Environmental Geology of Lake and Porter Counties, Indiana An Aid to Planning

By **EDWIN J. HARTKE, JOHN R. HILL,** ***and*** **MARK RESHKIN**

ENVIRONMENTAL STUDY 8

DEPARTMENT OF NATURAL RESOURCES
GEOLOGICAL SURVEY SPECIAL REPORT 11

PRINTED BY AUTHORITY OF THE STATE OF INDIANA
BLOOMINGTON, INDIANA: 1975

STATE OF INDIANA
Otis R. Bowen, ***Governor***
DEPARTMENT OF NATURAL RESOURCES
Joseph D. Cloud, ***Director***
GEOLOGICAL SURVEY
John B. Patton, ***State Geologist***

For sale by Geological Survey, Bloomington, Ind. 47401

Price $2.00

Contents

Illustrations

Illustrations

Table

Environmental Geology of Lake and Porter Counties, Indiana-
An Aid to Planning

***By* EDWIN J. HARTKE, JOHN R. HILL, *and* MARK RESHKIN[1]**

Abstract

Lake and Porter Counties are subdivided into three physiographically and geologically distinct regions: (1) the Calumet Lacustrine Plain, (2) the Valparaiso Morainal Area, and (3) the Kankakee Outwash and Lacustrine Plain. The surficial deposits of these regions, which range in thickness from 40 feet near the Kankakee River to more than 250 feet near Valparaiso, Ind,. Are the products, either directly or indirectly, of the Wisconsinan Age of glaciation. The Calumet lake plain is characterized by low-lying complexly intermixed clay, sand, and silt deposits, mostly of glacial Lake Chicago origin, The Valparaiso Moraine forms high ground in the two counties and is composed of clay-rich to fine sandy till. Sand and fine gravel deposits constitute the bulk of the Kankakee Outwash and Lacustrine Plain, this area being the low-lying outwash and flood plain for the glacially derived rivers as well as for the present Kankakee River.

The two-county area has an abundance of geologic and geologically related resources; some of the most important are: (1) groundwater of the Kankakee Outwash and Lacustrine Plain and Valparaiso Morainal Area, (2) sand deposits of glacial Lake Chicago and of recent origin, (3) rich soils developed on the Valparaiso Moraine and Kankakee outwash plain, and (4) surface water in the form of streams, rivers, and small lakes. Some of these resources have already been damaged during the course of man's habitation and use, but all can, with proper understanding of the problems and the willingness to act, be saved from further unnecessary degradation.

Certain kinds of land use, which are partly dependent on the local geology, are potential sources of difficulty. These include (1) siting and use of sanitary landfills, (2) placement of septic systems, sewage lagoons, and industrial holding ponds, (3) management of flood plains, (4) development of the Lake Michigan shoreline, (5) construction of all kinds in areas where little is known about the engineering and hydrologic properties of the materials, (6) disposal of industrial wastes by deep well injection methods, and (7) development of groundwater supplies without sufficient hydrologic and geologic data.

The environmental problems of Lake and Porter Counties, are related to geology, are as varied and complex as the materials themselves. Specific questions related to a given problem are best answered by the competent consultant equipped to do so. This report, though intended to supply valuable geologic information on a variety of land use related subjects, should not replace onsite evaluation of the salient parameters involved with each problem that potentially arises whenever man uses earth materials or otherwise disturbs or rearranges the natural earth condition.

Introduction

Lake and Porter Counties, lying at the south end of Lake Michigan, are the northwesternmost counties in Indiana (fig. 1.) Most of the population of 633,367 (1970 U.S. census) is concentrated in Northern Lake County, where one of the nation's great urban-industrial complexes is situated. The rural areas to the south and east, however, have experienced the greatest growth pressure during recent years and are being rapidly transformed into urban and suburban communities. Porter County, for example, had a 42-percent population increase between 1960 and 1970 according to 1970 U>S> census figures. The two counties are destined to experience continued urbanization because of their pivotal position at the south end of Lake Michigan in what is predicted to become a continuous megalopolis along the southern shore of Lake Michigan.

Population growth and urban expansion are profoundly affecting northwestern Indiana and result in urban renewal and redevelopment, further industrialization.

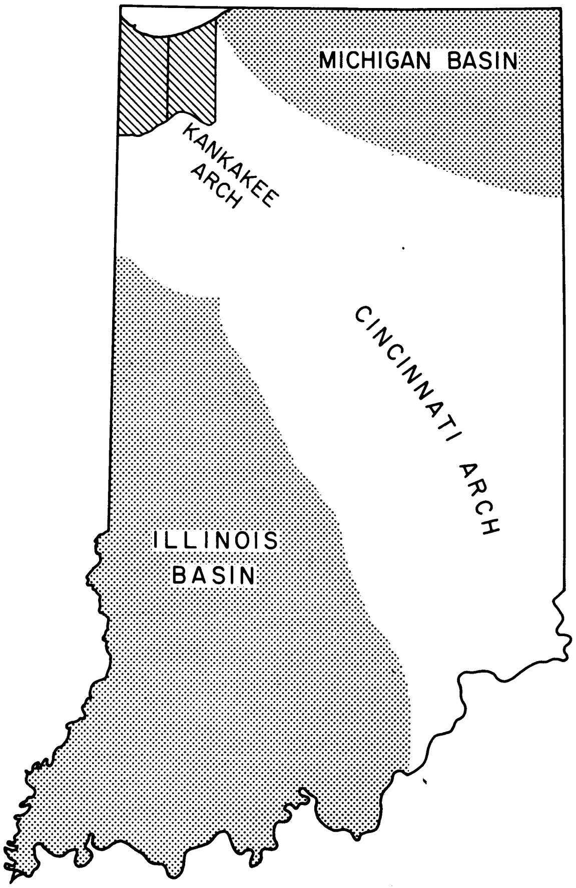


Figure 1. Map of Indiana showing location of study area and major bedrock structural features.

and suburban development spreading through present agricultural lands. Planning problems related to zoning for the most appropriate use of available land and requiring the use of geologic data are numerous, varied, and complex. These planning problems involve: (1) transportation routes and facilities, including air, water, and land services; (2) basic city services and utilities, including water supply and quality, separation of sanitary and storm sewers, sewage treatment, solid waste disposal, power plant sites, and drainage for flood control and other purposes; (3) sites for schools, hospitals, and other essential public facilities; (4) adequate supplies of industrial minerals; and (5) the need for recreational and open space.

Urban growth raises many questions relating to land use, but most prominent among them is evaluating the advantages and disadvantages of one use of land as compared with another. The characteristics of the earth materials and of the surface water and groundwater determine to a significant degree how land can be most effectively and safely used. Correlation of requirements for a planned use of the land with geologic considerations helps avoid development of areas where limitations resulting from the natural conditions of the land would produce future environmental quality problems. This becomes especially true where suitable sites are no longer available and marginal lands are considered.

In the past, factors other than geology have often determined land use. Now, however, geologic information can be used early in the planning process for continued development of city and suburban areas and can be of great aid in preparing for the future growth of Lake and Porter Counties. With this premise in mind, data are presented in this report on environmental geology, which partakes of hydrology, hydrogeology, mineral resources, and engineering and other considerations. Geologic information can be used in many ways to plan for simultaneous growth and development and maintenance of environmental quality (pl. 1).

NATURAL CHARACTER OF THE LANDSCAPE

The northern reaches of Indiana are comprised of a great variety of glacial landforms. Designated the Northern Moraine and Lake Region (Malott, 1922), the area was the last part of the state where the great lobes of the most recent continental glacier melted and receded northward. (See p. 7-9.) Landform features resulting from the precursor of present-day Lake Michigan (glacial Lake Chicago) are an equally prominent part of the landscape.

Lake and Porter Counties lie wholly within three generally east-west-trending subdivisions of the region (fig. 2): the Calumet Lacustrine Plain, the Valparaiso Morainal Area, and the Kankakee Outwash and Lacustrine Plain (Schneider, 1966, p. 50). The unique physical character of each of these landform areas has had a great influence on the sequence of human activities and is reflected in the history of the area.

CALUMET LACUSTRINE PLAIN

The heavily populated and industrialized northern part of Lake and Porter Counties is an area of generally low relief that occupies the bed of glacial Lake Chicago. Until the very latter part of the 19th century, the natural character of the landscape was altered little from that which existed when the present shoreline of Lake Michigan developed 10,000 or 12,000 years ago. Three relict shorelines capped by sand dunes, some rising 40 feet above the surrounding plain, represent successively lower stages of glacial Lake Chicago. The high dunes of the present shoreline trend in an east-west arc through the area. High and dry, they

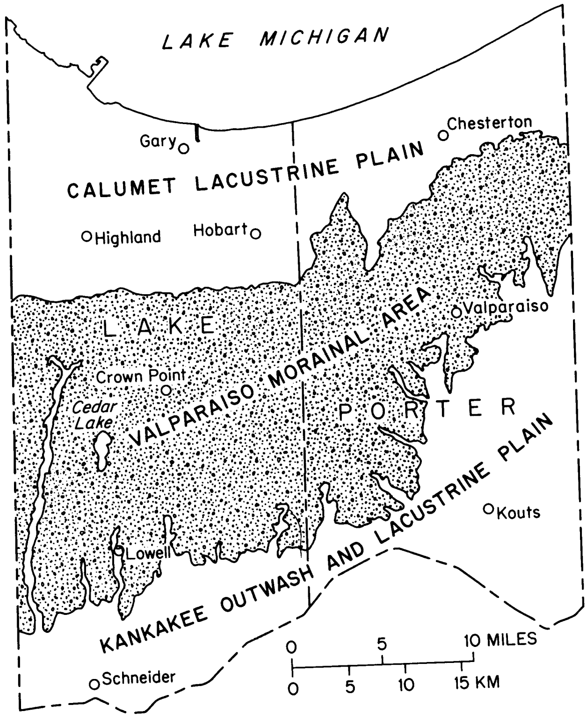


Figure 2. Map showing physiographic units

become major transportation routes through an otherwise relatively impenetrable wetland area, first as Indian trails and later as highways and railroads.

The region is named after the Calumet River, a sluggish stream originating in and receiving drainage from the Valparaiso Morainal Area. The river origi nally meandered westward on the Calumet Lacustrine Plain from its source in LaPorte County, through a swampy lowland between two former beach ridges into Illinois, where it reversed its flow direction. The reversal in Illinois redirected the flow of the Little Calumet eastward through the present Grand Calumet River flood plain to its termination in Lake Michigan at the site of the modern Marquette Park Lagoon in Gary.

The French were the first to name the river Calu met. The name has several possible derivations, among them the assertion that Calumet is the French version of the Indian word "Gekelemuk," which means a low body of deep, still water. Because of the heavy growth of reeds in the Calumet River during the wilderness era, the name "Chalemel" (French for reed) may also have been the root for the present name of the river. The term Calumet Region has come to be applied to the area about the head of Lake Michigan (Meyer, 1954) and is used now to describe all the area of the Calumet Lacustrine Plain and the northern slopes of the Valparaiso Morainal Area to the drainage divide.

VALPARAISO MORAINAL AREA

The Valparaiso Morainal Area is a complex system of rolling hills extending in an arc, approximately paralleling the southern shore of Lake Michigan, from northeastern Illinois, through northwestern Indiana, and into southwestern Michigan. The moraine ranges in elevation from 700 to well over 800 feet above sea level. Many of the hills exceed 850 feet and a few reach elevations of 950 feet near Valparaiso, Ind. (Schneider, 1966, p. 51). The moraine complex has gently rolling topography in Lake County but be comes more rugged east of Valparaiso in Porter County. Travel across the relatively dry morainal belt was much easier than across either of the wetland regions to the north or south. The morainal upland therefore figures prominently in the early history of the are a.

KANKAKEE OUTWASH AND LACUSTRINE PLAIN

A large sandy and poorly drained plain, the Kankakee Outwash and Lacustrine Plain, comprises approximately the southern quarter of both Lake and Porter Counties and is the most recent of the three land scape regions to face the pressures of impending urbanization. Large portions of the area were once marshland associated with the meandering Kankakee River, which, for 8 or 9 months of the year, was flanked on both sides by wetlands. The marsh area was 3 or 4 miles wide and contained water 1 to 4 feet deep (Meyer, 1935). The low marshland was broken by infrequent islands of sand blown into dunes. The sand islands were the sites of Indian encampments and later of pioneer homes. The Kankakee marsh was an effective barrier to early southerly exploration of both counties, but the area has been progressively drained by ditches constructed during the past 60 years.

LAND USE

Effective, efficient, and protective land use information and guidance must be the goal of any environmental report. This report was designed to provide general information of a geologic nature that can best be used by local officials and planners to produce environmentally oriented land use plans.

A knowledge of past land use can be helpful in understanding the current state of land use and may aid planners in their consideration of future land use plans. Two stages have been recognized in terms of human modification of the natural environment: an early period, lasting into the 20th century, during which man's activities were adapted to the constraints of the natural -environment; and a later period, continuing into the present, when, at an ever-accelerating pace, man has modified the natural environment to satisfy his demand for agricultural, industrial, and residential land. These stages were not concurrent everywhere throughout the two counties.

In preparing the wetlands for industrial development, dunes are being leveled, and sand pits dug, as the earth materials are used extensively to fill in remaining low, wet areas as well as areas behind breakwaters of the landfills in Lake Michigan. The lakeshore has become primarily an industrial corridor with urban-residential development progressing inland from this belt. Thus industry became hemmed in, so to speak, and began filling in Lake Michigan to gain land for expansion. The need for land for industrial development continues, as indicated by the several areas in the lake currently being filled (pl. 1).

Most of Porter County and the Valparaiso Morainal Area and the Kankakee Outwash and Lacustrine Plain of Lake County were used for agriculture throughout the first half of the 20th century. It has been only within recent years that population growth and outward migration from northern Lake County have resulted in extensive residential development in the form of a suburban sprawl. Population predictions indicate extensive future development of the Valparaiso Morainal Area for residential and commercial uses with a subsequent decrease in agricultural use. The construction of superhighways contributes to this southward trend in urban development, and new communities are expected to grow near the exits of these major north-south access routes. Knowledge and use of earth resource data in this area are vital factors for planners in formulating land use policy as growth continues.

The Kankakee Outwash and Lacustrine Plain has been an agricultural area for most of this century. Drainage of the marsh occurred later than drainage of the Calumet Lacustrine Plain. The Kankakee River and its multitude of drainage ditch tributaries have drained more than half a million acres of land for farming throughout the river basin in Indiana and Illinois. Cognizance of certain geologic and hydrologic facts presented herein will aid in developing a land use plan in this area.

Interstate Highway 65 has created a new direction for urbanization-south. Public utilities are already considering sites in the area for electric power plants and waste-water disposal facilities. Commerical concerns and industrial plants have already been constructed and are in operation adjacent to U.S. Highway 30 east of Valparaiso on the outwash plain. Proposals to establish a third major Chicagoland airport in the area have received state government approval and if brought to fruition would signal a boom in land development throughout all areas of both counties.

The major thrust of development will probably be redevelopment in the Calumet Lacustrine Plain and will greatly expand nonagricultural land uses in the Valparaiso Morainal Area and the Kankakee Outwash and Lacustrine Plain.

Geologic History

BEDROCK GEOLOGY

The consolidated rocks of Lake and Porter Counties include more than 4,000 feet of limestone, dolomite, sandstone, and shale of Cambrian through Devonian age, which rest on a granitic basement that is designated Precambrian. These *sedimentary*[2] rocks (fig. 3) constitute a series of strata that are relatively flat lying but that are gently flexed to form a saddlelike structure. This saddle, a part of the Kankakee Arch, rises between the Michigan Basin to the northeast and the Illinois Basin to the southwest (fig. 1). Figure 3 presents a simplified view of the bedrock to a depth of more than 4,000 feet by use of a generalized stratigraphic column which shows the approximate age, thickness, and lithology of the units in the bedrock sequence.

Structural dip, or inclination of the bedrock units, is generally southeastward, although the dip is northeastward in the northeast sector of Porter County. Average dip is about 5 to 7 feet per mile.

The bedrock surface (fig. 4), which lies beneath 15 to 270 feet of unconsolidated glacial material, is largely a preglacial erosional feature and is not reflected by the present glacially derived land surface. The highest and coincidentally the shallowest area of bedrock lies under the Kankakee plain in southern Lake County. This bedrock high is part of a northeast-southwest-trending ridge of Devonian limestone and shale in the southern part of the two counties. The general attitude of the bedrock surface (fig. 4) indicates that surface drainage was northward from all but the south edge of the area. The aforementioned bedrock ridge was the drainage divide. Bedrock elevation ranges from a low of about 450 feet above sea level near Lake Michigan to a high of about 650 feet on the ridge in the south under the Kankakee plain.

Lying at the top of the bedrock sequence is the youngest unit, the Antrim Shale. Precambrian granite (primarily a light-colored acidic *igneous* rock) is the oldest in the sequence and forms the base on which the sedimentary units were deposited.

---

[2]Geologic terns in italics are explained in the glossary.

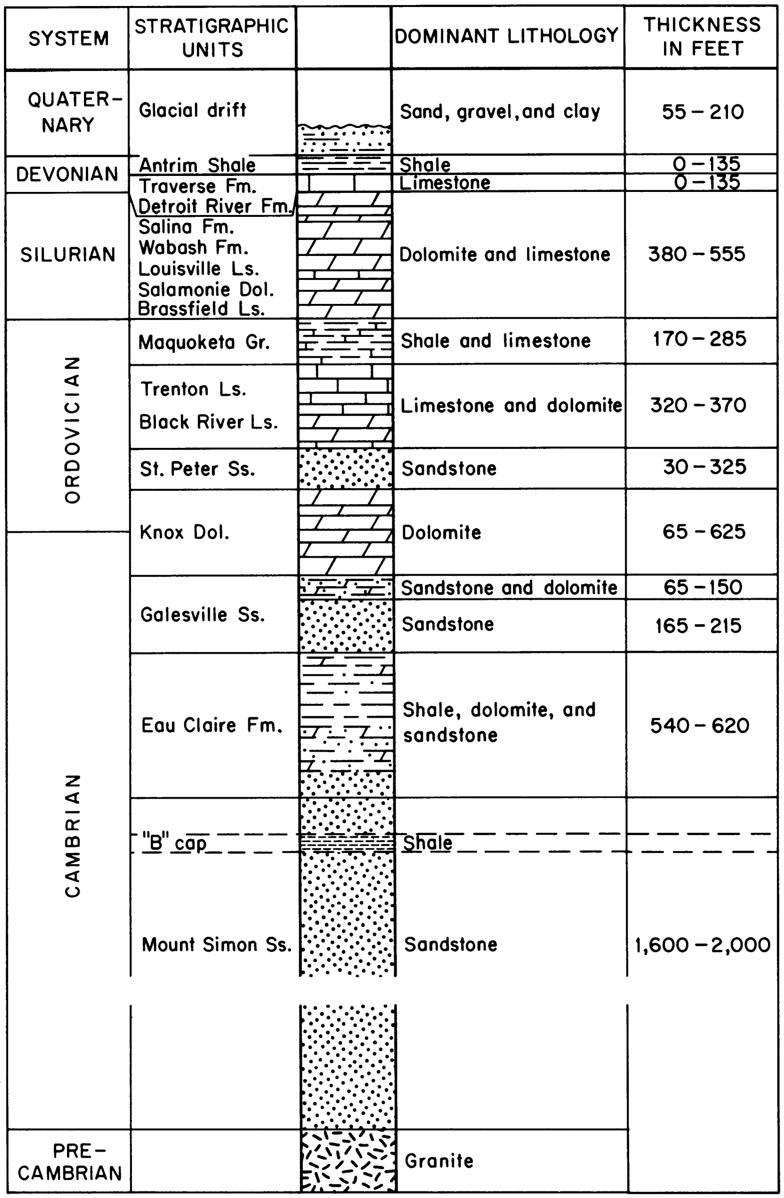


Figure 3. Generalized column showing lithologies and names of bedrock formations.

The approximate geologic age of the Antrim Shale is 260 million years, but that of the granitic rocks exceeds 600 million years.

The succession of sedimentary rocks (fig. 3) was deposited on the granitic *basement rock* in shoreline and near-shore environments as the area alternately rose and fell relative to sea level. The sandstones (believed to be beach deposits) and shales (shallow marine deposits) are thought to have been derived from the *Canadian Shield.* The limestones were deposited in moderately shallow waters, and dolomite and dolomitic limestones resulted from postdepositional alteration of the limestone. The Silurian limestone and dolomite near the top of the bedrock column contain significant fractures and (or) solution features. The solution features are the result of percolating groundwater, at a time when these rocks were at or near the surface, which dissolved the soluble carbonate rock along fractures and joints. These somewhat interconnected openings decrease in size and number with depth and may be filled or partly filled with sediment.

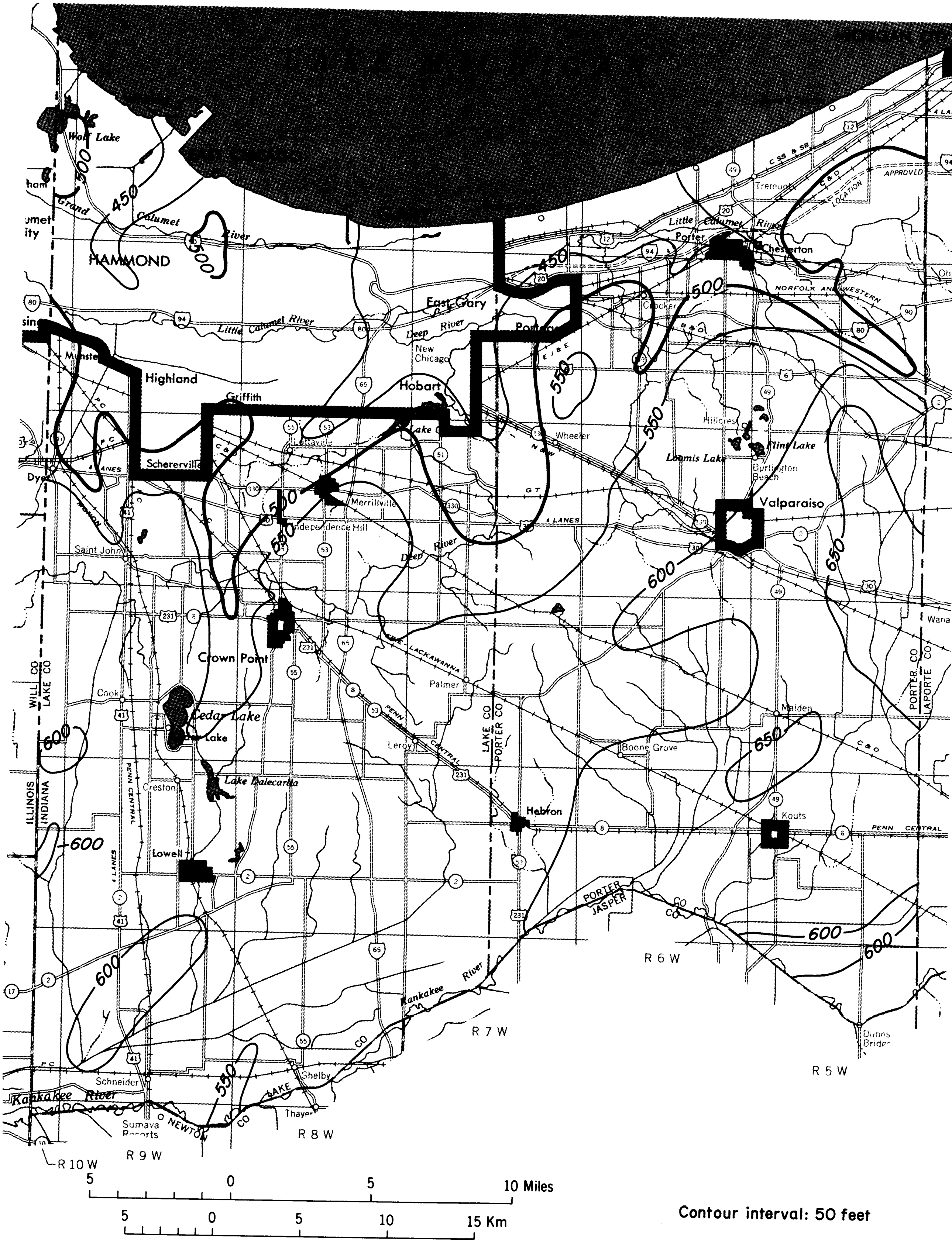


Figure 4. Map showing bedrock topography. From Burger, Keller, and Wayne, 1966.

The bedrock should not present construction related problems because of the thickness of the glacial materials, nearly everywhere more than 50 feet thick, and the limited extent of the previously mentioned solution features. The environmental significance of the bedrock stems from the water and mineral resources it contains and from its potential as a storage reservoir for undesirable liquid wastes. Therefore, knowledge of and consideration for bedrock potential can and should be an integral part of any land use plan.

GEOLOGY OF THE UNCONSOLIDATED DEPOSITS

The unconsolidated materials which overlie bedrock in Lake and Porter Counties were deposited, directly and indirectly, by glacial forces during the great Ice Age, that is, the *Pleistocene* Epoch (Quaternary Period). More specifically, these deposits were laid down during the last major ice advance, during the *Wisconsinan Age,* by the combined agents of ice, wind, and water. As discussed on pages 2-3, the two counties are divided into three distinct physiographic areas: (1) the Calumet Lacustrine Plain, (2) the Valparaiso Morainal Area, and (3) the Kankakee Outwash and Lacustrine Plain (fig. 2). The earlier section was a discussion of the topographic expression and natural character of these areas; the following is a general treatment of the mode of origin and properties of the geologic materials found in the three *physiographic* belts.

CALUMET LACUSTRINE PLAIN

Sediments of the Calumet Lacustrine Plain consist of a variety of materials, including fine lake silt and clay, paludal deposits of muck and peat, great expanses of sand beach with accompanying sand dunes, sand and fine gravel laid down as glacial outwash and as till inclusions, and clay-rich till units of varying thickness and areal distribution (pl. 1).

Most of the sand and clay sediments were deposited late during the Wisconsinan Age as lake-bottom and near-shore deposits of glacial Lake Chicago. Sediment-laden meltwater from the retreating glacier trapped by the Valparaiso Moraine to the south, east, and west and by the retreating Lake Michigan ice lobe to the north accumulated in ever-increasing volumes to form Lake Chicago. As the silt and clay settled out of suspension, great thicknesses of mud accumulated across the lake basin. Outwash sand and gravel washed into the lake and settled rapidly, forming bars and ridges of coarse materials that were subsequently reworked by wave and current action. When the Valparaiso Moraine was breached near what is now Palos Park, Chicago, by the flood of meltwater, Lake Chicago began to lower. This lowering of lake level was punctuated by three semistabilized water levels, at which time sand beaches and their accompanying near-shore *foredunes* were formed. These relict beaches have been named Glenwood, Calumet, and Toleston and have elevations above mean sea level of 640, 620, and 605 feet. With each successive lowering of lake level, the shoreline retreated farther northward, thus exposing the lake clay and sand deposits of the previous level.

