presence of saline water in Silurian-Devonian aquifer may have also resulted from contamination by wells tapping deeper sandstone aquifers. The piezometric head in the deep aquifers was originally greater than that in the Silurian-Devonian aquifer. Flowing, unused, and uncased wells have allowed upward leakage of water and may have created some local saline zones in the Silurian-Devonian aquifer system. Drilling shallower wells in sandstone aquifer may alleviate the problem of saline water. Representative ranges of chemical analyses of Silurian-Devonian water are given in Table 3–5.

Several hydrographs are shown in Figures 3–15, 3–18, and 3–27 to represent the long-term water-level trend. Only in the Milwaukee-Chicago area is there a notable declining trend caused by extensive pumping.

Several hydraulically connected bedrock units make up the Cambrian-Ordovician aquifer system underlying most of the Lake Michigan basin (Figures 3–16, 3–19, and 3–28). Rock units are primarily sandstones with intervening dolomite beds, and the aquifer system is generally called sandstone aquifer. In the Illinois area one of the lower dolomite formations, the Eau Claire, contains much shale, reducing permeability and virtually separating lower sandstone (Mount Simon) into a distinct aquifer. In this appendix the Mount Simon is discussed, where appropriate, with the Cambrian-Ordovician aquifer system.

An overlying thick shale formation (Maquoketa) confines the Cambrian-Ordovician sandstone aquifer nearly everywhere in the basin except in the northwestern and northern parts. East of Lake Michigan in the Lower Peninsula of Michigan and at approximately 2,000 feet at Chicago, water in the aquifer is saline. Sandstone aquifer characteristics apply only to the freshwater aquifer in the western part of the basin.

Thicknesses of rock units containing the freshwater system range from nearly 500 feet to more than 1,500 feet in the confined part (Table 3–4). Units gradually thicken to the east and south. The Chicago area has the thickest section, partly because of downfaulting near Waukesha, Wisconsin. West of the confining bed, erosion has removed some of the Cambrian-Ordovician aquifer system, and many units wedge out against the Precambrian basement rocks. Maximum thickness of the unconfined part of the sandstone aquifer is 600 feet.

The Cambrian-Ordovician sandstone aquifer is one of the nation's more productive aquifers. Even though the sandstone has low average permeability, its thickness and areal extent create a vast reservoir for ground-water development in the region west of Lake Michigan. Well yields range from several tens to more than 2,000 gpm. Low values are related to the thinner western parts of the aquifer.

Most recharge to the sandstone aquifer system occurs by percolation through surficial deposits directly overlying the aquifer systems outcrop area and also through the dolomite beds. Walton[73] calculated that approximately 0.02 mgd per square mile of recharge occurs through glacial drift in northeast Illinois. In the Illinois and Wisconsin area, recharge occurs principally west of the border on the Maquoketa shale confining layer (Figure 3–20). An appreciable amount of ground water is derived from the upper Mississippi River basin. Additional recharge is due to leakage through the Maquoketa shale from overlying Silurian aquifer because the potentiometric level of the deep aquifer is now lower than the Silurian. Walton[73] calculated about 0.001 mgd per square mile of recharge occurs through the shale in northeast Illinois, approximately 11 percent of 1958 Chicago area pumpage. Percentage of water derived from shales will increase due to increased leakage as head differential between the Silurian and Cambrian-Ordovician aquifers increases. In 1961 and 1966, it was estimated that an additional 27 percent of pumpage in a larger area came from overlying unconsolidated and dolomite aquifers through leakage from uncased or poorly constructed wells.[51]

The underlying Mount Simon aquifer is tapped by a few wells in the Chicago area and by many in the Fox River valley to the west. The high head in the Mount Simon aquifer causes upward movement of ground water into the Cambrian-Ordovician aquifer through open wells. The Mount Simon aquifer contributed 16 percent of the total pumpage in 1961.

The amount of recharge to the sandstone and Mount Simon aquifer system is not dependent upon available precipitation but on permeability of the sandstones and hydraulic gradient. Greatest recharge will occur when the water-level gradient is steepest. Aquifer transmissivities have been determined for many places in Wisconsin and Illinois. Transmissivity generally decreases downdip to the east and to the south ranging from 10,000 to 50,000 million gallons per day (mgd) per foot.

It has been calculated that the sandstone aquifer in northeastern Illinois has a perennial recharge of 40 mgd from the northwest.[56] Annual pumpage began exceeding this figure in 1959. Farther north, the Milwaukee area was pumping approximately 13 mgd. The Green Bay area was pumping approximately 10 mgd during this time. It has since dropped to approximately 6 mgd. These Wisconsin area pumping rates approach the perennial yield. Additional significant recharge is derived from leakage from the overlying dolomite aquifer. Water available from storage by drawing pumping levels below the top of the sandstone aquifer may be considered reserve supply.

Natural ground-water discharge from Cambrian-Ordovician aquifer in the Lake Michigan basin originally occurred very slowly upward through the confining layer into streams and the Lake. Discharge occurred west of the saline zone (Figure 3–20) after deep circulation from the recharge area. Saline water has evidently not migrated westward toward the Chicago and Milwaukee pumping areas, even with nearly 700 feet of pressure decline at Chicago.

Representative hydrographs of the long-term water level trend are shown in Figures 3–16, 3–20, and 3–28. Steadily declining water levels in the Chicago-Milwaukee pumping areas contrast with other areas. Problems concerning these areas are discussed later.

Chemical quality of sandstone aquifer water is generally good, but the water is hard. Mineral content increases to the east and south and with increasing depth. Representative ranges of some chemical constituents are given in Table 3–5. Highly saline water has been encountered in deep wells along much of the west shore of Lake Michigan (Figures 3–4 and 3–20). South of Milwaukee the saline zone occurs in underlying Mount Simon aquifer below 2,000 feet. In the area immediately north of Milwaukee the saline zone apparently begins just beneath the St. Peter sandstone unit of the Cambrian-Ordovician aquifer system at approximately 1,000 feet. Investigations into controlling factors of the saline zone have not been made. Preliminary views[50] indicate a relation to synclinal troughs in bedrock formations in Wisconsin. Farther north there seems to be a relation between saline water and the presence of gypsum beds in geologic section.

3.4 Ground-Water Potential

Ground-water potential is estimated on the basis of the amount of ground water discharged to streams within the area. As discussed in Section 1, this method provides related data on drainage basins throughout the Great Lakes Basin. It does not consider ground water in storage (significant in thick aquifers, such as the deep sandstone aquifer in River Basin Group 2.2, for short-term consideration) nor recycling of the ground-water runoff from induced recharge.

Natural discharge of ground water from unconsolidated aquifers sustains the base flow of most streams. The amount of discharge is dependent on the amount of storage in the ground-water drainage area. Extensive deposits of sand and gravel provide good storage and usually account for the highest base flows. Figure 3–29 shows estimates of ground-water yield in Lake Michigan basin using base-flow data obtained from stream-gaging stations and surficial geology interpretations. Areas with the greatest area of sand and gravel deposits have the greatest ground-water potential. Elsewhere large yields are obtained from areas containing extensive buried sand and gravel aquifers. Table 3–6 tabulates relative ground-water potentials. The table should be used with caution because estimated ground-water yield data are applied to surface drainage area above a gaging station and may not represent the contributing ground-water drainage area. However, the estimates are useful in indicating better areas for ground-water development and in comparing water-use data in the same area. River Basin Groups 2.1 and 2.4 have areas with the largest ground-water yield.

Managers of areal water resources must remember that ground-water outflow or yield makes up a large part of stream flow. Data from Figure 3–29 and Table 3–6 cannot be added to surface-water discharge data to determine the water resource of an area. Capture of ground water by wells before it enters natural discharge areas such as streams and lakes normally reduces streamflow. In most uses pumped ground water not consumed is directly or indirectly returned to a stream, although quality is reduced. Most small streams and lakes in urban areas of the Lake Michigan basin are suffering from this reduced quality. Where ground water is diverted from the local hydrologic system, streamflow depletion will result and streams may flow only during storm runoff.

3.5 Problems, Needs, and Management Considerations

3.5.1 General

Although the Lake Michigan basin has the most bountiful ground-water supplies in the entire Great Lakes Basin, there are areas where natural or man-made conditions create problems. In some places the ground-water resource is inadequate for other than domestic and rural use, although this is more often a problem of improper well locations or outmoded supply and distribution systems. A few areas have highly saline bedrock aquifers or poor unconsolidated aquifers, prohibiting major ground-water use.

Man-made problems include extensive lowering of bedrock aquifer water levels in metropolitan areas. This results in increased pumping costs and mining of water from storage. Contamination of shallow aquifers by waste disposal and of deep aquifers by leakage of poor quality water from multi-aquifer wells have also occurred. Emphasis is on reducing major problems by wise management. These problems are discussed by river basin group.

3.5.2 River Basin Group 2.1

River Basin Group 2.1 covers a diversified area, ranging from the sparsely populated, forested north typified by a wild rivers area, to industrial areas on the lower Fox River and in the south. Both natural and man-made problems are present.

The Green Bay, Wisconsin, area had a problem with declining water levels in the sandstone aquifer system due to concentrated and steadily increasing pumpage (to 13 mgd) from an aquifer of relatively low transmissivity.[11] In 1957 the City of Green Bay began using Lake Michigan water. This halted the decline by reducing pumpage to approximately 6 mgd. Water levels, which had dropped as much as 400 feet below land surface, rapidly began to recover. They continued to rise until 1961 when a relatively stable level was established. A slight downward trend in water levels has now resumed (Figure 3–16), particularly in the DePere area. Increasing pumpage will probably repeat the declining water level trend of the pre-1957 period. Studies in 1960 indicated that 30 mgd of ground water is available from sandstone aquifer in the area without exceeding perennial yield.[26] Construction of new wells to the west would disperse water-level decline and save on pumping costs. Additional surface-water sources and new wells in the Silurian carbonate aquifers would also relieve pumpage demand on the sandstone aquifer as it approaches the 30 mgd usage. Artificial recharge of the aquifer is not economically feasible at present.

Increasing pumpage in the Lake Winnebago area also creates increasing pumping lifts. Proper spacing of new wells and increased use of surface water should forestall rapid declines in this area.

Where the Silurian carbonate aquifer lies close to the surface, such as in Door County, pollution of shallow ground water is occurring. Wisconsin drilling codes now require 100-foot cased wells in such problem areas. Improved methods of private waste disposal are needed to protect aquifers in this and similar areas.

Saline water is present in the sandstone aquifer near the bottom of the aquifer and in the eastern counties (Figure 3–15). At Lake Winnebago and to the east, poor quality water with a high sulfate content is found at relatively shallow depths and inhibits construction of freshwater wells. Migration of poor quality water toward pumping centers is occurring. Highly mineralized water in the dolomite aquifer at Manitowoc and Sheboygan apparently comes from deep sandstone zones under high hydrostatic head. It has migrated through open wells into the upper aquifer. Wisconsin State codes now prohibit abandonment without proper filling and sealing of all holes, including saline wells, but leaking wells seem to have caused significant local deterioration of freshwater aquifers. Continued surveillance of well-abandonment procedures is imperative.

Ground water with a high sulfate content and reportedly sulfur water is present in Marinette and Menominee Counties[50] and at one location in Door County. Apparently the sulfur water, probably created by hydrogen sulfide gas, occurs locally only in the upper unit of Cambrian-Ordovician aquifer in southern Menominee County.

Hard water in all the aquifers and a locally high iron content of water in sandstone and sand and gravel aquifers are problems. Individual softening treatment seems to be a solution to the first problem. Iron treatment is generally mandatory for municipal supplies and for some industrial uses.

Water quantity is a common problem only in the upper Menominee River basin. Reported well yields in much of this area are less than 10 gpm. Streamflow data show a high base flow, which implies significant water storage in the basin. Extensive sand and gravel deposits, numerous lakes, or hydroelectric reservoirs store and slowly release water to sustain the high base flow. Well fields must be selected with care in this area to tap sand and gravel aquifers, preferably those in hydraulic contact with lakes or streams.

Basic ground-water studies have been made for many counties in the two-State area. River basin group studies of entire water resources have been or are being done in Wisconsin (Figure 3–13). There have been numerous general ground-water studies of the area.

Several recent studies add to knowledge of the ground-water resources of this area. The first covers the Pine-Popple River basin, a wild river area.[40] An appraisal has been made of the water resources and hydrologic system of this relatively natural area. The study was made by the U.S. Geological Survey in cooperation with the Wisconsin Geological and Natural History Survey.

Water resources of the Menominee-Oconto-Peshtigo River basin area in Wisconsin[41] is another study. A detailed reconnaissance has been made by the U.S. Geological Survey in cooperation with the Wisconsin Geological and Natural History Survey.

A third study covers water resources of the Lake Michigan area in Wisconsin.[54] This detailed study was made by the U.S. Geological Survey in cooperation with the Wisconsin Geological and Natural History Survey.

Lastly there is a study of ground water in Marquette County, Michigan. A basic ground-water inventory is being taken by the U.S. Geological Survey and preliminary maps of surficial deposits are being made by the Michigan Geological Survey. Results will be published in the Michigan Department of Natural Resources Water Investigations Series.

Subsequent studies need to concentrate on the problems that have developed or are inherent in the hydrologic system. Four studies are recommended:

(1) A quantitative appraisal of the lower Fox River basin is needed for optimum management of the aquifer systems in this high-use area.

(2) A detailed study of the localized areas of poor quality water in the bedrock aquifers is needed. The origin and movement of this water, if any, should be known before continued development takes place. Monitor wells have been established in some areas of Wisconsin to keep a check on changes in the quality and movement of the water. Probably the most critical sites are those where individual wells tap both deep and shallow aquifers and permit interchange of aquifer waters.

(3) A carbonate hydrology study of the Door Peninsula area is a prerequisite to controlling the pollution problem. Very little is known of the hydrologic system, especially the porosity system and the rate of ground-water movement. A special study for Door County has now been approved.

(4) River basin group studies of the entire water resources need to be done for the Michigan part of the area to provide a quan-

titative appraisal of the ground-water potential.

3.5.3 River Basin Group 2.2

River Basin Group 2.2 is a unique area in the Great Lakes Basin because it is almost entirely urbanized. Consequently, demands and effects on the ground-water resources are extreme.

The area, including its contiguous area within the Planning Subarea 2.2 boundary (Figure 3–13), represents the most heavily pumped ground-water in the Great Lakes Region. Approximately 100 mgd of more than 200 mgd of ground water pumped in northeastern Illinois in the mid-1960s came from deep sandstone wells.[51] In the same period an estimated 30 to 35 mgd were pumped from the same sandstone aquifer in Wisconsin. In comparison, a total of 1,100 mgd of ground water was withdrawn in 1965 in the entire Great Lakes Basin.[38] In addition to the heavy pumping problem, poor quality ground water exists in several localities.

The Chicago-Milwaukee region of declining water levels is perhaps the most serious ground-water problem in the Great Lakes Basin because of its effects on so many people. In the heavily pumped Illinois area, which lies mainly within the upper Mississippi River basin, projections of water-level decline and increased costs to users seem only to have spurred greater development and use. The consequence of this overdevelopment is that ever-increasing amounts of ground water are being pumped. Eventually increased use of Lake Michigan water will probably be required. The growing cone of influence, predominantly westward (Figure 3–20), now causes ground water to flow northwest from Indiana, west from Lake Michigan, and south from Wisconsin, all from within the Great Lakes Basin. The amount is not appreciable at present, but problems of relocation or establishment of new pumping centers, increased pumping lifts, depletion of water in storage, and potential migration of saline waters are of immediate concern.

Heavy pumpage in the sandstone aquifer began approximately 100 years ago. As a result the cone of influence is expanding far outside the Great Lakes Basin. Water level or artesian pressure had declined nearly 700 feet at Chicago and more than 300 feet at Milwaukee by 1970. Near Milwaukee the center of water-level decline (which reached nearly 400 feet in 1961) has moved westward out of the Great Lakes Basin due to increased pumpage to the west. Milwaukee reduced pumpage by increased use of Lake Michigan water. Pumpage has been relatively constant at more than 20 mgd for the past two decades in the Milwaukee area.

Walton [72] has estimated future water-level declines to the year 2010 (Figure 3–20) in the sandstone aquifer in the Chicago region. These estimates are based on increasing pumpage at existing pumping centers and no increased use of Lake Michigan water. Pumpage would increase from approximately 100 mgd to 243 mgd by 2010, and pumping level at most pumping centers would "be at critical stages a few feet above the top of the lowermost and most productive unit of the aquifer."[72] In addition, 1,000-foot pumping levels would be common by 1980. Even though pumpage would greatly exceed the maximum 46 mgd practical sustained yield under 1961 conditions, there would still be 1.5×10^{13} gallons of a total of 1.6×10^{13} gallons in storage in the upper units of the sandstone aquifer. Walton states further that it would take ". . . 4,500 additional production wells in upper units of the Cambrian-Ordovician aquifer to mine [this total] water in storage during a 50-year period."[72]

Dispersal of pumping centers would increase sustained yield by 19 mgd even with the addition of two new pumping centers.[72] Most investigators of the Illinois portion of Planning Subarea 2.2 conclude that much additional ground-water potential is available in unconsolidated and Silurian dolomite aquifers, but projected demands by 2020 will still require other sources of water. Reuse of water, less per capita water use facilitated by meter installation, and increased use of Lake Michigan water are expected to be solutions to water shortages.

Salinity of ground water is a problem primarily in the southern area. Indiana has saline water in most bedrock formations, with good quality bedrock water available only in the northwest part of the Silurian-Devonian aquifer. Saline water is present in deeper parts of the sandstone aquifer from the Milwaukee area south throughout the river basin group. Water in unconsolidated aquifers is saline in some parts of the Lower Peninsula of Michigan.

Hardness and high sulfate content are problems in the shallow unconsolidated and Silurian-Devonian aquifers. Carbonate rock causes high hardness through most of the area. Sulfate is a local problem.

Silurian and Devonian formations are exposed or are near the surface at many places in the area. Contaminants from poor waste-disposal systems can easily migrate into and through the solution channels and fractures of the dolomite formation. Careful evaluation of waste-disposal sites is needed throughout the area to prevent pollution of the shallow aquifer.

Although no major man-made deterioration of freshwater aquifers is known in the heavily pumped lakeshore area of Milwaukee-Chicago, its occurrence seems possible. Bergstrom[3] showed the 1,500 mg/l isocon line of the Mount Simon sandstone aquifer water exists as far west as Des Plaines. East of this line dissolved solids content is greater than 1,500 mg/l. Continual decline of the water level, now approaching 700 feet, induces upward movement of the saline water. Lateral migration of the upper saline water can and propably does occur. Some erratic occurrences of saline water are known. Migration northwestward into the Chicago area from the Gary area is probable. Some isolated saline occurrences may be related to upward leakage from deep wells drilled in the late 19th century.

Walton[72] indicates that upward leakage from the Mount Simon aquifer (saline in part) is presently only 1 mgd (approximately 2 percent of the current sustained yield) and could increase to 3 mgd (4.6 percent) under maximum sustained yield. Such leakage is small compared to current pumpage of more than 100 mgd. However, pumpage of Mount Simon wells, and indicated leakage through abandoned wells, could combine with lateral movement of poor quality water from the sandstones extending into Indiana, to deteriorate the freshwater sandstone aquifer.

Good management of ground-water resources in River Basin Group 2.2 seems imperative and several studies are needed in the immediate future. In areas where deep drilling has encountered basal saline water, properly cased holes can eliminate its upward flow and potential for contamination. A better delineation of the depth of occurrence of saline waters is needed to prevent indiscriminate deep drilling. Data in the Wisconsin area indicate that wells draw saline water from the bottom units, but termination of the well some feet higher would have eliminated the saline water. In some instances salinity has increased through the years of pumpage. Special site studies should be made at these places to determine means of preventing deterioration of freshwater aquifers.

Careful management and allocation in poor quality areas improve conditions. Some water users may be able to tolerate poor quality water, leaving the better quality water to be used by those who require it. Blending of poor and good quality water from two or more wells may be feasible in some instances. Recharge of ground water into poor quality zones, using coolant or other good water, should improve chemical quality as well as reducing pumping levels. Recharge through wells can increase ground-water temperature of the area and become detrimental in the long run.

In the Chicago area there are approximately 1,300 feet of additional drawdown available. This may cause some to think that concern for water supply can be postponed for a number of years and to assume that Lake Michigan would be the ultimate replacement supply when wells run dry. In 1961 through 1966 in northeastern Illinois, 82 new deep wells were drilled, 49 of which were drilled for new or existing municipal or subdivision use, and 26 for industrial and commercial use.[51] Permitting new high water-use developments in heavily pumped areas puts increasing demands on the hydrologic system and in turn increases population demands. In situations where additional development will compound water supply and population problems, well-field development in other areas or water-saving methods need to be considered. Dispersal of wells in a ground-water system is a basic way to reduce excessive pumping lifts, although increased transmission-line costs may offset the economic benefits. Increased drafts and consequent greater costs can induce new water-use efficiency or improvements in the economy of pumping. Curtailment of excessive water use for public supplies by installation of meters or apportionment of new water development for nonpublic consumption are two other alternatives.

The problem of declining water levels in the Milwaukee-Waukesha area is not as severe as in Chicago. However, the two cones of influence are beginning to overlap and declines will increase faster. These two States and Indiana should appraise their mutual water resources and determine the future course of water developments on each other and on the two major basins they straddle.

Management should consider supplementing current ground-water pumpage with additional Lake Michigan water where legally possible to reduce or stop the lowering of water levels. Increased use of Lake Michigan water during winter or during high lake levels could allow pumpage to be reduced and slow or partially reverse the water-level decline. Present practice requires not only continuing pumping-lift and pump-column extensions, but endangers future use of the system. Economics may eventually eliminate pumping as costs become prohibitive. This could stabilize pumpage draft at a level only the public or certain industries could afford.

Saline-water migration would not be forestalled in any event. The saline problem, as well as the aforementioned overdevelopment problem, go hand-in-hand in the Chicago-Milwaukee area and require monitoring to determine the progressive changes.

A plan to use underground storage for sewer and storm overflows is being tested for the Chicago metropolitan area.[45] The plan calls for temporarily storing overflows in a tunnel and reservoir system constructed in Silurian and upper Cambrian-Ordovician aquifers. Both vital aquifers would be protected from contamination by maintaining a negative head in the tunnel collection system in the Niagara dolomite and by installation of recharge wells around the tunnel-reservoir complex. Recharge with treated water would maintain a head of fresh water, causing continual inflow to the tunnel preventing outward leakage and contamination of the aquifers.

Deep waste disposal through wells is occurring at five sites in Indiana (Figures 3–18 and 3–19). Three wells below 4,000 feet inject into brines in Cambrian sandstones. Two wells are relatively shallow and dispose wastes into the Silurian and Devonian rocks at only 295 and 650 feet. A 2,629-foot injection well into Devonian rocks is used in the Chicago area. Wisconsin does not allow deep waste disposal.

Bergstrom[3] has made a study of subsurface disposal potentials in Illinois:

> The greatest hazard exists in northern Illinois, especially in northeastern Illinois, where fresh water extends to great depth, barrier conditions between potable and saline waters are mainly unknown, the pumpage from deep aquifers is substantial, and the concentration of industry and need for waste disposal are great. Here the most rigorous requirements are needed as to natural requirements, testing, engineeering, safeguards, monitoring, and well abandonments.

Needless to say, these apply to sites throughout the Great Lakes Basin.

Water rights, especially ground water, have not been of serious concern in this part of the nation except for interbasin diversion. When water shortages develop, people begin to assert their legal or presumed rights. The most apparent concern in the heavily pumped Milwaukee-Chicago area would be increased costs of pumpage in Wisconsin and Indiana due to water level declines caused by Illinois pumpage. As of 1969, sandstone aquifer water level decline along the Wisconsin-Illinois border, directly attributable to Illinois pumping, ranged from 200 feet near Lake Michigan to a 50-foot minimum approximately 35 miles west (Figure 3–20). Along the Indiana border water level decline was approximately 200 to 600 feet (Figure 3–20). Some of this decline may have been caused by Indiana pumpage.

In addition to attempts to reduce excessive water use, conjunctive use of surface and ground water is a potential solution to some water supply problems in certain areas. Areas of aquifer overdraft can revert seasonally to surface-water sources when streamflow is plentiful and allow partial recovery to occur. Artificial recharge using wells, particularly injection of cooling water return, has proven feasible in many areas. If recharge of this water to the aquifer system is considered, increase in ground-water temperature must also be evaluated. In the Chicago area seasonal use of Lake Michigan water could reduce ground-water overdraft and be more feasible than recharge by wells.

Illinois and Wisconsin have an excellent program of monitoring water levels and pumpage in critical pumping areas. Periodic publications relate pumpage to water levels in two major aquifer systems. Addition of a few observation wells near their State borders is needed. The addition of a chemical-quality monitoring system in each State seems warranted for any saline water migration. Indiana should develop a monitoring system, especially in its northwest area, to extend observations of the increasing effects of Illinois pumpage.

Ongoing studies in River Basin Group 2.2 on both land and water resources and their development are almost completed. For example, the Southeastern Wisconsin Regional Planning Commission is completing a comprehensive plan for the Milwaukee River watershed. Reports will complement those on the adjacent Fox River watershed in southeastern Wisconsin. These reports have been confined ". . . to documenting the existing and probable future water resource and resource-related problems of the watershed, out of this documentation will grow definitive plans and concrete recommendations for both public works facility construction and for land and water management policies within the watershed." The Indiana Department of

Natural Resources is developing a State Water Plan. Preliminary appraisal of the ground-water potential of the Lake Michigan drainage has been compiled.

Subsequent studies in River Basin Group 2.2 should involve the three States and three aquifer systems concerned. They should be oriented to quantitative measurements. Studies using aquifer models to predict effects of current and proposed stresses on the hydrologic system would be appropriate.

3.5.4 River Basin Group 2.3

Pollution of bountiful ground water is a local problem in River Basin Group 2.3. There also are areas of concentrated pumpage that create problems.

There are few regions where ground water is not plentiful. Only in the Ottawa basin are inadequate yields for other than domestic wells likely to occur. Here surficial deposits and bedrock aquifers are thin. The bedrock aquifers contain too few fractures for adequate permeability for high-capacity wells, or contain salty water. Induced filtration from streams offers the best opportunity for developing large well yields. In areas of shallow water table or thin aquifers, horizontal-well collectors or galleries have proven very efficient in obtaining high yields.

Near Lansing potential ground-water supply is adequate for future needs. Large quantities of water are available from glacial drift, the Saginaw Formation, and from streams by induced infiltration. However, overdevelopment could result because the Lansing metropolitan area covers only a small part of the area of potential water supply and has a concentrated large water demand. Without proper management serious overdevelopment could occur.[69] The hydrograph of an observation well in the Saginaw Formation at Lansing (Figure 3–22) shows adjustment of water level to withdrawals.

Areas of aquifer overdraft need to revert to surface-water sources when streamflow is plentiful, allowing surface-water recharge to replenish ground-water storage. Kalamazoo has attempted conjunctive use of surface and ground water to solve a water-supply problem.[1]

Areas of induced recharge from streams are at heavily pumped areas in the Lansing and Jackson areas. Depletion of streamflow in the Lansing area is of concern because adequate streamflow is needed to assimilate the effluent even though the "captured" flow pumped through wells is returned to the streams as treated sewage effluent.

Pollution of aquifers by introduction of man-made contaminants or by man-caused migration of natural contaminants is a serious local problem in River Basin Group 2.3. Both shallow unconsolidated aquifers and deeper bedrock aquifers have been or can be affected by current practices. Pollution of ground water is more serious than that of surface water because of its long-lasting effects, non-detection for long periods, and the general nonfeasibility of reclaiming the aquifer.

The most common pollution problem is seepage of wastes into shallow, unconfined aquifers. Septic tanks, leaching fields, well disposals, land fills, spillage, and leakage all add waste contaminants to sand and gravel aquifers and to porous bedrock formations near the land surface. Productive sand and gravel aquifers are particularly subject to extensive waste disposal in heavily populated areas and elsewhere.

Industrial waste disposal in deep wells is becoming more common. State agencies in Michigan regulating the injection of industrial wastes into the subsurface formations are the Water Resources Commission and the Geological Survey. Regulations state that waste stored in geological strata must not create a hazard to safety, health, or welfare of people or resources. In other words, the disposal program must insure that wastes will be confined to the stratum officially approved as the disposal reservoir. The locations of two known industrial disposal wells which dump into the Devonian aquifer system are shown on Figure 3–23.

There are some areas of naturally poor quality water in River Basin Group 2.3. Highly saline waters are present in parts of all the bedrock aquifers. However, the Saginaw and Marshall Formations do contain considerable areas with fresh water. High salinity is related to water occurring in the deeper bedrock formations. It moves upward through abandoned mining and test holes with improper seals, or by an increased head differential sometimes caused by pumping overlying freshwater aquifers. This situation occurred in the Grand Rapids area, where municipal pumping had to be halted to prevent further contamination.[55] At present, glacial-drift aquifers have not been extensively contaminated by saline water in this area.

Water in the drift is generally hard to very hard. It often has a high iron content.

High iron is also common in the deep sandstone aquifers. Sulfates in excessive amounts are found in the Michigan Formation and may migrate into the glacial drift.

There were no ongoing ground-water studies in River Basin Group 2.3 in 1970. A comprehensive study of the Grand River Basin was nearing completion.[68] Several county or areal basin studies have been made. Regional planning, particularly that concerned with interstate water use, requires basic knowledge of existing problems. The following are general study needs:

(1) A detailed water-resources reconnaissance of the major aquifer systems should be completed. It is desirable that an appraisal be made of glacial-drift aquifers within major drainage systems. It is also important that separate appraisals be made of each bedrock aquifer. Local demands on all the aquifer systems can be correlated within the entire system. This type of appraisal has been done in the *Grand River Basin Comprehensive Study*. It has provided a broad picture of where ground-water resources have been or can be developed for major water supplies.[68]

(2) Regional or countywide appraisals of the quantity and quality of water resources with special reference to ground water should be completed. These should be done on the aquifer-system basis, if possible, so that flow between aquifers and local demands on the system can be correlated within the entire system. Periodic determination of potential yield should be made for each unit in the planning subarea. As long as yield values are qualified as to probable accuracy, they will provide a starting point for planners. This type of appraisal was done for Kalamazoo.[1]

(3) Surficial formations should be recorded on 7½-minute topographic maps to determine aquifer locations and recharge areas. Topographic base maps at the 7½-minute scale are available in approximately half of River Basin Group 2.3. One small area had no topographic maps at all. Mapping was in progress there in 1970.

(4) A better network of observation wells in each of the bedrock aquifer systems is needed. This would provide a base for comparison between natural conditions and those changes imposed by man. Two hydrographs for the unconsolidated aquifers (Figure 3–21) illustrate no unusual effects under natural conditions, whereas the hydrographs on Figures 3–22 and 3–23 show effects in pumping areas.

(5) A network of chemical quality monitoring wells is needed for areas where there is present or potential water deterioration. Individual aquifers need monitoring to establish quality changes with major withdrawals, particularly in multi-aquifer systems. A much better delineation of saltwater zones in each of the aquifer systems is needed as is their relation to points of freshwater withdrawal.

3.5.5 River Basin Group 2.4

River Basin Group 2.4 has relatively minor ground-water problems, primarily a few small low yield or poor quality areas.

There is poor potential for large volume ground-water development from glacial-drift aquifers in the Upper Peninsula portion of the river basin group because of large areas of lake and till-plain deposits. These deposits are fine-grained, have relatively low permeability, and water-bearing zones provide low well yields. However, bedrock is at or near the land surface and is capable of producing moderate yields.

Chemical quality problems exist locally. Solid waste disposal in land fills is practiced in many towns. This type of disposal has recently been shown to cause ground-water contamination under certain conditions, so continual surveillance is required. Solid and liquid wastes are disposed of by paper companies and incidents of ground-water contamination from such waste disposal have reportedly occurred in the area. Dispersal of liquid wastes requires great care to prevent ground-water contamination.

Operation of brine and salt wells in Manistee, Mason, and Muskegon Counties has caused ground-water contamination. There are approximately 100 natural-brine wells and 20 salt wells in this area. Some public water supply wells at Manistee have been contaminated by wastes from these wells. Regulations to prevent pollution are in force, but the brine and salt wells have not always been properly operated and spillage has occurred. Currently, the State Water Resources Commission has issued orders to prevent further pollution and to clean up the existing situation.

A recent impetus to oil test drilling in the northwestern Lower Peninsula has created a renewal of public interest in the potential of ground-water contamination by this industry. Accidental or improper disposal of oil-field brines poses a serious threat.

In the Upper Peninsula water in the unconsolidated aquifers is generally of good quality except that much of it is hard and in many places high in iron. Locally it can contain high chlorides. In bedrock aquifers the water is generally hard. Sometimes it has a high iron content, and in places it is high in calcium sulfates derived from gypsum. Saline water is present in parts of the Silurian and late Ordovician rocks in the Upper Peninsula.

There are no "active" industrial waste-disposal wells in River Basin Group 2.4. As of August 4, 1968, there were three plugged wells and one proposed new well in the Muskegon area.

Hydrographs of observation wells in the unconsolidated aquifers (Figure 3–24) show no adverse effects. There are no long-term observation wells in the bedrock aquifers.

Studies covering well inventory, chemical sampling, and geologic mapping have been or are being done in all Upper Peninsula counties of River Basin Group 2.4. No studies have been completed in the Lower Peninsula. One is currently under way in the Manistee area.

Regional planning will require several appraisals. Detailed water-resources reconnaissance of the major aquifer systems is necessary, including the unconsolidated and bedrock aquifers in both the Upper and Lower Peninsulas. Quantitative appraisals of the Traverse, Manistee, Muskegon, and Big Sable river basin groups are needed. The Manistee and Muskegon groups each have potential for ground-water yield of one billion gallons per day. A study should be made of the effects on ground water of industrial processes and wastes and salt spreading on highways. This is particularly important in the Traverse, Manistee, Muskegon, and Big Sable river basin groups. The study should include research on ways to reduce pollution from impounded wastes, waste spreading, and on the safety of deep-well disposal. Detailed studies are needed of localized areas of poor quality water in unconsolidated aquifers, such as in Muskegon County. A network of chemical quality monitoring and revision of the existing network of observation wells, related to specific aquifers, is needed to establish natural and changing conditions imposed on the hydrologic system by man.

TABLE 3–4 General Stratigraphy and Major Aquifer Systems in the Lake Michigan Basin

Era	System	Group	Formation	Thick- ness (ft.)	Major aquifers: Well yields[1] (gpm)	Major aquifers: Well depths[2] (ft.)	Remarks
RIVER BASIN GROUP 2.1 Michigan							
Cenozoic	Quaternary			0-200	50-500	20-125	Sand, gravel in drift.
Paleozoic	Ordovician		Trenton	200-275			Limestone.
			Black River				Limestone.
			St. Peter (?)	0-25	50-300	50-175	Sandstone.
		Prairie du Chien					Limestone.
	Cambrian		Trempealeau (?)	0-600			Sandstone.
			Munising				Sandstone.
Wisconsin							
Cenozoic	Quaternary			0-300	50-1000	20-150	Sand, gravel in drift.
Paleozoic	Devonian		Milwaukee	0-130			Shale with dolomite.
	Silurian	Niagaran series		0-500	100-600	75-300	Dolomite.
	Ordovician		Maquoketa	0-400			Shale.
			Galena-Decorah-Platteville	0-250			Dolomite.
			St. Peter	0-300			Sandstone. High yields.
		Prairie du Chien	Oneota	0-260	100-1000	50-900	Dolomite.
	Cambrian	Trempealeau	Jordan	0-55			Sandstone.
			St. Lawrence	0-85			Dolomite.
			Franconia	0-200			Sandstone.
		Dresbach	Eau Claire	0-270			Sandstone. High yields.
			Mt. Simon				Sandstone.
RIVER BASIN GROUP 2.2 Illinois (Planning Subarea 2.2)							
Cenozoic	Quaternary			0-400	100-1000	50-200[3]	Sand, gravel in drift.
Paleozoic	Silurian	Niagaran series		100-470	100-1000	75-300	Dolomite.
		Alexandrian					
	Ordovician	Maquoketa		0-250			Shale; semi-confining bed.
		Galena					Carbonate. Low yields.
		Platteville		200-350			
		Ancell					
			Glenwood	100-650			Sandstone. Moderate yields.
			St. Peter				
		Prairie du Chien		0-340	500-1000	1000-1500	Dolomite and sandstone. Low yields.
	Cambrian	Trempealeau	Eminence	50-400			Dolomite. Generally low yields.
			Potosi				
			Franconia				Dolomite and sandstone.
			Ironton	105-270			Sandstone. Highest yields.
			Galesville				
			Eau Claire	235-450			Shale and siltstone; semi-confining bed.
			Mt. Simon	2000+	100-500	1700-1900+	Sandstone. 300 feet fresh.

[1] Range is that of high-capacity wells.
[2] Range is that of all wells.
[3] Estimated.

TABLE 3–4(continued) General Stratigraphy and Major Aquifer Systems in the Lake Michigan Basin

Era	System	Group	Formation	Thick-ness (ft.)	Major aquifers: Well yields[1] (gpm)	Major aquifers: Well depths[2] (ft.)	Remarks
RIVER BASIN GROUP 2.3							
Indiana							
Cenozoic	Quaternary			30-525	50-2500	50-300	Sand, gravel in drift.
Paleozoic	Mississippian		Coldwater	?-500			Shales.
			Sunbury				
	Devonian		Ellsworth	?			
			Antrim	60-200			
		Traverse		40-175			Carbonates. Possibly saline.
Michigan							
Cenozoic	Quaternary			0-550	100-1000	20-375	Sand, gravel in drift.
Paleozoic	Pennsylvanian		Grand River	0-475	50-700	50-500	Sandstone.
			Saginaw				Sandstone, shale, and coal.
	Mississippian	Grand Rapids	Bayport	0-125			Limestone. Saline.
			Michigan	0-400			Shale, gypsum. Gas.
			Marshall	0-300	100-1800	50-500	Sandstone. Saline in part.
RIVER BASIN GROUP 2.4							
Michigan (Lower Peninsula)							
Cenozoic	Quaternary			0-1200(?)	100-1000	50-300	Sand, gravel in drift.
Mesozoic	Jurassic		"Red Beds"	0-220			Sandstone, shale, and gypsum.
Paleozoic	Pennsylvanian		Grand River				Sandstone.
			Saginaw	0-550	50-100	300-700	Sandstone, shale, and coal. Brines and sulfates at bottom.
	Mississippian	Grand Rapids	Bayport	0-625			Limestone, shale, and gypsum. Oil and gas.
			Michigan				
			Marshall	0-300	50-500	200-1450	Sandstone and salty water. Oil and gas.
			Coldwater	0-1050			Shale. Some gas.
	-----?-----	-----?-----	----?----				
	Devonian		Ellsworth	0-625			Sandstone and shale. Brines and salts.
			Antrim	0-650			Shale.
		Traverse		0-800			Limestone. Oil and gas.
			Rogers City	0-315	50-100	20-780	Limestone. Oil, gas, and brines.
			Dundee				
		Detroit River		0-1600			Carbonates, sandstone, salt, and anhydrite. Oil, gas, and brines.
			Bois Blanc	0-950			Dolomite. Oil, gas, and saline water.
	Silurian		Bass Islands	0-200			Dolomite. Possibly saline water.
Michigan (Upper Peninsula)							
Cenozoic	Quaternary			0-300	150-500	10-150	Sand, gravel in drift.
Paleozoic	Silurian		"Mackinac breccia" Bass Is.	0-300			Dolomite and gypsum which have been brecciated.
			"Mackinac breccia" Salina	0-600	50-500	20-500	Sandstone, shale, and salt which have been brecciated.
			Engadine	10-175			Carbonate and salt.
			Manistique	0-525			Carbonates.
			Burnt Bluff				
		Cataract		0-250	Unknown		Dolomite and shale. Saline water in Schoolcraft and Delta Counties.
	Ordovician	Richmond		0-450	50-100	20-200	Carbonates. Generally saline.
			Bills Creek	0-400			Shale. Saline water.
			Trenton	0-300	100-200	20-1200	Limestone. Saline, in part.
			Black River				
		Prairie du Chien		0-425			Sandstone and dolomite.
	Cambrian		Trempealeau	0-750	50-500	20-100	Dolomite and sandstone.
			Munising	0-1175			Sandstone.

[1] Range is that of high-capacity wells.

[2] Range is that of all wells.

TABLE 3-4(continued) General Stratigraphy and Major Aquifer Systems in the Lake Michigan Basin

Era	System	Group	Formation	Thick-ness (ft.)	Major aquifers: Well yields[1] (gpm)	Major aquifers: Well depths[2] (ft.)	Remarks
			Indiana				
Cenozoic	Quaternary			0-300	100-500	20-80[3]	Sand, gravel in drift.
Paleozoic	Mississippian		Coldwater	0-500			Shales.
			Sunbury				
			Ellsworth				
	Devonian		Antrim and New Albany	0-200			Shales.
		Traverse		0-175			Carbonates. Possibly saline, but unexplored.
			Rogers City				
			Dundee				
		Detroit River					
			Bois Blanc				
	Silurian		Bass Islands	400-600	50-500	300-400	Carbonates. Fresh water only in Lake County.
			Salina				
	Ordovician			2700±			Sandstone and dolomite. Saline, industrial use in Hammond only.
	Cambrian						
			Michigan				
Cenozoic	Quaternary			0-600	100-500	20-200	Sand, gravel in drift.
Paleozoic	Mississippian		Ellsworth	?			Shale.
	Devonian		Antrim				Shale. Reportedly fresh water in top zone.
		Traverse		116	?		Carbonates. Probably saline, but unexplored.
		Detroit River		170			
			Wisconsin				
Cenozoic	Quaternary			0-425	100-1000	50-350	Sand, gravel in drift.
Paleozoic	Devonian		Milwaukee	0-200			Shale with dolomite.
	Silurian	Niagaran Series		0-645	100-800	75-300	Dolomite.
		Alexandrian Series	Mayville				
	Ordovician		Maquoketa	0-265			Shale; semi-confining bed.
			Galena-Decorah-Platteville	200-345	500-1300	50-1500	Dolomite. Low yields.
			St. Peter	80-270			Sandstone. Moderate to large yields.
	Cambrian	Trempealeau	Jordan	0-120			Sandstone and dolomite. Low to moderate yields.
			St. Lawrence				
			Franconia	0-150			Sandstone. Moderate to large yields.
		Dresbach	Galesville				
			Eau Claire	0-405			Sandstone. Low yields.
			Mt. Simon	770+			Sandstone. High yields.

[1] Range is that of high-capacity wells.

[2] Range is that of all wells.

[3] Estimated.

TABLE 3–5 Chemical Quality Characteristics of the Major Aquifer Systems in the Lake Michigan Basin

Aquifer system	Hardness (mg/l)	Sulfate (mg/l)	Chloride (mg/l)	Iron (mg/l)	Total dissolved solids (mg/l)	Temperature (°F)	Remarks
			RIVER BASIN GROUP 2.1				
			Michigan				
Quaternary	50-400	5-75	0-50	0-3	100-450	44-49	
Cambrian-Ordovician	150-350	10-70	5-60	0.2-8	200-900	47-49	High iron in deep sandstones; Menominee County has sulfate over 1,000 mg/l in lower unit, "sulfur" water in upper.
			Wisconsin				
Quaternary	40-450	1-90	1-30	0-1.5	125-500	54	Most mineralized in eastern third.
Silurian	90-500	5-250	1-30	0-2	250-600	46-60	Saline in part in Manitowoc County.
Cambrian-Ordovician	70-350	0.5-90	2-125	0-1	130-700	53-56	More highly mineralized, in part, in Brown and Calumet Counties and along Lake Michigan shore. Sulfate over 600 mg/l near Marinette in middle unit.
			RIVER BASIN GROUP 2.2				
			Illinois (Planning Subarea 2.2)				
Quaternary	120-610	5	1-120	0.2-12	310-1100	52	Lake County data only.
Silurian	70-950	400-1000	1-170	0-7	300-1400	54	
Cambrian-Ordovician	170-340	757	1-320	0-5	300-1450	54-62	
Cambrian (Mt. Simon)	?-4000+	?-800+	50-400+	0.2	1500-3800+	60-66+	Increasing salinity at depth and to southeast.
			Indiana				
Quaternary	50-1000	1-500	1-300	0-7	150-2000	---	
Silurian-Devonian	50-700	1-6	1-25	0.1-5	300-1500	---	Fresh water only in northwest.
Cambrian-Ordovician	---	---	---	---	2000-3500	---	Industrial use only in Hammond area.
			Michigan				
Quaternary	150-350	5-80	3-90	0-3	200-450	---	
			Wisconsin				
Quaternary	100-450	20-300	1-30	0.5-1	200-500	52-54	
Silurian	90-550	5-350	1-50	0.5-1	200-800	46-60	
Cambrian-Ordovician	160-1000	45-500	5-30	0.5-2	300-1300	56-61	
			RIVER BASIN GROUP 2.3				
			Michigan				
Quaternary	100-700	1-500	0-700	0-10	150-1100	42-55	
Pennsylvanian	20-800	0-500	0-400	0-9	250-1500[1]	45-54	
Mississippian (Marshall)	150-400[2]	25-200[3]	2-150[4]	0.1-7	200-700[5]	50-55	
			Indiana				
Quaternary	225-400	10-150	1-50	0.1-7.5	250-500	54	
			RIVER BASIN GROUP 2.4				
			Michigan (Lower Peninsula)				
Quaternary	125-400	5-100	0-50	0-1	150-500	46-50	
Pennsylvanian	---	---	---	---	---	---	Unknown.
Mississippian (Marshall)	200-750	20-150	5-1100	0.2-11	630-780	50	Saline water in southern and western part.
Devonian	185-195	4-9	1-2	0-0.9	200-225	45	Saline water in most of area.
			Michigan (Upper Peninsula)				
Quaternary	60-400	1-50	0-200	0-5	100-600	44-48	
Silurian (Burnt Bluff-Bass Islands)	100-700	5-500	0-120	0-5	200-900	44-49	Saline water in southern part of Mackinac County.
Cambrian-Ordovician (Munising-Trenton)	150-300	15-75	5-200	0-3	200-500	47-50	

[1] Only Clinton County exceeds 1,000 mg/l.

[2] Barry, Kent, and Ottawa Counties range up to 750 mg/l.

[3] Barry, Kent, and Ottawa Counties range up to 1,500 mg/l.

[4] Barry, Kent, and Ottawa Counties range up to 7,000 mg/l.

[5] Barry and Kent Counties exceed 3,000 mg/l.

TABLE 3-6 Estimated Ground-Water Yield from 70 Percent Flow-Duration Data in the Lake Michigan Basin

Subbasin	Runoff at 70-percent duration (cfsm)	Subbasin yield (mgd)	State totals (mgd)	River Basin Group totals (mgd)
		RIVER BASIN GROUP 2.1		3,880
		Michigan	920	
Menominee Complex	0.15	100		
Menominee River	0.50	820		
		Wisconsin	2,960	
Menominee River	0.50	500		
Peshtigo River	0.40	300		
Oconto River-Pennsaukee Complex	0.40	270		
Suamico Complex	0.10	30		
Fox River	0.40	1,700		
Green Bay Complex	0.10	160		
		RIVER BASIN GROUP 2.2		490
		Illinois	90 [1]	
Chicago-Milwaukee Complex	0.20	90		
		Indiana	110	
Chicago-Milwaukee Complex	0.25	110 (100u) (20b)		
		Michigan	40	
Chicago-Milwaukee Complex	0.35	40		
		Wisconsin	250	
Chicago-Milwaukee Complex	0.30	250 (e8b)		
		RIVER BASIN GROUP 2.3		2,850
		Indiana	550	
St. Joseph River	0.50	550 (561)		
		Michigan	2,300	
Black River	0.40	90		
Grand River	0.30	730		
Kalamazoo River	0.55	710		
Ottawa Complex	0.30	30		
St. Joseph River	0.60	740		
		RIVER BASIN GROUP 2.4		4,490
		Michigan	4,490	
Bay De Noc Complex	0.05	40		
Escanaba River	0.30	180		
Manistique River	0.80	750		
Manistee River	0.90	1,160		
Muskegon River	0.55	940		
Sable Complex	0.65	810		
Seul Choix-Groscap Complex	0.05	20		
Traverse Complex	0.35	590		
			Lake Basin total	11,710 mgd

[1] Planning Subarea 2.2 yield 480 mgd (507u, 60b).

Note: Estimates based on flow-duration data for period of record (to 1960 and more than 10 years in Wisconsin, to 1964 and more than 9 years in Michigan, and to 1960 and more than 9 years in Indiana) at all gaging stations within the subbasin; extrapolations within drainage area and to ungaged areas based on surficial geology.

(Figures in parentheses are maximum yield computations from published area quantitative studies;b,bedrock;u,unconsolidated)

Section 4

LAKE HURON BASIN

4.1 General

The Lake Huron basin contains several moderate-sized areas where large supplies of ground water are available for development. Most of these areas are in the southwestern upland part of River Basin Group 3–1. The Au Sable River basin group has the greatest potential. Demand for water supplies has been small, since this area is relatively undeveloped. Large supplies are also available in small portions of western and southern areas of River Basin Group 3.2. Aquifers here require careful development to avoid contamination by saline water. Elsewhere in the basin there are no known large sources of ground-water supplies. Development of large supplies of water in these portions of the basin requires use of Lake Huron stream waters.

