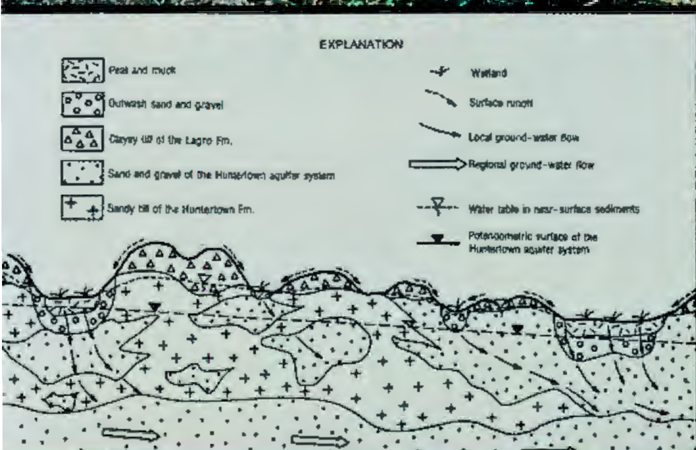
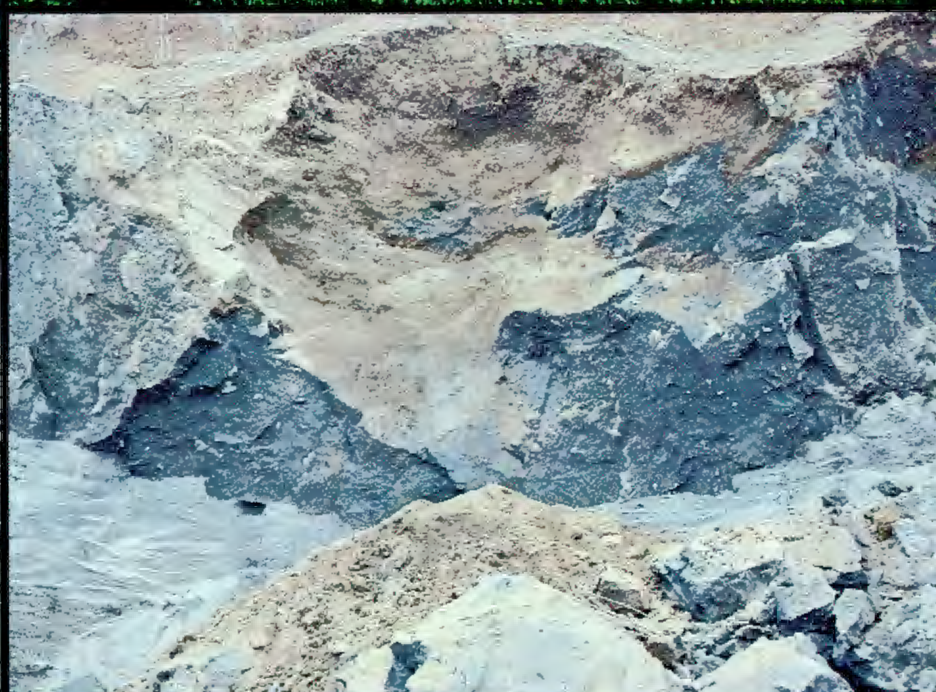
THE HYDROGEOLOGY OF ALLEN COUNTY, INDIANA

A Geologic and Ground-Water Atlas

Special Report 57





INDIANA UNIVERSITY
INDIANA GEOLOGICAL SURVEY

DEPARTMENT OF PLANNING SERVICES
ALLEN COUNTY, INDIANA

STAFF OF THE INDIANA GEOLOGICAL SURVEY

ADMINISTRATION (Phone 812/855-5067)
Norman C. Hester, Director/State Geologist
John R. Hill, Assistant Director
Pat Gerth, Secretary (Assistant Director)
Charlotte Smith, Financial Officer
Helen Stephenson, Financial Records Assistant
Tammy Watson, Secretary (Director)

BASIN RESEARCH COORDINATOR (Phone 812/855-4213)
Brian Keith, Petroleum Geologist

EDUCATION EXTENSION (Phone 812/855-7636)
John R. Hill, Geologist and Head
Jeff Kirby, Assistant Geologist

ENERGY RESOURCES SECTION (Phone 812/855-5412)
John A. Rupp, Geologist and Head
Jerry R. Burton, Geological Technician
James T. Cazee, Geologic Draftsman
Sherry Cazee, Sample and Core Curator
Mary Decker, Secretary
Lloyd Furer, Stratigrapher
Stanley J. Keller, Petroleum Geologist
Maria Mastalerz, Coal Geologist
Todd Thompson, Sedimentologist
Charles W. Zuppann, Petroleum Geologist

ENVIRONMENTAL SECTION (Phone 812/855-7428)
Edwin J. Hartke, Geologist and Head
N. K. Bleuer, Glacial Geologist
Steve Brown, Glacial Geologist
Donald L. Eggert, Environmental Geologist
Anthony Fleming, Glacial Geologist
John Haddan, Field Laboratory Technician
Denver Harper, Environmental Geologist
Nancy Hasenmueller, Environmental Geologist
Ray René, Geophysicist
Carl B. Rexroad, Paleontologist
M. Sue Shaver, Secretary

GEOCHEMISTRY (Phone 812/855-2687)
John B. Comer, Head
Tracy Branam, Geochemist
Marilyn DeWees, Secretary
Margaret V. Ennis, Geochemist

INDUSTRIAL MINERALS PRINCIPAL GEOLOGIST (Phone 812/855-2687)
Donald D. Carr, Geologist

MINERAL RESOURCES (Phone 812/855-2687)
Henry L. Barwood, Head
Marilyn DeWees, Secretary
Walter A. Hasenmueller, Geologist
Kathryn R. Shaffer, Mineral Statistician
Nelson R. Shaffer, Geologist

PHOTOGRAPHY SECTION (Phone 812/855-1370)
Barbara T. Hill, Head
John Day, Photographic Specialist

PHYSICAL FACILITIES AND FIELD SERVICES (Phone 812/855-3596)
Sam Frushour, Head
Jay Arnold, Drilling Foreman
Thomas Chitwood, Geological Technician
Sam Riddle, Driller

PROGRAM COORDINATOR (Phone 812/855-1351)
Gordon S. Fraser, Geologist

TECHNOLOGY TRANSFER SECTION (812/855-7636)
Richard T. Hill, Head

EDITORIAL (Phone 812/855-7636)
Deborah DeChurch, Editor

GRAPHICS AND CARTOGRAPHY (812/855-5893)
Rea Kersey, Cartographic Specialist
Kari Lancaster, Cartographic Specialist
Roger Purcell, Senior Cartographic Specialist
Kimberly Sowder, Senior Cartographic Specialist
Wilbur Stalions, Cartographic Specialist

INFORMATION TECHNOLOGY (Phone 812/855-7428)
Paul Irwin, GIS/Database Analyst

PUBLICATION SALES (Phone 812/855-7636)
Janis Fox, Senior Publications Assistant
Pat Gerth, Publications Specialist/Associate Head

For sale by Publication Sales, Indiana Geological Survey,
611 N. Walnut Grove, Bloomington, Indiana 47405

TABLE OF CONTENTS

PAGE

ILLUSTRATIONS

TABLES

SIDEBARS

PLATES (in jacket)

THIS PAGE INTENTIONALLY LEFT BLANK

CHAPTER 1

INTRODUCTION AND METHODOLOGY

by Anthony H. Fleming

BACKGROUND

Allen County is in northeastern Indiana, adjacent to the Ohio state line and about 33 miles south of the Michigan state line (fig. 1). The county is approximately 671 square miles in size and had a total population of about 300,000 in 1990. The county seat is the City of Fort Wayne, one of the most rapidly growing metropolitan areas in Indiana.

Ground water is the principal source of water for more than half of the residents and much of the industry in the county. The City of Fort Wayne is the only area in the county served by a public water supply derived from surface sources. Population growth is greatest in outlying areas, thus it is likely that the percentage of county residents and businesses served by ground water will grow in the future.

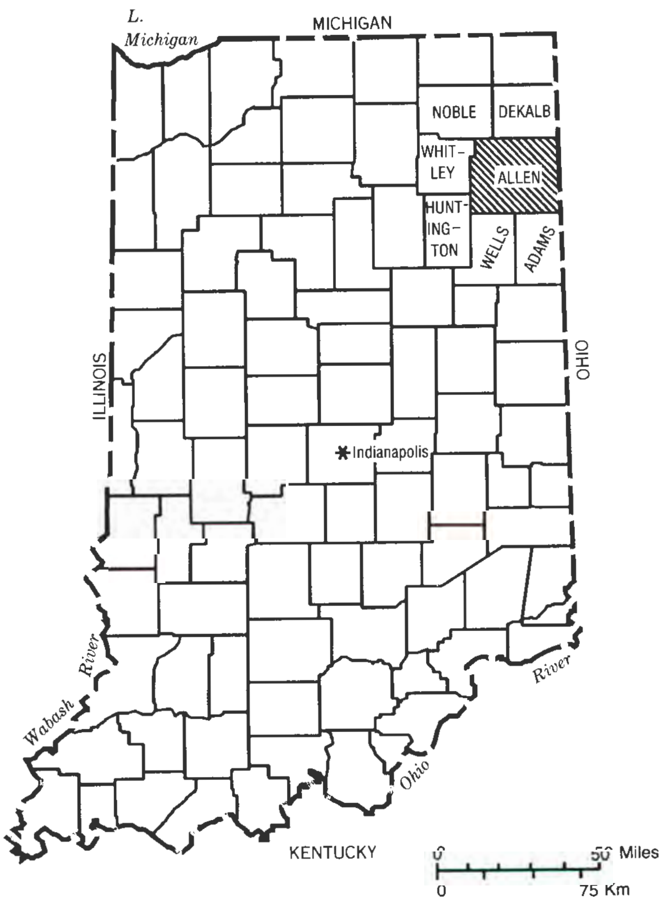


Figure 1. Map of Indiana showing location of Allen County.

Due to the humid climate and abundant precipitation (approximately 35 to 40 inches per year), the growing reliance on ground water in Allen County is unlikely to be threatened by inadequate quantity. Although a few widely scattered localities do exist in the county where ground-water availability is somewhat limited, a far more significant threat is the potential for contamination of productive aquifers by activities or facilities located in areas where the ground water is naturally susceptible to pollution. The high economic, societal, and environmental costs of polluted ground water are well known and far exceed the relatively minimal costs associated with preventing ground-water contamination in the first place. For example, several million dollars have reportedly been spent attempting to clean up soil and ground-water contamination at just one Superfund site in Allen County, whereas the cost of this study is less than $200,000. Growing recognition of these costs, coupled with the highly publicized nature of many ground-water contamination incidents and the identification of a wide variety of potential contaminants and activities that can negatively impact ground-water quality (U.S.E.P.A., 1980; Pye and Kelley, 1984), have led to a heightened awareness of the need to protect ground-water quality on the part of concerned citizens and local officials.

This study was initiated at the request of several Allen County agencies in order to provide information needed to understand and protect the ground-water resources of the county. The results are designed to be incorporated into the land-use planning process and can be used for a wide variety of planning and screening activities. The information contained in this study is presented at too coarse a scale to be suitable for most site-specific activities but it provides a useful regional perspective for more detailed site investigations.

PURPOSE AND SCOPE

The main goal of this study is to provide the citizens of Allen County with the technical and scientific information needed to understand the geologic framework within which ground water occurs so that appropriate steps can be implemented to protect the resource. Because of natural variations in a variety of conditions that can influence the availability of ground water and the rate at which contaminants can migrate into it, the natural **sensitivity** of ground water to contamination differs considerably from place to place. The primary objectives of the study, therefore, are to identify, describe, and map the principal geologic and hydrogeologic features and elements that collectively form the hydrogeologic framework and that contribute to important geographic variations in ground-water conditions.

The report covers a wide range of ground-water related topics and is supplemented by ten plates that show a variety of important geological and hydrogeological elements. These plates serve as the primary illustrations for the topical discussions that follow and are frequently referred to throughout the report. Numbers and titles of the plates are listed separately in the table of contents.

Any detailed discussion of ground water and its intimate relationship to the complex sequences of geologic materials it occurs within is necessarily technical in nature, and the use of many names and terms specific to these topics is virtually impossible to avoid. At the same time, however, this report and the accompanying plates are intended for a diverse audience that includes geologists, public officials, businesses, consultants, and the general public, many of whom will have little if any scientific background in the field of geology. In order to accommodate this conflict, every attempt has been made to explain each geologic term and name in the simplest possible language at the point where it is introduced in the report. These terms and names are also highlighted in boldface and are defined in a glossary at the end of the report. In addition, the general discussion of geologic and ground-water conditions is supplemented by several sidebars throughout the report. These sidebars are highlighted and enclosed in boxes. They provide more in-depth coverage of topics of a more technical or geographically specific nature that may be of particular interest to certain segments of the readership.

The report is organized into five main chapters. This chapter introduces the study, describes the approach used to define and map geologic and hydrogeologic elements, and identifies the principal limitations of the study. This chapter also gives a brief overview of several commonly used terms and important concepts.

The second chapter provides a detailed description of the geologic history, geographic distributions, and physical characteristics of the bedrock formations and unconsolidated deposits, and details their relationship to the modern landscape of Allen County. The information contained in Chapter 2 may be particularly useful to those scientifically-minded readers who are looking for an in-depth understanding of the geologic history and physical properties of the glacial deposits that may have a significant bearing on ground-water movement. This information is not absolutely essential, however, for most readers to generally understand the hydrogeologic framework presented in subsequent chapters.

The third chapter provides an overview of key ground-water principles and concepts, and establishes the hydrogeologic framework of Allen County. This framework relates the general hydrogeologic behavior of the geologic units to their physical, chemical, and spatial characteristics as described in Chapter 2. The fourth chapter identifies eleven distinct hydrogeologic regions in Allen County based on the geologic and hydrogeologic framework and principles presented in the preceding chapters. Sections covering each region describe the typical range of geologic conditions and emphasize the availability of ground water and its sensitivity to contamination. The final chapter summarizes the study results and offers suggestions and recommendations for protecting ground-water quality in Allen County.

SOME IMPORTANT TERMS AND CONCEPTS

Most of the geologic terminology used in this report is introduced and defined in the appropriate locations in the text. A few terms and concepts, however, are of such central importance that a brief discussion is in order at this point.

Ground water is defined as all water that occurs within openings in rocks and soil below the surface of the Earth. Ground water is present to depths of thousands of feet, but for all practical purposes only ground water within several hundred feet of the surface is of acceptable natural quality to sustain plants and animals and sufficiently accessible to the land surface to constitute a source of water for human use. The **water table** defines the boundary between the **saturated zone** and the **unsaturated zone** (fig. 2). Below the water table, ground water fills all the openings in the rock and soil, whereas openings in the unsaturated zone above contain both water and air. Due to a combination of pressure and elevation, ground water at any given location in the subsurface is under **hydraulic head**, which is represented by the elevation to which ground water will rise in a well installed at that location. Another representation of hydraulic head is the elevation of the water table. Hydraulic head values differ from place to place, as evidenced by the slope of the water table, which typically mimics the configuration of the land surface, but in a more subdued fashion. Ground water always flows from higher hydraulic head to lower hydraulic head, and in most instances this flow direction is parallel to the direction of regional slope on the overlying land surface. Consequently, ground water usually flows away from high points on the land surface to discharge in rivers, lakes, and other low parts of the landscape. This entire regime of ground-water movement is known as a **flow system**. Places where large amounts of infiltrating water enter the flow system are known as ground-water **recharge areas** and localities where ground water is generally moving toward the land surface are known as ground-water **discharge areas**.

Most of the midwestern United States was invaded by **glaciers** on several occasions during the **Pleistocene Epoch,** otherwise known as the **Ice Age**, which took place during the last one million years or so. Unlike the ancient **bedrock** of the region, the sediments left by the glaciers have not been deeply buried and cemented since they were deposited,

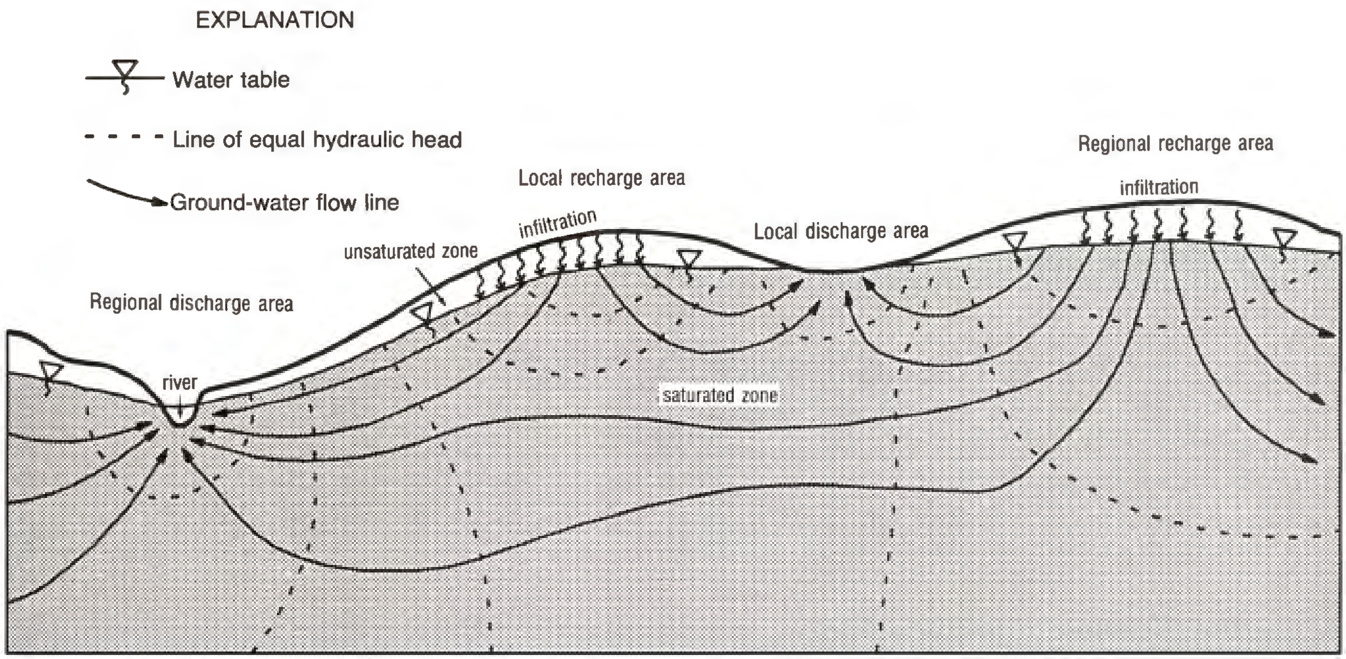


Figure 2. Schematic diagram illustrating selected components of an idealized ground-water flow system assuming relatively homogeneous subsurface geology.

hence they are referred to as **unconsolidated**. Allen County is underlain by a particularly thick sequence of unconsolidated deposits that are of central importance to the occurrence and protection of ground water. Depending on the manner in which they were deposited, certain kinds of unconsolidated materials can contain and transmit very large amounts of ground water, as can some types of bedrock. These major water-bearing formations are referred to as **aquifers**, whereas rocks and unconsolidated materials that do not yield ground water readily are known as **confining units**, or **aquitards**. The study of ground water and its relationship to geological materials and processes is known as **hydrogeology**.

Ground water discharges naturally onto the land surface via **springs**, which are generally located where the water table intersects the land surface. Ground-water discharge also maintains the base flow of rivers and streams during times when precipitation is lacking, and is important to the water budgets of many types of lakes and wetlands. Most ground water used for human activities, however, is extracted from **wells** (fig. 3). A well can be constructed in a variety of ways, but by far the most common type is a drilled well. These are installed by using a mechanically powered drilling rig to turn a cutting tool, known as a bit, which drills a borehole through the ground until a sufficiently productive formation is encountered. At that point, a **well casing** is installed in the borehole. If the well is made in unconsolidated deposits, a **well screen** is employed in the water-bearing zone on the end of the casing to prevent sand from entering the well. In solid rock, however, no screen is employed and the borehole remains open in the water-bearing zone below the bottom of the well casing. Once the well casing has been installed, a critically important step is the installation of some kind of **annular seal** in the space between the well casing and the side of the borehole. The two most common materials used to seal this **annular space** are cement and a swelling type of clay known as **bentonite**. This procedure is also known as **grouting**, and prevents surface runoff and other potential sources of contamination from moving down through the annulus into the water-producing zone. Ideally, a well should be grouted from just above the water-producing zone to the ground surface.