The lowering of Lake Chicago was not, however, a continuous process. On the contrary, the lowering stages were punctuated by numerous high water periods, at which time the lake level rose as much as 25 feet, only to fall after a short period to a new level which also was only temporary. The three major lake levels mentioned above, then, are as much average representatives of the multiple lake levels as they are true, long-term, static water levels.

Along the northern limb of the Valparaiso Moraine, the lake sediments directly overlie the northward sloping till deposits of the moraine (fig. 5). Toward the western extreme of the moraine in Indiana, the northern slopes are gentle, thus providing a broad, gradually sloping shoreline on which moderate to heavy volumes of sediment were deposited throughout late Wisconsinan time. In contrast, the eastern extreme of the moraine exhibits more steeply dipping northern flanks than its western part in Lake County. Sediments deposited in the eastern sector are of only minor inland breadth and vertical depth. The mapped deposits of glacial Lake Chicago, therefore, are broad and well developed in much of Lake County but are narrow and relatively poorly developed in Porter County.

The relationships among the lake mud, sand, and gravel deposited during the Lake Chicago cycle are further complicated by the truncation of these sediments in several known localities, which is the possible result of northward drainage off the Valparaiso Moraine into the lake basin. Further, depressed areas on the Calumet Lacustrine Plain provided settling ponds in which bottom mud accumulated. Varying thicknesses of organic muck and peat also formed in topographic lows. As the shoreline of Lake Chicago retreated northward in response to the general lowering of lake level, ever-increasing expanses of lake bottom were exposed to surface erosion and alteration, as well as to aeolian deposition of sand and silt. With numerous minor fluctuations in lake level, discussed above, these terrestrial sediments either were washed away by lake currents or were covered over by lake bottom mud or

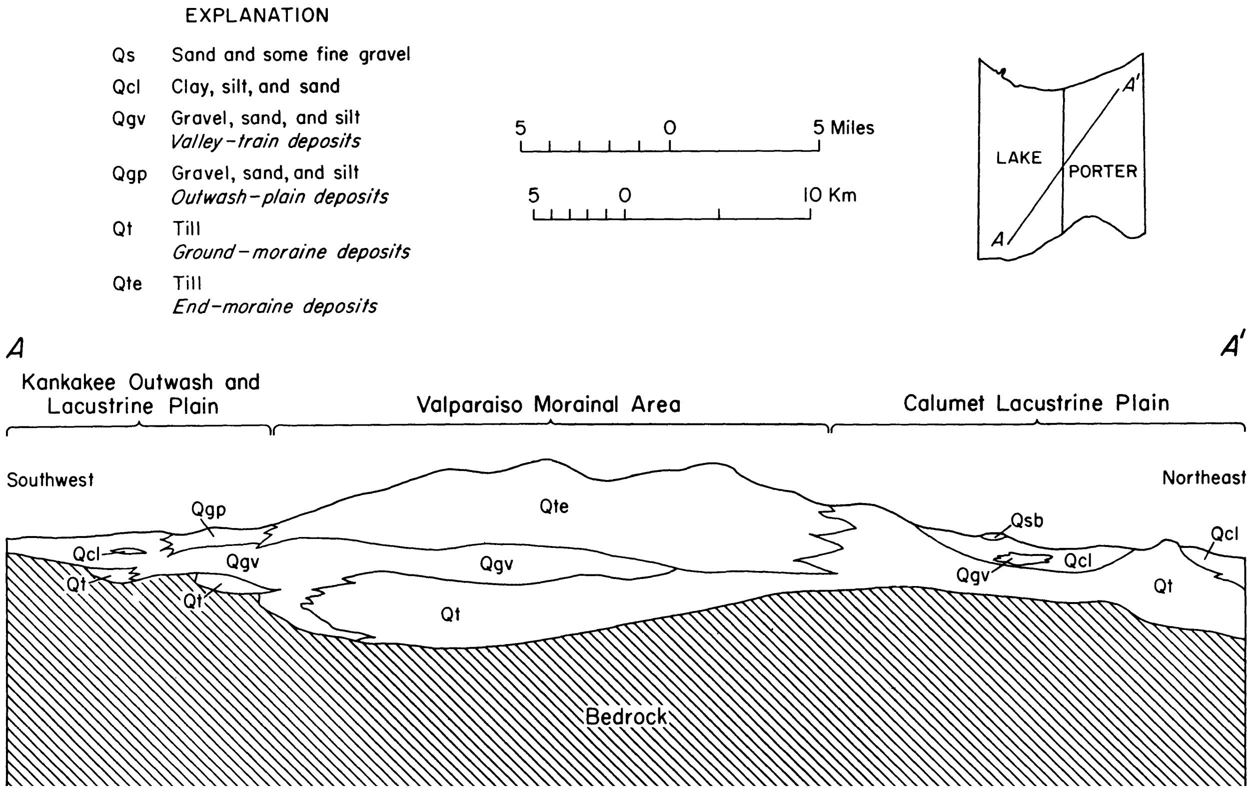


Figure 5. Generalized south west-northeast cross section showing physiography and interrelationships of unconsolidated deposits. Vertical exaggeration is about 75. (See pl. I for explanation of geologic units.)

sand. The result is a bewildering complexity of interstratified lake and terrestrial sediments, most of which are indistinguishable from one another.

The areas mapped as Qt (pl. 1) north of Chesterton and west of Hobart are surficial exposures of *ground moraine*. This map unit is composed of a silt to clay loam till which was deposited prior to deposition of the Lake Chicago sequence and of the Valparaiso Moraine as well. The ground moraine probably covered much of Lake and Porter Counties at one time, but glacial and stream erosion stripped away some of the unit while greater portions were covered by other materials. The disposition of this unit farther south is discussed later in the section. On the Calumet Lacustrine Plain, the ground- moraine formed high ground and was therefore not covered by lake sediments, as it was probably never under water long enough for appreciable sedimentation to have occurred.

VALPARAISO MORAINAL AREA

The Valparaiso Moraine, as discussed on page 3, extends around the southern tip of Lake Michigan from Illinois through northwestern Indiana and into Michigan. Actually, the Valparaiso Moraine is a composite of several end moraines, one superimposed atop the other in response to minor fluctuations of the terminus of the retreating tongue of glacial ice called the Lake Michigan Lobe. Only two morainic ridges are discernible in Indiana, the Valparaiso Moraine itself, which is by far the largest and most distinct in Indiana, and the more subdued Tinley Moraine. Because the till lithologies of the two moraines are indistinguishable, differentiation is based primarily on physiography and drainage characteristics of the landforms. The bulk of the till is a clay-loam material that has a wide variety of rock inclusions ranging in rock type from dolomitic to crystalline erratics in Lake County to predominantly shale fragments and crystalline rock fragments in Porter County. The overall texture of the upper till is sandier in the east than in the west, and sand pockets are common near Valparaiso.

The moraine is dotted by numerous small lakes just north of Valparaiso that formed in ice-block depressions called *kettle holes.* Dalecarlia and Cedar Lakes in Lake County, though much larger than the lakes farther east, also originated as kettle depressions. The lakes are maintained by a combination of surface runoff, stream input, and groundwater springs. Other depressed areas on the moraine, which formerly were the sites of small lakes, are now filled with muck and peat deposits.

Beneath the Valparaiso morainal complex, at depths ranging from 15 to more than 100 feet, is another, older till deposited earlier during the Wisconsinan glaciation (mapped as Qt on pl. 1). The lower till is similar in lithology and texture to the upper Valparaiso morainal till but was deposited by actively advancing ice in the form of gently rolling ground moraine and is therefore denser and more highly preconsolidated than is the upper till of the end-morainal sequence. Much of this lower till, as mentioned earlier, was truncated by readvancing ice and fluvial erosion.

A layer of sand and fine gravel lies between the upper and lower tills across the southern half of the Valparaiso Morainal Area. This coarse sediment unit is outwash of the glacial-recessional stage that occurred between the deposition of the upper and lower tills, and it is laterally contiguous with the outwash deposits of the Kankakee Outwash and Lacustrine Plain.

KANKAKEE OUTWASH AND LACUSTRINE PLAIN

Extensive glacial outwash, lake, and river deposits in the form of a broad sandy, muck-veneered plain were deposited in numerous cycles during the Wisconsinan glaciation to form the Kankakee Outwash and Lacustrine Plain. At about the same time the retreating Lake Michigan Lobe was depositing outwash in the area, a complex lake system was forming in Illinois and in a small part of Indiana in southern Lake County. These lakes, named Wauponsee and Watseka, were interconnected for an unknown length of time and were maintained by meltwater from the receding glacier. The depth and extent of glacial Lake Wauponsee in southern Lake County probably varied during the final stages of ice retreat as fluctuating volumes of water were supplied to the area. Much of the fine silt and clay deposits common at depth throughout the area were undoubtedly laid down in large part during the Lake Wauponsee-Watseka part of Wisconsinan time. Sand and fine gravel deposits which He both above and below the clay sediments are mostly of glacial outwash origin and, in extreme southern Lake and Porter Counties, have been reworked by fluvial action of the Kankakee River. Once glacial Lakes Wauponsee and Watseka had drained, the Kankakee outwash area was left as a low marshy wetland, at which time decaying aquatic vegetation formed a veneer of muck and peat over the sandy outwash deposits.

When, in the early 1900's, the outwash plain was drained by extensive ditching, prevailing westerly winds reworked the exposed surface sands into rolling dunes. Although much less extensive and considerably less spectacular than the dunes of the Calumet Lacustrine Plain, the Kankakee outwash dunes form the higher elevation landforms that rise above the otherwise flat outwash and lake plain.

The total thickness of the sediments on the Kankakee Outwash and Lacustrine Plain ranges from a low of 15 feet at several localities along the Kankakee River to a maximum of 65 feet near the southern flank of the Valparaiso Moraine.

Engineering Geology

As available unused land becomes more and more a premium commodity, the need for careful planning increases. Because it is very difficult, if not impossible, to predetermine the exact use of a given tract of land at a given time, the best approach to land use suitability planning is to consider the positive and negative aspects of the different areas on the basis of available geologic, engineering, and geographic data. This section is intended to provide a broad review of the engineering properties of the discrete geologic units in Lake and Porter Counties and to provide more detailed descriptions of specific problem areas.

TERMINOLOGY

The following discussion of technical terminology and engineering geology concepts is designed to aid the layman in better understanding the body of text that follows. The term size, or size grade, as applied to all samples in this report, refers to the subdivision of the various particulate constituents of a given soil unit according to their mean diameter. The common size classes accepted by geologists, engineers, and soil scientists include the terms clay size, silt size, sand size, granule, etc. (table 1). Several different size scales corresponding to these classes are in common use. The one used here is the Wentworth scale of particle sizes (table 1).

Table 1. Modified Wentworth scale of particle sizes

Size class	Diameter of particles (mm)
Clay	Less than 0.004
Silt	0.004 to 0.063
Sand	0.063 to 2.0
Granule	2.0 to 4.0
Pebble	4.0 to 64.0
Cobble	64 to 256
Boulder	Greater than 256

The term Atterberg limits and related indices, liquid limit, plastic limit, and plasticity index are used throughout this section as a useful characteristic of assemblages of soil particles. The limits are defined on the principle that a fine-grained soil, such as a silt or clay loam, can exist in any of four physical states, depending on its water content (Lambe and Whitman, 1969, p. 33). When dry, a given soil is solid; after addition of water it becomes semisolid; with more water it becomes plastic; and finally it behaves as a liquid at a given state of saturation. The plastic limit, then, is the amount of water, expressed as weight percent of the soil sample weight, at which the material behaves plastically. The liquid limit is the relative weight percent of water at which the soil becomes a liquid. The plasticity index, used by soils engineers in classifying potential soil strengths, is determined by subtracting the plastic limit from the liquid limit. Soils, such as sandy loams, that have insufficient amounts of silt and clay to bind the soil together are said to be nonplastic, because Atterberg limits do not apply to noncohesive soils.

Atterberg limits are usually used in combination with field moisture data, that is, the weight percent of water in a soil sample at the time the sample was removed. Once obtained, field moisture values are compared with the Atterberg limit data to establish the actual plasticity of the in-place soil with respect to its potential limit. From such comparisons, the relative soil strength and related physical limitations of a given unit can be determined.

The carbonate content within a given soil unit is another applied measure in engineering geology. Carbonate content of a soil affects the strength of the soil, its cohesiveness, and acidity (pH). A soil of high lime content is generally more highly indurated and coherent than is a similar soil with lower carbonate content. The presence and amount of carbonate within a soil are also used to determine whether the soil has been leached, thus telling the observer whether the sample came from a disturbed or from an undisturbed locality. The relative percentages of calcium carbonate and calcium magnesium carbonate within the soil unit are used as criteria for its classification.

The term compressive strength deals with the ability of a soil unit to support a given load and is usually expressed in tons per square foot. All the figures for compressive strength presented here were determined by means of a hand penetrometer, which was used only on split spoon or Shelby tube samples.

DATA AND INTERPRETATIONS

The three physiographic areas (see p. 2-3) are separately unique in their engi eering geology and form a convenient basis for discussion.

CALUMET LACUSTRINE PLAIN

The Calumet Lacustrine Plain is a geologically heterogeneous area that has interlayered sand, lake clay, and till forming the bulk of the sedimentary units. Not only does the unit lithology vary vertically, but abrupt changes occur laterally as well. (See p. 7.)

Each soil type, whether sandy or clayey, has its own unique properties that place the unit somewhere on the spectrum between well and poorly suited to a given use. Generalizations about the lithologic sequences of Lake Chicago origin are useful in making broad, sweeping plans for an area. When dealing with specific and areally limited localities, however, predicting vertical variability and, more specifically, the type of unit expected at a given depth becomes nearly impossible. It is therefore our intent to provide a generalized overview of the geology and associated engineering properties, leaving specific questions to be answered by the consultant equipped to do so.

Most of the sediments of the Calumet Lacustrine Plain are water-laid sands and clays, the windblown dune sands being next in abundance. All the sand deposits, whether wind or water laid, have very similar strength properties, are not plastic, and serve as excellent groundwater carriers. The series of auger samples nos. 36 through 53 (fig. 6; appendix) provide a reasonably detailed view of the shallow subsurface on a set of north-south lines in the Gary and East Chicago area. The alternate layering of lake clays over sand, and the reverse, is the general mode of deposition on the Calumet lake plain, as is apparent from the boring data.

The sand units vary in mineralogy and, to a lesser degree, in grain size and shape. The most abundant sand-size mineral is quartz, which constitutes about 75 percent by weight of the sand-mineral suite. Feldspars and carbonates make up most of the remainder. Carbonates ranging in concentration from a trace near the surface to as much as 15 percent at depths in excess of 20 feet constitute the primary nonsiliceous mineral assemblage. *Heavy minerals,* such as garnet, magnetite, and rutile, account for only a trace to a maximum of 3 percent. Most of the sand units are well graded and have little or no silt and clay. When the sands are compacted and saturated, their *shearing strengths* are high; their workability as a construction material is good; and their compressibility is low (Asphalt Institute, 1969). Dry dune sand assumes a stable profile when the sand face

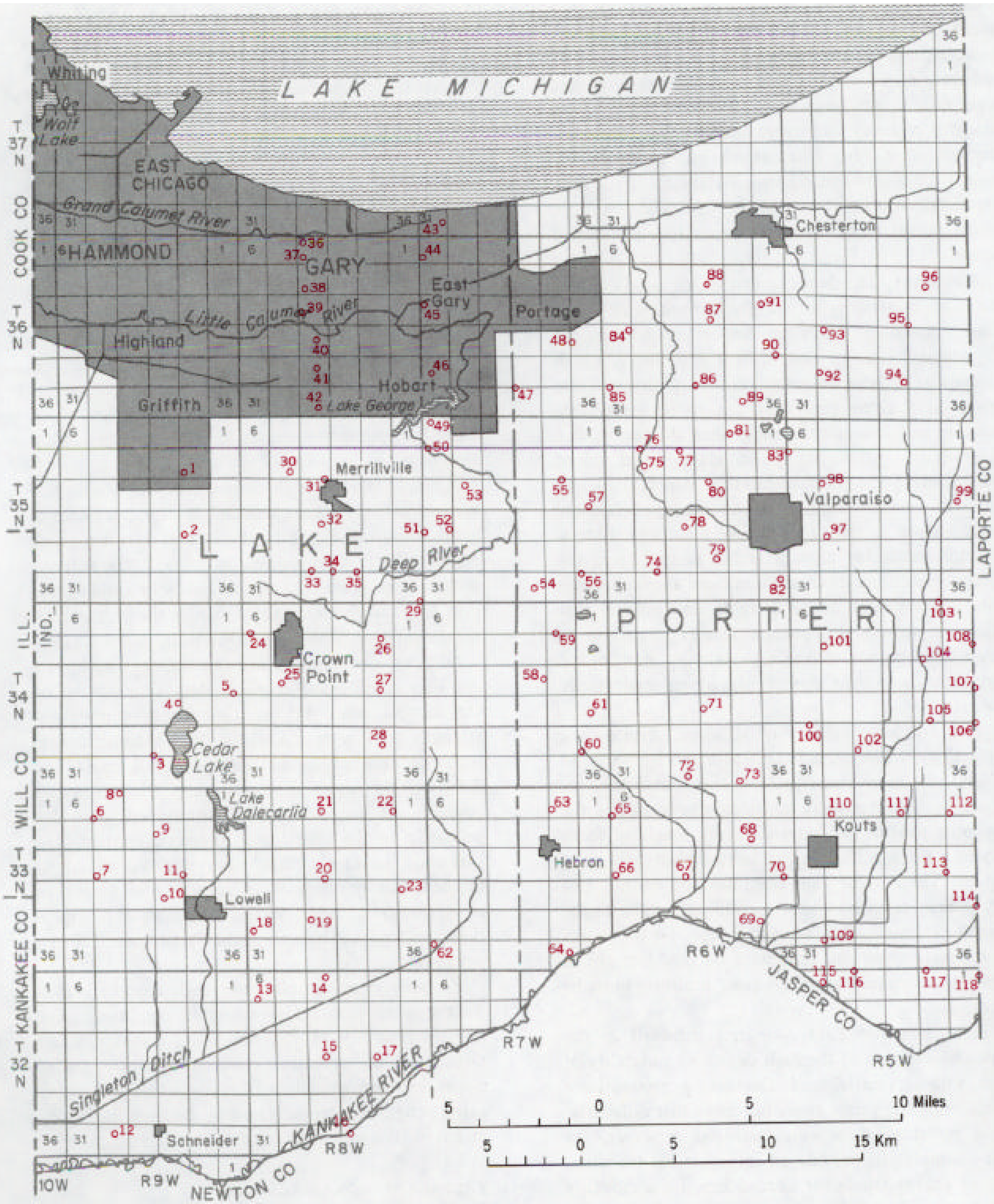


Figure 6. Map showing numbered auger hole locations. Numbers refer to appendix.

exceed an angle of 320 with the horizontal. All sand dunes are subject to extreme alteration by wind, however, unless held fast by dense vegetation. Broad, low-lying dunes are much more easily stabilized than high dunes. Although sand provides an excellent base for highway and other construction, tunneling through or digging foundations into sand can obviously be a problem. Chemical stability of the sand units throughout the Calumet lake plain is high, which results from the stable mineralogy mentioned above.

Abundant clay deposits (unit Qcl, pl. 1) reflect the clay mineralogy of locally derived shale units. Clay mineralogy plays an important role in the physical behavior of clay units. For instance, a high percentage of clay minerals of the montmorillonite group in a given clay unit can cause appreciable swelling and loss of coherency when the clay is wet. Similarly, a group of hybrid clays called mixed layered clays can produce physical effects similar to those of montmorillonite. Expanding layer clays are not common in the Calumet lake plain area. Illite is the dominant clay mineral and is derived from the nearby shale formations as mentioned above. Because illite is considered to be a stable clay mineral that offers no structural problems directly related to its physical properties, it is safe to state that most of the clay deposits on the Calumet plain are mineralogically stable.

The structural stability of all clays, despite their mineralogy, however, is greatly affected by water. In general, the more water present, the weaker the clay aggregate. The Atterberg limits data presented in the appendix provide the percentages by weight of water required for specific soils to behave plastically or as liquids. These values are absolutes and do not give any indication of how near a given soil unit is to the plastic or liquid limit while in place. To determine how near a given soil unit is to its liquid or plastic limit, a determination of *ambient* moisture must be made.

Field moisture data were not included in the appendix because of the high degree of variability of such values, rainfall and fluctuating groundwater levels being the prime contributors to this variability. Field moisture data were gathered, however, for many samples to provide an indicator for the variation in soil moisture over a broad area. Field moisture checks for 10 samples taken at 15-foot depths gave values of 15 to 25 percent water by weight. Samples taken from lake clay units contained an average of 40 to 43 percent clay and about 45 to 50 percent silt. Liquid limit values ranged from 30 to 48 percent for these samples, and plastic limits ranged from 18 to 23 percent. Of the 10 samples for which field moisture checks were run, eight had moisture content in excess of 18 percent, which means that the in-place soil was near or in excess of its plastic limit. Because soils which are at or above their plastic limits can creep and slump, slope stability and foundation collapse problems are likely if slope angles meet or exceed an angle of 1.50 with the horizontal. Clayrich soils, such as those in and near Munster and Hobart, should be thoroughly tested prior to undertaking any construction involving excavation and extensive surface grading which could result in oversteepened slopes. Proper drainage of clay soils helps to maintain safe moisture content within the soilstrength specifications of most construction jobs. In poorly drained areas, it may be necessary to use cutand-fill or piling techniques to achieve stable foundation bases.

Compressive strength, which is a function of texture, moisture content, and soil density, is a factor of great importance to the builder and construction engineer. It is, as explained on page 10, the measure in tons per square foot of the ability of a soil to support load. More importantly, it tells the engineer the maximum load that a given soil unit, under ambient conditions, can support without failing. The appendix lists compressive strength data as measured on the sample site. At the time these compressive strength tests were made, the lake sediments with high clay content had a strength range of from 0.5 to 2.5 tons per sq ft. The variability in compressive strength, as could best be determined, was due primarily to the variation in moisture content. The silty-clay sediments that were sampled could, if drained, sustain compressive loads of 6 to 8 tons per sq ft; however, under average conditions of precipitation, the median strength probably lies near 1.5 tons per sq ft.

Properly drained soils have higher strength than do the same soils under saturated conditions. The low permeability of clay-rich units makes drainage difficult, but vegetative cover and gently graded slopes improve drainage. In many situations, aggregate strength can be increased by draining the soil by means of tiles and other conduit.

VALPARAISO MORAINAL AREA

The Valparaiso Morainal Area, underlain by at least two till units, contains the most uniform and thickest unconsolidated deposits in Lake and Porter Counties. The upper till unit, which actually makes up the form and relief of the moraine, is, on the average, a silt-clay loam ranging in strength from 1.5 to 3 tons per sq ft. Beneath the upper till, and separated in some places by a variable thickness of outwash sand and fine gravel, is a lower, more densely compacted till ranging in strength from 2 to 5 tons per sq ft. In Lake County, the upper till, which forms the Valparaiso Moraine, ranges in thickness from 15 to about 50 feet, but the same unit in Porter County thickens to nearly 150 feet in the areas just west and north of Valparaiso. In addition, the surface till is decidedly sandier in eastern Porter County, as can be seen from the boring data in the appendix. The lower till is very thin or absent in many areas because of glacial and fluvial truncation during and prior to the formation of the Valparaiso Moraine.

Field moisture data from numerous localities across the moraine indicate that the saturation level of the top 20 feet of till is 20 to 50 percent below the plastic and liquid limits of the materials. Slope stability, even in the higher elevation areas in Porter County, is good, although vegetation cover is necessary to maintain most slopes against hydraulic erosion, oversaturation, and subsequent creep.

In Lake County the average depth to the sandy outwash zone (see p. 8) is about 25 feet, and in Porter County this depth increases to 40 feet. Pockets or blebs of sand and fine gravel are incorporated in the upper till throughout the moraine. The main outwash layer is actually part of the Kankakee outwash plain to the south and is hydraulically connected to it. An abundant supply of groundwater is therefore within the outwash layer below the Valparaiso till. Where the till is in contact with the saturated sand and gravel unit, it becomes saturated, thus sharply lowering both bulk density and strength of the till. In like manner, most of the outwash blebs within the till are saturated and serve to maintain the surrounding till in a state of near to complete saturation. The effective loss of till strength in close proximity to saturated sand and gravel bodies is commonly in excess of 50 percent, that is, sufficient to cause construction problems in areas affected. At the southern extreme of the Valparaiso Moraine, where the till mantle over the underlying outwash is less than 25 feet, care should be taken in planning construction requiring deep subsurface excavations. In all projects, exploratory borings should be made in a given area to a depth at least 10 feet deeper than the maximum planned depth of the excavation or piling.

As discussed earlier, the general till texture ranges from a silt to clay loam (Lake County) to a sandy silt loam along the southeastern flank of the Valparaiso Moraine (Porter County). The morainal topography is subdued in the west and hilly in the east, thus providing better surface drainage in Porter County. This combination of good surface drainage and sandy soil texture accounts for the basically stable and strong materials available in most of northern Porter County.

As well drained and stable as they may be, even the most secure valley walls and hillsides can slump or creep if they are not properly protected. An ample quantity of vegetative cover is required to hold even gentle slopes and to prevent excessive erosion due to runoff. With the steady increase in suburban development, the need to conserve remaining forests and soils is of paramount importance. One way to serve this need, in addition to zoning green belts, is for the developer to build with the general grain of the land; that is, to avoid alteration of slopes and drainage lines wherever possible and to remove as little surface soil as possible. When surface soil is removed, it is advantageous in many places to stockpile it, so that after construction it can be returned to provide a fertile soil in which to restart vegetation. Wind and water erosion can be controlled early in the construction phase if grading and stripping are done only in those areas where immediate building is planned. Postconstruction runoff erosion is a serious problem that is often overlooked in the planning and development stages. As houses and roads, driveways, and other paved surfaces are added to a given area, especially an area of high relief, such as the Valparaiso Moraine, surface runoff is increased many fold over the same area under natural conditions. This increase in surface runoff and potential runoff should be evaluated and compensated for even before ground is broken. Large, high-volume drainageways, holding and sedimentation ponds, and extensive revegetation are a few ways in which hydraulic erosion can be controlled.

The lower till unit, discussed above and mapped as Qt on plate 1, is similar in most respects to the till of the Valparaiso Moraine. Lower relief and greater bulk density than for the Qte or Valparaiso morainal deposits are the major differences between the two units. Atterberg limits data, textural analyses, and mineralogic data are nearly identical for both upper and lower tills. The lower till, however, generally has a somewhat higher compressive strength than the upper unit. Suitability for construction based on materials alone is about the same for both units.