Chief sources of ground water are aquifers in the glacial outwash and in some places the morainal deposits. Bedrock is dominantly Paleozoic sedimentary carbonates, shales, and sandstones. The sandstone or carbonates, especially where they can be recharged from overlying permeable glacial deposits, are sources of moderate supplies of ground water.

Other than low well yields, a major ground-water problem is the presence of highly mineralized water in some parts of the bedrock. Pollution also has been a problem in the basin. There is a potential for local pollution from solid waste disposal, industrial wastes, oil-field brines, highway salting, and laundromat wastes. Protection must be afforded to sources of ground water.

Presently, ground-water sources have been developed intensively for water supply at points of need. Unfortunately, these points are generally not at the best potential sources. Some ground-water resources are relatively untapped and are therefore still available for regional development. The wide distribution of aquifers suggests other potential uses. Possible applications include use of ground water for low-flow augmentation, sewage assimilation, and replenishment of surface reservoirs. These uses could materially aid the solution of water quality and water quantity problems. Tapping of unused aquifers on a regional basis could also lower the water table to provide underground storage capacity for increased natural recharge, and could conceivably reduce flood discharges as well as base flow.

Small population, large recreational use, minor industrial development, limited irrigation, and local highly mineralized water have restricted the development of ground water in River Basin Group 3.1. In River Basin Group 3.2 development of ground water has been restricted by limited quantities, highly mineralized water, major industrial development locally, and large withdrawals of surface supplies.

4.2 Physiography and Drainage

This section discusses the part of the Lake Huron drainage basin lying within the United States. All of it lies in portions of the Upper and Lower Peninsulas of Michigan. It consists of 16,200 square miles of drainage area (Figure 3–30).

The Lake Huron basin lies within the Central Lowland physiographic province. Most streams draining the United States part are relatively short and have small drainage basins. The Saginaw River basin is the largest, consisting of more than 6,200 square miles. It drains into Saginaw Bay — a depression at one time occupied by a glacial ice lobe.

Glaciation produced the present topography. This basin is characterized by hilly glacial moraines in the western and southern areas which greatly contrast with the flat glacial-lake plains in the east. Several hills reach altitudes of 1,300 feet, while the plains are 600 feet above sea level.

Most of the basin is covered with thick glacial sediments; only in the eastern part are the glacial deposits thin and bedrock sometimes exposed (Figure 3–2). Glacial deposits are reported to be as much as 850 feet thick in the hilly morainal northwestern area. They are largely composed of silty and clayey lake sediments. Till-plain, morainal, and outwash deposits are less common.

Glacial processes were also responsible for disrupting the formed drainage of major streams in the basin. Great quantities of glacial drift were deposited in stream valleys and drainage ways and caused many lakes to be formed. Principal preglacial drainage was to the west through the area of the present Grand River drainage system. Following melting of the glaciers, streams readjusted to the new surface features and drained to the east. Postglacial stream development reworked the adjacent glacial deposits and formed flood plains and alluvial deposits.

Bedrock underlying the Lake Huron basin consists of Paleozoic sedimentary carbonates, shales, and sandstone. It forms the northeastern part of the Michigan structural basin. Older consolidated rocks form the northeastern rim of the structural basin and the younger rocks lie in the middle. The outcrop pattern is shown in Figure 3–3. The type of bedrock has played an important role in the formation of major physiographic features. Where the bedrock directly underlying the glacial drift consists of relatively resistant carbonates and sandstones, erosion has formed escarpments and hilly topography. Where shales are present they have been easily eroded and now underlie the lake bottoms and other low areas.

Like other areas in the Great Lakes Basin, the Lake Huron basin was forested with white pine. Today, after extensive logging and forest fires, most of the pine is gone.

4.3 Ground-Water Conditions

Although there is little generalized information about ground-water conditions in the Lake Huron basin, there is detailed information in three areas (Figure 3–30). From publications on these areas and geologic studies conditions in other areas have been projected to show that some ground water is available throughout the basin. The ground water varies greatly in amount and quality. Water occurs in aquifers in glacial deposits, which vary considerably in permeability and in ability to yield water to wells. The bedrock contains aquifers generally yielding moderate to small amounts of water. The chemical quality of this water may be poor. Moderate and large supplies adequate for industry and municipalities are restricted to the western and southern sections of the basin.

Buried preglacial channels filled with unconsolidated sediments are present in the bedrock. They have not been mapped and their ground-water potential has not been explored. A major channel underlies the Au Sable River in Oscoda County but little is known of its occurrence. Such buried channels may have a large ground-water potential and thus warrant exploration.

4.3.1 Unconsolidated Aquifers

Unconsolidated sediment aquifers consist of sand and gravel beds in glacial drift and postglacial alluvium. Areas of outwash, some moraines, and buried bedrock channels offer the best potential for ground water. Surficial deposits and their estimated ranges of well yields are shown in Figures 3–31 and 3–36 for River Basin Groups 3.1 and 3.2. The higher yielding areas are associated with outwash and some of the moraines. Lower yields correlate with till plain and lake deposit areas that contain large percentages of clay and silt. The presence of high-yielding areas in the till plains, moraines, or lake deposits may indicate buried outwash deposits.

The surficial geology and well yields of Figures 3–31 and 3–36 show that much of the basin is covered with lake deposits having well yields less than 10 gpm. Outwash is largely restricted to the western and local southern parts of the basin. It has well yields reported to be more than 500 gpm. Yield data have been generalized by area.

Of special importance is the Au Sable River basin in the central part of River Basin Group 3.1. Here thick outwash deposits and high well yields have been reported. There is a good potential for stream infiltration. This area probably has excellent potential for development of large ground-water supplies. There are two small areas in River Basin Group 3.2 where yields are reportedly more than 500 gpm and large supplies have been developed. One of these is in the northwestern part of the Saginaw Bay area, the other in the southern part of the basin.

Hydrologic characteristics of unconsolidated sediment aquifers in the Lake Huron basin are included in Table 3–7. The thickest deposits are in the Lower Peninsula portion of River Basin Group 3.1 where thickness ranges from 0 to more than 850 feet and the sediments may contain one or more aquifers. Well depths are usually less than 400 feet. River Basin Group 3.2 has the highest yields, ranging from

100 to 1,200 gpm with wells generally less than 350 feet deep.

4.3.2 Bedrock Aquifers

Bedrock aquifers are present in most parts of Lake Huron basin. There are five major aquifer systems, but only one may be present in a given area. The aquifers generally coincide with the outcrop pattern of geologic formations, making a series of successive aquifer systems from north to south along the northern rim of the Michigan structural basin. The general stratigraphy and hydrologic characteristics of each aquifer system are included in Table 3–7 and their occurrence and stratigraphic relationships are shown in Figures 3–32, 3–33, 3–34, 3–35, 3–37, and 3–38. Chemical quality characteristics of the aquifer waters are included in Table 3–8. The aquifer systems are discussed from the youngest, or uppermost in the stratigraphic sequence, to the oldest or deepest system in each river basin group. The youngest recognized bedrock unit is of Jurassic age, but it is not presented here because it has no known aquifer significance.

The youngest aquifer system, in Pennsylvanian rocks, occurs in the central part of Lake Huron basin. It lies almost entirely in River Basin Group 3.2 (Figure 3–37). These rocks are present only in a small area of River Basin Group 3.1, in Arenac County. This unit is considered insignificant. The Saginaw and Grand River Formations, consisting of 75 to 750 feet of sandstone, limestone, and shale, make up the Pennsylvanian aquifer system. Coal, brines, and gypsum are also present.

Wells penetrating the Pennsylvanian aquifer reportedly have yields up to 500 gpm and depths that range from 100 to 600 feet. The water is very hard, 130 to 725 mg/l, and moderately high in mineral content, 200 to 800 mg/l (Table 3–8). Saline water occurs in the central part of the system (Figure 3–37).

Recharge to the Pennsylvanian aquifer occurs through the glacial drift. Discharge, including the saline water, occurs to streams and flows into Saginaw Bay. Two hydrographs show long-term water level fluctuations (Figure 3–37). The Genesee County hydrograph (Ge–9dc) shows effects of ground-water withdrawals over the last 17 years. The Bay County hydrograph (Ba–22ad) shows a short-term recovery trend as the result of cessation of pumping after the aquifer becomes saline. The aquifer is used quite extensively in the basin.

The next oldest aquifer, the Mississippian (Marshall) aquifer system, underlies the southern two-thirds of the Lower Peninsula portion of Lake Huron basin and is the largest yielding bedrock aquifer in the basin. The aquifer is composed of sandstone or siltstone. It ranges in thickness from 50 to 350 feet (Table 3–7). Beneath the freshwater zone the formation contains oil, gas, and brines. The aquifer crops out beneath the glacial drift in a northwest-southeast band across the southeastern part of River Basin Group 3.2 (Figures 3–32 and 3–38). Little is known of aquifer potential of the confined part of the system.

The higher yields of wells in the Marshall aquifer are reported to range up to 500 gpm. Well depths are from 50 to 650 feet. The chemical quality of water from the aquifer is hard to very hard, 130–470 mg/l, and moderately mineralized, 250–600 mg/l (Table 3–8). Saline water, as shown on Figures 3–32 and 3–38, occurs in the eastern and central parts of the basin. It coincides with the central part of the Michigan structural basin.

Recharge to the unconfined part of the Marshall aquifer occurs principally through the glacial-drift cover. Natural discharge occurs to streams and probably directly into Lake Huron. A hydrograph of a well in Sanilac County (Sa–33dd) shows the long-term water level trend caused by natural conditions (Figure 3–38). The Marshall aquifer is not extensively used as a source of water supply in the basin because of productive overlying unconsolidated aquifers.

The Devonian aquifer system is the northernmost bedrock aquifer in the Lower Peninsula part of the Lake Huron basin (Figure 3–33). This system consists of the Traverse Group, Rogers City Formation, and the Dundee Formation, a series of limestone beds with some interbedded shales. These are as much as 1,300 feet thick (Table 3–7). Beneath the freshwater zone in places, the aquifer contains oil, gas, brine, or salt.

Wells in the Devonian aquifer system reportedly yield up to 200 gpm from depths of 100 to 600 feet. The water is very hard, 150–300 mg/l, but only moderately mineralized, 250–370 mg/l (Table 3–8). Where the aquifer system is confined by overlying bedrock, the water is saline. Recharge to the unconfined part of the aquifer occurs indirectly through glacial drift and directly where the limestone is exposed. A hydrograph for a well in Presque Isle County (PI—8bb) shows long-term water level fluctuations caused by natural conditions (Figure 3–33). The Devonian aquifer is widely used as a source for domestic and stock water in the basin.

The southern two-thirds of the Upper Peninsula portion of the basin is underlain by the Silurian aquifer system (Figure 3–34). This system is composed of carbonates in the Engadine, Manistique, and Burnt Bluff Formations that are as much as 700 feet thick (Table 3–7). The overlying Silurian and Devonian rocks—the Bois Blanc and St. Ignace Formations, and possibly the Salina—can be considered a part of the Silurian aquifer system because they are permeable from being brecciated and faulted. Their well-yielding capabilities are unknown.

The Silurian aquifer system has yields up to 100 gpm from wells 50 to 120 feet deep. Permeability of the carbonate rocks has developed as a result of solution activity along fractures and bedding planes. Table 3–8 data show the water as very hard, 250–300 mg/l, and moderately mineralized, 250–650 mg/l. The aquifer contains saline water where it is confined, as in the St. Ignace area and the Lower Peninsula. Recharge to the Silurian aquifer occurs through glacial drift and where the aquifer is exposed. A hydrograph of a well in Mackinac County (Ma–7aa) shows the long-term water level trend due to natural conditions (Figure 3–34). The Silurian aquifer is used as a source of water for domestic and stock water in the basin.

The lowermost freshwater aquifer, the Cambrian-Ordovician aquifer system, occurs in the northern third of the Upper Peninsula part. To the south the system probably contains saline water. The system consists of sandstone grading upward to dolomite and then to carbonates. The system is 2,000 feet thick in some areas. The aquifer system is separated into two units in Table 3–7 because of differing rock types and well yields. The northern part of the system includes the sandstone and dolomite units of the Jacobsville sandstone to the Prairie du Chien Group. The southern part of the system includes overlying carbonates of the Black River and Trenton rocks. In the northern part the system has ground-water potential with well yields up to 300 gpm and well depths from 75 to 1,000 feet. To the south, where the carbonates are present, potential well yield is smaller, 50 to 100 gpm. Well depths range from 50 to 500 feet. The carbonate units of the aquifer system are best developed in the near-surface portion where greater solution activity has increased the permeability.

Saline water is present beneath the freshwater zone in the upper unit of the Cambrian-Ordovician system, but the sandstone unit is generally fresh to 1,000 feet in Chippewa County. The water in both units of the aquifer if hard to very hard, 150–350 mg/l, and moderately to highly mineralized, 250–700 mg/l (Table 3–8).

Recharge occurs to all the units through the glacial drift or directly wherever the bedrock is exposed. The Cambrian-Ordovician aquifer is a source of water for domestic and stock use in the basin.

4.4 Ground-Water Potential

As discussed in the first section, ground-water potential of the Lake Huron basin was estimated from the low-flow characteristics of streams. Flow-duration data[27] for the 70 percent value on the flow-duration curve were used to compile Figure 3–39. Areas shown with high 70 percent values (0.40 to 0.78 cfsm and greater) indicate where ground water is contributing much of the stream discharge from significant ground-water storage in shallow aquifers. Data from Figure 3–39 were used in turn to compile Table 3–9 of estimated ground-water potential. Conservative estimates should be used to provide first approximations of potential yield. Other factors were not considered in estimating this potential, such as reuse of ground water as it moves from place to place, inducement of streamflow into the ground (stream infiltration), and withdrawal of water from ground-water storage.

The flow-duration data indicate that the Au Sable River basin has the greatest ground-water potential in the Lake Huron basin. Further study is needed, however, to delineate the shape and size of the unconsolidated and Marshall aquifers and the possibilities of induced stream infiltration.

4.5 Problems, Needs, and Management Considerations

4.5.1 General

The Lake Huron basin has a limited potential for large ground-water resources. Areas that do have large potential supplies are located away from Lake Huron and other large lakes in the basin, and therefore can provide a good water supply where access to large surface-water sources is not available.

Presently, the northern part of the basin is serving primarily as a recreational area. Stream and lake waters and limited ground-water resources should be adequate to satisfy developing water needs. The southern part of the basin is industrialized and demands for water cannot always be adequately supplied by either streams or Lake Huron water. Further consideration should be given to full development of larger ground-water resources. For this to be realized, systematic exploration, testing, and management of the aquifers on a regional basis will be necessary. Only then can long-range planning consider the potential of the underground water resource in solving water supply or water quality problems.

Some natural conditions can develop into serious problems through the current activities of man. Specific problems, needs, and management considerations of each of the two river basin groups are discussed separately.

4.5.2 River Basin Group 3.1

There are no aquifers covering large areas in the Upper Peninsula portion of River Basin Group 3.1 known to be capable of yielding large (more than 300 gpm) ground-water flows to individual wells. The glacial drift is relatively thin. In many places the saturated thickness is not great enough to form good aquifers. The known and suspected presence of buried valleys, with their potential of containing good aquifers, should be considered in future ground-water exploration. Lake deposits of glacial origin are generally of low permeability. Development of large ground-water supplies usually cannot be expected from the bedrock. Even though a few high yields from bedrock aquifers have been reported and flowing wells are common, the chances of similar yields elsewhere are small. Some of the bedrock is impermeable shale. Solution openings in carbonates are not well developed below the water table. Based on well records, sandstones are the best aquifers.

The quality of water in the Upper Peninsula varies considerably within the same aquifer. Generally, the water is hard and sometimes high in iron content. Poor quality water is present in some of the Silurian rocks in Mackinac County.

In the Lower Peninsula many low well yields are reported in the eastern part adjacent to Lake Huron. Morainal and lake deposits here are usually thin. Good to excellent yields are available to the west and southwest.

The quality of water in the Lower Peninsula is generally good, although water from the glacial-deposit aquifers is often hard and high in iron. Water in the Marshall Formation is saline in the southeastern part of the basin. In both the Marshall and the Devonian (Dundee and Traverse) aquifers, the water apparently is saline where the aquifer is confined by overlying bedrock. Highly mineralized water has moved upward and outward from the bedrock to shallow depths in some areas. In the eastern and southeastern parts of the basin, water in the glacial aquifers has become saline.

Local pollution problems have been experienced in the Lake Huron basin as they have in other areas of the State.[9] Solid waste disposal, industrial wastes, oil-field brines, highway salting, laundromat wastes, and other deleterious substances are of concern as pollutants. Continued and strengthened surveillance by State pollution-control agencies is needed to protect potential sources of ground-water supplies in the western part of the basin. There were no deep waste disposal wells (excluding oil-field brine-injection wells) in River Basin Group 3.1 as of June 1971.

Detailed reconnaissance studies that cover well inventory, chemical sampling, and geologic mapping have been done in the Upper Peninsula. None have been done in the Lower Peninsula portion of the basin, but one study is underway in the Rifle River basin to provide information on the water resources of that area.

Regional planning will require:

(1) comprehensive geohydrologic studies of the major aquifer systems, including the unconsolidated and bedrock aquifers, in both the Upper and Lower Peninsula. A detailed study would include accurate delineation of areas where water-bearing formations may be contaminated, and where this contamination would prevent or impede future ground-water development.

(2) quantitative appraisals of the Cheboygan and Au Sable basins as potential areas of major ground-water development. These have estimated potential yields of 510 and 785 mgd, respectively.

(3) chemical-quality monitoring network. A revision of the existing network of observation wells related to specific aquifers is also needed to establish natural and changing conditions imposed on the hydrologic system by man.

4.5.3 River Basin Group 3.2

In the northwest area there is considerable potential for development of ground water. In general, however, River Basin Group 3.2 has little potential for development of large volumes. In many places the glacial drift is thin and largely composed of lake deposits and till plain deposits, which generally have low permeability and low well yields. The two principal bedrock aquifers, the Grand River-Saginaw and the Marshall, may yield large volumes of ground water locally, but over the aquifer areas as a whole, yields would be moderate.

In addition to the scarcity of large ground-water supplies, there is a definite problem with poor quality water, especially in the central basin area. Saline water is often found at depths less than 100 feet in either drift or bedrock. Part of the poor quality probably results from natural migration of saline water upward and outward from inner and deeper bedrock formations in the Michigan basin. In other instances the poor quality results from leakage through uncased or poorly constructed borings drilled for coal, salt, or brines. These borings are generally located in the counties adjacent to Saginaw Bay. Many of the wells have since been plugged and the brine leakage reduced.[9] In still other areas the natural balance between fresh and salt water has been disturbed by draining or pumping.

Management will be needed in the Midland area, where industrial requirements for streamflow have exceeded the supply. Lakes and streams available for recreation are also limited here. In addition, a large nuclear power plant is planned for the area, and cooling water from it would have to be released to a stream. There is a need for a comprehensive water resources investigation of this area as a guide in solving thermal pollution. Surface reservoirs to store seasonal excess streamflow for later release to augment deficient flow have been recommended. These could also be used for recreation. Other possible hydrologic solutions are the use of ground-water reservoirs for storage and subsequent pumpage to augment low streamflow. This storage is potentially available in glacial-drift formations in the northwest.

There were eight active industrial waste disposal wells and one standby in River Basin Group 3.2 as of June 1971. Eight of the wells dumped their wastes in the saline part of the Marshall Formation and one in the Devonian (Dundee Formation) aquifer system. These wells are located in Gratiot, Midland, and Bay Counties.

To obtain the necessary information for proper planning of water resource development, the following ground-water investigations are needed:

(1) comprehensive water resources studies of the geohydrology of the unconsolidated and bedrock aquifers

(2) quantitative appraisal of the northwestern part of the Saginaw basin. The entire basin has a potential for a yield of more than one billion gallons per day.

(3) determination of the hydrologic system of saline areas in the central and eastern parts of the basin. Such knowledge would permit an evaluation of fresh ground-water sources and its relationship to the saline ground water.

(4) a network of wells to monitor chemical quality, and revision of existing observation wells, so that they relate to specific aquifers. This would establish both natural and man-made conditions.

TABLE 3–7 General Stratigraphy and Major Aquifer Systems in the Lake Huron Basin

Era	System	Group	Formation	Thick-ness (ft.)	Major aquifers: Well yields[1] (gpm)	Major aquifers: Well depths[2] (ft.)	Remarks
			RIVER BASIN GROUP 3.1 Michigan (Upper Peninsula)				
Cenozoic	Quaternary			0-400	0-200	50-400	Sand, gravel in drift.
Paleozoic	Devonian	"Mackinac Breccia"	Bois Blanc	0-250	Unknown		Brecciated carbonates.
	Silurian		St. Ignace	0-300			Brecciated dolomite and shale.
			Bass Islands	0-600			Brecciated inter-bedded shale and carbonates. Saline in part.
			Salina				
			Engadine	10-175	50-100	50-120	Carbonates.
			Manistique	0-525			
			Burnt Bluff				
		Cataract		0-200			Dolomite and shale.
	Ordovician	Richmond		0-240			Carbonates. A minor aquifer locally.
			Bills Creek	0-250			Shale.
		Trenton-Black River	Trenton-Black River	0-210	50-100	50-500	Carbonates. "Sulfur water."
	------?------	Prairie du Chien		180-600	100-300	75-1000	Sandstone and dolomite.
	Cambrian		Trempealeau				
			Munising	900-1200			Sandstone.
			Jacobsville				
			Michigan (Lower Peninsula)				
Cenozoic	Quaternary			0-850	50-900	50-300	Sand, gravel in drift.
Paleozoic	Pennsylvanian		Saginaw	50-400			Sandstone, shale, and coal. Present only in small area of Arenac Co. Brines and sulfates at bottom.
	Mississippian	Grand Rapids	Bayport	0-25			Carbonates, shale, and gypsum. Oil and gas.
			Michigan	50-250			
			Marshall	50-300	50-500	50-650	Sandstone. Some brine, oil, and gas.
			Coldwater	925-1150			Shale. Some gas.
			Sunbury	10-250			Shale and sandstone. Some oil, gas, and brine.
	------?------	-------------------	Berea				
			Bedford				
	Devonian		Antrim	150-650			Shale. Gas.
		Traverse		640-850			Limestone and shale. Oil, gas, and brine in confined areas.
			Rogers City	80-460	50-200	100-600	Limestone. Oil, gas, and brine in confined areas.
			Dundee				
			RIVER BASIN GROUP 3.2 Michigan				
Cenozoic	Quaternary			0-650	100-1200	25-350	Sand, gravel in drift.
Mesozoic	Jurassic		"Red Beds"	0-150			Sandstone, shale, and gypsum.
Paleozoic	Pennsylvanian		Grand River	75-750	50-500	100-600	Sandstone, shale, limestone, and coal. Brines and sulfates.
			Saginaw				
	Mississippian	Grand Rapids	Bayport	15-125			Carbonates, shale, and gypsum. Oil and gas.
			Michigan	50-500			
			Marshall	50-350	50-500(?)	50-650	Sandstone and siltstone. Oil, gas, and brines.

1 Range is that of typical high-capacity wells.

2 Range is that of all wells.

TABLE 3–8 Chemical Quality Characteristics of the Major Aquifer Systems in the Lake Huron Basin

Aquifer system	Hardness (mg/l)	Sulfate (mg/l)	Chloride (mg/l)	Iron (mg/l)	Total dissolved solids (mg/l)	Temperature (°F)	Remarks
			RIVER BASIN GROUP 3.1				
			Michigan (Upper Peninsula)				
Quaternary	75-170	10-20	0-15	0-0.1	100-175	44-52	
Silurian (Burnt Bluff-Engadine)	250-300	20-550	0-15	0-1	250-650	44-55	Saline water in southern part of Mackinac County and where confined by bedrock.
Cambrian-Ordovician (Jacobsville-Trenton)	150-350	30-60	100-300	1	250-700	---	Saline locally.
			Michigan (Lower Peninsula)				
Quaternary	100-300	0-80	0-50	0-1.5	80-400	45-50	Saline locally in east and southeast area.
Mississippian (Marshall)	130-470	3-450	3-300	0.5-2	---	46-55	Saline in southeast area.
Devonian (Dundee and Traverse)	150-300	5-80	0-40	0-1	250-370	47	Saline where confined.
			RIVER BASIN GROUP 3.2				
			Michigan				
Quaternary	100-550	0-600	0-450	0-11	160-700	46-54	Saline locally.
Pennsylvanian (Saginaw and Grand River)	130-725	15-500	0-630	0-5	200-800	50-55	Saline in central part of area.
Mississippian (Marshall)	200-380	10-300	0-450	0-4	250-600	49-55	Saline in part of area.

TABLE 3–9 Estimated Ground-Water Yield from 70 Percent Flow-Duration Data in the Lake Huron Basin

Subbasin	Runoff at 70-percent duration (cfsm)	Subbasin yield (mgd)	State totals (mgd)	River Basin Group totals (mgd)
		RIVER BASIN GROUP 3.1		
		Michigan (Upper Peninsula)		
Les Cheneaux-St. Marys Complexes	0.05	45	45	1,945
		Michigan (Lower Peninsula)		
Cheboygan River	0.50	510	1,900	
Presque Isle Complex	0.05	20		
Thunder Bay River	0.40	325		
Alcona Complex	0.10	10		
AuSable River	0.60	785		
Rifle-AuGras Complex	0.35	250		
		RIVER BASIN GROUP 3.2		
		Michigan		
Kawkawlin Complex	0.05	15	1,270	1,270
Saginaw River	0.30	1,210		
Thumb Complex	0.05	45		
			Lake Basin total	3,215 mgd

Note: Estimates based on flow-duration data for period of record, adjusted to the 1931-60 period, at all gaging stations within the subbasin; extrapolations within drainage area and to ungaged areas based on surficial geology.

Section 5

LAKE ERIE BASIN

5.1 General

Although the Lake Erie basin has the least overall ground-water potential of any Great Lakes basin, glacial drift provides excellent aquifers in selected areas of Michigan, New York, and Ohio. Carbonate aquifers are significant in western Ohio and northern New York areas. Areas of limited ground-water potential occur in the lake plains along the southern shore of Lake Erie east of Sandusky and in the upland areas of Pennsylvania and New York. In these places, conjunctive use of surface water and ground water is necessary to provide adequate water to most areas.

Chemical quality of the ground water has been a limiting factor in its development. However, most poor quality water can be improved by treatment, so the problem becomes economic. Water from surficial sand and gravel aquifers is generally good to fair in quality. Iron is usually present. The water can be hard and contain appreciable dissolved solids. Bedrock aquifers consistently yield hard to very hard water with dissolved solids quantities often above the recommended limit of 1,000 mg/l. Saline water is present locally, and increasingly with depth. Iron and sulfate contents may be relatively high in local areas and increase treatment costs. A better understanding of the fresh water portion of the aquifers will aid in developing ground-water supplies and do away with common misconceptions concerning ground-water quality.

Pollution of aquifers, particularly the carbonate near-surface aquifers, has been a local problem in Ohio and New York. Stricter controls for waste disposal and more advanced treatment facilities are being established to stop further pollution. Saltwater leakage from oil-test holes has been a problem in Pennsylvania and in isolated cases in Ohio.

Solutions to ground-water needs in specific problem areas will require detailed studies. Critical factors will include finding optimal economics for adopting surface-water versus ground-water sources when both require treatment. Both sources also require treatment before disposal into streams. One benefit of ground-water use is augmentation of streamflow, currently being considered in Ohio.

5.2 Physiography and Drainage

For this appendix, the Lake Erie basin includes Lake St. Clair and its drainage area. Collectively, the drainage area within the United States is 21,460 square miles, the second largest drainage area of the five Lakes. Except for the 6,586-square-mile Maumee River basin, the tributary system consists of relatively small drainage areas draining into the Lake system (Figure 3–40).

Most of the basin lies within the eastern lake section of the Central Lowland physiographic province. The headwaters areas of streams beginning in eastern Ohio lie in the Appalachian Plateaus province, as does an area extending east through Pennsylvania into New York (Figure 3–1). Glaciation of the entire basin has created rolling morainal hills of moderate relief in the Michigan area. There are extensive lake plains bordering the Lake system, much of the Maumee basin, and maturely dissected till-covered uplands of the Appalachian Plateaus province. The basin divide has altitudes higher than 1,000 feet. The greatest altitudes reach 2,300 feet in the Cattaraugus watershed of New York.

Prominent physiographic features include the great Maumee lake plain, which was the vast Great Black Swamp before man drained it, the inland Portage Escarpment along the southeastern shore of Lake Erie, and the deeply incised headwater valleys of Pennsylvania and New York. Several prominent linear sand beaches parallel the Lake Erie shore, remnants of beaches of the glacial lakes. Other linear hills are moraines deposited at the glacial ice margins.

Bedrock exposures are increasingly prominent toward the eastern part of the basin. Along the escarpment and in the incised valleys, gently dipping shales and sandstones have been exposed by erosion or were not covered by drift. Many of the incised valleys are partially filled with thick deposits of glacial drift, especially in the New York area. Buried valleys are known in other parts of the basin, and there are undoubtedly many that have not been discovered. These buried valleys sometimes contain major sand and gravel aquifers.

Bedrock underlying the Lake Erie basin consists of sedimentary rocks of Paleozoic age. Formations west of the Sandusky-Maumee drainage divide dip gently northwestward toward the Michigan structural basin. East of the divide the formations dip southeastward in Ohio and southward in Pennsylvania and New York. The near-surface rocks consist principally of carbonates in Indiana, western Ohio, and the northern part of the New York area. Shales and sandstone are dominant in the other areas (Figure 3–3).

The drift overlying the bedrock is dominantly fine-grained throughout most of the basin, except in Michigan and local areas in New York and Ohio (Figure 3–2). The outwash and morainal deposits in these areas consist of coarse-grained material which contains significant ground-water resources. The lake plain areas are underlain by lacustrine deposits of clay, silt, and fine sand of low permeability. Similarly, low-permeability clayey till mantles most of the bedrock upland of the Appalachian Plateaus province and provides no aquifers of large water-yielding potential.

5.3 Ground-Water Conditions

Ground water occurs in several types of aquifers in the Lake Erie basin. Major aquifers are those in unconsolidated sediments and in near-surface bedrock formations. In contrast to the three upper Great Lakes basins, the Lake Erie basin has much less significant unconsolidated sediment aquifers. It does not have the multiplicity of bedrock aquifers in a particular area. A general description of the aquifer system follows. Ground-water conditions in each of the four river basin groups are presented separately in figures and tables.

5.3.1 Unconsolidated Aquifers

Glacial outwash, alluvium along streams, and buried-valley deposits offer the best potential for high yielding aquifers. Wells yielding more than 500 gpm are usually possible in these types of deposits, and where recharge from adjacent streams is available, such as in parts of Michigan and Indiana (Figures 3–41 and 3–43). Lesser yields are available in most upper reaches of stream valleys in the remainder of the basin. Elsewhere, the thin cover of clayey till or lake deposits contains poor aquifers. However, yields adequate for domestic use are available in all but a few areas. Buried valleys have been discovered in some local areas and offer high potential for large yields. Many of these valleys have been discovered in the Ohio area east of the Black River and in New York.

It has been found, however, that many of these buried valleys, like normal valley fills, contain interbedded tills and lacustrine deposits which do not make good aquifers. This occurs mainly in north-trending valleys which had no through-flowing glacial streams during deposition. Ground-water divides here do not always coincide with the surface divides as ground water moves into or out of the basin.

In addition to the presence of very permeable material and a source of recharge, an adequate thickness of sediments is needed to have good aquifers. Drift thicknesses up to 1,100 feet[37] in buried valleys are known within the basin, but most of the drift is much thinner, particularly in and east of Ohio. Wells are generally less than 300 feet deep. Yields more than 50 gpm are possible in much of the area. Aquifer and well data for each of the river basin groups are included in Table 3–10.

The chemical quality of water from the unconsolidated-sediment aquifers is generally fair to good. The water is commonly hard to moderately hard, and some of it is high in iron. Normal ranges of some constituents are presented in Table 3–11. Sulfate or chloride problems exist locally where upward ground-water movement occurs from saline bedrock. Methane gas has been found in glacial drift at Oakland County, Michigan, and elsewhere.[36] In many areas, wells are drilled through the shallow aquifers to obtain better quality water from the bedrock.

Recharge to unconsolidated sediment aquifers occurs from infiltration of rain and snow both directly and indirectly into the deposits. Indirect recharge occurs by runoff from adjacent less permeable surface deposits or by slow seepage through overlying deposits. Most recharge occurs during the late fall and spring dormant seasons when evapotranspiration rates are low. An example of the amount of total recharge that can occur to unconsolidated sediment is shown by a study in New York. LaSala[30] estimated recharge rates to the sand and gravel deposits in the Tonawanda-Cattaraugus basin from 0.5 to 4 mgd per square mile. Higher values occur where extensive surface runoff from the watershed is added directly to the aquifer. Ground water moves toward the stream drainage system and emerges as base flow of the stream. In local areas adjacent to streams, extensive withdrawal of ground water through pumping wells can include recharge from stream water.

5.3.2 Bedrock Aquifers

Several bedrock formations in the Lake Erie basin are significant aquifers (Table 3–10). In descending sequence, the first aquifer occurs in the Sharon and Saginaw Formations of Pennsylvanian age. The Saginaw Formation is present in a small area at the southwest corner of Livingston County, Michigan. Because there are no well data, little is known of its potential. The Sharon Formation is present only on the hilltops of the Cuyahoga and Grand River basins in eastern Ohio (Figure 3–48). The formation is a sandstone or conglomerate and is the most significant bedrock aquifer present. The Sharon generally yields up to 50 gpm. Where it is thickest, it will yield as much as 100 gpm to wells. The chemical quality of the water is fair, although high iron content and high hardness are common (Table 3–11).

The next major aquifer in the Lake Erie basin is the Marshall Formation of Mississippian age. It is present only in a small part of Michigan (Figures 3–42 and 3–44). The Marshall Formation is a light-colored, fine- to medium-grained sandstone that locally contains considerable shale. It is mantled everywhere by glacial deposits.

The Marshall Formation is a good water source except where shale is present. Well yields (Table 3–10) are generally as great as 500 gpm, but reach as much as 1,000 gpm in the Pontiac area of Oakland County. The City of Jackson, just outside the basin, has wells that have yielded 2,000 gpm of good quality water. These exceptionally high yields suggest there may also be a good potential for the aquifer in the area west of Ann Arbor. Although water quality in the Marshall Formation is generally good, wells penetrating the sandstone are reported to yield salty water in some localities, especially where the Marshall is relatively thin and wells penetrate close to the contact between the Marshall and the underlying formation. Generally, bedrock underlying the Marshall contains salty water. If physical conditions are right, the salty water may move up into the Marshall. Kunkle[29] reports that water from wells deeper than 80 feet may be brackish in Washtenaw County. Table 3–11 gives a summary of principal chemical constituents reported from a very limited number of wells penetrating the Marshall.

Two other important Mississippian aquifers are the Berea and Cussewago sandstones in the eastern part of the basin. Rau[48] made a comprehensive study of the ground-water availability of these two aquifers. He has presented the data in a thorough, well-illustrated format for the potential ground-water developer's use. The lower aquifer, Cussewago sandstone, is present in the basin only in a small part of Portage and Trumbull Counties, Ohio, and in Pennsylvania. The sandstones in some areas are directly connected. Their locations and relationships are shown in Figures 3–44 and 3–49.

Berea sandstone ranges from coarse-grained in the western part of the basin to fine-grained with shale beds in the east. The formation thickens and is greatest in the northwestern part but averages 50 feet. Well yields are generally less than 50 gpm, but as much as 100 gpm are reported. The higher yields are in the northern part of the aquifer in Portage and Trumbull Counties. In the Vermilion basin the Cuyahoga Formation contains a little water and is generally developed with the Berea to add a few gallons a minute (Table 3–10).

Chemical quality of water from Berea sandstone is relatively poor (Table 3–11). The water is hard to very hard and needs softening for most uses. Sulfate, chloride, and iron contents are high in some areas. Chloride increases with depth in the aquifer and to the south where brines are present. The zone of saline water is shown on Figures 3–44 and 3–49.

The Cussewago sandstone is medium-grained and poorly consolidated. Well yields are generally less than 50 gpm. Yields as much as 200 gpm have been reported where the formation is thickest, or where recharge is more readily available, such as under the Grand River. No chemical analyses of the aquifer water are available, but it is believed the water is similar to that of the Berea.

Recharge to the aquifers occurs directly and indirectly from precipitation. In addition, streams flowing across outcrop areas provide recharge where the aquifer head is lower than stream level.

The next lower rock system contains Devonian carbonate aquifers. In some places these are in direct connection with the underlying Silurian carbonate aquifers. For purposes of this section, the Devonian and Silurian carbonate aquifers are considered as one. Where significant data, such as different saline zones within the units in Ohio, are available, individual aquifers are presented on separate maps.

The freshwater part of the Silurian and Devonian aquifer systems extends from Wayne County, Michigan, throughout most of the Maumee and Sandusky River basins and in the Tonawanda Creek basin of New York (Figures 3–44, 3–45, 3–46, and 3–51). The system in River Basin Group 4.1 is not shown because the rocks do not contain a major aquifer. Carbonate formations dominate the rock system with minor sandstone and shale beds present. Thickness ranges to more than 800 feet. The aquifer system varies greatly in both areal and vertical permeability. Carbonate solution seems to have taken place principally where the rocks were exposed prior to glaciation. Postglacial solution has probably occurred also, especially where the aquifer is directly present under a relatively thin cover of glacial drift.

Well yields in the carbonates are very good, up to 500 gpm in the western portion of the basin (except Michigan where wells have yields less than 20 gpm) and up to 200 gpm in the New York area. Because of the heterogeneity of the solution and fracture openings, test wells should obtain data where high yields are desired. Well yields and depths are presented in Table 3–10.

Special note should be made of the high yield area in New York. Here the Camillus shale unit contains gypsum which is highly soluble. Solution has removed gypsum beds, particularly near streams, and created a highly porous rock. Well yields in these areas[30] range up to 1,000 gpm, making the Camillus shale the most productive unit in River Basin Group 4.4.

Water quality of the carbonate aquifers is fair to poor. Chemical characteristics are shown in Table 3–11 for the entire aquifer system or for separate units where wells draw from specific formations. The water is extremely hard and contains a high amount of dissolved solids. Sulfate content increases with depth in some areas of Ohio and is a problem locally in New York where it is associated with the Camillus shale. Iron content is commonly high throughout the area. Along with hardness it necessitates treatment of the water for public and some industrial uses. Many areas use water containing more than the 1,000 mg/l dissolved solids recommended limit without treatment. Most of the aquifer waters in the Michigan portion are too saline for use. Saline water is present beneath the Silurian aquifer throughout the Lake Erie basin.

Recharge to the aquifer systems occurs by vertical leakage through the glacial drift or confining bedrock layer and directly through outcrops of cavernous carbonates. Indirect recharge through highly permeable materials in buried valleys also is significant. The amount of recharge varies with the depth to the carbonate-aquifer water level, among other things. Rowland and Kunkle[49] computed recharge rates to the carbonate aquifer in the Maumee River basin versus ground-water use. Recharge rates vary from 0.006 to 0.075 mgd per square mile, depending upon the pumpage rate. There is higher recharge with higher pumpage, which lowers the water level. For comparison, the 70 percent flow-duration data used in this appendix to compute estimated ground-water yield for the same area (Table 3–12) ranged from 0.030 to 0.078 mgd per square mile. Most recharge water is derived from precipitation, but stream water can also recharge the aquifers in some areas where conditions are right.

5.4 Ground-Water Potential

As discussed in Section 1, ground-water potential for an area was estimated on the basis of stream-discharge data. Flow-duration values for the 70 percent point, a conservative estimate of ground-water runoff per square mile, were used to compile Figure 3–52 and to tabulate yield values in Table 3–12. The estimates do not consider the ground water in storage nor actual reuse or recycling of ground water.

In comparison to the other basins in the Great Lakes, the Lake Erie basin has the lowest estimated ground-water potential. On the basis of ground-water runoff at the 70 percent flow-duration point, only 1,930 mgd of ground water is derived from this basin, the second largest in total land area. The low yield is directly related to the character of the rocks. Glacial drift is fine-grained and relatively thin in most of the area (Figure 3–2). Near-surface bedrock is predominantly shale (Figure 3–3).

Areas shown in Figure 3–52 as having good ground-water yield are those in areas of thick, coarse-grained glacial drift. Outwash, moraines, and sediment-filled valleys are dominant in these areas and provide good recharge and storage characteristics. For example, in the Cattaraugus basin in New York, which includes relatively small areas of unconsolidated material in the narrow valley-fill areas (Figure 3–50), the ground-water potential based on flow-duration data is an estimated 150 mgd (Table 3–12). La Sala's[30] calculations for total recharge to sand and gravel deposits in this area and some minor valleys in the Tonawanda basin of western New York were 155 mgd.

The poor ground-water yield areas indicated in Figure 3–52 are generally related to the thin drift cover. Here again, data on ground-water yield should be used with caution. Stream-discharge data for some basins indicate a very low ground-water yield, but there is evidence of thick buried-channel deposits containing water which moves out of the basin by underflow. Long-term yield potential could be critical here, with respect to potential recharge to the buried aquifer after extensive development. A similar situation exists in the central Maumee basin area. This has poor-yield indications, but the carbonate aquifer wells will yield several hundred gpm. Furthermore, Rowland and Kunkle[49] show that ground-water development can increase aquifer potential by increasing recharge. These examples point out the need for studies on long-term yield potentials under development conditions. In summary, the estimated ground-water yield map (Figure 3–52) can be used to compare relative potentials of ground water in various areas, and give a measure of the existing ground-water discharge from a basin under existing conditions of recharge, evapotranspiration, and pumpage.

5.5 Problems, Needs, and Management Considerations

5.5.1 General

Although Lake Erie basin has the least productive aquifers of the Great Lakes Basin, there is still a plentiful supply of ground water in some areas. Small ground-water supplies, barely adequate for domestic supplies, occur along much of the eastern lakeshore and in upland areas. Areas lacking in ground water are generally near surface-water sources, especially Lake Erie, so the problem is primarily economic.

Probably the greatest ground-water problem throughout the Lake Erie basin is water quality. Much of the ground water is hard and high in dissolved solids. Locally it contains excess iron, flouride, or sulfate. Saline water is present relatively close to the surface in most of the basin. Although pollution has been a problem, strong action by most of the States now controls poor waste disposal practices. Major problems and needs requiring management attention are discussed by river basin group.

5.5.2 River Basin Group 4.1

River Basin Group 4.1 is one of the most heavily populated and industrialized areas in the Great Lakes Basin. The area has been subject to intense urbanization and consequent change in water use from rural-domestic to suburban needs. It has now reached the urban stage with a municipal water system. Municipalities drew water locally at first, but later water had to be imported from greater distances. Wells were again drilled in rural areas or water was obtained from distant surface sources.

The Detroit metropolitan area, one of the largest urban areas in the United States, is a major example of the progressive land- and water-use changes. The amount of water necessary to support present and predicted growth of the Detroit complex is considerable. Ground water, present in large supplies only in limited areas of sand and gravel, is not adequate to meet this demand. Only surface-water sources from the Great Lakes system can serve this metropolitan complex. However, ground water will still continue to play an important role in the growth of the area in industrial developments and in initial stages of new urbanization, until it is more economical to convert to a surface-water system.

Total reliance on ground water in this heavily populated area would result in over-development. For example, in Pontiac prior to 1963, ground-water pumpage was concentrated in a small segment of a buried glacial-channel aquifer at considerable distance from the area of recharge. This caused a 100-foot drawdown of water level throughout central Pontiac.[13] In 1963, Pontiac joined the Detroit water system and discontinued its well supply.

Water levels have since recovered more than 40 feet in some wells.

Very low yields can be expected from unconsolidated aquifers in the lake plains part of the area. The lake deposits, from surface to bedrock, are generally fine-grained and do not readily transmit water. The moraines contain aquifers made up of poorly sorted deposits that produce only low yields. With the exception of the Marshall Formation, which is limited in area, bedrock gives low yields or water too highly mineralized to be of general use.

The chemical quality of the ground water is likely to be poor in much of the area because of the presence of saline bedrock water. High chloride and sulfate content is common. High iron content is particularly common in water from the surficial aquifers. Pumping some sand and gravel aquifers can sometimes increase the sodium and chloride content of water from wells. Ferris and others[13] found that when drawdown in a buried outwash aquifer at Pontiac was appreciable, the resultant gradient developed between an aquifer and the underlying bedrock induced upward migration of chloride water from the bedrock.

Three known waste disposal wells have been constructed in bedrock (Silurian-Devonian aquifer system) in this area (Figure 3–42). One well is located on the south side of Detroit and injects wastes at a depth of 563 feet. To determine areas where subsurface waste disposal is feasible, a study should be made of the saline portion of the hydrologic system and its possible problems, such as abandoned wells and test holes.

A comprehensive and detailed study of hydrologic changes created by urbanization in the metropolitan area should also be made. Such a study would contribute appreciably to hydrology in both research and practical application to water-resources management.

Although many municipalities in the area anticipate problems in obtaining additional good quality water supplies, little or no regional ground-water information is available for planning purposes. Geologic conditions in headwater areas of major streams appear to be favorable for considerable additional ground-water development. Studies covering well yield, geology, water quality, and baseflow investigations, as well as surface-water data, have been published in U.S. Geological Survey Hydrologic Atlases. A comprehensive appraisal of the geology and ground-water resources of all of southeastern Michigan is under way. This will provide a broad picture of ground-water resources and their possibilities as major water supplies. Another detailed study of all water resources in Washtenaw County is being made. It will update groundwater information from the Kunkle study.[29] Many bedrock aquifers in the area contain water unfit for most uses because of poor chemical quality. It may be feasible to displace the poor quality water with fresh water in some aquifers. Such a project would entail removal of inferior water by pumping and recharging with fresh water by induced recharge facilities or injection through wells. Study of this would provide information on the practicability of storing fresh waters in saline water reservoirs, and on hydraulic principles involved.

5.5.3 River Basin Group 4.2

Ground-water supplies in River Basin Group 4.2 are of relatively adequate quantity with the exception of a few areas. Water quality is the most critical problem. In much of the area, water from the carbonate-rock aquifers is very hard, commonly more than 200 mg/l, and highly mineralized. A number of communities whose only supply is ground water are using water with a dissolved solids content considerably higher than the 1,000 mg/l limit suggested by the U.S. Public Health Service[67] for drinking water. Water from glacial aquifers is typically much less mineralized but is usually quite hard. Iron is often excessive in ground water from most of the aquifers, particularly those associated with shale, sand, and gravel. Water from carbonate rock systems in localized areas is apt to have objectionable amounts of hydrogen sulfide.

In much of the area thin drift overlying porous limestone results in conditions conducive to ground-water contamination. A serious situation exists in the Bellevue area of Huron County, Ohio, and part of Erie County south of Sandusky. There are no natural surface streams draining the area. For years sewage and waste were dumped into sinkholes or wells drilled for that purpose in the cavernous terrain. As a result, municipal and domestic water-supply wells have had to be abandoned because of contamination of the limestone aquifer. The high cost of installing municipal sewage facilities has been one of the main obstacles in remedying the situation. However, a sewage system and secondary treatment facilities are now being constructed. Accidental pollution can occur anywhere. Bacterial pollution of the Silurian aquifer at Millbury

(Wood County), Ohio, was found to be caused by defective pipes in two wells.[35]

Recent restrictions on disposal of wastes into streams is leading to the use of deep wells for waste disposal. Such a well has been drilled into the Mount Simon sandstone (of Cambrian age) at Lima, Ohio (Figure 3–4). The planning of well-disposal systems must consider potential contamination of fresh and brackish water aquifers. Brackish water aquifers are a potential water supply source now that demineralizing of water is becoming economical. Sedam and Stein[52] have prepared a map of Ohio's saline water resources with this in mind. Saline zones also are being considered more feasible as potential reservoirs for temporary storage of fresh water.[5]

Low well yields occur in both bedrock and unconsolidated sediment aquifers. In the northwest corner of Ohio and in an area approximately 10 miles wide extending southward through Erie, Huron, and Crawford Counties, the bedrock is relatively impermeable Devonian shale and yields only meager amounts of water to wells. The buried Teays preglacial drainage system has tributary valleys in the southwestern part of the Maumee basin. Sediments filling it are fine-grained and yields to wells typically are low. However, the thick-saturated deposits are of significance to the water-yielding capabilities of adjacent bedrock aquifers.[39]

Representative long-term hydrographs do not show a pronounced dewatering of the aquifers in the region (Figures 3–43, 3–44, 3–45, and 3–46). Wells tapping carbonate aquifers at Lima, Ohio, were originally flowing, but municipal and industrial development has lowered water levels to approximately 150 feet below the surface. This dewatering at Lima seems to have leveled out somewhat in recent years despite additional exploitation of the aquifers. In some localities in northwestern Ohio, artesian wells in glacial sand and gravel no longer flow. Chief causes of this are increased water use and decreased recharge owing to land drainage.