Mappable geologic formations and features are commonly given formal names based on the geographic locality where the formation or feature was first recognized or described in detail. Nearly all of the geologic formations discussed in this report extend well beyond the borders of Allen County and have previously been given names based on places outside of the county (for example, the Lagro Formation). As a consequence of this study, however, there are a number of newly recognized features, most of which are **glacial terrains** or ground-water-related map units. Because this report is oriented specifically toward Allen County and the extent of these mapped features outside of the county is unknown, they have been given informal local names (for example, Huntertown aquifer system; Arcola plain) that represent geographic locations familiar to most Allen County residents. Figure 4 is a map of Allen County that shows the political subdivisions, geographic localities, and other

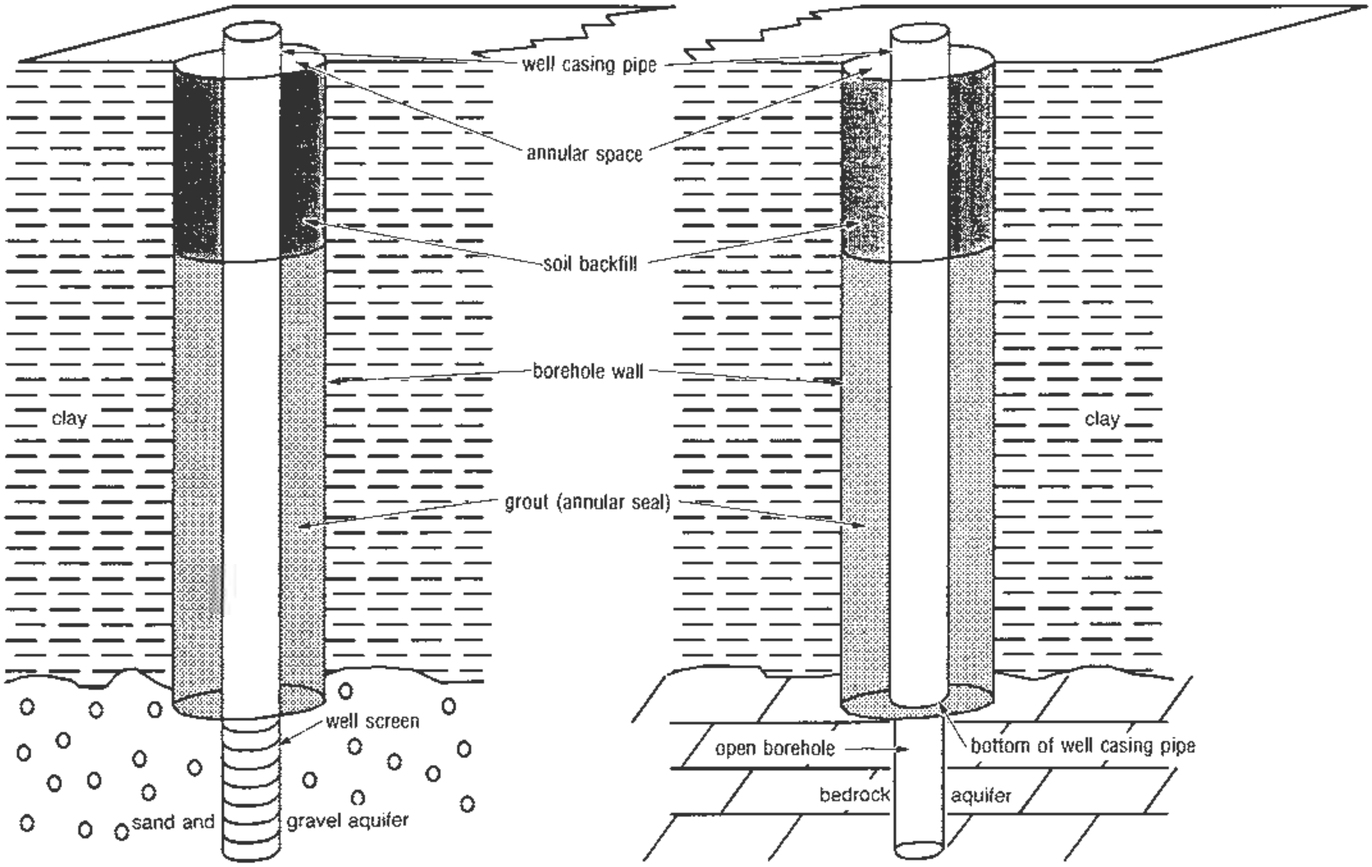


Figure 3. Schematic diagram illustrating the major components of typical wells drilled in sand and gravel (left) and bedrock (right). The diameter of the borehole and casing, and the length of the screen or open borehole depend on the particular application of the well and the water-yielding characteristics of the aquifer. In Indiana, the annular space is required to be grouted for a minimum of 25 feet above the well screen or open borehole.

features that are referred to throughout this report, either as map unit names or for purposes of general geographic reference.

METHODOLOGY

General Strategy

The geologic maps and interpretations of hydrogeological conditions presented in this report rely heavily on abundant and detailed information concerning the subsurface configuration of geological materials. Such information is not generally available from conventional geologic maps, which traditionally show only the type of material present within a few feet of the land surface and commonly are published at scales of 1:100,000 or smaller. More importantly, the particular goals and objectives of this study require a three-dimensional approach to the analysis and mapping of geologic conditions that differs considerably from the more traditional methods typically used to construct a map of near-surface geology. Specifically, interpretation of the three-dimensional geometry and characterization of the physical properties of both aquifers and confining units in the glacial deposits depends to a large degree on recognizing the nature of the depositional environments that prevailed during each of several major glacial episodes as well as on identifying the lateral and vertical relationships between sequences of sediments produced by different glacial episodes.

The basic system employed during this study to define and map the glacial deposits integrates two fundamental concepts of glacial geology:

1) that there are predictable successions of geologic materials in the subsurface, called **vertical sequences,** whose distributions and characteristics are intimately related to the particular glacial depositional environments and episodes that produced them; and

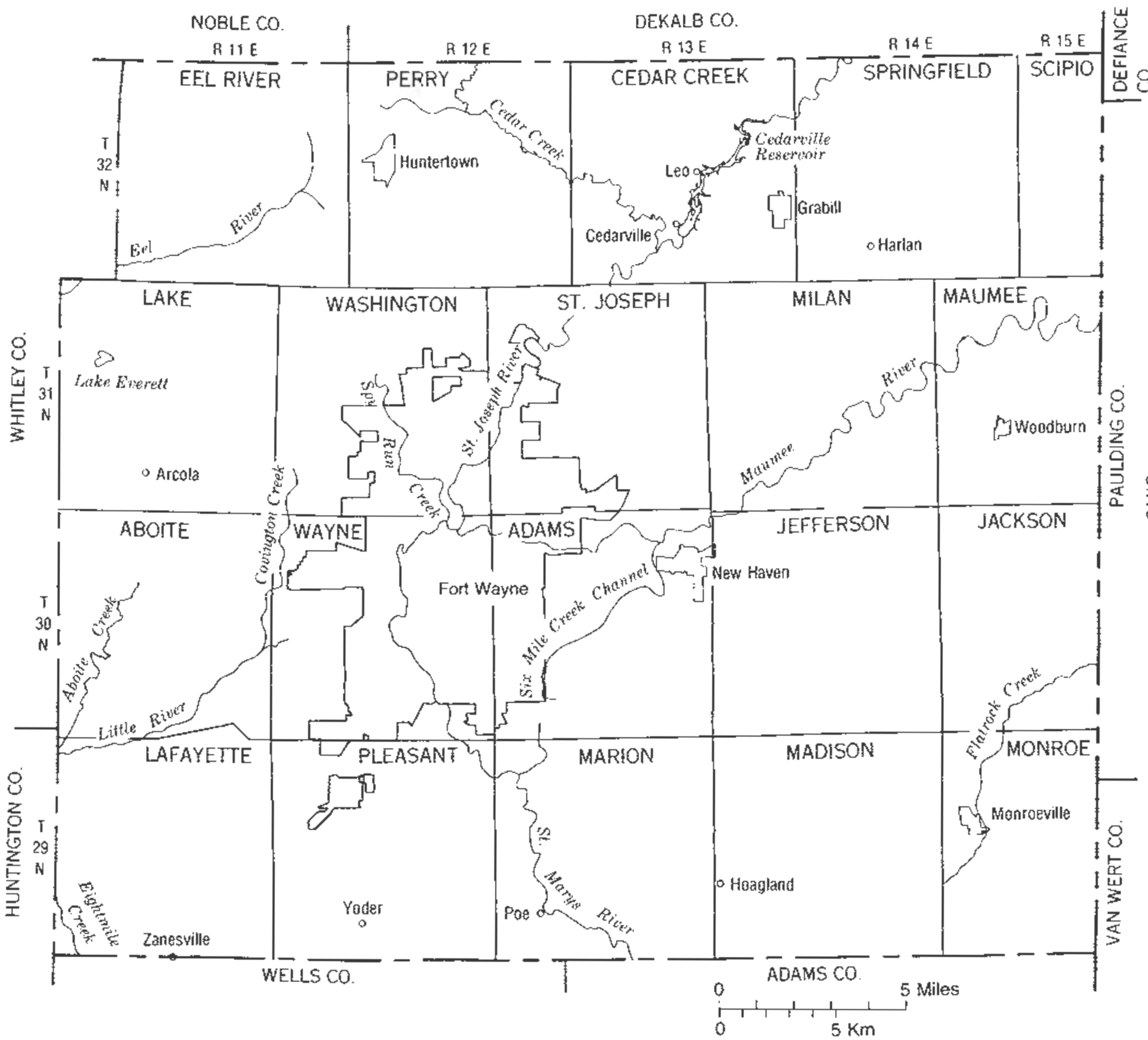


Figure 4. Map of Allen County showing political subdivisions and geographic localities referred to in the text.

2) that there is commonly a basic relationship between surface terrain characteristics (namely, landscape configuration) and the nature of the vertical sequence underlying each particular landscape.

The basic association between a vertical sequence, landscape, and the glacial episode(s) that produced them is known as a **glacial terrain**, and a map showing the geographic distribution of such associations is referred to as a **glacial terrain map**. Recognition of glacial terrains is the basis for this study, and is discussed in further detail in Chapters 2 and 4.

Data Sources and Map Compilation

Many sources of information were used during this study, including descriptions contained in published sources, unpublished data on file at various agencies, as well as data collected specifically for this study. Some of the information, such as topographic maps and the Soil Survey of Allen County (Kirschner and Zachary, 1969), is available in areal (map) format, but the great majority is represented by records of approximately 7,000 discrete boreholes of various kinds,

Table 1. Types, sources, and applications of data used in this study. Abbreviations of data sources: IGS = Indiana Geological Survey; USGS = United States Geological Survey; SCS = Soil Conservation Service, U.S. Department of Agriculture; IDNR = Indiana Department of Natural Resources, Division of Water; IDOT = Indiana Department of Transportation; ST&E = Soil Testing and Engineering, Inc., Fort Wayne.

Type of Data	Source	Application/Information
Topographic maps	USGS	Configuration of terrain; surface water; base maps
Soil survey	SCS	Soil maps and properties
Aerial photography	IGS	Landforms;surficial geology; ground-water recharge and discharge areas
Water well records	IDNR	Subsurface geology; water levels; high capacity wells
Gamma-ray logs	IGS	Subsurface geology and sequences
Sediment samples	IGS	Subsurface geology; physical characteristics
Seismic shots	IGS	Bedrock surface
Test wells	IGS	Various
Oil and gas records	IGS	Bedrock surface
Foundation and highway test borings	IDOT; ST&E	Subsurface geology; soils
Miscellaneous test borings and monitoring wells	Various	Subsurface geology; water levels; soils

such as water wells. The sources and characteristics of the principal types of information used in this study are listed in table 1, and the locations of discrete subsurface data points are shown on Plate 1.

Water well records represent the most abundant and widely distributed type of subsurface data used during this study (pl. 1). The site descriptions provided by well drillers on approximately 5,000 (83 percent) of these records were of sufficient precision to allow their exact geographic locations to be determined either by direct field observation or from detailed county plat maps. The remainder of the water well records were generally located to within a quarter section (approximately 1,000 to 2,000 feet of their true locations), but because their precise locations are not verified, they do not not appear on Plate 1. Approximately 150 additional water well records and gamma-ray logs of wells located in immediately adjacent parts of surrounding counties were also used during this study but are not shown on the plate.

The kinds of geologic materials encountered during the drilling of water wells are usually reported by drillers in a more or less generic fashion on water well records (for example, sequences of "blue clay-sand-hardpan-sand," and so on). These descriptions may be difficult to relate to specific glacial episodes or vertical sequences without some type of independent geologic framework. Therefore, to establish this framework, a cooperative program was initiated with private water well contractors to allow the Indiana Geological Survey (IGS) to collect samples of geologic formations and **gamma-ray logs** during the construction of private water wells. The samples and (or) gamma-ray logs were collected from 204 wells over a period of 18 months. The opportunity to be on-site during well construction led to other interpretive benefits, such as a first-hand knowledge of the terminology some of the individual drilling contractors employ on their water well records to describe particular geologic materials, as well as insights into ground-water conditions across the county that have resulted from their many decades of collective drilling experience. The down-hole data were supplemented by descriptions and samples taken from about two dozen small to large surface exposures of the glacial sediments.

More than 1,000 sediment samples were described and analyzed at the IGS Materials Testing Facility to determine the grain size, clay mineralogy, and other diagnostic physical properties of the different depositional sequences. The **texture** of a particular sediment is one of the most important diagnostic properties because it provides clues regarding the history of glacial deposition and because it has a direct relationship to hydrogeologic properties. Texture refers to the proportion of particles of different sizes within a sediment, and is generally measured as the percentage of gravel (>2.0 mm diameter), sand (0.049 to 2.0 mm diameter), silt (0.002 to 0.049 mm diameter), and clay (<0.002 mm diameter). Texture and other physical properties, such as the predominant types of pebbles and the presence of certain clay minerals, may be useful for determining the source of the glacier that deposited a particular sequence.

Gamma-ray logs record the amount of natural background gamma radiation emitted by different types of sediments, which in Allen County is largely a function of the amount of clay minerals and shale fragments they contain. Consequently, the different glacial units commonly have distinctive gamma-ray signatures on the log that reflect bulk differences in grain size as well as the mode of deposition. By comparing sediment samples from known depths with the gamma-ray logs, the relationship between measurable physical properties of the sediments and the gamma-ray log signatures of specific depositional sequences was determined (fig. 5; see sidebar, **Gamma-Ray Log Signatures Of Glacial Sequences**, page 9). This relationship was employed to identify and map the distribution, thickness, and other characteristics of the major glacial aquifers and confining units across the county.

The mapping procedure was initially carried out using the 20 USGS 7.5-minute (1:24,000) topographic quadrangle maps that cover Allen County (pl. 1). The locations of all discrete subsurface data points (for example, gamma-ray logs, water well records) were plotted on these maps and a network of geologic cross sections was constructed. The number of cross sections constructed per quadrangle ranges from eight to 57, and depends on the availability of subsurface data points and on the percentage of the quadrangle that lies within Allen County. To facilitate interpretation of subsurface relationships, geologic cross sections were constructed at a variety of orientations that allow major terrain features and depositional sequences to be viewed from at least two azimuthal perspectives. The goal was to include every data point on at least one cross section and to keep the spacing between adjacent cross sections as close as practical (generally about one mile or less). For the entire county, 337 cross sections were constructed, representing a total length on the land surface of 1,325 miles. Some of these are incorporated into the four, much longer cross-sections presented on Plate 10.

Specific interpretations of the glacial terrains and their hydrogeologic properties were made primarily on the basis of the down-hole gamma-ray logs and sediment samples. The gamma-ray log signatures and associated physical properties of the sediments provided a basic and consistent geologic framework that could be filled out and extended across the county using water well records and other subsurface information. It is important to note that neither the gamma-ray logs nor water well records are evenly distributed in a geographic sense (pl. 1). The average number of well records per section is about nine, but some sections contain as many as 100 records, whereas a few contain none. Similarly, gamma-ray logs were obtained on an opportunistic basis wherever new water wells were being drilled, hence their distribution underrepresents some parts of the county (in particular, areas served by public water supplies). The reliability of the mapping and interpretation varies directly with both the density and quality of these subsurface data points.

Once the hydrogeologic framework was established, a series of maps showing key geologic and hydrogeologic features (such as major aquifers, confining units, flow systems, hydrogeologic regions) was constructed for each quadrangle. These hydrogeological quadrangle maps constitute the main part of an open-file report (Fleming, 1992) available for examination at IGS and the Allen County Department of Planning Services. Plates 1 through 10 of this report were compiled at a scale of 1:63,360 (one inch to one mile) from the quadrangle maps. Due to the difference in scale, certain geologic and hydrogeologic features shown on the quadrangle maps may be presented in a somewhat more generalized format on the plates.

Statement of Limitations

The interpretations of geologic units and ground-water conditions presented in this report and on Plates 1 through 10 are not absolute and are subject to several types of error and uncertainty. One of the largest sources of uncertainty is the irregular distribution of subsurface information (pl. 1), which makes determining the continuity of certain units and the range of variation in certain sequences problematic in some places. This difficulty is mostly applicable to relatively deeply buried units that generally do not appear at the land surface, whereas the continuity of surface units can in most cases be determined from other types of information, such as landscape characteristics and aerial photography.