The Valparaiso Morainal Area is well suited for all types of construction from industrial to residential. The primary limiting factor in the eventual parceling off and zoning of land on the moraine is the availability of sufficient quantities of fresh water. (See p. 20-35.)

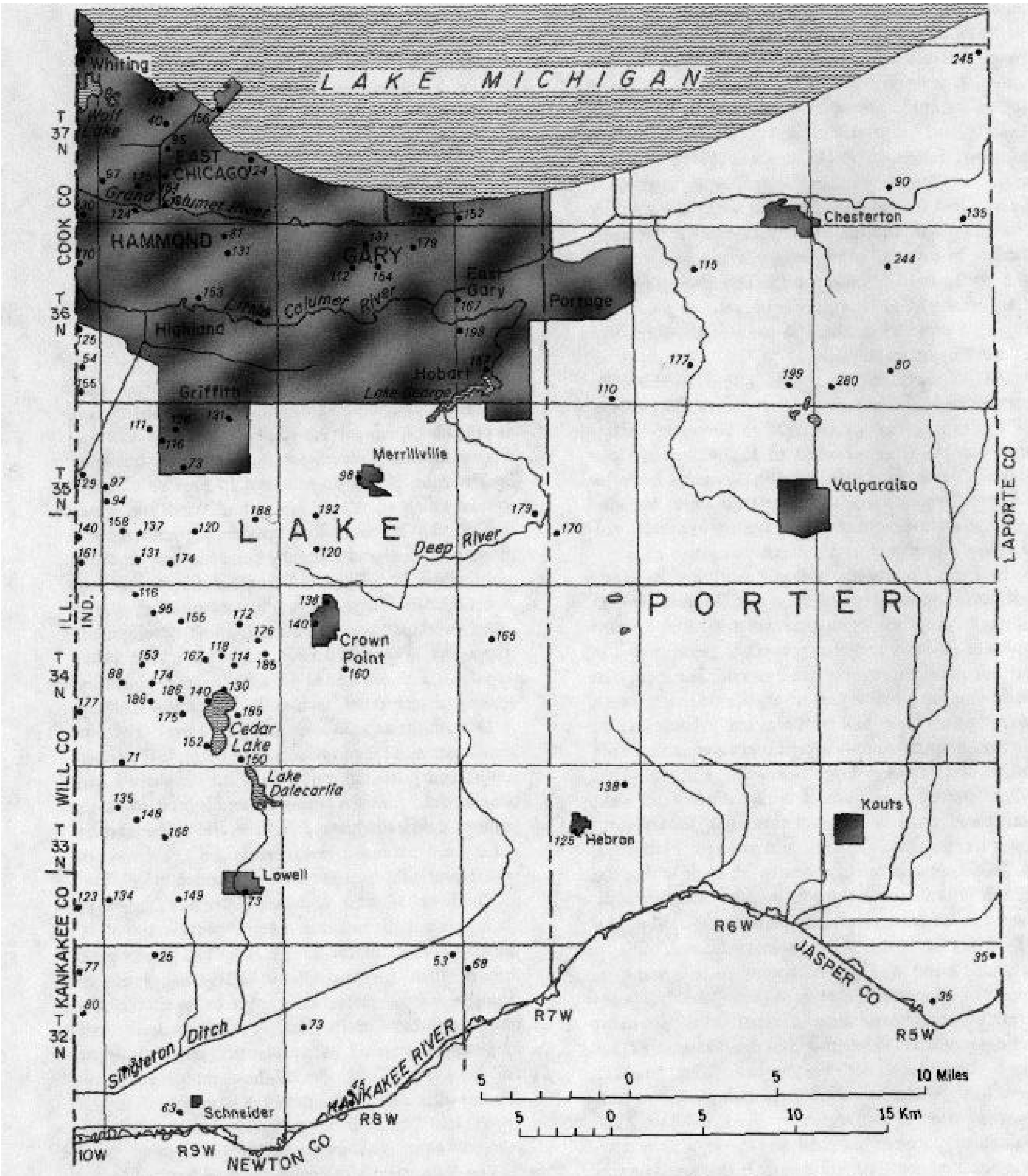


Figure 7. Map showing drift thickness at well locations in Lake and Porter Counties.

KANKAKEE OUTWASH AND LACUSTRINE PLAIN

The Kankakee Outwash and Lacustrine Plain is underlain by interlayered sequences of sand; fine, shaly, and dolomitic gravel; and clay. Sand and fine gravel (2 to 8 mm. in diameter) are the predominant size fractions, the coarse sand deposits exceeding gravel in quantity. Clay is present mostly as blebs within the sand and gravel, although clay layers deposited in glacial Lake Wauponsee (see p. 9) are also present in southern Lake County. The clay pockets range in thickness from only a few inches to more than 20 feet and range in lateral extent from only a few feet to more than 450 feet.

The entire Kankakee Outwash and Lacustrine Plain has a very high water table (3 to 10 feet below grade), which during early spring may actually intersect the surface. The high degree of saturation keeps the clay deposits at or above their plastic limits and in many areas near the Kankakee River causes the clay units to meet or exceed their liquid limits. The problems involved in excavation and piling in this area, as a result of the high water table, are obvious, to say nothing of the difficulties in attempting to install septic systems. Even the placement of footings for such installations as transmission line towers may be altered by saturated plastic clays which cannot support the load of the structures.

The coarse fractions, sand and gravel, lie mostly below the water table except in some sand dunes. The deposits of subaqueous origin are moderately stable in the engineering sense and should support great loads with proper foundation and footing designs. Numerous on-site borings[3] are necessary to avoid structural problems due to clay bodies and (or) abrupt changes with depth in sediment densities and strengths. Where heavy construction, such as large buildings, is planned, pilings set on bedrock would be a ready solution to the sediment-strength problem. Figure 7, which is an isopach map of glacial drift for the two counties, may be used to locate the areas on the Kankakee outwash plain where bedrock is nearest the surface.

In general, the Kankakee Outwash and Lacustrine Plain is not well suited to heavy construction because of the high water table and susceptibility to flooding during high water stages of the Kankakee River. Should the land in this physiographic unit be needed for construction sites, further ditching and the addition of an artificial levee could reduce the problem of a high water table and of flooding.

[3]Engineering geology data for each geologic unit in Lake and Porter Counties are summarized on plate 1.

Lake Michigan Shoreline in Indiana

Over the years, considerable effort has been brought to bear on the subject of sediment transport,deposition, and erosion along coastal areas on the oceans and inland freshwater lakes. Lake Michigan has received, especially in recent years, much attention regarding shoreline erosion that has resulted in extensive property damage. Beach erosion and construction, however, have been taking place on Lake Michigan since its formative days more than 12,000 years ago. Fluctuations in lake level, storms, variations in sediment supply, and a host of other variables have combined to maintain the shoreline in a state of continuous adjustment. When man interferes with a natural system that is in *dynamic equilibdum,* such as the Lake Michigan shoreline, this balance is at least temporarily altered from the natural state. The sand buildup east of and the erosion west of the Michigan City Harbor breakwater are examples of the effect that manmade near-shore features have on sediment distribution along the shore.

The forces that cause sediment movement in the near-shore and shore environments are relatively simple, but the mechanics of the interrelationships between these forces and the materials on which they act are very complex. For example, waves are primarily generated by wind and tend to act in the general direction from which the wind prevails (Gross, 1967, p. 101). Waves can produce erosion and deposition and can cause sediments to move along the shoreline because most waves strike the beach at an angle. Strong winds blowing toward land create high waves, which erode the shoreline. Low waves moving slowly landward, however, carry sediments onto the beach (Russell and Macmillan, 1952, p. 111). Erosion and deposition along the shore are in constant balance and are affected by sediment supply, wave energy, water depth, and many other variables. In short, where there is deposition there must be, somewhere else in the system, erosion to supply the sediments necessary for the deposition. For those interested in a more detailed discussion of lakeshore mechanics, we suggest reading Russell and Macmillan (1952) or one of the many fine sources of coastal hydrologic information currently available.

The erosional problems just west of the Michigan City breakwater complex are serious, and numerous methods of protecting the shore have been proposed. It is apparent from the sediment pattern adjacent to the breakwater on either side that longshore drift in the near-shore environment is from east to west. The accumulation of sand along the east edge of the breakwater is a classic example of sediment buildup on the updrift side of any lakeward projection. Many case histories of sediment accumulation and erosion around manmade structures in Lake Erie (Hartley, 1964) have parallels in the Michigan City complex. For example, at Huron, Ohio, sediments have accumulated along the east edge of the harbor breakwater, while severe beach erosion has taken place just west of the harbor jetties. Similar combinations of erosion and deposition about jetties have occurred at Mentoron-the-Lake, Fairport, Ashtabula, Conneaut, and Eastlake, Ohio. At each locality, erosion has taken place on the downdrift side and sediment buildup on the updrift side.

Probably the single greatest contributor to the intensified erosion along the Lake Michigan shoreline over the past several years has been the rise in lake level. In 1973 the lake level equalled the modern high level set in 1952, and the net effect has been to move the energy system described above farther inland (Larsen, 1973).

In conclusion, we note that the beach is an everchanging feature of the land subject to accelerated modification by storms, high water periods, and man's intervention with the natural system. The only certain way of avoiding nature's destructive forces is to provide an adequate buffer zone between the lake and man's onshore structures. Saving those structures that are already in jeopardy will be expensive and will require much more information about the Lake Michigan shoreline in Indiana and about near-shore hydrology than currently exists.

Water Resources

SURFACE HYDROLOGY

The surface hydrology of the Lake and Porter area provides a good example of man's alteration of nature to suit his needs. The natural drainage was extremely poor in both the Kankakee Outwash and Lacustrine Plain and the Calumet Lacustrine Plain. These areas were swampy and subject to frequent flooding. Therefore, drainage in these two physiographic units (fig. 2) has been extensively modified. In adapting the surface drainage to meet man's needs, the northern Calumet beach area was ditched and drained, thus providing a suitable environment for the expanding industrial complex and accompanying urbanization. In the south, the Kankakee outwash area was ditched and the Kankakee River straightened to open up this fertile area for agriculture. The water table was lowered as much as 5 to 10 feet in both areas. Swamps were replaced by subdivisions, industrial plants, and cornfields. These drained lowlands are still subject to frequent flooding because the drainage areas are large and the stream gradients quite low, even after extensive alteration. The already adequate surface drainage of the rolling highlands of the central Valparaiso morainal area has been altered only slightly by these modifications.

The humid, temperate climate of the area, in which rainfall exceeds *evapotranspiration,* combines with the aforementioned geologic properties to produce the still extensive swampy conditions and high flood hazards in the Calumet Lacustrine Plain and the Kankakee Outwash and Lacustrine Plain. The climate is determined by the midcontinental location of the area in the temperate zone between 410 and 420 north latitude. Local weather patterns are also affected by Lake Michigan. Temperature and weather variations can be both drastic and abrupt in the region. Total annual precipitation averages 37 inches per year and snowfall 30 to 40 inches per year. The mean temperature is 500 F, the mean maximum being 850 F in July and the mean minimum 150 F in January.

The standard assumption (American Society of Civil Engineers, 1957) of about one-third infiltration and two-thirds evapotranspiration and runoff for this climatic-vegetative-geologic zone indicates that about 12 inches of annual precipitation is available for groundwater recharge and that 25 inches evaporates directly, is consumed by vegetation, or enters the surface water system as runoff. Runoff can be direct and immediate by the surface, somewhat delayed through the upper soil layer, or substantially delayed as the portion of a stream's base flow derived from groundwater.

There is but little consumptive use of surface water in the two counties south of the Calumet Lacustrine Plain because groundwater is more readily available. Local topography does not present sites readily adaptable to large surface impoundments; therefore, surface water other than that from Lake Michigan must be considered an improbable source for future needs. The single substantial exception to the nonuse of surface water is for the water supply system in Valparaiso. Valparaiso uses both surface water and groundwater. The supply is partly derived directly from the unconsolidated aquifer east of town but mostly from Flint Lake, one of a series of kettle hole lakes, north of town. The lake level is maintained by a single continually pumped well that supplies highly mineralized water which is diluted in the lake. In this example the lake is primarily used as a natural dilution system for the poor quality groundwater.

There are two main watersheds that drain Lake and Porter Counties: the Kankakee on the south and the Calumet on the north. The drainage divide between them, which runs along the Valparaiso Moraine, is a part of the north-south Continental Divide (fig. 8). Water that is carried by the eastern sector of the Little Calumet along with the Kankakee River drains through the Mississippi River system into the Gulf of Mexico.

CALUMET WATERSHED

The Little Calumet (fig. 8), draining an area of about 382 sq mi, is a complex river consisting of two branches and having two flow directions within one of the branches. Flow of the western branch of the Little Calumet River, recorded by a U.S. Geological Survey gaging station at Munster, Ind., averages 62.7 cubic feet per second (cfs). The extremes range from a recorded high of 1,5 10 cfs to a low of 0.4 cfs. Flow through Burns Ditch to Lake Michigan from the eastern branch and the eastward-flowing part of the western branch averages 203 cfs, the maximum being 3,270 cfs and the minimum 45 cfs.

In contrast with most rivers that develop their own drainage system through erosion, the old course of the Little Calumet River reflected physical features that resulted from glaciation. Beach ridges formed during the different stages of glacial Lake Chicago determined the original course of the river as it slowly meandered westward from LaPorte County to Illinois, turned back toward the east through a U-curve, and finally emptied into Lake Michigan through the Grand Calumet. The present Little Calumet is intercepted in the northwest comer of Porter County by Burns Ditch. This part of the drainage feeds Lake Michigan. The western sector of the river flows simultaneously in two directions. The exact location of the area of reversal or of the divide (fig. 8) is dependent on river stage and rainfall. West of the divide the Little Calumet flows westward through the Calumet Sag Canal into the Mississippi system, but east of the divide it flows eastward into the St. Lawrence system. Flow in the Little Calumet is very sluggish because of its slight gradient of about 0.5 foot per mile and numerous physical obstructions in its channel. Low areas adjacent to the river are frequently flooded. These flood plains present serious hazards to development. The approximate extent of the maximum flood of record is shown in figure 8.

Water quality in the Little Calumet is poor. This is due both to its sluggish nature and the large amounts of municipal and industrial wastes it carries. The Indiana State Board of Health recorded the following biochemical data for the Little Calumet at Hammond in 1969: Nitrates averaged 1.5 parts per million (ppm), maximum 3.3 ppm; phosphates averaged 2.3 ppm, maximum 8.0 ppm; biochemical oxygen demand (BOD) averaged 6.0 ppm, maximum 23.0 ppm; coliform bacteria per 100 ml averaged 300,000, maximum 3,200,000.

The Grand Calumet, which is north of and flows parallel to the Little Calumet, presents identical quality problems for the same reasons. Samples taken near Hammond provided the following results: Nitrates averaged 0.2 ppm, maximum 0.7 ppm; phosphates averaged 4.7 ppm, maximum 9.2 ppm; BOD averaged 12, maximum 32; coliform bacteria per 100 ml averaged 1,000,000, maximum 10,000.000.

VALPARAISO DRAINAGE DIVIDE

The centrally located, east-west-trending Valparaiso Morainal Area forms the divide between the two principal watersheds of the two counties. It is generally well drained except for some ice-depressional features. These saucer-shaped depressions may be lakes or bogs filled with muck and peat and are generally partly or totally isolated from the main surface drainage systems. In addition to the poor or nonexistent surface drainage of these features, the lowpermeability till beneath the muck and peat allows little water loss through infiltration. The result is a bog or marsh which remains wet even through extended dry periods.

The runoff and infiltration from the major part of this central highland area feed the Little Calumet and Kankakee Rivers. As they flow to the Little Calumet River, streams on the north slope, such as Deep River and Salt Creek, follow tortuous routes dictated by irregular deposits of glacial drift. In contrast, streams on the south slope of the moraine, such as Eagle Creek, flow directly south to the Kankakee outwash plain through channels etched by glacial meltwater that poured off the leading edge of the ice sheet.

Flooding is not a major problem on the moraine because the rolling topography promotes adequate runoff. Flash floods can occur, however, as a result of high-intensity, short-duration rainfall. The frequency of such floods will increase as urban development spreads over the land and causes increased direct runoff.

The natural lakes of the two-county area are *kettle hole lakes* and are nearly all on the moraine. These lakes may be partially or completely isolated from either major surface drainage system. The isolated nature of a kettle hole lake results in relatively large fluctuations in water level. These fluctuations require consideration during development of lakeshore property.

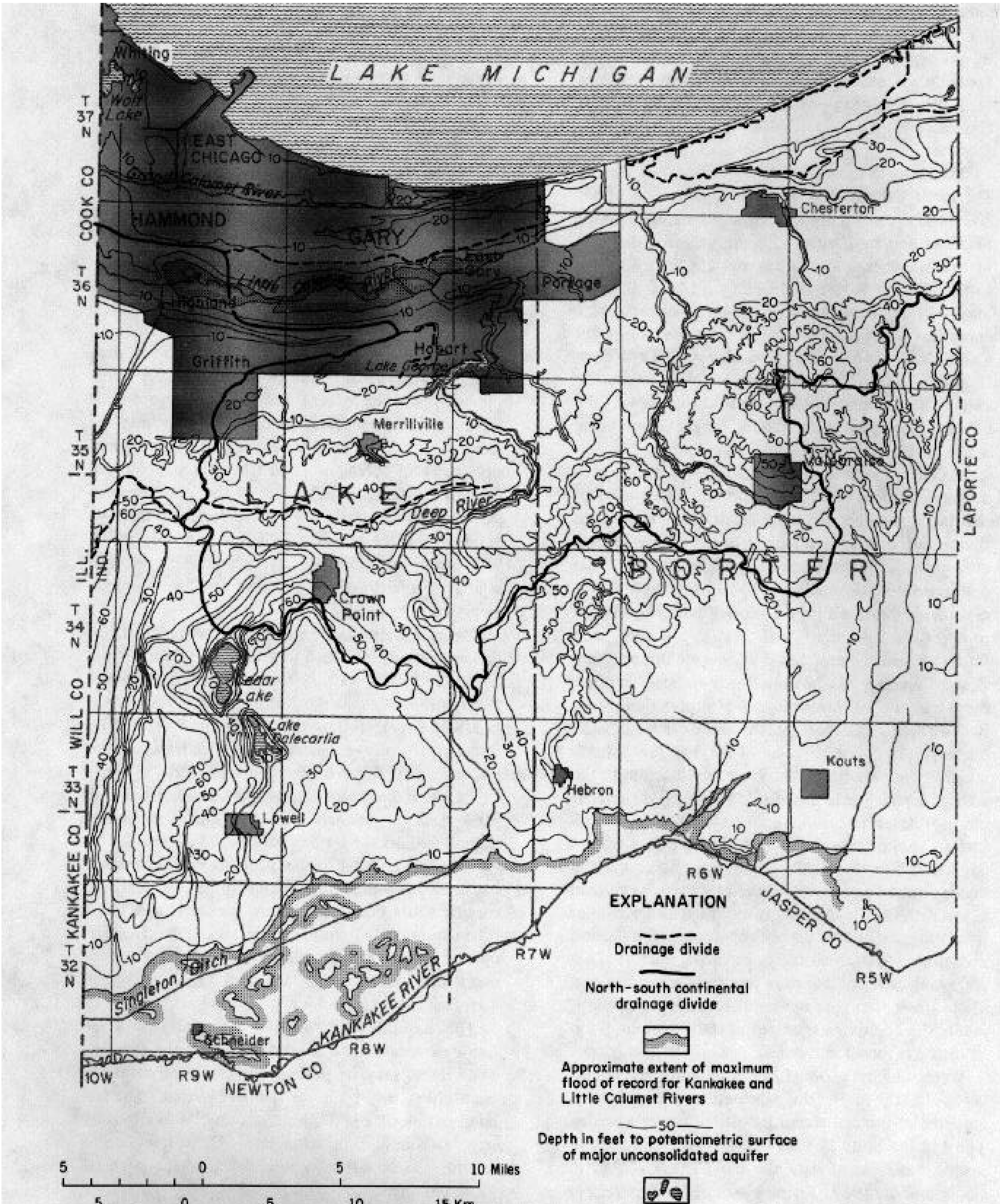


Figure 8. Map showing surface and subsurface hydrologic features in Lake and Porter Counties.

These kettle hole lakes are generally, but not in all examples, connected to the water table. They may be fed by springs and seeps that issue from a perched water table or by surface runoff alone. Contamination is more critical in this type of closed system than it is in a lake with normal surface outflow. The pollutants are largely retained because water is lost from the lake only through infiltration or evaporation, or in some lakes through limited surface outflow.

KANKAKEE WATERSHED

The Kankakee River, draining an area in the two counties of 450 sq mi, was a sluggish stream in its natural state. An erosional feature in the outwash area of the Wisconsinan Glacier, it meandered through marshland and swamps that formed when streamflow decreased below that of the torrents released by the melting glacier. Man altered the Kankakee by straightening and deepening its channel to improve drainage and reduce flood damage, thereby opening the land for agricultural development. The extensive system of ditches constructed through the low-lying marshes of the Kankakee outwash plain dewatered the area and reduced the water table level to between 5 and 10 feet below the surface. The organically rich soils of this area now support an intensive agricultural industry.

The lowlands remain subject to frequent flooding because of the high water table, low stream gradient (less than I foot per mile), and large drainage area. The extent of the maximum flood of record is depicted in figure 8.

The U.S. Geological Survey gaging station at Momence, Ill., indicated an average annual streamflow of 29 billion cu ft per year (U.S. Geological Survey, 1969, p. 211). Rainfall for the drainage basin averages 95 billion cu ft per year, which means that 66 billion cu ft per year is lost through evapotranspiration or infiltrates to and is stored in the groundwater system. The average flow is 1,848 cfs, the maximum being 8,240 cfs and the minimum 620 cfs.

Water quality records of the Indiana State Board of Health for the Kankakee River at Shelby (1969) showed that water quality was relatively good for a modern river. It received less waste and carried more water than other major streams in the two counties. The record in ppm indicated that nitrates were: average 1.3, maximum 2.9; phosphates: average 0.3, maximum 0.8; BOD: average 2.3, maximum 5.5; and coliform bacteria: average 7,000, maximum 20,000 counts per 100 ml. The higher nitrate level is probably due to fertilizer runoff in this agricultural area.

ENVIRONMENTAL MANAGEMENT

Proper watershed management involves planning for flood protection, water quality protection, recreational usage, water supply supplementation, and perhaps some inland navigation for larger pleasure craft.

Flood protection may involve channel improvements that expedite peak runoff and zoning to prevent construction of facilities susceptible to flood damage in flood-prone areas.

Flood plains perhaps best serve as recreation areas. Most streams are naturally scenic and with minimum construction afford opportunities for picnicking, hiking, boating, etc. If highly flood-prone areas were set aside for recreation space within green belts, floods would not be nearly so costly with regard to loss of life and to property damage. The less flood-prone areas within the flood plain are generally well suited to agricultural use. Crops may survive the infrequent flooding of short duration that takes place on the higher areas within the flood plain.

Water quality should be protected by insuring that all inflow into surface waters meet strict standards. Clean water may have two useful applications: water supply and recreation. Water quality control and improvement could permit use of surface water as a supplement to groundwater for consumption through either direct pumpage from the stream or indirect induced infiltration to an adjacent well system. Water contact sports require higher water quality standards than do general water supplies because they cannot be treated effectively.

Dredging and widening of the Little Calumet River as proposed by the U.S. Army Corps of Engineers for flood prevention could also make this river available for water sports and recreation and for basing larger pleasure craft inland.

The Little Calumet-Grand Calumet and the Kankakee watersheds require separate management philosophies. According to 1970 population figures compiled by the Indiana Department of Commerce, the area drained by the Little Calumet and Grand Calumet Rivers supports more than 90 percent of the residents and nearly all heavy industry of the two counties. Controlling the use of the flood plain, treatment of sewage, and construction-caused erosion could make these rivers an ideal natural resource for rest and relaxation within immediate reach of area residents. The rehabilitation of these rivers will primarily entail a cleanup process for the Little and Grand Calumet Rivers because the quality of both is presently unacceptable in this role.

In contrast, the Kankakee, with acceptable quality, requires protection to maintain that quality. Urban development is moving southward with increasing affluence, increasing population, and the construction of new highways. Therefore, the Kankakee and tributary flood plains should be protected from random development, sewage treatment should meet the highest standards, and erosion-controlling techniques should be required in all construction projects.

GROUNDWATER

Groundwater is a critical factor in the environmentally oriented development of Lake and Porter Counties. Presently about 13 percent of the total domestic water supply in the area is derived from the ground. This 13 percent constitutes nearly 100 percent of the total domestic, commercial, industrial, and rural water supply for the rapidly growing communities south of the Calumet Lacustrine Plain. Many of the larger industries have private water supplies. Industries near Lake Michigan take the water that they use in manufacturing processes from the lake but depend on public or private water companies for their potable water needs.

About 87 percent of the water supply for the two counties is withdrawn from Lake Michigan. Nearly all of it is used by the municipalities on the Calumet Lacustrine Plain. The municipalities to the south on the Valparaiso Moraine and the Kankakee outwash plain rely almost entirely on groundwater. The differing reliance on Lake Michigan in the north and on groundwater in the south is based on cost, ease of acquisition, and availability. In the north Lake Michigan provides a convenient supply of acceptable quality. This convenience, plus the fact that the groundwater supply in the Calumet Lacustrine Plain is insufficient to support the needs of the area, dictates the use of lake water. Unconsolidated and bedrock aquifers in and beneath the glacial moraine and outwash to the south hold large quantities of potable water and are easily tapped. According to Rosenshein and Hunn (1968a, b), daily groundwater use amounted to about 13.5 million gallons per day (mgd) and total development potential amounted to nearly 600 mgd. This potential is probably optimistic for several reasons: (1) the 600-mgd total predicates ideal area-wide development; (2) normal annual precipitation must be realized to permit adequate recharge; and (3) continued building and improved drainage will reduce infiltration and the high water level needed to support maximum withdrawals.

By definition groundwater is present below every point on the earth's surface. To classify groundwater as a resource, however, an aquifer must be present within a readily accessible depth. Currently about 10 percent of Indiana's water supply is derived from aquifers, and the national average is about 19 percent. The 13-percent figure given for domestic groundwater use in the study area is significantly reduced when private industrial supplies are considered. Groundwater, which is generally most practical to develop and maintain on a small scale, is primarily used by individuals and small industries and communities.

Groundwater has an advantage over surface water in that it has minimal temperature and quality fluctuations through the seasons and is less susceptible to contamination. The soil and rock cover serves to dampen temperature fluctuations and to act as a filter to remove contaminants.