A study of the northwestern Ohio carbonate aquifers by the Ohio Division of Water has recently been finished, and it gives an overall appraisal of this system.[42] This study will provide greater knowledge of water-supply capabilities, water quality, optimum locations for development, and will assist in planning regional growth. Part of the area has been studied for needs and development plans.[43] Regional appraisals of potential available ground water such as those done by Rowland and Kunkle[49] are needed. Water quality is such a problem in some areas that research or emphasis on new economical treatment methods should be encouraged. Low-cost demineralization of moderately saline water and removal of hydrogen sulphide would solve many quality problems in this region.

5.5.4 River Basin Group 4.3

Low-yielding aquifers characterize much of River Basin Group 4.3. Except for the sandstone aquifer area and a few areas of thick sediments, the aquifers are capable of yielding only a few gallons per minute to wells. The preponderance of shale formations limits occurrence of bedrock aquifers, and glacial-drift cover consists principally of clay-rich till. The upper Cuyahoga watershed has the best ground-water potential.

Mineral content of water at relatively shallow depths in the bedrock causes problems. The salinity of bedrock aquifers generally increases toward the south. Oil and gas seeps are common in Pennsylvania, indicating that freshwater bedrock aquifers may not be present, especially near Lake Erie. Along Lake Erie, potable ground-water sources in many areas have been contaminated by salt water and oil leaking from improperly abandoned oil and gas test holes. Iron and manganese are present in most aquifer waters, causing particular trouble with well-screen incrustation in the Akron area.

Water-level hydrographs (Figures 3–47, 3–48, and 3–49) do not show any long-term water level decline. Some show responses to pumpage increases (Po–2, Figure 3–47) or to reduction of pumpage (L–1, Figure 3–47, and Ln–1, Figure 3–49).

A better potential for obtaining good-quality water and large well yields lies in the unconsolidated aquifers. Detailed studies of these deposits are needed, including those in buried valleys. The recharge potential of these aquifers should also be considered.

A new study in Ohio may aid this water-short area. The Ohio Division of Water is supervising a program for exploring the potential of buried-valley aquifers in northeastern Ohio. A water-resources study of the headwaters of Conneaut Creek in western Crawford County, Pennsylvania, is being done by the U.S. Geological Survey in cooperation with the Pennsylvania Topographic and Geologic Survey. In Pennsylvania, a detailed map of saltwater zones, along with locations of abandoned oil and gas wells, should be prepared. This will permit a program of proper plugging of such abandoned wells.

5.5.5 River Basin Group 4.4

Poor chemical quality of ground water is probably the greatest problem with major ground-water supplies in River Basin Group 4.4. Water containing more than 1,000 mg/l of dissolved solids is present at relatively shallow depth throughout most of the area. The Buffalo and northeastern area is most critical as both bedrock and surficial deposit waters are too mineralized for public use. Shallow saline water is present locally in Pennsylvania. In general, however, individual domestic wells can obtain potable water from shallow aquifers throughout this area.

Much of the area underlain by thin glacial deposits (generally upland areas), and Devonian shale bedrock contains aquifers capable of yielding water only for domestic wells. Thick unconsolidated material usually underlies the glaciated valley floors in New York. This unconsolidated material may contain aquifers capable of yielding large quantities of water. The dolomite aquifer at the northern edge of the basin also produces small quantities of ground water.

The sand and gravel aquifer at Gowanda (Cattaraugus County), New York, has been significantly dewatered. The public-supply well has decreased in yield from 500 to 200 gpm since 1928. The water level has declined from 7 feet above ground level to 150 feet below ground in 1963.[30] Additional ground-water supplies are available in nearby aquifers.

Deep-well waste disposal of steel pickle liquor is being tested at a site in Buffalo (Figure 3–51). Brines in Cambrian sandstones at 4,000 feet are considered the most feasible disposal horizon.[28]

Most of River Basin Group 4.4 was covered by the detailed ground-water study by LaSala.[30] A water-resources study by the U.S. Geological Survey covering the New York portion southwest of the Cattaraugus basin is being published by the New York State Water Resources Commission.

TABLE 3–10 General Stratigraphy and Major Aquifer Systems in the Lake Erie Basin

Era	System	Group	Formation	Thick-ness (ft.)	Major aquifers: Well yields[1] (gpm)	Major aquifers: Well depths[2] (ft.)	Remarks
			RIVER BASIN GROUP 4.1 Michigan				
Cenozoic	Quaternary			0-600	100-1500	20-300	Sand, gravel in drift.
Paleozoic	Pennsylvanian		Saginaw				Sandstone and shale.
	Mississippian		Marshall	50-150	50-500	40-330	Sandstone and shale. Oil, gas, and brine.
			RIVER BASIN GROUP 4.2 Indiana				
Cenozoic	Quaternary			50-500	100-600	75-225	Sand, gravel in drift.
Paleozoic	Mississippian		Bedford(?)	400			Shale with limestone and sandstone.
	Devonian		Antrim	60-200			Shale.
			New Albany	100			Shale.
			Sellersburg				Limestone.
			Jeffersonville	500	50-500	150[3]	Limestone.
			Pendleton				Sandstone.
	Silurian	Niagaran Series	New Corydon				Limestone.
			Huntington				Dolomite.
			Michigan				
Cenozoic	Quaternary			0-200	50-500	50-115	Sand, gravel in drift.
Paleozoic	Mississippian		Marshall		50-100	150-240	Sandstone.
			Coldwater				Shale.
			Sunbury	?			Shale.
			Berea				Sandstone.
	------?------	------------	Bedford				Shale.
	Devonian		Antrim				Shale
		Traverse					Limestone. In Monroe Co.
			Rogers City	0-200	500-700	60-90	Limestone.
			Dundee				Limestone.
		Detroit River					Carbonates.
			Sylvania(?)				
	Silurian		Bass Islands				Dolomite. Saline in part.
			Ohio				
Cenozoic	Quaternary			10-400	50-1500	30-160	Sand, gravel in drift.
Paleozoic	Mississippian	Cuyahoga		0-20	50-60	30-150	Shale and sandstone.
			Berea				Sandstone.
	------?------	------------	Bedford	0-500(?)			
	Devonian		Ohio (Antrim)				Shales.
		Traverse	Olentangy				
			Delaware				Limestone.
		Detroit River	Columbus	0-200	60-500	40-310	Carbonates.
	Silurian	Bass Islands	Raisin River	0-400	50-600	50-400	Carbonates.
			Tymochtee				Dolomite, salt, and gypsum.
			Greenfield				Dolomite.
			Lockport	150-230			Carbonates.

[1] Range is that of typical high-capacity wells.

[2] Range is that of all wells.

[3] Estimated.

TABLE 3-10(continued) General Stratigraphy and Major Aquifer Systems in the Lake Erie Basin

Era	System	Group	Formation	Thick-ness (ft.)	Major aquifers: Well yields[1] (gpm)	Major aquifers: Well depths[2] (ft.)	Remarks
RIVER BASIN GROUP 4.3							
Ohio							
Cenozoic	Quaternary			0-400	50-1500	50-350	Sand, gravel in drift. High yields in isolated sites.
Paleozoic	Pennsylvanian	Pottsville	Sharon	0-100	50-100	35-130	Sandstone and conglomerate.
	Mississippian	Cuyahoga	Cuyahoga	0-180			Shale and sandstone.
			Berea	0-235	50-100	30-275	Sandstone.
			Bedford	0-50			Shale; semi-confining bed.
			Cussewago	0-30			Sandstone.
Pennsylvania							
Cenozoic	Quaternary			0-150	50-200	15-150	Sand, gravel in drift.
RIVER BASIN GROUP 4.4							
New York							
Cenozoic	Quaternary			0-600	50-1400	10-200	Sand, gravel in drift.
Paleozoic	Devonian	Conneaut Canadaway Java-Genesee Hamilton		0-2600			Shale and siltstone. Low or no well yields common.
			Onondaga	0-175	50-200	60-150	Carbonates.
	Silurian	Bertie	Akron				
		Salina	Camillus	0-400	500-1000	30-125	Shale. High yields in solution channels in gypsum beds.
		Niagaran Series	Lockport	150	50-75	20-70	Dolomite.
Pennsylvania							
Cenozoic	Quaternary			0-150	50-200	15-75	Sand, gravel in drift.
Paleozoic	Devonian	Conneaut	Chemung	0-200		15-125	Shale and sandstone. Low yields.

[1] Range is that of typical high-capacity wells.

[2] Range is that of all wells.

TABLE 3–11 Chemical Quality Characteristics of the Major Aquifer Systems in the Lake Erie Basin

Aquifer system	Hardness (mg/l)	Sulfate (mg/l)	Chloride (mg/l)	Iron (mg/l)	Total dissolved solids (mg/l)	Temperature (°F)	Remarks
			RIVER BASIN GROUP 4.1				
			Michigan				
Quaternary	50-480	0-320	10-700	0-7	150-600	48-56	
Mississippian (Marshall)	160-460	10-150	10-400	0-2	260-700	---	Locally saline.
			RIVER BASIN GROUP 4.2				
			Indiana				
Quaternary (Sand and gravel)	250-1000	3-300[1]	3-20	0.5-4	325-1000[1]	---	Adams County has sulfates and dissolved solids over 1000 locally.
Silurian-Devonian (Huntington-Sellersburg)	500-1000	350-1000	5-50	0.5-3	600-1500	---	
			Michigan				
Quaternary (Sand and gravel)	170-325	10-55	5-25	0-1.5	200-415	---	
Mississippian (Marshall)	315	28	16	0.2	348		Hillsdale County only, 1 analysis.
Silurian-Devonian (Bass Islands-Traverse)	112-115	14	2	0.1-0.2	140-148	---	Hillsdale County only.
			Ohio				
Quaternary (Sand and gravel)	165-820	1-480	3-315	0.15-2.2	170-1050	51-55	
Mississippian (Berea-Cuyahoga)	70-400	30-75	5-60	0.20-0.90	400-520	55-56	
Devonian (Detroit River)	300-1250	100-930	5-110	0.02-4	300-1700	55-58	
Silurian (Bass Islands)	375-1600	240-1500	5-50	0.05-2.6	280-2700	54-56	
(Lockport)	330-920	130-800	5-45	0.05-2.6	470-1670	50-56	
			RIVER BASIN GROUP 4.3				
			Ohio				
Quaternary (Sand and gravel)	100-500	5-200	3-150	0.10-5.7	270-750	51-55	
Pennsylvanian (Sharon)	100-550	25-250	2-40	0.03-4	150-650	52-54	
Mississippian (Cussewago-Berea)	100-600	10-680	3-220	0.10-5	200-2000	52-55	Salinity increases southward.
			Pennsylvania				
Quaternary (Sand and gravel)	100-200	10-40	5-10	0.10-0.15	170-250	49-51	
			RIVER BASIN GROUP 4.4				
			New York				
Quaternary (Sand and gravel)	100-350	5-100	2-75	0.03-0.08	175-300	40-56	
(Buffalo-NE area)	500-1200	300-1000	20-550	0.25-0.50	600-2000		Upward ground-water flow from Camillus Shale aquifer.
Devonian (Shales)	100-500	5-125	5-100	0.10-0.50	150-500	52-55	Saline at depth.
Silurian-Devonian (Carbonates)	250-700	50-400	5-250	0.08-5.6	350-800	54	Saline at depth.
Silurian (Camillus)	400-1900	150-1500	25-2000	0.07	80-5000	53	Fresh water only where locally recharged.
Silurian (Lockport)	350-600	150-400	10-50	0.5-3	450-700	48-52	Saline and sulfur water beneath Camillus Shale and in deeper zones in Lockport.
			Pennsylvania				
Quaternary (Sand and gravel)	75-300	30-80	0-50	0.6-0.5	250-500	49-56	Saline locally.
Devonian (Chemung) (Canadaway)	50-250	3-80	0-150	0.2-0.5	200-500	48-49	Saline locally. Gas seeps probably from deeper sources.

[1] May be as high as the Silurian-Devonian aquifer.

TABLE 3-12 Estimated Ground-Water Yield from 70 Percent Flow-Duration Data in the Lake Erie Basin

Subbasin	Runoff at 70-percent duration (cfsm)	Subbasin yield (mgd)	State totals (mgd)	River Basin Group totals (mgd)
		RIVER BASIN GROUP 4.1		
		Michigan	600	600
Black River	0.05	20		
St. Clair Complex	0.10	40		
Clinton River	0.25	125		
Rouge Complex	0.15	70		
Huron River	0.30	165		
Swan Creek Complex	0.10	20		
Raisin River	0.20	160		
		RIVER BASIN GROUP 4.2		
		Indiana	120	635
Maumee River	0.14	120 (133u) (75b)		
		Michigan	50	
Maumee River	0.15	50		
		Ohio	465	
Maumee River	0.10	320 (250b)		
Toussaint-Portage Complex	0.04	30		
Sandusky River	0.06	60		
Huron-Vermilion Complex	0.08	55		
		RIVER BASIN GROUP 4.3		
		Ohio	300	315
Black-Rocky Complex	0.07	40		
Chagrin Complex	0.25	60		
Cuyahoga River	0.30	160		
Grand River	0.07	30		
Ashtabula-Conneaut Complex	0.05	10		
		Pennsylvania	15	
Ashtabula-Conneaut Complex	0.15	15		
		RIVER BASIN GROUP 4.4		
		New York	350	380
Tonawanda-Buffalo Complex	0.17	160 [1]		
Cattaraugus River	0.43	150 [1]		
Erie-Chautauqua Complex	0.20	40		
		Pennsylvania	30	
Erie-Chautauqua Complex	0.15	30		
			Lake Basin total	1,930 mgd

[1] Estimated available recharge to the unconsolidated-sediment aquifers is 155 mgd (LaSala, 1968).

Note: Estimates based on flow-duration data for period of record (generally more than 10 years or adjusted to the 1931-60 period) at gaging stations; extrapolations within drainage area and to ungaged areas based on surficial geology.

(Figures in parentheses are maximum yield computations from published area quantitative studies: b, bedrock; u, unconsolidated)

Section 6

LAKE ONTARIO BASIN

6.1 General

Generally moderate to poor ground-water resources are available throughout much of Lake Ontario basin. Most of the basin is underlain by fine-grained sedimentary or igneous rocks. Better yielding aquifers occur locally in carbonate rocks in central New York, sandstone and carbonate rocks along the St. Lawrence Valley, and sand and gravel in the glacial drift in valley bottoms. The greatest estimated ground-water yield in the basin and one of the greatest in the entire Great Lakes Basin occurs in the Adirondack area of River Basin Group 5.3

Water-critical areas occur along the entire Lake Ontario lowland from Niagara Falls to the Black River. Bedrock aquifers are low-yielding, and saline water is present in much of the lowland south of the Lake. Sustained summer droughts create severe water shortages in the dairy counties of the Ontario lowland and particularly in the Black River valley. Locally, the sand and gravel aquifers are very productive.

The high seasonal runoff areas of the Adirondacks and Tug Hill represent a challenge to water managers, especially in connection with summer droughts. Conjunctive use of surface and ground water will be a necessity to serve the water needs of the area adequately. However, the presence of the vast restricted Adirondack Forest Preserve, in which little or no development of any kind is allowed, makes this more difficult.

River basin studies, some in detail, have been completed on nearly the entire basin (Figure 3–53) so that the ground-water conditions and problems are fairly well known except in the Adirondack province. Networks of observation and chemical-quality monitoring wells are needed for both areal and aquifer coverage. Water spreading on elevated glacial terraces and deltas seems to offer recharge potential to sustain low flow and stabilize well yields in many parts of the valley systems. Forest management to increase snowpack and modify extremes of streamflow is also promising.

6.2 Physiography and Drainage

The Lake Ontario basin is the smallest of the five Great Lakes basins, with only 13,340 square miles of land surface in the United States. However, the basin contains some of the larger drainage systems. The Oswego River drains some 5,000 square miles, and the Genesee, Black, and Oswegatchie Rivers have an average of approximately 2,000 square miles each. The Black River basin is the most easterly major area draining directly into Lake Ontario. The St. Lawrence complex, Oswegatchie River, and the Grass-Raquette-St. Regis River systems drain directly into the St. Lawrence River.

Four major physiographic provinces are represented in the basin (Figure 3–1):

(1) The Appalachian Plateaus province includes the hilly uplands covering the southern half of the Genesee and Oswego drainage and the unique Finger Lakes region.

(2) All the lowlands bordering Lake Ontario and extending along the St. Lawrence River through the Thousand Islands are part of the eastern lake section of the Central Lowland province.

(3) The broad lowland extending to the outlet of the Great Lakes Basin is part of the St. Lawrence Valley province.

(4) The Adirondack province includes the mountainous headwaters of the Black, Oswegatchie, and Grass-Raquette-St. Regis River systems.

The Adirondack Mountains are the highest points in the Great Lakes Basin. Therefore, Lake Ontario basin has the greatest extremes in altitude of the five Lake basins—from more than 4,000 feet in the Mountains to 150 feet above sea level at the outlet of the basin. The deeply incised valleys of the Appalachian Plateaus and the severely eroded Adirondack Mountains account for much of the basin's rugged topography.

Lake Ontario basin physiography provides one of the more scenic areas of the Great Lakes Basin. Much of its attractiveness is related to the glacial history of the region. Niagara Falls and its gorge, the beautiful, historic

Finger Lakes region, the forested, lake-dotted Adirondack Mountains, and the Thousand Islands of the St. Lawrence River give the basin features appreciated by both its citizenry and the recreation seekers of the nation. There are many glacial features throughout the basin. In contrast to upper Great Lakes Basin areas, glaciation of the Lake Ontario area involved less extensive deposition of material but developed more rugged landscape. Southward ice movement was inhibited by the highlands of the Adirondack and Appalachian Plateaus provinces.

Notable points of geologic interest, some of which should be considered for preservation in the form of parks, are drumlin fields in Ontario and Wayne Counties; numerous waterfalls in the Finger Lakes region (many are already in parks); kame, kettle, and esker topography in the Adirondack foothills and Tug Hill areas; meltwater channels, caves, solution channels, and disappearing streams in the lowlands of the Black and St. Lawrence Rivers; and many fossiliferous bedrock exposures throughout the basin.

Glacial deposition resulted in a relatively thin veneer of shaly till over most of the Appalachian Plateau region. Deposition in the narrow, deeply incised bedrock valleys was as much as 1,000 feet, but much of the deposit is composed of fine-grained material. Glacial movement was southward against the uplands, so meltwater was generally ponded in front of the ice front. Material settled into the ponds and lakes as the glacier retreated. There was little chance for outwash to form extensive well-sorted deposits. Local delta deposits were created from drainage flowing into the lakes. The last stages of the glacial lakes formed one large lake (Lake Iroquois) which covered land now in the Central Lowland province. A thin veneer of lake clays, silts, and fine sands mantles the area. Former beaches, deltas, and sand bars mark the extent of Lake Iroquois in much of the lowland. The lowland and some of the upland have a gently rolling topography with scattered hills representing moraines, kames, and drumlins left by the glaciers.

The Adirondack area was also mantled with glacial drift, but here the source material was principally igneous rock, and as a consequence the drift is coarser than that elsewhere in the basin. Meltwater streams flowed off the Adirondack highlands into Lake Iroquois and earlier glacial lakes and caused sorting of the glacial material. Well-sorted outwash and deltaic deposits are more common in the Adirondack province than elsewhere in the basin.

After the ice front forming glacial Lake Iroquois melted back from the St. Lawrence lowland area, marine waters invaded the St. Lawrence Valley and joined the lake. Marine clays and silts were deposited in this "Champlain Sea" at least as far west as Ogdensburg, in St. Lawrence County (Figure 3–2).

Bedrock exposures are common in the basin. Generally, the bedrock is not very permeable and does not provide major ground-water supplies. Except for a carbonate sequence cropping out along the north edge of the Appalachian Plateaus province, shales and siltstone dominate the Adirondack province. Another, older carbonate sequence with underlying sandstone is present in the Black River and St. Lawrence lowlands. These sedimentary rocks crop out around basement rock composing the Adirondack Mountains (Figure 3–3). The Adirondacks consist principally of an igneous-metamorphic complex of some of the oldest rocks on the continent. The sedimentary rocks gently dip away from the Adirondacks. In the Appalachian Plateaus province they dip gently southward.

6.3 Ground-Water Conditions

Ground-water resources are moderate to poor in much of the Lake Ontario basin. The dominance of either the fine-grained or igneous bedrock formations, and the fine-grained nature of much of the unconsolidated sediments preclude the occurrence of large-producing aquifer systems. Moderate-yielding carbonate aquifers in selected areas and thick-saturated deposits of medium- to coarse-grained glacial deposits in small valley-fill areas provide ground-water sources to most of the populated areas.

6.3.1 Unconsolidated Aquifers

Highest yielding aquifers in the basin are in the unconsolidated sediments. Sand and gravel beds within glacial deposits provide the best aquifers, but are of limited scope (Figures 3–54, 3–56, and 3–58). Glacial materials deposited by running meltwater or reworked by modern streams to create alluvial deposits generally contain well-sorted sand and gravel beds. Good sustained well yields are rather common in sand and gravel units that have good recharge. The Genesee River basin, in particular, has productive sand and gravel units adjacent to stream-recharge sources (Figure 3–54). In contrast, River Basin Group 5.2 does not have extensive units of good aquifer material, and the aquifers are not high-yielding. Unconsolidated sediments are quite extensive in the Adirondack part of River Basin Group 5.3, but little is known of the extent or thickness of sand and gravel units. Streamflow, precipitation, and cursory geologic data indicate a good ground-water potential in these unconsolidated sediments.[70]

Well yields as high as 2,000 gpm are possible in the best areas. Depths of glacial deposits are highly variable. Greatest thicknesses (1,000 feet) are known in the Oswego basin. Aquifer data are presented in Table 3–13. Figures 3–54, 3–56, and 3–58 show that more than half the Lake Ontario basin probably has a poor potential for other than domestic yields from the unconsolidated sediments.

Chemical quality of ground water in the unconsolidated sediment aquifers ranges from poor to excellent. Quality data in Table 3–14 indicate that the better water generally occurs in River Basin Group 5.3. Headwater areas of all regions generally produce water low in dissolved solids. Iron is the most prevalent problem. Below the headwater areas in the basin, ground water usually comes in contact with carbonate material and becomes increasingly hard and more mineralized. In the Genesee-Oswego areas, sulfate and chloride contents increase markedly in the lowlands where outflow of deep bedrock aquifers contributes highly mineralized water to shallow aquifer systems. Areas where highly mineralized waters are known are depicted on Figures 3–54 and 3–56.

Recharge potential from precipitation and streamflow is excellent. Studies elsewhere in New York under similar conditions indicate up to 4 mgd per square mile of recharge are possible to sand and gravel units. The ground-water potential has been depicted conservatively because of the lack of detailed studies. Most of the area of good potential aquifers is within the Adirondack Forest Preserve.

Many of the aquifers in unconsolidated sediments receive recharge directly from precipitation. Runoff from the till-covered mountains adds appreciably to the recharge. The highest precipitation in the State occurs in River Basin Group 5.3, approximately half of it in the form of snow. This heavy snowfall in most upland areas contributes extensive recharge to the unconsolidated aquifers. In contrast, because the lowland areas receive only half as much precipitation and soil permeability is generally low, recharge in the lowlands is much less.

6.3.2 Bedrock Aquifers

There are several significant bedrock aquifers in the Lake Ontario basin (Figures 3–55, 3–57, and 3–59). In some areas these provide the only ground-water source, while in others they are secondary to the overlying unconsolidated sediment aquifers. The bedrock units are significant aquifers only where they intrude into overlying sediments or are exposed. The upper part of these exposed formations makes up the major bedrock aquifer system, and this is considered the upper water-bearing zone. All rock units are shown as a single aquifer on the map for each river basin group, but different water-yielding and chemical quality characteristics make it useful to describe the various units separately.

The youngest rock formations are Devonian shales in the Genesee and Oswego River uplands. Fractures in the shale create an aquifer system capable of yielding water to wells at rates less than 100 gpm (Table 3–13). The chemical quality of the water is good, with hardness the main concern (Table 3–14). Saline water is present at depths greater than approximately 300 feet.

The next major aquifer system occurs in carbonate rocks in the Lower Devonian and Upper Silurian Series. Figures 3–55 and 3–57 show that the carbonates extrude in a narrow band along the north edge of the Appalachian Plateau border. The carbonates extend south, dipping below the Devonian shales, but decreased permeability and the presence of saline water inhibit their potential as aquifers. Well yields reach 500 gpm in the Oswego River basin, where extensive solution of the carbonates has taken place and stream recharge is available. Fifty-gpm wells are more common in most of the area (Table 3–13). Chemical quality of this carbonate-aquifer water is fair to poor, as shown in Table 3–14. Saline water, high in chlorides or sulfates, is a problem in the eastern part of the basin, where it is present at shallow depth (Figure 3–57). Saline water is present elsewhere, but at greater depths. Salinity of the aquifer is caused by upward circulation of water through underlying salt beds. The water is very hard.

Silurian shales (Salina Group) underlying the above-mentioned carbonate rocks are exposed along the south edge of the Ontario lowlands (Figures 3–55 and 3–57). These are of local significance as major aquifers in the Oswego basin. Wells yielding as much as 1,000 gpm have been reported (Table 3–13) where gypsum beds in the Camillus shale of the Salina Group have dissolved, and where nearby streams can provide recharge. Well yields elsewhere generally are less than 50 gpm. Chemical quality of the water is generally poor. As shown in Table 3–14, dissolved solids, hardness, sulfate, and iron content commonly exceed recommended limits.[67] Chloride content increases with depth because of saline water associated with the salt beds.

Lockport dolomite is the next bedrock aquifer unit. It crops out in a band from Niagara Falls through the eastern edge of the basin (Figures 3–55 and 3–57). This unit forms the escarpment for Niagara Falls. Well yields in the Lockport generally are 50 gpm or less, but yields as high as 300 gpm (Table 3–13) are available in highly permeable areas adjacent to streams. Extremely permeable zones occur along the Niagara River where 2,200 gpm yields are reported. The chemical quality of Lockport dolomite water is poor (Table 3–14). Fresh water occurs only in the upper zones of the dolomite. It is commonly hard, contains sulfate and sulfide gas, and is increasingly saline with depth.

There are some waterbearing sandstone units within a series of thick shales of Ordovician and Silurian age. These extrude along the south side of Lake Ontario and extend north of Oneida Lake (Figures 3–55 and 3–57).

Well yields are likely to be less than 10 gpm (Table 3–13). The Rochester area has yields up to 600 gpm, but these are rare. Saline water is very common in the western part of the aquifer, and salinity increases with depth everywhere. Chemical quality of the water is poor (Table 3–14). All but the uppermost units generally suffer excessive hardness and mineral content.

Another carbonate-rock sequence including a major aquifer system occurs in the northeastern part of the basin. These carbonates are of Ordovician age and underlie most of the Lake Ontario basin. They are exposed only along the Black River valley and along the St. Lawrence lowland (Figures 3–57 and 3–59). Only the mapped outcrop areas are known to be productive. Saline water is present elsewhere. Wells yield only up to 50 gpm in most of the outcrop area, but near Watertown yields of 200 gpm are common. Chemical quality of this water is good but hard (Table 3–14). Saline water occurs at shallow depth locally in the Black River valley, and more commonly in the St. Lawrence lowland. Saline water generally is found at greater depth, but is evidently contributing to shallow local saline zones (see references 62 and 70).

The lowermost major aquifer occurs in sandstones of Cambrian age overlying the Precambrian basement rock. This unit extrudes along the northwestern flanks of the Adirondack Mountains (Figure 3–59). The outcrop area is known to contain fresh water only in the upper zones. Elsewhere saline water is present. Well yields are moderate, with 50 gpm yields common in known areas (Table 3–13). Little is known of ground-water potential in St. Lawrence County. Well yields as high as 450 gpm are reported in the Watertown area, where individual wells draw water from both the Ordovician carbonate and the Cambrian sandstone aquifer systems. Chemical quality of the water is good except for moderate hardness (Table 3–14).

6.4 Ground-Water Potential

Ground-water potential for the basin was estimated on the basis of stream-discharge data. The data are presented as estimated yield in Table 3–51 from a compilation of ground-water discharge per square mile shown in Figure 3–60. The estimates are conservative, representing the annual ground-water runoff without considering ground water in storage.

The estimated 4,910 mgd ground-water yield in the Lake Ontario basin ranks second to the Lake Michigan basin in ground-water potential. The greatest potential in the Lake Ontario basin is in the Adirondack Mountains, where major ground-water use is unforeseen. High-yield areas are related to the presence of sand and gravel deposits in the valley streams. These permeable sand and gravel deposits, along with high precipitation, provide for excellent recharge and storage capabilities. Areas of good ground-water potential do not blanket the regions as it might seem on the map. Only sand and gravel deposits, as outlined in Figures 3–54, 3–56, and 3–58, represent possible aquifer locations. The potential of these aquifers is additionally enhanced because most of them are located along streams, so that well development will induce stream recharge. Table 3–15 shows that River Basin Group 5.1 has the least ground-water potential in the basin.

6.5 Problems, Needs, and Management Considerations

6.5.1 General

The Lake Ontario basin has extremes in ground-water availability and chemical quality. Problems result because large ground-water supplies are found in areas of lesser demand and the poorest quality water is in the areas of greater need. Management and planning are therefore extremely important in adjusting supply to needs and in making best use of the total available water. Specific problems and considerations are discussed according to river basin group.

6.5.2 River Basin Group 5.1

The moderate ground-water supply of River Basin Group 5.1 requires careful development to overcome local problems. Poor well yields occur in areas such as the uplands of the southern part of the basin where the glacial drift is thin, or in the Lake Ontario lowland, where deposits are fine-grained. Most of the bedrock consists of carbonates and shale which are also low-yielding.

Mineralized and hard ground water is present at relatively shallow depth almost everywhere. Careful, shallow exploration is needed to obtain fresh water. Poorer quality water generally occurs in the northern part of the basin, as a result of northward movement of ground water through carbonate, salt, and gypsiferous rocks. Salt mining and stockpiling operations in the central Genesee River basin result in leaching of saline water to local streams and probably also to local ground water. Pollution from oil-field wastes, including oil and brines, has occurred in the past in Allegany County and still persists. Hydrogen-sulfide gas is a local problem in ground water, especially in the Niagara Falls-Lockport area where gas is present in the Lockport dolomite aquifer. The gas can be eliminated from well water by aeration or by the addition of chlorine.[23]

A deep waste disposal well at Niagara Falls had been planned (Figure 3–55) for disposal of chloride and hydrochloric acid in Cambrian sandstone brines at a 2,830-foot depth. The brines are considered the most feasible disposal area,[28] but as LaSala[30] has postulated, upward migration of saline water in this general area and dispersal of contaminants must be considered.

Increased ground-water development in the Niagara Falls area may cause a decline in individual well yields. Proper well spacing however can reduce well interference and prevent excessive drawdowns and loss of yield. In addition, control of well development in saline water areas is needed to prevent contamination of the shallow freshwater zones. Proper sealing of present and future abandoned wells encountering saline water will prevent further contamination. New York currently has authorized the filling of abandoned oil-test holes in one area under a special contract.

The recent water-resources study covers much of the Genesee River basin area.[19] Detailed site studies will be required for any major future use of ground water in the Genesee basin. There is a detailed study[23] of the western part of the Niagara-Orleans complex and a general one[21] of the Rochester area. A recent study begun on the Ontario lowland, including the entire complex, was reduced in scope, resulting only in an unpublished summary of ground-water conditions. A comprehensive study seems important for this complex, particularly because of the indicated low-yield capabilities of the surficial and shale aquifers. Such a study might be bypassed, because of general indications of poor yield, for specific site studies where development is desired. The proximity of Lake Ontario water is an asset.

6.5.3 River Basin Group 5.2

Ground water is generally available throughout River Basin Group 5.2 in quantities sufficient only for domestic and farm supplies. Moderate to large supplies for industry and municipalities are available in limited areas of sand and gravel valleys adjacent to streams or lakes. Bedrock aquifers in hydraulic contact with streams can also produce large quantities of water.

Water quality is the greatest ground-water problem. Over half of River Basin Group 5.2 has water containing more than 1,000 mg/l dissolved solids at depths of less than 500 feet (Figure 3–57). Fresh water usually occurs above the saline water in relatively thin zones. The uplands in the south and northeast have most of the better quality ground water, but these areas are also the poorer yielding. Sand and gravel aquifers in the valleys contain better quality water, but in much of the lowland areas, ground water is generally hard, containing excess calcium, sulfate, or chloride. High-chloride water (saline water) in the central part of the area is derived in part from ground-water solution of the salt beds.

Local ground-water contamination has occurred in the area. Wastes entering the shallow bedrock aquifers from septic tanks are the most general problem. Discharge of treated effluent into streams is affecting stream quality, and in turn affecting downstream users who pump wells adjacent to streams. Contamination from winter road salting is common and causes deterioration of local supplies of surface and ground water.

Three detailed reconnaissance studies on ground water cover most of River Basin Group 5.2 (see references 7, 8, and 24). A study on the remaining Ontario lowland area adjacent to the Oswego River basin is needed to determine where potable ground water is available. General knowledge of the conditions has been obtained by an unpublished general reconnaissance study.

The poor water quality and low-yield capabilities of the aquifers indicate that a detailed study will be needed for ground-water development. The nearness of Lake Ontario as a surface-water supply will be a dominant factor in requirements for large quantities of water. Most critical in developing ground-water supplies in the northern half of the basin will be possible deterioration of the chemical quality of ground water. Heavy pumping can induce the poorer quality water from deeper zones or streams to move toward the wells. Development of large supplies will generally be confined to present stream valleys. Consideration of the downstream ground- and surface-water users is imperative to insure maintenance of water quality and quantity.

The northeastern upland, Tug Hill Plateau, has a high water-yielding potential. Ground-water storage in the shale bedrock is negligible, but some valleys have excellent storage potential in the glacial drift. Precipitation exceeds 55 inches on Tug Hill, with about half stored in the annual snowpack. Recharge and sustained streamflow potentials are large. This practically uninhabited and much-reforested area is a valuable asset in managing the total water resources of this part of the Lake Ontario basin.

6.5.4 River Basin Group 5.3

River Basin Group 5.3 is hydrologically unusual in the Great Lakes Basin because of its contrasts and special features. Many of these features concern ground-water resources, but most are only significant in overall management of the land and related resources of this area.

Topographically, the area contains the highest and lowest altitudes in the Great Lakes Basin. Physiographically, it is part of four major regions and has the Adirondack Mountains and the St. Lawrence Valley as dominant features. Annual runoff varies more than other areas in the Great Lakes Basin, from the most (at 55 inches on Tug Hill) to nearly the least (less than 10 inches) at the mouth of the St. Lawrence. The forested area is not proportionately as great as in the Lake Superior drainage, but nearly half the river basin group is in forests, most of which are in the "untouchable" Adirondack Forest Preserve. Population is the second lowest of the Great Lakes river basin groups. The area also contains the greatest milk-producing area (Lewis County) in the nation, and part of one of the most popular vacation lands (Adirondacks) in the northeast. The area probably has the greatest water resources with the lowest population density in the entire Great Lakes Basin.

Major ground-water resources generally are not available in the areas where they are needed. Within the Black River valley and the St. Lawrence lowland areas, well yields over 100 gpm are rare. The carbonate and sandstone aquifers provide the most reliable sources for quantities less than 100 gpm, with the exception of the carbonate aquifers in the Black River valley. Local sand and gravel aquifers along the Black River have good well yields. Elsewhere, ground water in glacial drift or crystalline bedrock is generally available only in small quantities, except in the Adirondack valleys where conditions are relatively unknown. Water problems occur during droughts, especially for the dairy farms in the Black River valley.

Chemical quality of the ground water is good for the most part, but hard water is prevalent. The carbonate aquifer contains saline water at shallow depths in many places in the northern lowland area, the Black River valley, and locally at Watertown (Figure 3-59). Salinity increases with depth in all areas. Wells should be drilled without penetrating saltwater zones, to prevent saltwater contamination of the upper freshwater zones. High-sulfate content can also be a problem in the carbonate aquifer area. Iron problems in the ground water generally occur in sand and gravel aquifers.

Ground-water studies in River Basin Group 5.3 have resulted in one detailed study for the Massena area.[62] A detailed reconnaissance of the Black River basin with little emphasis on the Adirondack Mountains portion[70] has been completed. The remainder of the area was scheduled for a general study, but this was curtailed before completion. A study of the occurrence of saline-water zones at Watertown and the St. Lawrence Valley should be done to delineate these zones and facilitate safe development of freshwater aquifers. If ground-water development is to occur in the Adirondack Mountains, detailed geologic mapping and test drilling of the unconsolidated sediments will be needed. Bedrock in the mountains is not capable of large yields.

Development and use of both surface and ground water is a necessity in much of the area, particularly to insure adequate water during periodic droughts. Ground-water supplies alone are not adequate to provide for municipal, industrial, and dairy needs in this area. Wood-processing and hydroelectric plants compete with communities on the Black River for surface water during low flows. The dairy industry also is seriously hampered by water shortages. The drought of the early 1950s illustrated this, when available water sources were not adequate.

Low streamflow conditions in the Black River may be improved by artificial recharge of the vast sand plains along the margin of the Adirondack Mountains. Excess runoff from winter snows could be diverted onto the forested, largely unsaturated thick sand plains to recharge the ground-water reservoir. Subsequent increased ground-water seepage to springs and streams would greatly increase and sustain the low flow in the Black River. The hydrologic system created would be much like that of the natural hydrologic system on the sand plain northwest of Carthage, where seepage from the Black River occurs through the permeable limestone channel and enters the sand aquifer. The water-table aquifer supplies water to several 250 gpm wells and discharges through numerous springs to the north.

Forest management can improve existing ground-water resources by providing optimum snowpack, runoff, and recharge capabilities, especially on the sand plains. Several communities tap sand-plain springs on forested watersheds.

TABLE 3–13 General Stratigraphy and Major Aquifer Systems in the Lake Ontario Basin

Era	System	Group	Formation	Thickness (ft.)	Major aquifers: Well yields (gpm)[1]	Major aquifers: Well depths (ft.)[2]	Remarks
			RIVER BASIN GROUP 5.1 New York				
Cenozoic	Quaternary			0-645	50-1000	10-320	Sand, gravel in valleys.
Paleozoic	Devonian	Conewango		0-520			Shale, sandstone, and conglomerate.
		Conneaut		0-625			Shale, sandstone, and siltstone.
		Canadaway		0-1450			Shale, sandstone, and siltstone. Oil.
		Java		0-200	< 40	20-350	Shale, sandstone, and siltstone.
		West Falls		0-1200			
		Sonyea		0-225			Shale.
		Genesee		0-175			Shale and limestone.
		Hamilton		0-600			Shale and limestone. Gas.
			Onondaga	0-150	50-150	40-300	Limestone. Gas.
	Silurian	Bertie	Akron	0-110			Dolomite.
		Salina	Camillus	0-600	< 50	20-250	Shale, dolomite, and salt.
			Vernon				Shale.
			Lockport	0-300	50-300[3]	25-300	Carbonates.
		Clinton		80-190	50-125[4]	10-240	Carbonates, shale, and sandstone.
			RIVER BASIN GROUP 5.2 New York				
Cenozoic	Quaternary			0-1000	50-2000	10-325	Sand, gravel in valleys.
Paleozoic	Devonian	Java-West Falls		0-700			Shale, siltstone, and sandstone.
		Sonyea		0-350			Do.
		Genesee		0-700			Do.
			Tully	0-25	50-100	15-325	Limestone.
		Hamilton		0-1200			Shale, siltstone, and limestone.
			Onondaga				Carbonates. Yields generally low.
		Helderberg-Ulster		0-340	50-500	20-275	
	Silurian		Akron-Cobleskill				
		Bertie					
		Salina	Camillus	0-850			Shale, carbonates, gypsum, and salt. High yields in north adjacent to streams.
			Vernon		50-1000	30-200	
			Lockport	0-150	50-300	10-210	Dolomite. High yields not common.
		Clinton		250			Shale, sandstone, and limestone.
		Albion (Medina)		500	50-600	20-390	Sandstones and shales. High yields not common.
	Ordovician		Oswego				
			Lorraine	800			Shales. Low yields. Gas.
		Trenton-Black River	Utica				Shale.
				125+	50-200	100-150	Limestones. Fresh water only in Jefferson County. Gas to south.

1 Range is that of typical high-capacity wells.

2 Range is that of all wells.

3 Upper part of Lockport yields as much as 2,200 gpm at Niagara Falls.

4 Highest yields in upper sandstone of Rochester Shale of Clinton Group.

TABLE 3–13(continued) General Stratigraphy and Major Aquifer Systems in the Lake Ontario Basin

Era	System	Group	Formation	Thick-ness (ft.)	Major aquifers: Well yields[1] (gpm)	Major aquifers: Well depths[2] (ft.)	Remarks
			RIVER BASIN GROUP 5.3 New York				
Cenozoic	Quaternary			0-220	50-150	10-100	Sand, gravel in stream valleys. Very little data in most of area.
Paleozoic	Ordovician		Oswego	0-100(?)			Sandstone and siltstone. Minor occurrence.
			Lorraine	0-800			Shale.
		Trenton	Utica				Shale.
				0-125+	50-500	20-300	Carbonates. Saline and gas locally.
		Black River		0-135			
			Ogdensburg	0-500			
	------?------		Theresa	0-300			Dolomite and sandstone. High yields only in Watertown area.
	Cambrian		Potsdam	0-230	50-450	20-300	Sandstone. High yields only in Watertown.
Precambrian							Metamorphic and igneous. Weathered zones produce high yields in Watertown area only.

[1] Range is that of typical high-capacity wells.

[2] Range is that of all wells.

TABLE 3-14 Chemical Quality Characteristics of the Major Aquifer Systems in the Lake Ontario Basin

Aquifer system	Hardness (mg/l)	Sulfate (mg/l)	Chloride (mg/l)	Iron (mg/l)	Total dissolved solids (mg/l)	Temperature (°F)	Remarks
RIVER BASIN GROUP 5.1							
New York							
Quaternary	160-1220 [1]	0.6-990 [2]	5-160	0.2-1.3	80-1600 [3]	45-53	Increasing mineralization northward.
Devonian (Shale-sandstone)	55-335	1.4-4.3	8-180	0.6-1.2	160-510	---	
Silurian-Devonian (Carbonates)	245-545	45-180	4-90	0.1-0.6	315-745	---	
Silurian (Salina)	380-1540	65-1150	5-95	0.4-0.19	510-2000	50	Higher iron in Rochester area.
Silurian (Lockport)	165-800	60-185	5-25	0.02-0.89	330-540	53-54	Hydrogen sulfide common. Saline in lower zones.
Ordovician-Silurian[4] (Queenston-Clinton)	110-1200	40-135	10-275	0.05-0.85	550	47-53	Saline at depth.
Pennsylvania							
Data on Quaternary (lower values) and Devonian aquifers above apply							
RIVER BASIN GROUP 5.2 [5] [6]							
New York							
Quaternary	200-1000	1-1000	1-300	---	300-2000	---	
Devonian (Shales)	50-500	1-150	1-125	---	300-900	---	
Silurian-Devonian (Carbonates)	50-1500	35-1250	3-75	---	300-2900	---	Syracuse and east has shallowest saline water.
Silurian (Salina)	250-1600	50-1500	10-350	Highest	300-2000	---	
Silurian (Lockport)	100-600	30-350	5-25	---	300-800	---	
Ordovician-Silurian (Shale-sandstone)	100-800	20-200	5-300	---	200-2000	---	Saline water common.
RIVER BASIN GROUP 5.3 [7]							
New York							
Quaternary	50-400	50-140	5-200	0.1-5	50-600	42-50	
Ordovician (Carbonates)	200-500	40-500	2-300	0.2-1	250-2000	47-50	Saline locally.
Cambrian (Sandstones)	250-400	50-100	20-300	0.05-0.20	400-600	47-50	Based on 4 analyses. Salinity increases with depth.

[1] Allegany County upper range is only 365.
[2] Allegany County upper range is only 56.
[3] Allegany County upper range is only 365.
[4] Rochester area only. Samples include water from underlying Queenston, not considered major aquifer in this report.
[5] No iron data available, all aquifers reportedly have iron-water problems.
[6] The Ontario lowland generally has saline water at shallow depth.
[7] Areal coverage poor.

TABLE 3-15 Estimated Ground-Water Yield from 70 Percent Flow-Duration Data in the Lake Ontario Basin

Subbasin	Runoff at 70-percent duration (cfsm)	Subbasin yield (mgd)	State totals (mgd)	River Basin Group totals (mgd)
		RIVER BASIN GROUP 5.1		
		New York	530	550
Genesee River	0.30	460		
Niagara-Orleans Complex	0.10	70		
		Pennsylvania	20	
Genesee River	0.30	20		
		RIVER BASIN GROUP 5.2		
		New York	1,290	1,290
Oswego River	0.20	1,020 [1]		
Salmon River Complex	0.25	260		
Wayne-Cayuga Complex	0.01	10		
		RIVER BASIN GROUP 5.3		
		New York	3,070	3,070
Black River	0.90	1,170		
Perch River Complex	0.01 [2]	30		
Oswegatchie River	0.60	640		
Grass-Raquette-St. Regis Complex	0.60	1,230		
			Lake Basin total	4,910 mgd

[1] Estimated available yield from area study (Gilbert and Kammerer, 1970) totals 850 mgd.

[2] No flow-duration data available, runoff estimated.

Note: Estimates based on flow-duration data for period of record (generally more than 14 years, and adjusted to 1931-60 period in the Black River basin) at all gaging stations within the subbasin; extrapolations within drainage area and to ungaged areas based on surficial geology.

SUMMARY

General

The Great Lakes Basin has a bountiful ground-water supply which has been overlooked in some areas and overused in other areas. Its relationship to surface water has not been fully understood in many cases. An understanding of the complete hydrologic system of an area is necessary before extensive use of one segment, surface water or ground water, is undertaken. For example, dam construction can change the conditions of recharge to the ground-water system; well fields constructed near streams can reduce the low streamflow; irrigation can raise the water table and affect the chemical quality of the ground water; waste disposal can affect ground-water and surface-water quality; and drainage systems can deplete the ground-water system.

Based on stream-discharge data, it was conservatively estimated that 26,000 mgd of ground water is available within the Great Lakes Basin. Maps such as Figure 3–5, showing ground-water availability, can be based on several types of data used. Well yields usually are the most widespread information available in ground-water studies. Well data indicate the potential for an individual well tapping an aquifer, but they do not tell a planner how much ground water is available in a given area. Aquifer yield per unit area per unit time is needed to project a safe development of that area. However, data for such a compilation are available only from detailed studies of small areas. Thickness, permeability, potential recharge, area and type of discharge, water levels, and areal extent of the aquifer are the types of data needed. Thus, most existing reports on local studies are probably of greatest value to determine well spacing, rate and amount of lowering of water levels, and optimum well yields to permit efficient ground-water withdrawal. Quantitative studies of aquifer parameters and potential stresses on the system are needed to evaluate the long-range potential.

Aquifer parameters are needed to evaluate the yield of a system, but the amount of potential recharge to that system and the amount of discharge that can be captured before discharge are critical data needed to determine the potential yield. Recharge evaluation considering the area of recharge and its precipitation, soil characteristics, and water-table conditions is needed. However, present data are not available to make a good evaluation. Data usually lacking are soil permeability and moisture characteristics, the availability of recharge from streams, and information about overlying or underlying formations. Minimum values are usually estimated by multiplying the area of recharge by a percentage of precipitation falling on the area. This must be applied to the area of the aquifer. Such an estimate does not consider the amount of water available from storage in the aquifer, usually a very large amount which can be considered a mineable source for a given length of time. An aquifer can be practically dewatered temporarily and thus add appreciably to the yield. In addition, dewatering of an aquifer generally induces greater recharge from adjacent formations and streams and also reduces evapotranspiration from the near-surface water table. Determination of the amount of ground water in storage was not attempted, but it should be done to properly evaluate the resource.

Very few studies of this nature have been made in the Basin. Studies probably can be made only in those areas where ground-water demands are rapidly increasing, and many data are available. However, this type of study should be made in any comprehensive evaluation of an area's water resources. Many potentially good ground-water systems probably have been abandoned or bypassed in favor of a surface-water source because of lack of knowledge about the long-range potential of an aquifer.

To further refine the water budget of the Great Lakes system, a more accurate appraisal of the direct ground-water inflow or outflow to the Lakes is needed.

Illinois

Northeastern Illinois has large ground-water resources. The deep, thick sandstone aquifers provide a major water supply with well yields commonly high. The overlying dolomite aquifer and the discontinuous sand and gravel aquifers are very prolific and can provide much more water than is currently being drawn from them. The deepest sandstone aquifer (Mount Simon) is limited in use because of marginal chemical quality and the economics of deep-well construction and subsequent pumping costs.