A different kind of problem is that the lateral and vertical boundaries between major depositional sequences are not always clear, even when high-quality data are available. Certain types of materials common to two adjacent or subjacent sequences may in places have very similar physical characteristics that make it virtually impossible to distinguish them, especially in areas where down-hole data are lacking. A good example of this problem is the map (pl. 4) showing the top of the Trafalgar Formation. This horizon is a significant ground-water flow system boundary in the northern part of the county and can be readily identified from gamma-ray logs and sediment samples because it

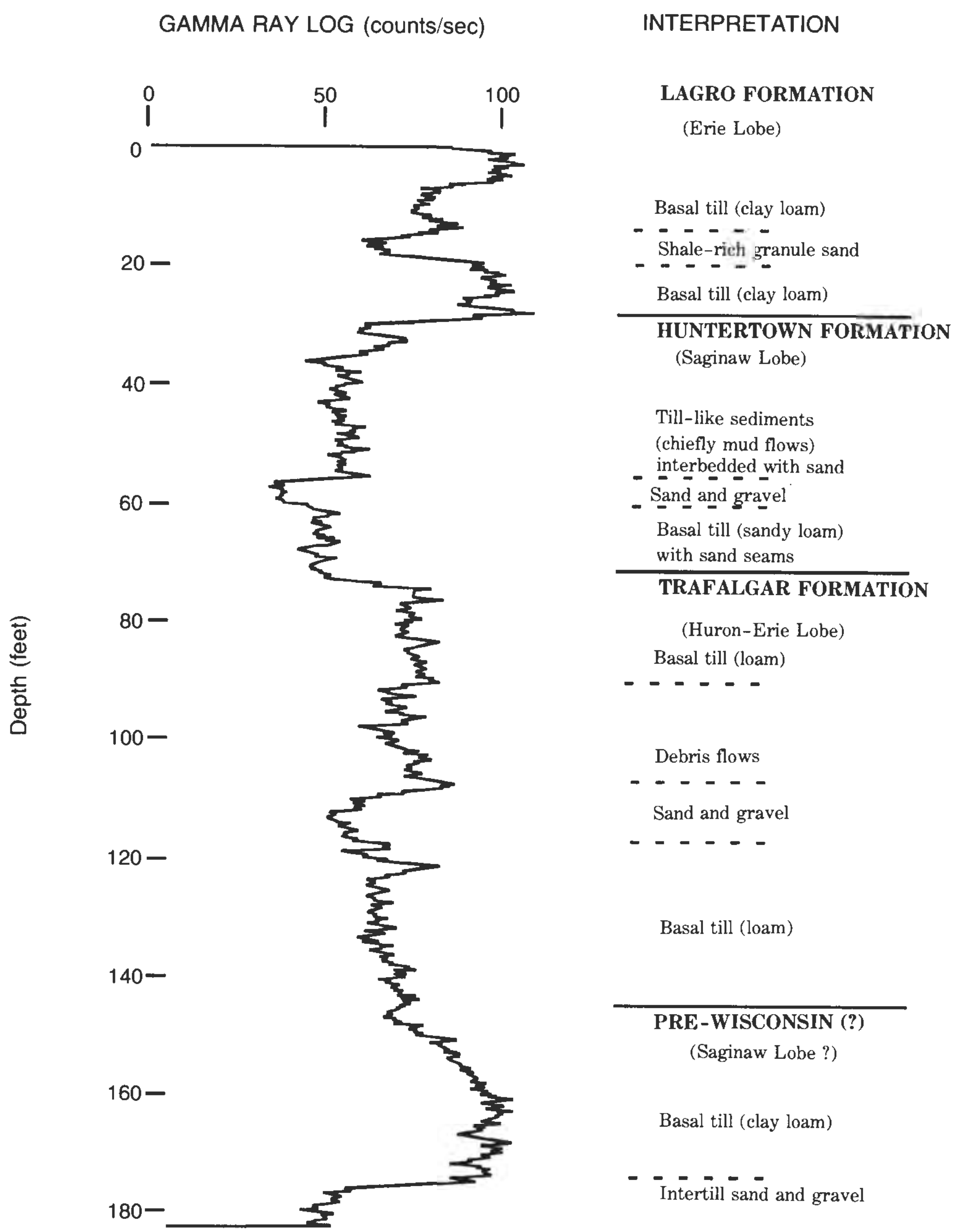


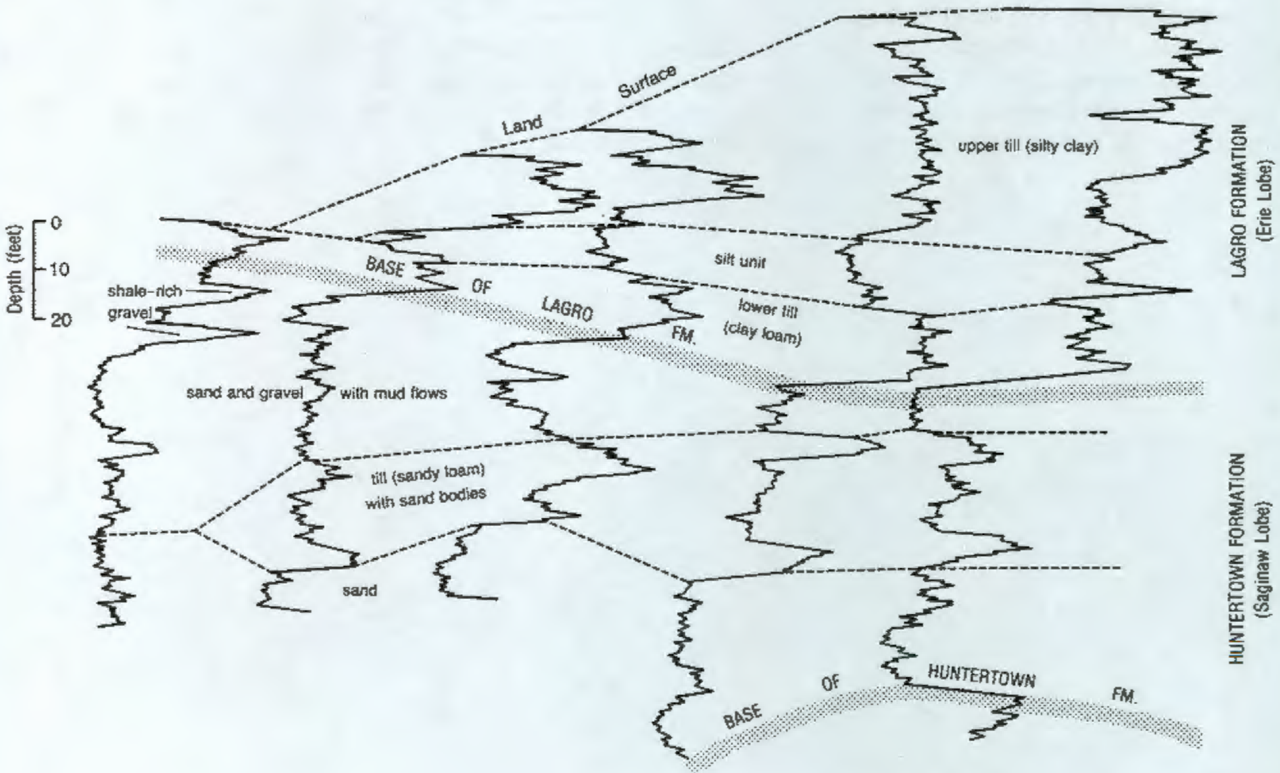
Figure 5. Gamma-ray log signatures of glacial sediments from a water well in northwestern Allen County. The sediments in this hole constitute a stack of late Wisconsin and older(?) sequences composed chiefly of glacial till and till-like sediments. Each till unit tends to produce a characteristic log response that reflects the texture of the unit and the regional mineralogy of the source area. This consistency gives rise to the distinctive till stratigraphy shown in this example, which can be traced over large areas in northern Allen County using other gamma-ray logs.

has fairly distinctive physical characteristics. Over sizable areas where such first-hand data are not available, however, this horizon can generally be distinguished only where water well drillers report the characteristically abrupt increase in hardness associated with the **overconsolidated** Trafalgar tills. On well records, this break is typically marked by the appearance of "hardpan" (as opposed to the terms "clay" or "sandy clay" that typically denote the softer overlying till units). In some places, however, parts of these overlying till units may also be relatively hard, hence the use of the term "hardpan" may not always be definitive. Likewise, the top of the Trafalgar Formation is composed of sand and gravel in

Gamma-Ray Log Signatures of Glacial Sequences

The natural, or background, gamma radiation emitted by glacial sediments is determined by the presence of rocks and minerals containing radioactive elements such as potassium-40, thorium, and uranium. In general, clay minerals contain the greatest concentrations of these elements, thus glacial sediments rich in clay or shale fragments tend to produce the highest gamma-ray count on a down-hole log. This means that fine-grained sediments such as glacial till or lacustrine mud will typically log higher than coarse-grained materials such as sand and gravel.

Many glacial sediments also exhibit a typical log pattern, or variation, that can be indicative of the type of process or environment that deposited the material. Sediments that are characteristically uniform in their physical properties, such as glacial till, tend to produce a correspondingly uniform pattern on a gamma log. In contrast, sediment assemblages characterized by much variation in grain size or that are composed of closely interleaved materials of different grain sizes typically exhibit less uniform gamma-ray log patterns. These relationships can be used to identify and trace different sediment assemblages, as well as individual till units, over significant distances in the subsurface. They may also help to clarify the particular assemblages being referred to by such descriptions as "hardpan" and "soft waxy clay" that commonly appear on water well records.



some places. Unless down-hole samples are available, it is usually not possible to distinguish sand and gravel of the Trafalgar Formation from sand and gravel associated with the overlying Huntertown or Lagro Formations. Consequently, the placement of the top of the Trafalgar Formation as shown on Plate 4 is somewhat subjective in certain areas.

Third, the distributions and geologic histories of the different geologic materials and sequences presented in this report, and their arrangement into specific hydrogeologic regions, are in large part based on the author's interpretations. Obviously, it is not possible to directly observe the actual depositional environments nor the large-scale subsurface arrangement of the glacial sequences. Consequently, interpretations of the ancient glacial deposits below Allen County are based on a comparison with modern analogues that are believed to be representative of the types of conditions that prevailed in northeastern Indiana during the Ice Age. Similarly, data that pertain to the specific hydrogeologic properties of the geologic materials in Allen County are not as plentiful or as detailed as might be desired. Thus, the hydrogeologic properties of many of the geologic materials in Allen County must be inferred from studies conducted on similar materials and geologic sequences in other regions. In summary, there is every reason to believe that the interpretations presented herein are largely accurate, but the possibility always exists that conditions in some places or in some geologic units may differ significantly from those postulated.

A final type of error can arise from the misuse of the information presented in this report. Specifically, the use of plates 1 through 10 at any scale larger than the published scale of one inch to one mile could lead to serious difficulties. The geologic and hydrogeologic information depicted in the plates is intended to illustrate the range of conditions at a regional, or county-wide scale. Such information is not a substitute for detailed site-specific studies, because geologic conditions at such a local scale may differ considerably from those shown on the plates for all of the reasons noted earlier in this section. The information presented in this report, however, is appropriate for showing the *different ranges of conditions* that might be expected between several different sites (namely, the regional hydrogeologic settings of those sites), which may be highly useful for comparative, or screening, purposes. Similarly, by providing a regional perspective for a particular site, this report illustrates the range of conditions that might occur at that site. Such knowledge may highlight the need to acquire additional site-specific information and may be useful in the development of drilling projects or other types of investigations.

CHAPTER 2

GEOLOGIC FRAMEWORK

by Anthony H. Fleming

GENERAL SETTING

The geology of Allen County has been described in a number of publications dating back more than 100 years. The earliest comprehensive treatments of the regional glacial geology were provided by Dryer (1894; 1889) and Leverett and Taylor (1915). These pioneering efforts established the basic geologic framework of the area and represent remarkably perceptive and accurate accounts given the limited amount of detailed stratigraphic information available at that time. Several more recent studies directly or indirectly related to various aspects of Allen County geology include Ault and others (1973), Bleuer (1974), Wayne (1963; 1968), Foley and others (1973), Gooding (1973), Zumberge (1960), and Bleuer and Moore (1972; 1974; 1978). The latter established the general glacial stratigraphic framework of the county and identified a number of key characteristics of the glacial deposits. The surficial geology and bedrock geology of Allen County were mapped at a scale of 1:250,000 by Burger and others (1971) and Johnson and Keller (1972), respectively.

The diverse array of landforms present in Allen County is primarily the result of processes and events that occurred during and immediately following the most recent period of glaciation. The bedrock present at depth below Allen County does not figure prominently in the modern landscape, insofar as it is buried by glacial deposits that are known to range from about 30 feet to more than 300 feet thick (pl. 3). However, the regional configuration of the bedrock surface did exert some influence on the dynamics of the ice sheets, and thus indirectly affected the characteristics of some of the deposits.

In general, glacial deposits are thickest in the northern part of the county, which is considerably more rugged and topographically varied than the southern part, a difference that reflects regional-scale differences in conditions during the most recent ice advances. The modern drainage pattern largely reflects the system of meltwater drainage that developed at the end of the last ice advance. Virtually all of the rivers, streams, and large wetland areas in the county occupy former meltwater channels, ice-block depressions, and outlets of glacial lakes.

On a regional basis, the county can be thought of as the boundary between three contrasting physiographic regions (fig. 6). Much of the northern part of the county is typified by belts of hummocky, morainic topography punctuated by numerous irregular lowlands that locally contain extensive peat bogs, small lakes, and other types of wetlands. This area is part of a much broader region of similar aspect in northeastern Indiana that has been referred to as the Steuben Morainal Lakes Area (Malott, 1922; Schneider, 1966). In comparison, the topography over much of the southern part of the county is more subdued and is closely allied in origin and appearance with the Tipton Till Plain (Malott, 1922; Schneider, 1966), the physiographic region that makes up most of central Indiana. The principal topographic relief in this part of the county is provided by the southern limbs of the Wabash and Fort Wayne Moraines (fig. 6) and by valleys of small- to medium-sized streams incised into the otherwise flat or gently rolling plain. In contrast to either of these areas, the eastern part of Allen County contains a flat, nearly featureless plain that is cut by the small valley of the Maumee River. This region, which also extends over much of northwestern Ohio, represents the former bottom of ancestral Lake Erie and historically has been termed the Maumee Lacustrine Plain (Malott, 1922; Schneider, 1966).

Although these three regions are convenient for comparing the general physiographic setting of Allen County to settings in other parts of the state, a more local perspective is required for purposes of the present study. At such a scale, Allen County can be subdivided into a variety of smaller regions, each of which contains a relatively distinctive association of one or more types of landforms that differ from landforms in surrounding regions in terms of size, shape, composition, and origin. In most cases, the sediments that underlie each of these landform regions are composed of one or two typical assemblages of glacial deposits, here termed **vertical sequences**. Such sequences are indicative of specific modes, or styles, of glacial deposition, as are the landforms above. Each of these associations of landforms and their underlying sequence(s) of sediments have experienced a common geologic history and are referred to as **glacial terrains** throughout this report. These terrains, discussed in more detail later in this chapter, represent the intimate relationship in the glacial and near-glacial environment between process (geologic history), material (vertical sequence), and form (landscape configuration). The particular characteristics of each terrain greatly affect the occurrence of ground water, the nature of surface drainage, and a variety of other hydrologic and environmental qualities. Consequently, glacial terrains form the basis for most of the subsequent discussion and interpretation of the geologic history and ground-water conditions in Allen County.

BEDROCK GEOLOGY

Bedrock of Silurian and Devonian age (see sidebar, **Geologic Time and the History of Bedrock and Glacial Deposition**, page 15) is present at depth below the glacial deposits throughout Allen County (pl. 2). Because there are no natural bedrock outcrops in Allen County, knowledge of bedrock characteristics is gained chiefly from cuttings, drill cores, and geophysical logs taken from wells and test holes, and from exposures in several local quarries. The principal bedrock types represented in Allen County include:

1) limestone, composed of calcium carbonate;
2) dolomite, composed of calcium-magnesium carbonate; and
3) shale, composed chiefly of clay and some silt.

For simplicity, the limestone and dolomite bedrock are collectively referred to as "limestone" or "carbonate" bedrock throughout this report.

Four rock units can be mapped in Allen County (pl. 2). From youngest to oldest these are:

1) the Antrim Shale (late Devonian), composed mostly of dark brown to black shale. The base of the formation commonly consists of black or dark grey limestone interbedded with calcareous grey shale, especially in western Allen County where this lower unit reaches thicknesses of up to 35 feet. The Antrim forms the bedrock surface over much of northern and central Allen County, and attains a maximum known thickness of about 90 feet near the Dekalb County Line;
2) the Traverse Formation (middle Devonian), composed chiefly of thinly bedded grey limestone and much lesser dolomite and shale. The Traverse Formation reaches a maximum thickness of about 75 feet in northern Allen County;
3) the Detroit River Formation (early to middle Devonian), composed of interbedded limestone and dolomite that locally contain abundant evaporite minerals such as gypsum and anhydrite (calcium sulfate). The base of the formation is commonly marked by a greenish sandy shale. The thickness of the Detroit River ranges from less than 35 feet in southern Allen County to as much as 70 feet to the north. The Detroit River and Traverse Formations collectively form the bedrock surface over much of eastern and western Allen County;
4) the Salina Group (Silurian), a complex assemblage of massive light grey or tan dolomite, lesser limestone and shale, and much lesser dolomitic siltstone deposited in or near a regionally extensive reef bank. The Silurian rocks form the bedrock surface in the southernmost part of Allen County, and have a known thickness of between 400 and 600 feet.

The bedrock formations below Allen County dip gently northward at an angle that ranges from about 10 feet per mile in the south to as much as 30 feet per mile in the northeast (pls. 2 and 10). The bedrock structure reflects the position of the county between the northern flank of the Cincinnati-Kankakee Arch and the southern edge of the Michigan Basin. The large flexure evident in the southward extent of the Antrim Shale in the central part of the county may be partly fault-controlled. Good evidence for faulting associated with this structure was found near its eastern margin in northeastern Allen County, and near its center in the northern part of the county (pl. 2). The faults may be related to the development of the Michigan Basin, or to other faults that may have a more recent movement history, such as the Bowling Green Fault of northwestern Ohio. Data are insufficient at this time, however, to determine the regional relations of these faults, or to ascertain the timing of their most recent movements. A more detailed discussion of the bedrock geology is beyond the scope of this report, and the reader is referred to Bleuer and Moore (1978), Gray, Ault, and Keller (1987), and Shaver and others (1986), and references therein for additional information.

BEDROCK SURFACE

The buried bedrock surface (pl. 2) is entirely erosional in origin, in contrast to the constructional glacial topography of the present-day landscape. The configuration of this buried surface more or less represents the land surface that existed prior to the Ice Age. The total relief on the bedrock surface (approximately 200 feet) is comparable to that of the modern land surface, but the pre-glacial landscape in Allen County would have resembled in many ways that now found in unglaciated parts of southeastern and south central Indiana. Although the buried bedrock surface cannot be directly observed and has undoubtedly undergone extensive modification by glacial erosion, a number of inferences can be drawn concerning various characteristics of the pre-glacial landscape.

Those parts of the bedrock surface underlain by limestone generally constitute a gently north-sloping dissected **karst** plain that is locally cut by narrow steep-sided valleys with 50 to 150 feet of local relief. The ability of infiltrating precipitation, which is slightly acidic, to preferentially dissolve limestone is evidenced on this buried karst surface by the presence of numerous relict **solution features** seen in quarry exposures throughout northeastern and north-central Indiana (Nowacki, 1991). These features include sinkholes, small caves, and enlarged **joints** and **bedding planes** (see sidebar, **Karst: Characteristics and Origin,** page 16). Numerous isolated hills and small depressions, similar to features common to the Mitchell Plain of south-central Indiana, were evident during the compilation of bedrock surface data for Plate 2, especially in western Allen County.

Most of the karst development probably occurred well before glaciation, although additional karst formation could have taken place in localities where the bedrock was at or

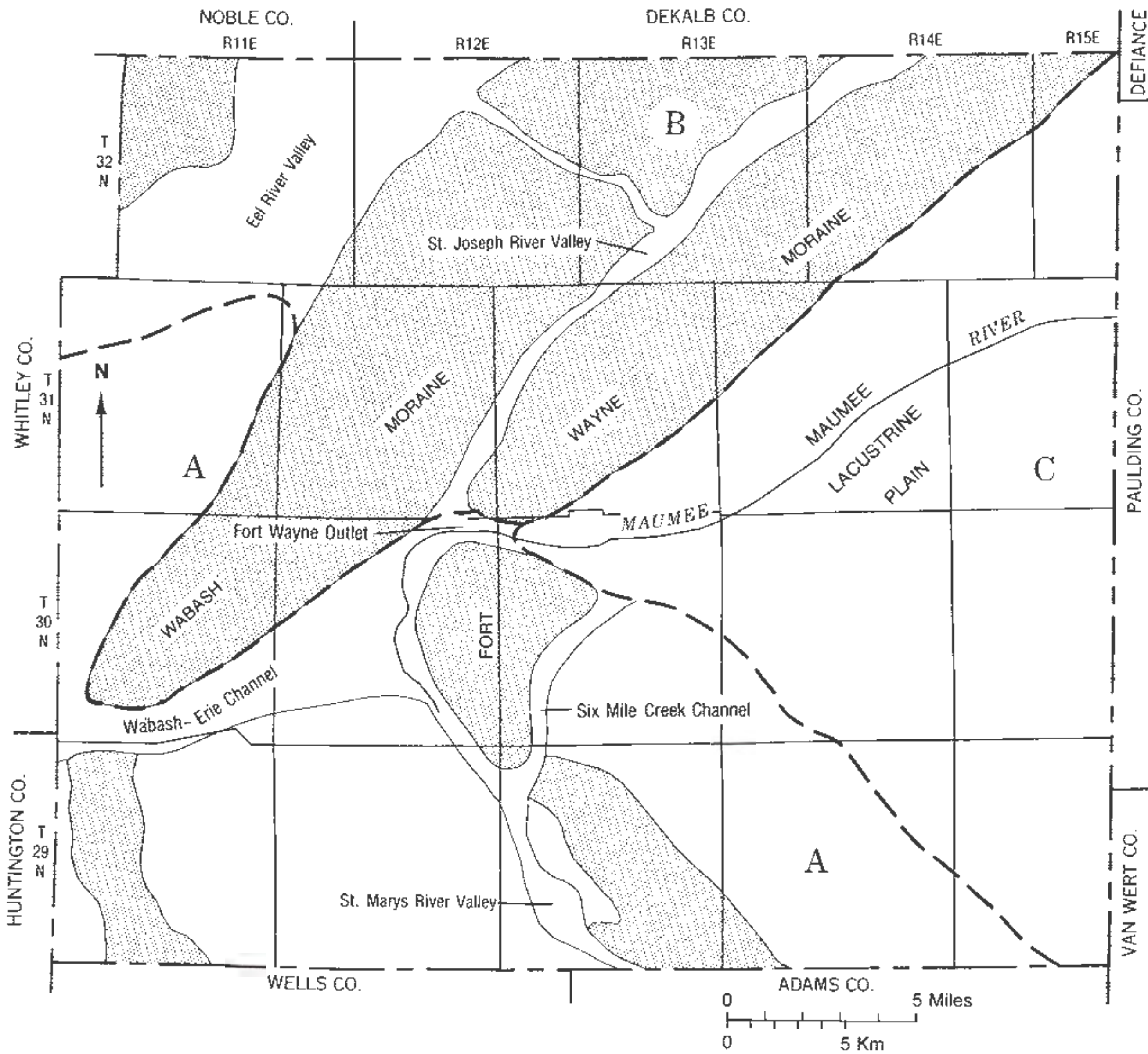


Figure 6. Map of Allen County showing selected glacial landforms and their relationship to major physiographic regions of Indiana as defined by Malott (1922) and Schneider (1966). Heavy dashed lines denote the transitional boundaries between: A = the Tipton Till Plain; B = the Steuben Morainal Lakes Area; and C = the Maumee Lacustrine Plain.

near the land surface during warm interglacial periods. Pre-glacial karst features appear to be more numerous in the western half of the county, perhaps owing to greater glacial erosion of the bedrock surface to the east along the axis of ice flow out of the Erie Basin.