Groundwater has some major disadvantages. These are its generally higher mineralization, high development costs on large-scale projects, and the extremely difficult problem of decontamination when it becomes contaminated. Groundwater is naturally mineralized through chemical reactions with the earth materials through which it percolates. Naturally slow percolation allows the soil-water interface to reach equilibrium. Therefore, water moving through chemically less stable soils is more highly mineralized, and water moving through toxic refuse is contaminated. Once contamination occurs, the slow percolation of groundwater along with its inaccessibility makes decontamination very difficult and time consuming.

For this report the subsurface will be considered in accord with three separate *hydrologic (aquifer)* systems (fig. 9). These are: (1) the unconsolidated system, (2) the shallow bedrock system, and (3) the deep bedrock system. The systems differ in depth, geology, developmental potential, and water quality. There is also little, if any, direct hydraulic connection between the three.

As will be seen farther on in this section, the groundwater systems of the central and southern parts of the two counties are capable of meeting the expected growth requirements of the next 30 years. The bulk of the groundwater is presently withdrawn from the glacially derived sand and gravel aquifers of the unconsolidated system. This is the shallowest, most permeable, and therefore most easily developed of the three systems. The jointed and solutionchanneled limestone and shale of the shallow bedrock system present a second, less productive zone. The deep bedrock is a potential source, although poor quality and great depth make it uneconomical and impractical at present.

Water levels are generally high in this semihumid climatic region, where annual precipitation exceeds evapotranspiration. The top of the zone of saturation (water table) ranges between the ground surface level

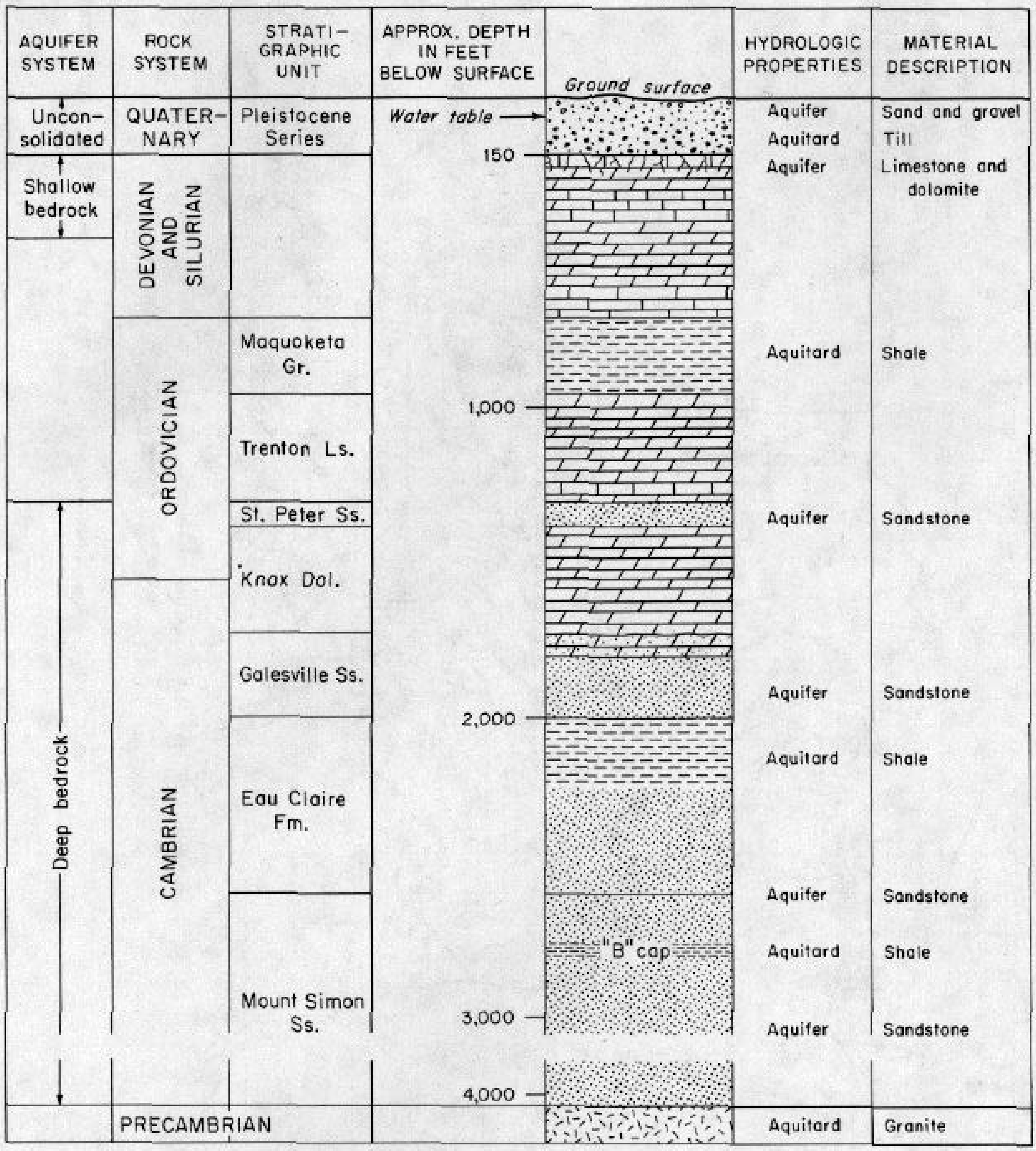


Figure 9. Geologic column from surface of Valparaiso Moraine to Precambrian basement showing locations of aquifer systems, hydrologic properties, and material descriptions.

in the Calumet beach and Kankakee outwash areas to 70 feet below the surface on the higher Valparaiso Moraine. The *potentiometric surface* map, showing an imaginary surface coinciding with the hydrostatic pressure in an aquifer (fig. 10), and the map showing the depth to the potentiometric surface (fig. 8) pro vide a graphic representation of the static level of the groundwater in the unconsolidated system in the two counties. This surface generally correlates very closely with the water table in the area.

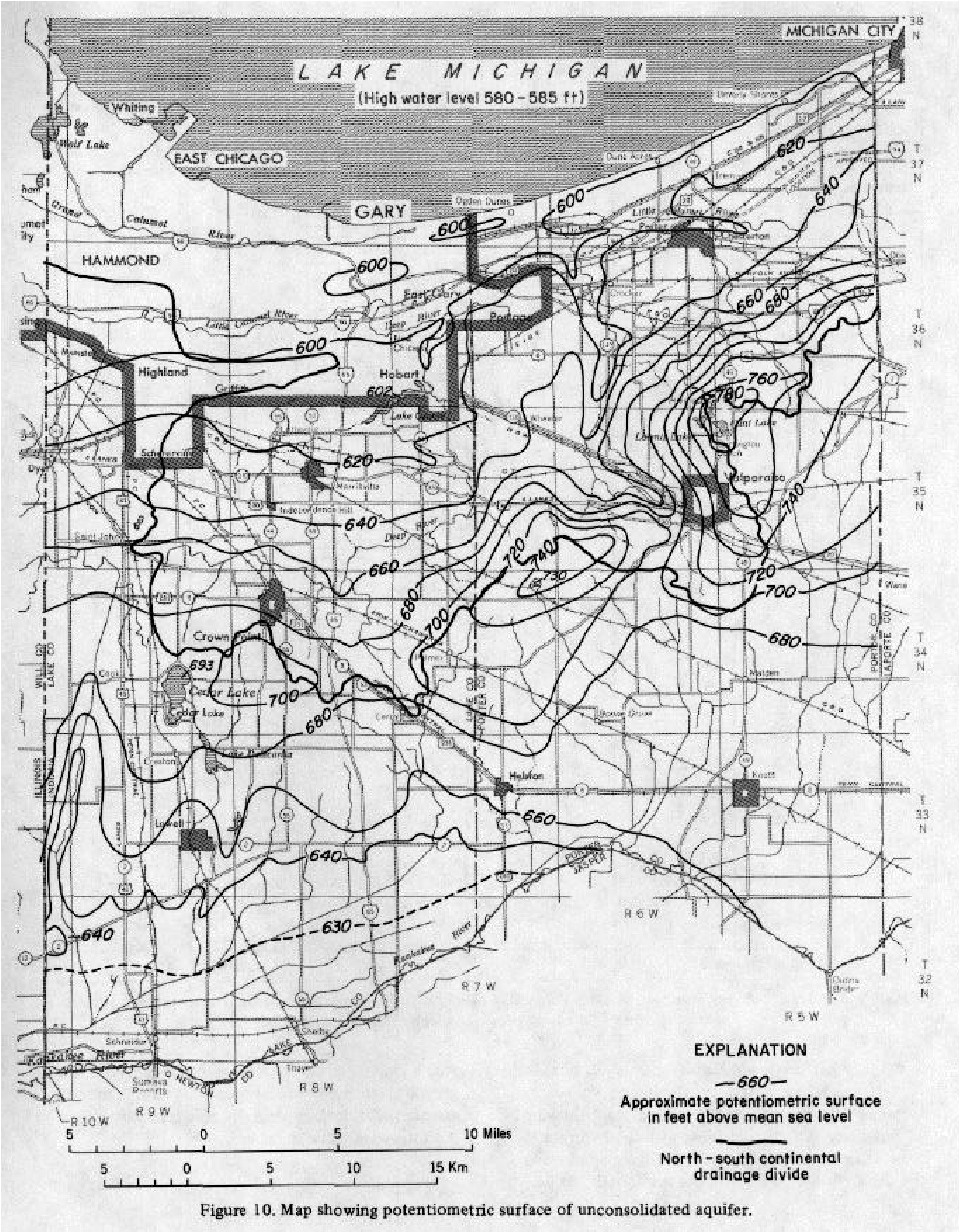


Figure 10. Map showing potentiometric surface of unconsolidated aquifer.

SYSTEM DEVELOPMENT

Achieving maximum production from a given groundwater system requires application of the proper development principles during well construction by a qualified specialist. The hydrogeologist is perhaps best qualified to handle the problem of supply and quality, and either the hydrogeologist or a competent well driller can manage well design and contamination protection. Numerous well records, maintained by the Division of Water, Department of Natural Resources, are available, thus permitting a cursory view of potential aquifers. Further acquisition of information regarding quantity and quality requires geophysical study and hydrologic testing. Both of these techniques have been extensively developed for use in the geologic conditions found in the two-county area.

Preliminary studies done by Rosenshein and Hunn (1968a, b) indicate that the production rate from the unconsolidated and shallow bedrock systems can be increased by more than a factor of 30 from the 1967 rate of about 14 million gallons per day. Production techniques have been established for the aquifer conditions prevalent in Lake and Porter Counties; these techniques should permit the 30-fold increase and will certainly insure maximum sustained production from the available aquifers.

Groundwater quality discussed later presents minor local problems related to excessive iron, hardness, and hydrogen sulfide content. Quality problems, however, can be minimized through the use of proper materials and treatment facilities. It is also important to consider contamination during the developmental phase. Only proper well-construction techniques and safeguards taken during drilling and installation will prevent initial contamination by chemicals and bacteria and later ease leakage problems.

CONTAMINATION

Groundwater contamination is the entry of any undesirable substance into a usable groundwater resource. Septic systems, sanitary landfills, settling ponds, stock pens, waste injection wells, excess fertilizer and insecticide spraying, sewer system leaks, highway salt, and even polluted lakes and streams are sources of groundwater contaminants. Fortunately, the soil and rock through which these contaminants move act as filtering agents. Filtering action is much more effective in the *aerated zone* above the zone of saturation than below the water table. Other factors that influence filtration are ion exchange capacity (the ability to remove contaminants from water by the exchange of ions), grain size, depth to water table, and climate. Each of these factors was considered during compilation of the maps showing groundwater pollution potential, areas of relative potential suitability for sanitary landfills and for settling ponds, and areas of relative failure potential of septic systems (figs. 11, 24, 25, and 26). For example, the highly permeable sand and gravel that cover the surface in much of the Calumet beach and Kankakee outwash areas provide little filtering action for leachate before it enters the shallow groundwater system. In contrast, the glacial tills and lake clays of the Valparaiso Moraine retard flow and provide relatively good filtration because they are fine grained and have low permeability and high ion exchange capacity.

Groundwater contamination is particularly critical because in many places it remains undetected until irreversible damage has occurred. The inaccessible nature and slow movement of groundwater make rehabilitation expensive and difficult. Once contaminated, an aquifer will remain so until it purges itself or is purged artificially. In an environment where movement is expressed in feet per year this is quite a long process.,

Present overall groundwater quality in the area is the result of natural chemical and physical processes in the subsurface. Only locally has man significantly altered quality. Man's effect is, however, becoming an increasing concern. Since contamination potential from surface sources is quite high over much of the area (fig. 11), random development and waste disposal operations should not be permitted. Diligent use of the various maps and figures in this section as a guide for planning will reduce the possibility of contamination to a minimum.

WATER USAGE

The industrial cooling or processing water from Lake Michigan) from public water supplies in the two counties in 1972 was about 92 million gallons per day (mgd) (Indiana State Board of Health, 1973). Of this amount, about 12 mgd is pumped from the ground; the rest is taken from Lake Michigan. About 5.5 mgd of the 12 mgd is produced by 12 public well fields; 4.4 mgd is pumped from glacial materials and 1.1 mgd from bedrock. Each of these 12 fields appears to be capable of increased production. There are also other nearby locations within the same aquifers but outside the area of influence of the active fields that would provide an additional supply if properly developed.

The limiting factor controlling the ultimate production of an aquifer is the amount of recharge available to maintain a sustained supply. The 30-fold

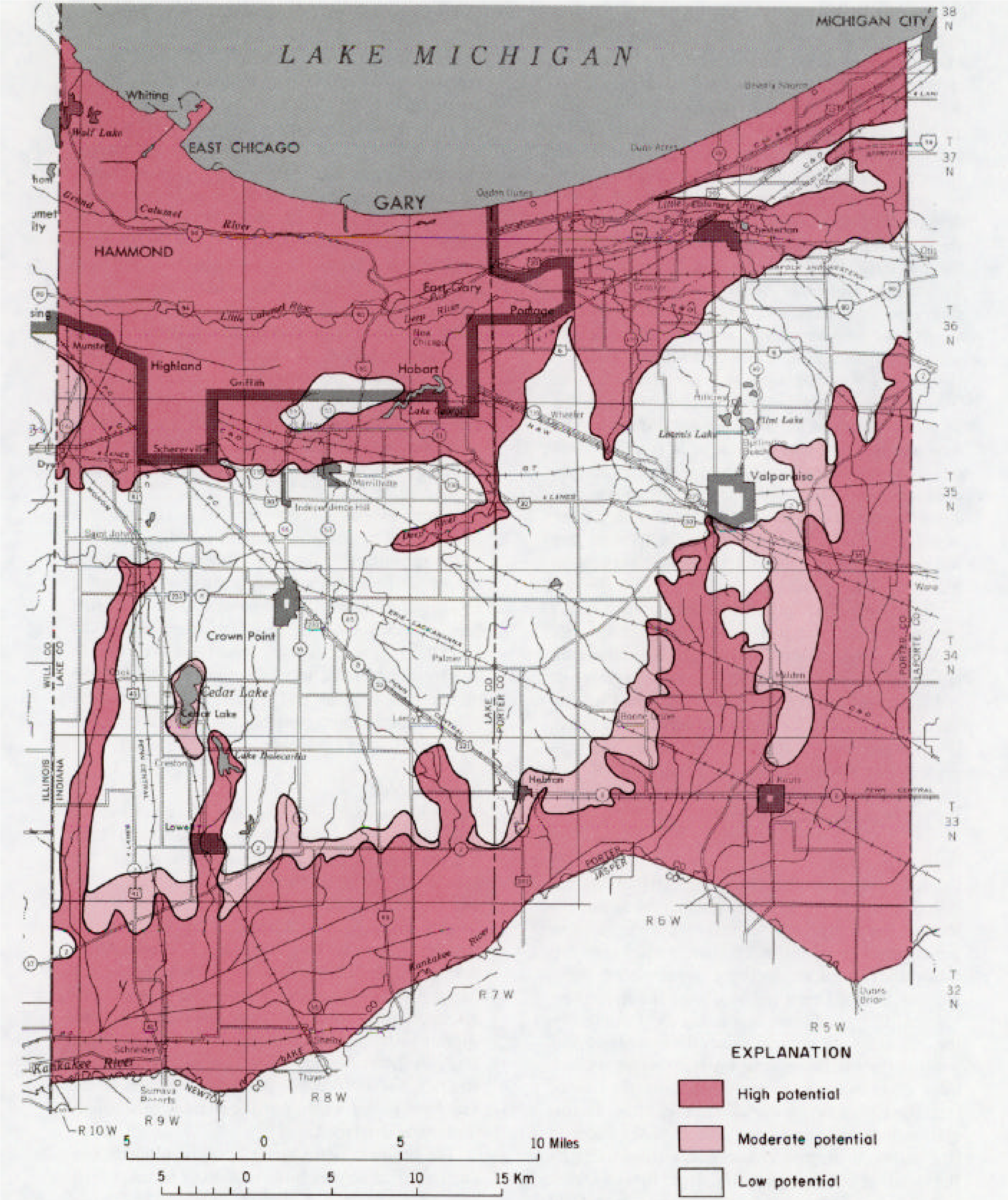


Figure 11. Map showing groundwater contamination potential.

potential for increased production mentioned earlier indicates that water consumption can be greatly increased without seriously affecting groundwater balance. A much more detailed study would be required to provide a more accurate prediction of the *maximum sustained yield* that can be expected in the two-county area.

AQUIFER SYSTEMS

Two of the three principal aquifer systems, the unconsolidated system and the shallow bedrock system, contribute about 97 percent of the present groundwater supply. The remaining 3 percent is withdrawn from sand lenses in the till and from fractures in the Antrim Shale. The third major system, the deep bedrock system, is discussed here because of its potential as a source of supply. A brief description of the geology, chemistry, and hydrology of these three systems is provided on the following pages.

UNCONSOLIDATED SYSTEM: The unconsolidated system is composed of three heterogeneous sand and gravel aquifers, two of which are hydraulically connected. They are here designated the Calumet, Valparaiso, and Kankakee aquifers. There are other isolated minor aquifers in the heterogeneous glacial materials capable of providing supplies for small industries or farms. These small aquifers have neither the lateral extent nor the production capability of the three major ones.

The present total yield of the unconsolidated aquifer system is about I I mgd. Rosenshein and Hunn (1968a, b) believed that there was potential to increase this yield by more than one order of magnitude. Realization of such an increase would require a great deal of care in planning and development and the assurance of adequate protection from overdevelopment and contamination.

The Calumet beach deposits, consisting of waterand wind-laid fine sand, form the northern water table aquifer. This aquifer is not used extensively at present because the area derives its supply primarily from Lake Michigan. The Calumet aquifer extends from Lake Michigan through a wedge-shaped area encompassing the northern quarter of Lake County and narrowing to cover the northern tenth of Porter County. The Calumet aquifer is a water table or unconfined aquifer ranging from 5 to 75 feet in thickness. Average thickness is about 20 feet. Beneath the aquifer is a nearly impermeable clay till averaging about 50 feet in thickness. The sand is exposed at the surface throughout most of the area.

There are, however, pockets of muck and peat as well as made land that form a thin cover in depressional areas. The water table ranges in position from the surface in low interdunal areas to 45 or even 90 feet below the surface in the higher dunes. It is generally less than 15 feet below the surface through most of the area.

The demand on this aquifer is light and present use is confined to domestic and small commercial facilities. In fact, the Calumet aquifer is incapable of supplying the heavy industrial and urban demand in the area. Because its development potential is limited to direct infiltration of precipitation and is limited by its relatively thin saturated thickness, generally less than 15 feet, a high sustained withdrawal rate is not possible.

The Calumet aquifer is particularly susceptible to contamination. A combination of shallow water table and permeable sands creates a very definite hazard for groundwater users if waste disposal facilities are nearby. (See p. 40 and 46 for sanitary landfill and septic information.)

Water quality is generally good in the aquifer. Sulfate (fig. 12) ranges from 10 to 150 ppm, hardness (fig. 13) as calcium carbonate from 50 to 500 ppm, and iron (fig. 14) from 0. 1 to greater than 2.5 ppm.

The Calumet aquifer requires protection from contamination even though it is not used extensively. Base flow for the Little Calumet River, Grand Calumet River, Deep River, and Hart Ditch is supplied by the Calumet aquifer. The rest of the discharge moves laterally into Lake Michigan or vertically through the underlying till into the bedrock. It is evident from this flow pattern that the groundwater will affect quality well beyond the point of any actual contamination.

The central Valparaiso aquifer (fig. 15) is in part a water table aquifer and in part an *artesian* aquifer. It is a confined heterogeneous layer of sand and gravel and intermixed clay and silt lenses lying on and covered by glacial till. The covering glacial till acts as an *aquitard, so* that a pressure head is developed in much of the Valparaiso aquifer. Where this occurs, water in a well drilled into the aquifer will rise above its confined level, although not necessarily to the ground surface.

This aquifer ranges from 10 to 90 feet in thickness and lies from 10 to 80 feet below the surface. The entire sequence is heterogeneous, for the upper and lower tills both contain lenses of sand and gravel. These lenses within the confining layers may produce small to moderate quantities of water, depending on their size and their location with respect to the piezometric surface.

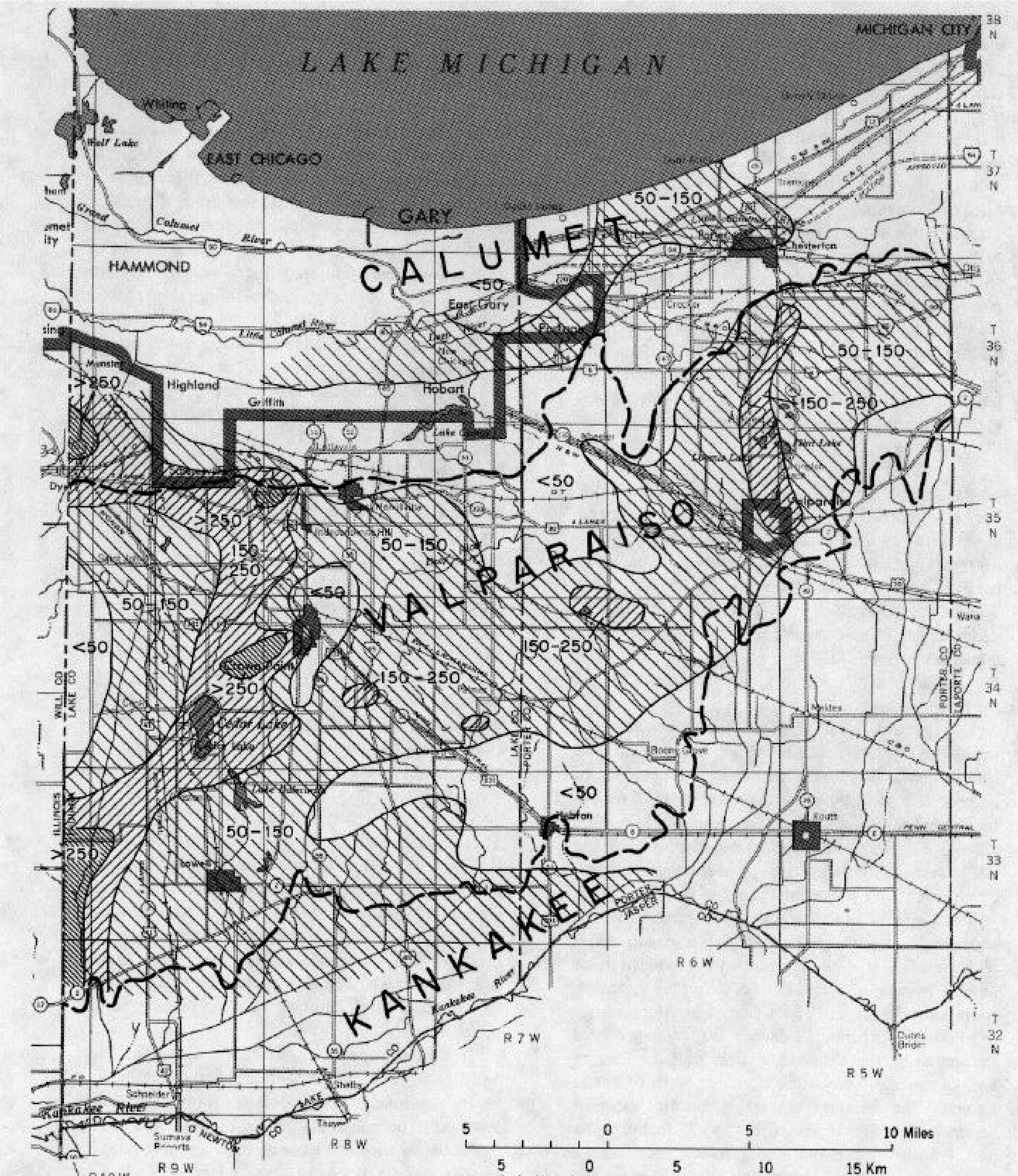


Figure 12. Map showing water quality in ppm sulfate in unconsolidated aquifer system and approximate areal extent of each aquifer.

Figure 13. Map showing water quality in ppm hardness as CaCO3 in unconsolidated aquifer system and approximate areal extent of each aquifer.