The principal problem is one of heavy pumpage in small areas. The sandstone-aquifer system is being mined as pumpage locally exceeds recharge.[51] Because new or expanding industrial use makes greater demands on the ground-water resource, management might consider directing new development toward areas of greater or little-used water sources. Shoreline areas may have to rely almost entirely on Lake Michigan water to reduce the overdraft on the deep aquifers, or use surplus Lake Michigan water, possibly during the winter months. Improvements in pollution control are needed where surface waters recharge, or potentially recharge, the aquifers.

Illinois has made excellent studies of its water resources and their uses for the future. These studies have proven the value of water-data collection over the years and have indicated the need for improved collection. Deep-well disposal has been considered undesirable in this region. They have pointed out that pollution control, water reuse, and inter-basin diversions for municipal supply are necessary for the existing highly developed northeastern Illinois region, and they suggest that the development of "new" cities versus continuing metropolitan sprawl should be considered.

Study needs include the following items:

(1) a continuing appraisal of the effects of extensive ground-water withdrawal in the area

(2) other solutions to ground water supply when the limit of pumping lifts is reached

(3) quantitative model study to predict the effects of current and proposed stresses on the hydrologic system

Indiana

Indiana has moderate to excellent supplies of ground water in the Great Lakes Basin. The best potential exists in the St. Joseph and Elkhart River basins, where thick deposits of outwash sand and gravel are common. Elsewhere, moderate to good supplies are available from sand and gravel aquifers within the general glacial drift sequence. Carbonate aquifers in the eastern and western portions of the basin provide moderate to good supplies. Some limited areas of carbonates are present locally, but they are not of sufficient areal extent to be defined.

Water quality is moderately good, but hard to very hard, calcium carbonate, high iron-content water predominates in the basin. High sulfate content generally is present in water from carbonate aquifers in the eastern part of the area. Dissolved solids content commonly exceeds 1,000 mg/l. Deeper bedrock aquifers in the northern part of the area, capped by shale of Devonian and Mississippian age, contain brackish to saline waters at moderately shallow depths (300–600 feet). These sources are not used, but are overlain by more prolific sand and gravel aquifers of the glacial sequence. The deep Ordovician and Cambrian bedrock aquifers present in Illinois become less permeable and more saline in Indiana and are not generally used.

Unconsolidated aquifers, both surficial and buried, lend themselves well to artificial and induced recharge. Because of the potential of these deposits for replenishment and their vulnerability to pollution, the aquifers must be protected. Constant surveillance will be required.

Deep-well disposal of industrial wastes currently occurs in the northwest part of the area. Some wells are relatively shallow (300–400 feet) and an evaluation of the use of these disposal zones versus future water needs may be required.

Indiana is just completing a State Water Plan which will outline specific study needs. The basin area presently is fairly well covered with basic ground-water studies.

Michigan

Michigan has large ground-water resources in most of its area. The better aquifer systems are provided by extensive deposits of thick glacial drift. Bedrock aquifers provide moderate supplies in the eastern part of the Upper Peninsula and in the central and south-central parts of the Lower Peninsula.

Water quality probably is the most pressing problem in Michigan. Saline water is present in many of the shallow bedrock aquifers of eastern Michigan and locally elsewhere. Some of the salinity is due to contamination by interaquifer flow from borehole and mining activities, but most is due to upward leakage from the bedrock aquifers. Poor-yielding aquifers are present in the western part of the Upper Peninsula where Precambrian bedrock is present. Here and in the rest of the Upper Peninsula good unconsolidated aquifers are scattered and not always near places of demand.

Industrial waste is being injected into at least 21 deep wells in Michigan. Such disposal is now under regulation by Michigan law. Other means of disposal and methods of abandoning deep test holes are being more carefully controlled than formerly.

Study needs include the following items:

(1) studies of ground-water potential of the large areas of glacial drift and the bedrock aquifers of the Lower Peninsula

(2) regional or county appraisals of ground-water resources in the Lower Peninsula

(3) delineation and monitoring of poor quality areas to determine their extent and whether changes are occurring naturally or from man's activities

Minnesota

The Minnesota part of the Great Lakes Basin has ground water in small to moderate amounts. Mining and wood processing are large users of surface water in the St. Louis River basin. Most of the remaining area has low needs. Sand and gravel and a bedrock unit provide moderate to large supplies in the Mesabi district. Mining and processing requirements on the iron range and industrial development in the Duluth area rely almost wholly on surface-water supplies. Ground water is high in iron, manganese, siliceous compounds, and hardness.

Pollution of ground water by mining activities has largely been curbed. Urban waste presents the greatest problems.

Study needs include the following items:

(1) mapping of the occurrence and extent of the glacial drift. Such studies would aid in the location of the water-bearing units and the units controlling ground-water movement.

(2) enlargement of the surface-water gaging network to make an adequate evaluation of the surface waters

New York

New York has a wide range in quantity and quality of its ground-water resources within the Great Lakes Basin. Small yields dominate throughout the crystalline areas of the Adirondack region and most of the shale and limestone rocks of the remaining area. Moderate to high yields are locally available in sand and gravel aquifers in stream valleys and glacial-outwash sites. Sandstone and limestone in the St. Lawrence Valley produce moderate yields. Limestone and dolomite aquifers in the western area and local sand and gravel aquifers along streams throughout the area offer the best possibilities for large ground-water supplies.

Saline water is a problem throughout most of the lowland area south of Lake Ontario. The presence of salt beds and saline water within the circulation pattern of the ground-water system has led to aquifer contamination. In the St. Lawrence lowland, local occurrence of saline water is attributed to postglacial marine inundation.

Local pollution of shallow ground water is occurring in bedrock areas having a thin drift cover, especially the areas underlain by carbonate rock along the Ontario and St. Lawrence lowlands.

One deep disposal well is proposed in the Buffalo area. Disposal in brines well below the freshwater aquifer system is being considered.

New York has made detailed studies of most of the river basin groups in the region. Quantitative studies are needed in the more heavily populated regions to obtain potential yield information.

Specific study needs include a detailed reconnaissance of both the Ontario and the St. Lawrence lowland areas for their ground-water potential.

Ohio

Ohio has moderate ground-water supplies available in both unconsolidated deposits and bedrock aquifers. The unconsolidated aquifers are more prevalent along the basin boundary. Carbonate aquifers occur in most of the western half of the area. Sandstone aquifers of lesser yield occur in the eastern part. The poorest ground-water yield area occurs along the Lake Erie lowland.

Quality of ground water is more of a problem in Ohio than quantity. The ground water generally is hard to excessively hard and dissolved solids content commonly exceeds recommended limits. Brackish and hydrogen-sulfide-bearing water is present in some aquifers at relatively shallow depths. Salinity is a greater problem in the shallow bedrock aquifers of eastern Ohio.

Deep-well disposal of wastes has started in two known wells in the area. Ohio has recently developed regulations and controls on disposal practices and on the abandonment of test holes in efforts to prevent deterioration of freshwater aquifers.

Ohio has, along with New York, excellent areal coverage of ground-water studies.

Study needs should be directed to the following items:

(1) recharge studies by river basin group or aquifers to determine potential ground-water yields

(2) detailed studies of the local unconsolidated aquifers which offer potential for good-quality water

Pennsylvania

The small part of Pennsylvania that lies within the Great Lakes Basin has small to moderate ground-water supplies. Locally, especially along the Lake Erie shore and in some upland valleys, the glacial drift consists of several tens of feet of sand and gravel capable of yielding moderate water supplies. The best potential is in thicker unconsolidated sediments adjacent to perennial streams where induced recharge is feasible. The shaly bedrock generally is of low yield, high in salt content, and contains some gas. High iron content in unconsolidated aquifer water is a local problem. In a few places saline water from the bedrock discharges into shallow aquifers.

Study needs include the following items:

(1) detailed local studies for any moderate to large source of ground water

(2) delineation of saltwater zones to permit control of man-made contamination

Wisconsin

The area of Wisconsin within the Great Lakes Basin has extremely variable ground-water supplies. High-yielding areas of sand and gravel, dolomite, or sandstone exist in eastern Wisconsin and locally in the northern portion. Low-yielding areas of thin glacial drift on Precambrian crystalline rocks commonly exist in the northern parts.

The chemical quality also is variable. Waters are of generally excellent quality in the shallow aquifers, and saline at depth in the eastern bedrock aquifers. Water hardness increases from west to east and generally with depth.

Most problems other than the poor-yield and saline-water areas are the result of heavy pumping in the sandstone aquifer. The Milwaukee-Racine area has a steadily lowering water level from local and Chicago-area pumping. Artesian pressures in the sandstone aquifer at Milwaukee have dropped as much as 400 feet since the first wells were drilled. Subsequent recovery of approximately 100 feet has occurred as pumpage declined. Areal water levels have started declining slightly in the City of Green Bay. There was a temporary recovery in the 1950s when Lake Michigan water was first used and pumpage requirements were reduced.

Pollution of shallow sand and gravel or dolomite aquifers is becoming more serious, particularly in the Door Peninsula. Improvements of waste disposal methods are urgently needed. Special provisions for well construction in Door County have been incorporated into the well code, and installations of septic tanks are now under strict Statewide regulations.

Wisconsin currently has a law denying permits for new wells over 70 gpm capacity if they adversely affect availability of water to any public utility's water supply.

Study needs include the following items:

(1) a comprehensive quantitative study of the long-range potential of the aquifers in the Milwaukee-Racine area. Several studies have been completed in this area and the general hydrogeologic conditions are known. Coordination with Illinois seems imperative to inhibit continuous lowering of the deep-aquifer water level.

(2) a detailed study of the salinity problem in eastern Wisconsin. The general conditions are known, but the source of salinity in some areas is not. Curtailment of well contamination, if present, and prevention of future contamination should be the goal of such a study.

(3) quantitative appraisal of the lower Fox River basin to determine optimum management of the ground-water system

GLOSSARY

artesian water—ground water under sufficient hydrostatic head to rise above the aquifer in which it is encountered by a well. Originally, artesian referred to water freely flowing from wells tapping confined aquifers. Technical usage now applies the term to water in a confined-aquifer (artesian) system.

artesian well—a well tapping a confined aquifer in which water rises above (artesian pressure) the bottom of the confining layer.

artificial recharge—addition of water to an aquifer, directly or indirectly, by means of wells, pits, trenches, or spreading systems.

average annual runoff—average water-year runoff for the total period of record.

base exchange—a chemical reaction where clay particle cations may be replaced by cations in solution, such as sodium replacement by calcium, making the clay more flocculent. Hard ground water supplying the cations may be softened by this process.

base flow—see base runoff. Base flow is often used in the same sense as base runoff.

base runoff—sustained or fair-weather runoff. In most streams, base runoff is composed largely of ground-water effluent. When the terms base flow and base runoff are applied to natural flow in a stream, base runoff is the logical term.

basement—rock complex, generally of igneous and metamorphic rocks, overlain by unconformable sedimentary strata.

bedrock—any solid rock exposed at the surface or overlain by unconsolidated material.

brackish water—a qualitative term for that water having a mineral content between that of fresh water and sea water.

capillary fringe—the suspended water zone directly above the water table in which water is held in the pore spaces by capillarity. Water content decreases upward from complete saturation near the water table to zero at the top of the capillary fringe.

cone of depression—a cone-like depression of the water table or the potentiometric surface, formed in the vicinity of a pumping or flowing well. The land surface area included within the limits of the cone is known as the area of influence of the well.

confining bed—a formation which, although porous and capable of absorbing water slowly, will not transmit it fast enough to furnish an appreciable supply to a well or spring. Clay is an example. As most confining beds (formerly called aquicludes) are leaky, the term aquitard is sometimes used because of its connotation of retardation rather than prevention of water movement. The term confining bed is now preferred in place of both aquiclude and aquitard.

disposal well—a well drilled or used for disposal of brines or other fluids in order to prevent contamination of the surface by such wastes.

drawdown—the difference between water level before pumping began and water level during pumping.

esker—a long, narrow ridge of sand and gravel confined to what once was the bed of a stream flowing beneath or in the ice of a glacier, and which has been preserved since the ice melted.

evapotranspiration—the process of returning water to the atmosphere through both direct evaporation and transpiration of vegetation.

flow-duration curve—a cumulative frequency curve showing the percent of time during which specified discharges were equaled or exceeded in a given period.

glacial drift—any rock material transported by a glacier and deposited by or from the ice or by or in water derived from melting ice.

ground-water runoff—that part of stream runoff derived from ground-water seepage; natural ground-water discharge.

ground-water storage coefficient—the volume of water released from or taken into storage in an aquifer per unit surface area of the aquifer, per unit change in the component of head perpendicular to that surface. In unconfined aquifers it corresponds to the specific yield.

high-capacity well—for purposes of this report, a well capable of yielding more than 50 gpm, usable for light industrial and small municipal needs.

induced recharge—increased ground-water recharge from surface-water sources by pumping nearby wells.

kame—a conical hill or short irregular ridge of sand or gravel deposited in contact with glacier ice.

karst topography—irregular topography formed over limestone that has been honeycombed by solution activity creating sinks and caverns. Disappearing and emerging streams are common.

kettle—a depression in glacial drift, made by the wasting away of glacial ice that had been either wholly or partly buried in the drift.

lacustrine deposits—material deposited in a lake environment.

leaching—the process by which soluble substances, such as organic and mineral salts, are dissolved out of soil or rock by percolating water.

lignin—an organic substance of many plants. It contributes to the dark coloring of surface waters draining areas of decaying vegetation.

moraine—an accumulation of glacial drift having initial constructional topography, built by the direct action of glacier ice.

outcrop—the exposure of a stratum at the surface of the ground. On an areal geology map a formation is shown as an area or outcrop even if it is covered by surficial deposits. Subcrop is sometimes used for this latter connotation.

potentiometric surface—the static head or water level. In an aquifer, it is the level to which water will rise in tightly cased wells. The water table and artesian level are examples. This term replaces the term piezometric.

saline water—that water containing dissolved solids in concentrations exceeding 1,000 milligrams per liter.

soil—in pedology, that earth material which has been so modified that it will support rooted plants. In engineering geology, all unconsolidated material above the consolidated rock, regardless of its origin.

specific capacity (well)—the yield of a well per unit of drawdown after a specified period of pumping, generally expressed as gallons-per-minute (gpm)-per-foot of drawdown.

specific yield—the ratio of the volume of water a saturated rock will yield by gravity to its own volume.

surficial deposits—unconsolidated sediments lying on the bedrock, consisting of residual, alluvial, eolian, lacustrine, or glacial deposits.

till—nonsorted, nonstratified sediment carried or deposited by a glacier.

transpiration—the process by which water vapor escapes from a living plant and enters the atmosphere.

water table—the upper surface of a zone of saturation except where that surface is formed by an impermeable body.

LIST OF ABBREVIATIONS

cfs—cubic feet per second, a standard unit of measurement of a stream discharge

cfsm—cubic feet per second per square mile of drainage area

gpm—gallons per minute

mgd—million gallons per day

mg/l—milligrams per liter

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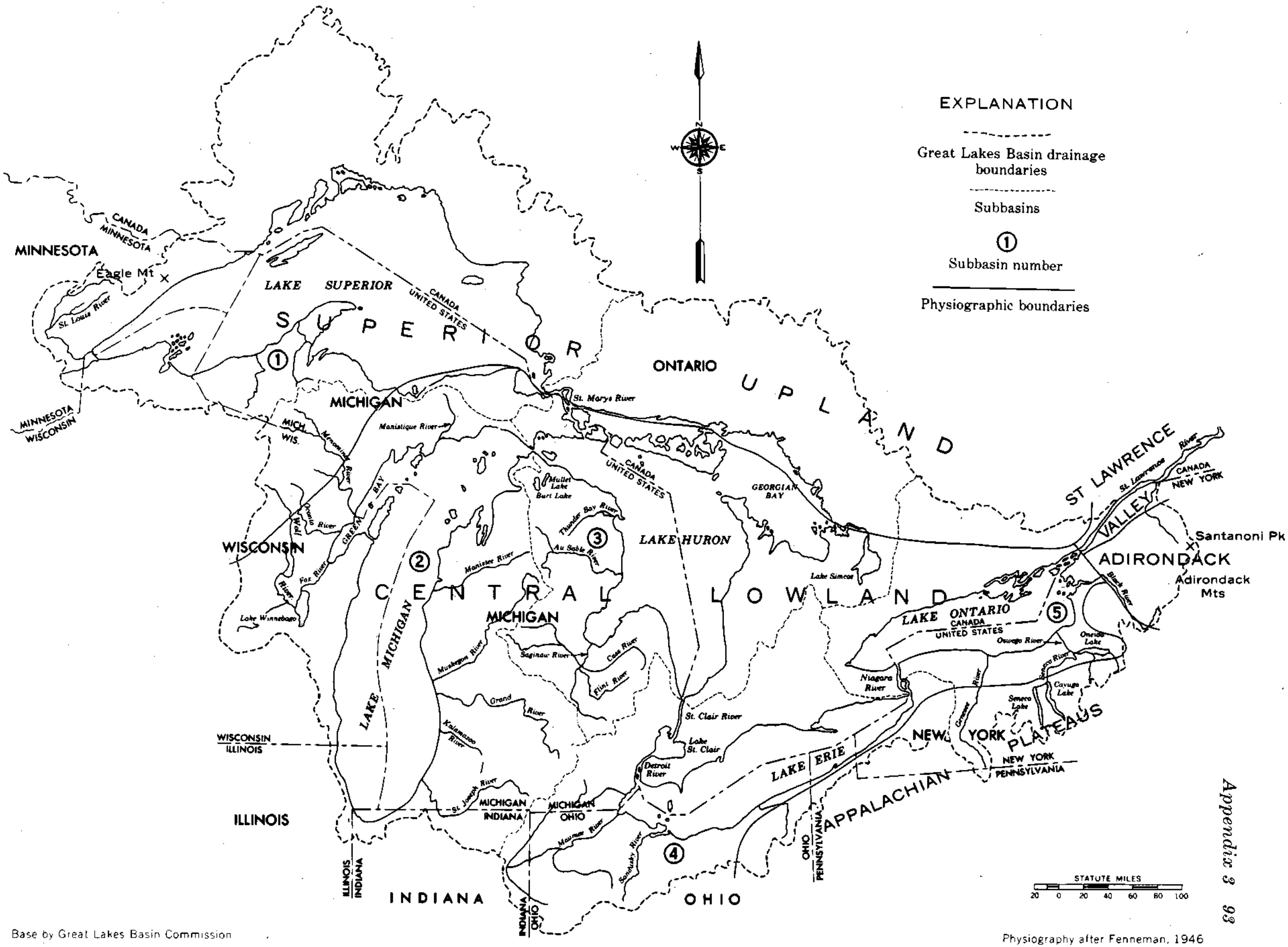


FIGURE 3–1 Great Lakes Basin Showing Drainage System and Physiographic Regions

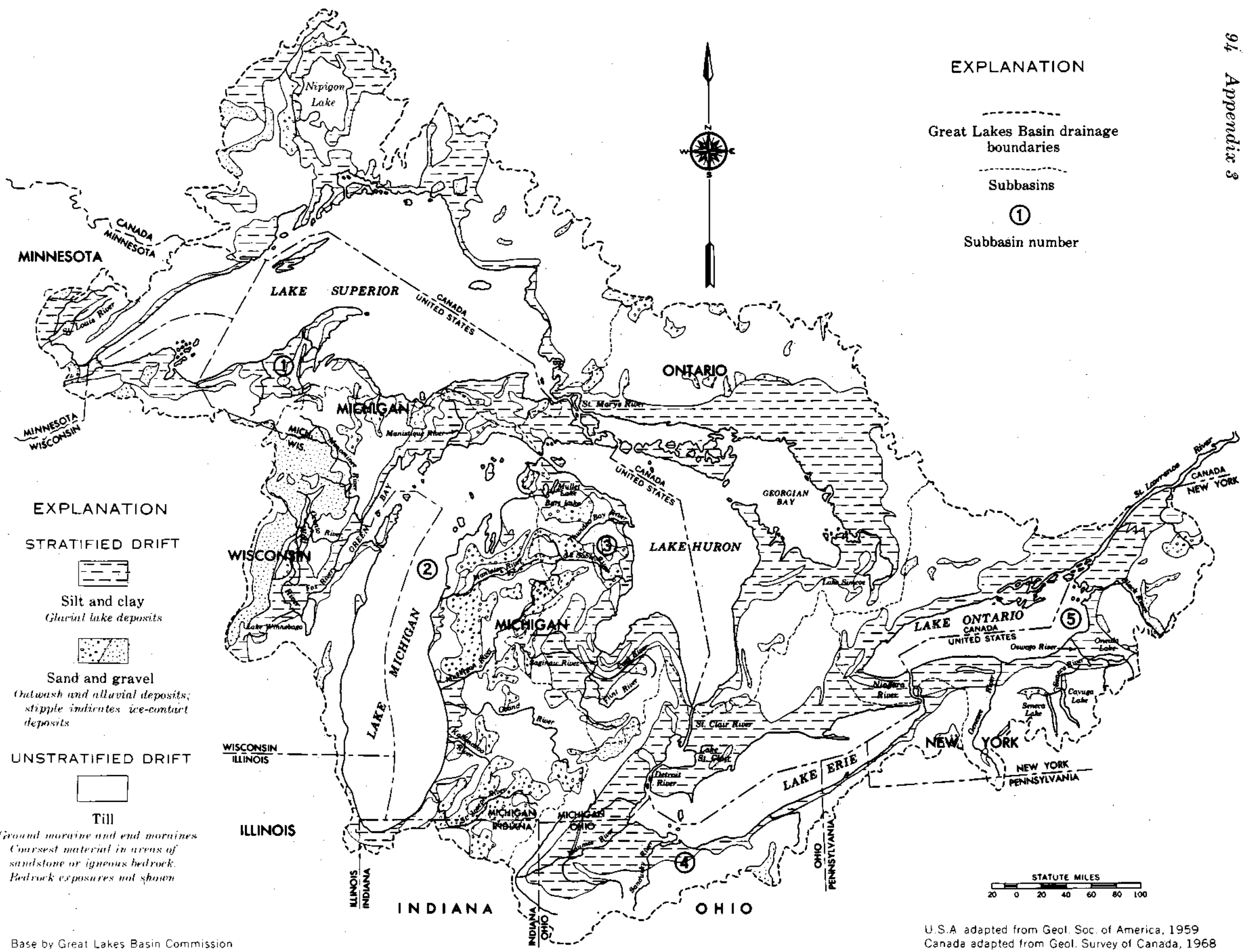
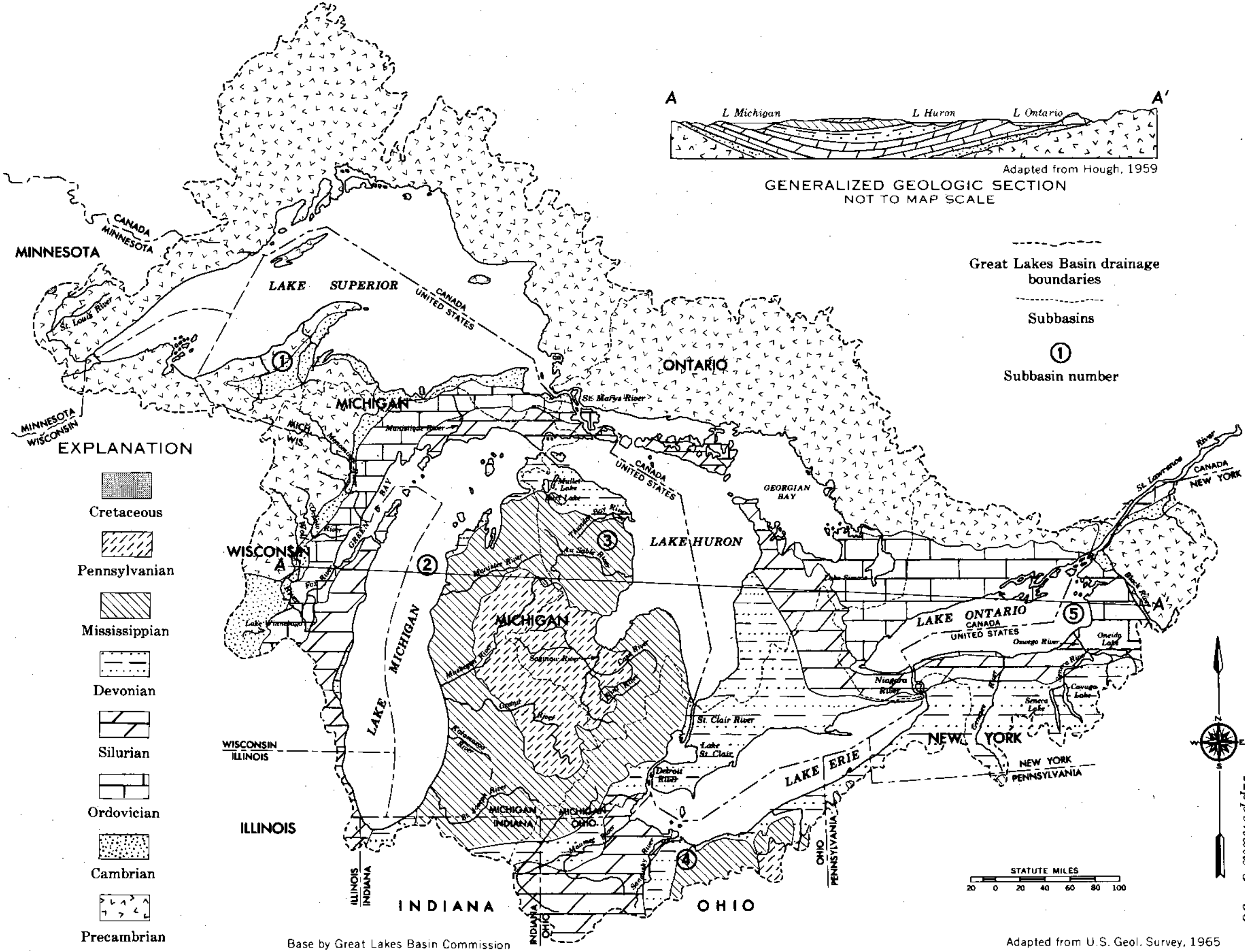
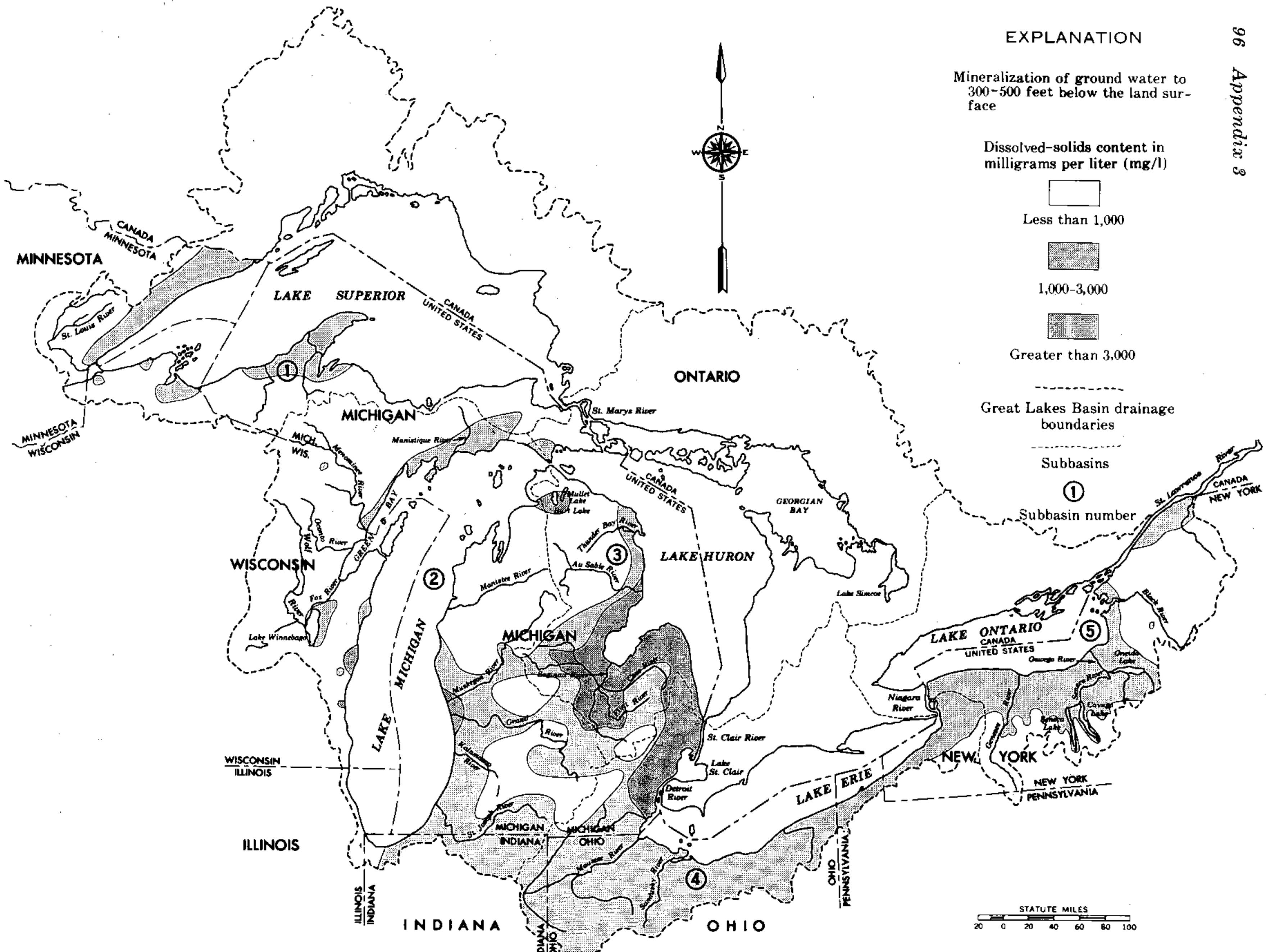


FIGURE 3-2 Glacial Geology of the Great Lakes Basin

FIGURE 3-3 Bedrock Geology of the Great Lakes Basin



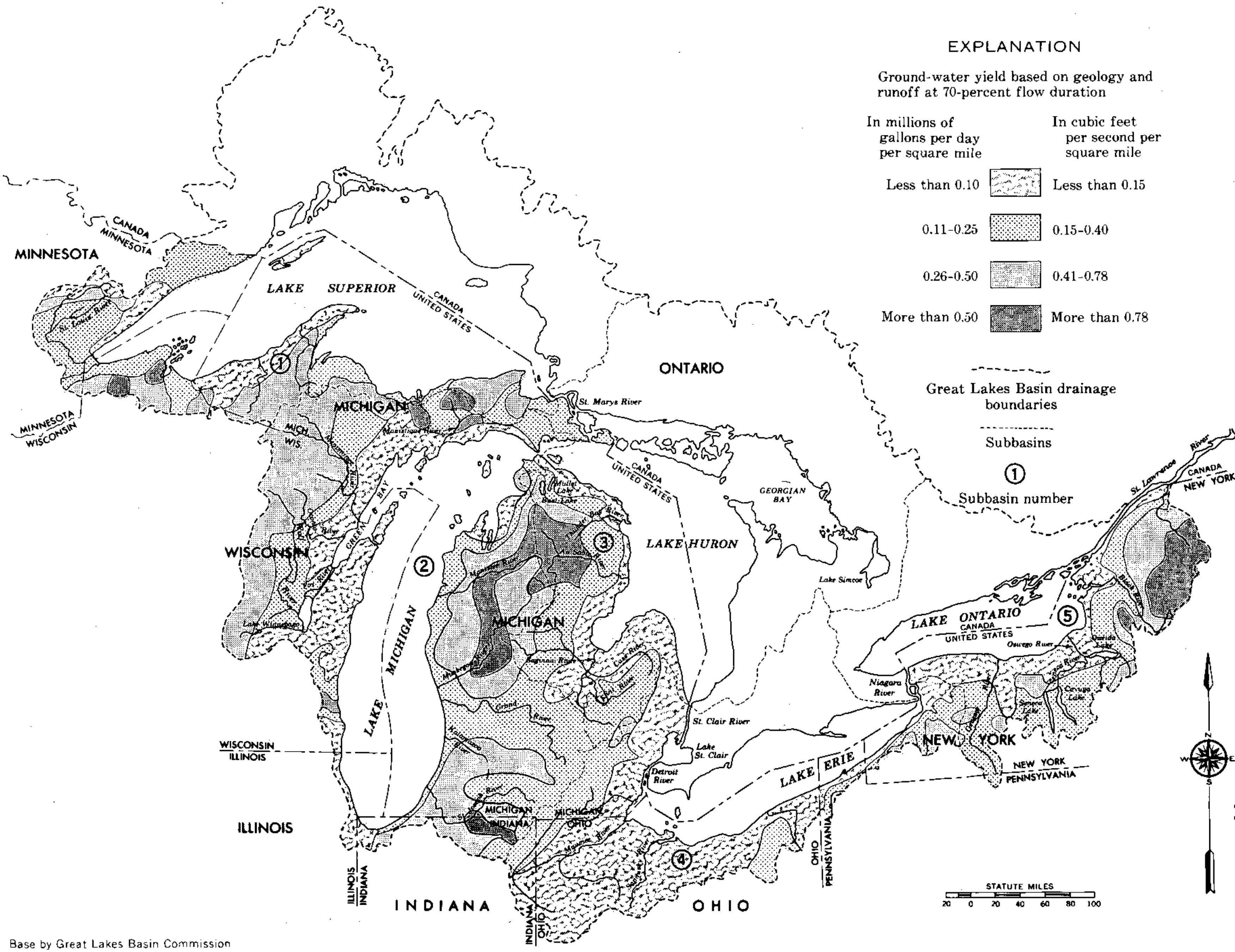


Base by Great Lakes Basin Commission

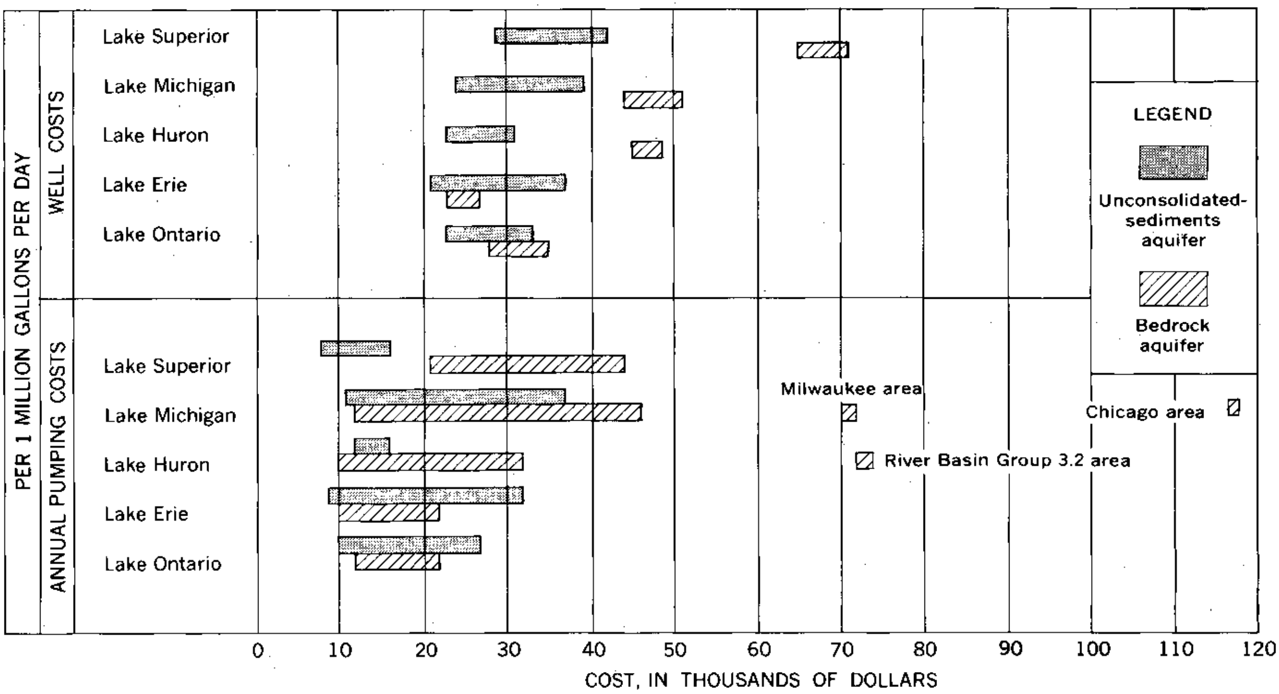
Adapted from Feth and others, 1965

FIGURE 3-4 Areas of Mineralized Ground Water at Shallow Depth in the Great Lakes Basin, United States

FIGURE 3-5 Estimated Ground-Water Yield in the Great Lakes Basin, United States



Base by Great Lakes Basin Commission



Assumptions:

1. Number of wells needed to produce 1 mgd is based on 60 percent of the maximum yield range for typical high-capacity wells.
2. A test well is needed for each production well in unconsolidated and carbonate aquifers.
3. Well depths are based on 75 percent of the maximum well depth of the range for all wells.
4. Pump costs are based on using 70 percent of the available drawdown with the pump intake 10 feet off the bottom of the well or the top of the screen.
5. Pumping costs are based on 50 percent wire-to-water efficiency, electric power at 2 cents per kWh, and continuous pumping with lift at 70 percent of available drawdown. (See text explanation.)
6. Transmission-line costs from well house to distribution system are not included (the 1970 totals are estimated at $11.00 per foot of 10-inch line).
7. Operation and maintenance costs are not included, but they are usually estimated at 2 percent of capital costs.

FIGURE 3-6 Costs of Producing Ground Water in the Great Lakes Basin

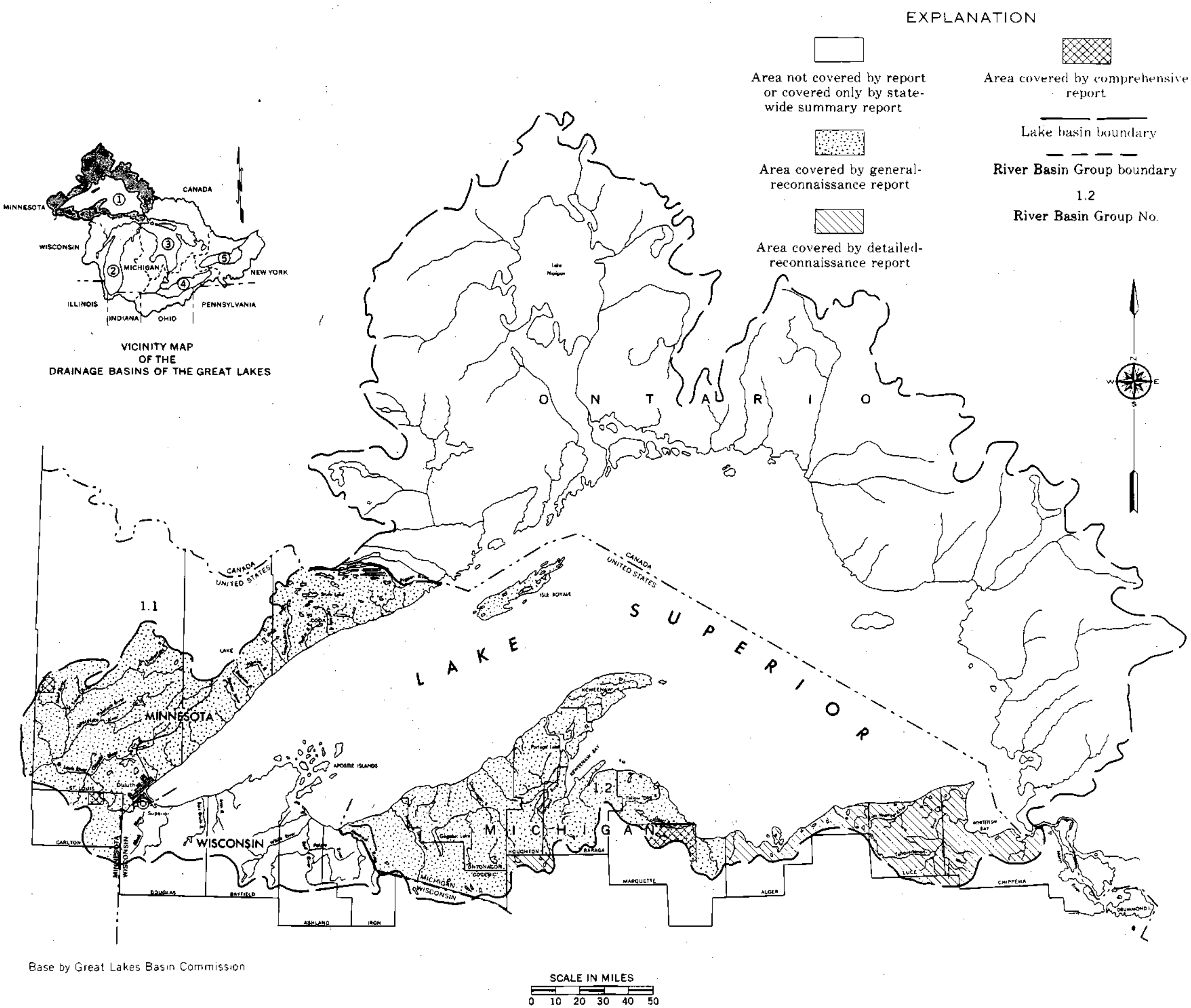
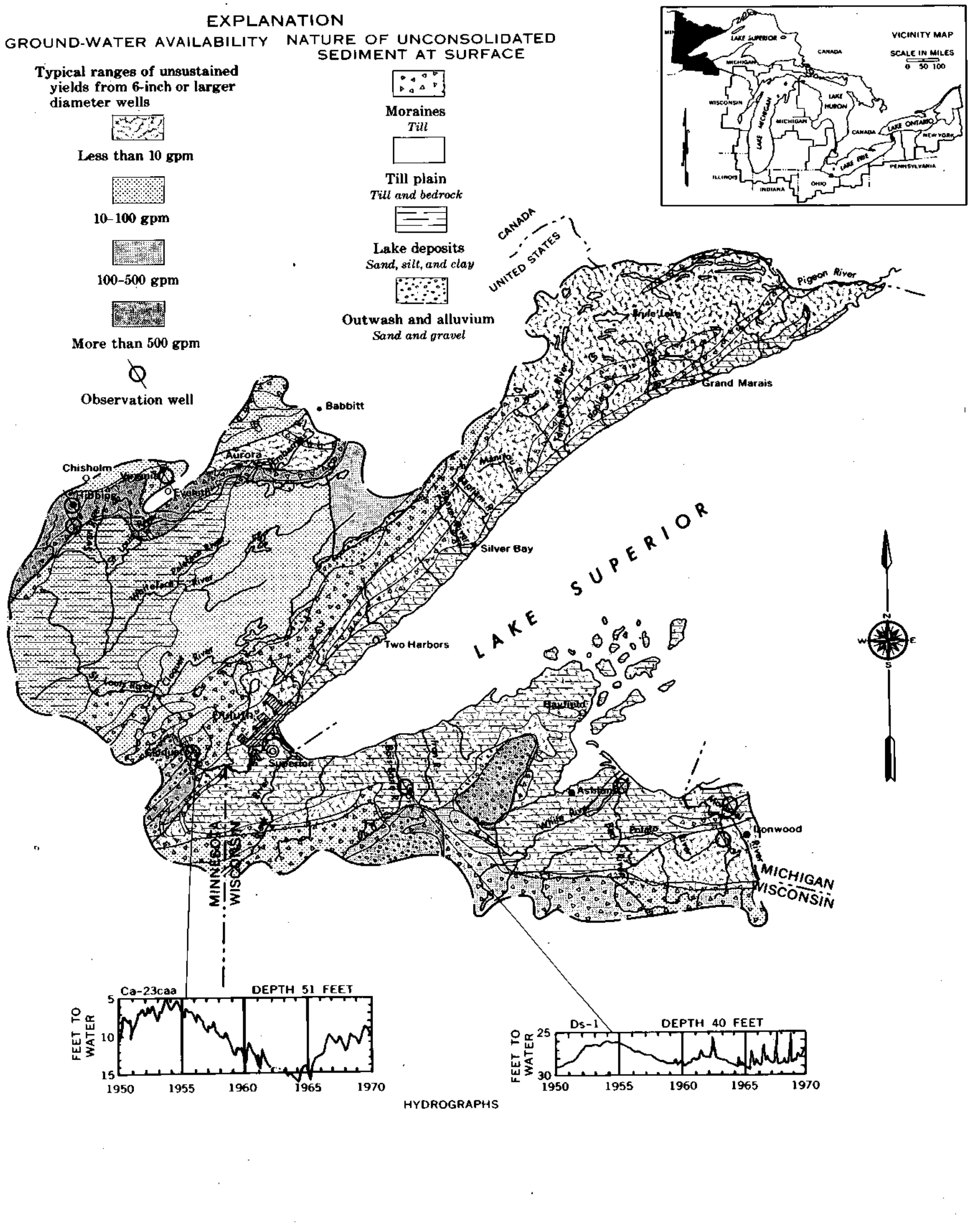


FIGURE 3-7 Map of the Lake Superior Basin Plan Area Showing River Basin Groups and Areas Covered by Ground-Water Reports



Base by Great Lakes Basin Commission

Geology adapted from: Leverett, 1929; Thwaites, 1956; and Geol. Soc. Am., 1959

FIGURE 3–8 Ground Water in the Unconsolidated Sediments in River Basin Group 1.1

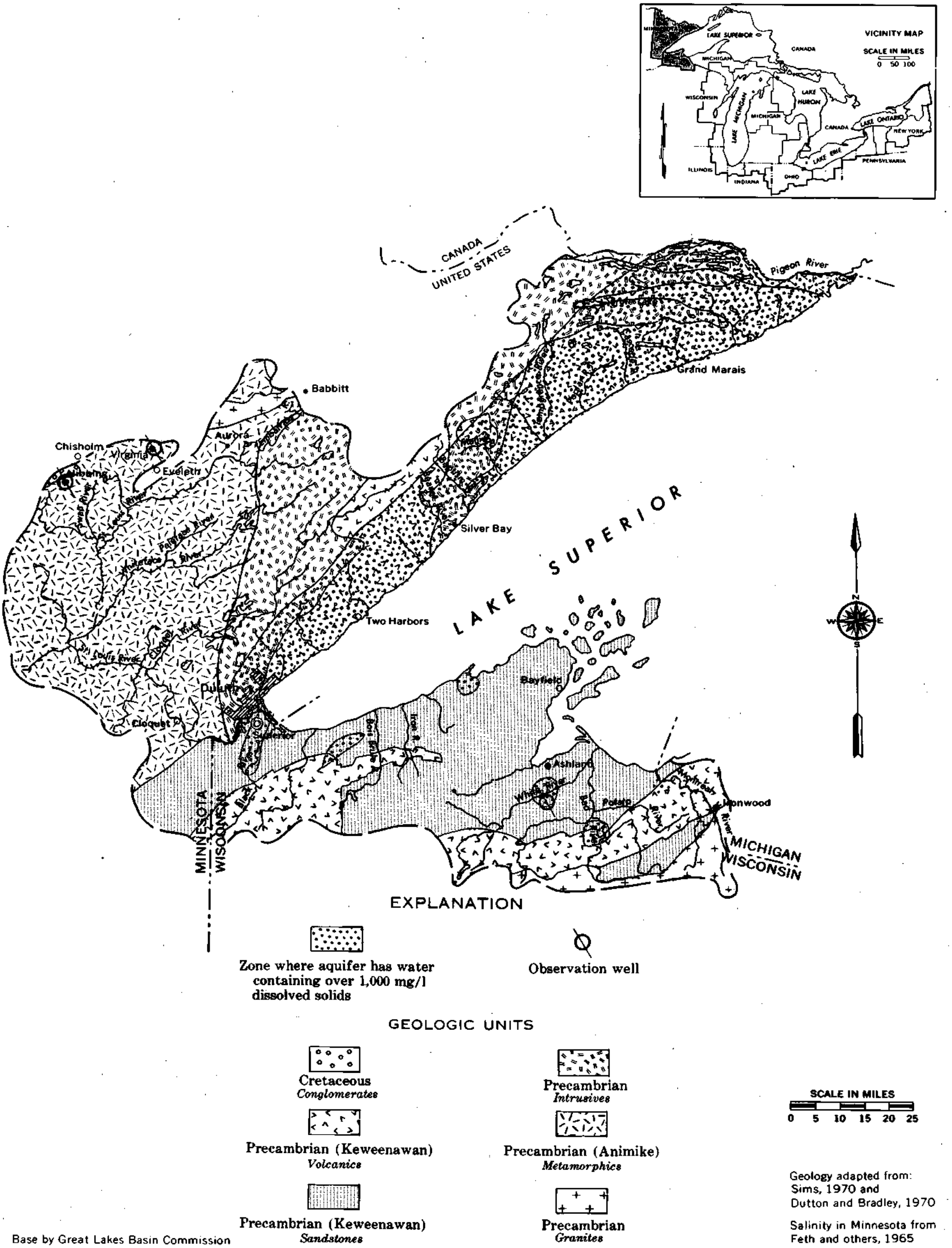


FIGURE 3–9 Bedrock Geology and Areas of Mineralized Ground Water in River Basin Group 1.1