In contrast, the topography of that part of the bedrock surface underlain by the Antrim Shale appears to be more subdued, forming a broad north- to northeast-sloping low-land cut by small northeast-trending valleys. The two parts of the bedrock surface are generally separated by a gentle north-facing regional slope, which marks the change from the soft, easily eroded Antrim Shale north of the escarpment to the more resistant carbonate rocks to the south.

At least one regionally significant drainage divide was present on the pre-glacial landscape of Allen County, as is the case today (pl. 2). Most of the pre-glacial drainage was northwestward to the Metea Valley (Wayne, 1956), a major southwest-oriented pre-glacial valley whose headwaters mostly appear to have lain in northwestern Allen County. The northern and eastern part of the county, however, drained north and northeastward to the Butler Valley (Wayne, 1956; Gray, 1982), whose buried course generally trends eastward toward Lake Erie across northwest Ohio. Several bedrock valleys in the extreme southern parts of Marion and Madison Townships (fig. 4) appear to drain southward, presumably joining a tributary of the Teays Valley near Decatur, in Adams County (Bruns and others, 1985; IDNR-Division of Water, unpublished data).

GLACIAL GEOLOGY

Overview

During the past one million years or so, ice sheets have repeatedly invaded northeastern Indiana, leaving behind a diverse assemblage of unconsolidated sediments over 400 feet thick in some places. The bulk of the glacial sediments in Allen County were deposited during the most recent period of glacial activity, known as the **late Wisconsin Age**[1],

[1]A few states use the term "Wisconsinan" to refer to this time period, and this was the policy of the Indiana Geological Survey from about 1970 to 1993. Before 1970, IGS had used the simpler and historically established term "Wisconsin," which is also the name preferred by the U.S. Geological Survey and the Wisconsin Geological and Natural History Survey. The term "Wisconsin" has been reinstated for formal use by the Indiana Geological Survey.

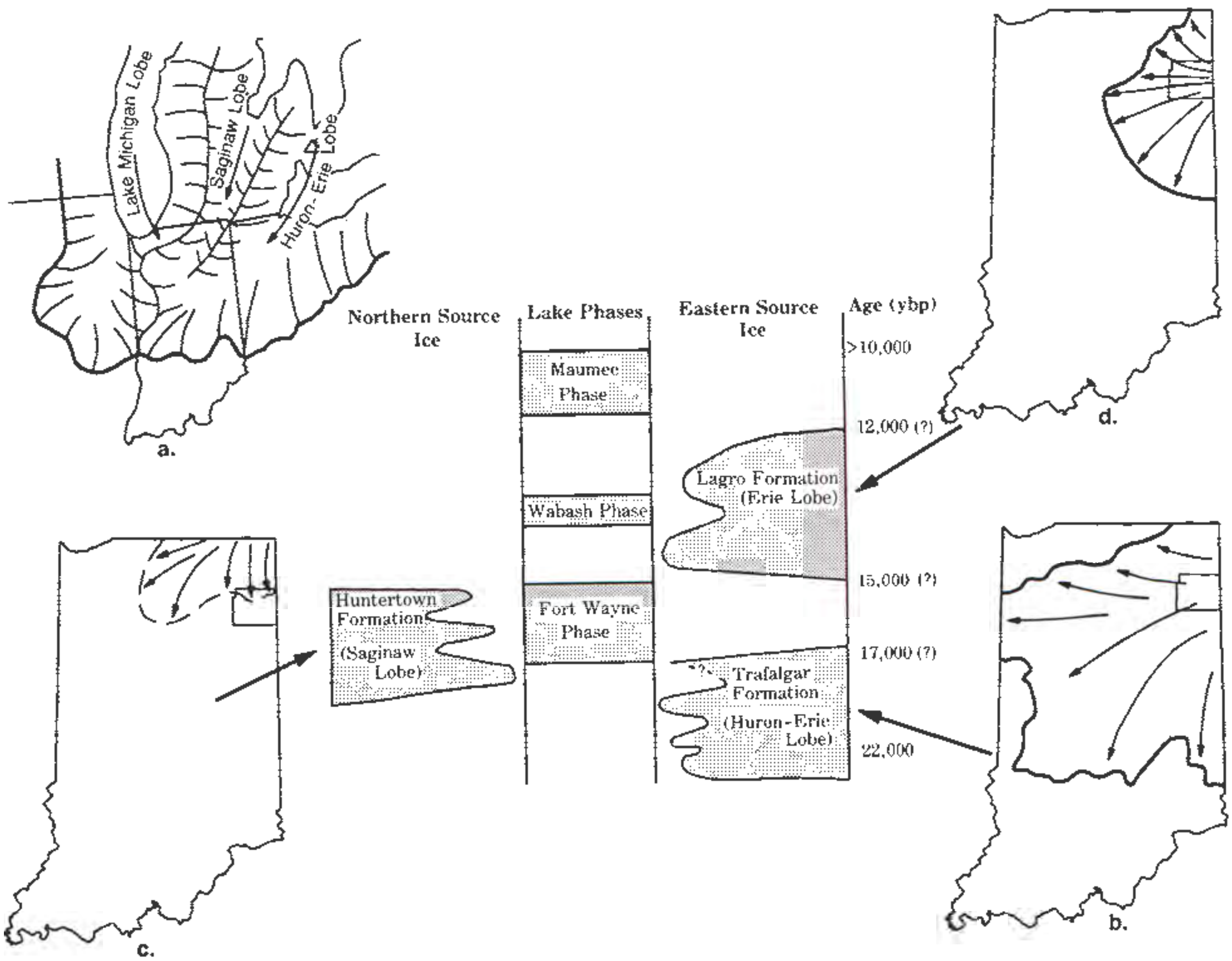


Figure 7. Generalized distributions and temporal relationships of glacial lobes in Indiana and their relationship to phases of ancestral Lake Erie in Allen County during the late Wisconsin Age. a) Relative positions of glacial lobes at their maximum advance in Indiana; b) Huron-Erie Lobe at its maximum advance; c) Saginaw Lobe advances into northern Indiana and covers northern Allen County at its maximum advance; d) maximum extent of the Erie Lobe during the last major glacial episode to affect northeastern Indiana.

Geologic Time and the History of Bedrock and Glacial Deposition

The time span represented by the geologic materials below Allen County is measured in hundreds of millions of years. The adjacent geologic column depicts the major periods of geologic time and the predominant events and rock types deposited in northeastern Indiana.

The period of time between late Precambrian and middle Paleozoic is represented by the bedrock formations below northeastern Indiana. Most of these rocks lie at great depth below the bedrock surface in Allen County, however, and are of only minor importance in human affairs. The oldest rock formations present at the bedrock surface are of Silurian age and represent a period of major reef development in a shallow sea that covered much of the upper Midwest. A period of nondeposition accompanied by localized emergence of the old sea floor followed during the early Devonian. Limestones and shales of middle and late Devonian age record the reestablishment of marine conditions and the gradual subsidence of the sea floor to form the large Michigan Basin to the north. Circulation in parts of this sea was evidently limited, and evaporation of sea water caused salts to become sufficiently concentrated in some parts of the basin to deposit halite (rock salt) and gypsum (calcium sulfate).

Rocks representing the upper part of the Paleozoic Era are present elsewhere in Indiana but not in Allen County. Rocks from all of the Mesozoic Era, as well as most of the Tertiary Era, are also absent from Allen County. This missing interval, known as an **unconformity**, represents a major gap of some 360 million years in the geologic record of which little is known, at least concerning events in northeastern Indiana. The hiatus ended when glaciers advanced into northeastern Indiana at the beginning of the Ice Age, some one million years ago.

ERAS	PERIODS	APPROX. LENGTH IN YEARS	ROCK TYPES IN NE INDIANA	
CENOZOIC	QUATERNARY (PLEISTOCENE EPOCH)	1 MILLION	*Glacial till, sand, gravel, silt, marl, clay, and peat deposited during and after continental glaciation* **0-400 ft**	
CENOZOIC	TERTIARY	65 MILLION	No deposits in northeastern Indiana	
MESOZOIC	CRETACEOUS	78 MILLION	No deposits in northeastern Indiana	
MESOZOIC	JURASSIC	64 MILLION	No deposits in northeastern Indiana	
MESOZOIC	TRIASSIC	37 MILLION	No deposits in northeastern Indiana	
PALEOZOIC	PERMIAN	41 MILLION	No deposits in northeastern Indiana	
PALEOZOIC	PENNSYLVANIAN	34 MILLION	*Shale, sandstone, mudstone, clay, coal, limestone, and conglomerate.* Not present in northeastern Indiana but extensive in nearby parts of Michigan **1,000 ft**	
PALEOZOIC	MISSISSIPPIAN	40 MILLION	*Shale, mudstone, sandstone, limestone, and gypsum.* Extensive deposits in northeastern Indiana, north and west of Allen Co **1,000-1,500 ft**	
PALEOZOIC	DEVONIAN	48 MILLION	Upper part: *carbonaceous shale* **100 ft** Lower part: *limestone, dolomite, shale, and gypsum* **70-140 ft**	
PALEOZOIC	SILURIAN	30 MILLION	*Dolomite, limestone, siltstone, and shale deposited in regionally extensive reef platform* ***(the Fort Wayne Bank)*** **400-600 ft**	
PALEOZOIC	ORDOVICIAN	70 MILLION	*Shale and limestone* *Limestone, dolomite, and sandstone*	Not present at the bedrock surface in northeastern Indiana
PALEOZOIC	CAMBRIAN	65 MILLION	*Sandstone and dolomite*	Not present at the bedrock surface in northeastern Indiana
PRECAMBRIAN ERAS		4 BILLION	*Granite, marble, gneiss, and other igneous and metamorphic rock types*	Not present at the bedrock surface in northeastern Indiana

and are less than 22,000 years old. When the continental ice sheet advanced into the Great Lakes region at the beginning of the late Wisconsin Age, ice flow developed along distinct axes, or lobes, according to the orientations of the individual Great Lake basins and their major bays (fig. 7). The principal glacial lobes and the order in which they affected Allen County during the late Wisconsin Age were the Huron-Erie Lobe, the Saginaw Bay Sublobe of the Huron Lobe (hereafter referred to simply as the "Saginaw Lobe"), and the Erie Lobe.

The geometric configuration, or **stratigraphy**, of glacial deposits indicates that Allen County experienced at least three major glacial episodes during the late Wisconsin Age, each consisting of one or more ice advances by a particular lobe (fig. 7). These episodes were closely spaced in time and began with the advance of the Huron-Erie Lobe from the northeast, followed by the advance of the Saginaw Lobe out of southern Michigan and into northern Allen County, and culminated with the readvance of the Erie Lobe from the east.

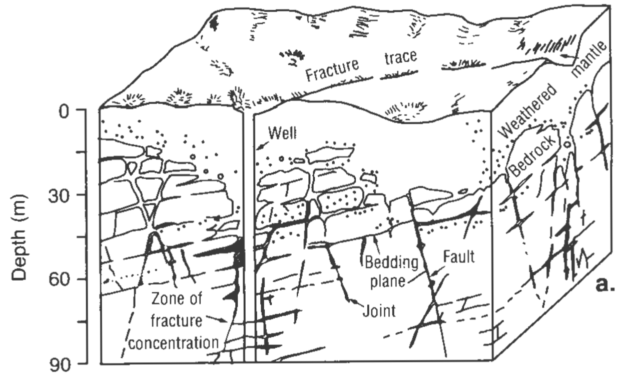
These alternating episodes of general ice advance were punctuated by and, in at least one instance, accompanied the presence of a large glacial lake in the central and eastern portions of the county. The basin formerly occupied by the lake is contiguous with a much larger basin that extends across much of northwestern Ohio to present-day Lake Erie. Hence, the glacial lakes that existed in this area at several times during the late Wisconsin appear to represent phases of ancestral Lake Erie. The latest lake phase known in Allen County formed as the Erie Lobe was making its final retreat from Indiana at the close of the late Wisconsin, and has historically been referred to as **Glacial Lake Maumee** (Dryer,

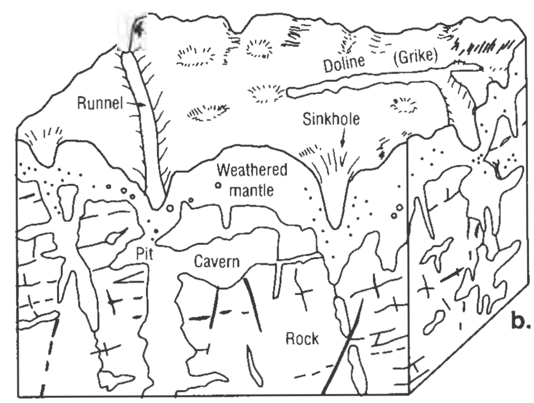
Karst: Characteristics and Origin

Karst is the geologic term used to describe the distinctive type of landscape formed on limestone that has undergone extensive cave formation. Over many thousands or millions of years, limestone (calcium carbonate), and to a lesser extent, dolomite (calcium-magnesium carbonate), will gradually dissolve in the presence of ground water. Ground water is derived mainly from precipitation. The precipitation incorporates carbon dioxide from the atmosphere as it falls, as well as from the soil as it percolates downward. When dissolved in water, the carbon dioxide forms carbonic acid, a weak acid. The mildly acidic ground water then attacks the limestone along preexisting openings such as bedding planes and fractures (fig. a).

Many types of **solution features** result from this process, some of them subtle and others of spectacular dimensions (fig. b). The most common result is the enlargement of bedding planes and joints, a process that further increases the flow of ground water through the rock. Over time, further dissolution of the limestone along the walls of these openings can greatly enlarge their size, leading to a system of large voids within formerly solid limestone. Extensive interconnection of such voids creates caves and caverns. When the roof of a void collapses, it may undermine the land surface above, forming a funnel-shaped depression called a sinkhole. Mature karst areas such as the Mitchell Plain of south-central Indiana can have hundreds of sinkholes in a single square mile and extensive systems of caves at depth.

Karst limestone represents one of the rare geologic situations when ground water can actually flow in underground rivers, some of which may be of spectacular size. In typical karst terrains, however, most of the ground water movement is through well-interconnected networks of smaller, pipe-like solution features, which tend to be more numerous and widely distributed than large caverns. Thus, ground water flow in karst terrains is predominantly along discrete conduits, and can be quite rapid. Because of this characteristic, the most productive wells in karst terrains are typically developed along zones of concentrated fractures or solution features, or at the intersections of two or more fractures.





1889; Leverett and Taylor, 1915) and its basin as the **Maumee Lacustrine Plain** (Malott, 1922). Several phases of ancestral Lake Erie figured prominently in the history of glacial deposition in Allen County and in the resulting arrangement of vertical sequences. To avoid potential conflicts and confusion with existing terminology, the three main episodes, or phases, of glacial lakes that are known or are inferred to have existed in Allen County during and after the late Wisconsin glaciation are referred to in this report as the Fort Wayne, Wabash, and Maumee phases of ancestral Lake Erie, respectively (fig. 7).

Characteristics of Late Wisconsin Sediments

Each of the three major periods of ice advance left behind a distinctive assemblage of sediments, referred to here as the **Trafalgar Formation, Huntertown Formation,** and **Lagro Formation**, respectively (fig. 7, table 2). The sediments contained within each of the three formations typically are characterized by diagnostic textural attributes and depositional styles that reflect environmental conditions specific to the glacial episode that produced them. Consequently, each formation is a distinct stratigraphic entity that can, in most

Table 2. General characteristics of glacial sequences in Allen County.

Unit	Predominant Sediments	Where Deposited
Post-glacial sediments	Dune sand	On or near sand sources (for example, outwash).
	Peat and muck	Wetlands in depressions and meltwater channels.
	Alluvium	Floodplains along streams and rivers.
	Palustrine sediments	Wetlands, chiefly in Wabash-Erie Channel.
	Lacustrine sand and gravel	Beaches, bars, and spits of ancestral Lake Erie.
	Lacustrine silt and clay	Deeper water of ancestral Lake Erie.
Lagro Formation (Erie Lobe)	Outwash sand and gravel	In and near St. Marys, St. Joseph, and Eel River Valleys; locally in smaller streams; also in aprons in front of advancing ice (forms part of intersequence unit).
	Lacustrine silt and clay	Small ponds on, below, or in front of ice margin.
	Ice-contact stratified sand and gravel	Subglacial meltwater channels.
	Glacial till, clay loam to silty-clay	Below ice near ice margin; the principal surface till throughout Allen County.
Huntertown Formation (Saginaw Lobe)	Lacustrine sand	Deltas along north edge of ancestral Lake Erie (Fort Wayne Phase).
	Lacustrine silt, clay, and sand	Ancestral Lake Erie.
	Ice-contact stratified sand, gravel, and mudflows	Fans and channels in, on, and against disintegrating ice in northern Allen County.
	Glacial till, loam to sandy loam	Below ice near ice margin.
	Outwash sand	Aprons and channels in front of advancing ice.
Trafalgar Formation (Huron-Erie Lobe)	Outwash sand and gravel	Aprons and channels in front of advancing ice; fans and sub-glacial channels; aprons and channels in end moraines (forms part of intersequence unit).
	Ice-contact stratified sand, gravel, and mudflows	Fans and channels in, on, or against ice; in buried morainal complex in western Allen County.
	Glacial till, loam, severely overconsolidated	Below ice near ice margin.
Unnamed sediments of probable pre-Wisconsin age (chiefly in northern Allen County) (Saginaw and Huron-Erie Lobes)	Sand and gravel	Buried bedrock valleys; aprons and channels.
	Glacial till, loam and clay loam	Below ice near ice margin.
	Lacustrine silt and clay	Buried bedrock valleys.

cases, be readily identified and traced regionally in the subsurface on the basis of diagnostic physical properties, downhole geophysical logging characteristics, and stratigraphic relationships to other formations.

Several types of sediments are prominent components of one or more of the above-named formations and are also present over significant segments of the land surface. The physical characteristics and architecture of these differing sediment types provide direct clues to the types of depositional environments that existed in Allen County at different times during the late Wisconsin Age, and they also strongly influence the occurrence, movement, and sensitivity to contamination of ground water.

Outwash generally consists of sand and(or) gravel deposited by meltwater in front of an ice margin, and forms bodies ranging from narrow channels to broad, regionally extensive fans and aprons. Outwash deposited during the initial advance of each glacial lobe commonly occurs at the base of each of the three formations and is referred to throughout this report as **basal outwash**. Outwash also occurs abundantly in some of the major river valleys, which originated as **sluiceways** that drained significant ice margins. Sand and gravel also occurs as **ice-contact stratified deposits**, which represent deposition by meltwater in, on, or against glacier ice. Sand and gravel bodies of this type commonly have highly irregular shapes and sizes and may be chaotically interstratified with a variety of other deposits.