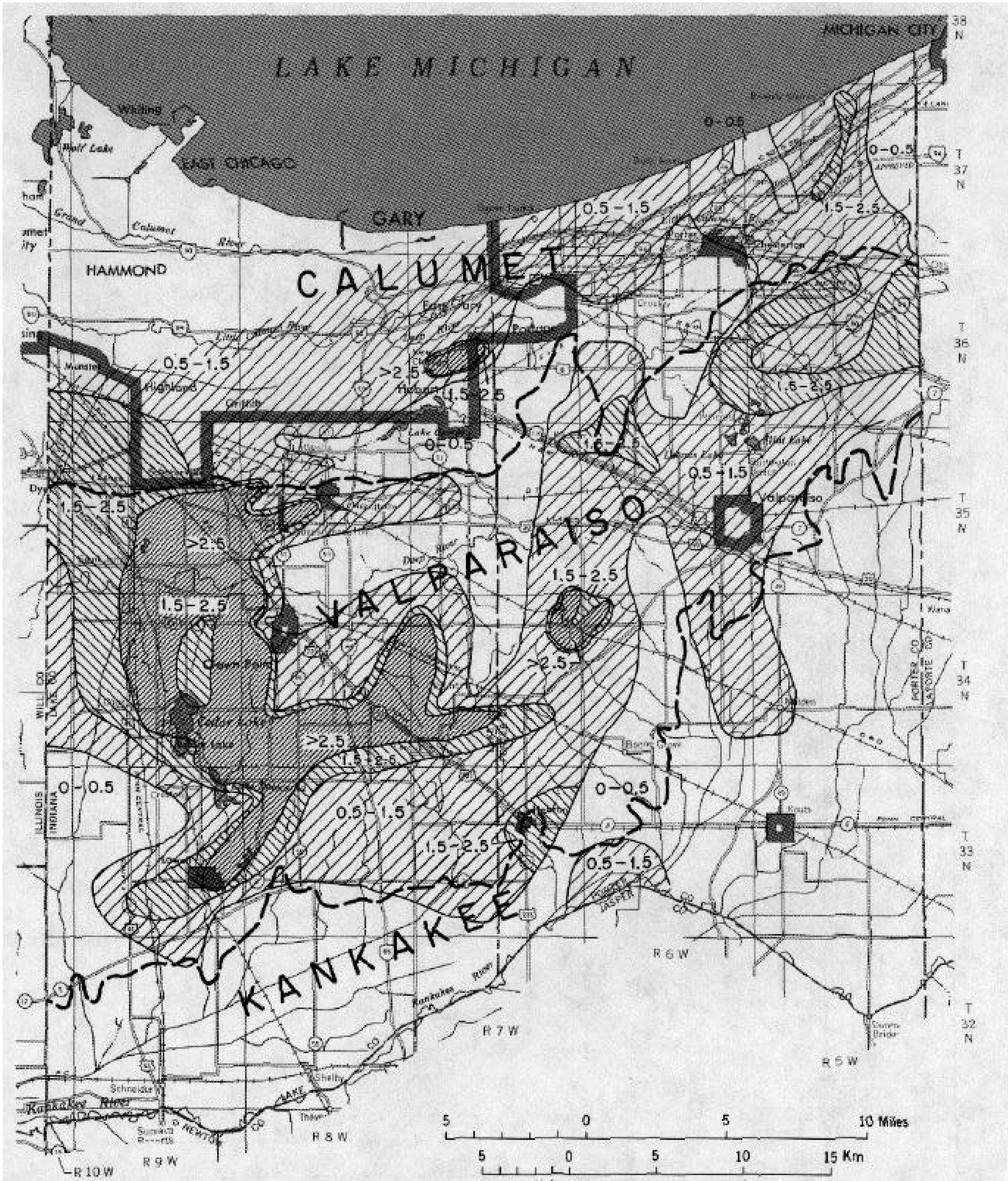


Figure 14. Map showing water quality in ppm iron in unconsolidated aquifer system an approximate areal extent of each aquifer.

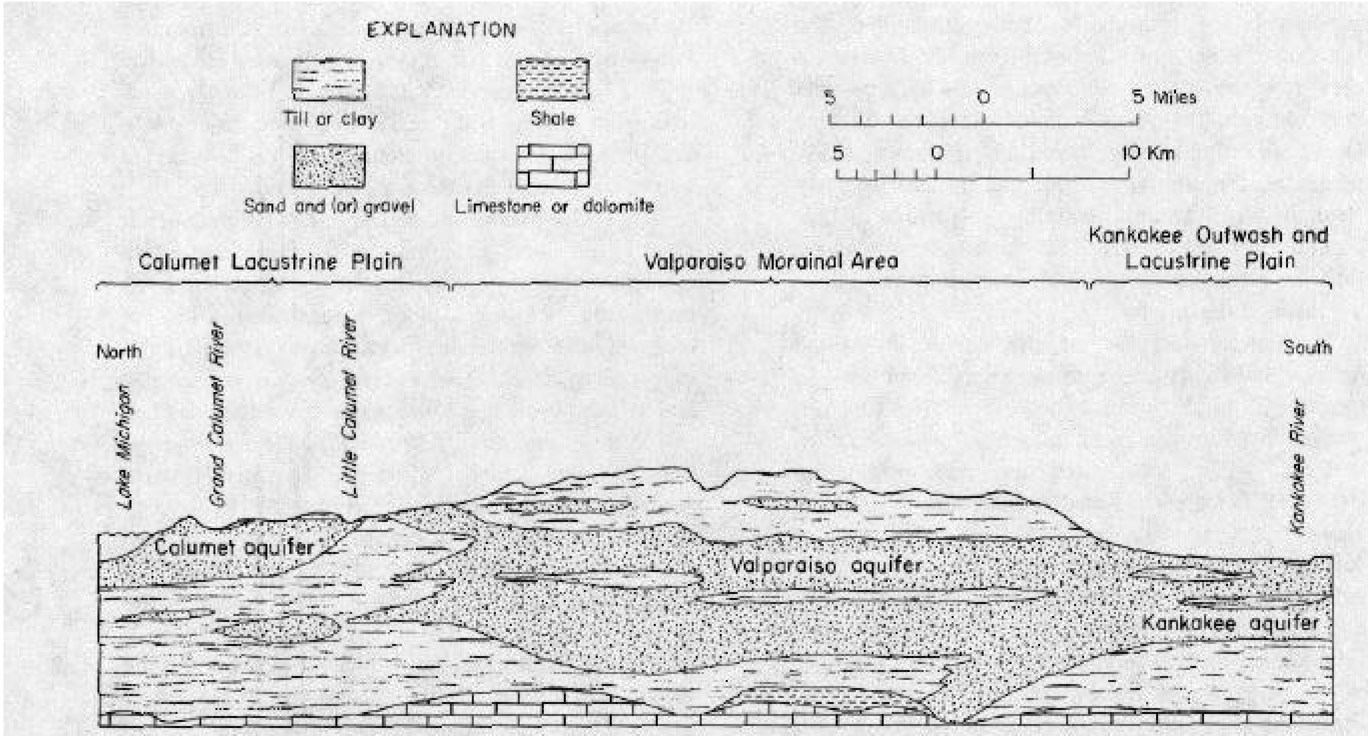


Figure 15. Idealized north-south cross section through Lake County showing positions of unconsolidated aquifers.

The Valparaiso aquifer is recharged primarily from the confining layer above. The recharge rate presents one major limitation in the development potential of the aquifer. Therefore, the maximum sustained yield of the Valparaiso aquifer depends directly on the permeability and storage capacity of the overlying glacial till. The recharge rate is controlled by a combination of average annual infiltration, which determines the amount of water available for recharge, and the permeability of the confining or covering layer under ideal maximum *head* differential conditions. The average annual infiltration determines the total water available, and the permeability determines the rate at which it becomes available.

Using an average vertical permeability of $7 X 10^{-3}$ gpd per sq ft for the confining layer, Rosenshein (1967) computed that the aquifer, when fully developed, would provide a sustained yield of more than I X 105 gpd per sq mi. This is a generalized estimate for the entire aquifer; specific localities, therefore, may vary considerably.

The contamination potential (fig. 11) is not as high with this type of confined aquifer as it is with the Calumet and Kankakee aquifers. The confining till acts as a filter to remove a large part of the potential contaminants. This filtering action is most effective in the near-surface unsaturated zone.

Water quality (figs. 12, 13, and 14) is somewhat poorer than in the Calumet and Kankakee aquifers, S04 ranging from 50 to more than 750 ppm, hardness from 140 to 750+ ppm, and iron from 0.1 to 5.0 ppm. These higher concentrations are due to the slow percolation and resultant increased contact of the groundwater with the overlying till.

The southern Kankakee aquifer is an unconfined water table aquifer. It extends from the Valparaiso Moraine to the Kankakee River (fig. 15). The Kankakee is a heterogeneous aquifer exposed at the surface over much of its lateral extent and underlain by a clayey till that thins in a southwesterly direction. The aquifer is composed primarily of sand and some gravel. Overall, however, it contains a random mixture of discontinuous silt and clay lenses. There are also thin layers of muck and (or) silt in places at its surface. The production potential of this aquifer is highest where the following combination of conditions exists: the water table is high, generally less than 10 feet below the surface; the aquifer is thick; the material is permeable sand and gravel devoid of extensive clay lenses; and a hydraulically connected sizeable stream is nearby.

The Kankakee aquifer is hydraulically connected to and partially recharged by the Valparaiso aquifer on the north. Its southern boundary within the two counties is the Kankakee River. The degree of hydraulic conductivity between river and aquifer depends on the permeability of the streambed. The Kankakee River and the numerous ditches in the area may be either recharge or discharge points, depending on the water budget balance of the area. During an extended dry season and periods of heavy irrigation, the aquifer is recharged by the river, particularly in an area of pumping. In periods of high groundwater levels, however, the aquifer discharges into the Kankakee River and into other streams flowing through the aquifer.

Production potential of the aquifer is limited because it is a surface aquifer ranging from only 10 to 50 feet in thickness and there is therefore not enough head or water in storage to provide a high sustained yield. Anticipated maximum production from well fields in the Kankakee outwash is 500 gpm. However, a properly designed field in an area of sufficient transmissibility (permeability times thickness) adjacent to the Kankakee River may develop a considerably greater sustained yield. Such a well field placed parallel to and within 500 to 1,000 feet of the river would induce recharge from the river. Resultant production could be as much as 100 percent higher, depending on transmissivity, streambed permeability, width, flow, and head, than in a similar hydrologic environment not hydraulically connected to the river. Induced recharge has the advantage of naturally filtering river water and diluting it with groundwater, thereby moderating temperature fluctuations and improving quality. River water generally has less dissolved solids but more biologic contaminants. Therefore, through the use of induced infiltration, the resultant filtering and mixing of river water with groundwater will produce a better overall quality and require less treatment. A detailed geologic and hydrologic study of the outwash adjacent to the river could determine the feasibility of establishing such a system as well as discover potential high yield areas.

Induced recharge does have the adverse effect of diminishing streamflow. The amount and percentage of water removed from the stream depend on several factors. Some important factors include aquifer characteristics, stream channel permeability, pumping rate, and well field construction and location. Using the Kankakee River as an example of the effects of induced recharge on streamflow, removal of 20 mgd would reduce the flow in the area of recharge by about 10 percent during the period of lowest recorded flow. Much of this loss would be compensated for downstream by recharge to the river from bank storage.

Water quality (figs. 12, 13, and 14) in the Kankakee aquifer is generally quite good. The approximate ranges of some of the major constituents are as follows: (1) SO_4 from 5 to 250 ppm, (2) $CaCO_3$ hardness from 150 to 800 ppm, and (3) iron from 0.1 to 7.5 ppm. Water quality trends may be determined by superimposing the above-mentioned figures.

The entire unconsolidated aquifer system depends directly on local precipitation for its recharge, although there may be some local recharge from the underlying bedrock. Under natural conditions of recharge, the water table fluctuates with rainfall and evapotranspiration. This natural system is balanced and relatively stable. When water is withdrawn from the system unnaturally through wells or artificial drainage, the balance is altered. In most systems recharge will increase and compensate, to a given limit, for withdrawal. In case of excessive withdrawal the water table will be lowered, and streamflow will be decreased. Once the balance, determined by recharge versus discharge, is exceeded and water is removed from storage, water levels will drop and the supply will diminish until the aquifer is no longer usable. It is therefore extremely important not to exceed the safe sustained yield of an aquifer.

Urban and industrial development places increasing pressure on water resources in its area of influence. Every geographic area has a given limit for water supply development, and excessive development can cause serious problems, such as surface subsidence and groundwater depletion. Therefore, it may be most practical to establish limits on regional development, so that the local water supply potential is not exceeded.

Unfortunately, the same development that produces increased water requirements tends to reduce the supply available by decreasing the surface area required for infiltration and therefore recharge. There are methods to increase recharge that should be considered when planning for substantial development. These include holding basins, ditches, canals, irrigation, and injection wells.

SHALLOW BEDROCK SYSTEM: The shallow bedrock system is composed of Silurian and Devonian limestone, dolomite, and shale. These units dip to the east, exposing increasingly older rock at the bedrock surface toward the west. Before the advance of the glaciers, which produced the thick unconsolidated materials, bedrock was at or near the surface. During this time or at some other time when the bedrock was at the surface, some karst development took place, and limited solution features in the upper 200 to 300 feet of carbonate bedrock were produced.

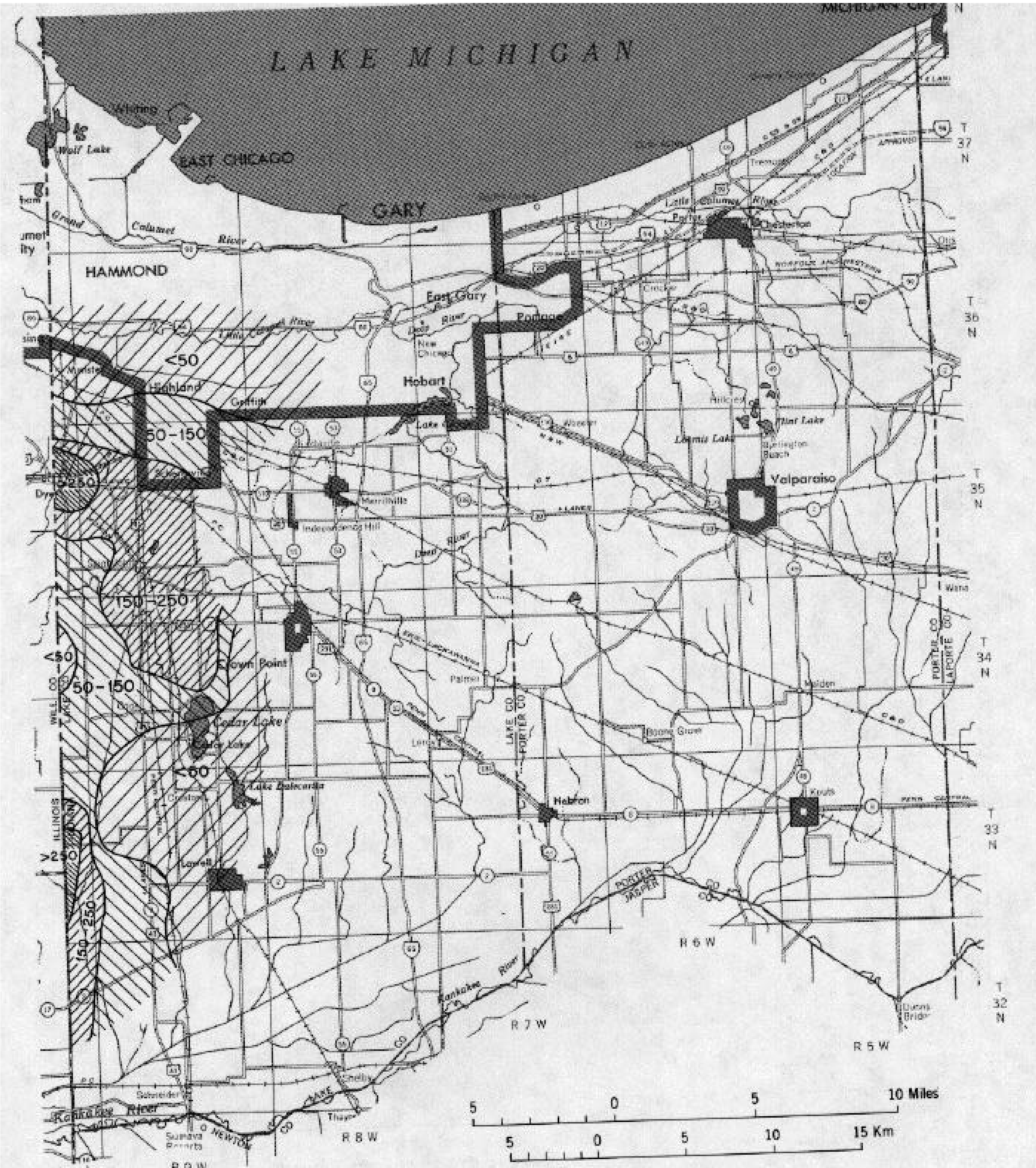


Figure 16. Map showing water quality in ppm sulfate in shallow bedrock aquifer.

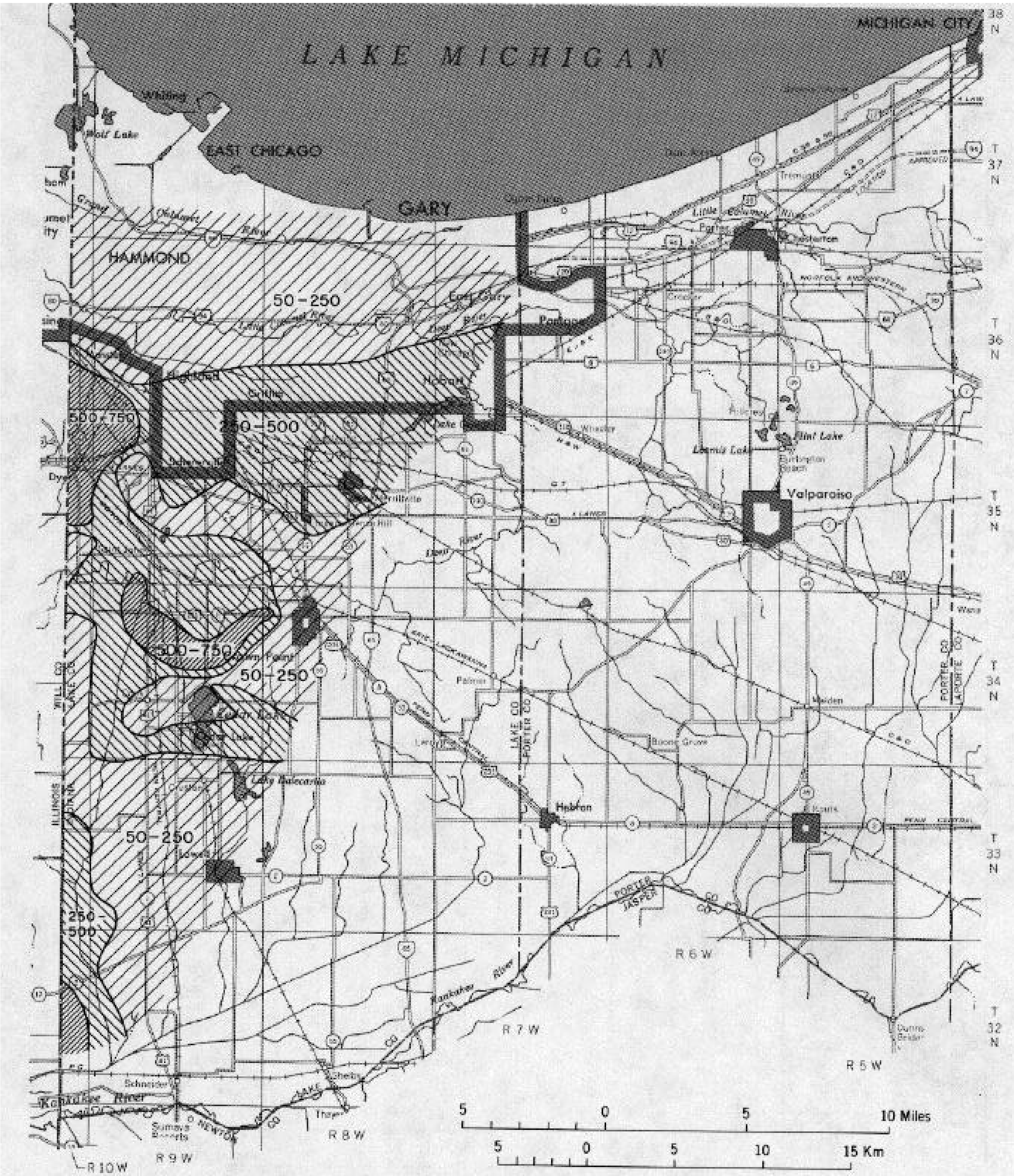
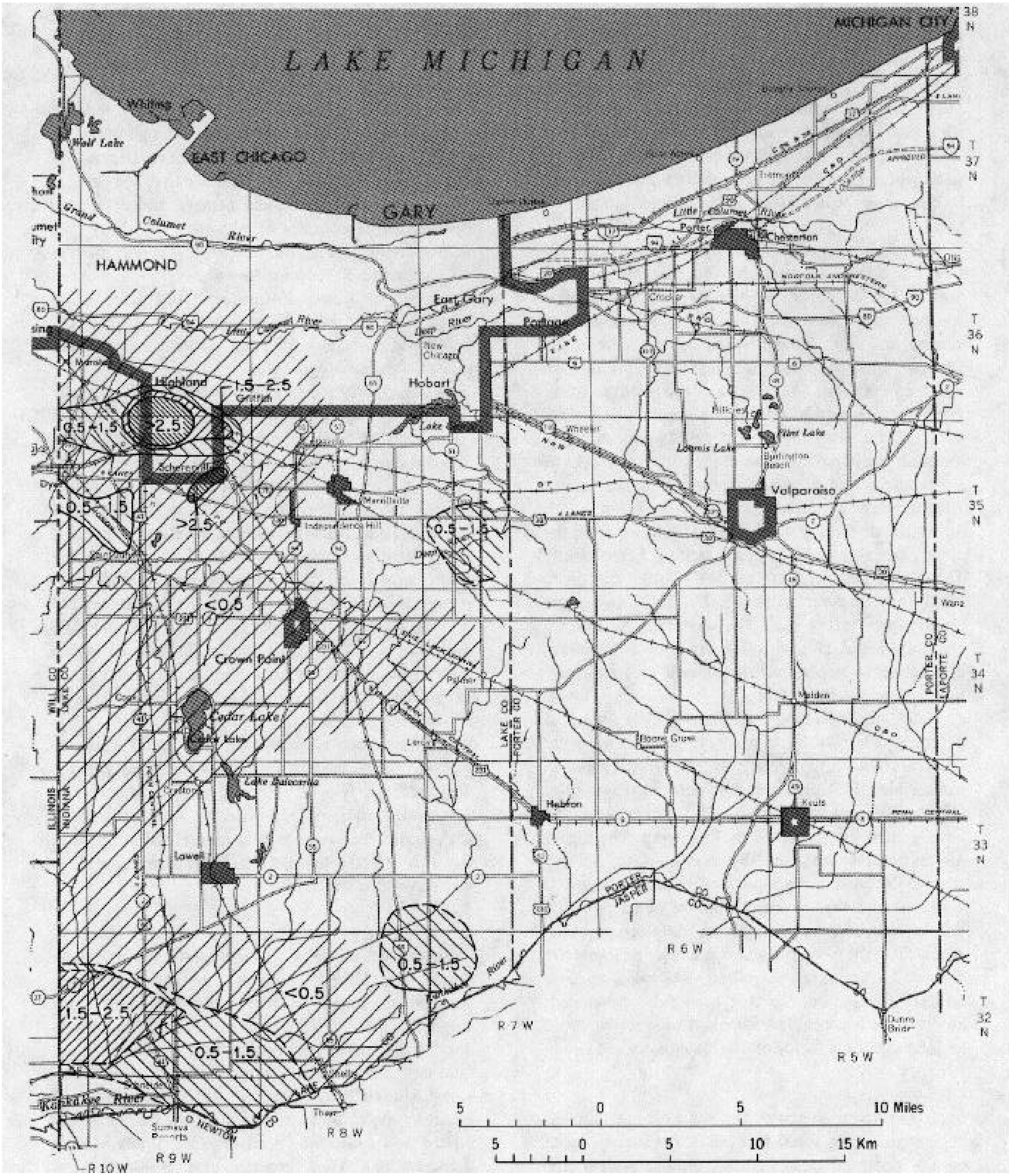


Figure 17. Map showing water quality in ppm hardness as CaC03 in shallow bedrock aquifer.



Fi gure 18. Map showing water quality in ppm iron in shallow bedrock aquifer.

These solution features and joints and fractures in the limestone, dolomite, and shale have created the effective porosity in this aquifer system.

Depth to the shallow bedrock system (fig. 7) ranges from a minimum of about 15 feet in the Kankakee Outwash Plain to a maximum of about 270 feet in the Valparaiso Moraine. Water levels in wells within the system can be expected to rise nearly to the piezometric surface of the unconsolidated system (fig. 10)

Most bedrock wells penetrate only the upper 50 feet, but a few have been developed at levels as deep as 300 feet. Deeper wells generally produce less water because the solution features and joints become smaller and less abundant with depth. Wells in the shallow limestone and dolomite may produce as much as 200 gpm. Wells in the shale produce water from fractures and joints and are generally useful for domestic supplies only. Porosity and permeability in the shale are much less than in the carbonate rocks of the system, and a maximum production of about 20 gpm can be expected.

Nearly all the 2.5 X 106 gpd withdrawn from the system are produced by wells in western Lake County. This is due to the fact that the Silurian carbonate rocks form the surface there, but Devonian shales predominate to the east. The western Lake County communities of Dyer, Lowell, St. John, Schererville, and Schneider depend on the Silurian carbonate section for their water supply.

Water quality (figs. 16, 17, and 18), which is determined largely by the overlying till, is generally good. Sections of the shale, however, present a hydrogen sulfide (H_2S) problem. Iron content ranges from 0.1 to 5.0+ ppm, SO_4 from 100 to 250+ ppm, and $CaCO_3$ hardness from 150 to 750+ ppm. The higher concentrations are generally restricted to isolated areas as depicted in the water quality maps.

As can be seen from the nature of its porosity, the system will be difficult to develop properly. Areas of solution features and fractures of joints are difficult to predict; therefore, well placement is critical. The system has not been fully developed; however, with proper development production could be increased by a factor of 10 (Rosenshein and Hunn, 1968b, p. 19).

DEEP BEDROCK SYSTEM: Three sandstone units at depths exceeding 1,400 feet below the surface make up the potential deep bedrock aquifer system (fig. 19). These are the sandstone horizons in the upper Mount Simon Sandstone and the lower Eau Claire Formation, the top of the lower Eau Claire ranging between 2,200 and 2,800 feet beneath the surface; the Galesville Sandstone, which is about 1,800 feet below the surface; and the St. Peter Sandstone, 1,400 feet below the surface. The geology of these units is discussed in greater detail in the sections on "Bedrock Geology" and "Subsurface Liquid Waste Injection." Their great depth and marginal to poor water quality make them economically unattractive for use at present. But with increasing demand and decreasing surface and near-surface supply, these units may play an important part in the future water supply picture of the area. Because these units have not been developed, aquifer performance is unknown. Cores taken from gas storage and waste injection projects, however, indicate that these sandstones do have potential for development.

Water quality (fig. 19) and permeability generally decrease in a southeasterly direction. Total dissolved solids increase to the southeast with increasing depth and distance from the recharge area. Primary recharge is thought to occur in the outcrop area in northern Illinois and southern Wisconsin. Very little vertical recharge takes place because of nearly impermeable shales which cap these sandstones. Total dissolved solids range from 300 ppm. in the northwest to 5,000 ppm in the southeast for the St. Peter Sandstone, 400 ppm to 16,000 ppm for the Galesville Sandstone, and 400 ppm to 30,000 ppm for the lower part of the Eau Claire Formation and the Mount Simon Sandstone. The mineral content in each is too high to allow use without treatment.

The increased emphasis on deep liquid waste injection poses a serious threat to water quality in the deep bedrock system. Injection of toxic wastes into any of the aquifers in the system will contaminate that aquifer and remove it as a potential resource in the area affected by injection. (For a study on deep waste injection see p. 37.)