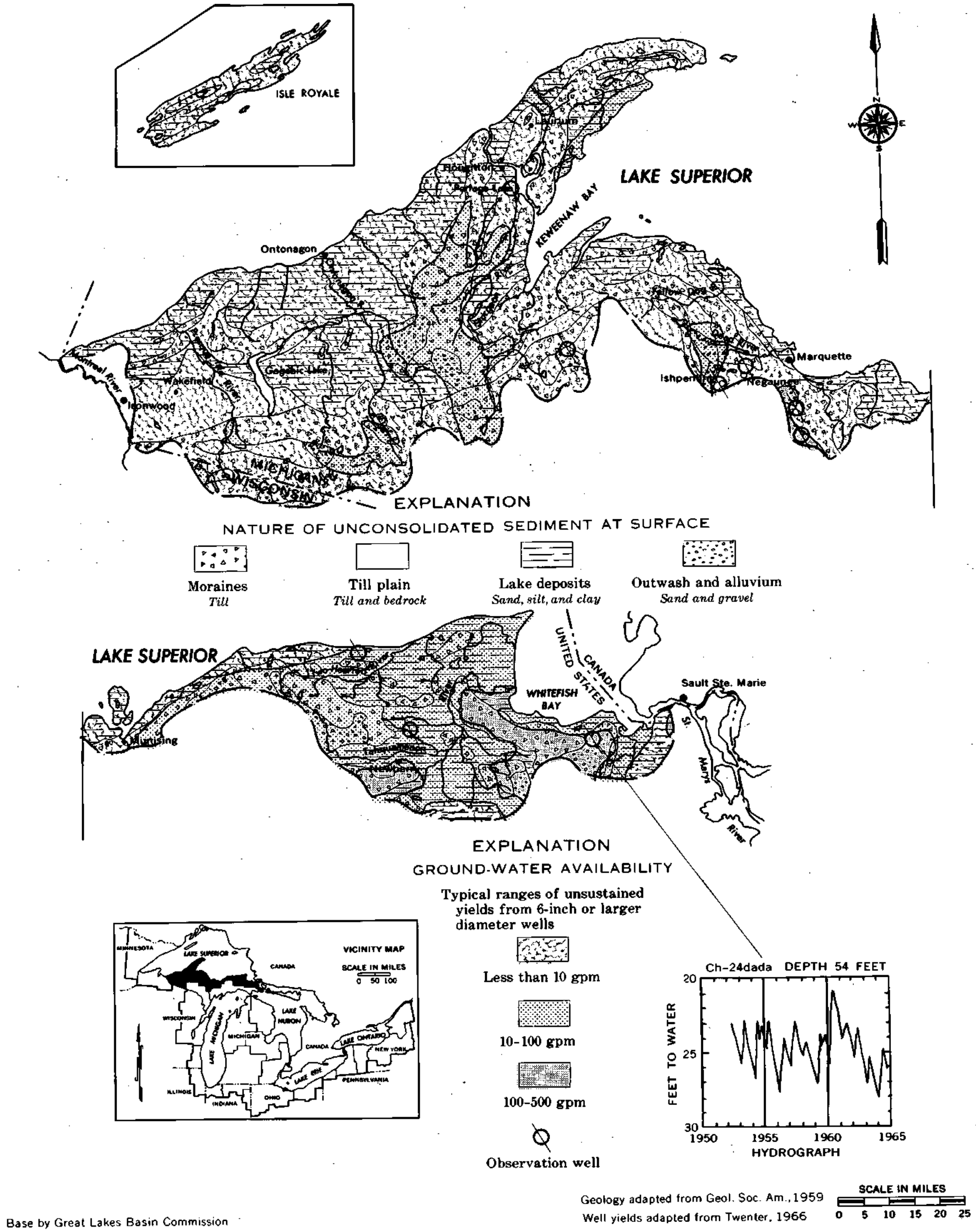


FIGURE 3–10 Ground Water in the Unconsolidated Sediments in River Basin Group 1.2

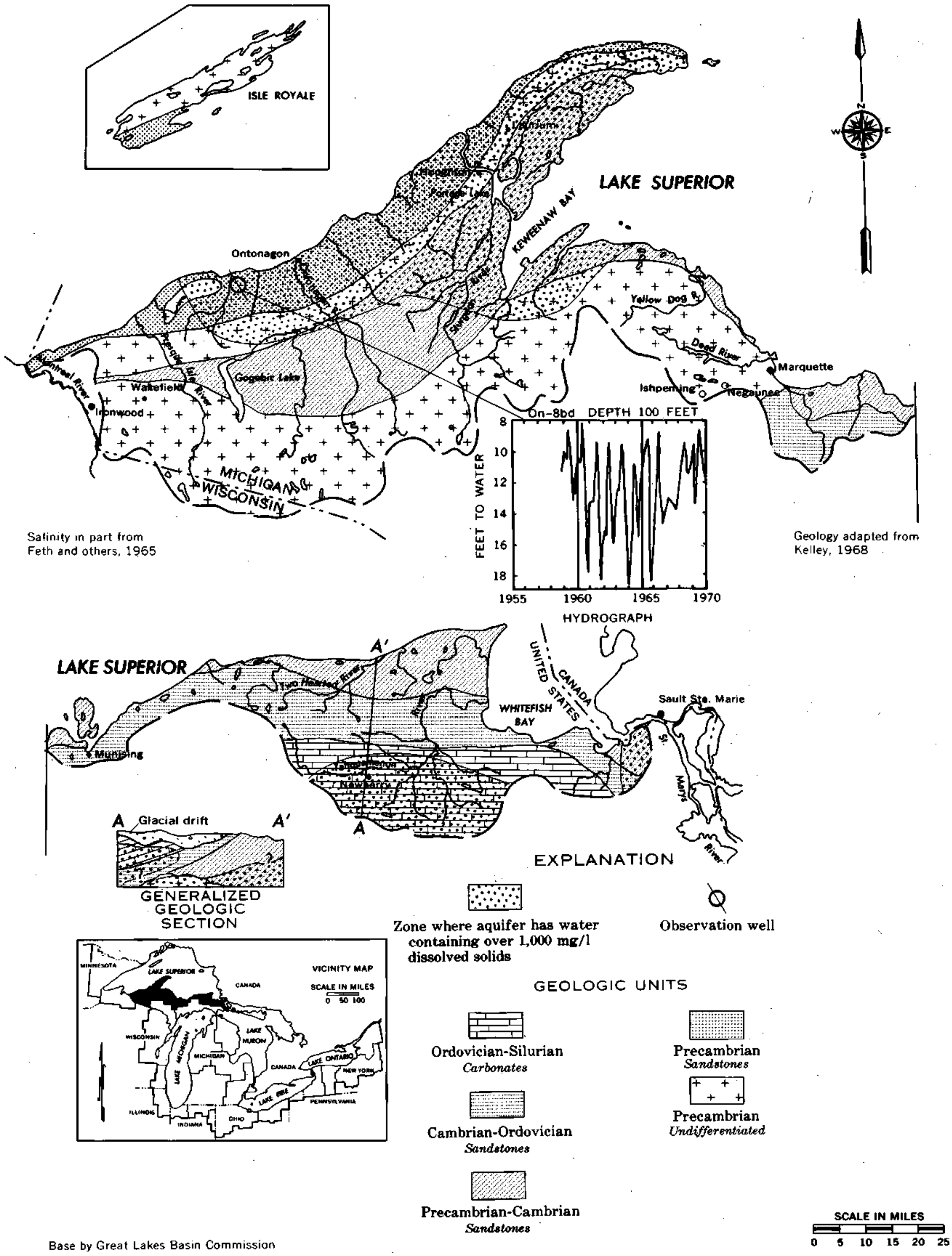


FIGURE 3–11 Bedrock Geology and Areas of Mineralized Ground Water in River Basin Group 1.2

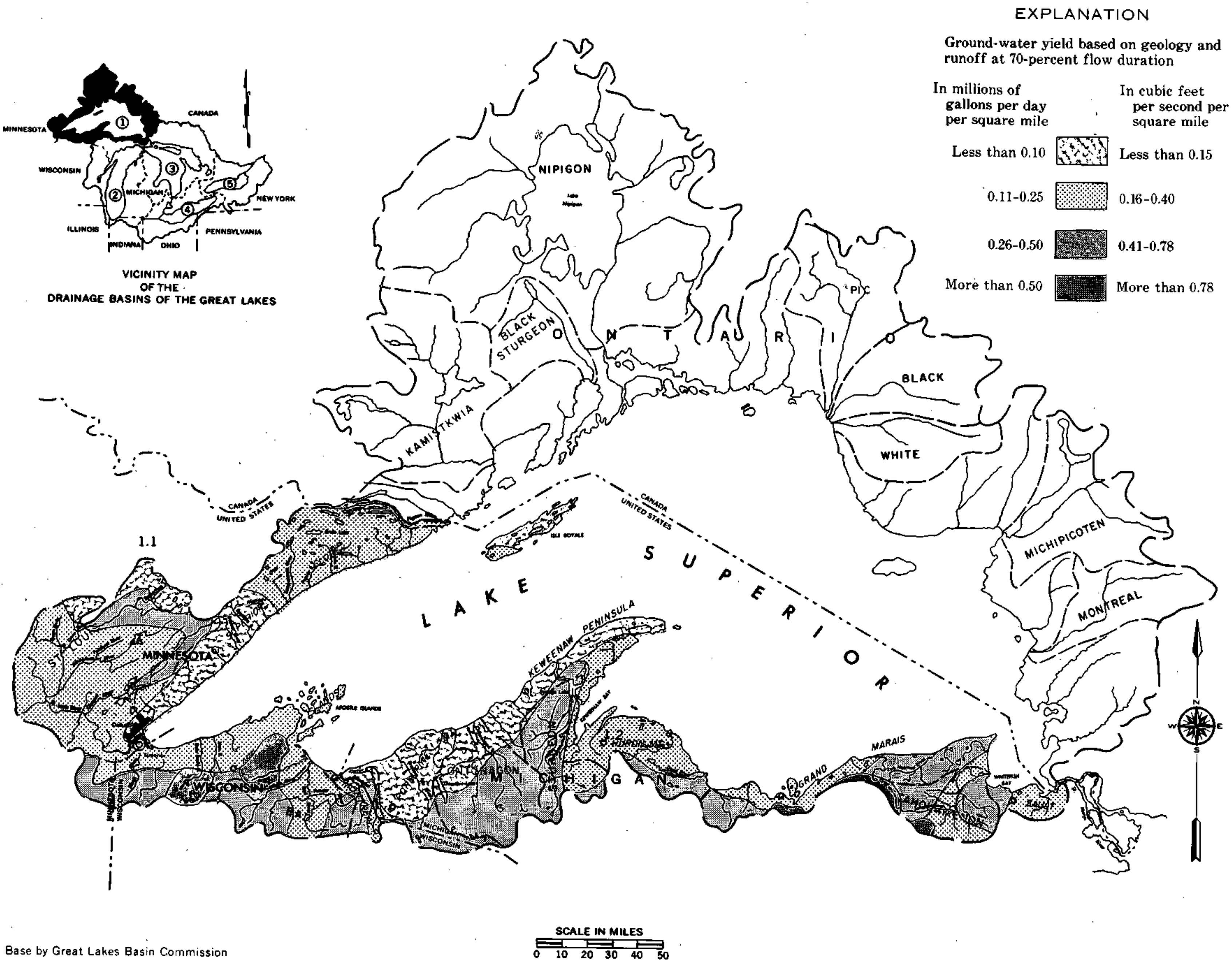


FIGURE 3-12 Estimated Ground-Water Yield, as Runoff, in the Lake Superior Basin, United States

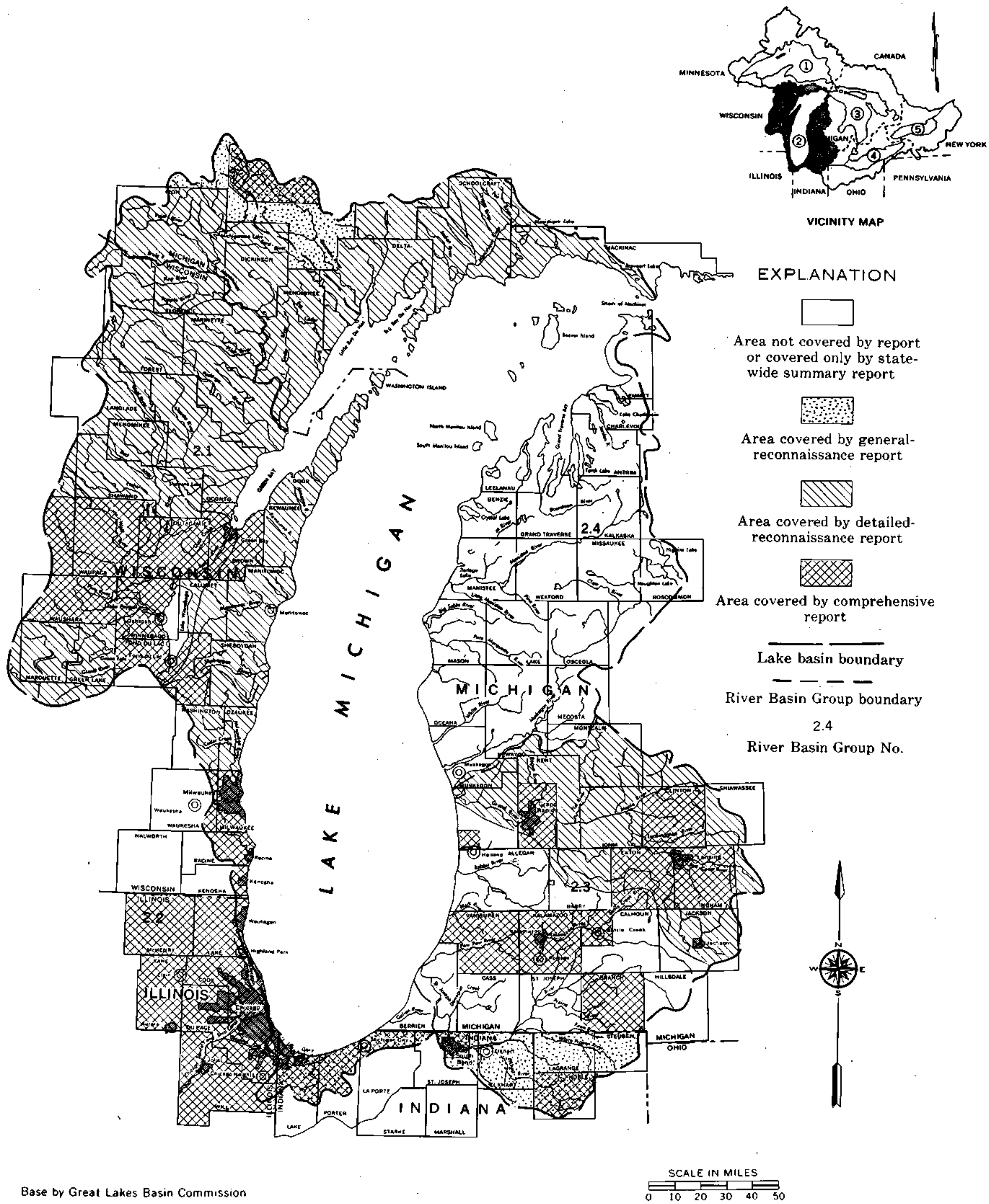


FIGURE 3–13 Map of the Lake Michigan Basin Plan Area Showing River Basin Groups and Areas Covered by Ground-Water Reports

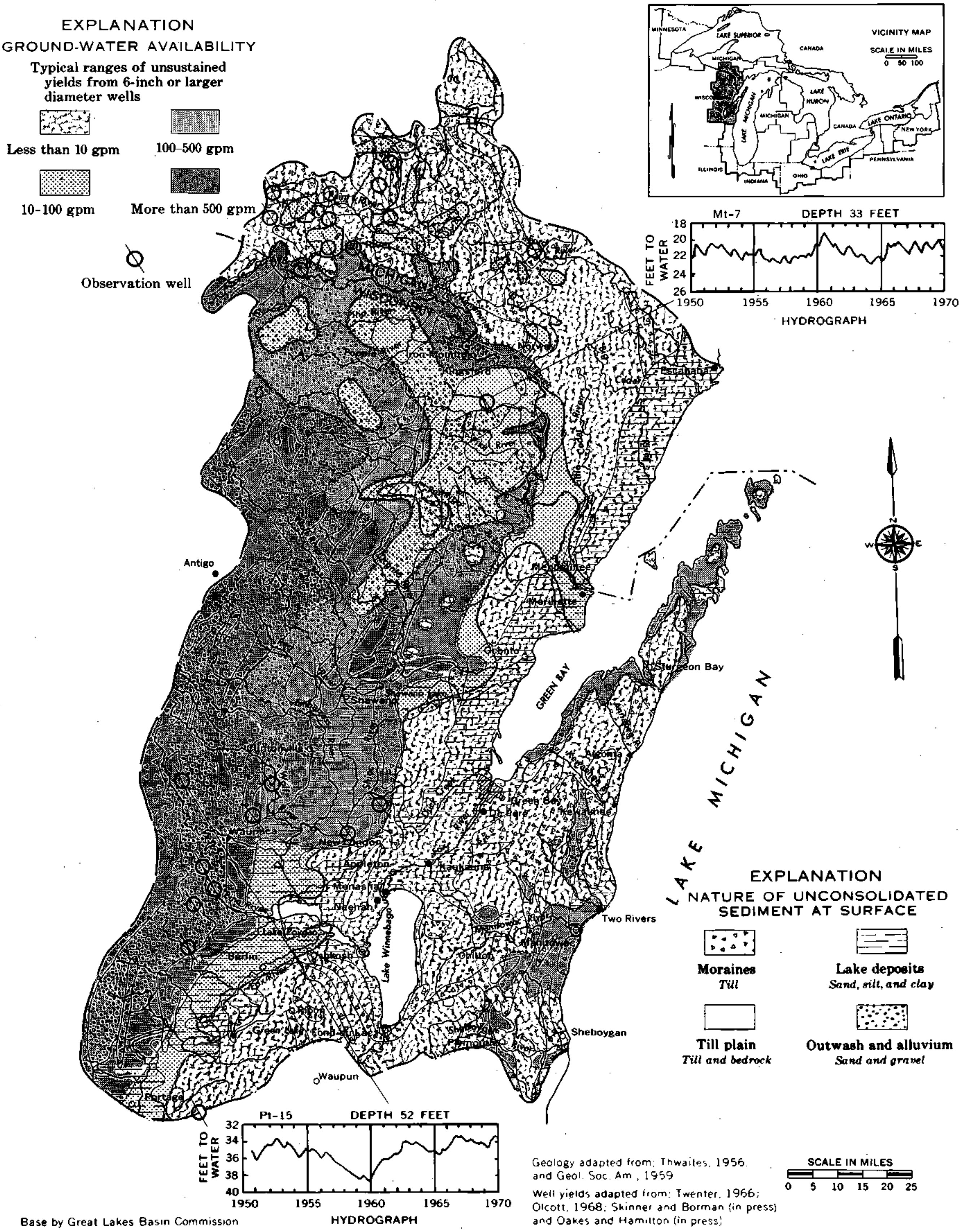


FIGURE 3-14 Ground Water in the Unconsolidated Sediments in River Basin Group 2.1

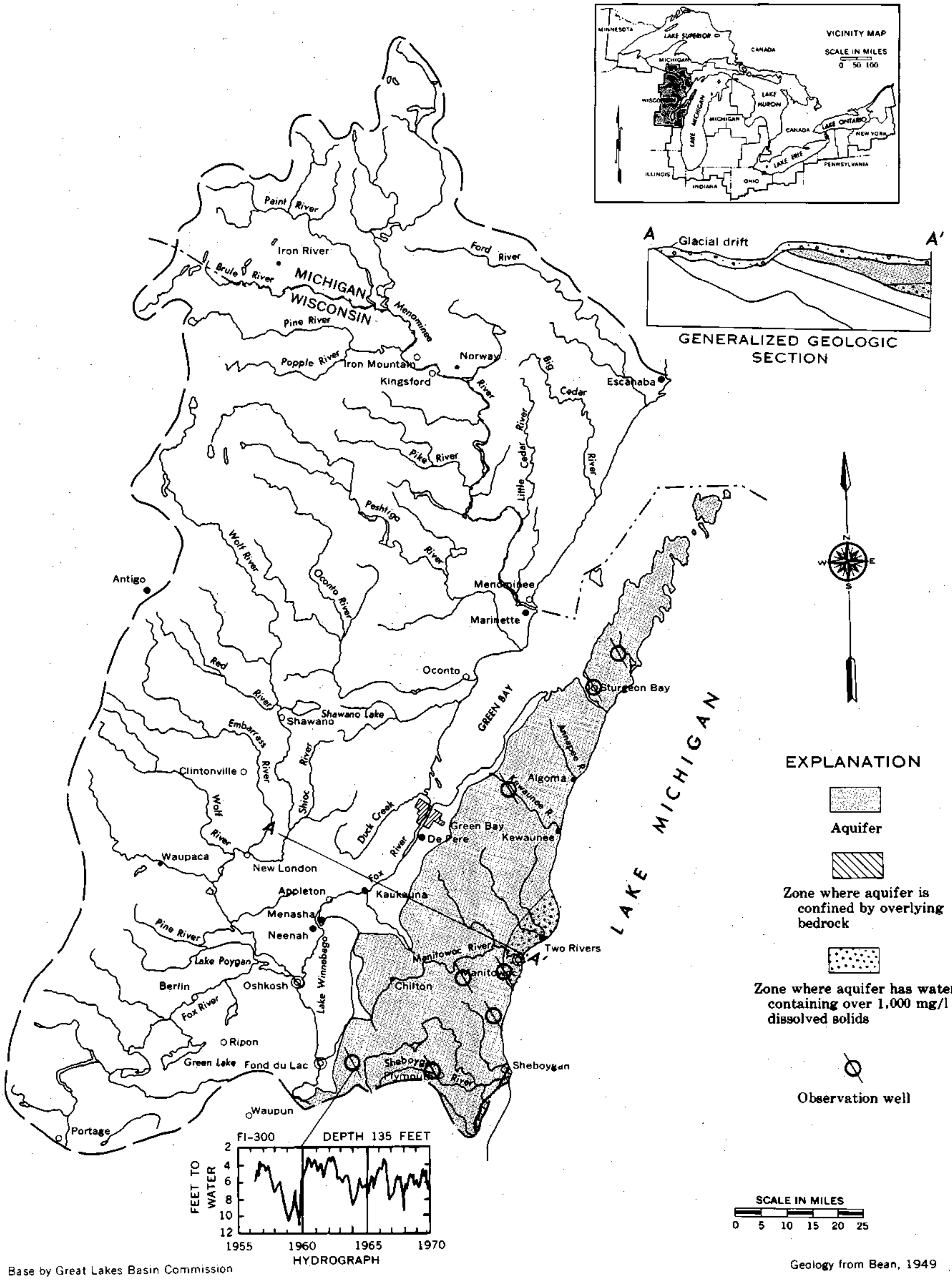


FIGURE 3-15 The Silurian (Niagara) Aquifer System in River Basin Group 2.1

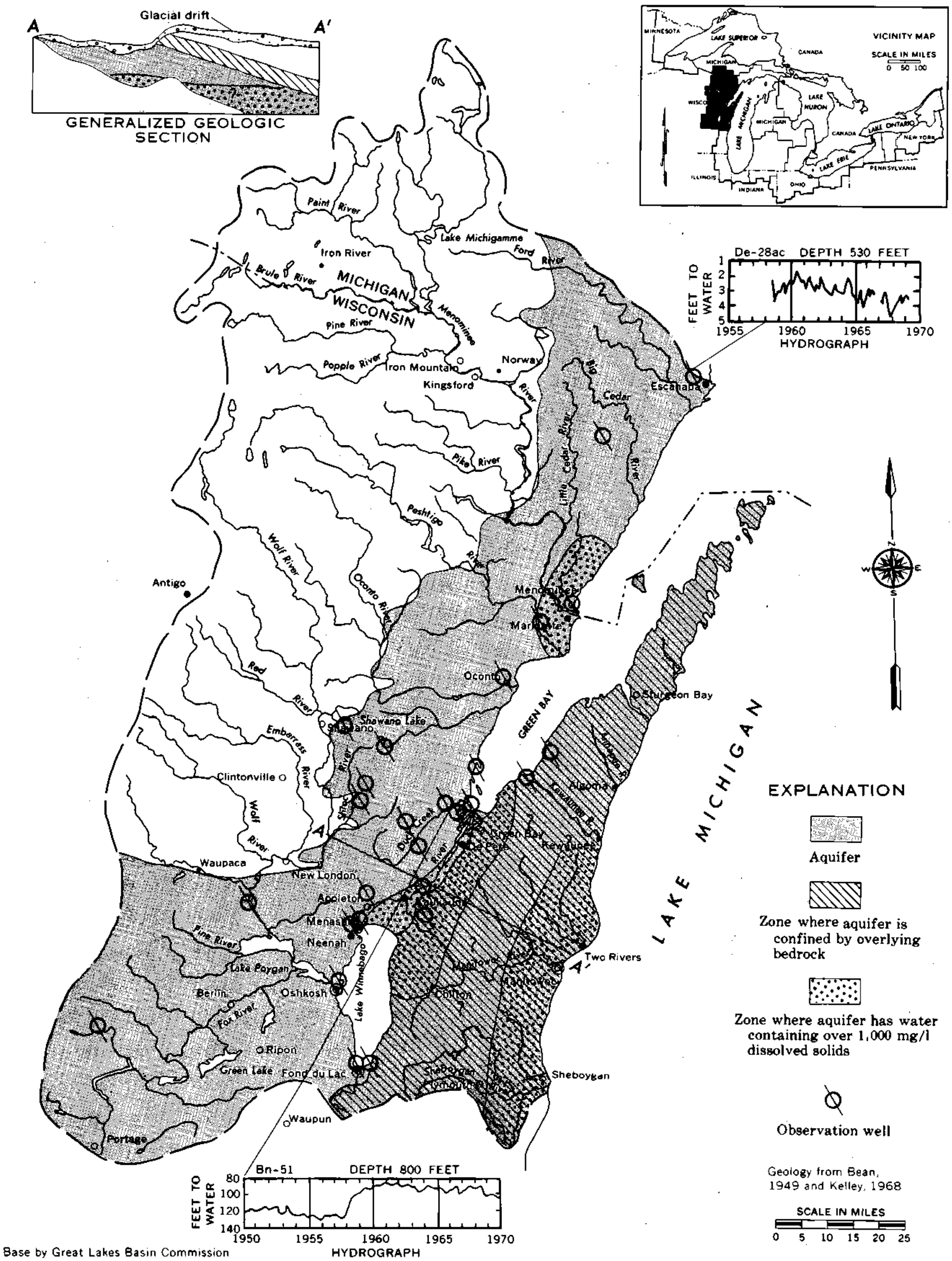


FIGURE 3-16 The Cambrian-Ordovician Aquifer System in River Basin Group 2.1

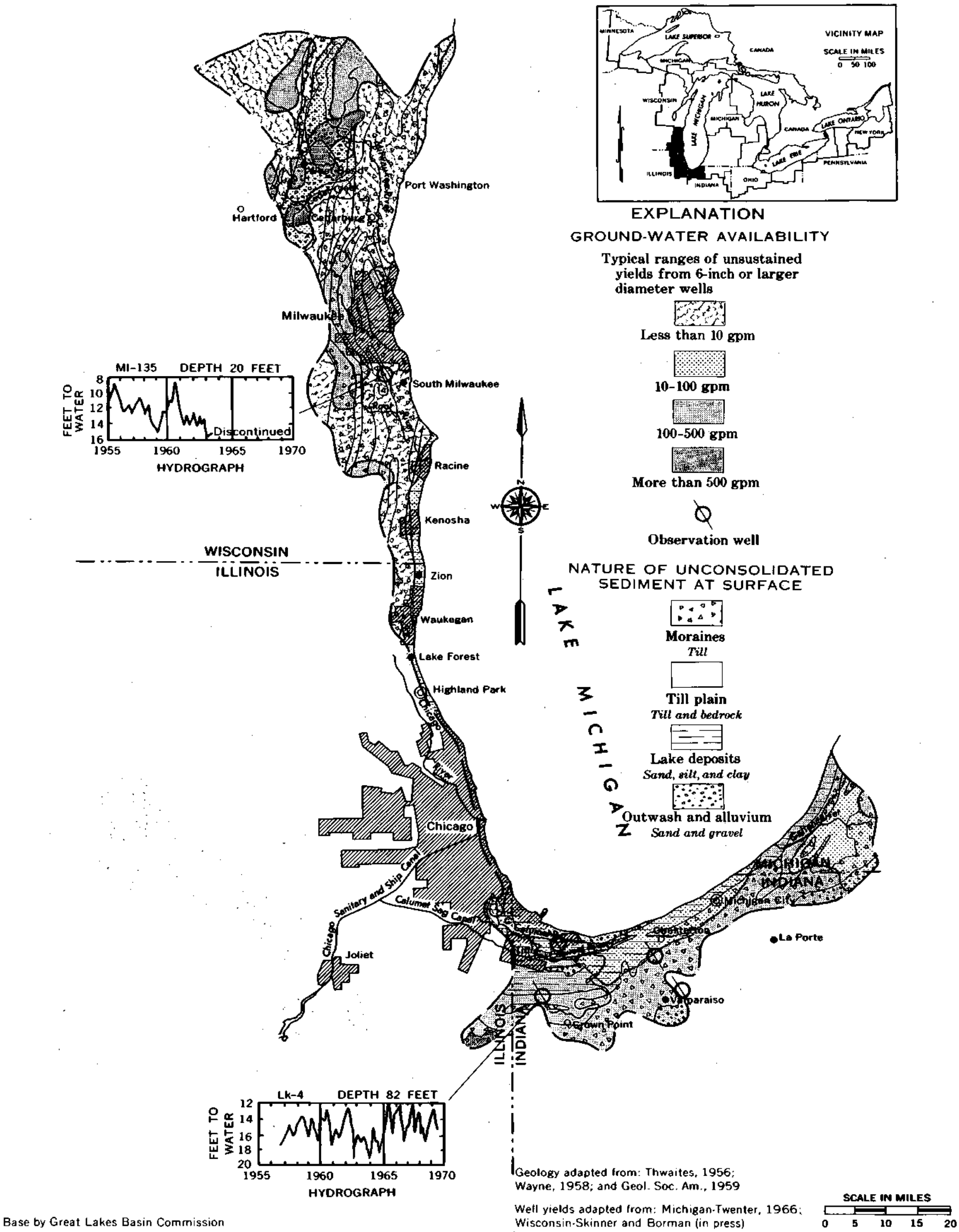


FIGURE 3–17 Ground Water in the Unconsolidated Sediments in River Basin Group 2.2

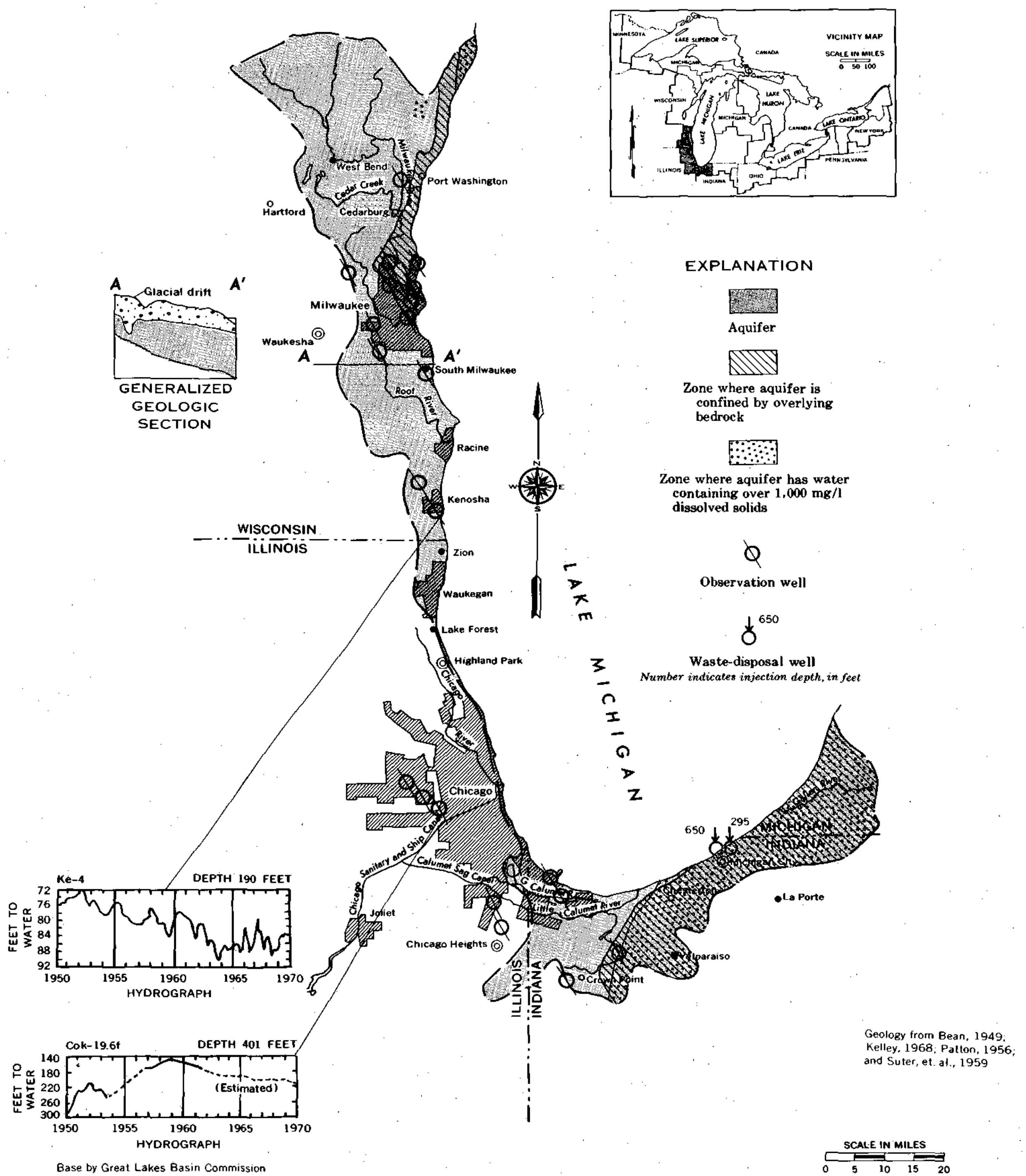


FIGURE 3–18 The Silurian Aquifer System in River Basin Group 2.2

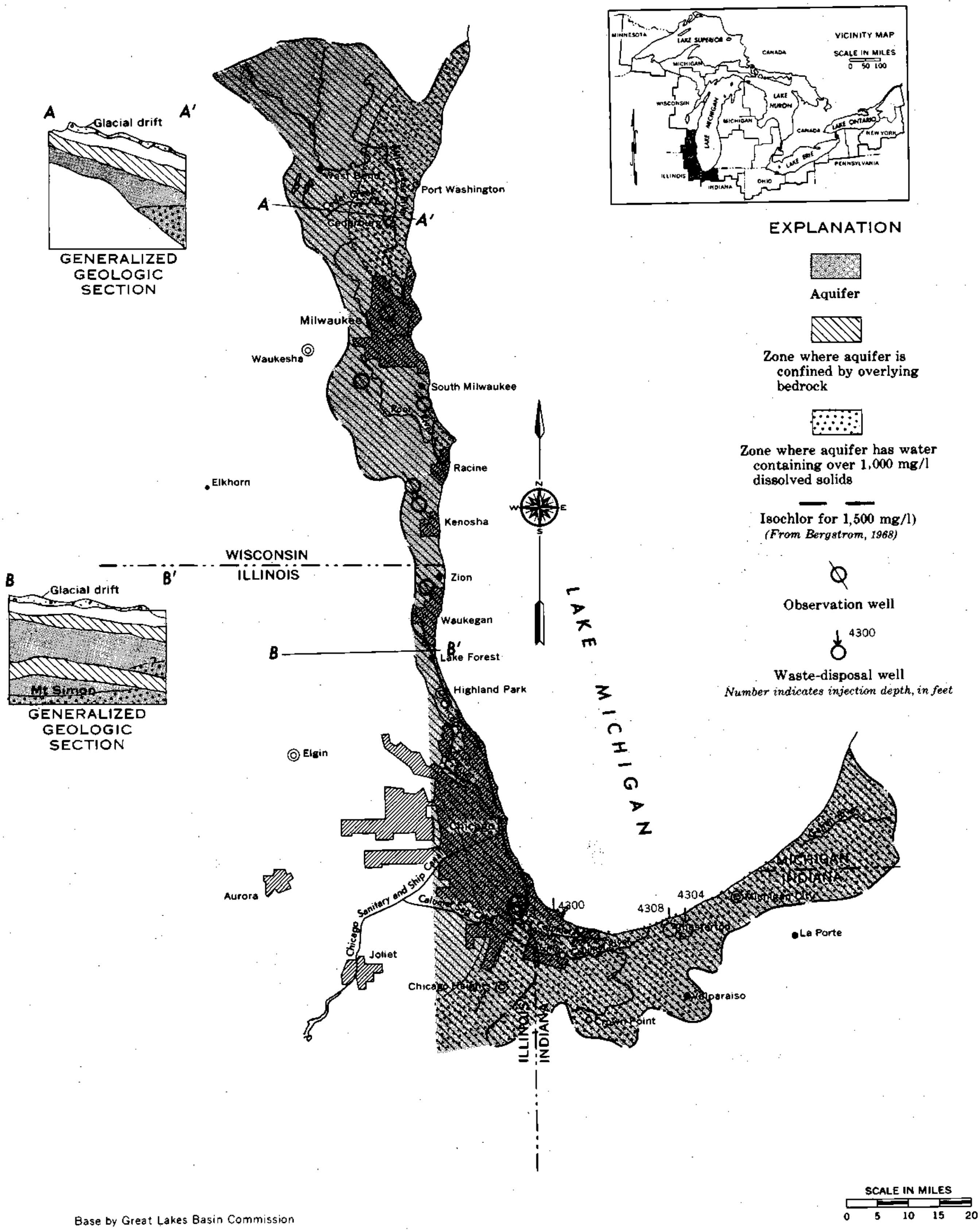


FIGURE 3–19 The Cambrian-Ordovician Aquifer System in River Basin Group 2.2

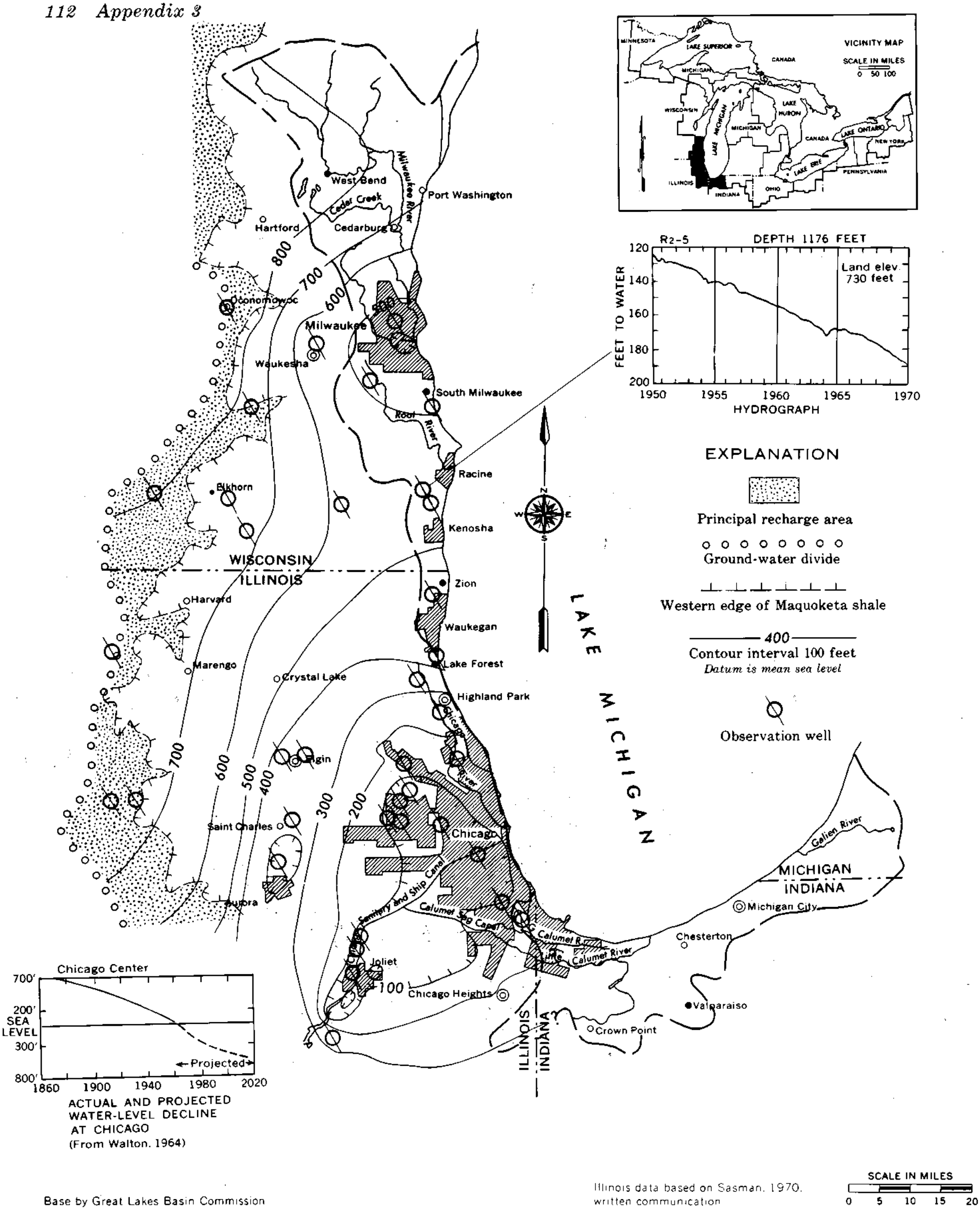


FIGURE 3–20 Potentiometric Surface of the Cambrian-Ordovician Aquifer System, 1969, in the Chicago-Milwaukee Area

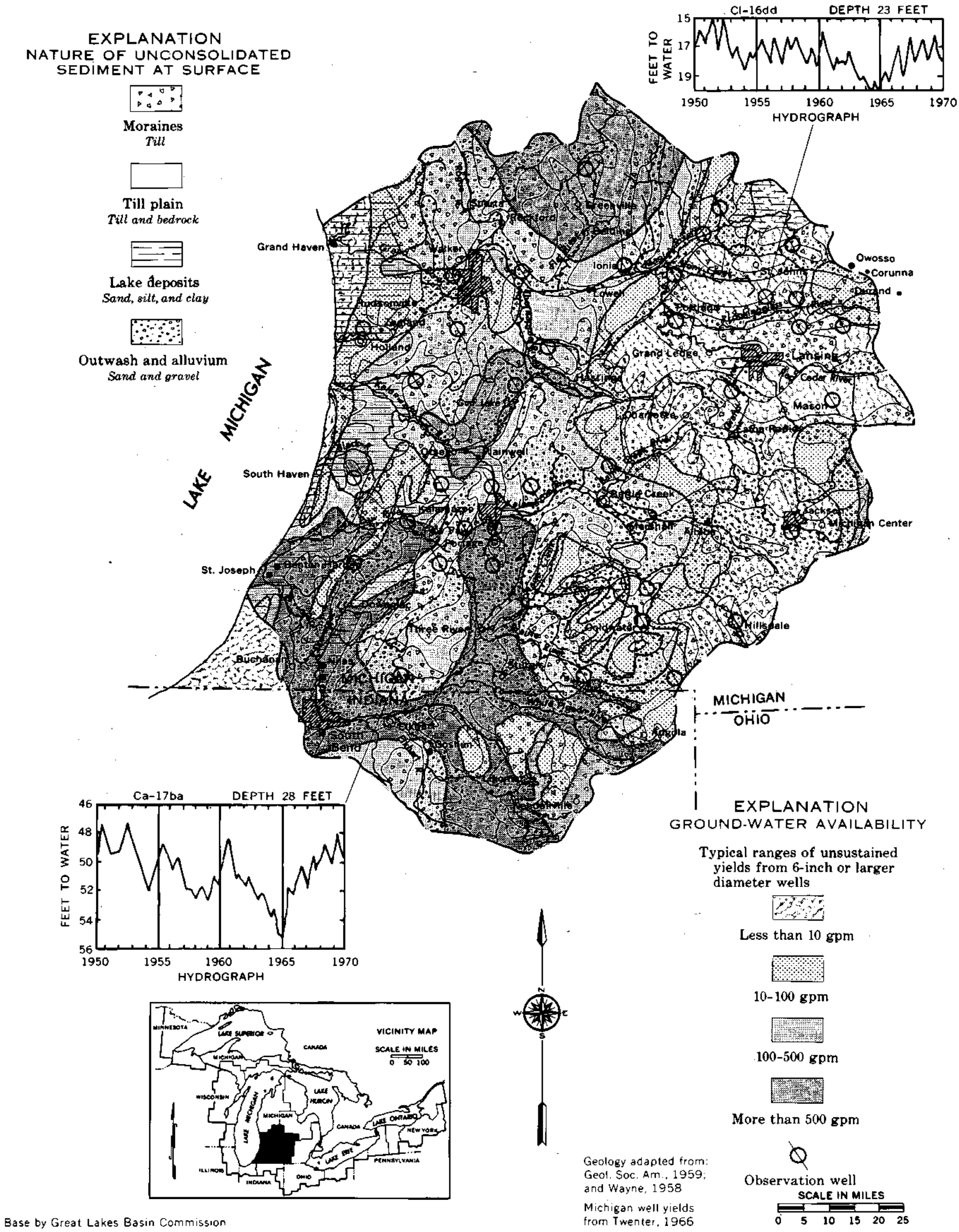


FIGURE 3–21 Ground Water in the Unconsolidated Sediments in River Basin Group 2.3