Glacial **till** is a compact, poorly sorted material deposited directly by glacial ice with little or no reworking by meltwater or mass movement. Till typically contains particles ranging in size from clay to large boulders. The relative proportions of these different particle-size classes within a particular till unit is a function of the **source area** of the ice as well as the predominant mode of till deposition. Each of the three late Wisconsin formations contains a distinctive, regionally extensive till sheet whose texture reflects the particular source area of the glacial lobe that deposited it. For example, till of the Huntertown Formation typically has a sandy loam texture, reflecting the abundant outwash the Saginaw Lobe incorporated as it advanced into Allen County, whereas till of the Lagro Formation is commonly a clay loam, reflecting incorporation of fine-grained lake mud as the Erie Lobe advanced through the bed of ancestral Lake Erie. The textural names (for example, clay loam, sandy loam) used in this report to describe the glacial tills and other unconsolidated sediments are those defined and employed for many years by the Soil Conservation Service (1975; Kirschner and Zachary, 1969).

Many recently deglaciated landscapes are typified by extreme instability due to a combination of steep slopes, oversaturated sediments that have recently thawed, and the loss of support caused by the ongoing melting of buried ice blocks. Consequently, mass movement deposits are common in the glacial environment and a variety of names have been applied to them. Among the more common of these names are **mudflows**, which generally refer to mass movement of relatively fine-grained sediments such as till, and **debris flows**, which may be of any composition. Mass movement deposits formed in the glacial environment may be derived from materials of almost any composition, including sand and gravel. Because they typically form during the general retreat or melting of an ice sheet, mass movement deposits are frequently associated with ice-contact stratified deposits. Many mass movement deposits are massive and unsorted in appearance, much like glacial till, and are difficult to recognize in both modern and Ice Age deposits. Thus, the term **till-like sediment** is frequently applied in situations where the distinction between true glacial till and mass movement deposits is unclear.

Lacustrine (lake) sediments of several ages are also widespread in Allen County. These include abundant fine to medium sand, deposited in **deltas** where meltwater drained into ancestral Lake Erie; sand and gravel deposited by waves along beaches; lake mud (silt, clay, and lesser sand) deposited in relatively quiet water in deeper parts of lake basins; and various mass-movement deposits generated by melting ice blocks and icebergs.

The late Wisconsin formations typically constitute the entire sequence of glacial deposits in the southern half of Allen County and the upper 100 to 200 feet in the north. Consequently, they are of great significance to the groundwater resource as well as to other environmental resources and engineering concerns in the county. Because of their importance, the depositional histories, geological characteristics, and relationship to glacial terrain regions of the late Wisconsin sediments are the principal focus of the following discussion. Relatively little is known of the sequences of pre-Wisconsin deposits in northern Allen County, consequently they are discussed only briefly.

Pre-Wisconsin Glacial Deposits

Deposits of probable pre-Wisconsin age are locally significant constituents in the subsurface of northern Allen County, but are generally of limited extent elsewhere. These older deposits are arbitrarily defined as all unconsolidated sediments below the apparent base of the Trafalgar Formation. They appear to form a northward-thickening, wedge-shaped mass as much as 150 feet thick in the northern third of the county, and include two or more tills, sand and gravel, and some lacustrine mud.

In northeastern Allen County, units presumed to be of pre-Wisconsin age include a thick section of grey, loam-textured tills of eastern source that closely resemble the tills of the Trafalgar Formation, whereas in northwestern Allen County, they contain pinkish-brown, clay loam- to loam-textured till deposited by an earlier advance of the Saginaw

Vestiges of Ancestral Lake Erie

The Great Lakes evolved as a consequence of continental glaciation. They were formed primarily by the overdeepening and widening of preexisting bedrock valleys along zones of poorly resistant bedrock by large ice masses, called glacial lobes. The Great Lakes did not assume their present configuration until after the late Wisconsin Age, but large glacial lakes of a variety of shapes and sizes were present in the region at various times during the late Wisconsin Age, and perhaps earlier. The region that includes northwestern Ohio and Allen County, Indiana was the location of a drainage divide prior to the Ice Age (pl. 2) but ultimately became a natural basin for large lakes to form in once glacial conditions were established. The deposition of thick sequences of glacial deposits, many of pre-Wisconsin age, created a sharp rise in the land surface to the north and west of the basin, whereas a similar effect was created by the rise in the bedrock surface to the south. Drainage to the east and northeast would likely have been blocked by ice flowing out of the Huron-Erie lowland, hence it seems possible that glacial lakes could have been present in this region at any number of times.

The first clear evidence in the geologic record of a *large* glacial lake in this region is associated with the now buried upper surface of the Trafalgar Formation (pl. 4). Moraines on that surface prevented drainage from occurring to the west and south, and the retreating Huron-Erie ice front blocked eastward drainage. The Saginaw Lobe, advancing into the basin from the highlands to the north, shed abundant meltwater and sediment into the basin. In fact, sequences of lake sediments up to 60 feet thick and derived from a variety of sources are well preserved in parts of this basin, despite their partial erosion and subsequent burial during the readvance of the Erie Lobe later during the Wisconsin age. Evidence from northwestern Ohio and elsewhere in the Lake Erie Basin similarly suggests the presence of one or more extensive glacial lakes during this interval (Leverett and Taylor, 1915; Forsyth, 1965; 1973; and personal communication). This period of lake formation, termed the Fort Wayne phase in this report, is one of at least three distinct forerunners of modern Lake Erie identified in Allen County.

Lobe. Due to the scarcity of deep data points in the northern part of the county, stratigraphic relationships between these older deposits remain enigmatic, and they are not discussed in detail.

Trafalgar Formation

The Trafalgar Formation (Wayne, 1963; Bleuer and Moore, 1974; 1978;) is a regionally extensive sequence composed of loam-textured till, sand and gravel, silt, and mud flows. The unit forms the land surface in most of central Indiana (Gray, 1989) and represents the most extensive advances of late Wisconsin ice into Indiana from the basins of Lakes Huron and Erie. In northeastern Indiana, the Trafalgar is largely buried by younger glacial deposits, obscuring some of the details of its depositional history and internal architecture. However, the Trafalgar Formation is significant to both engineering and ground-water concerns, and the configuration of its now-buried upper surface (pl. 4) exerted considerable influence over the style of deposition during later advances of the Saginaw and Erie lobes.

In many places in Allen County, the bulk of the Trafalgar Formation is composed chiefly of dark grey severely **overconsolidated** loam till (table 3) and till-like sediment that contains small lenses and pods of sand and silt, particularly toward the top of the formation. Much of the till exhibits a weak horizontal **fabric**, or alignment of grains, and is interlayered with very thin seams of sand a few grains thick. Due to the extreme hardness of the till, the top of the Trafalgar Formation is usually a well-defined horizon. It is usually reported as "hardpan" by water well drillers and can be difficult to excavate or auger, even with large equipment. During the installation of monitoring wells by IGS in southern Allen County, as many as 200 **blow counts** were required to drive a sampling device through less than one foot of this till, and in at least one local quarry, the till must be blasted to expose the underlying bedrock.

Sand and gravel bodies of various dimensions are common in many places within the Trafalgar Formation and appear to represent several kinds of depositional environments. The most extensive bodies were deposited as outwash in front of the advancing Huron-Erie Lobe, and now form the base of the formation in many parts of the county. The largest of these are shown as unit Tb on Plate 6. Mappable bodies of basal outwash are locally more than 30 feet thick and some cover more than 50 square miles.

Large linear southwest-trending **channels** that cut through part or all of the formation are also prominent constituents in some places (pl. 4). The channels are mostly filled with sand, although sand and gravel, and more rarely, cobble- and boulder-bearing gravel are locally present. The largest of these channels is over a mile wide, nearly 15 miles long, and locally contains sand and gravel over 75 feet thick. The apparent tops of many channels coincide with the buried surface of the Trafalgar Formation, and their bases commonly rest on the bedrock.

Some of the channels occur as localized features throughout the southern half of the county, but the large majority are clearly concentrated along an arcuate, northwest-to-southeast-trending belt that crosses the southwestern and west-central sections of the county. Along this belt, the top of the Trafalgar Formation rises sharply and forms a well-defined series of ridges that are suggestive of a buried morainic system (Bleuer, 1974) (pl. 4). The consistent southwest orientation of the channels across this belt, together with their coarse, locally boulder-bearing characteristics, suggest that they initially formed in **tunnel valleys** and(or) large **crevasses** that drained meltwater from the ice at the time the morainic system was being formed.

Numerous sand and gravel bodies of various sizes and origins occur near and along the top of the Trafalgar Formation. Small- to medium-sized lenses and sheets of dense sand are quite common within the uppermost part of the formation. Most of these probably formed in small channels and ponds during the disintegration of the ice sheet. In rare instances, these form mappable bodies along vague but persistent horizons within the uppermost 10 to 20 feet of the formation (unit Tx, pl. 6).

In the southern and western sections of the county, sand and gravel commonly occurs along the well-defined stratigraphic horizon between the top of the Trafalgar Formation and base of the overlying Lagro Formation (pls. 4 and 6). Some bodies appear to be physically within and, therefore, part of the Trafalgar Formation. In contrast, the geometry of other bodies suggests that they formed as outwash deposited on top of the Trafalgar Formation during the subsequent advance of the Erie Lobe and are, therefore, part of the Lagro Formation. Both types of bodies may be present together, as in western Allen County. Because of its apparent mixed origin, the sand and gravel along this horizon was designated as the **intersequence unit** by Bleuer and Moore (1972; 1978) and that name is used elsewhere in this report and on Plate 6.

The most extensive bodies of intersequence sand and gravel are in the southwestern and west-central parts of the county, where their distribution appears to be closely related to the buried morainic complex noted earlier (pl. 4). In that area, the intersequence unit is composed of a complex of small- to medium-sized outwash aprons and channels that typically range in thickness from a few feet to 30 or 40 feet. In some places, however, the intersequence unit coalesces with channels and other large sand and gravel bodies in the underlying Trafalgar Formation, resulting in composite sand and gravel units 50 to 100 feet thick that locally bottom out on the limestone bedrock.

It is not known whether the series of ridges evident on the buried Trafalgar surface in southwestern Allen County formed as a **recessional moraine** during a significant stand of the Huron-Erie ice-front, or at the terminus of a minor readvance, but the interpretation of these features as some type of morainic complex appears warranted. As the front of the glacier retreated eastward from this position, meltwater became impounded between the moraine and the ice front, initiating the first of three regionally extensive phases of ancestral Lake Erie (see sidebar, **Vestiges of Ancestral Lake Erie**, page 19). This earliest lake is here termed the Fort Wayne phase (fig. 7) because lake sediments deposited within its basin appear to be particularly thick and extensive in and near the city of that name. The presence of the Fort Wayne phase had both a direct and indirect influence on glacial deposition in the central and eastern sections of the county during the entire period leading up to the readvance of the Erie Lobe and deposition of the Lagro Formation. The story of the Fort Wayne phase is closely intertwined with the histories of the Huntertown and Lagro Formations and is, therefore, included in the corresponding sections.

Huntertown Formation

The Huntertown Formation (here named) is a complicated assemblage of outwash sand, sandy loam- to loam-textured till, ice-contact stratified deposits, and glaciolacustrine sediments deposited by the Saginaw Lobe and its meltwaters in northern Allen County and adjacent counties to the north. These sediments had previously been considered as an "unnamed member" of the Lagro Formation (Wayne, 1963; Bleuer and Moore, 1974; 1978) which, based on current applications of stratigraphic terminology to Pleistocene materials, might imply that they were deposited by the Erie Lobe. This sequence is worthy of formational rank for several reasons:

1) it constitutes a mappable unit;
2) it can be clearly demonstrated to have been deposited by the Saginaw Lobe;
3) the overall sandy character and generally chaotic internal stratigraphy of the sequence is markedly at odds with the decidedly clayey and uniform qualities of the Lagro Formation, as defined here;
4) the sequence is clearly older than and lies unconformably below the clayey sediments of the Lagro, and are younger than and lie unconformably atop the loamy sediments of the Trafalgar Formation; and
5) its presence throughout northeastern Indiana, either at the land surface or within the near-subsurface, is closely associated with and appears largely responsible for the distinctive hummocky surface topography that characterizes this entire region of the state.

Table 3. Physical attributes of late Wisconsin till units in Allen County.

Formation	Grain-size Range Percent			Characteristic Color[1]	Consistency	Thickness Range (ft)	Hydraulic Conductivity[2]	
	Clay	Silt	Sand				Primary[3]	Secondary[4]
Lagro	30-60	30-50	10-20	Light grey (10YR 6/1)	Medium to very stiff	0-105	0.00003 (10^{-8})	0.03-0.0003 $(10^{-5} - 10^{-7})$
Huntertown	15-20	20-35	40-60	Light brown (10YR 5/3)	Soft to very stiff	0-75	n.a.	n.a.
Trafalgar	15-20	30-45	35-50	Dark grey (10YR 4/1)	Hard to very hard	0-100+	0.0003 (10^{-7})	0.03-0.003 $(10^{-5} - 10^{-6})$

[1]Color of dry sample designated by standard Munsell names and notation.
[2]Hydraulic conductivity values are in feet per day (centimeters per second).
[3]Primary hydraulic conductivity was determined from large undisturbed samples with no visible fractures or sand seams that were tested in a flexible-membrane triaxial permeameter.
[4]Secondary hydraulic conductivity for till of the Trafalgar Formation was determined from large undisturbed samples that contained visible but small sand seams. For till of the Lagro Formation, values were determined from large undisturbed samples that contained visible oxidized fractures. Both types of samples were tested in a flexible-membrane triaxial permeameter. The secondary hydraulic conductivity values for both of these tills also reflect the results of field testing using both physical and geochemical techniques.

The Huntertown Formation is at or near the land surface in a sizable part of northwestern Allen County centered on the town for which it is named, and its buried hummocky upper surface dominates the landscape of much of northern Allen County (pl. 5). The internal stratigraphy of the formation suggests a pattern of steady, possibly rapid ice advance into north-central Allen County, followed abruptly by stagnation of the glacier. The latter event was punctuated by minor and probably localized readvances of the ice margin, during which deposition was successively localized along a series of recessional margins. The presence of the Fort Wayne phase of ancestral Lake Erie near the southern terminus of the glacier, in north-central Allen County, created a large sediment sink that captured much of the drainage from the Saginaw Lobe, and led to a predominance of glacio-lacustrine deposits in the distal portions of the formation (pl. 4).

The base of the Huntertown Formation in most places is marked by a sheet of outwash that ranges from less than 5 feet to more than 50 feet thick. The outwash is composed chiefly of medium to coarse sand and some gravel, is widely present over a large part of Eel River, Perry, northern Washington, and Cedar Creek Townships, and is sporadically present over portions of Springfield and Lake Townships (fig. 4, pl. 6). The thickest sections of basal outwash occur in valleys on the underlying Trafalgar surface (pl. 4). These valleys acted as sluiceways that conducted meltwater to the south, away from the advancing Saginaw Lobe. The basal Huntertown outwash is the principal aquifer for much of northwestern Allen County. To the southeast, the outwash grades laterally into progressively finer lacustrine sand and some silt, which were deposited primarily in small deltas along the northern edge of the glacial lake.

A discontinuous sheet of till between 15 and 75 feet thick overlies the basal outwash in some places. The till is typically a light yellowish-brown or grayish-brown loam or sandy loam that is relatively soft (medium to stiff consistency range), and is locally riddled with small to very large bodies of sand (table 3). The structure and texture of the till suggest that some units were deposited directly by ice, whereas others are mudflows and other till-like sediment reworked by meltwater and mass movement. Much of the till may have been deposited in an environment characterized by large masses of stagnant ice because it is commonly associated with ice-contact stratified sand and gravel.

Ice-contact stratified sand and gravel is a major component of the Huntertown Formation, especially in Eel River, Perry, and Cedar Creek Townships (fig. 4, pl. 6), where the largest bodies are localized along several former ice margins. Further to the southeast, small fan-deltas (pls. 4 and 6) appear to mark the terminus of the glacier, where the ice front stood in or just to the north of ancestral Lake Erie at its maximum advance. The Saginaw Lobe appears to have retreated through a process of mass stagnation characterized by several minor readvances and the gradual melting of large blocks of ice that were honeycombed with meltwater-bearing crevasses and tunnels. Many irregular bodies of ice-contact stratified sand and gravel were deposited in tunnels and channels on, against, and in the disintegrating ice. The collapse of the ice sheet released abundant oversaturated sediment, triggering numerous mudflows that accumulated in depressions, meltwater channels, and other low areas. Thin units of till probably formed near the base of the disintegrating ice. All of these types of sediment are intimately commingled in the upper one-half to two-thirds of the Huntertown Formation over much of northwestern Allen County, forming a massive **ablation complex**. Numerous blocks of ice of all sizes were buried within this ablation complex; subsequent collapse of the sediments when the ice blocks melted helped to create the hummocky topography that characterizes northwestern Allen County and most of the Steuben Morainal Lakes Area (Malott, 1922; Bleuer and Moore, 1974).

Within the ablation complex, several probable ice-marginal features can be identified (pls. 5 and 6). Some of these are evident on topographic maps and appear as well-defined northeast-to-southwest-trending, somewhat arcuate belts composed of relict collapse topography that contains long, linear depressions. The largest and most topographically obvious of the former ice margins is located between the county line and the Eel River north of Huntertown, where it forms a broad belt of chaotic collapse topography as much as 1.5 miles wide and several miles long. Small- to medium-sized **ice-contact fans** were deposited along some of the ice margins, and the meltwater locally cut sizable **ice-marginal channels** that became filled with outwash. The ice-marginal deposits are composed chiefly of coarse sand and some gravel, and are up to 60 feet thick and several miles in length. Loamy or sandy till-like sediment is a common component of some of the fans. In some places, meltwater erosion in front of the ice margins cut into the outwash sheet that forms the base of the Huntertown Formation. Subsequent deposition of fan materials directly over the basal outwash sheet locally resulted in total sand and gravel thicknesses close to 100 feet.

Lagro Formation

The Lagro Formation was originally defined by Wayne (1963) to include most of the surface till units in the northern quarter of Indiana, regardless of their source or composition. The characteristic clayey surface till of Allen County and adjacent areas was called the New Holland Till Member (Wayne, 1963; Bleuer and Moore, 1978). In this report I follow the example of Gray (1989) and restrict the definition of the Lagro Formation to the clay-rich tills that were deposited by the Erie Lobe during the last period of glacial advance into northeastern Indiana. In Allen County, the formation contains at least two distinct fine-textured till units, but their relationship to the New Holland Till Member of Wayne (1963) is not known and that terminology is not employed here.

The Lagro Formation is present below virtually all the land surface in Allen County, with the exception of major stream valleys and meltwater channels where the Lagro has been removed by erosion, and a broad area of hummocky **interlobate** topography northwest of Huntertown where the Lagro is discontinuous (pl. 5). Over most of the county, the thickness of the Lagro is typically about 25 to 40 feet, but it ranges from less than 10 feet in dissected areas to over 100 feet along the crest of the Wabash Moraine in Washington Township. The Wabash and Fort Wayne Moraines are regionally extensive till ridges that outline significant ice-marginal positions of the Erie Lobe, and the till commonly exceeds 60 feet in thickness in the cores of the moraines.

Two or more distinct till units can be recognized within the Lagro Formation at many places within and eastward of the Wabash Moraine (pl. 5). The uppermost till unit, which appears to make up the bulk of the Wabash and Fort Wayne Moraines, is generally thicker and somewhat more clayey than the lower unit(s) (fig. 8). A geographic relationship of a generally similar nature for the surface tills of the Lagro Formation has been noted by Gooding (1973), who documented a marked increase in the clay content of the till atop and inside of the Wabash Moraine, and a corresponding increase in sand and silt content in the surface till outside of the moraine. Sheared lenses of lacustrine mud have been observed at the base and within the lower part of the top till unit in downhole sample sets and gamma-ray logs collected from several areas inside of the moraine (for an example, see sidebar, **Gamma-Ray Log Signatures of Glacial Sequences**, page 9).