SUMMARY OF GROUNDWATER POTENTIAL

Groundwater supplies in combination with water drawn from Lake Michigan will be sufficient to support the projected growth of the two counties for the next 20 to 30 years. Increased groundwater production will come primarily from the unconsolidated sand and gravel of the Calumet, Valparaiso, and Kankakee aquifers, which are parts of the unconsolidated aquifer system, because they are both the most productive and easily developed of all the aquifers in the three systems. These are also most easily contaminated by pollutants from the surface. Among the bedrock aquifers, the shallow bedrock aquifer is most productive, and it has the greatest potential in the west where wells are

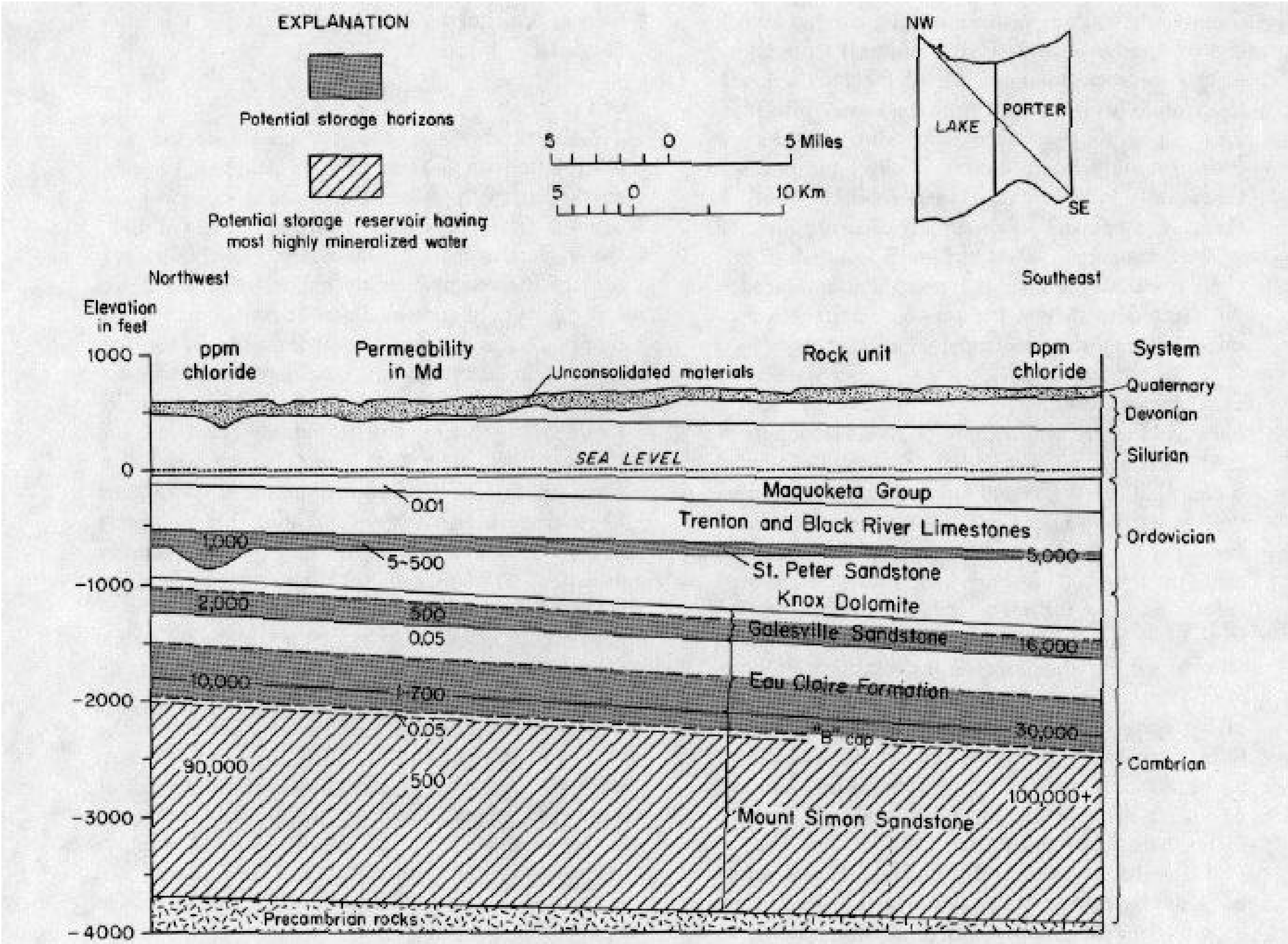


Figure 19. Northwest-southeast cross section showing structure, approximate permeability, and water quality in deep bedrock aquifer .

completed in joints and cavities in the otherwise impermeable limestone and dolomite. Contamination from the surface is not as great in the shallow bedrock as it is in the unconsolidated system, but direct waste injection or leakage of wastes injected below the unconsolidated system may ren er the shallow bedrock useless as a water resource. The deep bedrock aquifer system is unused at present because other sources are both of better quality and are more easily developed. The deep system does have development potential, though, and should be protected as a beneficial reserve. The greatest danger to the deep bedrock system is possible contamination from deep waste injection.

Water quality is generally good for both the unconsolidated and bedrock systems. The primary quality problems are the sulfides and sulfates associated with the organically rich shales and tills and the CaC03 hardness from the calcium-rich tills and limestones. The water quality maps (figs. 12 through 14 and 16 through 18) present the generalized quality trends in the two counties. Water quality in the deep bedrock (fig. 19) is below potable standards but not so poor that there is no potential for use.

The Lake and Porter area is a water surplus area now, but too rapid or excessive development could render it a shortage area by the year 2000. Steps must be taken to protect this invaluable resource.

Industrial Minerals

Most of the economic mineral resources in Lake and Porter Counties are derived from the unconsolidated sediments which cover the two counties. Sand and gravel, lake clays, and clay-rich tills are the three major resources obtained from the *drift* deposits. In one area, southwest of Lowell in southern Lake County, the drift is sufficiently thin over a bedrock hight o permit unconsolidated sediment stripping to expose bedrock some 20 to 30 feet below grade. Dolomite is being quarried from the Lowell pit. Other areas along the Kankakee River also have shallow drift. In southeastern Porter County, the bedrock below drift is shale rather than dolomite. Peat, although not a mineral, is a naturally occurring material of some economic value, but much less than in previous years. Slag, a manmade material, is produced in sufficient quantities in the two counties to be considered an important industrial mineral.

SAND AND GRAVEL

Lake and Porter Counties have an abundant supply of sand, but there are few gravel deposits of economic value (pl. 1, units Qsa and Qsb). Two gravel quarries, both in southern Lake County, are in operation (as of June 1973). The gravel being quarried is fine and contains abundant shale, which must be removed before shipping the more stable gravel fraction to local users and to buyers in Illinois and elsewhere. Most of the gravel deposits in the two counties, however, are too fine and contain too much shale to be of aggregate quality. High-silica sand mining operations, which were once a big industry in the Calumet region, are now greatly reduced in size and number. Abundant good-quality high-silica sand still remains in northern Lake and Porter Counties, but it is inaccessible because the land containing these deposits is owned by private, state, and federal organizations, including public park systems, all of which refuse to remove the sand. The dune and sheet sand deposits on the Kankakee Outwash and Lacustrine Plain are too fine to meet aggregate specifications (Rooney and Ault, 1970, p. 183). Some sand deposits of the Kankakee outwash plain contain as much as 20 percent feldspar, however, and are therefore a potential commercial source of feldspar. Plagioclase is the dominant kind of feldspar and consists of both sodic and calcic varieties. Potassium feldspar accounts for a third of the total feldspar.

Another potential use for the sand deposits on the Kankakee outwash plain is manufacturing lime-silica bricks, which are made from a mixture of quartz sand and slaked lime. In the production process, discussed by French (1965), a mixture of 5 to 12 percent slaked lime and 95 to 88 percent quartz sand is pressed into brick form and then cured with superheated steam at a temperature of 150" C. The slaked lime component could easily be produced from the high-magnesium dolomite at the Lowell stone quarry, and nearby sand is abundant. Lime-silica bricks are used in construction as a substitute for the more familiar clay bricks.

CLAYS

Till-derived clay and lake clay constitute the claybearing units in Lake and Porter Counties. Virtually 0 the surficially exposed and areally extensive clay deposits are on the Calumet Lacustrine Plain north of the Valparaiso morainal boundary. Probably 95 percent of these sediments are impure mixtures of silt and clay with quartz and dolomite contaminants. The resulting impact on the clay industry in the two counties is abundant low-quality clay suitable for industrial and construction products, such as draintiles, backup bricks, and flowerpots (Harrison and Murray, 1964). The three major clay removal operations still in business are near Munster, Crocker, and Chesterton. In all three operations, the sediments being removed are not pure clay but are actually modified clay-enriched till. Auger-boring samples taken throughout the Calumet area indicate that nearly pure clays do exist at varying depths below the surface deposits, but the subsurface deposits do not seem extensive enough to warrant excavation.

Clay lenses of varying dimensions are also in the subsurface throughout much of the Kankakee outwash area, but they are also not worth the expense of mining. In general, the finer quality clay deposits are in the western third of the area mapped as QcI (pl. 1) of the Calumet Lacustrine Plain in Lake County.

PEAT

Peat, which forms from the decay of vegetable matter in poorly drained areas, is common in Lake and Porter Counties but is most abundant in Porter County (pl. 1, unit Qmp). It is used as a soil conditioner, as a part of potting soils, as a packing material for plants that require the retention of moisture during shipping, and a filler for organic fertilizers. It is also used in seed inoculants, seed and mushroom beds, earthworm culture, curing concrete, and making cloth, paper, ethyl alcohol, deodorant, disinfectant, absorbing agents, and some surgical dressings. The only current uses are botanically related. Peat production declined sharply from 1957 to 1972. But potential economic supplies of the commodity still remain. Peat deposits south of Valparaiso and between Crocker and Chesterton (pl. 1, unit Qmp) appear to have the most commercial value.

SLAG

Slag has economic value as a lightweight aggregate, although it is not a naturally occurring industrial mineral. A byproduct of the steel-manufacturing industry, slag is also used as a soil stabilizer, in mineral wool, and in roofing materials. As of 1970, about 4 million tons of lightweight aggregate had been produced in the two-county area, most of which had been used in landfill reclamation and the rest in fulfilling the needs listed above (Brown, 197 1?).

DOLOMITE

Bedrock is covered by great thicknesses of unconsolidated deposits (see p. 7-9) in most areas in the two counties. The area centered 1 1/2 miles east of U.S. Highway 41 and 4 miles southwest of Lowell in Lake County, however, has only a thin covering of till over bedrock (17 to 26 feet). Consequently, a bedrock quarrying operation was begun in 1970. The bedrock sequence is as follows: 9 feet of brown dolomite (Salina Formation) overlying more than 200 feet of dolomite or limestone rated as class A aggregate and possibly of fluxstone quality (Rooney and Ault, 1970). Possible use of the carbonate rocks in manufacturing lime-silica brick, as mentioned above, should certainly be explored.

Waste Disposal

SUBSURFACE LIQUID WASTE INJECTION

Subsurface liquid waste injection is the injection of undesirable liquids into a receptive formation below the earth's surface. The designation "deep well disposal" is commonly used to classify this type of liquid waste removal. The term "disposal" is misleading because the waste is being temporarily stored within the geologic environment and is not truly disposed.

Subsurface liquid waste injection is a risky procedure. At best use of the subsurface for safe waste storage requires that certain rigorously interpreted geologic criteria be met. The most important of these criteria is the availability of a porous and permeable receptor that does not contain a usable resource and that is enclosed at top and bottom by impermeable containing formations. Data on the deep bedrock in Lake and Porter Counties point to only one horizon, the Mount Simon Sandstone below the "B" cap, that meets all requirements, although some others may be satisfactory in certain areas. This section of our report is designed to provide a general overview of the waste injection possibilities in the study area as well as of some of the hazards involved. It is not meant to be an engineering analysis, for it does not contain sufficient data to pinpoint satisfactory injection horizons.

Placing liquid wastes deep beneath the earth's surface has received considerable attention recently, primarily because of the increasing controls placed on surface water quality. The oil industry was first to proceed with deep injection. Extensive surface contamination by oilfield brine forced the producers to return the brine to the subsurface. In some places injected brines have appeared unexpectedly at the surface or in groundwater supplies. For example, brine appeared at the surface in an oilfield in eastern Ohio after rising in improperly sealed abandoned oil wells. In West Virginia a rapidly increasing concentration of chlorides in a city water supply was traced to a brine injection well. The injected brine produced an overpressure in the resident saline formation fluid. This fluid was forced upward through an improperly sealed or corroded abandoned oil well and into the aquifer supplying the city water.

Industrial wastes are of a different and more hazardous nature, however. Many are toxic, carcinogenic, or otherwise more objectionable than the natural brines associated with oil and gas production. Great care must be taken to insure that these wastes are absolutely contained and that contamination of potential water or mineral resources is prevented.

GEOLOGIC AND HYDROLOGIC ASPECTS

In nearly all potential waste injection reservoirs the rock formation is fluid saturated. To provide storage, therefore, a pressure in excess of that in the resident liquid must be applied with the liquid wastes. This overpressure produces storage space by displacement and compression of the resident liquid through joint or pore expansion in the skeletal structure and by compression of the individual grains of the solid formation material. The rate, distance, and direction of movement of the waste depend on injection pressure and volume, the hydraulic head within the receptor system, the specific gravity and viscosity of the waste, and the nature of the receiving formation. The pressure front of the waste, which radiates much more rapidly than the actual physical movement of the waste liquid, will move radially away from the point of injection unless it is physically confined. To contain fluid movement associated with the pressure front, there must a suitable aquitard to restrict movement in undesired directions. Therefore, the injection zone, which must be porous and permeable, requires a cover (cap rock) and, depending on the nature of the liquids in the formations below, a base of very low permeability. A thick shale bed of extremely low permeability and wide lateral extent would be an ideal cap rock. The cap rock prevents or restricts vertical migration toward more shallow horizons with usable water resources or toward the surface.

SYSTEM	STRATIGRAPHIC UNITS	DOMINANT LITHOLOGY	WATER YIELDING POTENTIAL	WASTE INJECTION SUITABILITY	WASTE INJECTION REASON	WATER QUALITY NORTHWESTERN	WATER QUALITY SOUTHEASTERN
QUATERNARY	Glacial drift	Sand, gravel, and clay	Good–fair	Unsatisfactory	Fresh water	Fresh	Fresh
DEVONIAN	Antrim Shale Traverse Fm.	Shale	Fair		Fresh water	Fresh	Fresh
DEVONIAN	Detroit River Fm.	Limestone	Fair		Fresh water	Fresh	Fresh
SILURIAN	Salina Fm. Wabash Fm. Louisville Ls. Salamonie Dol. Brassfield Ls.	Dolomite and limestone	Fair		Fresh water	Fresh	Fresh
ORDOVICIAN	Maquoketa Gr.	Shale and limestone	Poor		Impermeable caprock		
ORDOVICIAN	Trenton Ls. Black River Ls.	Limestone and dolomite	Poor–fair	Unsatisfactory	Only slightly permeable (part of potential water source)	Slightly saline	Moderately saline
ORDOVICIAN	St. Peter Ss.	Sandstone	Fair	Unsatisfactory	Potential water source	Slightly saline	Moderately saline
CAMBRIAN	Knox Dol.	Dolomite	Poor–fair	Poor	Only slightly permeable (part of potential water source)	Slightly saline	Slightly saline
CAMBRIAN	Galesville Ss.	Sandstone and dolomite	Poor	Poor	Only slightly permeable	Moderately saline	Very saline
CAMBRIAN	Galesville Ss.	Sandstone	Fair	Poor	Potential water source	Moderately saline	Very saline
CAMBRIAN	Eau Claire Fm.	Shale, dolomite, and sandstone	Poor (upper part) Fair (lower part)	Poor (upper part) Fair (lower part)	Impermeable caprock (upper part) Somewhat permeable (lower part) Marginal water quality	Very saline	Briny
CAMBRIAN			Fair	Fair	Marginal water quality	Very saline (upper part)	Briny
CAMBRIAN	"B" cap	Shale	Poor	Poor	Impermeable caprock		
CAMBRIAN	Mount Simon Ss.	Sandstone	Fair	Good	Permeable and extensive	Briny (lower part)	
PRE-CAMBRIAN		Granite					

U.S.G.S. WATER SALINITY CLASSIFICATION	
Fresh	<1,000 ppm dissolved solid
Slightly saline	1,000 - 3,000 ppm
Moderately saline	3,000 - 10,000 ppm
Very saline	10,000 - 30,000 ppm
Briny	30,000 - 100,000 ppm

Figure 20. Generalized column of rock formations showing waste injection suitability.

The nature of the resident fluid and of the injection formation is an important factor in planning liquid waste injection. The fluid and formation should not be of potential economic value and must be compatible with the waste. For example, if the waste is not compatible and reacts with the resident fluid or the formation material to produce a precipitate, the pore spaces will fill and clog the well.

ENVIRONMENTAL HAZARDS

The primary environmental hazards of injection are: (1) surface contamination by leakage at the well head or by upward migration of the injected waste through a poorly sealed well or inadequate confining layers; (2) subsurface contamination of usable resident fluids either in the receiving formation or in some other formation containing a potential mineral resource; wastes may move through otherwise impermeable cap rock through faults, fractures, or solution cavities; and (3) high injection pressures that may be sufficient to release stored stresses and cause earth tremors.

POTENTIAL INJECTION HORIZONS

The relative suitability of the bedrock units can be estimated from existing deep well logs and operating injection wells. The description and rating of these units are shown in figure 20. Suitability is based, as described above, on the quality of the resident water, the porosity and permeability of the unit, and a suitable aquitard above and below the unit.

Very little study has been done on the water resource potential of the deep bedrock in this area because other and more convenient water sources have been available. These bedrock units do, however, provide large quantities of potable water and are heavily pumped just northwest of Lake County in the Chicago area. Both the quantity of water available and the quality in the deep bedrock decrease southeastward (fig. 19). The deterioration in quality is thought to be due to the increasing depth and distance from the recharge area. Recharge occurs primarily in northern Illinois and southern Wisconsin where these rocks crop out at the surface. The deep bedrock formations remain, however, a potential water source, even considering the poor quality, whose value will be enhanced by increasing demand, growing water shortages, and advancing water treatment technology. Therefore, waste injection in the deep system must be reckoned against the value of this potential water resource.

The rock units that appear to be capable of accepting large amounts of liquid are the lower part of the Mount Simon Sandstone, sandstones in the upper Mount Simon and the lower part of the Eau Claire Formation, the St. Peter Sandstone, and the Trenton Limestone. Each of these units has the required permeability, porosity, and cap rocks. The approximate depth and thickness as well as the permeability and water quality of each unit are shown in a northwestsoutheast cross section (fig. 19) through the two counties.

The geologic units and their geologic potential for waste injection are shown in figure 20. There are three shale horizons among these units that should provide a suitable barrier against upward movement of liquid wastes. These shale horizons define three separate intervals, each with the potential to receive and store liquids. They are: an impermeable shale informally known as the "B" cap, which ranges from 30 to 75 feet in thickness and averages 40 feet, and which covers the middle and lower portions of the Mount Simon Sandstone; the upper shale of the Eau Claire Formation, which caps the lower sandstone of the Eau Claire Formation and the upper sandstone of the Mount Simon Sandstone; and the Maquoketa Group, which caps the entire hydraulically interconnected sequence between it and the Eau Claire (in this sequence the Galesville and St. Peter Sandstones are the most uniformly permeable).

PROTECTIVE STANDARDS AND CRITERIA

As stated above, there are three separate bedrock horizons that on cursory inspection appear capable of accepting and storing liquid wastes. The fact that each of these horizons has the necessary geologic characteristics should not be sufficient justification for their use, however. The environmental impact of the potential destruction of a natural resource, in this case groundwater, should be given prime consideration.

The environmental impact of waste injection can be minimized by using strict standards to protect natural resources, in this case groundwater. Chloride, which is a good quality indicator for groundwater, may be used to delineate acceptable injection horizons. The figure of 10,000 ppm Cl would appear to be a desirable standard, since technology is available to treat to that level of concentration. If 10,000 ppm is used as the minimum Cl concentration to be protected, only the Mount Simon below the "B" cap meets this qualification throughout the two counties. The other horizons with injection potential each contain water with less than 10,000 ppm Cl in the northern half of the two counties and should therefore receive serious consideration as potential sources of groundwater. The desirability of injection into horizons other than the lower Mount Simon is

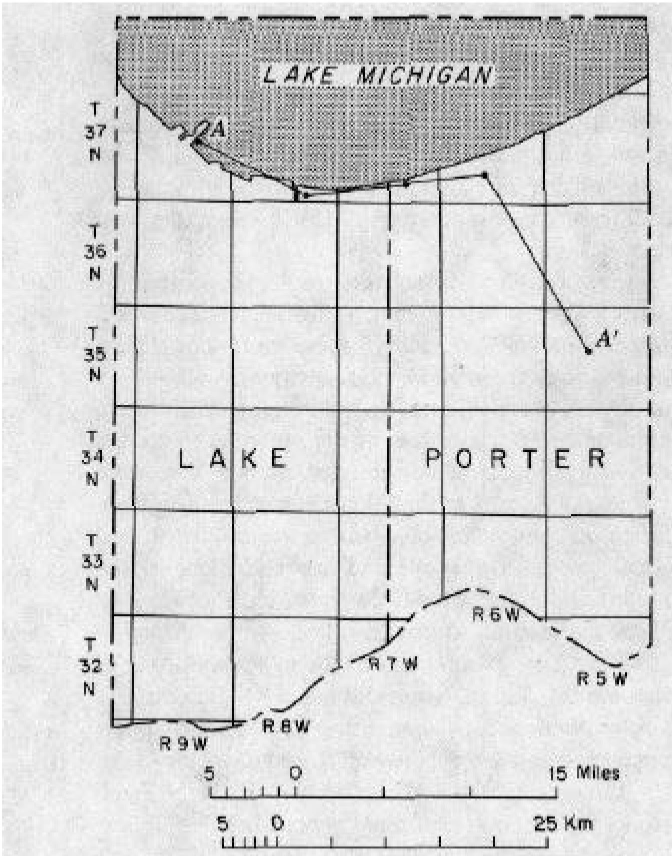


Figure 21. Map showing locations of injection wells. (See fig. 22 for cross section A-A'.)

therefore questionable.

Waste injection above the "B" cap and particularly above the Eau Claire in the northwest comer of Lake County could affect the deep water wells operating in the Chicago area. These formations provide large quantities of fresh water for the Chicago suburbs, and continuous heavy withdrawals from these formations have reversed the hydraulic gradient southeast of Chicago. This reversal of gradient is causing the withdrawal of water from storage in the aquifers under Lake County. Therefore, waste injection in Lake County above the "B" cap (fig. 21) and particularly above the Eau Claire could have a detrimental effect on the water quality in the wells near Chicago.

Injection wells at five sites are presently in use in northern Lake and Porter Counties (fig. 22). Four of these are near Lake Michigan, and one is near Valparaiso. The two wells in Lake County use the Mount Simon Sandstone below the "B" cap as the injection zone, and the wells in Porter County that are farthest from the source of higher quality water use the lower section of the Eau Claire Formation and the entire Mount Simon Sandstone as the injection horizon (fig. 23). The effects that injection already has had on the groundwater are unknown because the water quality figures listed in this report were taken prior to the beginning of injection. Because groundwater contamination is undetectable at the surface and effectively irreversible, a comprehensive net of observation wells should be constructed to monitor the results of these injection operations. By using observation wells, the movement of the injected wastes, the resident fluid, and the pressure front can be monitored and potential problems may therefore be avoided.

SANITARY LANDFILLS

With land becoming more and more a premium commodity in the Calumet region, the difficulty in choosing suitable solid waste disposal sites is rapidly increasing. Some of the larger cities, such as Chicago and Hammond, are turning to such alternatives to burying solid wastes as incineration and recycling. The problem of waste disposal is compounded by the great diversity of type of waste-industrial, chemical, demolition debris, and household garbage. The purpose of this section of our report is to delineate potential solid waste disposal sites, that is, sanitary landfills, in Lake and Porter Counties on the basis of available geologic data.

The most important factor to consider regarding the function of sanitary landfills is that the landfill should be designed to contain the waste materials so as to prevent contamination of surface water, groundwater, and air by both organic and inorganic pollutants. It is therefore important to choose a landfill site that is sealed at the sides and base by a sufficiently thick impermeable barrier to prevent the outward migration of liquid contaminants. In like manner, the refuse surface must be sealed on a regular basis to prevent blowing debris from escaping the area and to keep rats and other disease-carrying pests from contacting the decaying, germ-ridden waste.