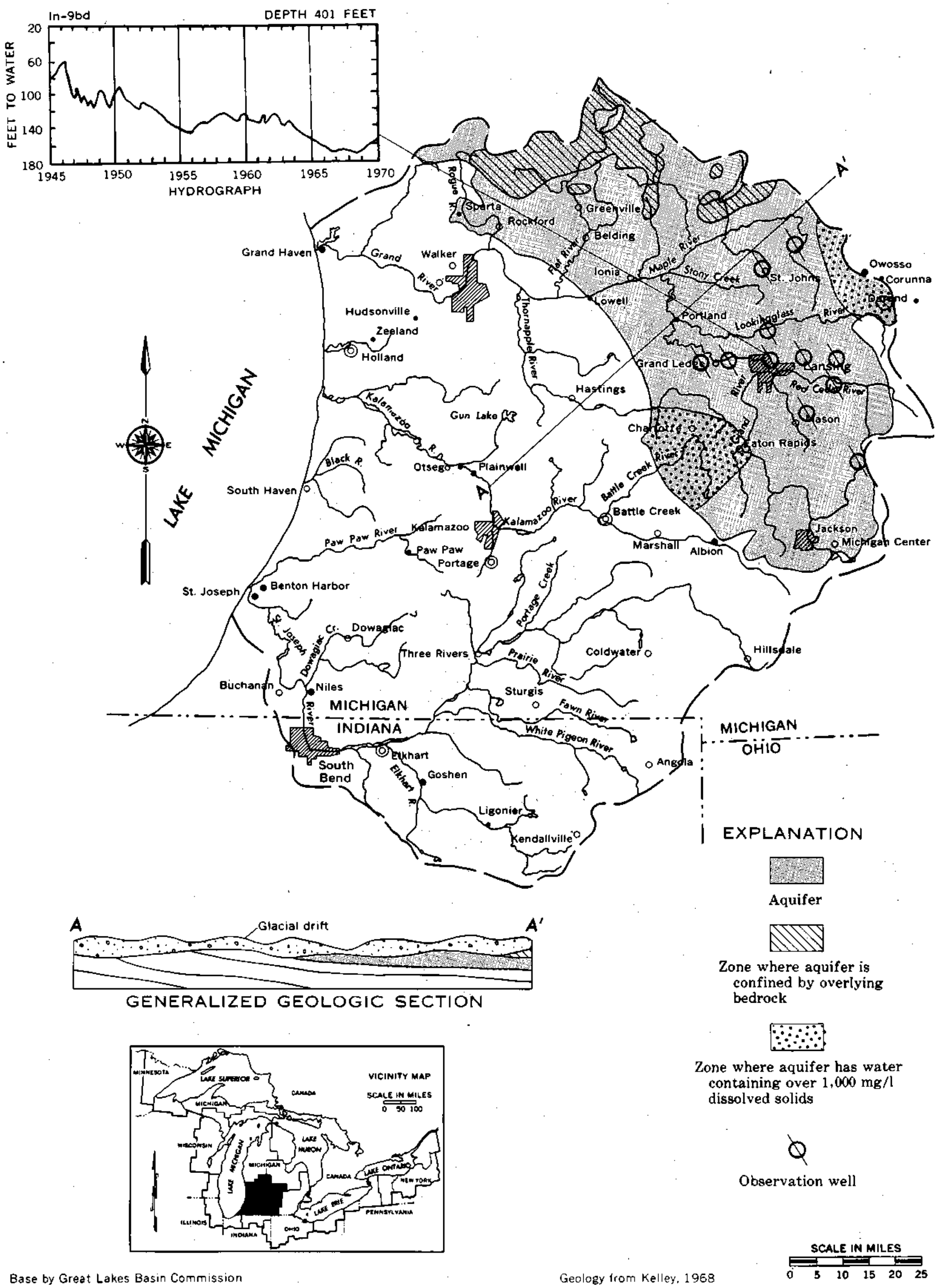


FIGURE 3–22 The Pennsyvanian (Saginaw) Aquifer System in River Basin Group 2.3

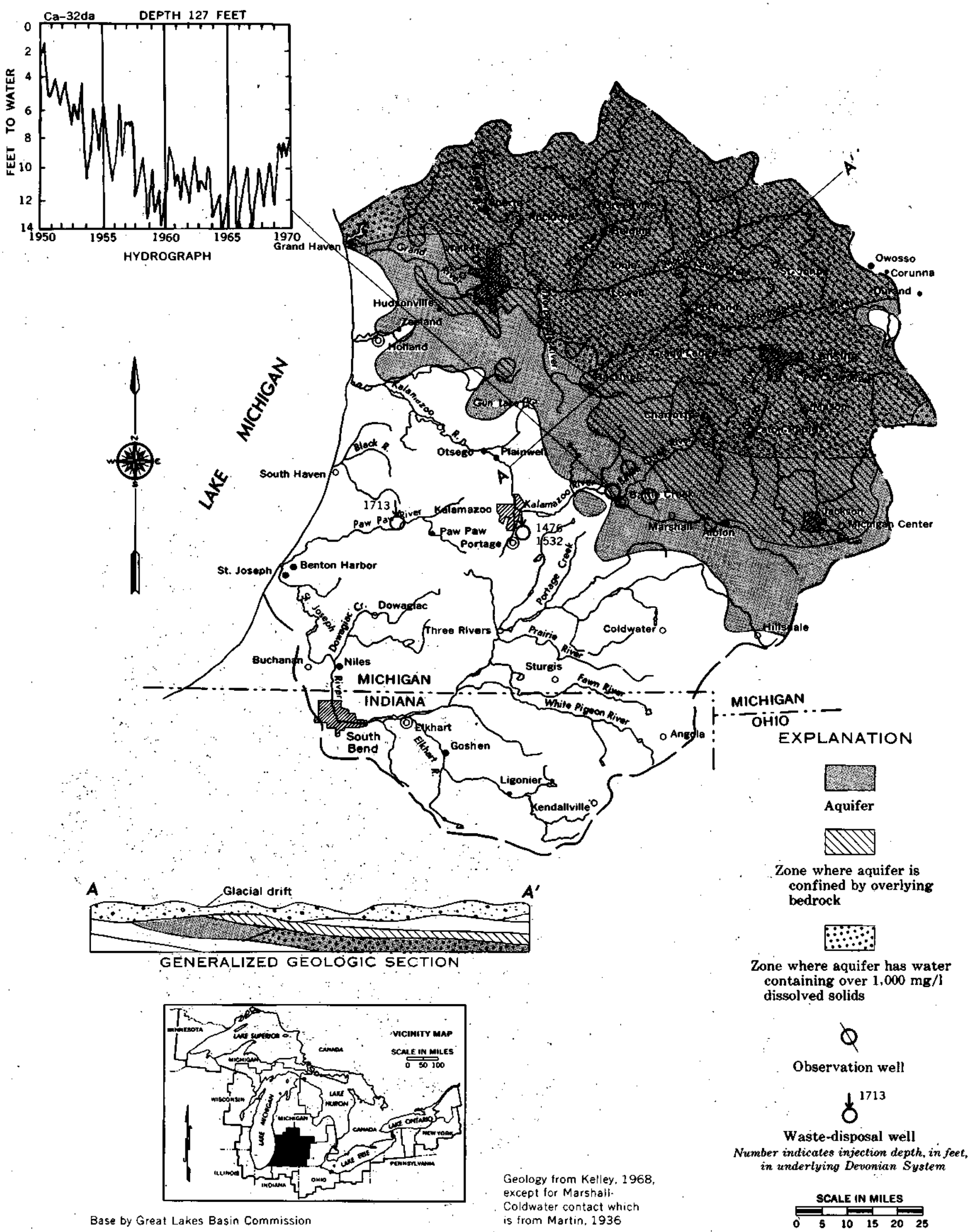


FIGURE 3–23 The Mississippian (Marshall) Aquifer System in River Basin Group 2.3

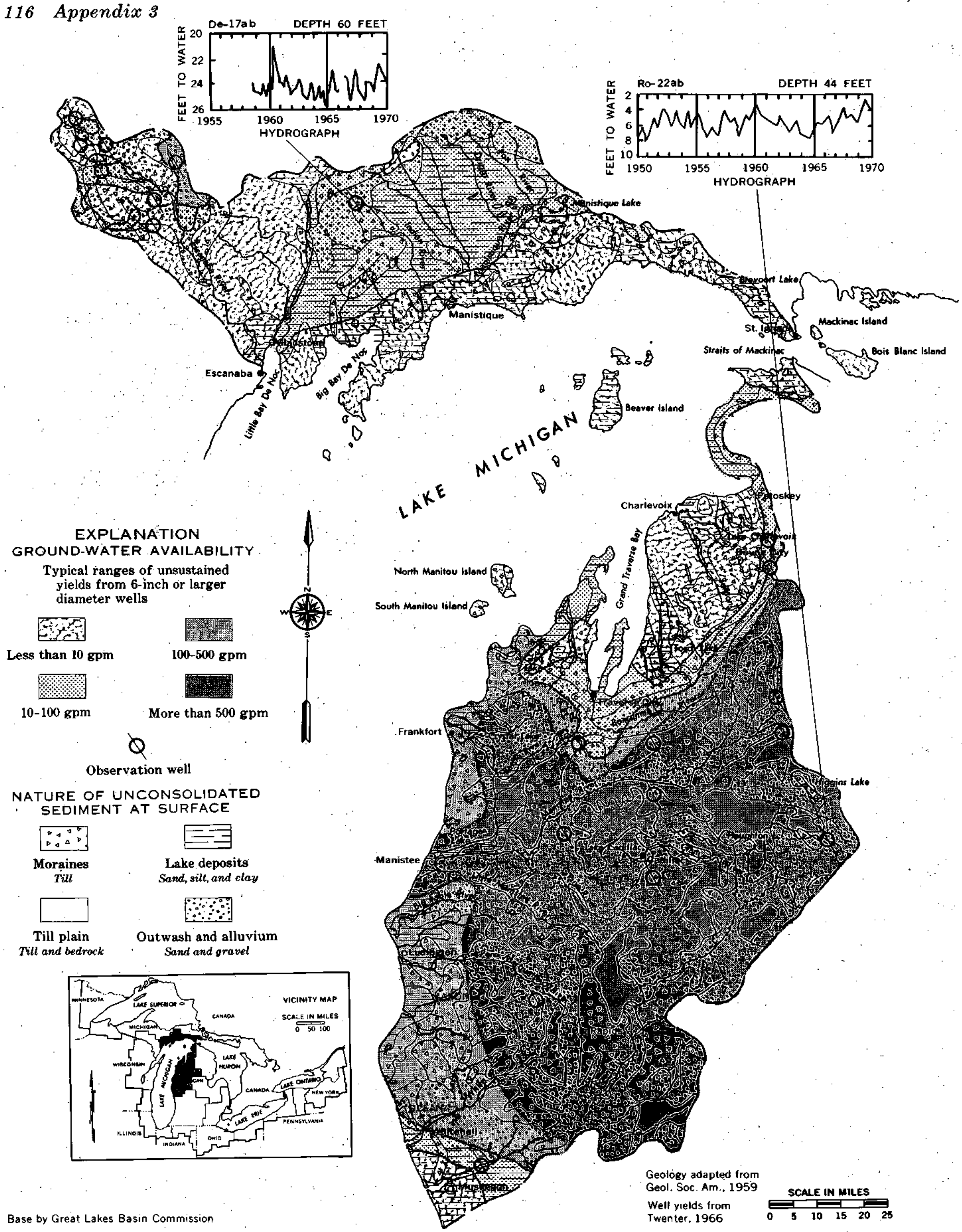


FIGURE 3–24 Ground Water in the Unconsolidated Sediments in River Basin Group 2.4

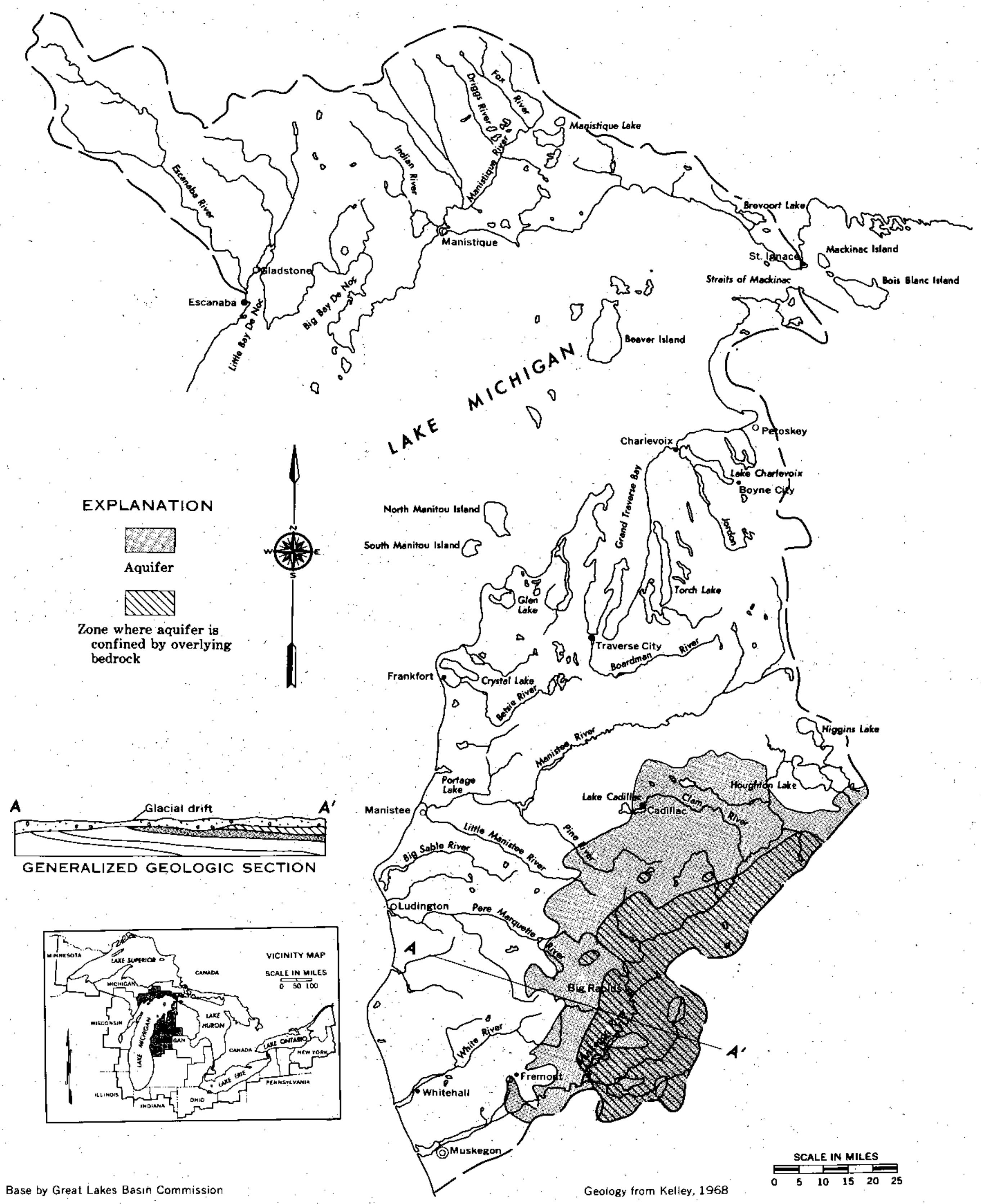


FIGURE 3-25 The Pennsylvanian (Saginaw) Aquifer System in River Basin Group 2.4

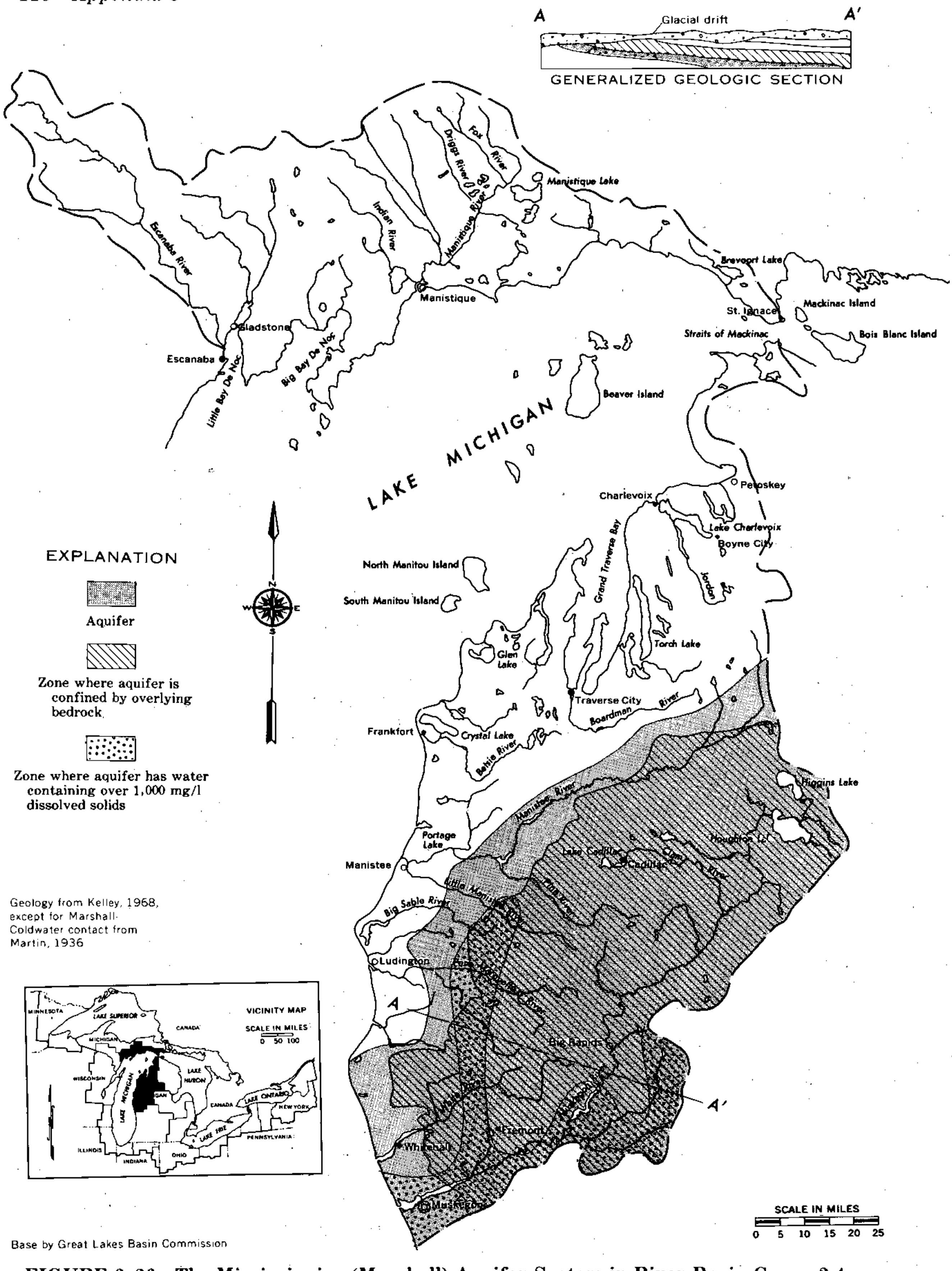


FIGURE 3–26 The Mississippian (Marshall) Aquifer System in River Basin Group 2.4

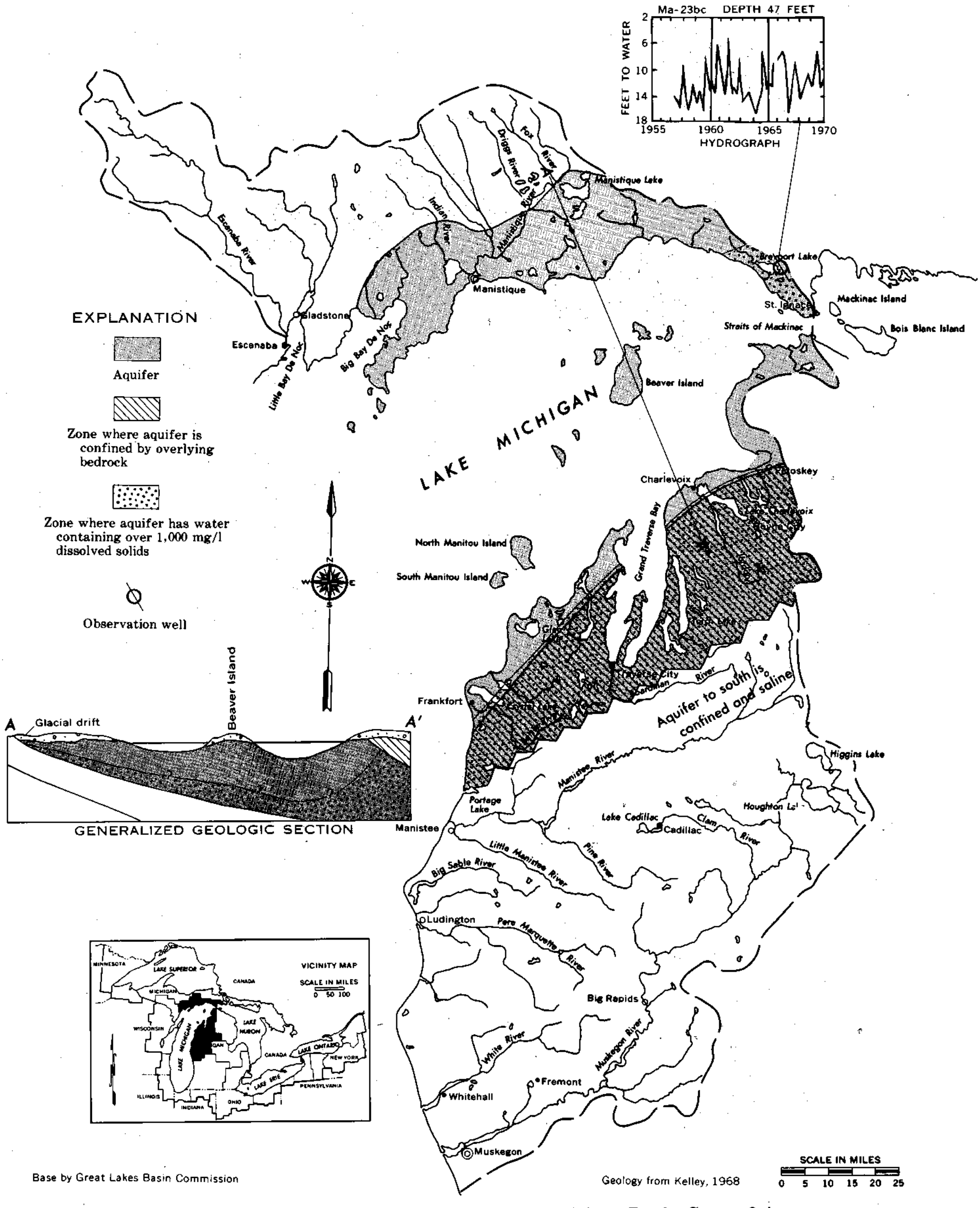


FIGURE 3–27 The Silurian-Devonian Aquifer System in River Basin Group 2.4

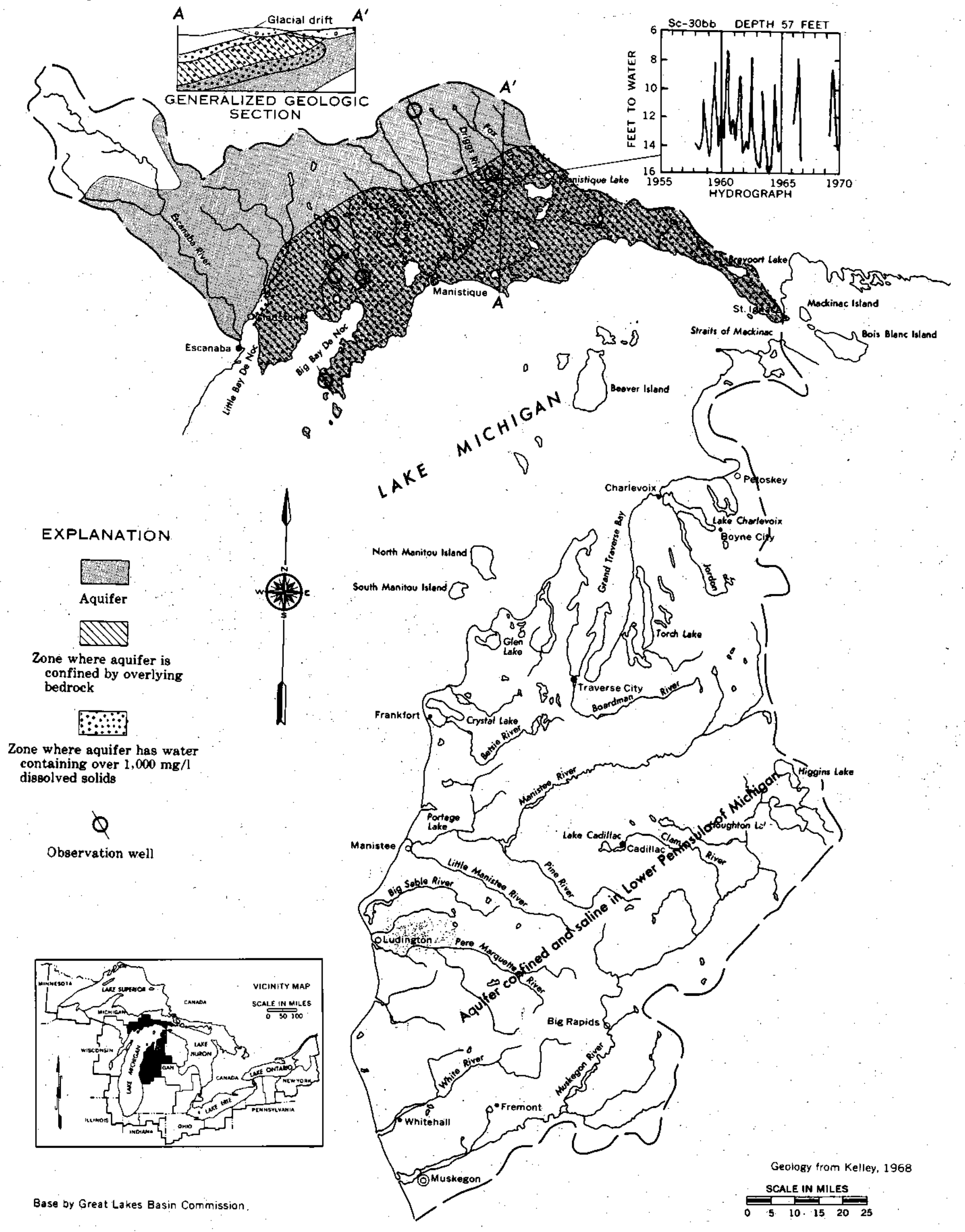


FIGURE 3–28 The Cambrian-Ordovician Aquifer System in River Basin Group 2.4

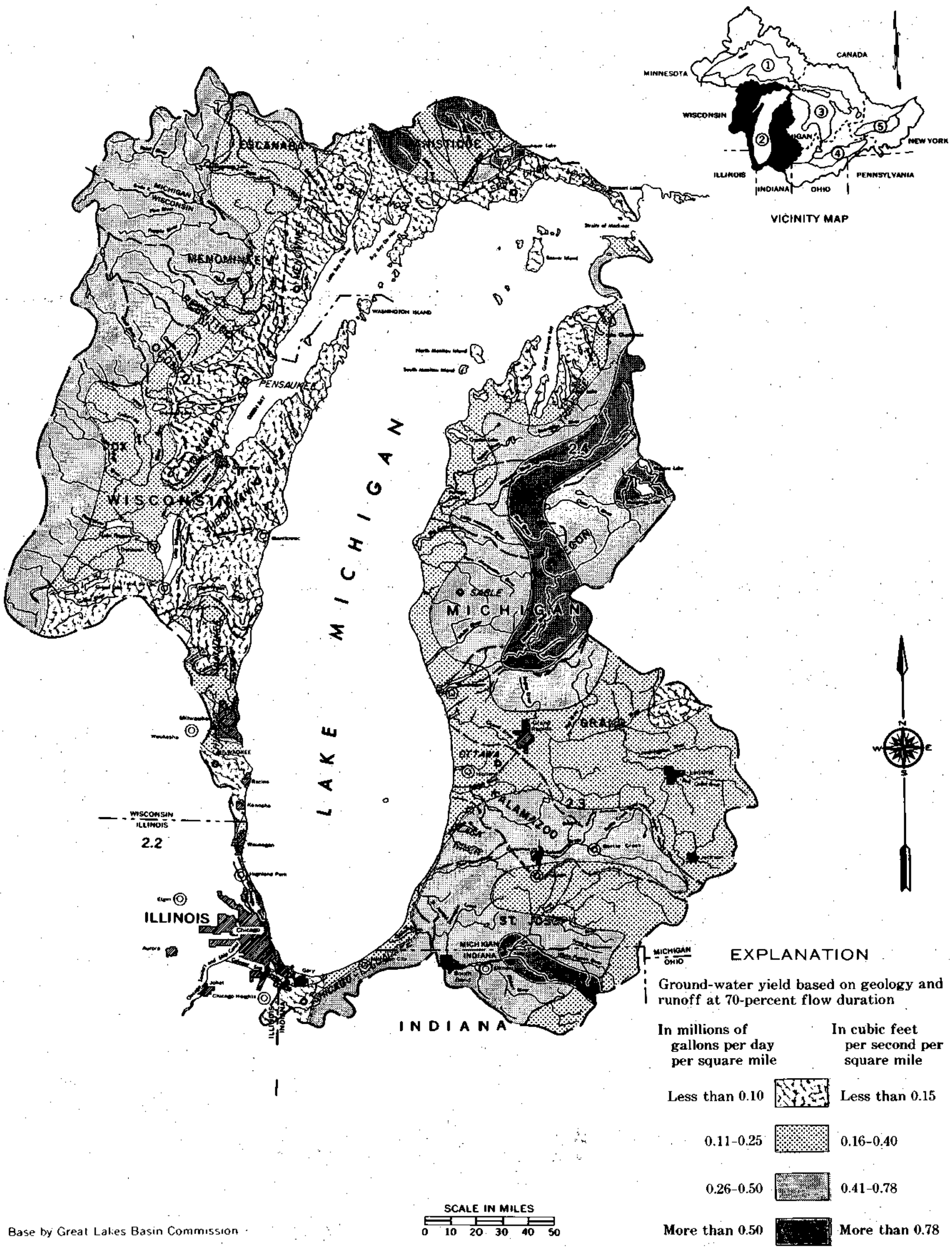


FIGURE 3–29 Estimated Ground-Water Yield, as Runoff, in the Lake Michigan Basin

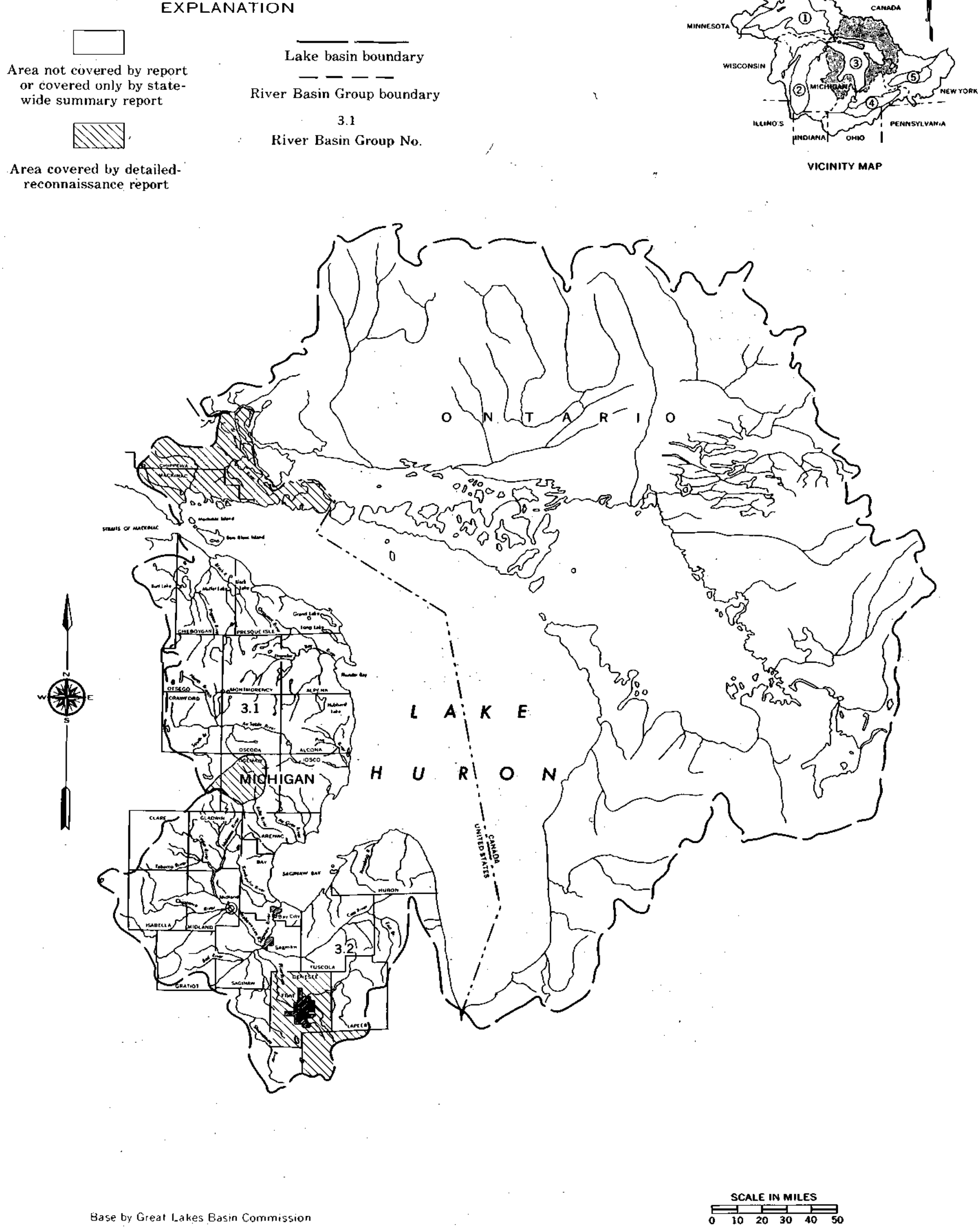


FIGURE 3–30 Map of the Lake Huron Basin Plan Area Showing River Basin Groups and Areas Covered by Ground-Water Reports

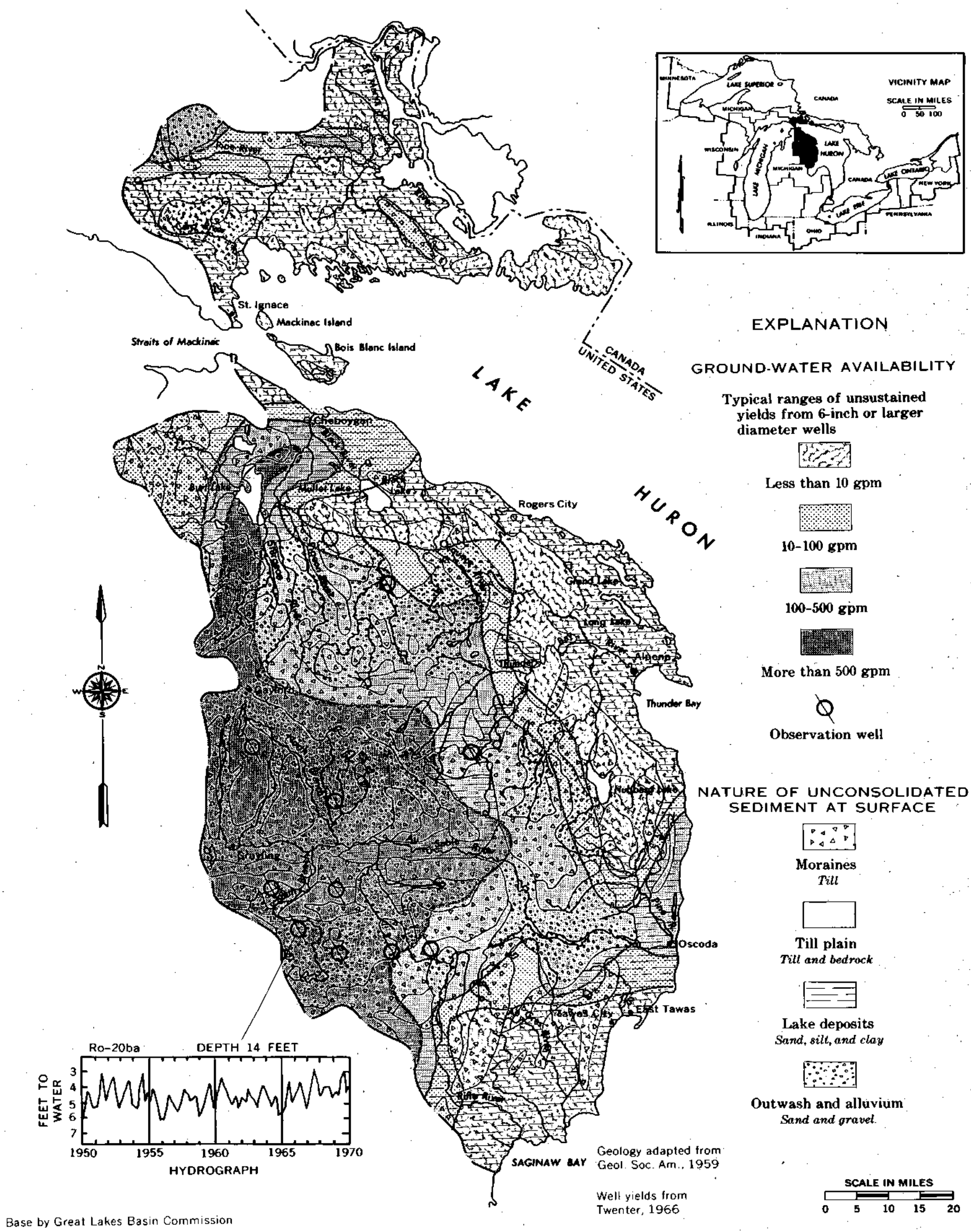


FIGURE 3-31 Ground Water in the Unconsolidated Sediments in River Basin Group 3.1

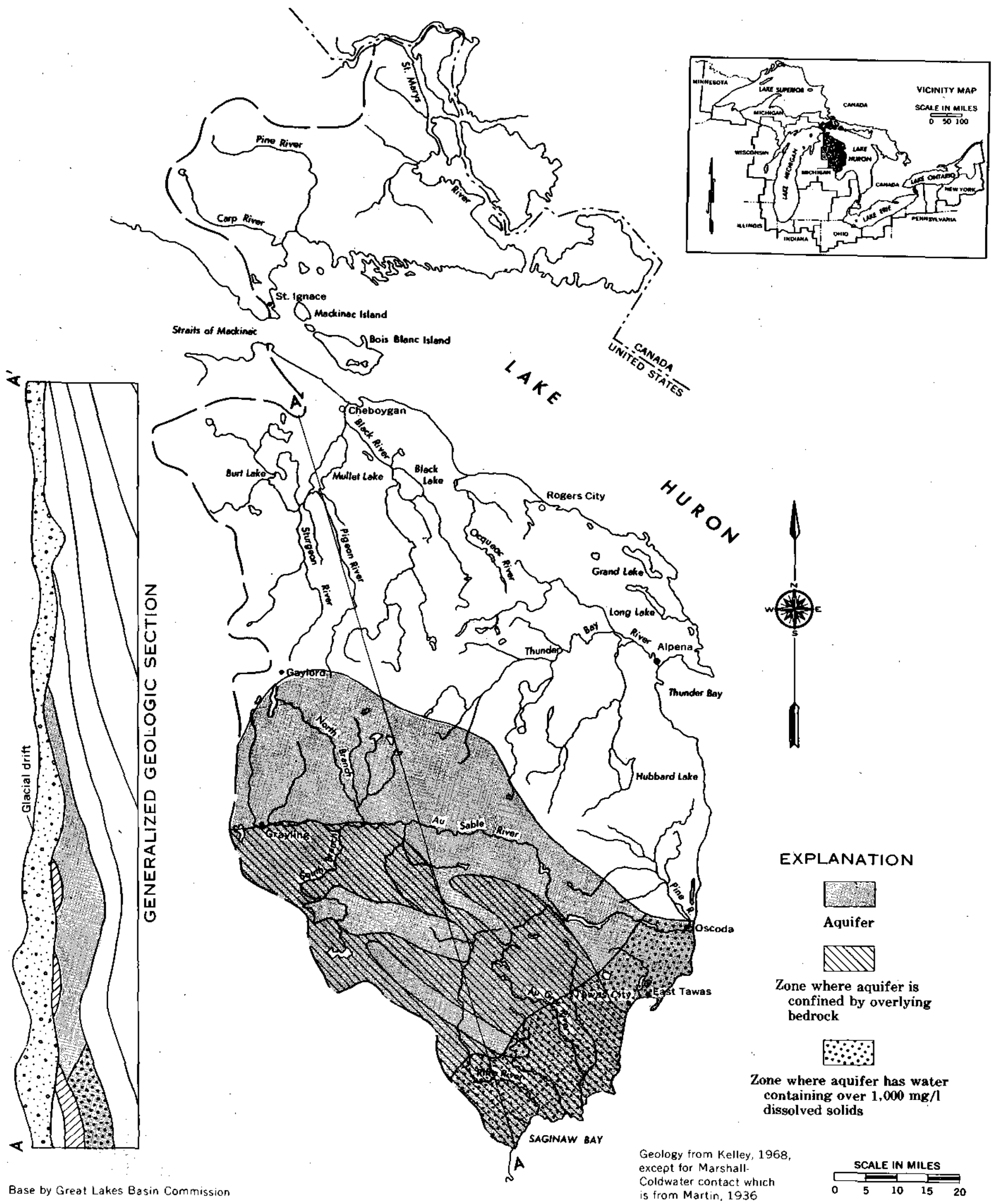


FIGURE 3–32 The Mississippian (Marshall) Aquifer System in River Basin Group 3.1

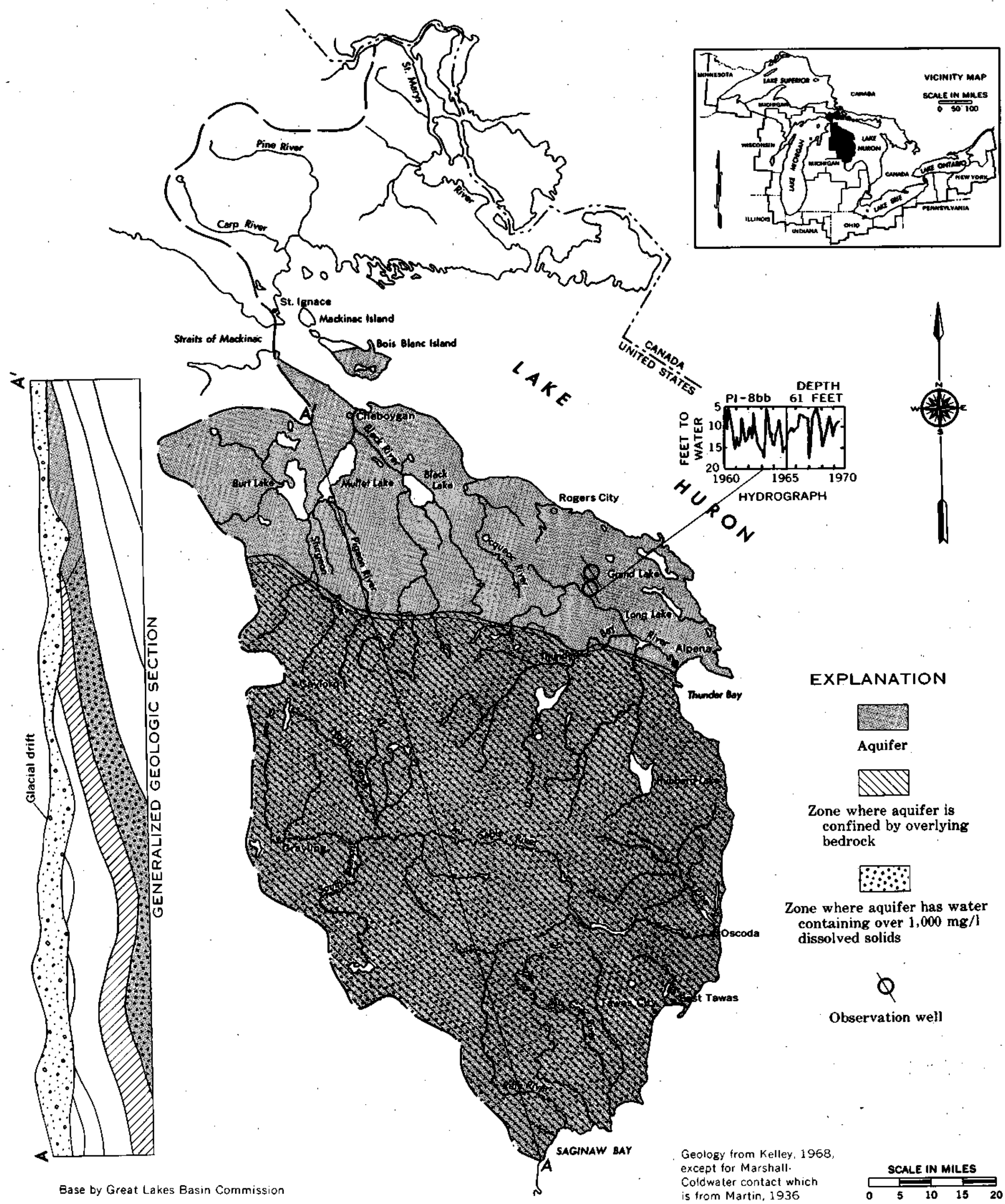


FIGURE 3–33 The Devonian Aquifer System in River Basin Group 3.1

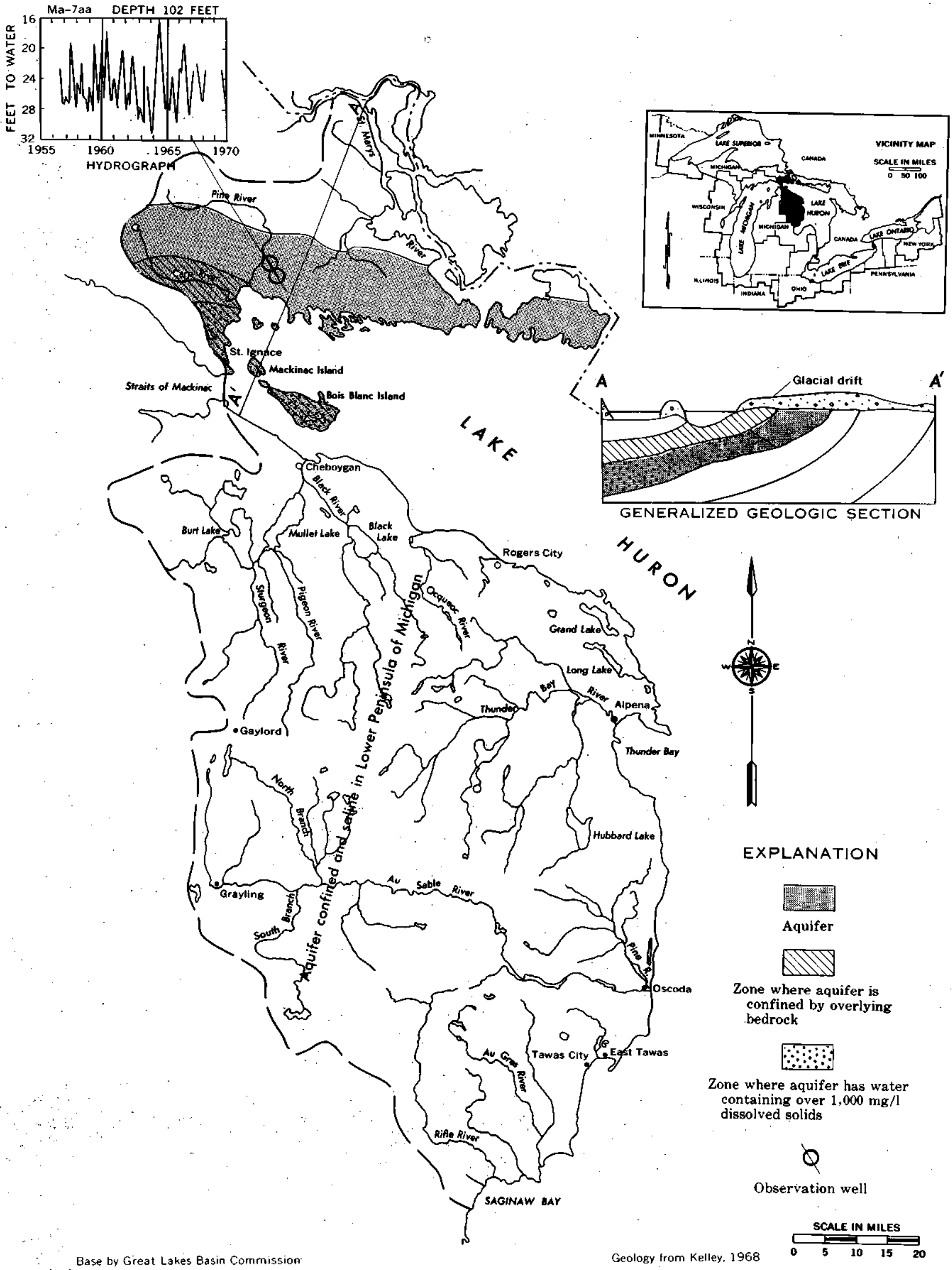


FIGURE 3–34 The Silurian (Burnt Bluff-Engadine) Aquifer System in River Basin Group 3.1