All these observations strongly suggest that the Erie Lobe experienced two distinct periods of ice advance that were separated by a retreat of unknown duration. This hiatus was evidently long enough to allow a significant lake phase to form in the Erie Basin and accumulate lake clay that was subsequently incorporated into the upper till deposited during the later ice advance. This phase of ancestral Lake Erie is the least well represented of the three phases that can be documented in Allen County and is largely inferred from the textural evidence presented above. It is hereby termed the Wabash phase for the moraine that contains the most compelling evidence of its existence and to distinguish it from the earlier Fort Wayne phase and the subsequent Maumee phase (fig. 7).

In Allen County, the Lagro Formation consists almost entirely of **basal till**, with lesser lacustrine silt and clay, and much lesser sand and gravel. The characteristic feature of the till units (fig. 8, table 3) is their very fine-grained texture, which sets them apart from the other till units observed

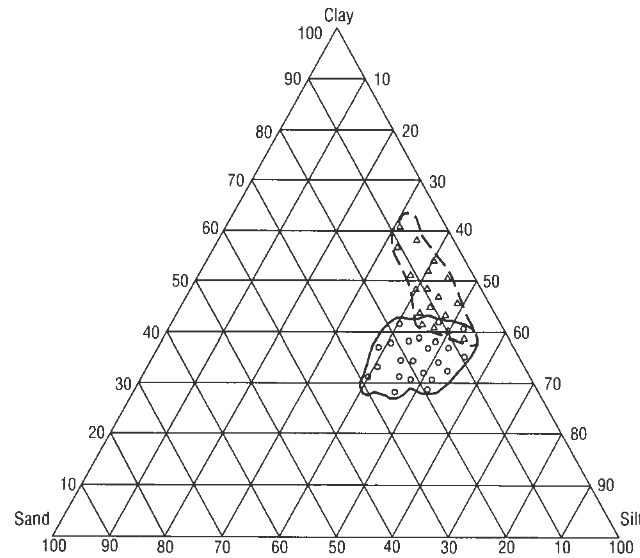


Figure 8. Textural diagram comparing textures of upper (triangles) and lower (circles) till units of the Lagro Formation. The more clayey upper unit appears to be present only within and behind the Wabash Moraine in Allen County, where it forms the principal surface till.

during this study. The tills typically contain less than 30 percent sand and more than 35 percent clay, and some samples of the upper till contain in excess of 60 percent clay. The abundant silt and clay were derived by incorporation of lacustrine mud as the ice sheet advanced across the bed of ancestral Lake Erie in northwestern Ohio and eastern Allen County. In most samples, the till is a light grey, stiff clay loam, silty clay loam, or silty clay that exhibits a prominent, moderately inclined fabric produced by the parallel alignment of flat, elongate shale fragments and numerous small streaks of silt and clay. In some large exposures, the till contains a few nebulous inclusions of severely deformed lake sediment that grade into the enclosing till. For the most part, pebbles and larger rock fragments are not prominent constituents, and the abundance of incorporated lake mud commonly gives the till a waxy appearance.

Abundant fractures are visible in the till in nearly every exposure. Most of the fractures are near-vertical and appear to be confined mainly to the top 20 feet of the unit. The fractures exhibit a definite structural relationship to ice-flow direction and show a variety of characteristics indicative of significant water movement through them (see sidebar, **Origins and Significance of Fractures in the Lagro Till**, page 24).

Discrete bodies of sand and gravel are rare within the Lagro Formation. The only known bodies large enough to show at the published map scale are confined to the north limbs of the Wabash and Fort Wayne Moraines, where they form one **esker** system and several other channel-like features within the till (pl. 5). Significant quantities of outwash deposited from the Erie Lobe ice front as it stood at the Wabash and Fort Wayne Moraines also occur within the Eel and St. Joseph Rivers, respectively. All of these bodies are typically composed of sand and gravel that invariably contains abundant granules of Antrim Shale. In parts of southern and western Allen County, the base of the Lagro Formation rests on the intersequence unit, a zone of sand and gravel that was deposited in part by Erie Lobe meltwater (discussed in the section on the **Trafalgar Formation**, page 19).

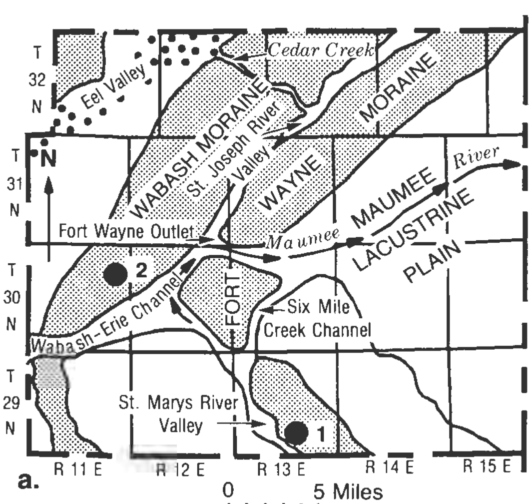
The character of the Lagro Formation in the highly irregular landscape that occurs mainly to the north of the Eel River differs in several important respects from that elsewhere (pl. 5). North of the Eel River, various evidence suggests that the Erie Lobe and Saginaw Lobe may have come into direct contact, resulting in the more pronounced knob-and-kettle topography of this area as well as a general slowing or blocking of the northward progress of the Erie Lobe. The configuration of this **interlobate** area is largely the result of the earliest advance of the Erie Lobe overriding and burying both the hummocky ablation complex of the Huntertown Formation as well as dead ice of the Saginaw Lobe. Consequently, the till is considerably less uniform in this region, both in its continuity as well as its textural attributes. It appears to thicken and thin abruptly, and is thin or absent in many places, particularly near depressions. The till is sandier in texture here, even having a loam composition in some places. This textural change may reflect incorporation of the overridden ice-contact stratified

Origin and Significance of Fractures in the Lagro Till

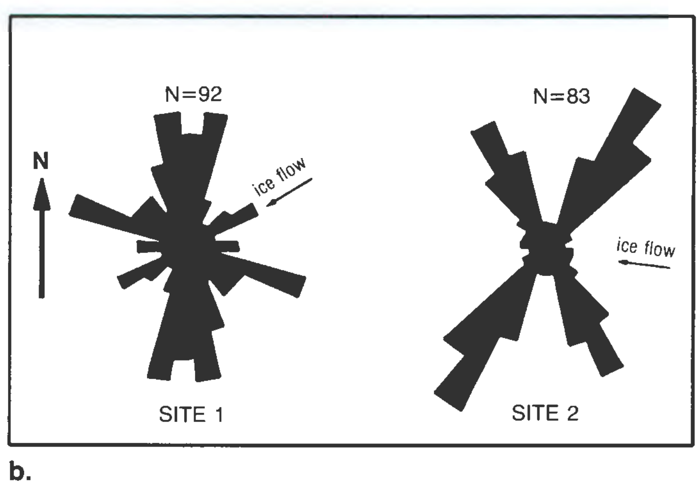
The presence of fractures and their effect on the engineering and hydrogeologic properties of fine-grained tills have become increasingly recognized in the past decade (Stephenson and others, 1988; Grisak and Cherry, 1975; Sharp, 1984; Herzog and others, 1989). A variety of hypotheses have been advanced to explain their origin and geometry, and it appears that several mechanisms may be involved (Connell, 1984).

In every large exposure of the Lagro Formation visited by the author in Allen County, numerous large near-vertical fractures were observed. The fractures were commonly open and seepage of water from some fractures was noted during wet periods. The till adjacent to many fractures characteristically shows oxidation haloes up to 24 inches wide, and the fracture surfaces locally contain crusts of calcite and various oxides of iron and manganese. All of these features indicate significant long-term water movement through the fractures.

The fractures commonly appear to be oriented in distinct sets that have preferred orientations. The orientations of a large number of fractures were measured in each of two exposures (fig. a). The results (fig. b) at both sites show the majority of fractures forming two principal sets that are arrayed conjugately (at a 60-degree angle) to local ice-flow direction, a structural relationship seen in basal till units elsewhere as well as between fractures and fold axes in areas of folded bedrock (Boulton, 1970; McGown and others, 1975; Mickelson and others, 1981; Connell, 1984). These observations suggest that, in a general way, it may be possible to predict the orientations of the predominant fracture sets at a particular location if the local ice-flow direction is known.



a.



b.

deposits of the Huntertown Formation. Sand and gravel units as well as debris flows are also much more prominent within the Lagro in this area. All of these attributes indicate that the depositional environment in this region was substantially different and characterized by much more variation than that which prevailed when the Lagro was deposited elsewhere. Consequently, it is not unreasonable to expect the hydrogeologic and engineering attributes of the Lagro to be substantially more variable in this region as well.

POST-GLACIAL DEPOSITS

Although the great majority of unconsolidated materials were deposited as a direct result of glacial activity, a variety of geologic events and processes have continued to operate to the present day. Consequently, post-glacial deposits are an important component of the landscape in several parts of Allen County, notably in low-lying regions. These deposits can be broadly organized into three groups, based on the processes and events that produced them:

1) organic sediments, such as peat and muck;
2) sediments associated with the latest, or Maumee phase, of ancestral Lake Erie and its outlets; and
3) alluvium, formed in all of the larger stream valleys.

Organic sediments are widespread in northern Allen County and are composed chiefly of thin muck over peat. The thickest and most areally extensive bodies fill large ice-block depressions and abandoned meltwater channels in the northwestern townships. The peat is locally in excess of 30 feet thick, and underlies broad wetland areas that probably originated as **kettle lakes**. Kettle lakes form in recently deglaciated landscapes when enclosed depressions become filled with ground water. The presence of saturated conditions prevents the decay (oxidation) of dead aquatic vegetation, and the lake gradually fills with peat and becomes a type of wetland known specifically as a peat bog.

The general distribution of organic sediments in Allen County closely parallels that of the Huntertown Formation (pl. 5). The organic sediments commonly are porous as well as saturated, and they form some of the most permeable soils mapped in Allen County (Kirschner and Zachary, 1969). As discussed in the appropriate sections of Chapters 3 and 4, the organic sediments, together with their associated wetlands, play a major role in the hydrologic regime of the Huntertown interlobate region (fig. 9) and in the recharge of underlying aquifers.

A regionally extensive phase of ancestral Lake Erie, known historically as Glacial Lake Maumee (Dryer, 1889; Leverett and Taylor, 1915) and here called the Maumee phase (fig. 7), formed at the close of the late Wisconsin glaciation between the front of the retreating Erie Lobe and the Fort Wayne Moraine. The lake eventually covered much of northwestern Ohio and extended into eastern Allen County at its maximum stand. Evidence for several different lake level elevations has been described by previous workers in this area (Leverett and Taylor, 1915; Bleuer and Moore, 1972; 1978). Changes in lake level were presumably related in part to minor readvances of the ice front and variations in meltwater discharge by the retreating Erie Lobe in northwestern Ohio.

Extensive blankets of sediments were deposited in the lake basin itself as well as within its outlets. The sediments were derived from the retreating ice front to the east and from the recently deglaciated landscape surrounding the basin. Laminated silt, clay, and much lesser fine sand accumulated in the relatively quiet water in the central portions of the basin, where they form a veneer up to 15 feet thick over the till units below. Along the edges of the basin, however, the water depth was substantially less. Wave energy was focused in these areas, reworking the till of the Lagro Formation as well as older deposits that were exhumed by the wave action. The wave action selectively removed the fine-grained component from these older deposits and concentrated the remaining sand and gravel in the form of beach ridges, spits, and offshore bars. The largest of these shoreline features is the distinctive ridge followed by State Route 37 between Fort Wayne and the Ohio State Line (pl. 5). Wave erosion completely removed the Lagro till in some places along this shoreline, exhuming deposits from older lake phases and depositing up to 25 feet of reworked sand and gravel. Much smaller beach ridges occur along the southern margin of the lake near Monroeville, and generally consist of a relatively thin discontinuous veneer of sand deposited over wave-scoured till.

The duration of the Maumee phase through time is not precisely known, although it is clear that the portion of the lake within Allen County remained at a relatively high level (approximately 770 to 780 feet) until it drained catastrophically. Available geomorphic evidence points to a relatively sudden breaching of the Fort Wayne Moraine along what is now the Maumee River Valley in present-day Fort Wayne (pl. 5). Such an outburst could have been triggered by melting of buried ice blocks and collapse of the sediments in this part of the moraine, or by a readvance of the ice front in northwestern Ohio that caused lake level to overtop a preexisting sag in the moraine. The resulting torrent of water scoured out a mile-wide outlet known as the **Wabash-Erie Channel**, parts of which are now occupied by the Maumee River in and near downtown Fort Wayne, and by the Little River several miles further to the southwest. Near Fort Wayne, the upper part of the Wabash-Erie Channel consists of northern and southern halves, which are separated by a slightly more elevated area underlain in part by till of the Lagro Formation and partly by remnants of an outwash fan (fig. 9, pl. 5). A secondary lake outlet follows Six Mile Creek and Trier Ditch between New Haven and the St. Marys River (see sidebar, **Geomorphic and Drainage Evolution near Fort Wayne**, pages 26-27).

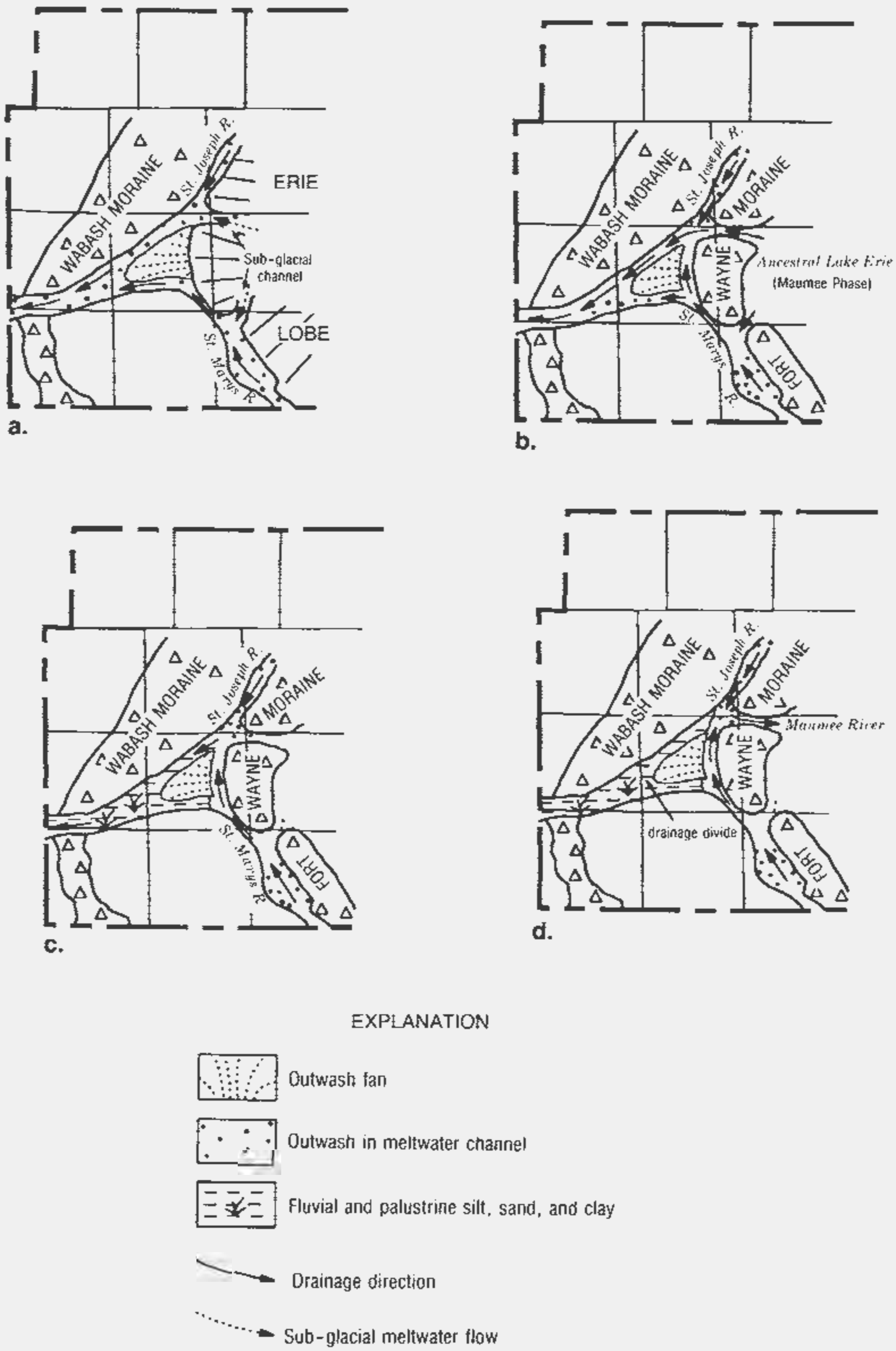
Geomorphic and Drainage Evolution near Fort Wayne

Downtown Fort Wayne lies within a broad valley complex at the confluence of the St. Joseph River, St. Marys River, Maumee River, and the now-abandoned Wabash-Erie Channel. The evolution of the modern drainage pattern as well as the origins of valleys themselves are closely related to the latest ice movements in this area and to the complex history of meltwater events, including the catastrophic demise of the Maumee Phase of ancestral Lake Erie.

Southwest of the Fort Wayne Moraine, the course of the Wabash-Erie Channel appears to have been determined by the presence of an earlier meltwater channel that formed when the Erie Lobe stood at the Fort Wayne Moraine (fig. a). There is abundant evidence for such a channel, including numerous outwash terraces on the valley walls above the floor of the channel and remnants of a large outwash fan in the head of the southern half of the channel just west of the moraine, in the southwest part of Fort Wayne (fig. 9, pl. 5). The course and origin of the St. Marys and St. Joseph Rivers provide even more compelling evidence for this interpretation. The pattern of both rivers clearly indicates that they originated as ice-marginal channels when the Fort Wayne Moraine was constructed. Yet the Maumee River did not exist at that time because any eastward drainage would have been blocked by both the moraine and the ice front itself. This leads to the inescapable conclusion that the presumably large volumes of meltwater being carried by these ice-marginal channels must have drained to the southwest.

The above conclusion is supported by the configuration of outwash bodies that underlie the river valleys in and west of downtown Fort Wayne (fig. a; pl. 5). The **outwash train** associated with the St. Joseph River Valley leads directly into the head of the Wabash-Erie Channel and is present below the floor of the channel for some distance southwest of the confluence with the Maumee River. Similarly, a sizable westward-thickening body of outwash is also preserved within the uppermost reaches of the Maumee River Valley where it cuts through the western part of the moraine, and is contiguous with outwash of the St. Joseph River. The eastern margin of this body appears to interfinger with the clayey till that cores the moraine, and the overall aspect of this body suggests that it was deposited by Erie Lobe meltwater discharging westward from an ice-walled channel or similar feature (fig. a). If this interpretation is correct, it lends support to the possibility that the outburst of lake water through the moraine was localized along a preexisting sag over this meltwater drainage feature (fig. b). This catastrophic drainage event has been referred to as the Maumee Torrent (Leverett, 1902; Fraser and Bleuer, 1988), and it effectively cleaned out most of the Erie Lobe sediments from the outlet, leaving an irregularly scoured surface on the Trafalgar Formation flanked by outwash terraces on the valley walls.

Following the catastrophic drainage of the lake, a slackwater type of environment persisted within the Wabash-Erie Channel for a period perhaps as long as hundreds, or even thousands of years (fig. c). Because the Maumee River was not to become established for some time, the St. Marys and St. Joseph Rivers continued to drain southwestward through a channel bottom characterized by a diverse array of localized lakes, wetlands, and sluggish river channels. Slackwater sediments deposited during this interval buried the irregularly scoured Trafalgar surface and further reduced the already low stream gradient within the outlet. Meanwhile, in the lake plain further to the east, the eastward-flowing course of the Maumee River had been established, perhaps along a previous subglacial meltwater route. Headward erosion of the river into the outlet, coupled with increased alluviation of the floor of the Wabash-Erie Channel, ultimately led to the capture of the St. Joseph and St. Marys Rivers by the Maumee River, resulting in the classic barbed drainage pattern (fig. d). The floor of the Wabash-Erie Channel has remained a wetland to this day, and just west of Fort Wayne it now contains the surface drainage divide between the Little River (Wabash River drainage system) to the west and the Maumee River (Great Lakes drainage system) to the east.