The diversity of matter found in a landfill includes household garbage, industrial wastes, both chemical and organic, demolition debris, metals of all types, paper, rags, rubber, and many other items. As these discarded byproducts of society break down chemically in the presence of infiltrated precipitation, a complex and very poisonous mixture called leachate is produced along with a series of gases that include carbon dioxide and monoxide, methane, chlorine gas, bromine gas, nitrous oxide, sulfur dioxide, and

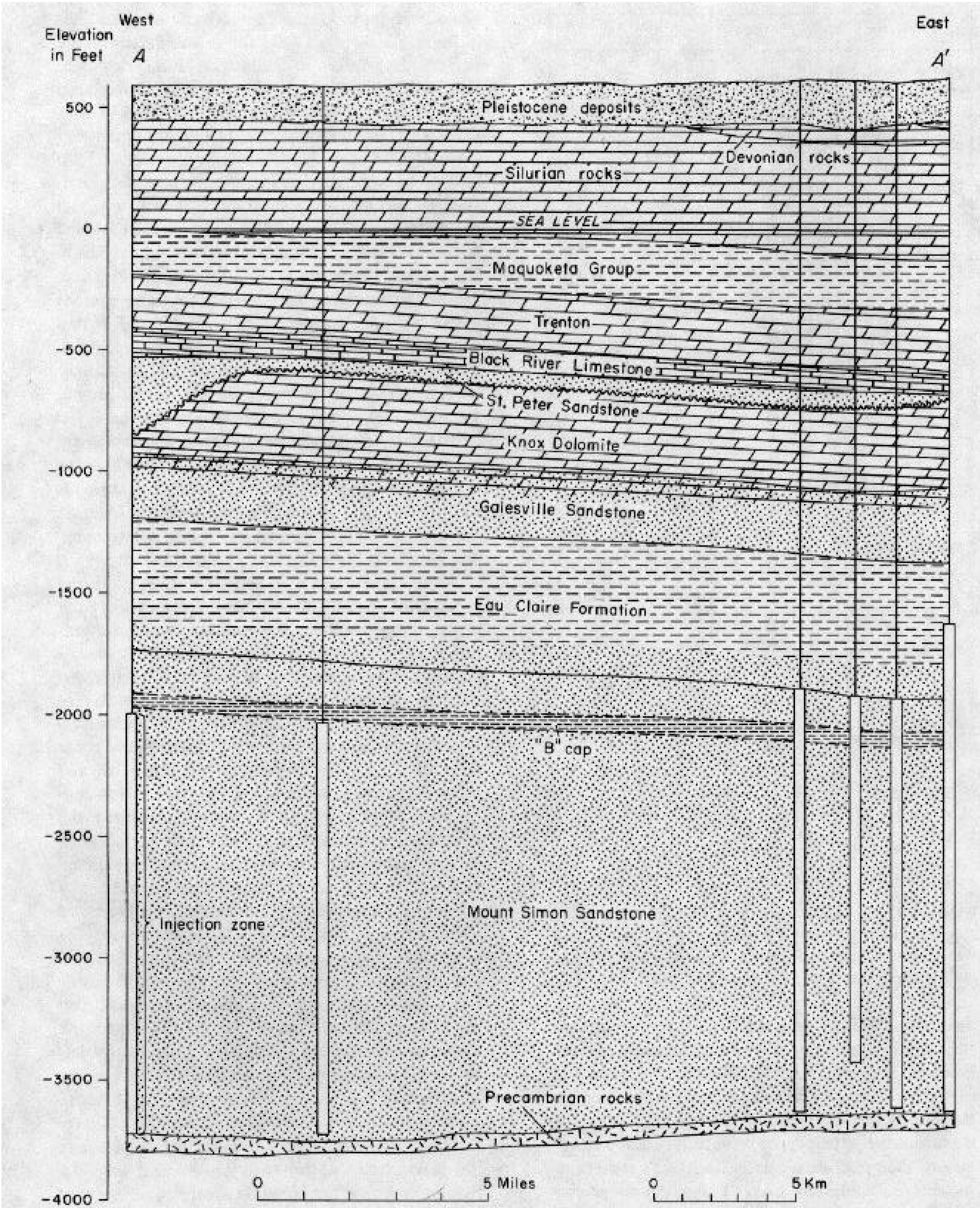


Figure 22. Cross section showing stratigraphic relationships of injection zones for active injection wells.

till or clay unit. Contact with sand and gravel deposits is most likely to be encountered on the eastern part of the moraine in Porter County. Cities which rely on groundwater for their municipal water supply, such as Crown Point, should be particularly careful when choosing landfill sites to insure adequate thicknesses of impermeable material between the base of the landfill and the top of the nearest water-bearing aquifer. Even though upper water-bearing units are not necessarily used for drinking water, many of them are hydraulically connected, by sand lenses or semipermeable zones within the till, to lower aquifers which are used as freshwater sources.

Landfilling on the Kankakee Outwash and Lacustrine Plain, south of the Valparaiso Moraine, should be avoided. This area is generally unfavorable not only because it has a very high water table but also because it is subject to seasonal flooding.

The thick sandy soils of the Gary-Hammond area also are poorly suited to sanitary landfilling because of their high permeability, high water table, and the absence of good cover material. The Gary municipal landfill is being operated in an area which is predominantly sand to a depth of 35 feet. Special monitoring and pumping systems now in use, however, help to maintain the type of control over leachate migration required by the State Board of Health. This type of landfill is not desirable but, as mentioned earlier, may be necessary because of the high cost of transporting wastes to better disposal sites. Sanitary landfill operations in sandy or gravelly soils can be engineered to comply with State Board of Health regulations by sealing the bottom and sides of the fill area with synthetic or clay liners. The present and proposed Gary landfill sites have the advantage of having an impermeable base consisting of clay loam till. It will probably be necessary to set a clay or other impermeable liner around the periphery of the new Gary fill site to prevent the escape of toxic leachates by lateral migration of groundwater. Lateral leachate migration may also be circumvented by pumping the landfill site continuously, thereby removing the toxic groundwater as it forms as well as insuring groundwater flow into, instead of away from, the fill site. The leachate would then be pumped to a treatment plant for decontamination.

Such large urban complexes as Gary and Hammond, which produce huge amounts of household and industrial wastes annually and are on land that is not suited to conventional sanitary landfills, must turn to other methods of waste disposal. Great strides are being made with new and improved methods of recycling glass, metals, and some paper. Incineration of garbage is another functional means of waste disposal, but it results in air pollution in place of land or water pollution. In some areas garbage has successfully been turned into swine feed. The Union Carbide Corp. is experimenting with techniques which turn household garbage into usable petroleum products. Other experiments are underway in which coal and ground garbage are mixed together and burned, the heat being used to generate electricity.

In summary, the city and county officials must choose among the numerous waste disposal techniques and use the least damaging and most economical method of refuse disposal. This information, together with that in the groundwater and engineering geology sections of this report, should provide the preliminary information necessary for the planner to choose the potentially best landfill sites, which should then be subjected to detailed onsite investigation

LIQUID WASTE STORAGE LAGOONS

Liquid waste storage lagoons present an inexpensive and relatively efficient natural biologic and physical means for storing and treating liquid wastes. Also, they can be constructed in complete harmony with the environment by those with a knowledge of geology and proper engineering design. Liquid waste storage lagoons can be used as settling ponds to allow precipitation and gravitational removal of soluble salts, solids, and colloidal particles; as aeration lagoons to decrease BOD (biochemical oxygen demand) and facilitate bacteria and virus removal; and as holding ponds to provide adequate storage for liquid wastes while awaiting treatment or dispersal. Lagoon size and design depend on the anticipated organic load of a sewage treatment facility and on the maximum required storage capacity of a chemical treatment facility. Normally, optimum depth for efficient lagoon operation is about 10 feet. If aerated lagoons are used, depth can be increased to 15 to 20 feet and still maintain the desired aerobic conditions at the surface. But if an aerated lagoon is used for biologic treatment, a second settling pond may be required to facilitate solids removal.

Four examples of facilities using lagoons are: (1) animal feed lots (animals produce 100 times more waste per unit weight than man), (2) municipal sewage treatment plants, (3) food-processing plants, and (4) chemical-manufacturing plants.

For the first three examples, biologic treatment is the primary concern, and an anaerobic settling pond, an aeration pond, and a polishing pond are generally required to produce the desired results. Example 4

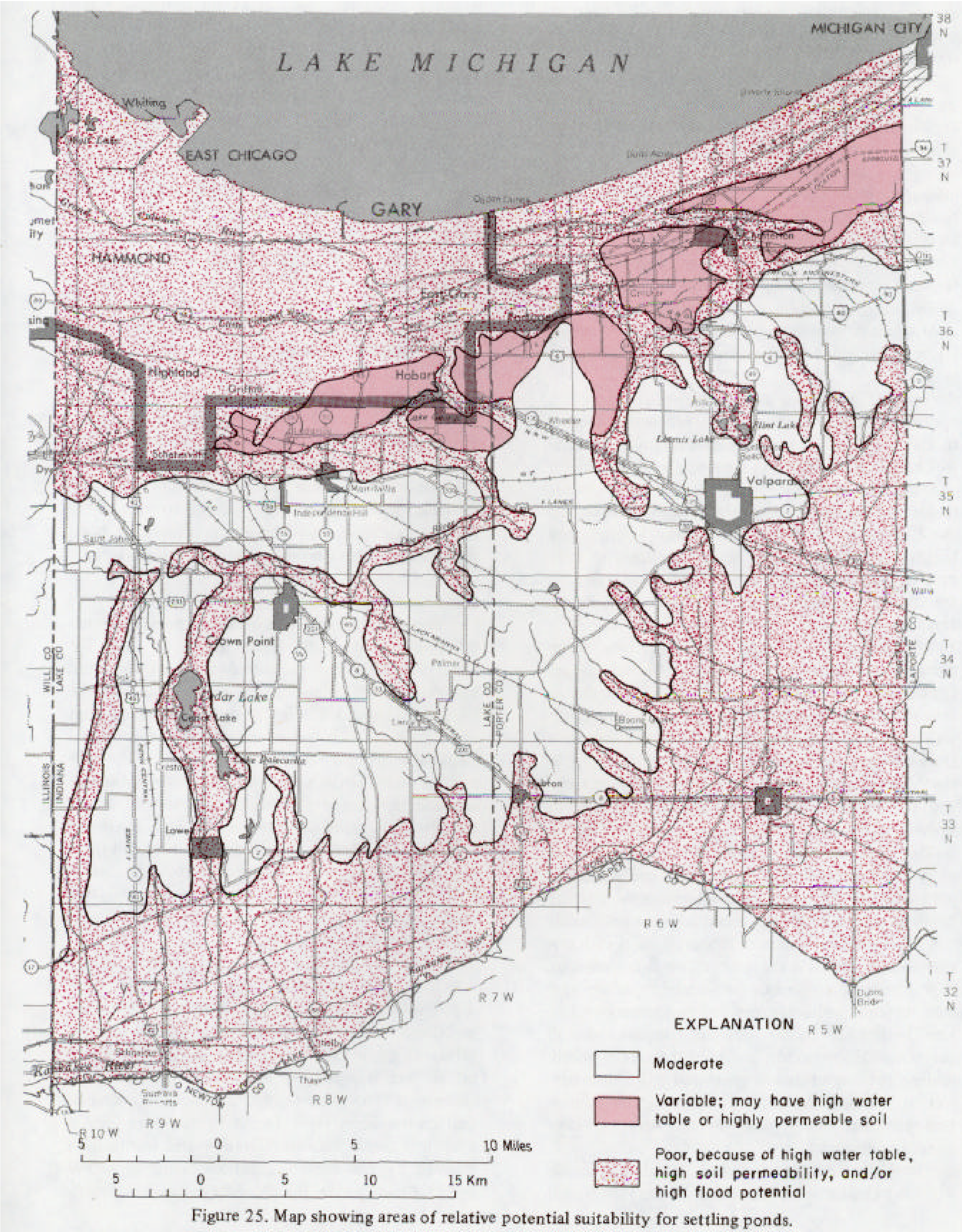


Figure 25. Map showing areas of relative potential suitability for settling ponds.

necessitates additional storage capacity in the form of a holding pond for waste chemicals awaiting further treatment.

The preceding discussion of uses suggests in itself the extreme environmental hazard posed by the seemingly innocuous liquid waste storage lagoon. In each example a potentially harmful liquid waste is held in an open pond. Unfortunate site selection and poor management can result in surface and subsurface contamination. The location and use of the proper geologic conditions are the primary concerns of this section of our report. Even though nearly any location can be made acceptable by adequate engineering design, such as bottom sealing and diking, ultimate environmental protection is achieved only by adapting and using the best natural geologic conditions available.

Geologic conditions that will provide protection against contamination include: a substantial section of clay-loam soil of low permeability to at least 20 feet below the base of the lagoon; a minimum depth beneath the pond bottom of 20 feet to the water table; and location above the maximum expected flood level. Water well logs, highway borings, and Indiana Geological Survey auger hole samples were used to delineate general areas of suitability (fig. 25) for storage lagoon construction in Lake and Porter Counties.

The different parts of the two-county area can be described in terms of three degrees of suitability as: (1) suitable, (2) variably suitable, and (3) unsuitable. These degrees of suitability (fig. 25) correspond fairly well to the physiographic units. Thus the Kankakee Outwash and Lacustrine Plain is mostly unsuitable, the Valparaiso Morainal Area is generally suitable, and the Calumet Lacustrine Plain is unsuitable to variably suitable.

The Kankakee plain is rated unsuitable because of its geologic materials, high water table, and associated poor drainage. This area has a heterogeneous mixture of predominantly highly permeable outwash sands and subordinate amounts of lacustrine clays with low permeability. Because the materials are heterogeneous, it is impossible to predict the suitability of any specific location without a detailed engineering evaluation. In addition to the problems encountered with the permeable materials, much of the area is poorly drained because of its low relief and is therefore subject to flooding. Also, the groundwater contamination potential is very high in this area of heavy groundwater usage.

The Valparaiso Morainal Area is rated generally suitable except at its edges, along stream valleys, and near lakes and bogs where the till is thin and the water table high. The bulk of the till is composed of a thick silt of low permeability to clay-loam material. The morainal area also has a typically depressed water table and good drainage. But the moraine is an area of groundwater recharge and of heavy groundwater usage. Care should be taken to minimize leakage and to monitor for potential loss into the groundwater system. The self-sealing effect of the slime deposited on the bottom by biologic activity should minimize leakage as long as water is maintained in the pond. However, the use of a sealant, such as bentonite, tar, or plastic, to preclude the possibility of seepage is highly recommended even for the clayey, silty tills of low permeability in the Valparaiso Moraine.

The Calumet Lacustrine Plain is ranked as unsuitable to variably suitable. The extensive areas of permeable beach sands and low-lying swamps pose a high contamination risk for surface water and groundwater. But the islands and extensions of till in the southern and eastern parts of the plain are potentially acceptable for storage lagoon sites. Acceptability of these till areas depends primarily on depth to water table and drainage. Each of these factors is marginal, however, and accounts for the variably suitable ranking.

SEPTIC SYSTEMS

The septic system provides a natural means of rehabilitation for domestic liquid wastes by using the upper 5 to 10 feet of the subsurface as a living filter. The major parts of the system are the tank and the tile field. The tank accomplishes the removal of scum and sludge through temporary storage and continual bacterial digestion. Scum rises to the top of the tank and the sludge settles to the bottom. Scum and sludge accumulation tends to stabilize as bacterial action converts solid to liquid. The field disperses the liquid part into the soil through a network of tiled and filled trenches. Therefore it is the component that is affected by the geology, and this is the reason why septic systems rely on satisfactory geologic conditions for safe and effective operation.

The proper geologic environment consists of soil with texture of the desired permeability, adequate depth to the water table, good drainage characteristics, and moderate relief. Soil permeability must be sufficient to permit percolation of the maximum liquid load imposed on the system but not great enough to allow unrestricted and unfiltered percolation to the water table. Depth to the water table is a critical factor because filtration and purification effected by soil bacteria must be complete before septic effluent enters the groundwater system. Purification is most effective in the unsaturated soil zone above the water table where aerobic conditions destroy harmful viruses and bacteria. Requirements on depth to the water table therefore vary greatly with the filtration and ion-exchange capacity of the material. Ion-exchange capacity is the ability of a solid to exchange surface ions with the ions of a gas or a liquid. For example, in a water softener the ions Ca^{++} and Mg^{++} are replaced by ion Na^{+} as the water passes through the ion exchanger. Good surface drainage is another requirement for an acceptable septic system because flooding saturates the tile field and results in failure of the field and in consequent surface water contamination. Therefore both lowlands bordering flood-prone streams and closed depressions are high risk areas for septic systems. Topography is also a factor, for tile fields installed in excessively steep slopes will produce seepage at the surface below the field. They may, through saturation, also cause weakening of the slope with attendant failure and slump.

Each of these factors has been considered in preparing the map of Lake and Porter Counties that indicates the degree of risk in installing septic systems in different areas (fig. 26). The two-county area has been classified in three categories, designated by numbers, on the basis of the degree of risk. In the areas designated by the number 1, a moderate risk is expected, but well-designed systems should function properly. The areas designated 2 have a high risk for septic system failure, so that special precautions are required to insure proper operation. There is extreme risk in the areas designated 3, and nearly all attempts to operate septic systems are expected to result in unsatisfactory operation or in outright failure.

Figure 26 further shows the causes for the three categories of risk: A, high water table, which leads to groundwater contamination or failure of the tile field and subsequent water mounding and blockage of household outlets; B, too low or too high permeability, which causes failure of the tile field and creates surface contamination or direct, essentially unfiltered percolation to the groundwater system; C, frequent flooding, which causes saturation and blockage of the tile system; and D, excessive slopes from which effluent may seep to the surface below the tile field or that may fail and slump when saturated by effluent from the tile field. Figure 26 is intended only as a guide for locating acceptable septic system sites; it cannot be used to approve or disapprove specific sites. A detailed onsite evaluation of each individual location must be made to establish ultimate suitability. Each site evaluation should ascertain that state and federal guidelines for septic system construction can be met. These standards are minimum and may not guarantee proper system functioning. Therefore a safety factor should be designed into each system.

Certain areas of each of the physiographic units in Lake and Porter Counties are unsatisfactory to totally unsuited for septic tanks, particularly in the Kankakee Outwash and Lacustrine Plain and the Calumet Lacustrine Plain. The muck and peat areas in the Kankakee plain are wet, thus obviating their use for septic system installations. The sands also pose a problem because they permit rapid and direct transmission of the effluent to the high water table. If the tile field were installed at or below the water table, *groundwater mounding* would result and the system would cease to function. Because one or a combination of these conditions exists throughout nearly all the Kankakee Outwash and Lacustrine Plain, it has the highest risk rating (fig. 26).

The most satisfactory combination of conditions for septic systems is in the eastern part of the Valparaiso Morainal Area. The grain size and permeability of the till materials at the surface of the moraine increase to the east to about 5×10^{-2} gpd per sq ft, thus permitting satisfactory infiltration rates, The depth to the water table and surface drainage are also more favorably disposed in the areas of moderate relief on the moraine. The western part of the Valparaiso Morainal Area is characterized by finegrained clayey till of lower permeability (7×10^{-3} gpd per sq ft). In this area very large tile fields are required to produce adequate percolation. The unacceptable areas on the moraine, as depicted in figure 26, are the stream valleys, bogs, and lakeshores.

The low-lying, poorly drained stream valleys and bogs of the Calumet Lacustrine Plain present hazardous conditions of high water table and flooding. Septic systems installed in areas with these conditions would most assuredly fail. The higher beach ridges have a lower water table and are well drained. Septic systems installed here should appear from the surface to work well because the permeable sands allow rapid infiltration. The effluent would not be effectively filtered before it reaches the water table, however, and direct contamination of the groundwater would result. These beach ridges have been placed in the high risk category because septic systems are effective only in those areas with enough fine-grained material to slow percolation and to allow adequate filtration. The island of till in north-central Lake County is also placed in the high risk category because of its marginal drainage and water table depth.

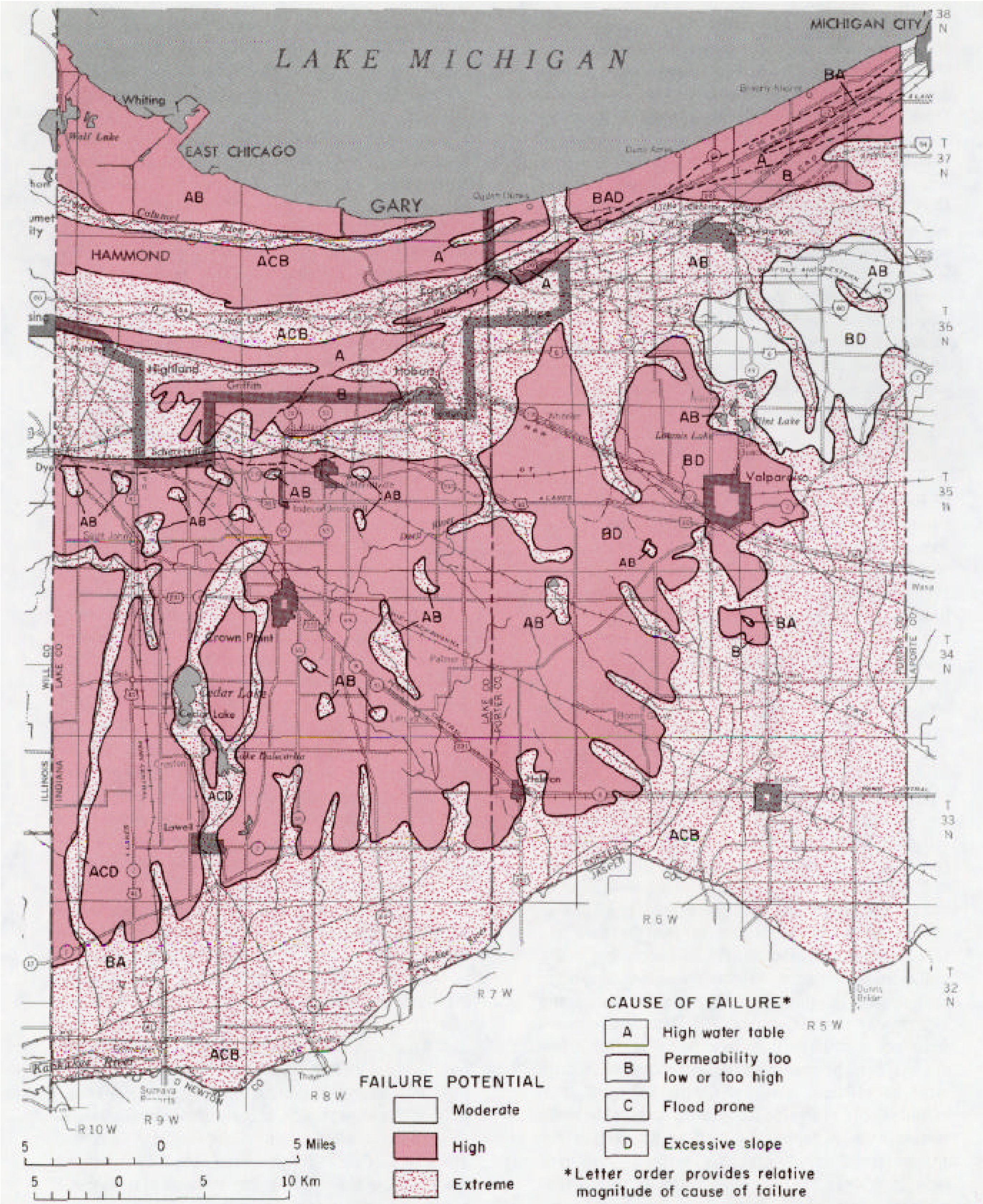


Figure 26. Map showing areas of relative failure potential of septic systems and causes of failure.

Acknowledgments

Much of the information collected in this report resulted from the assistance and cooperation of many individuals and organizations. Acknowledgment is due Mr. Leroy E. Becker, Indiana Geological Survey, for his compilation of bedrock sections and interpretations of bedrock logs; Mr. Ervin J. Kmiecik, chief sanitarian, Lake County Health Department, for his aid in delineating some of the basic and pressing environmental problems of the area; Mr. Mahlon J. Plumb, city engineer, Gary, for his assistance in obtaining approval to extract geologic materials for testing from within the city and for his cooperative work on the local landfill problem; Salisbury Engineering Co., Griffith, for supplying numerous boring samples and logs; and Mr. J. R. Whitehouse, superintendent, Indiana Dunes National Lakeshore, for use of the Leviton report and other information pertinent to the lakeshore erosion problem. Data have also been supplied by the Department of Natural Resources, Division of Water; the Layne Northern Co., Mishawaka; and the Lake and Porter Regional Transportation and Planning Commission, Highland.

Literature Cited

American Society of Civil Engineers, Hydrology Committee of the Hydraulics Division
1957 -Hydrology handbook: Am. Soc. Civil Engineers, 184 p.

Asphalt Institute
1969 - Soils manual for design of asphalt pavement structures: Chicago, Ill., Asphalt Inst., 265 p.

Bleuer, N. K.
1970 - Geologic considerations in planning solidwaste disposal sites in Indiana: Indiana Geol. Survey Spec. Rept. 5, 7 p.

Brown, B. C.
1971? - The mineral industry of Indiana: U.S. Bur. Mines 1970 Yearbook Prepr., 19 p.

Burger, A. M., Keller, S. J., and Wayne, W. J.
1966 -Map showing bedrock topography of northern Indiana: Indiana Geol. Survey Misc. Map 12.

French, R. R.
1965 - Lime-silica brick for masonry uses [unpub. rept.]: Indiana Geol. Survey, 4 p.

Gross, M. G.
1967 - Oceanography: Columbus, Ohio, Charles E. Merrill Books, Inc., 135 p.

Harrison, J. L., and Murray, H. H.
1964 - Clays and shales of Indiana: Indiana Geol. Survey Bull. 31, 40 p.

Hartley, R. P.
1964 - Effects of large structures on the Ohio shore of Lake Erie: Ohio Geol. Survey Rept. Inv. 53, 30 p.

Indiana State Board of Health
1973 - Data on Indiana public water supplies: Indiana State Board of Health Bull. S. E. 10, 83 p.

Lake-Porter Transportation and Planning Commission
1970 -Solid waste inventory: Lake-Porter Transp. and Plan. Comm., 64 p.

Lambe, W. T., and Whitman, R. V.
1970 - Soil mechanics: New York, John Wiley & Sons, Inc., 553 p.

Larsen, J. 1.
1973 - Geology for planning in Lake County, Illinois: Illinois Geol. Survey Circ. 481, 43 p.

Malott, C. A.
1922 - The physiography of Indiana, in Handbook of Indiana geology: Indiana Dept. Conserv. Pub. 21, pt. 2, p. 59-256.

Meyer, A. H.
1935 -The Kankakee marsh of northern Indiana and Illinois: Michigan Acad. Sci., Arts and Letters Papers, v. 2 1.
1954 - Circulation and settlement patterns of the Calumet region of northwest Indiana and northeast Illinois (first stage of occupancy -the Pottawatomie and the fur trader - 1830): Am. Assoc. Geographers Ann., v. 44, no. 3.

Rooney, L. F., and Ault, C. H.
1970 -Potential limestone and dolomite resources of northern Indiana, in Forum on geology of industrial minerals, 5th, 1969, Proc.: Pennsylvania Geol. Survey Mineral Resources Rept. M-64, p. 1,79-224.

Rosenshein, J. S.
1967 - Geohydrology of Pleistocene deposits and sustained yield of principal Pleistocene aquifer, Lake County, Indiana [unpub. Ph. D. thesis]: Urbana, Illinois Univ., 89 p.

Rosenshein, J. S., and Hunn, J. D.
1968a - Geohydrology and ground-water potential of Lake County, Indiana: Indiana Div. Water Bull. 31, 36 p.
1968b - Geohydrology and ground-water potential of Porter and LaPorte Counties, Indiana: Indiana Div. Water Bull. 32, 22 p.

Russell, R. C. H., and Macmillan, D. H.
1952 - Waves and tides: New York, Hutchison's Sci. and Tech. Pubs., 348 p.

Schneider, A. F.
1966 - Physiography, in Natural features of Indiana, 1816-1966, Indiana sesquicentennial volume: Indianapolis, Indiana Acad. Sci., p. 40-56.

U.S. Geological Survey
1969 - Water resources data for Indiana, 1968: U.S. Geol. Survey, Water Resources Div., 269 p.

Glossary

Aerated zone. The zone in which the interstices of the functional permeable rocks or sediments are not filled (except temporarily) with water.

Ambient. Under natural conditions.

Aquifer. A geologic formation through which usable quantities of water are free to move.

Aquitard. A formation of low permeability that restricts fluid movement.

Artesian. Of or referring to water under pressure.

Basement rock (complex). A name commonly applied to igneous or metamorphic rocks underlying the sedimentary sequence.

Canadian Shield. A stable elliptical area of low relief and about 1.9 million sq mi that consists of Precambrian granitic rock, is centered in the Hudson Bay area of Canada, and extends into the northern United States,

Drift. All materials, stratified and unstratified, deposited by glaciers and meltwaters therefrom.