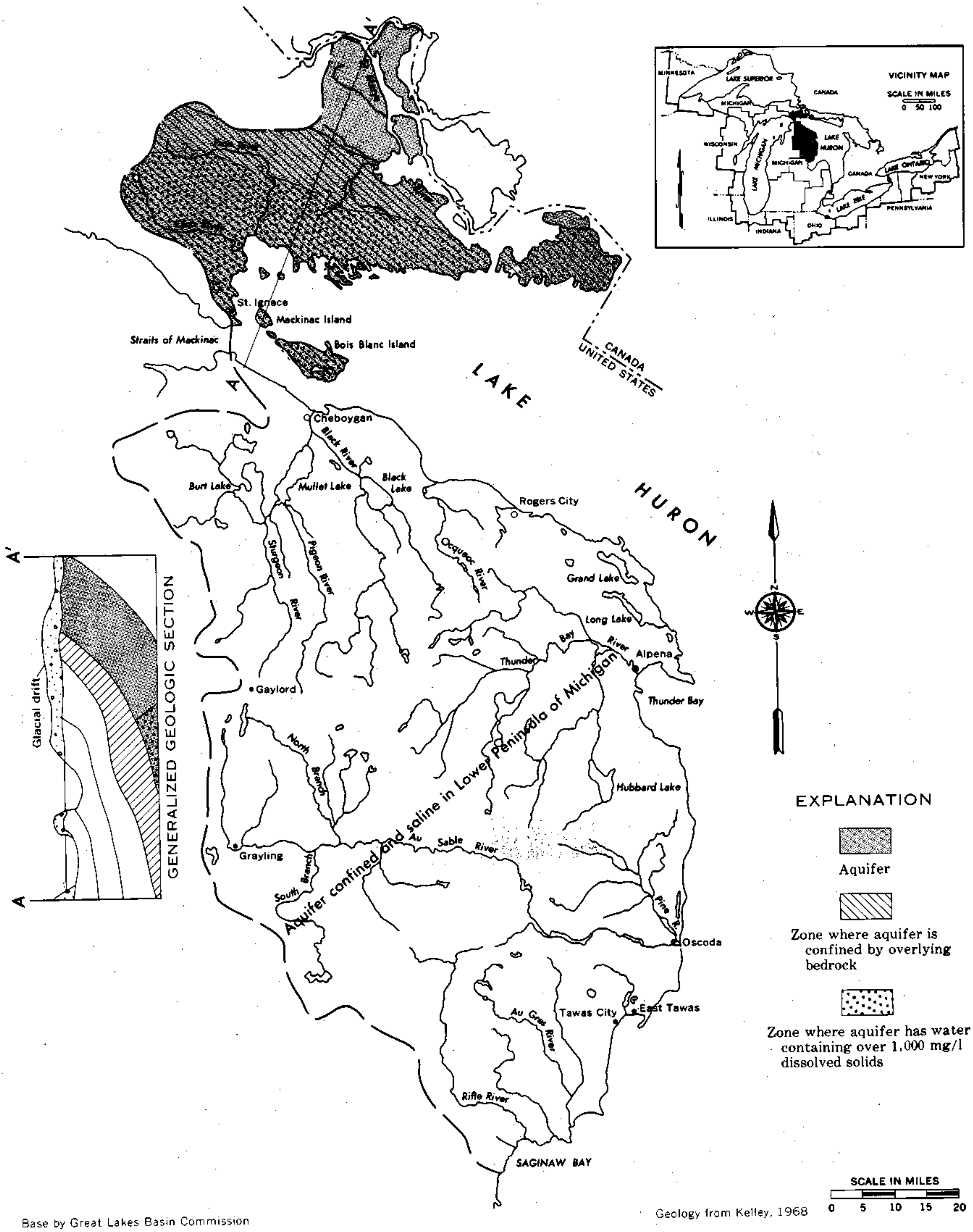


FIGURE 3–35 The Cambrian-Ordovician Aquifer System in River Basin Group 3.1

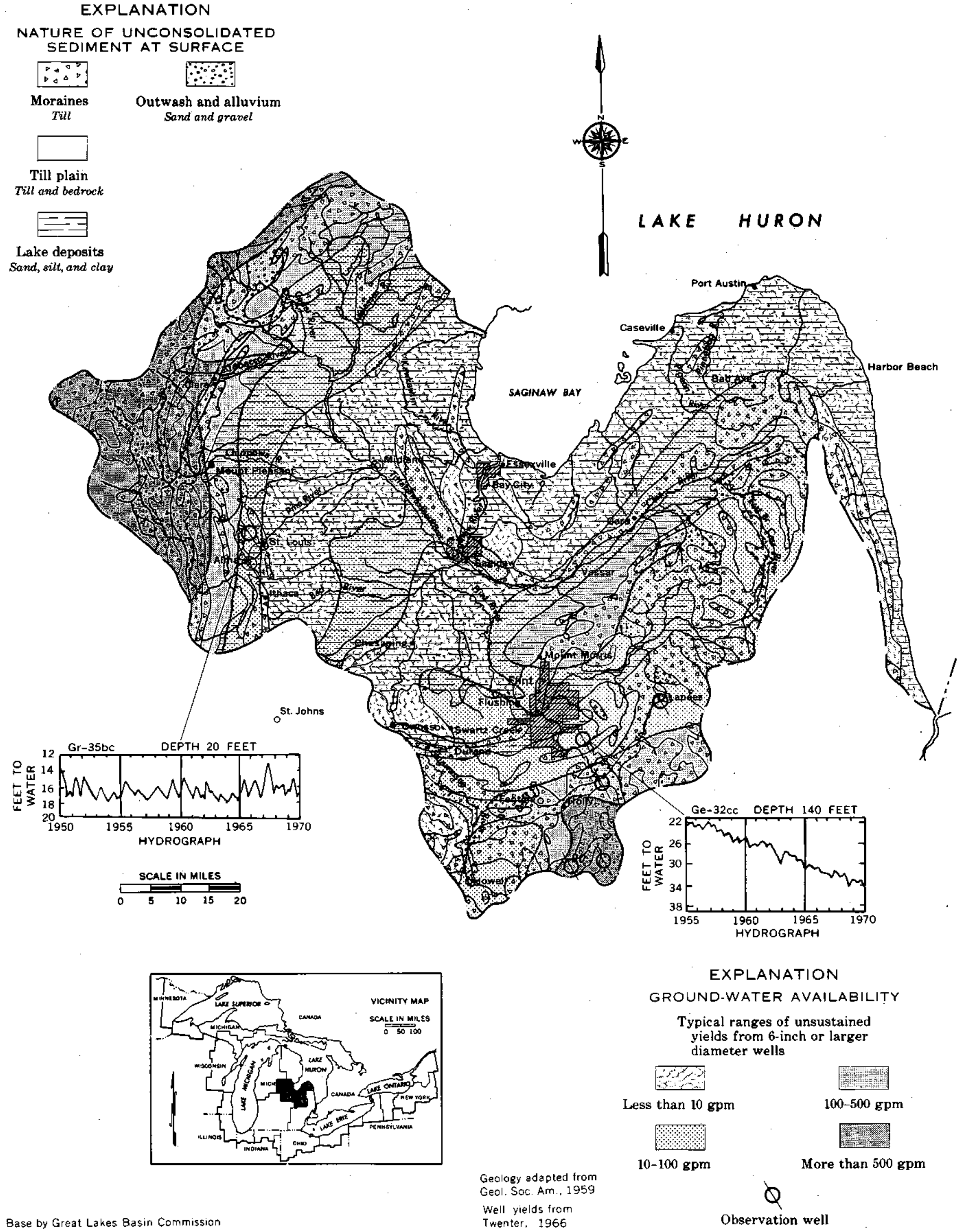


FIGURE 3–36 Ground Water in the Unconsolidated Sediments in River Basin Group 3.2

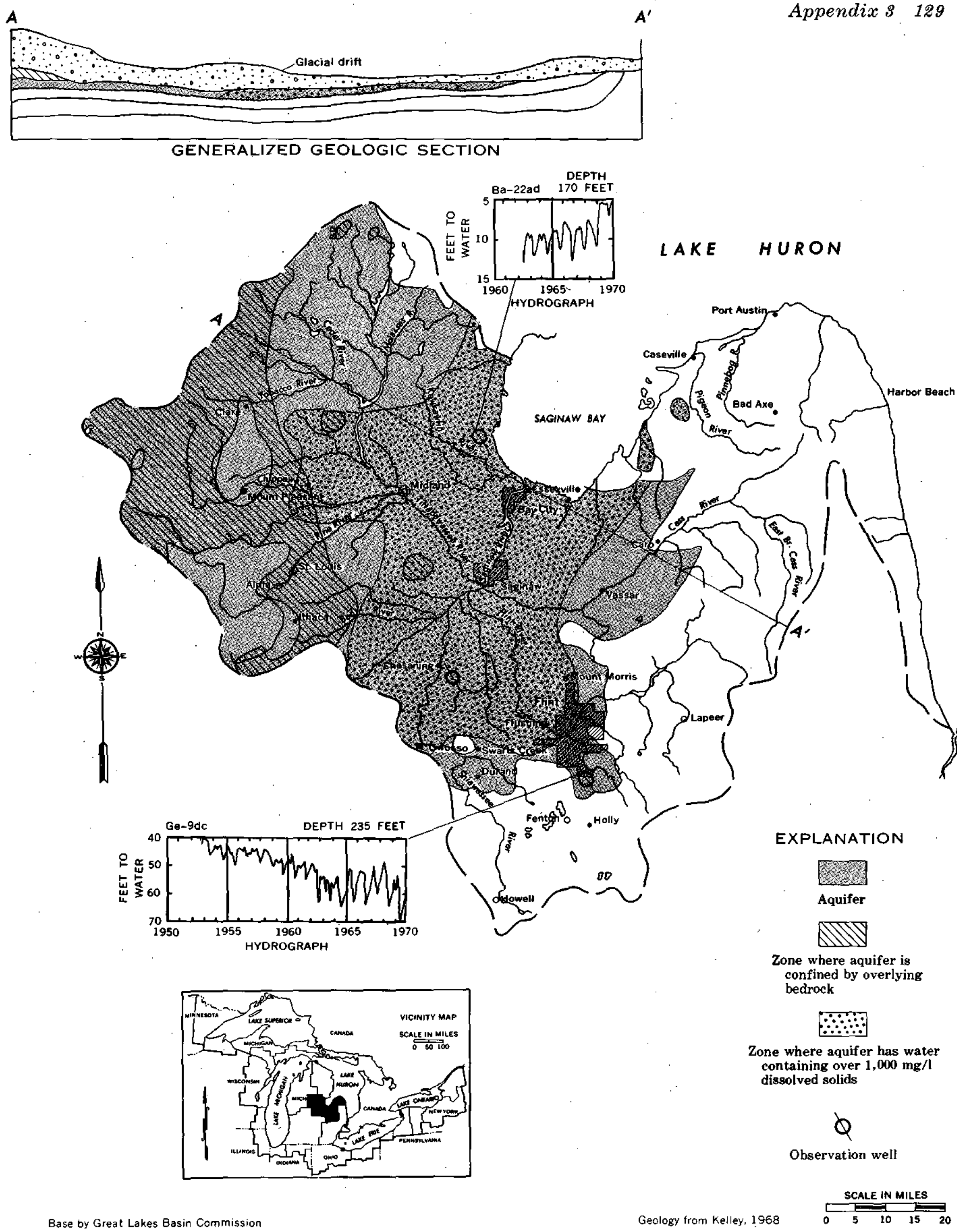


FIGURE 3–37 The Pennsylvanian (Saginaw) Aquifer System in River Basin Group 3.2

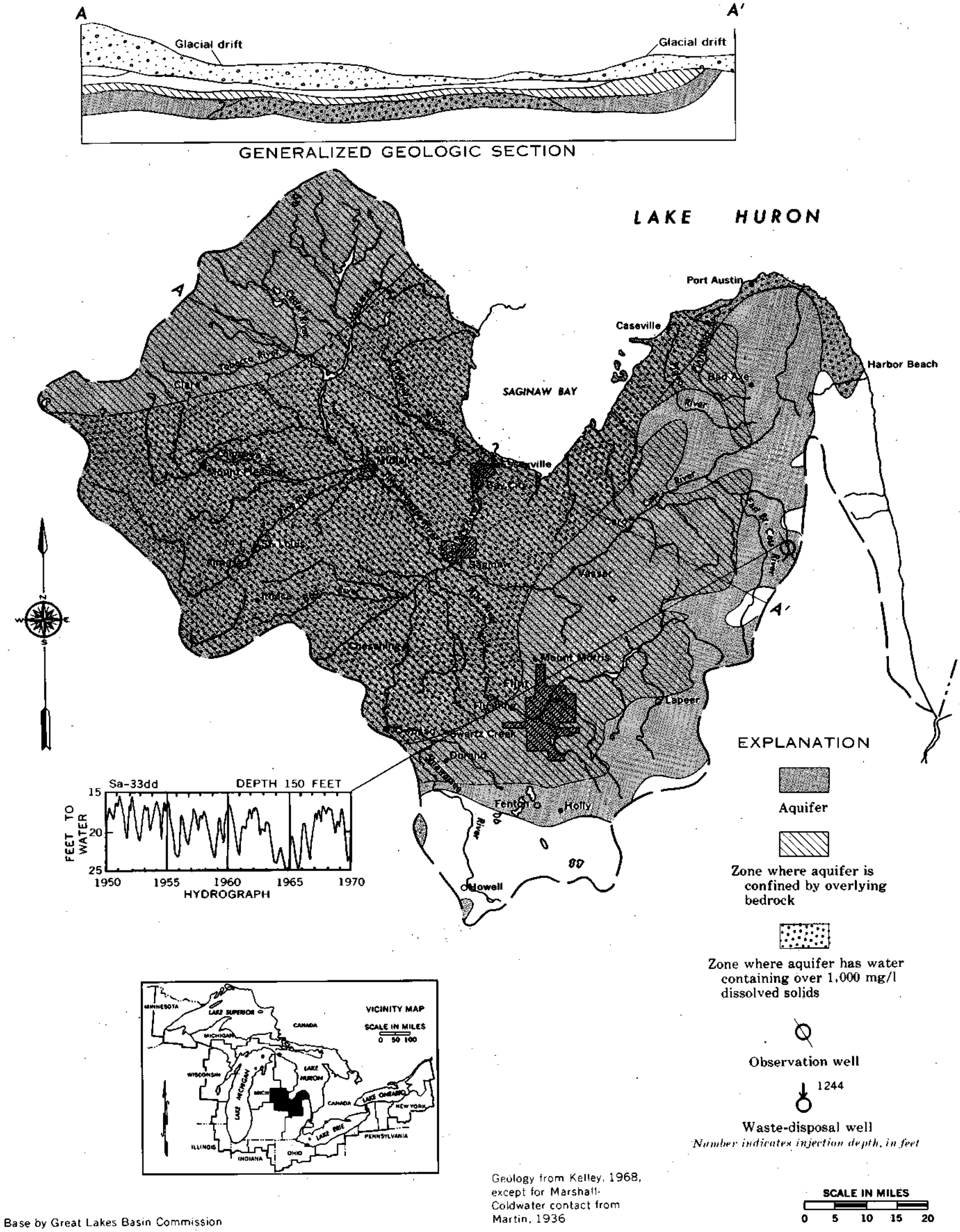
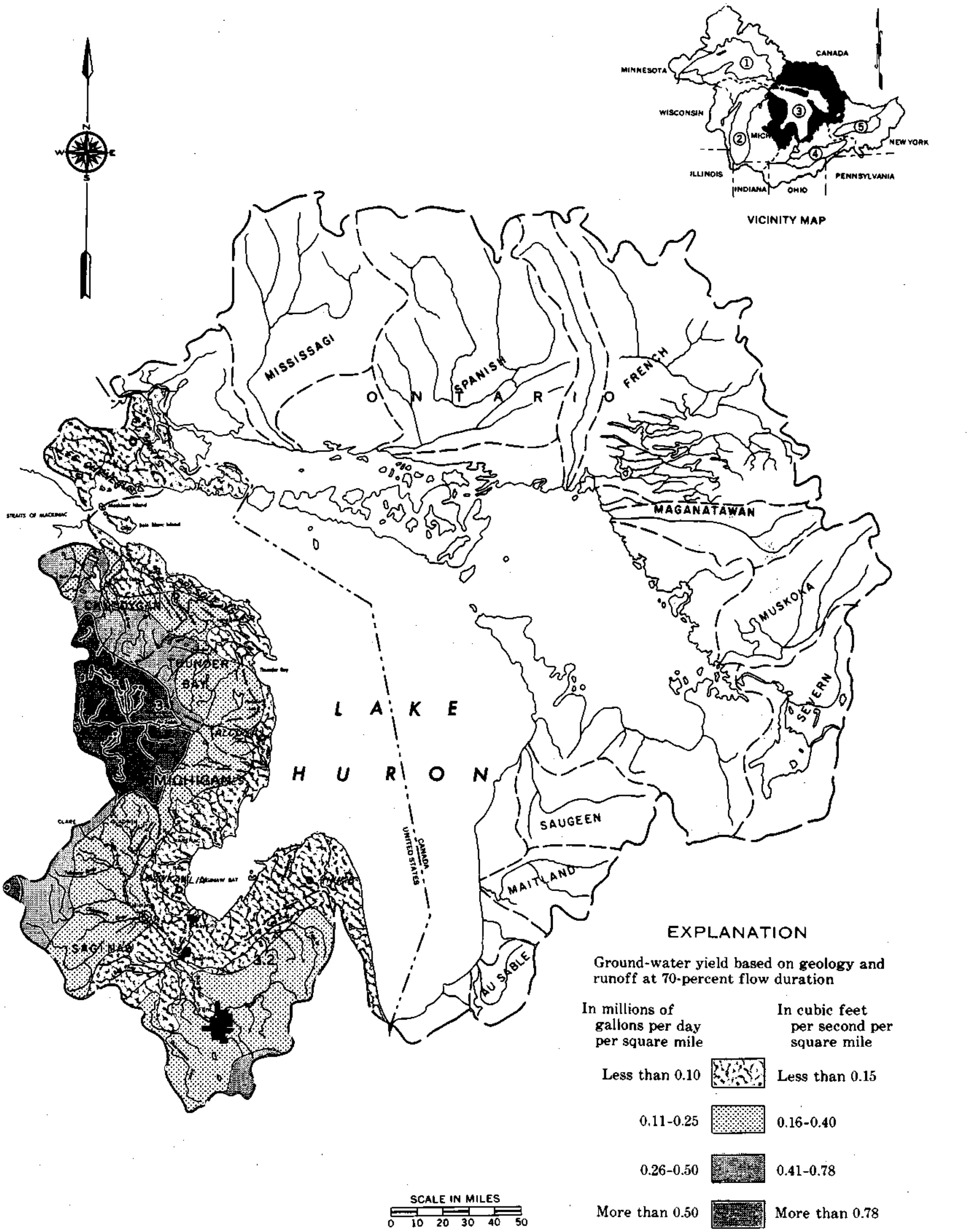


FIGURE 3–38 The Mississippian (Marshall) Aquifer System in River Basin Group 3.2



Base by Great Lakes Basin Commission

FIGURE 3–39 Estimated Ground-Water Yield, as Runoff, in the Lake Huron Basin, United States

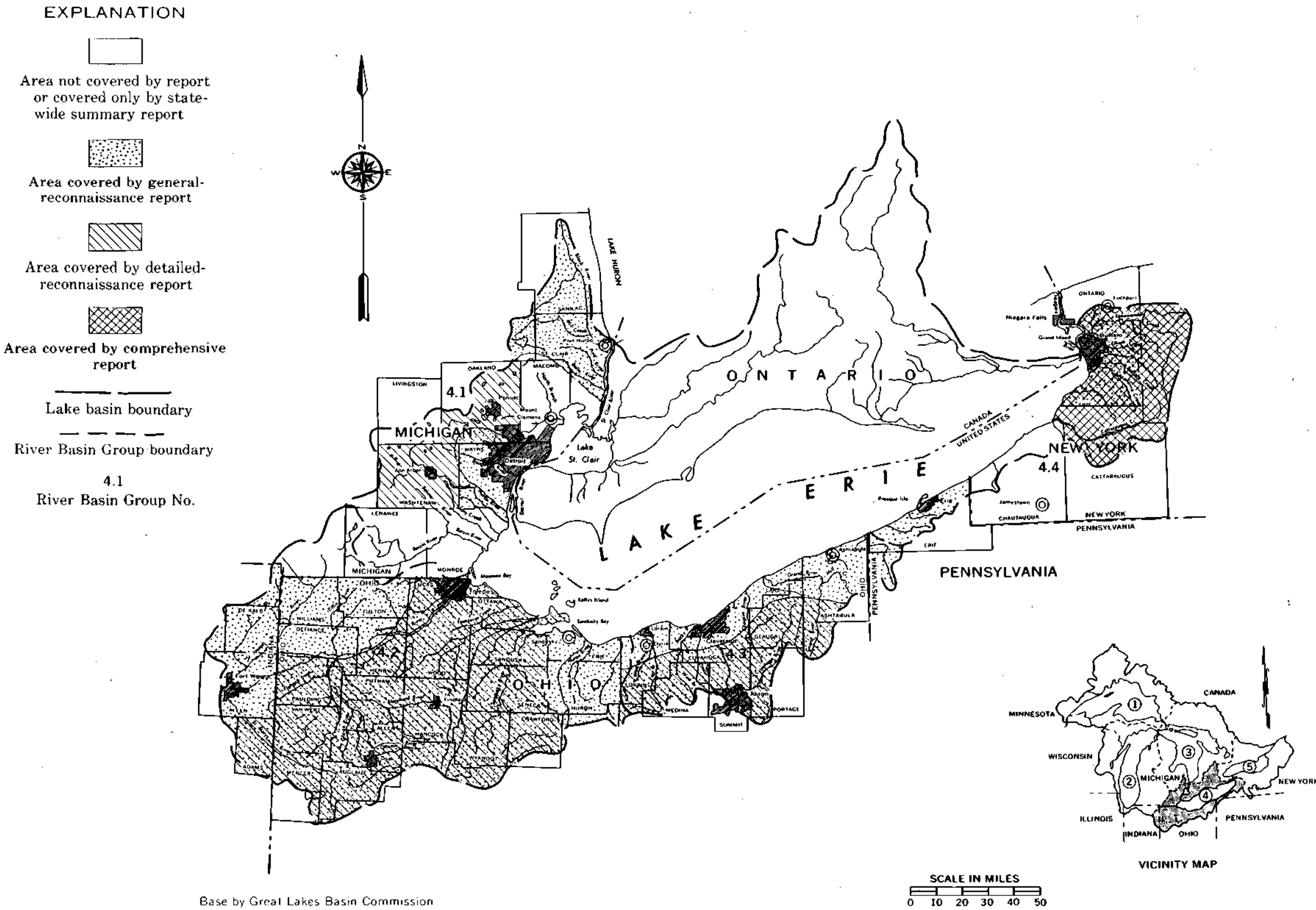


FIGURE 3-40 Map of the Lake Erie Basin Plan Area Showing River Basin Groups and Areas Covered by Ground-Water Reports

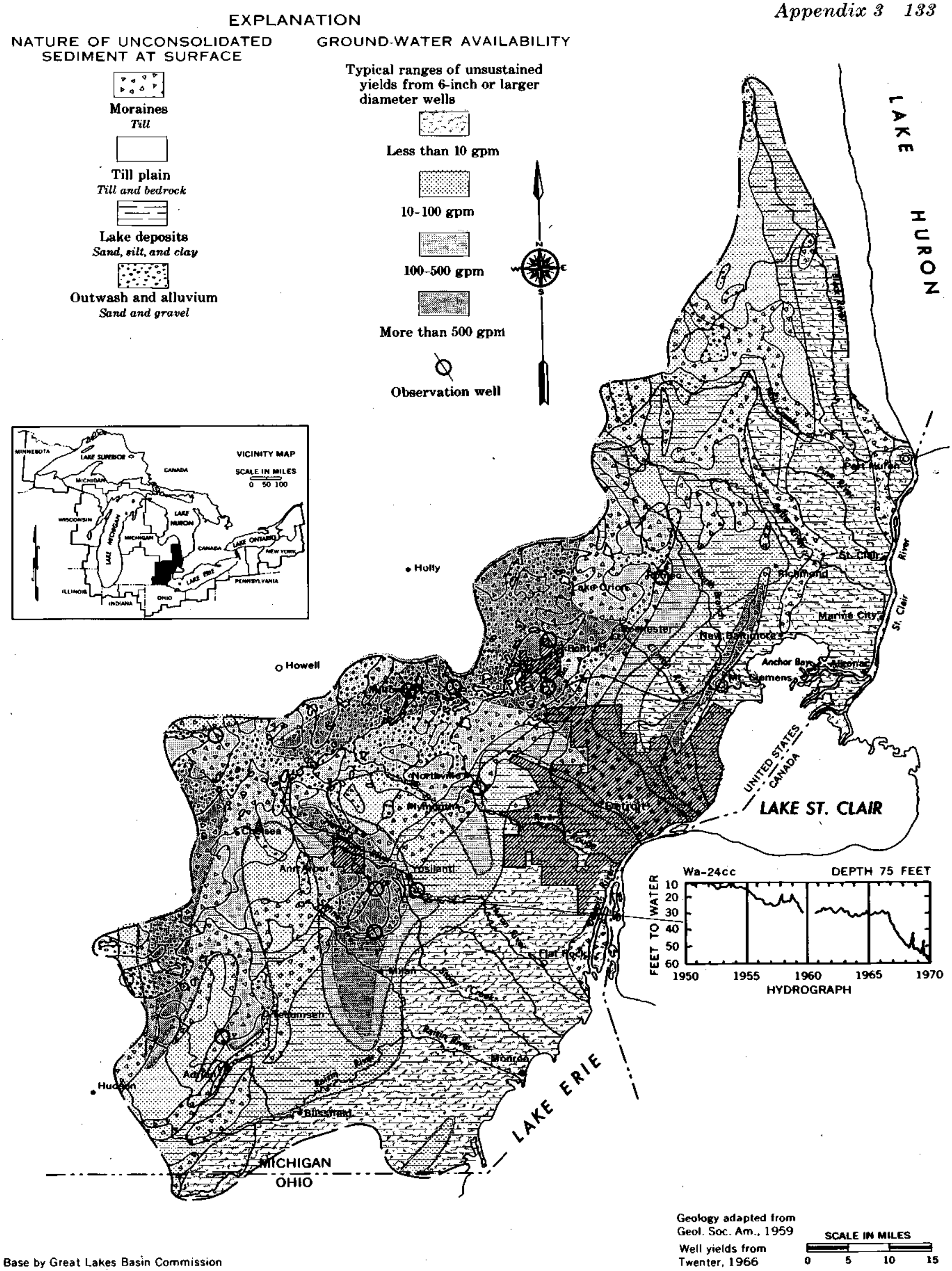


FIGURE 3-41 Ground Water in the Unconsolidated Sediments in River Basin Group 4.1

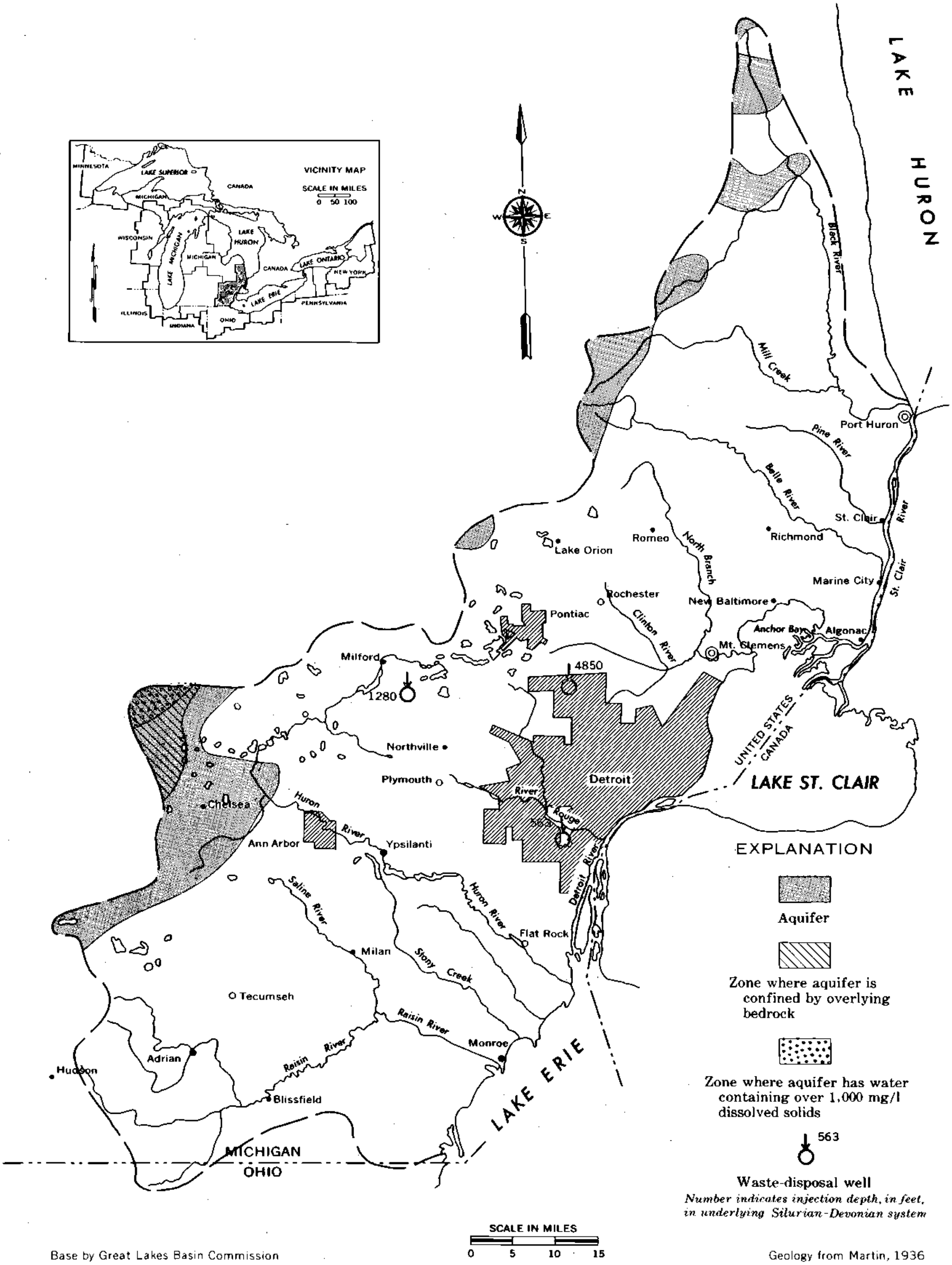


FIGURE 3–42 The Mississippian (Marshall) Aquifer System in River Basin Group 4.1

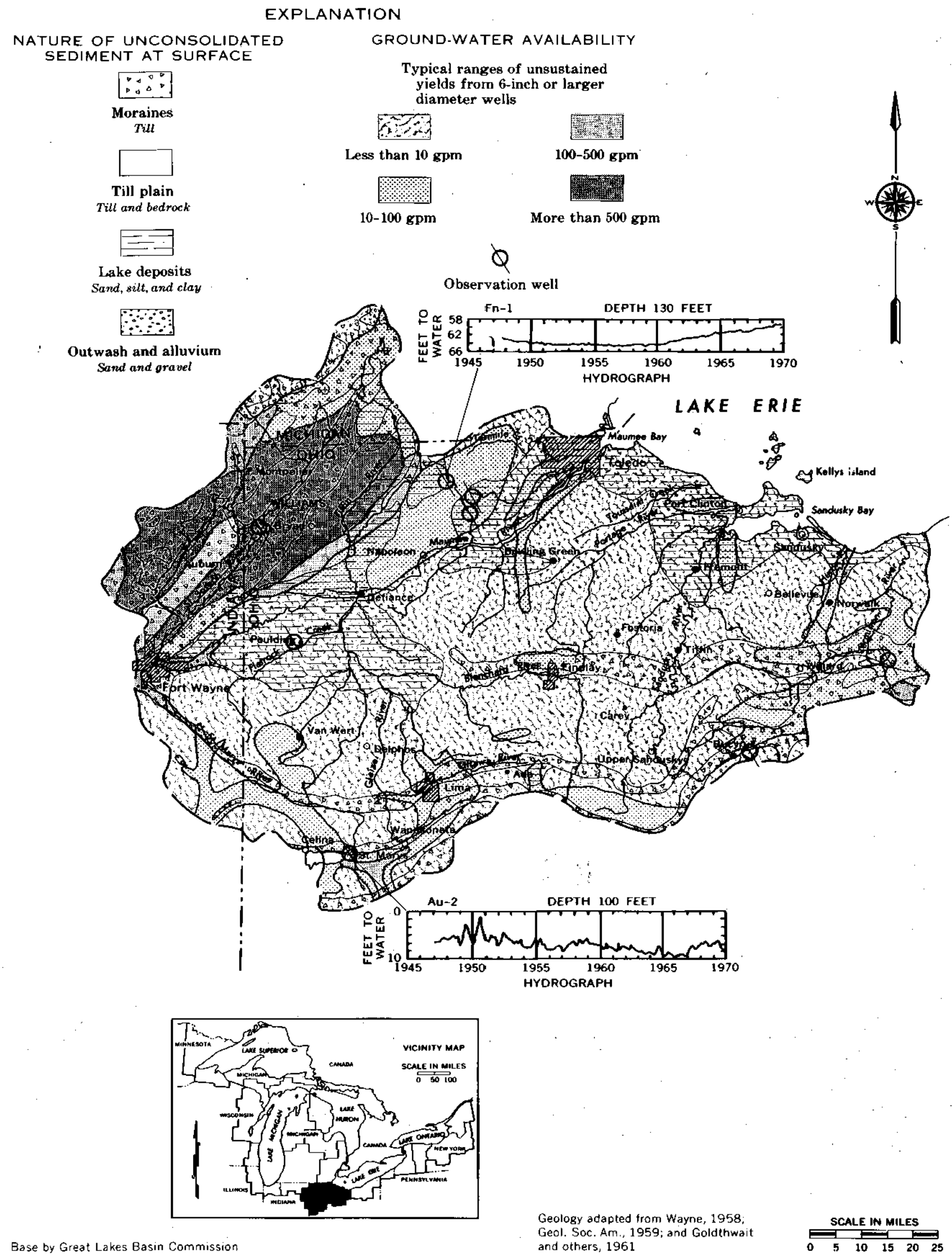
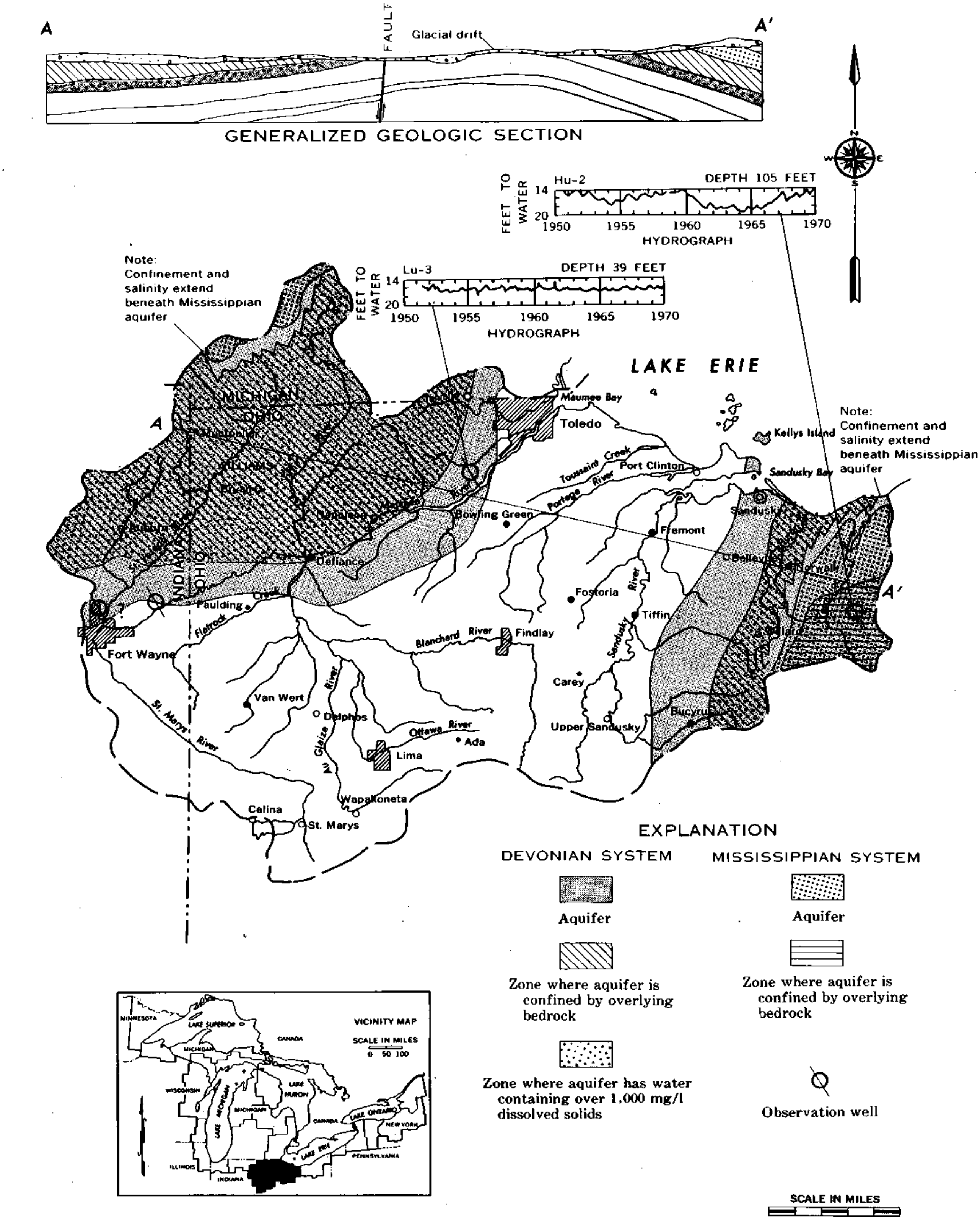


FIGURE 3–43 Ground Water in the Unconsolidated Sediments in River Basin Group 4.2



Base by Great Lakes Basin Commission

FIGURE 3-44 The Mississippian and Devonian Aquifer Systems in River Basin Group 4.2

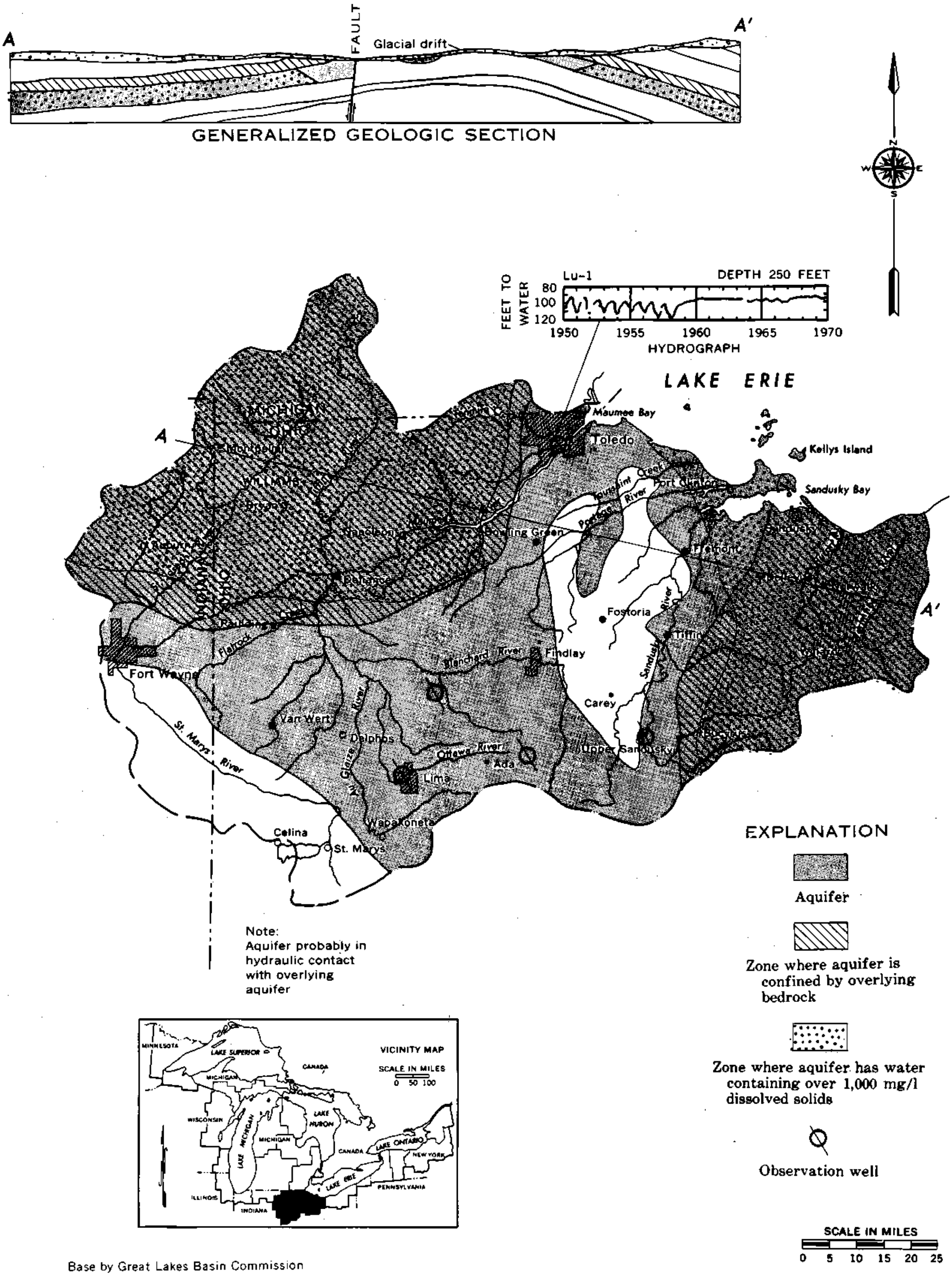


FIGURE 3–45 The Silurian (Bass Islands) Aquifer System in River Basin Group 4.2

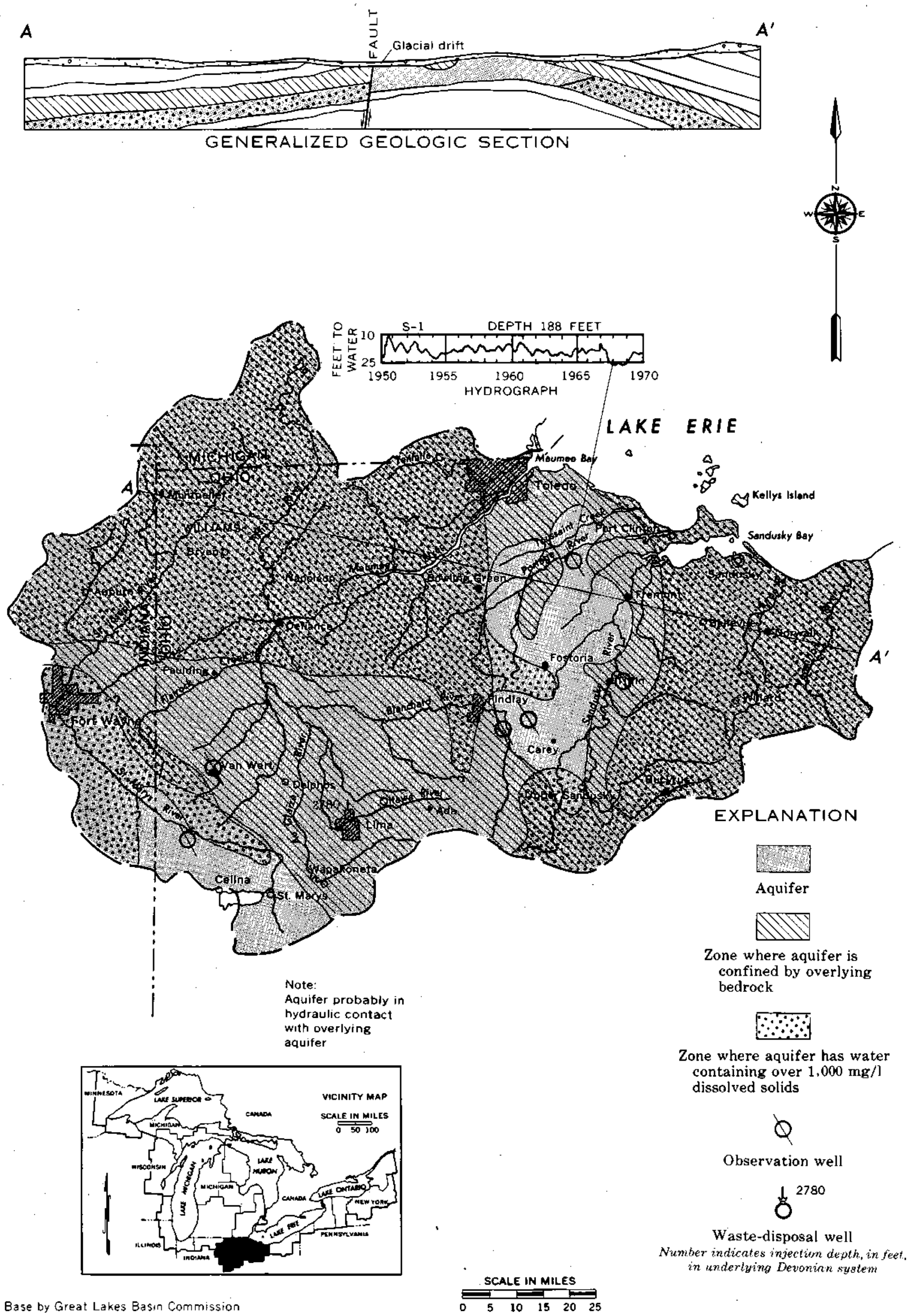


FIGURE 3–46 The Silurian (Lockport) Aquifer System in River Basin Group 4.2

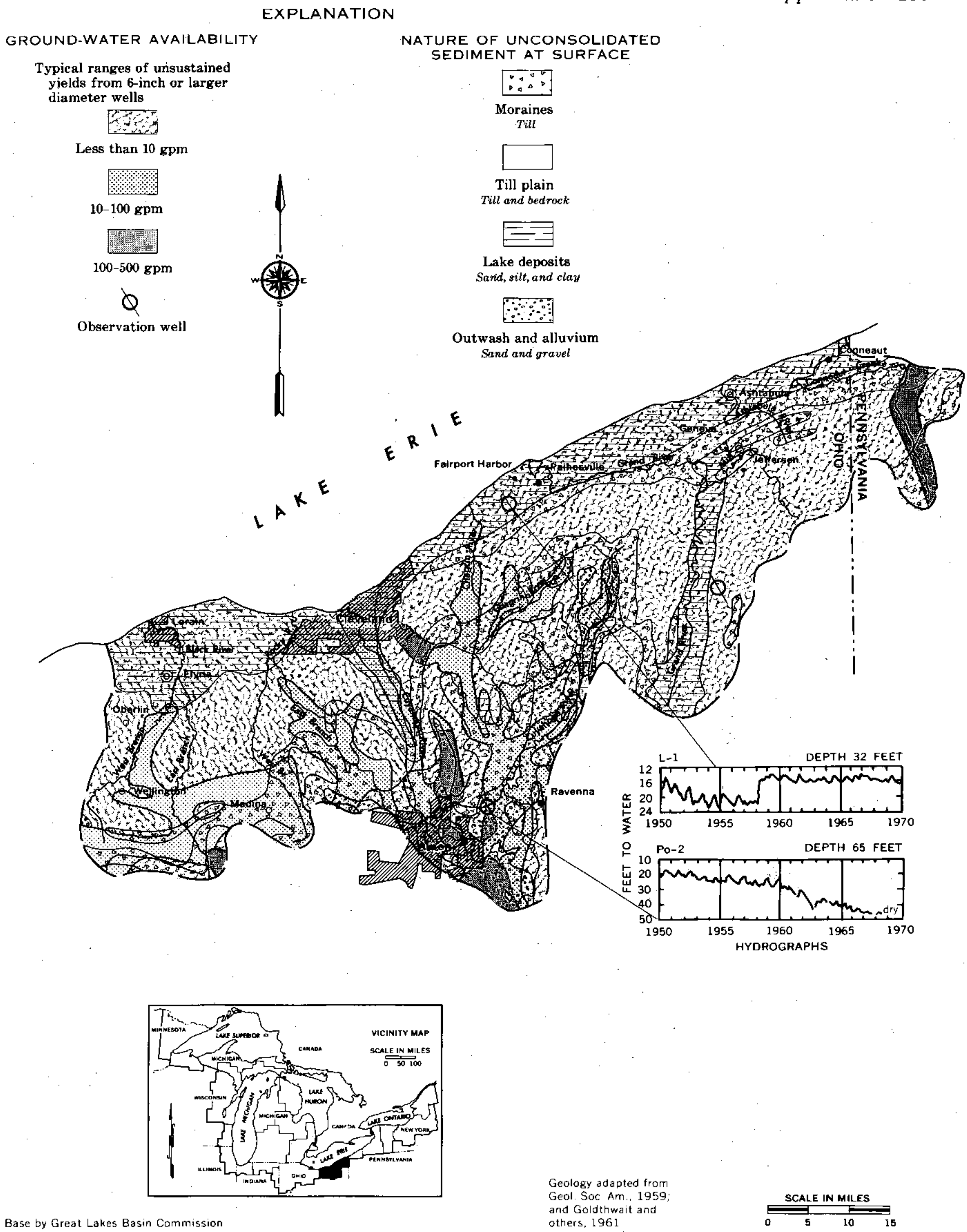


FIGURE 3–47 Ground Water in the Unconsolidated Sediments in River Basin Group 4.3