WABASH MORAINE
St. Joseph R.
ERIE
Sub-glacial channel
LOBE
St. Marys R.
a.
WABASH MORAINE
St. Joseph R.
MORAINE
Ancestral Lake Erie
(Maumee Phase)
WAYNE
St. Marys R.
FORT
b.
WABASH MORAINE
St. Joseph R.
MORAINE
WAYNE
St. Marys R.
FORT
c.
WABASH MORAINE
St. Joseph R.
MORAINE
Maumee River
WAYNE
drainage divide
FORT
d.
EXPLANATION
Outwash fan
Outwash in meltwater channel
Fluvial and palustrine silt, sand, and clay
Drainage direction
Sub-glacial meltwater flow

The flood waters removed all of the clayey till and associated outwash of the Lagro Formation along the axis of the main outlet, exposing the hard loam till and several large sand bodies of the underlying Trafalgar Formation. Deposition occurred within the outlet as the torrent subsided, producing a complex assemblage of post-glacial sediments up to 35 feet thick. These include localized bodies of reworked sand and some gravel, which are generally overlain by a variety of fine- to medium-grained, locally mucky alluvial, lacustrine, and palustrine (wetland) deposits. Several small dune fields, such as the one at Fox Island Nature Preserve, also occur in the outlet and act as islands amidst this otherwise expansive wetland. In contrast, the Six Mile Creek outlet contains only a relatively thin veneer of mostly fine-grained lacustrine and(or) alluvial sediment over Trafalgar or Lagro till.

The **alluvial valleys** of the St. Marys, St. Joseph, and Maumee Rivers have been deepened considerably by post-glacial erosion. The degree of incision is especially evident along the St. Marys and St. Joseph Rivers, where there are elevation differences as great as 50 feet between outwash terraces deposited by glacial meltwater and the modern valley bottoms. **Alluvium** (reworked sediment deposited along modern streams) is present throughout all three river valleys, as well as locally along larger tributaries such as Cedar, Aboite, and Flatrock Creeks. The composition and thickness of the alluvium along any particular reach of one of these valleys reflects the predominant type of sediment exposed on adjacent uplands and valley walls, and the prevailing stream energy. Locally thick, sandy or gravelly alluvium is common along the St. Joseph River and parts of Cedar Creek, for example, because these valleys contain appreciable outwash. Alluvium along the St. Marys and Maumee Rivers, in contrast, is typically fine- to medium-grained, reflecting the predominantly fine-grained till that flanks these valleys.

GLACIAL TERRAINS

It should be apparent from the preceding sections that, although the entire county generally experienced the same gross sequence of major events during and after the late Wisconsin glaciation, these events were not sufficiently ordered through time and space to produce a uniform landscape or subsurface geologic environment throughout the county. The depositional environment clearly varied from place to place during each of the three major periods of glacial advance as well as at other times. Similarly, various meltwater discharges and post-glacial events that greatly altered the landscape in one place were of much lesser intensity, or even nonexistent, elsewhere. Consequently, there is considerable variation between different regions of the county, expressed both as differences in the basic types of vertical sequences as well as by strongly contrasting landforms. Although it is not possible to depict these differences at the level of the individual landform or the individual water well, they can be represented quite well at a somewhat broader scale by identifying the different glacial terrain regions within the county (fig. 9).

As was noted at the beginning of the chapter, each of the major terrain regions is the product of a particular history of geologic events that is essentially common to that region alone, even though some of the events may be part of a much larger event that also affected other regions or the entire county. Consequently there is a close spatial and genetic relationship between the vertical sequences that underlie a terrain region and the association of landforms within it, and both of these components tend to have a relatively well-defined range of characteristics. The differences in vertical sequence or landform characteristics *within* a particular terrain tend to be slight when contrasted with the differences *between* terrains, and basically can be thought of as variation on a theme. Such *intraterrain* variation can be represented by subregions, which are essentially end members within a relatively well-defined range of conditions.

The use of this type of terrain model to represent a three-dimensional block of glacial material is extremely useful, both for understanding and characterizing the sediments themselves, but more importantly, for representing the different ways in which the terrain as a whole might interact with and affect other natural processes and resources, such as ground water. As it turns out, there is a very close relationship between the characteristics of each of the terrain regions in Allen County and the occurrence, movement, and sensitivity to contamination of the ground water that each contains. Therefore, the terrain regions described below provide a logical and convenient vehicle for discussing the different hydrogeological regions of the county (see Chapter 4; pl. 9), and they offer a good basis for understanding the hydrogeologic framework of the county as a whole.

As defined, a few of the terrain regions are generic, that is, they are morphologically defined regions (for example, till plains, end moraines) of generally like character that actually occur in two or more disjunct areas within the county. The majority of the regions, however, are restricted to a particular geographic area (for example, Cedar Creek Canyon, Arcola plain) on the basis of characteristics unique to that area. The following discussion focuses on the structure and geologic history of each terrain, and relates these characteristics to the glacial events and sediments described in preceding sections of this chapter. The gross geographic distribution of glacial sediments and the general landscape configuration of the different terrains are shown on Plate 5, whereas the structure of the vertical sequences that underlie them can be seen in the various cross sections on Plate 10.

Alluvial Valleys

Alluvial valleys are modern river valleys that contain relatively broad floodplains underlain by recent alluvium whose composition reflects that of the predominant source(s) of sediment. The principal alluvial valleys in Allen County are all relatively small and were formed initially by one or more episodes of meltwater discharge from the Erie Lobe. These include the St. Marys, Maumee, and St. Joseph River Valleys, as well as the Wabash-Erie Channel. However, based on a combination of terrain features, geologic history, and hydrogeologic characteristics, the St. Joseph River Valley and the Wabash-Erie Channel are sufficiently different to justify their definition as separate terrain regions. Thus, although the following discussion refers specifically to the valleys of the Maumee and St. Marys Rivers, the reader should be aware that most of the larger tributaries, such as Aboite and Flatrock Creeks, at least locally possess some of the characteristics of alluvial valleys, albeit on a much reduced scale.

The St. Marys and Maumee Rivers are both characterized by relatively small valleys with floodplains generally less than a quarter of a mile wide. The floodplains are composed of a variable thickness of predominantly fine- to medium-grained alluvium that overlies a stripped surface developed chiefly on loam till of the Trafalgar Formation. Clayey till of the Lagro Formation is the predominant material in the valley walls but is invariably absent from the valley bottoms. Outwash bodies are mainly in the form of small, widely scattered terraces high on the adjacent valley walls. The depth to bedrock is generally relatively shallow (pl. 3), except over buried bedrock valleys. Considerable segments of the St. Marys River Valley do, in fact, overlie a bedrock valley (pl. 2) that locally contains appreciable amounts of sand and gravel as well as till.

The St. Marys River originated as an ice-marginal channel in front of the Fort Wayne Moraine. It probably carried a significant load of sand and gravel during peak meltwater discharge, but any formerly extensive outwash bodies that might have been deposited at that time have since been re-

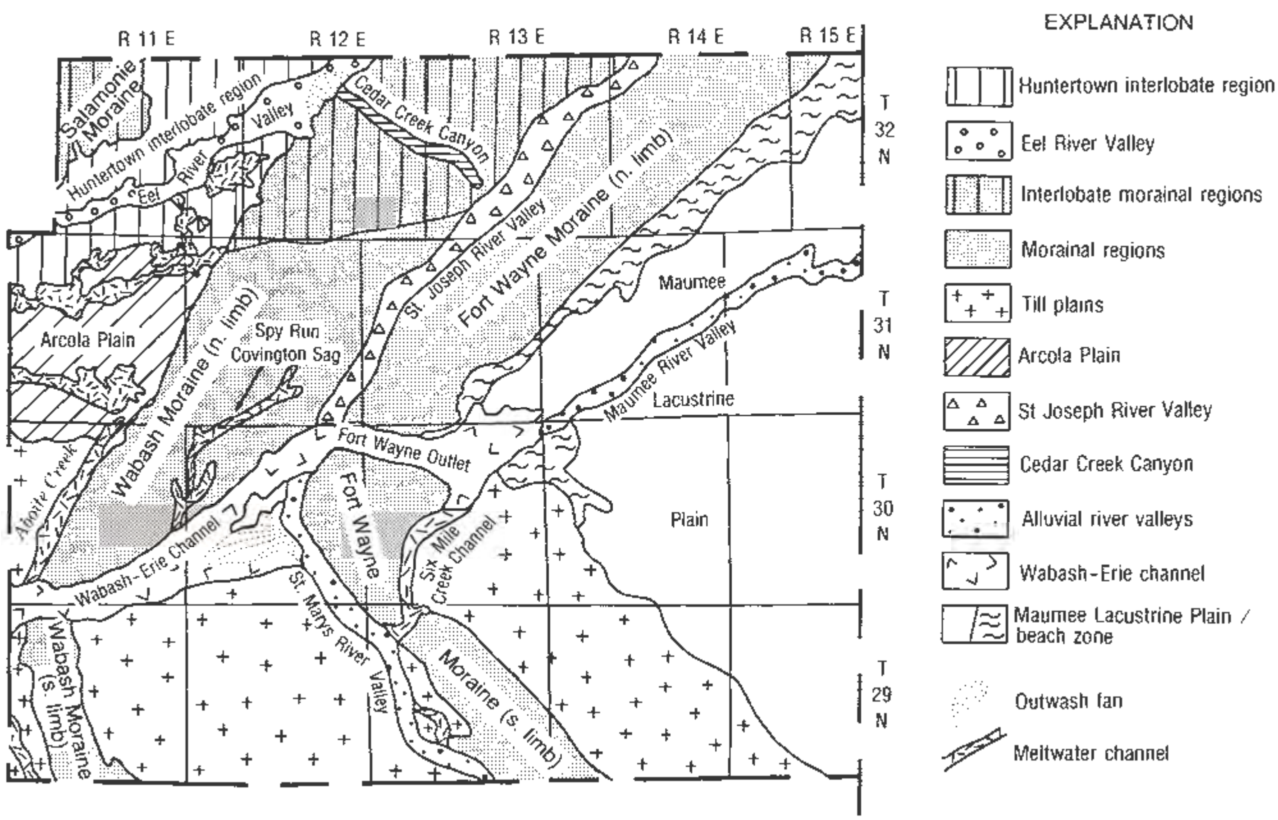


Figure 9. Glacial terrain regions and related features of Allen County.

moved by erosion. One relatively large and thick outwash body located above and north of the river in southern Marion Township (T29N, R13E, S20, S21, S28) (fig. 4, pl. 5) lies within an abandoned high-level meltwater channel that may represent an early course of the ice-marginal river. Two large outwash bodies are also present below the lowermost segment of the river in the vicinity of the Wabash-Erie Channel (pl. 5) but these are geologically related to the channel rather than to the river itself. The alluvium within the valley is mostly less than 15 feet thick. It is generally loamy in composition and appears to be derived mainly from the Lagro Formation, which makes up the valley walls and is the predominant unit at the land surface over much of the watershed.

The valley of the Maumee River lies almost entirely within the Maumee Lacustrine Plain, which is a distinct terrain unto itself (fig. 9). The valley formed long after glaciers had left the county, but its general course may well have been determined much earlier by meltwater erosion along a subglacial or ice-walled channel. In view of the post-glacial origin and eastward gradient of the modern valley, terraces of coarse sand and gravel found in several places along the river are difficult to explain as glacial outwash, and may be remnants of larger bodies deposited by meltwater in a channel below the ice. Alluvium within the valley is generally less than ten feet thick and is commonly sandy or loamy in composition, suggesting that it is derived from the adjacent terraces and sandy lake sediments that cap nearby parts of the Maumee Lacustrine Plain, or both, as well as from fine-grained sediments elsewhere within its watershed.

Till Plains

Till plains (fig. 9, pl. 5) are the most common glacial terrain in the southern part of the county. They typically are characterized by gently rolling to nearly flat constructional landscapes developed on clayey till of the Lagro Formation. The till ranges from less than 10 to more than 50 feet thick, but is typically between 25 and 40 feet thick. The general elevations of the till plains tend to rise subtly, with a corresponding increase in till thickness, as the gentle back sides (proximal to former ice margins) of the south limbs of the Wabash and Fort Wayne Moraines are approached. Small irregular mounds, generally less than 5 feet high and a few tens of feet wide, are common in many parts of the till plains. These **ablation hummocks** are composed of clayey till and till-like sediment deposited when the Erie Lobe melted.

Other kinds of surface sediments are rare within the till plains, although a thin veneer of lacustrine mud or sandy outwash occurs in widely scattered localities where meltwater collected in small ponds and channels amid the disintegrating ice. Virtually the only significant relief in the till plains is provided by the valleys of a few small- and medium-sized streams and abandoned meltwater channels. In many places, natural surface drainage is very weakly developed, resulting in poorly drained landscapes characterized by a preponderance of artificial ditches.

The typical vertical sequence found over much of this terrain is composed mainly of till, with the clayey Lagro Formation overlying the overconsolidated loam tills of the Trafalgar Formation. Small bodies of sand and gravel occur between the two till sequences in widely scattered locations in the southern townships, but are increasingly larger and more common to the west and southwest. Other sand and gravel units occur locally within the Trafalgar Formation, most commonly along its contact with the underlying limestone bedrock. The total thickness of unconsolidated deposits below the till plains ranges from about 60 to more than 120 feet. On average, this thickness is about equally divided between the Lagro and Trafalgar Formations.

Morainal Regions

The morainal regions of Allen County include the Wabash and Fort Wayne Moraines (fig. 9, pl. 5). These two regionally extensive Erie Lobe end moraines are broadly concentric about the western end of the Maumee Lacustrine Plain, a pattern that clearly reflects the shape of the Erie Lobe margin during the latest stages of late Wisconsin glaciation (Gray, 1989; Johnson and Keller, 1972; Burger and others, 1971). The apexes of both moraines are breached by the Wabash-Erie Channel, a characteristic that helps separate both moraines into relatively distinct northern and southern limbs.

Each moraine generally consists of one or more broadly arcuate ridges characterized by hummocky or rolling topography. The Wabash Moraine has the stronger surface expression, being considerably taller and broader in most places than its counterpart. Both moraines are composed chiefly of thick clayey till of the Lagro Formation. The till in and behind both moraines is generally finer-textured than the Lagro Formation tills outside of the Wabash Moraine, and was probably deposited by a distinctly younger advance of the Erie Lobe following the Wabash phase of ancestral Lake Erie (see earlier section on the Lagro Formation). The southern limbs of both moraines are relatively simple ridges whose crests are characterized by moderately rolling topography. They are cored by a relatively repetitive sequence of clayey tills that range in thickness from 20 to about 80 feet, but are most commonly between 30 and 60 feet thick. The two southern limbs are separated from each other by a till plain as much as 10 miles wide. Meltwater discharging from the ice front as it stood at each moraine cut ice-marginal channels, now represented by Eight-Mile Creek, which follows the toe of the Wabash Moraine, and the St. Marys River, which marks the front of the Fort Wayne Moraine.

In contrast, the northern limbs of both moraines are markedly taller, much broader, and more rugged than their southern counterparts. They are separated from each other only by the relatively narrow valley of the St. Joseph River, and they collectively form a broad belt of morainal topography that covers most of the north-central part of the county. The composition of the Lagro Formation is more variable

Geology of the Spy Run-Covington Sag

The Spy Run-Covington sag is a complex of modern streams, artificial ditches, wetlands, and small ponds developed within the confines of a west-to-south-trending topographic lineament that is between 7 and 8 miles long. The eastern, more prominent end of the sag is marked by the lower valley of Spy Run Creek and Shoaff Lake, whereas the southwest end is formed by the smaller valley of Flaugh Ditch (formerly Covington Creek). The central segment is less topographically pronounced and consists of a series of small depressions and extensively ditched wetland areas within a gentle southwest-trending topographic sag.

Thick sections of sand are present below much of the length of the sag, and are reportedly as great as 50 to 100 feet thick in some places. The sand appears to be at least partly associated with a complex of buried channels within the Trafalgar Formation (pl. 4). Clayey till of the Lagro Formation up to 25 feet thick overlies the sand in the central segments of the sag. Some sand and gravel along the southwestern segment forms outwash terraces, however, indicating a different origin. The eastern and central parts of the sag are capped by fine-grained fluvial and palustrine sediments.

The geometry of this lineament and the types of sediments present within it record a complex history. The large linear body of sand within the underlying Trafalgar Formation may have been deposited within a tunnel valley or similar type of meltwater conduit associated with the buried morainic complex discussed earlier in this chapter (pl. 4). Alternatively, this buried channel may well represent a former outlet of the Fort Wayne phase of ancestral Lake Erie, because it leads directly away from the western part of the lake basin (pls. 4 and 6). Subsequent filling of the channel with sand could have occurred when the Erie Lobe advanced into western Allen County following the closing of the lake basin.

The orientation and surface morphology of the lineament suggest that the modern topographic sag formed as a meltwater channel along the Erie Lobe margin shortly after the ice front retreated back from the crestal area of the Wabash Moraine. A preexisting sag, perhaps associated with the large channel deposit in the underlying Trafalgar Formation, may have helped to localize ice-marginal drainage. Meltwater from the ice front scoured the bottom of the channel, locally exhuming the thick sand section in the Trafalgar Formation below and depositing outwash in downstream parts of the ice-marginal channel.

The channel was abandoned when the ice front retreated back to the position of the Fort Wayne Moraine, leaving a series of small kettle lakes and linear depressions within the former sluiceway. Many of these eventually became partly or entirely filled with fluvial and palustrine sediments, resulting in the linear train of wetland areas that now characterizes the central segment of the sag. Headward erosion into this central segment by the two streams at either end has been slow, and has thus preserved it as a modern drainage divide between Spy Run Creek and Covington Creek, which is in turn part of the much larger mid-continental drainage divide between the Mississippi River and Great Lakes drainage systems.

within the northern limbs as well. In addition to thick sections of clayey till, locally extensive units of dense silt and channellike wedges of sand are also present. These bodies seem to be related to the northern limbs of the moraines, because they are not known to occur elsewhere in the Lagro Formation. The total thickness of till and other fine-grained sediments of the Lagro is commonly greater than 60 feet over large parts of the northern morainal regions, and exceeds 100 feet in some parts of the Wabash Moraine (pl. 5).

Several types of vertical sequences occur beneath the moraines, but the most common type is composed of thick till (100 to 200 feet or more) of the Lagro and Trafalgar Formations overlying bedrock or deeply buried sand and gravel units of the Trafalgar or older units. This sequence is generally thickest below the northern limbs of the moraines (pl. 3), where it locally includes a substantial thickness of pre-Wisconsin tills and other sediments. Another common sequence is characterized by laterally extensive bodies of sand and gravel at the base of the Lagro Formation and (or) at slightly greater depth. This type of sequence is best developed beneath the Wabash Moraine in western and southwestern Allen County, where the majority of sand and gravel bodies belong to the intersequence unit. A similar sequence occurs below both moraines in some parts of north-central Allen County (chiefly in St. Joseph and northern Washington Townships) (fig. 4), where sand units below the Lagro Formation represent the distal edge of the Huntertown Formation.

Both moraines are dissected in several places by abandoned meltwater channels oriented more or less perpendicular to the morainal crests. Some of these are now occupied by modern streams, but several others are essentially dry high-level hollows. The sediments underlying most of these former meltwater channels do not differ significantly from those elsewhere in the moraines. In most cases, the channels are characterized by a washed till surface below which the Lagro may be moderately thinned by erosion, and which may be capped in places by a veneer of outwash or organic sediment. The largest of these features is Cedar Creek Canyon, whose origin and morphology are sufficiently different to warrant classification as a separate terrain region.

Very large or even torrential meltwater discharges took place from the Erie Lobe margin in northern Allen County when it stood at each moraine. These discharges had a major effect on the landscapes as well as the immediately underlying sediment assemblages directly in front of each moraine. Several of the terrain regions discussed below, including the Eel River Valley, Arcola plain, and St. Joseph River Valley, received the brunt of these discharges. The distinctive modern landscapes of these regions are directly attributable to the effects of the meltwater.