Dynamic equilibrium. The state of changing forces in which a perpetual balance exists between the variants and the effect of these forces on physical objects.

Evapotranspiration. Loss of water from the soil both by evaporation and by transpiration from the plants thereon.

Field moisture. Moisture content of an in-place soil unit.

Foredunes. Dunes which form nearest the shore or other source of sand.

Ground moraine. The material carried forward in and beneath glacial ice and finally deposited from its under surface.

Groundwater mounding. A localized artifical groundwater high resulting from excessive infiltration or percolation or from a sub-water table alteration of permeability that reduces flow in a limited area.

Head. Pressure of a fluid on a unit area due to the height at which the surface of the fluid stands above the point where the pressure is determined.

Heavy minerals. The accessory detrital minerals of a sedimentary rock of high specific gravity which are separated in the laboratory from minerals of lesser specific gravity by means of liquids of high density, such as bromoform; also those commonly separated in their natural setting from lighter sediments by the sorting action of a transporting medium.

Hydrologic (aquifer) system. A unique aquifer or series of aquifers hydraulically interconnected.

Igneous. Of or referring to rocks that crystallize from a melt.

Karst. A limestone plateau or plain (or the characteristic physiography developed thereon) marked by sinks, or karst holes, interspersed with abrupt ridges and irregularly protruberant rocks; generally underlain by caverns and underground streams.

Kettle hole. A bowl-shaped depression of varying dimension that formed when a block of ice became detached from a retreating glacier, was buried in sediment, and was melted to result in a depression in the surface of surrounding materials.

Kettle hole lake. A lake formed in a bowl-shaped depression that was left when an isolated and wholly or partially buried ice block melted.

Maximum sustained yield. The rate at which groundwater can be continuously removed with lowering water levels to critical stages, without exceeding recharge, or without causing undesirable changes in water quality.

Outwash. Stratified drift deposited by meltwater streams beyond active glacier ice.

Paludal. Of or pertaining to swamps.

Physiographic. Pertaining to the land surface and the relations of air and water to it.

Potentiometric surface. The surface to which the water from a given aquifer will rise under its full head.

Pleistocene. The Ice Age; the earlier of the two epochs within the Quaternary Period of geologic time.

Sedimentary. Descriptive term for rock formed of sediment.

Shearing strength. The ability of a material to resist failure from shear; expressed in ft-lb

Till. Nonsorted, nonstratified sediment carried or deposited by a glacier.

Topographic. Pertaining to physical features of a given area, especially relief and contour of the land.

Wisconsinan Age. Fourth and final Pleistocene glaciation.

APPENDIX

Analyses and tests made on auger hole samples from Lake and Porter Counties

Hole No[1]	Thickness of unit (ft)	Size analysis2 Granule/sand/silt/clay (pct)	Carbonate content Calcite/dolomite/total (pct)	Atterberg limits Liquid limit (pct)	Plastic limit (Pct)	Compressive strength (penetrometer test)
1	3-10(7)	0 /85.4 /11.7 / 2.9	2.36/17.9 /20.27	Np[3]		NC4
2	0- 5(5)	1.1 /15.9 /44.9 /39.7	5.83/12.9 /18.8	No data		1.5 tons per sq ft
3	0- 7 (7)	.81/22.4 /38.9 138.6	.24/ 1.8 / 2.04	No data		1.5
	7-25(18)	3.37/40.8 /33.3 /25.9	2.38/13.5 /15.9	No data		0.75 to 1.0
4	0-10 00)	.76/ 9.44/40.7 /49.8	2.40/ 7.12/ 9.52	39	26	1.0 to 1.2
5	0-25 (25)	.42/ 8.81/41.16/50.03	6.79/17.38/24.18	37	17	No data
6	0-10 (10)	.97/30.7 /34.3 /35.0	2.1 /13.3 115.5	28	11	1.75 to 2.25
	10-20 (10)	.85/41.13/35.3 /23.6	5.7 /17.9 /23.6	20	10	1.5
7	0- 6 (6)	1.93/15.5 /41.5 /43.0	3.6 /14.0 /17.6	32	12	1.75
	6-25 (19)	.86/22.5 /40.4 /37.1	6.5 /14.2 /20.7	29	14	2.0
8	0-17 (17)	1.8 /27.7 /46.9 /25.3	3.1 /17.0 /20.1	26	10	1.75 to 2.5
	17-35 (18)	2.5 /28.7 /38.2 /33.1	6.9 /18.8 /25.8	27	13	2.25
9	0-10 (10)	1.94/27.93/39.23/32.84	5.32/14.46/19.9	30	14	.5 to .75
	10-16 (6)	2.45/35.6 /31.4 /32.9	2.86/14.7 /17.6	28	10	1.5
	16-35 (19)	2.4 /52.9 /31.7 /15.4	5.3 /22.3 /27.5	NP		NC
10	0- 8 (8)	1.22/19.9 /39.2 /40.9	2.9 / 9.18/12.06	30	21	1.75 to 2.2
	8-30 (22)	1.92/20.6 /38.1 /41.7	5.8 /13.6 /19.32	36	25	1.75 to 2.0
11	0-15 (15)	1.5 /22.2 /14.3 /63.6	9.191 7.12/16.3	No data		1.50 to 2.2
	15-30 (15)	2.92/28.5 / 4.54/26.04	6.7 /17.5 /24.2	No data		3.0
12	0- 5 (5)	.87/15.8 /44.9 /39.4	6.3 /11.02/17.3	36	18	1.5
	5-15 (10)	1.1 /31.4 /42.3 /26.3	2.4 /17.9 /20.3	36	25	1.5
13	0-30 (30)	.14/76.5 /11.8 /11.6	1.2 / 2.9 / 4.2	NP		NC
14	0- 9 (9)	1.31/94.87/ 2.57/ 2.56	4.23/36.7 /40.9	NP		NC
15	0.20 (20)	0 /94.7 / 1.93/ 3.37	8.92/13.8 /22.7	NP		NC
16	0- 5 (5)	.63/22.5 /35.7 /41.8	.971 1.61/ 2.58	38	21	2.2
	5-15 (10)	2.35/73.56/13.5 /12.9	16.6 /12.9 /29.6	NP		NC
17	0-30 (30)	2.54/28.71/38.18/33.10	6.96/18.83/25.79	27	14	2.5
18	0- 5 (5)	.63/22.5 /35.7 /41.8	.97/ 1.61/ 2.58	38/21	21	2.2
	5-15 (10)	2.35/73.56/14.5 /12.9	16.6 /12.9 /29.6	NP		NC
	15-35 (20)	.56/89.04/ 8.32/ 2.65	16.8 /14.4 /31.2	NP		NC
19	0-54 (54)	1.09/30.74/32.9 /35.4	.94/10.33/11.27	31/19	19	1.5 to 2.8

APPENDIX-Continued

Hole No.[1]	Thickness of unit (ft)	Size analysis2 Granule/sand/silt/clay (pct)	Carbonate content Calcite/dolomite/total (pct)	Atterberg limits		Compressive strength (penetrometer test)
				Liquid limit (pct)	Plastic limit (pct)	
20	5-10 (5)	.85/14.94/51.45/33.6	6.31/15.30/21.61	29	18	2.25 to 2.50
	10-20 (10)	IS /35.6 /31.8 /32.5	4.8 /16.2 /21.0	27	17	No data
	20-3S (I5)	6.5 150.0 /26.5 /23.3	3.4 /14.8 /18.2	21	16	1.2
21	0-20 (20)	1.41/49.6 /21.5 /28.8	6.98/15.l5/22.13	24	9	1.7
	20-40 (20)	.70/25.07/39.6 /35.2	5.8 /18.7 /24.6	26	16	2.0
22	0-10 (10)	1.1 /18.9 /46.4 /34.7	6.79/16.9 /23.7	23	15	1.5 to 1.7
	10-25 (15)	2.13136.68/39.6 /35.2	5.55/21.56/27-11	28	14	1.8 to 2.0
23	15-23 (8)	0 /84.5 /13.5 / 1.9	4.08/21.8 /26.0	NP		NC
	23-32(9)	1.52/90.75/ 7.4 / 1.9	3.14/73.4 /16.6	NP		NC
24	0-10 (10)	-7S/ 9.49/41.42/49.1	5.29/11.48/16.8	36	16	1.5 to 1.75
	10-25 (15)	1.41/23.64/29.65/46.71	3.92/14.23/23.15	30	13	1.0
	2S-40 (15)	1.20/ 9.53/42.13/48.34	9.16/15.15/24.31	34	15	.75
25	0-15 (15)	1.08/23.91/38.14/37.95	4.79/15.15/19.95	30	12	1.0
	15-20 (5)	.71/35-58/41.87/22.55	3.58/16.30/19.88	24	10	2.0
26	0-12 (12)	.33/ 2.45/54.1 /43.4	4.00/21.2 /25-1	30	18	.7
	12-50 (38)	1.20/86.46/13.9 / .35	3.08/19.06/22.15	NP		NC
27	0-11 (11)	.85/13.79/53.3 /32.9	5.04/13.09/18.13	29	18	2.0
	11-50 (39)	.15/91.19/10.04/ 1.23	2.84/17.91/20.75	NP		NC
28	25-30 (5)	1.88/30.5 /42.8 /26.7	4.31/16.1 /20.4	20	15	1.8
29	0-16 (16)	1.66/13.54/53.5 /32.9	4.28/12.5 /16.8	11	18	1.2
	16-50 (34)	2.67/35.6 /40.3 /24.0	7.63/15.23/22.86	21	15	1.0
30	0- 5 (5)	1.87/55.7 /18.3 /25.9	2.33/23.4 /25.7	30	19	2.2
	5-50 (45)	17.0 /88.6 / 8.6 / 2.8	3.54/24.11/27.65	NP		NC
31	0- 5 (5)	1.53/14.42/40.44/45.14	4.61/ .69/ 5.30	38	19	1.0
	5-12 (7)	1.52/92.43/ 8.50/ .93	3.27/30.9 /34.3	NP		NC
	12-20 (8)	.31/97.6 / 2.4 / .09	No data	NP		NC
32	0- 5 (5)	1.51/15.2 /40.02/44.8	5.34/ .46/ 5.80	37	20	.75 to 1.25
	5-20 (15)	.511 8.40/47.64/43.96	9.6 /16.3 /25-9	33	19	1.0
33	0-10 (10)	1.44/20.84/30.76/48.40	2.43/ 6.72/ 9.15	31	10	.5 to 1.0
	10-18 (8)	.49/ 8.6 /48.15/41.57	8.02/17.38/25.40	34	15	.75
	18-35 (17)	.96/11-09/49.36/39.55	7.03/18.77/25.81	29	12	75 to 1.25
34	0- 5 (5)	.83/ 7.89/47.12/45.0	4.61/12.98/17.59	38	14	No data
	5-10 (5)	1.46/11.72/48.4 /39.8	8.75/16.9 /25.7	30	12	.5 to .75
35	0-15 (15)	.81/10.6 /37.7 /52.0	7.29/14.60/21.90	36	26	.5
	15-25 (10)	.89/ 7.75/52.7 /39.7	8.49/20.17/28.66	30	13	1.0

36	0-50 (50)	.48/98.2 1.38/ .40	4.58/ 9.41/13.9	NP		NC
37	5-50 (45)	.19/98.6 2.33/ .97	9.4 /17.7 /27.1	NP		NC
38	0- 5 (5)	0 /93.7 5.38/ .49	1.70/ .69/ 2.39	NP		NC
39	0- 5 (5)	.50/94.84/ 3.6 / 1.6	4.05/18.14/22.2	NP		NC
	5-45 (40)	.33/87.79/ 7.51/ 4.70	6.62/ 9.18/15.7	NP		NC
40	0-10 (10)	0 /93.9 / 4.6 / 1.5	.98/ .92/ 1.89	NP		NC
	10-20 (10)	.50/14.3 /48.6 /37.1	10.9 /14.2 /25.1	31	17	.75
41	0- 5 (5)	.39/95.7 / 4.11/ .17	1.36/25.7 /27.1	NP		NC
	5-10 (5)	.77/17.83/45.8 /36.3	2.31/28.9 /31.2	No data		2.2
	10-25 (15)	.92/55.9 /26.3 /17.7	9.35/28.01/37.4	30	18	2.25
42	0- 5 (5)	1.57/12.59/41.75/45.66	9.85/23.4 /33.3	40	23	2.0
	5-17 (12)	.96/10.7 /45.1 /44.5	7.90/24.8 /32.8	30	18	2.5
43	0-50 (50)	1.2 /98.9 / 1.1 / 0	-72/ 5.0 / 5.72	NP		NC
44	0-50 (50)	0 /98.8 / 1.2 / 0	.93/11.7 /12.64	NP		NC
45	0-22 (22)	1.33/23.9 /43.0 /33.2	4.55/15.8 /20.4	No data		No data
	22-35 (13)	1.7 /29.1 /41.5 /29.4	4.8 /15.6 /20.4	No data		No data
46	0-38 (38)	.55/13.84/51.3 /34.8	5.05/21.56/26.62	30	17	1.8 to 2.0
	38-50 (12)	1.32/26.10/51.96/21.9	No data	No data		No data
47	Hit boulder at 2 ft below grade					
48	0-45 (45)	1.0 /23.6 /62.4 /13.9	No data	20	14	1.25
49	0- 7 (7)	.53/70.6 /19.1 /10.4	1.21/ 5.79/ 7.01	NP		NC
	7-40 (33)	.92/22.79/53.4 /23.7	4.09/20.40/24.5	28	18	1.5
50	0- 7 (7)	0 / 3.53/51.64/44.8	4.09/20.17/24.25	27	18	1.5
	7-35 (28)	1.0 /30.0 /47.7 /22.3	4.57/22.02/26.59	22	15	No data
51	0-16 (16)	0 /52.35/41.78/ 5.87	10.12/16.76/26.88	35	16	.75
	16-50 (34)	0 / 1.12/57.51/41.37	11.22/17-51/28.73	34	21	.50
52	0-10 (10)	.85/ 8.03/54.43/37.53	2.37/15.38/17.75	45	17	.25
	10-25 (15)	1.28/12.8 /55.7 /31.47	4.31/15.15/19.46	27	14	1.50
	25-50 (25)	1.78/ 6.25/56.80/36.95	6.72/17.22/23.94	30	14	1.0
53	Hit rock-at 3 ft					
54	0-25 (25)	1.1 /13.0 /46.2 /40.8	5.0 / 4.1 /19.1	27	17	1.5
	25-30 (5)	2.7 /40.2 /44.0 /15.9	4.3 /17.2 /21.5	20	15	No data
55	0-11(11)	1.2 / 6.7 /59.9 /33.4	4.8 /17.2 /21.2	24	16	2.2
	11-20 (9)	.501 6.6 /59.6 /33.9	8.5 /22.3 /30.7	27	15	1.75
56	0-30 (30)	1.4 / 8.8 /56.0 /35.2	6.9 /16.1 /23.0	24	14	1.5
57	0-22 (22)	0 /34.5 /63.5 / 2.0	No data	NP		NC
	22-25 (3)	2.9 /52.5 /32.6 /15.4	No data	20	14	1.5

APPENDIX-Continued

Hole No.[1]	Thickness of unit (ft)	Size analysis2 Granule/sand/silt/clay (pct)	Carbonate content Calcite/dolomite/total (pct)	Atterberg limits Liquid limit (pct)	Plastic limit (pct)	Compressive strength (penetrometer test)
58	0-20 (20)	.90/26.2 134.3 /39.5	1.9 / 4.8 / 6.8	32	19	2.75 (very dry)
	20-30 (10)	1.7 /18.1 /54.3 /27.6	3.6 / 3.4 /16.9	21	13	No data
59	0-25 (25)	.8 0/25.4 /25.9 /48.7	5.7 /16.6 /22.3	23	14	1.25
	25-32 (7)	2.3 / 8.0 /72.4 /19.6	6.2 /21.6 /27.8	21	14	1.0
60	0.25 (25)	1.5 124.3 /40.5 /35.3	4.0 /15.7 /19.7	23	19	1.5
61	0-25 (25)	1.2 /30.9 /29.4 /39.7	9.1 113.2 /22.3	27	14	1.75
	25-35 (10)	4.2 /16.0 /52.7 /31.3	7.9 115.5 /23.3	23	13	1.25 to 1.5
62	0-12 (12)	.84/ 6.42/63.9 /29.6	7.51/19.9 /27.45	No data		2.0
	12-35 (23)	1.59196.3 / 4.5 / 0	17.79/22.5 /40.3	NP		NC
	35-45 (10)	3.41/28.4 /27.6 /43.9	5.76/16.3 /22.06	No data		1.0
63	0-10 (10)	.90/ 2.7 /67.1 /30.2	1.9 /11.3 /13.2	24	14	1.2
	10-35 (25)	2.3 /27.3 /42.3 /30.4	6.7 /17.5 /24.2	23	13	1.0
64	0-10 (10)	3.1 195.5 / 4.0 / .50	No data	NP		NC
65	3-10 (7)	0 /28.0 133.3 /38.8	2.6 /17.2 /19.8	30	18	2.0
	10-29 (19)	2.6 /27.6 /36.6 /35-9	4.1 /14.0 /18.1	24	14	1.25 to 1.50
66	0-10 (10)	1.37/43.08/27.06/29.86	.73/ 2.53/ 3.25	38	15	.50
	10-50 (40)	1.25/93.54/ 5.64/ .82	7.21/17.91/25.11	NP		NC
67	10-50 (40)	1.42/96.761 2.19/ 1.04	6.42/15.46/21.89	NP		NC
68	0-24 (24)	2.80/ 9.35/58.36/32.28	9.15/16.07/25.22	26	15	1.0
	24-35 (11)	8.85/28.82/35.65/35.5	4.5 /15.2 /19.7	25/13	13	.8
69	0-15 (15)	4.77/97.26/ 1.351 1.39	8.60/12.73/21.33	NP		NC
	15-25 (10)	lS/10.20/39.29/50.51	2.86/14.00/16.86	34	16	1.25
70	2- 8 (6)	0 116.30/78.59/ 5.11	3.05/22.5 /28.54	19	15	1.5
	8-25 (17)	1.75/33.81/32.43/33.77	2.63/11.25/13.88	30	15	1.5
	25-30 (5)	3.09/48.70/30.22/21.08	2.15/ 7.35/ 9.51	23	14	.75
71	0-10 (10)	1.9 /46.7 /34.9 /18.5	No data	20	13	1.8
72	0- 8 (8)	4.35113.96/50.64/35.4	.97/ 1.15/ 2.12	23	15	.5
	8-50 (42)	1.02/86.14/11.83/ 2.03	4.47/23.65/28.12	NP		NC
73	0-10 (10)	3.57/56.19/20.51/23.30	1.22/ 1.151 2.36	31	13	1.25
	10-50 (40)	1.32/95.49/ 3.00/ 1.51	3.10/ 7.28/10.37	NP		NC
74	0-10 (10)	1.3 /74.4 / 9.21/34.0	No data	33	20	No data
	10-20 (10)	.60/44.9 /36.6 /18.5	No data	22	15	No data
75	0-15 (15)	1.2 /42.4 /22.5 /35-1	6.7 /16.3 /23.0	25	16	.75

76	0-14 (14)	1.3 /12.9 /52.3 /34.8	No data	28	17	1.2
	14-18 (4)	1.1 /11.7 /53.7 /34.5	No data	28	16	1.0 to 1.5
77	0-15 (15)	1.1 /36.5 /39.9 /23.5	No data	No data		No data
78	0-20 (20)	.70/36.6 /15.2 /48.1	6.2 /12.3 /18.5	33	13	1.5
	20-30 (10)	.60/38.1 /56.8 / 5.1	No data	No data		No data
79	0-12 (12)	1.7 /11.5 /50.0 /38.5	4.7 /15.2 /19.9	28	16	1.75
	12-20 (8)	1.4 /16.4 /46.9 /36.6	7.1 /16.4 /23.5	26	16	No data
80	0- 5 (5)	1.42/21.04 /40.7 /38.21	4.57/10.8 /15.3	38	16	.75
	5-35 (30)	.84/15.13 /41.6 /43.3	7.2 /14.0 /21.23	30	15	.90
81	0-17 (17)	2.8 /24.6 /38.3 /37.1	No data	26	16	No data
	17-50 (33)	3.9 /40.9 /39.1 /20.0	No data	20	14	No data
82	0-22 (22)	0 /34.5 /63.5 / 2.0	No data	No data		No data
	22-28 (6)	2.9 /52.5 /32.6 /15.4	No data	20	14	No data
83	0-20 (20)	1.3 / 3.9 /72.2 /23.3	6.5 /19.9 /26.4	22	13	.5
	20-40 (20)	1.9 /15.2 /72.1 /12.8	7.0 /22.3 /29.2	25	12	.75
84	0-50 (avg)	2.3 /70.9 /19.7 / 7.1	No data	NP		NC
85	0- 3 (3)	2.8 /24.3 /53.7 /21.9	No data	20	12	.75
	3-11 (8)	.80/14.4 /48.8 /36.9	No data	32	26	1.2
	11-30 (19)	.80/11.9 /47.4 /40.7	No data	32	18	1.0
86	0-10 (10)	1.8 /10.6 /55.7 /33.8	No data	27	is	No data
	10-45 (35)	1.9 /30.0 /49.7 /20.3	No data	22	12	No data
87	0-10 (10)	0 / .90 /21.2 /78.0	No data	46	28	No data
	10-15 (5)	1.2 /92.0 / 9.9 / .80	No data	NP		NC
88	0-20 (20)	2.0 /15.3 /73.9 /40.7	No data	No data		No data
89	0- 5 (5)	1.1 /76.1 /14.6 / 9.4	No data	NP		NC
90	0-10 (10)	.88/ 8.74/52.0 /39.2	8.25/19.24/27.49	27	17	.8
	10-50 (40)	2.06/42.65/30.45/26.9	6.29/ 1.99/26.22	21	7	1.0
91	0-48 (48)	.50/16.1 /64.0 /20.0	No data	No data		No data
92	0-32 (32)	2.6 /36.7 141.2 /22.1	No data	20	13	No data
93	0-15 (15)	3.1 /82.8 / 2.6 /19.8	5.0 /18.6 /23.6	19	10	1.5
94	0-15 (15)	.90/69.2 /21.5 / 9.3	No data	NP		NC
95	0-15 (15)	1.6 /20.0 /52.9 /27.1	No data	28	17	No data
	15-35 (20)	.30/ 5.6 /46.2 /48.3	No data	34	18	No data
96	0- 8 (8)	.70/26.6 /58.2 /15.2	No data	No data		No data
	8-30 (22)	1.0 /49.9 /20.6 /29.5	No data	21	13	No data
97	0-15 (15)	1.0 /33.3 /60.6 / 6.1	No data	No data		No data
98	0-35 (35)	11.0 115.0 /78.0 / 6.9	2.6 /10.3 /12.9	21	13	1.2

APPENDIX—Continued

Hole No. [1]	Thickness of unit (ft)	Size analysjs[2] Granule/sand/silt/clay (Pct)	Carbonate content Calcite/dolomite/total (pct)	Atterberg limits Liquid limit (pct)	Plastic limit (pct)	Compressive strength (penetrometer test)
99	0-16 (16)	0 /52.35/41.78/ 0	10.12/16.76/26.88	35	16	.75
	16-50 (34)	0 / 1.12/57.51/41.37	11.22/17.51/28.73	34	21	.5
100	0-10 (10)	.85/ 8.03/54.43/37.53	2.37/15.38/17.75	45	17	.25
	10-50 (40)	1.78/ 6.25/56.80/36.95	6.72/17.22123.94	30	14	1.0
101	0-35 (35)	2.8 /95.8 /28.6 132.8	No data	NP		NC
102	0-45 (45)	1.43/93.801 4.55/ 1.65	2.60/10.91/13.52	NP		NC
103	0-10 (10)	16.0 /82.9 /17.9 / .40	No data	NP		NC
104	0-50 (avg)	2.36/93.82/ 4.71/ 1.42	5.81/17.85/23.66 (bottom)	NP		NC
105	0-10 (10)	16-88/10.88/77.71/11.41	3.63/12.75/16.38	21	15	.75
	10-45 (35)	.28/97.91/ 2.74/ .65	9.13/22.27/31.40	NP		NC
106	0-20 (20)	.14/99.0 / .84/ .15	5.5 /19.74/25.25	NP		NC
	20-50 (30)	.15/97-08/ 2.49/ .44	6.06/16.69/22.75	NP		NC
107	0-10 (10)	3.59/18.94/62.92/18.14	.74/ .23/ .98	25	12	1.4
	10-30 (20)	8.31/96.58/ 2.78/ .64	3.65/ 8.81/12.45	NP		NC
108	0-50 (avg)	1.1 /7.1 / 2.26/ .65	4.09/16.69/21.28	NP		NC
109	10-50 (avg)	1.42/96.76/ 2.19/ 1.04	6.42/15.46/21.89	NP		NC
110	5-10 (5)	3.84/96.56/ 2.39/ 1.05	3.09/ 9.55/12.64	NP		NC
	10-50 (40)	.15/11.42/57.38/31.20	4.56/13.77/18.33	20	12	.75
ill	0-50 (avg)	1.47/97.56/ 1.56/ .88	5.77/12.45/22.72	NP		NC
112	0-50 (avg)	1.38/17.02/51.10/31.88	1.64/19.20/21.34	26	19	2 to 2.2
113	0-20 (20)	6.67/95.17/ 3.59/ 1.23	5.31/20.17/25.48	NP		NC
	20-40 (20)	2.26/24.1 /27.9 148.01	1.44/ 9.04/10.48	36	19	1.5 to 1.7
114	0_10 (10)	0 /35.1 /21.1 /43.8	8.5 /15.9 /24.5	27	15	1.0 to 1.25
	10-35 (25)	.43/23.44/28.33/48.23	7.53/16.46/23.99	31	16	1.5
115	5-10 (5)	3.84/96.56/ 2.39/ 1.05	3.09/ 9.55/12.64	NP		NC
	10-50 (40)	.15/11.42/57.38/31.20	4.56/13.77/18.33	20	12	.75
116	5-10 (5)	0 /85.3 113.5 / 1.44	6.36/30.0 136.4	NP		NC
	10-65 (55)	0 /90.12/ 8.10/ 1.79	6.85/22-97/34.82	NP		NC
117	0-35 (35)	.56/91.9 / 5.84/ 2.24	.47/ 3.64/ 4.11	NP		NC
118	0-30 (30)	.50/97.9 / 2.46/ 0	9.52/22.51/32.03	NP		NC
	30-50 (20)	9.70/14.21/56.95/28.84	3.86/15.76/19.62	24	15	1.75

Footnotes for appendix are on p. 57.

[1]Auger hole sites are plotted in figure 6.
[2]Percentages for granule, sand, silt, and clay as discussed in the text (p. 9) do not always total 100.
[3]NP - Nonplastic.
[4]NC - Nonclastic.