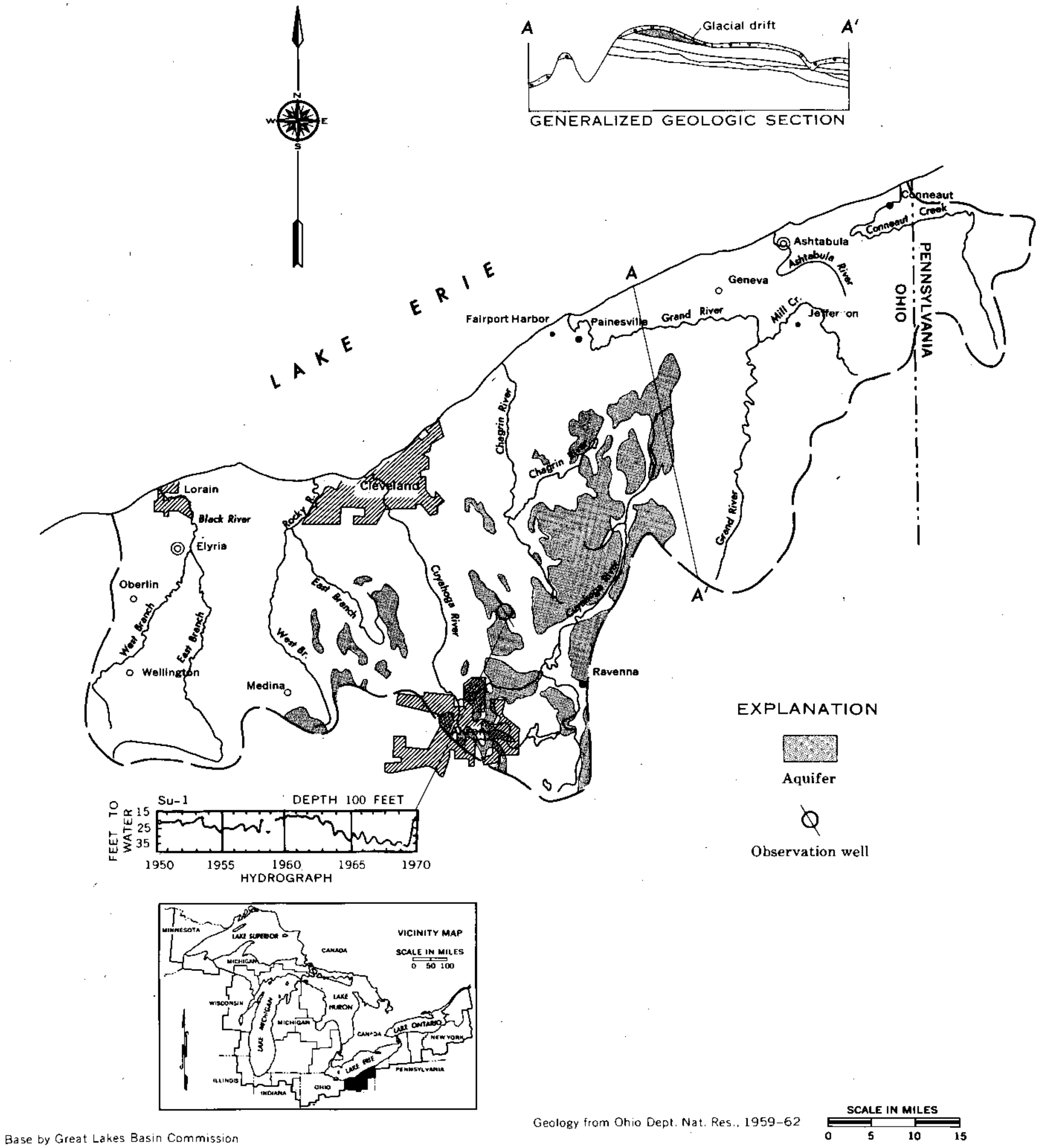
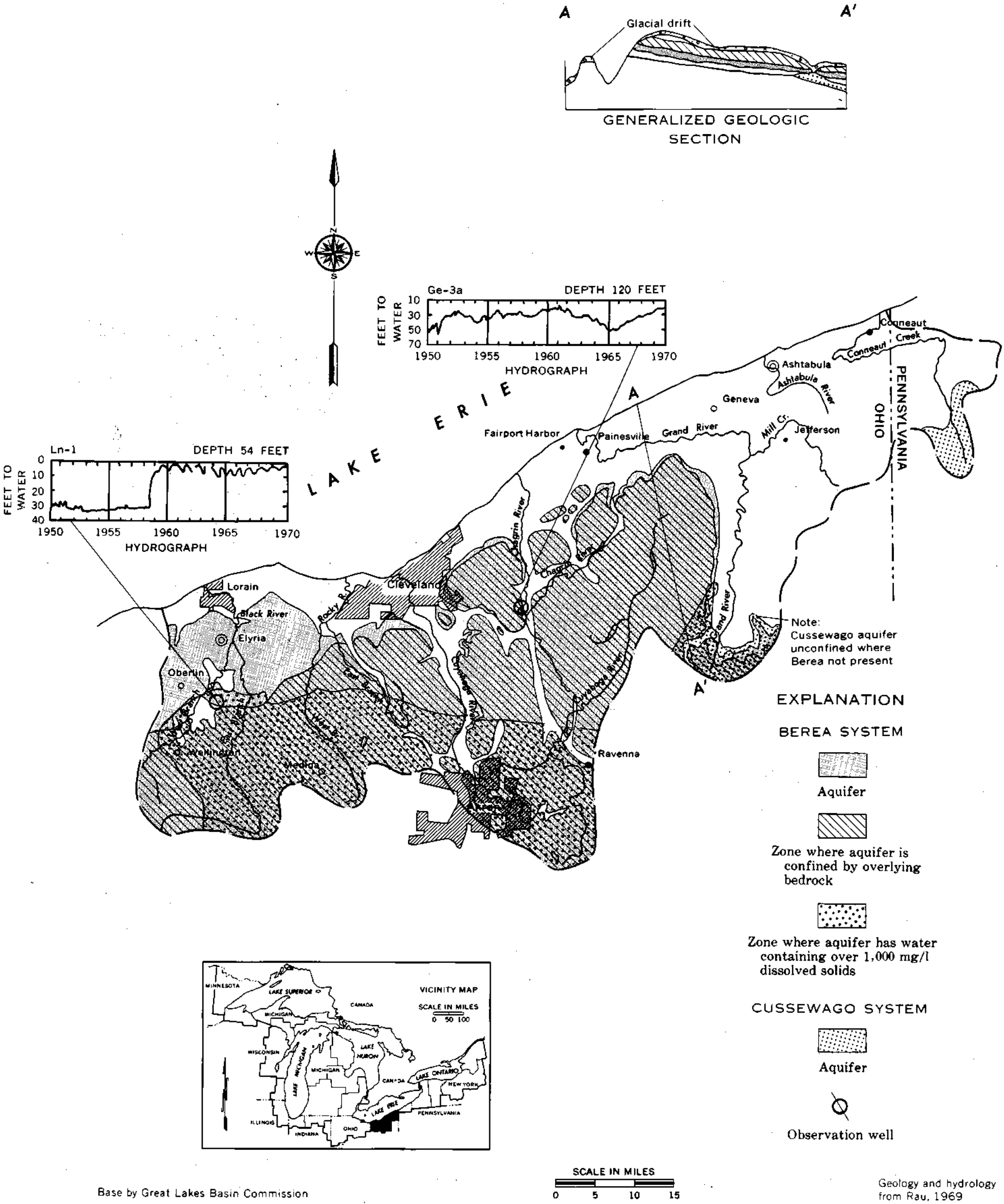


FIGURE 3–48 The Pennsylvanian (Sharon) Aquifer System in River Basin Group 4.3



Base by Great Lakes Basin Commission

Geology and hydrology from Rau, 1969

FIGURE 3-49 The Mississippian (Cussewago and Berea) Aquifer Systems in River Basin Group 4.3

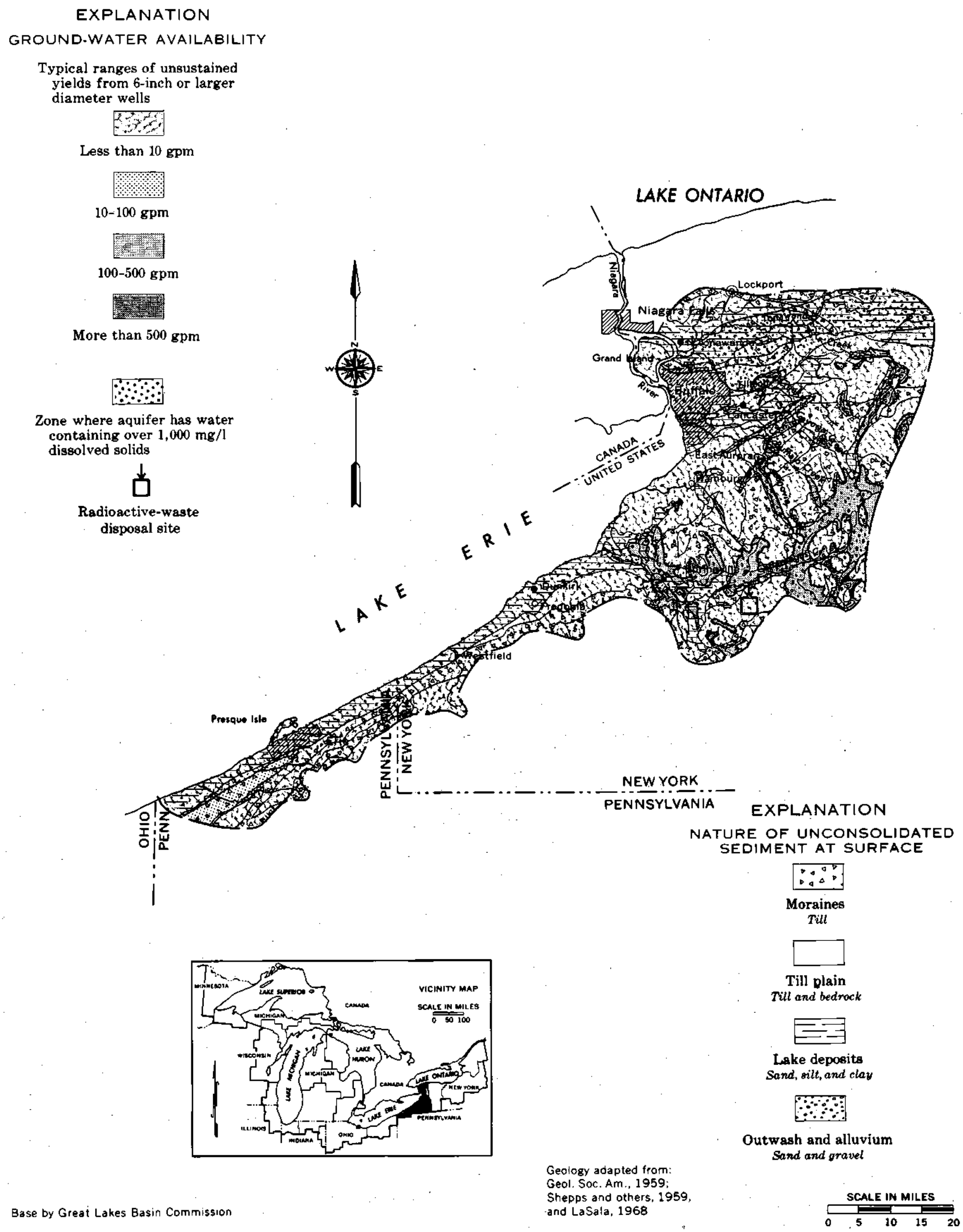


FIGURE 3-50 Ground Water in the Unconsolidated Sediments in River Basin Group 4.4

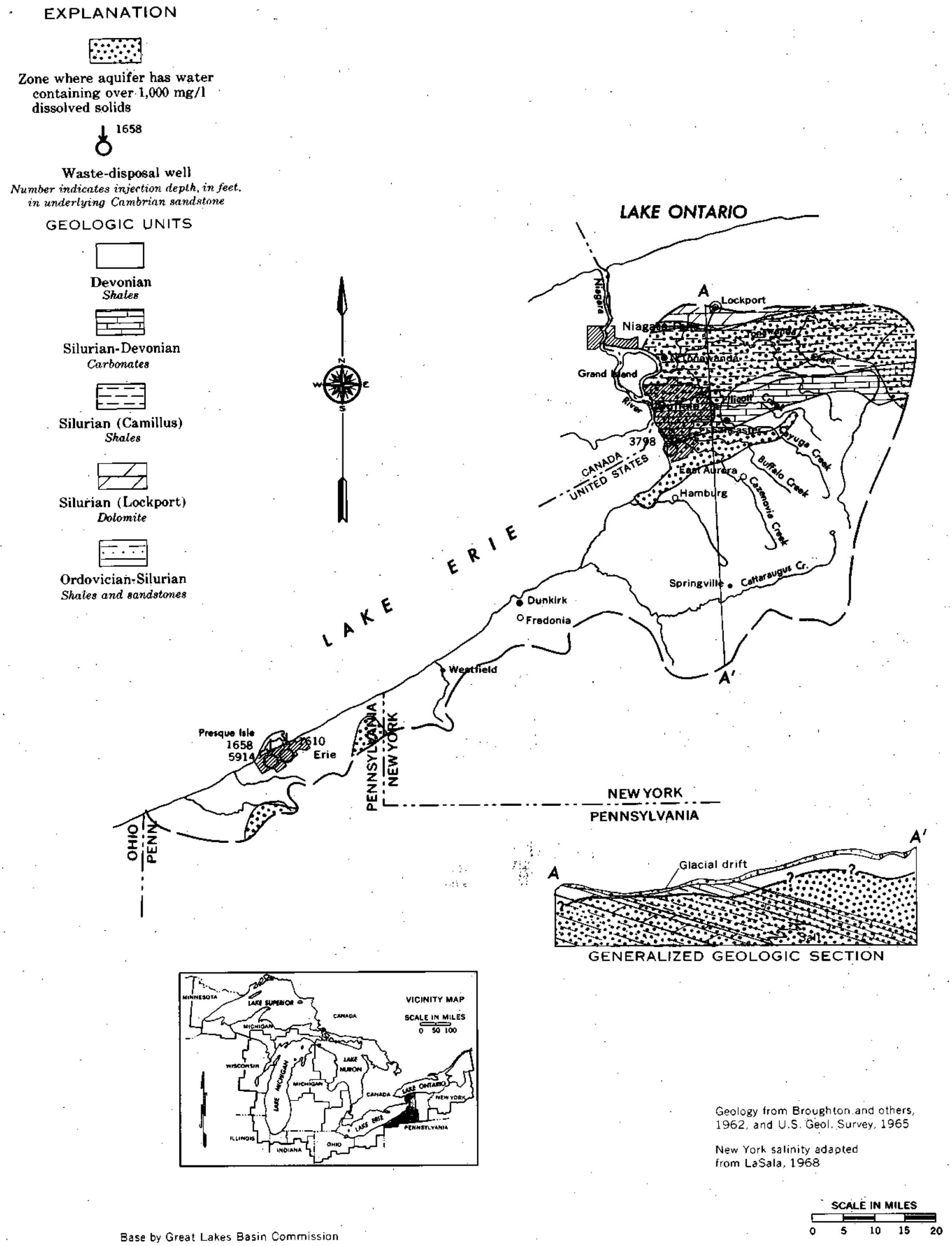


FIGURE 3–51 Bedrock Geology and Areas of Mineralized Ground Water in River Basin Group 4.4

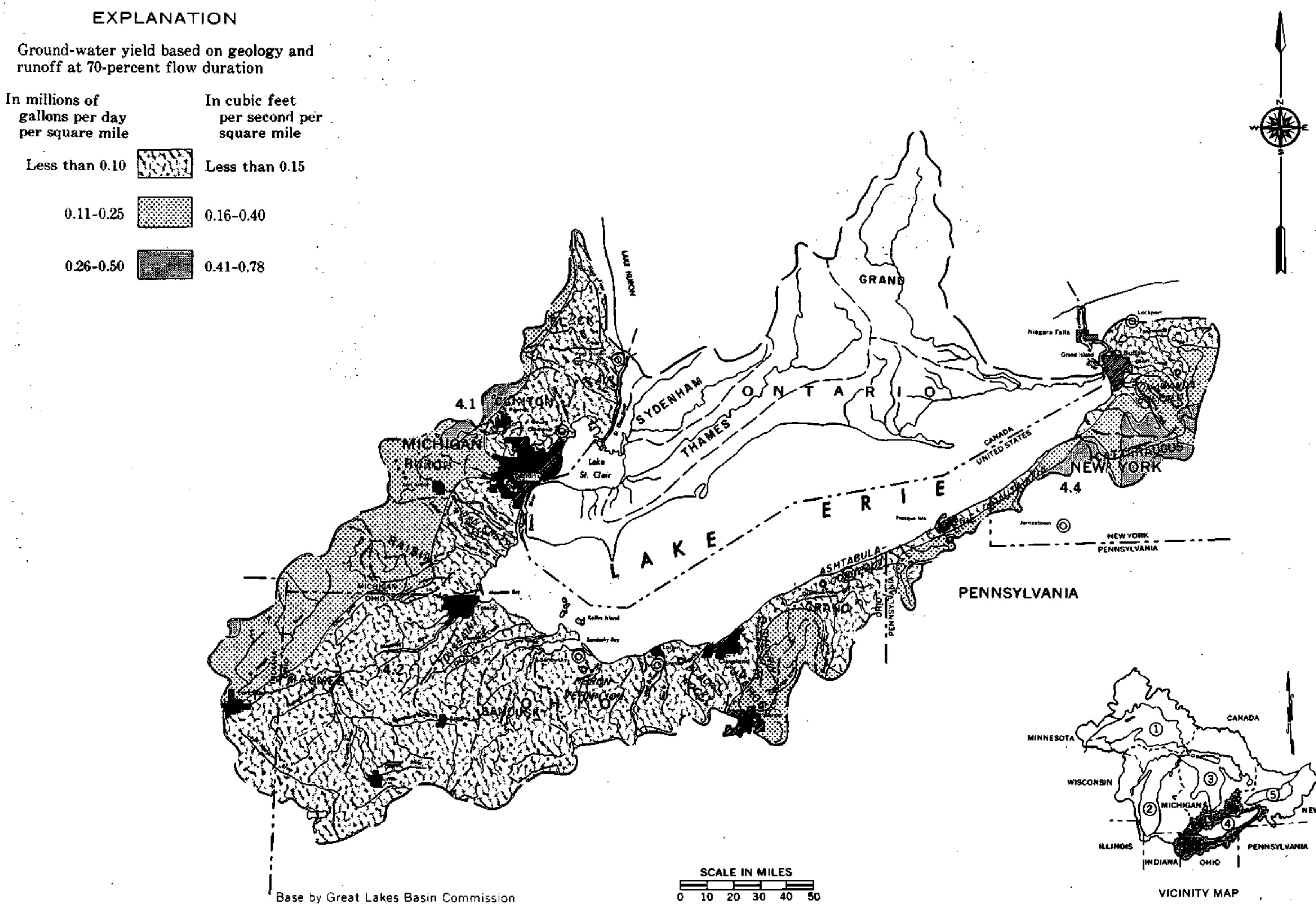


FIGURE 3-52 Estimated Ground-Water Yield, as Runoff, in the Lake Erie Basin, United States

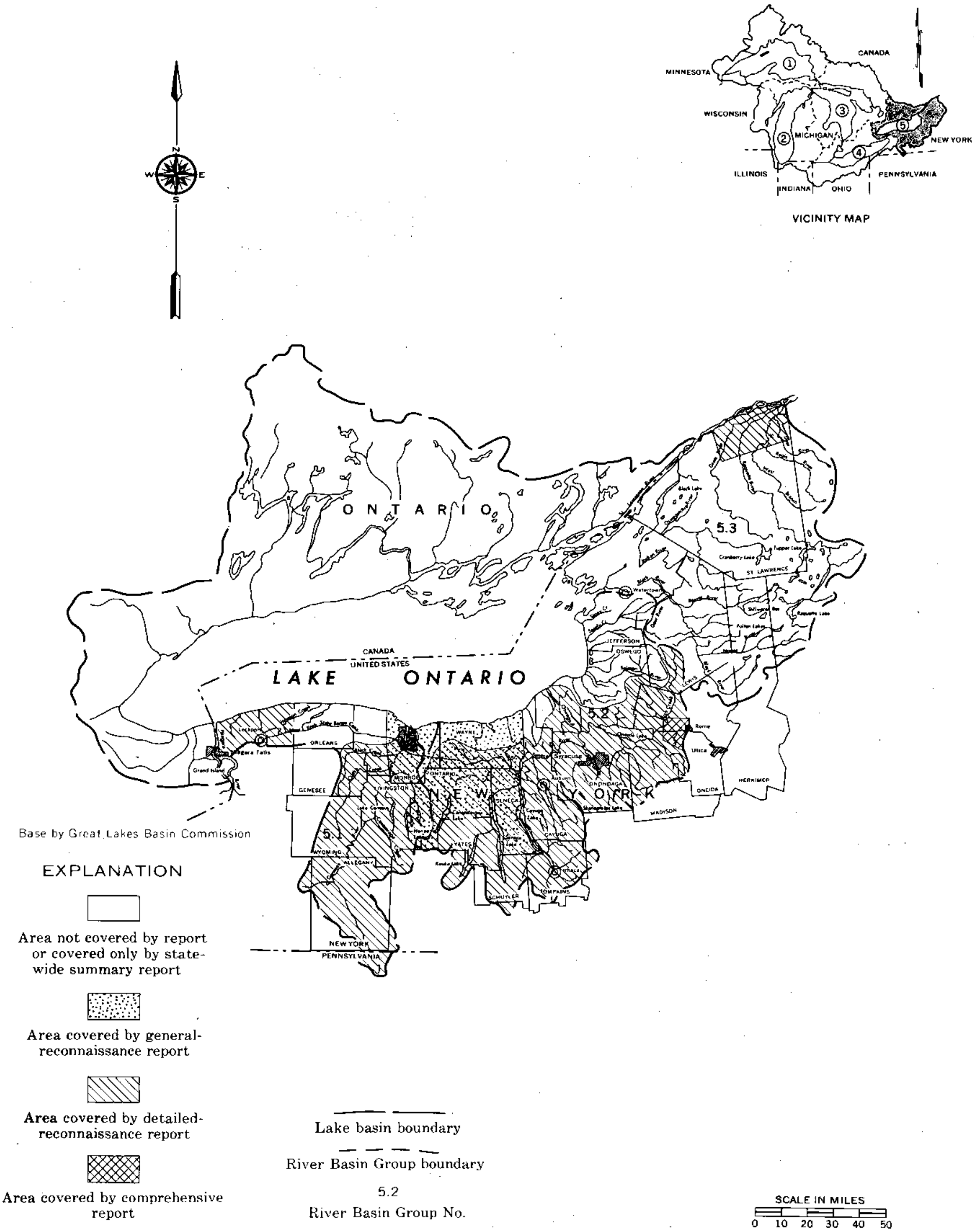


FIGURE 3–53 Map of the Lake Ontario Basin Plan Area Showing River Basin Groups and Areas Covered by Ground-Water Reports

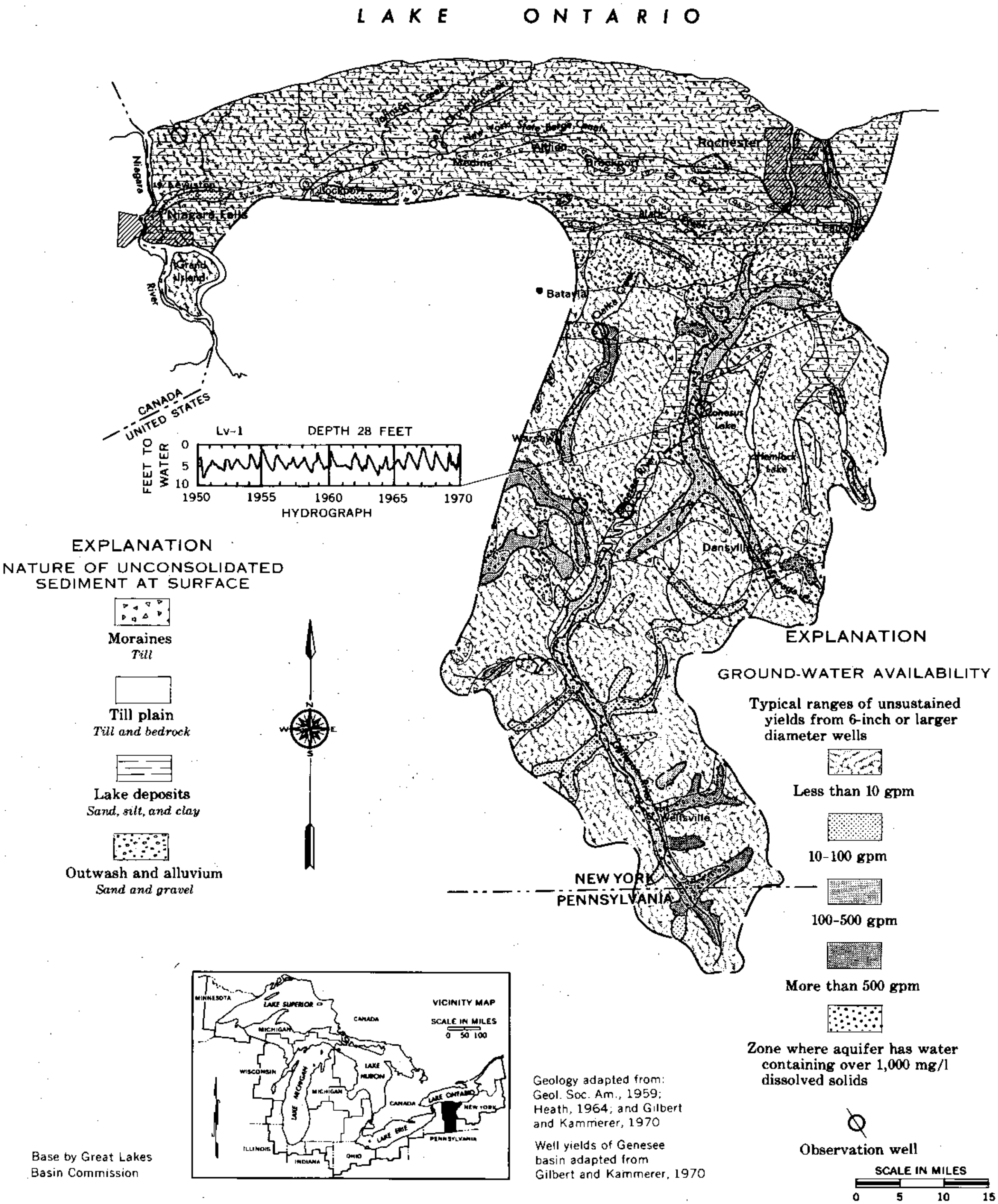


FIGURE 3-54 Ground Water in the Unconsolidated Sediments in River Basin Group 5.1

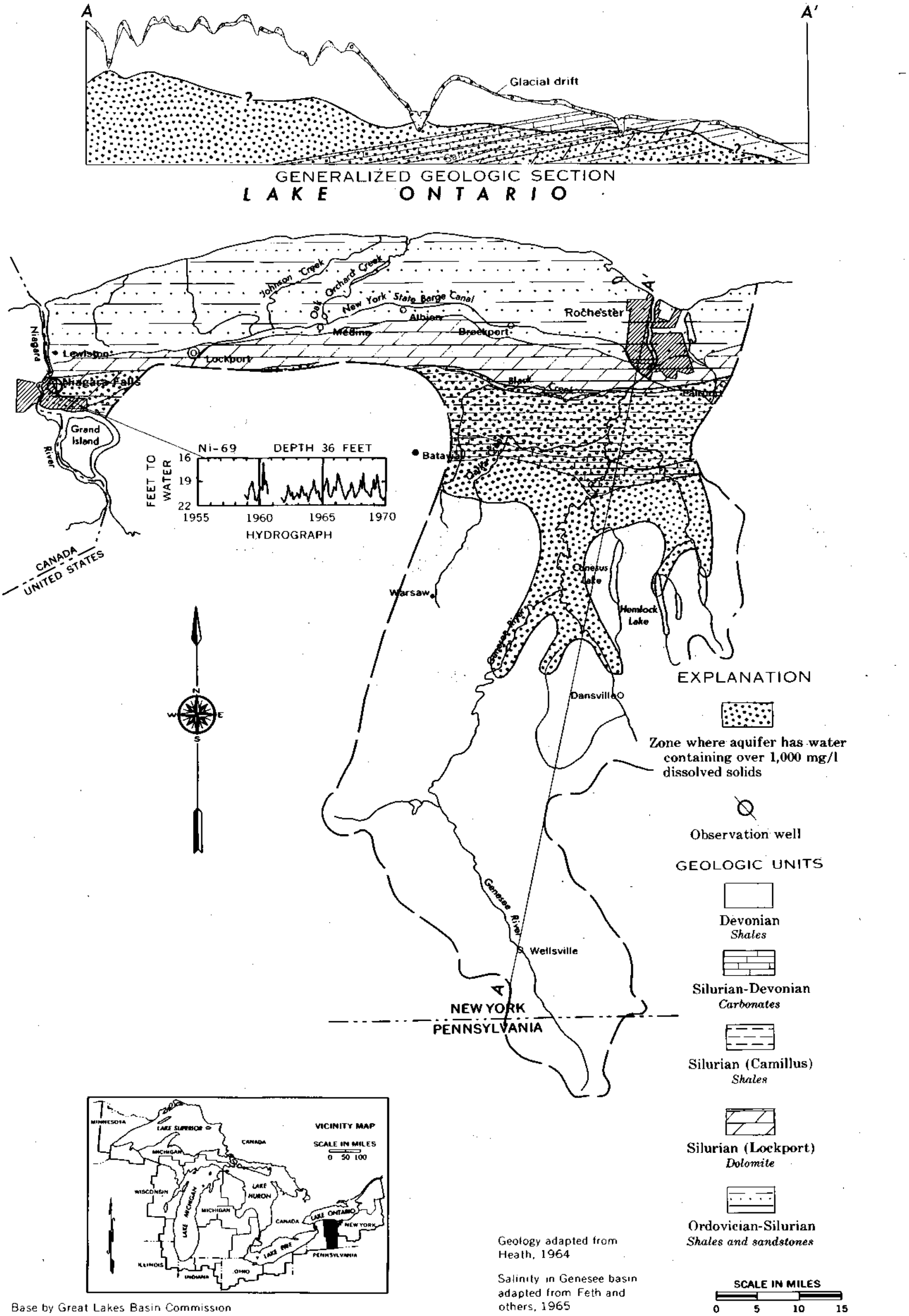


FIGURE 3–55 Bedrock Geology and Areas of Mineralized Ground Water in River Basin Group 5.1

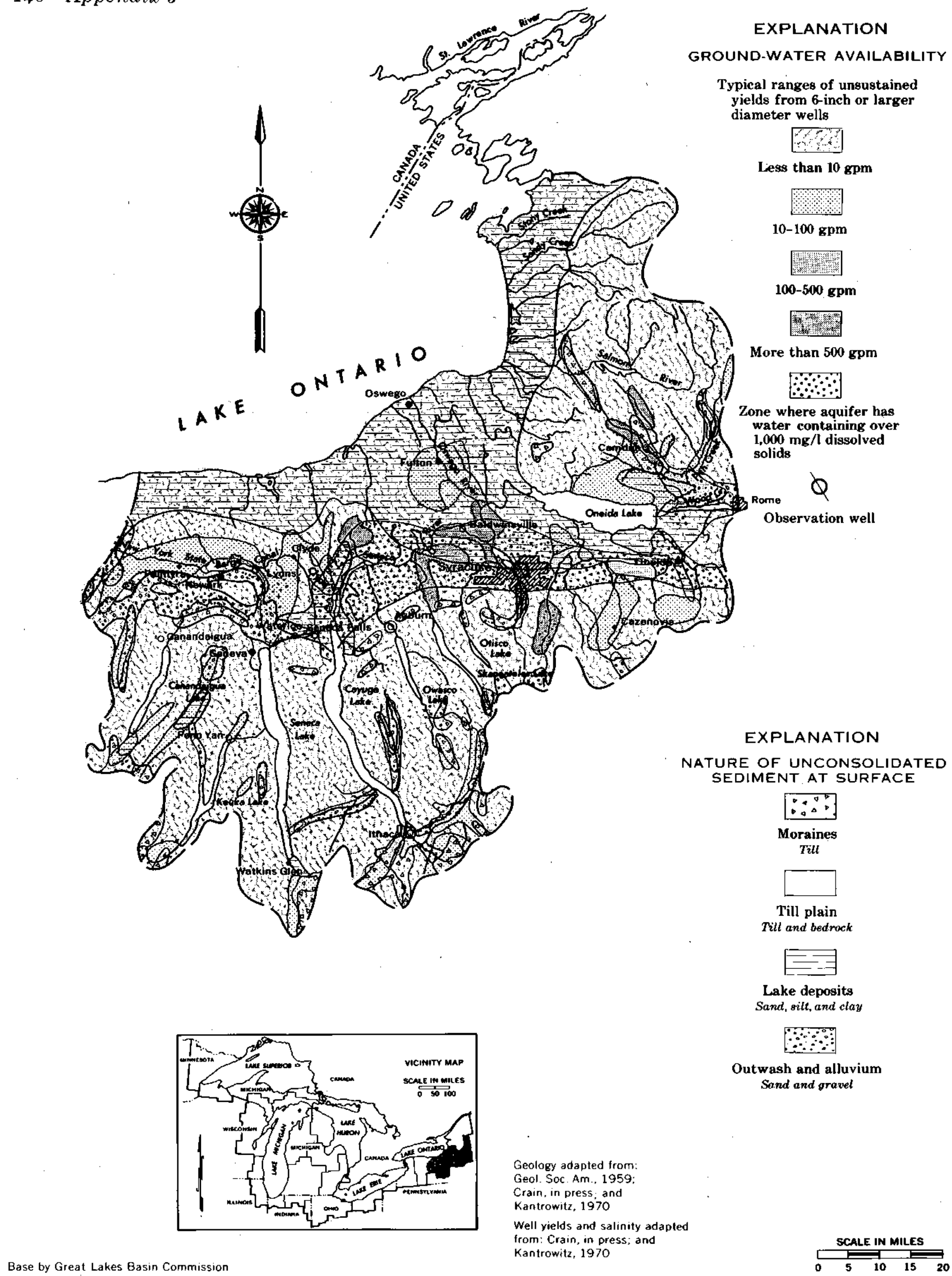


FIGURE 3–56 Ground Water in the Unconsolidated Sediments in River Basin Group 5.2

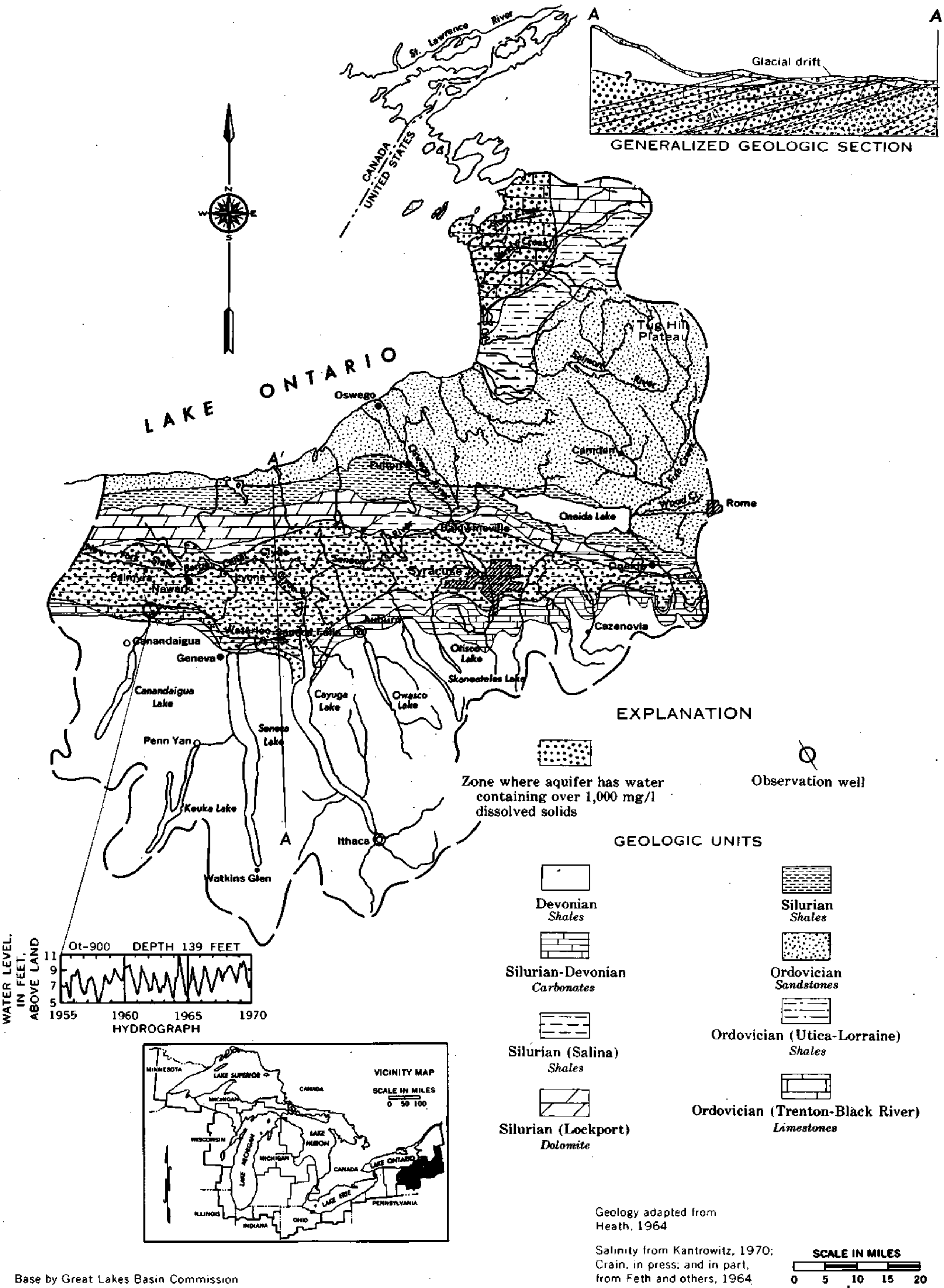


FIGURE 3–57 Bedrock Geology and Areas of Mineralized Ground Water in River Basin Group 5.2

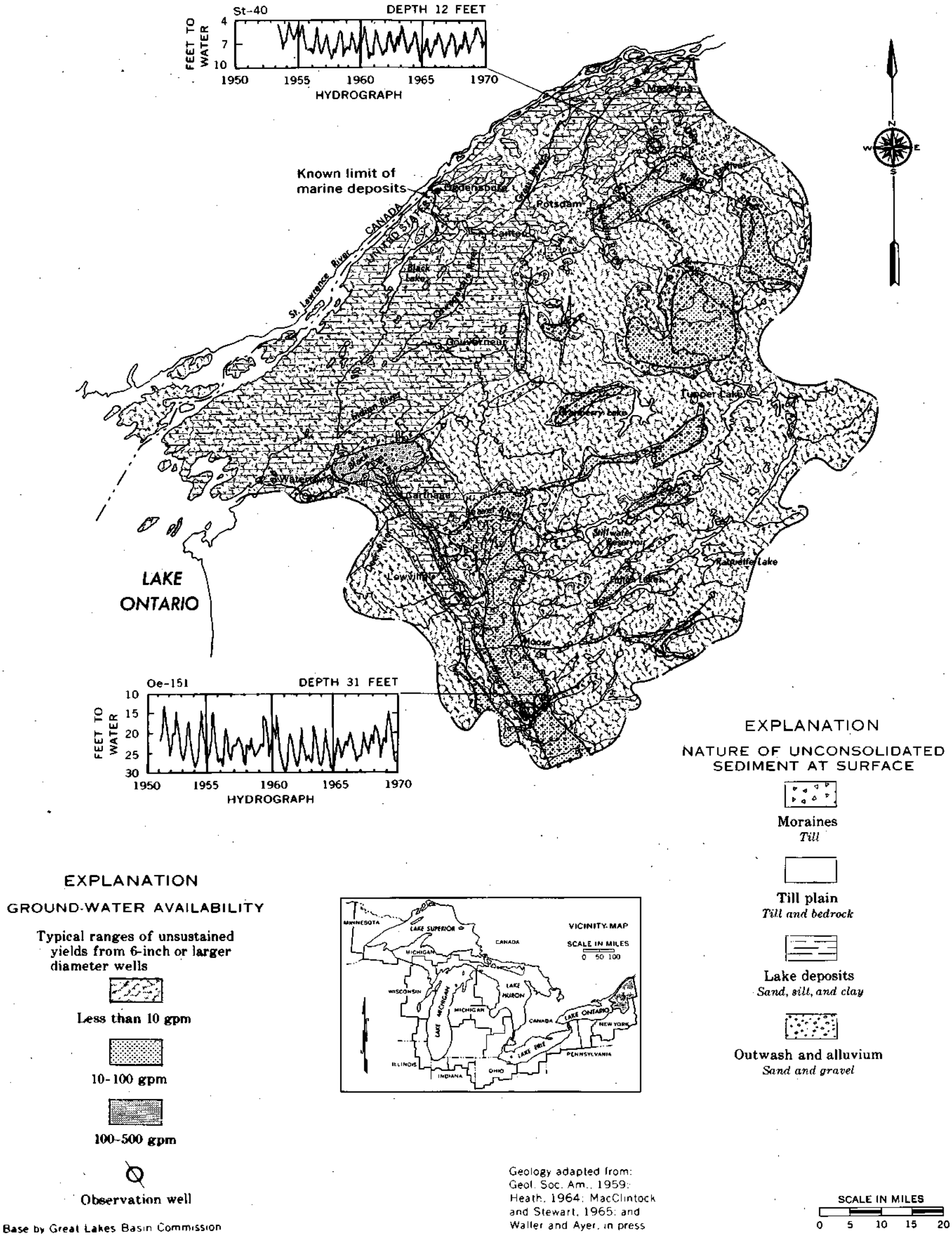


FIGURE 3–58 Ground Water in the Unconsolidated Sediments in River Basin Group 5.3

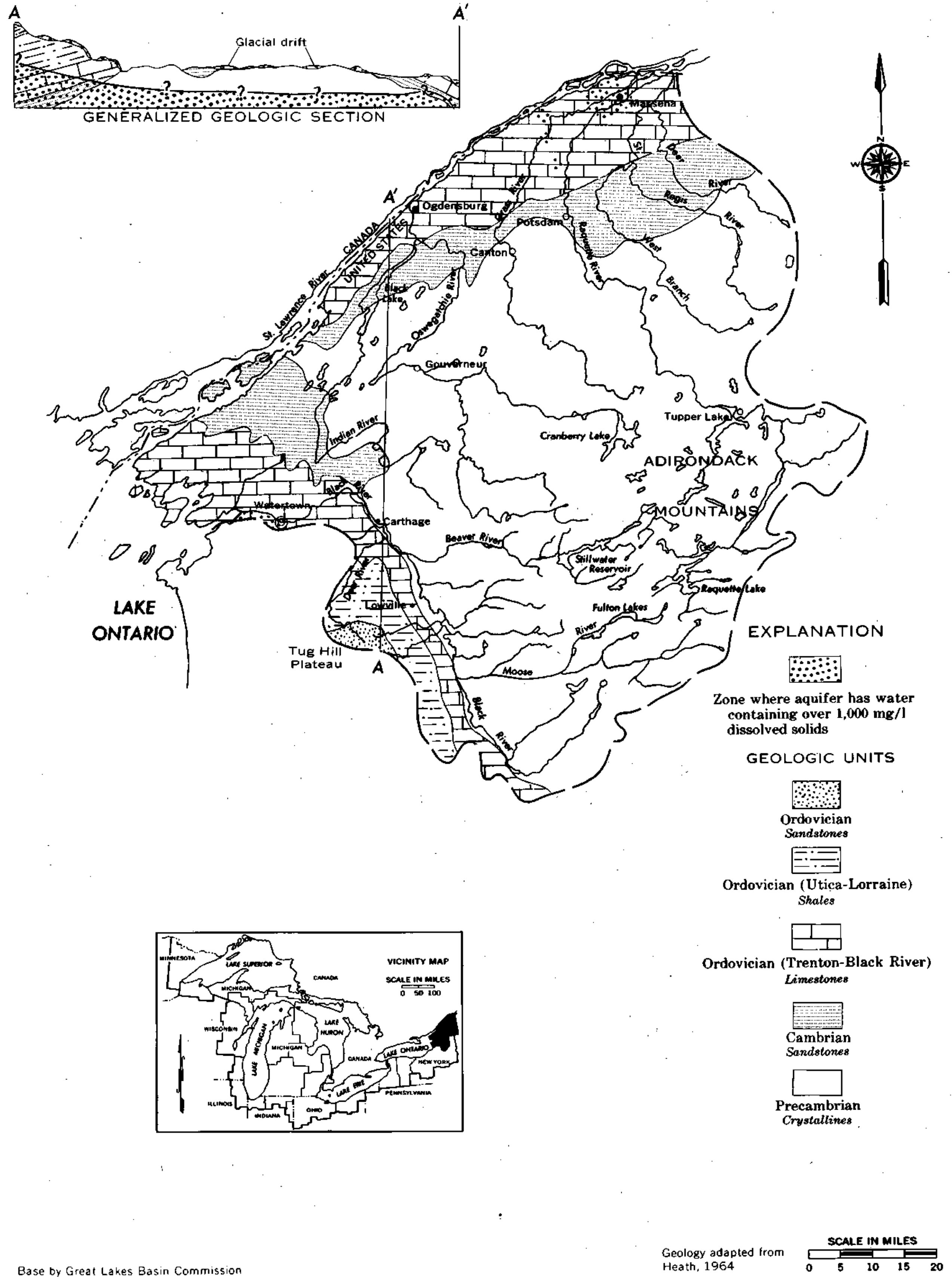
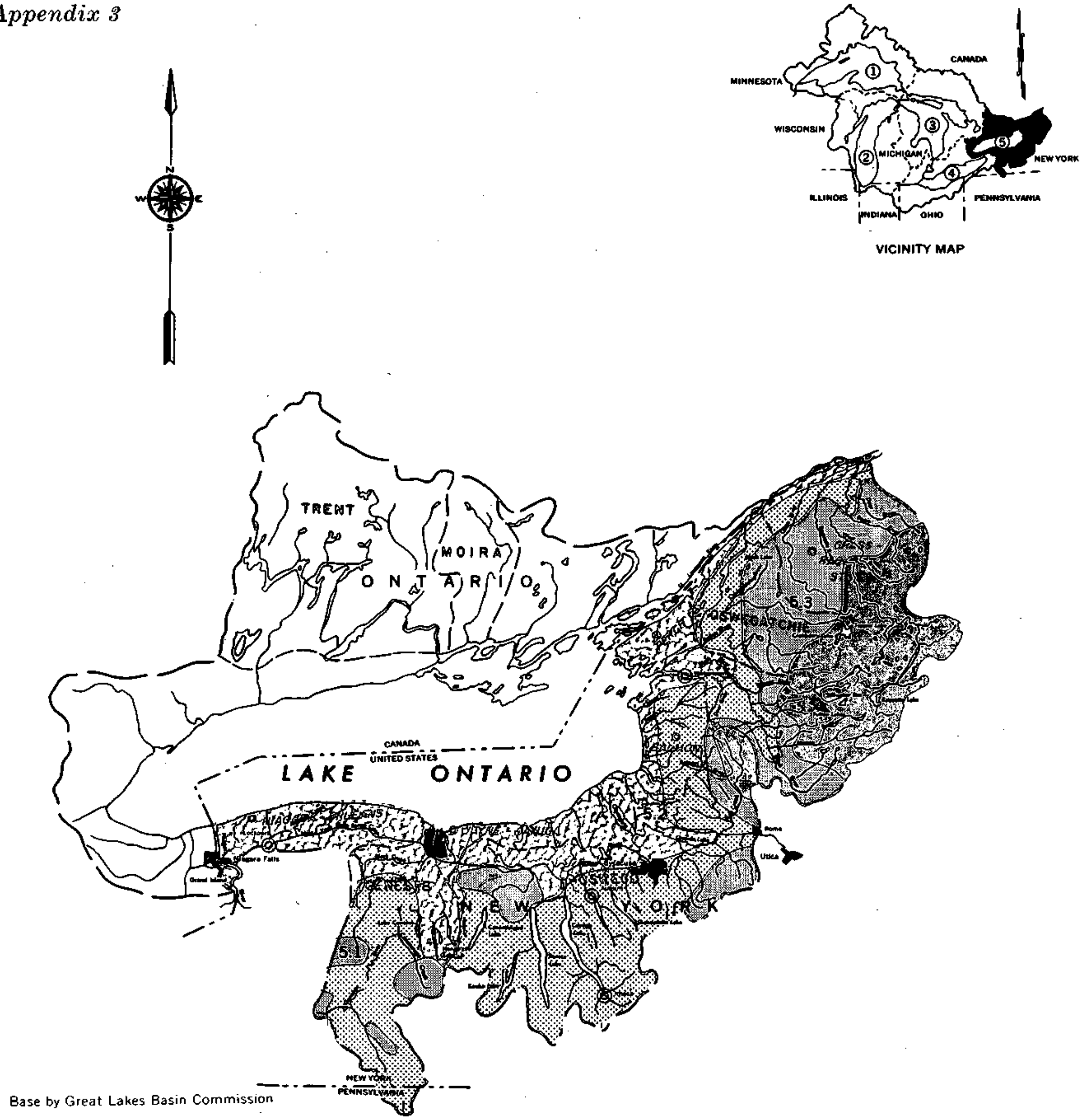


FIGURE 3–59 Bedrock Geology and Areas of Mineralized Ground Water in River Basin Group 5.3



EXPLANATION

Ground-water yield based on geology and runoff at 70-percent flow duration

In millions of gallons per day per square mile	In cubic feet per second per square mile
Less than 0.10	Less than 0.15
0.11-0.25	0.16-0.40
0.26-0.50	0.41-0.78
More than 0.50	More than 0.78

SCALE IN MILES

0 10 20 30 40 50

FIGURE 3–60 Estimated Ground-Water Yield, as Runoff, in the Lake Ontario Basin, United States

AUTHOR

TITLE GREAT LAKES BASIN FRAMEWORK STUDY – APPENDIX 3

DATE DUE	BORROWER'S NAME