An unusual meltwater channel of complex origin is located in the northwestern part of the City of Fort Wayne, where it forms a distinct terrain subregion entirely within the southeastern flank of the Wabash Moraine (fig. 9, pl. 5). For purposes of discussion, this feature is informally termed the **Spy Run-Covington sag**, for the creeks of the same names that occupy its eastern and western ends. Unlike the other abandoned meltwater channels within the Wabash Moraine, the sag is oriented more or less parallel or slightly oblique to the axis of the moraine. The sag generally separates the main crestal area of the moraine to the northwest from an irregular rolling tract with a pervasively washed appearance that lies to the southeast. It is also distinguished because it is underlain by thick (50 to 100 feet) sections of sand along much of its length, as well as a variety of fluvial and palustrine sediments, all of which indicate a long, polygenetic history for the sag (see sidebar, **Geology of the Spy Run-Covington Sag**, page 31).

Interlobate Morainal Regions

The interlobate morainal regions include the north limb of the Wabash Moraine in the northern tier of townships and the Salamonie Moraine in the extreme northwestern part of the county (fig. 9, plate 5). This type of terrain is in some ways similar to the morainal regions described above, but differs in three important respects:

1) the Erie Lobe end moraines are superposed upon strongly hummocky ice-disintegration topography of the Saginaw Lobe; consequently
2) the crestal areas of the moraines generally tend not to be clearly defined ridges, but instead form broad, somewhat amorphous belts of hummocky topography. This topographic character appears to largely be inherited from the buried Saginaw Lobe deposits; and
3) the till that cores the moraines tends to be somewhat thinner and less clayey than that in other parts of the Erie Lobe end moraines.

The internal relief and morphology of the interlobate morainal regions tend to be quite varied. In many places there are a considerable number of small to large enclosed depressions, and small abandoned meltwater channels are numerous. Most of these features are filled with organic sediment. In other places, there are fewer depressions and the land surface is characterized by broad, rolling hummocks and swales. In some places small groups of depressions and meltwater channels appear to be aligned along subtle northeast-to-southwest-trending topographic lineaments that extend for several miles. The lineaments lie at an oblique angle to the trend of the Erie Lobe moraines, and are instead parallel with the inferred orientation of buried Saginaw Lobe margins. This pattern suggests that the lineaments may be relict, or **palimpsest**, features from the buried Saginaw Lobe terrain below.

The Erie Lobe till is more variable in composition within the interlobate regions than elsewhere, and is most commonly clay-loam to loam in texture. Small lenses of interbedded sand, silt, and mud flows are numerous. The thickness of the Lagro Formation ranges from less than 20 feet to over 80 feet, but is most commonly between 20 and 50 feet. These sediments overlie a thick, heterogeneous sequence composed of ice-contact stratified sand and gravel, outwash, sandy loam till, and debris flows of variable composition, all of which collectively make up the Huntertown Formation. There is considerable local variation in the elevation of the Lagro-Huntertown contact, which is indicative of the strongly hummocky character of the Huntertown surface that was overridden by the Erie Lobe. The thickness of the Huntertown sediments is commonly 75 feet or more, and appears to be as great as 120 feet in a few places. These are underlain by overconsolidated loam till and lesser sand and gravel of the Trafalgar Formation, but the characteristics of the Trafalgar Formation, as well as any older sediments that may be present below these regions, are not well known because relatively few wells penetrate to this depth.

Huntertown Interlobate Area

This terrain contains some of the most irregular and hummocky topography in Allen County. It forms a broad, northeast-southwest trending belt centered on the Town of Huntertown, in northwestern Allen County (fig. 9, pl. 5). The terrain is bisected down its long axis by the Eel River Valley, which is discussed in the next section.

The main feature of the Huntertown interlobate region is its characteristic hummocky landscape, which contains numerous enclosed depressions, irregular ridges and hummocks, and abandoned meltwater channels. This landscape is largely a manifestation of the buried surface of the Saginaw Lobe deposits (Huntertown Formation), which generally lie at a depth of less than 20 feet (see sidebar, **Origin of the Interlobate Landscape in Northwestern Allen County**, pages 34-35). The landscape is almost entirely internally drained. Low-lying areas are very poorly drained and contain numerous wetlands, many of which could be classified as peat bogs.

The surface sediments in this terrain are the most variable of any region in Allen County. Hummocks and ridges are typically composed of loam or clay-loam till and till-like sediments of the Lagro Formation, but may also contain ice-contact stratified deposits in some places. The fine-grained sediments are less than 20 feet thick in most places, but may be slightly thicker below a few of the highest hummocks. The bottoms of depressions and abandoned meltwater channels are almost inevitably floored by organic sediments, which attain thicknesses of more than 25 feet in some locations. Sediments of the Huntertown Formation are commonly at the land surface along the edges of depressions and sluiceways, as well as in some upland areas.

Over much of the region, the complex assemblage of surface sediments is underlain by an equally complex sequence of ice-contact stratified deposits, till-like materials, and outwash that constitute the Huntertown Formation. Over large parts of the region, especially those closest to the Eel River Valley, ice-contact sand and gravel between 40 and 80 feet thick is present directly below the surface sediments. One or more discontinuous sheets of sandy loam till are present within or below the sand and gravel. These in turn overlie an extensive sheet of medium or course outwash sand up to 30 feet thick that forms the base of the Huntertown Formation.

Eel River Valley

The Eel River Valley forms the axis of the interlobate region of northwestern Allen County. It has had a somewhat more complex history than the immediately adjacent region, having been a large, active meltwater channel on at least two, and probably more, occasions. Today, the Eel River Valley in Allen County is an abandoned high-level meltwater channel that contains a major surface water divide between the Mississippi River and Great Lakes drainages. Much of the "valley" contains no natural through-flowing streams (although wetlands are abundant) and its "bottom" is barely below the surrounding areas in terms of surface elevation. Indeed, the term "river valley" is, perhaps, a misnomer for the modern Eel, and better reflects its former role of carrying large meltwater torrents when ice was active in this area (see sidebar, **Origin of the Interlobate Landscape in Northwestern Allen County**, pages 34-35).

The Eel River Valley is underlain by a complex sequence of sand and gravel, consequently its surface morphology largely reflects processes associated with meltwater flow and channel abandonment. The northeastern end of the valley, as well as its marginal areas further to the southwest, are generally somewhat streamlined in appearance, a characteristic indicative of large meltwater discharges through the valley in the past. A few areas, particularly along the highest terraces, are moderately **pitted**, with numerous small depressions attesting to the rapid burial of ice blocks by outwash. These outwash-dominated landscapes were shaped mainly by large meltwater discharges from the mouth of Cedar Creek (see the following section, **Cedar Creek Canyon**).

The landscapes formed on outwash contrast greatly with the axis of the valley to the southwest, which is almost perfectly flat. Here, the abandoned channel has gradually filled with as much as 30 or more feet of organic sediments, resulting in an extensive peat bog that is as much as a mile wide. Filling of formerly deeper parts of the sluiceway by organic sediments is one reason there is so little evidence today of a "valley."

The typical sequence below the surface of the valley consists of thick sand and gravel. The upper 20 to 40 feet of this sequence is Erie Lobe outwash derived predominantly from Cedar Creek, but also to some extent from Erie Lobe meltwater discharged from the front of the moraine northeast of Allen County (Gray, 1989). The outwash lies atop large-scale ice-contact fan deposits of the Huntertown Formation, which are laterally contiguous with those below the interlobate region on either side of the valley. This composite section of sand and gravel is thickest slightly to the north and west of the Town of Huntertown and near the mouth of Cedar Creek Canyon. Sand and gravel sections in these localities are commonly 70 to 80 feet thick, with a few reportedly being more than 100 feet thick. Below other parts of the valley, the sand and gravel is typically on the order of 40 to 70 feet thick, and generally thins somewhat as one progresses southwest down the valley toward the county line.

Cedar Creek Canyon

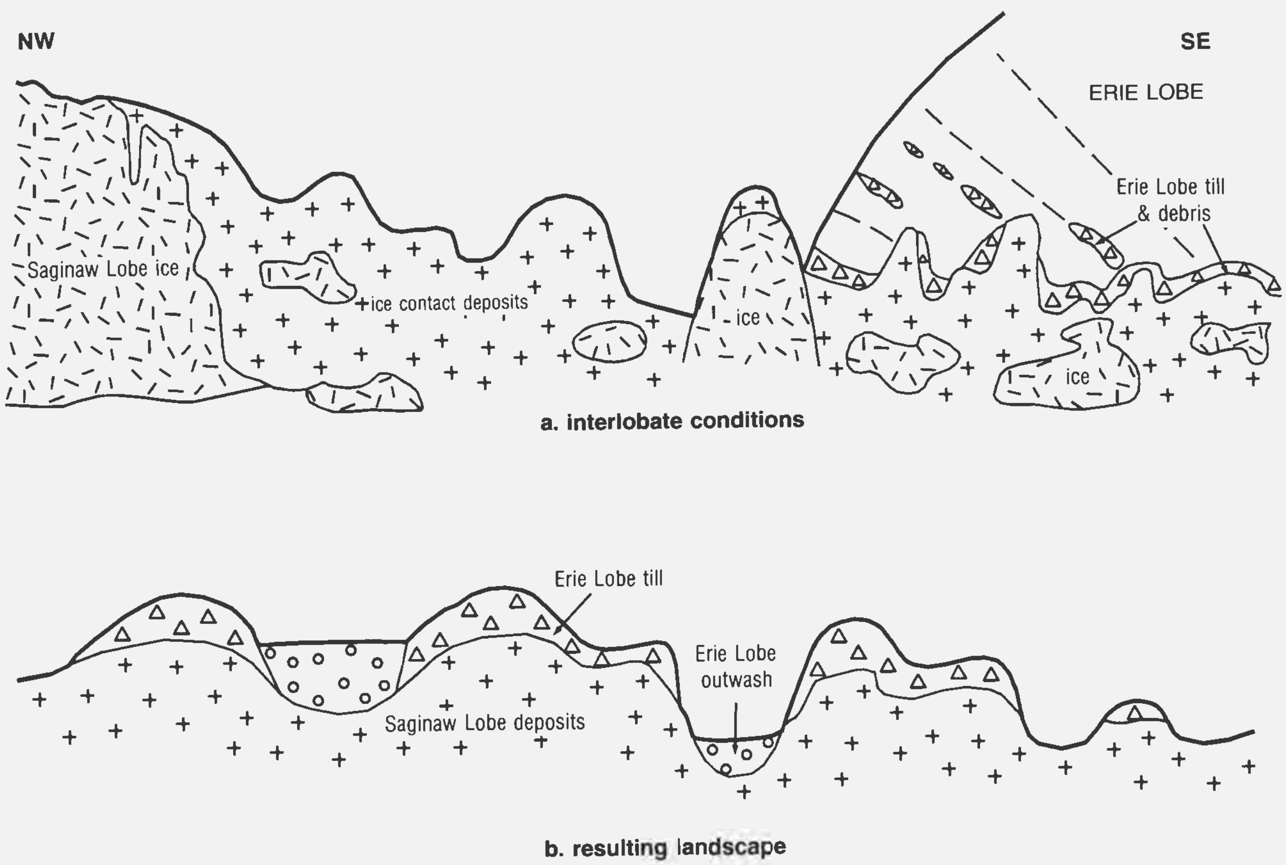
Cedar Creek Canyon is a deeply-incised stream valley that cuts across the north limb of the Wabash Moraine between the Eel River Valley two miles northeast of Huntertown and the St. Joseph River at Cedarville (fig. 9, pl. 5). The canyon consists of two segments of differing morphology. The upper segment includes the head of the canyon adjacent to the Eel River Valley, and extends for about four miles to the southeast. It follows an almost perfectly straight course perpendicular to the crest of the Wabash Moraine. The flat bottom of the canyon maintains a consistent width of about 1,500 feet through this segment and is flanked by near-vertical walls 50 to 80 feet high. The lower segment is more irregular, being characterized by several sharp bends and less imposing slopes along its flanks. The junction between the two segments is prominently marked by a sharp bend located exactly on the boundary between Perry and Cedar Creek Townships (fig. 4, pl. 5).

The straight upper segment of the canyon originated as a **tunnel valley**, a type of large subglacial meltwater channel that is typically incised deeply into the substrate below the sole of the glacier. The Cedar Creek tunnel valley acted as the principal drainage route for meltwater exiting the Erie

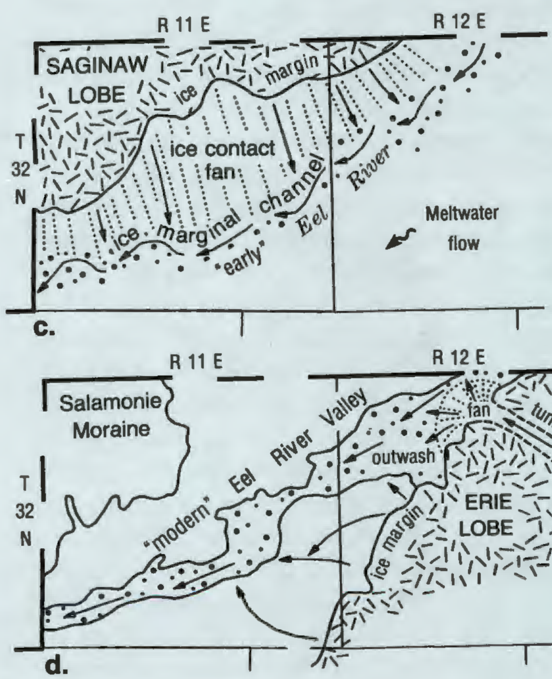
Origin of the Interlobate Landscape in Northwestern Allen County

The interlobate terrain in northwestern Allen County is part of a much broader region of similar aspect that covers a large part of northeastern Indiana. The complex landscape that characterizes this terrain was formed primarily by interaction between the Erie Lobe, advancing to the northwest, and the Saginaw Lobe, which was undergoing a general ice-margin retreat. The abundance of ice-contact features, as well as the chaotic and locally discontinuous nature of the Lagro Formation, suggest that the Erie Lobe encountered considerable resistance as it attempted to advance into this region. Such resistance would have been provided by a highly irregular bed composed of large mounds of ice-contact stratified deposits interspersed with massive blocks of dead Saginaw Lobe ice (fig. a). The resistance probably caused compression along the advancing ice front, resulting in the burial of additional masses of ice below a veneer of heterogeneous ablation sediments. Eventual melting of the buried ice caused the surrounding sediments to collapse, creating the characteristically irregular, high-relief landscape that dominates northeastern Indiana (fig. b).

The interlobate region in Allen County is bisected by the Eel River Valley, a glacial sluiceway that carried meltwater from both the Saginaw Lobe and the Erie Lobe. The general orientation of the valley and the sequence of deposits below it suggest that it originated along the edge



of a large ice-contact fan (fig. c), and that it may have continued to drain the retreating margin of the Saginaw Lobe for some time thereafter. Much later, the valley again became an active sluiceway when the Erie Lobe stood at the Wabash Moraine. The valley conducted much of the ice-marginal drainage from the northern limb of the moraine, including large torrents of meltwater discharged from the mouth of the Cedar Creek tunnel valley (fig. d). However, these later Erie Lobe events did not appreciably obscure the earlier course of the valley, because the direction and morphology of the modern valley are still highly suggestive of its Saginaw Lobe origin.



Lobe when the ice front stood at the Wabash Moraine. The meltwater carried considerable sand and gravel, some of which was deposited along the floor of the tunnel valley and now underlies the bottom of the modern canyon. The canyon is incised completely through the Lagro Formation and into the upper part of the Huntertown Formation, which here contains thick, extensive sections of sand. Consequently, parts of the upper segment of the canyon are underlain by composite sections of sand and gravel up to 80 feet thick.

The mouth of the former tunnel valley is located at the head of the canyon, and is flanked by the remains of an outwash fan that impinges on the southeastern side of the Eel River Valley. The meltwater deposited much of its load of outwash within the fan as it discharged from the ice front, although some outwash was also carried southwest by meltwater flowing down the Eel River (see sidebar, **Origin of the Interlobate Landscape in Northwest Allen County**, pages 34-35).

The lower segment of Cedar Creek Canyon also appears to have carried Erie Lobe meltwater, but it is less clear whether this segment originated as part of the tunnel valley. Its differing morphology suggests that it could have formed later, as the ice front was retreating back from the crest of the moraine. Thick sand and gravel is less common below this segment of the canyon, which is mostly underlain by a veneer of outwash deposited over a variety of lacustrine and ablation sediments of the Huntertown Formation. Thick sections of loam till and lesser sand and gravel of the Trafalgar Formation are typically present at somewhat greater depth.

In any event, early drainage through at least the upper section of the canyon was clearly northwestward to the Eel River. The Eel River Valley subsequently became choked with outwash near the mouth of the former tunnel valley, however, causing drainage in the canyon eventually to reverse as it was captured by headward erosion of Cedar Creek from the newly formed St. Joseph River. These events ultimately led to the establishment of the drainage divide that today characterizes the upper part of the modern Eel River Valley. Bleuer and Moore (1974; 1978) provide a more detailed discussion concerning the drainage history of Cedar Creek.

St. Joseph River Valley

The St. Joseph River flows in a narrow, deeply entrenched valley at the front of the north limb of the Fort Wayne Moraine (fig. 9, pl. 5). Over most of its course in Allen County it is the only feature that separates the otherwise broad belt of rugged morainal topography collectively formed by the north limbs of the Wabash and Fort Wayne Moraines. The bottom of the valley is generally flat or gently sloping, and is flanked by large outwash terraces that range from a few feet to as much as 60 feet higher than the modern floodplain. The walls of the valley range from precipitous to gentle and are composed predominantly of outwash and(or) clayey till of the Lagro Formation. A veneer of sandy or loamy alluvium is commonly present along the floodplain.

The modern valley originated as an ice-marginal channel when the Erie Lobe stood at the Fort Wayne Moraine. It drained the entire ice front in Allen County and adjacent Dekalb County, consequently it carried a large volume of meltwater. This led to deposition of an extensive outwash train along the entire length of the valley. This body of outwash can be traced southwest into the upper part of the Wabash-Erie Channel, indicating that the river drained to the southwest early in its history. Subsequent post-glacial incision of the river helped to deepen the valley and left the large outwash terraces as remnants of the once-massive valley train. Despite the large degree of post-glacial downcutting evidenced by these terraces, some parts of the valley bottom are underlain by as much as 50 to 60 feet of Erie Lobe outwash, which suggests that the outwash within some parts of the valley was probably well over 100 feet thick shortly after its deposition.

Subsurface evidence suggests that the course of the ice-marginal valley may have been partly determined by much earlier events. Extensive bodies of lacustrine sediments are present beneath the Erie Lobe outwash (pl. 4), and they interfinger with outwash, till, and ice-contact sediments of the Huntertown Formation to the northwest. The geometry of these Saginaw Lobe sediments indicates that they probably were deposited along the northern, or ice-contact, edge of the basin of the Fort Wayne phase of ancestral Lake Erie. Consequently, the course of the modern river valley appears to follow a relict topographic basin that originated long before the Fort Wayne Moraine and its ice-marginal channel were formed.

Arcola Plain

The Arcola plain is a mostly flat or very gently rolling, locally featureless expanse which is situated in front of the north limb of the Wabash Moraine in western Allen County (fig. 9, pl. 5). This region occupies virtually all of Lake Township (fig. 4) and extends into small parts of adjoining townships. It is named for the Town of Arcola, which lies in the south-central part of the region. The distinguishing features of this region are the pervasively washed appearance and very poorly drained character of the landscape. Local relief greater than a few feet is lacking except near two large abandoned meltwater channels, which contain expansive wetlands and thick accumulations of organic sediments. Small peat bogs are common, and a few small natural lakes occur in the northern part of the region.

Virtually all of the surface terrain characteristics indicate that the Arcola plain was shaped by large-scale meltwater discharges from the front of the Erie Lobe when it stood at the Wabash Moraine. Much of the meltwater appears to have flowed across the landscape as a broad sheet, locally coalescing into well-defined channels. Two abandoned high-level meltwater channels, each more than a mile wide in some places and extending several miles west from the moraine, appear to have been cut by large meltwater torrents discharged from prominent openings in the morainal front. Large portions of these channels are now almost completely filled by younger sediments as much as 65 feet thick.

Much of the landscape elsewhere in this region is underlain by clayey till of the Lagro Formation, commonly veneered by outwash, lacustrine mud, and(or) a lag of cobbles and gravel. The collective thickness of the till and lacustrine mud is usually in the range of 40 to 60 feet. The largest bodies of outwash form terraces up to 20 or more feet thick that flank the two large meltwater channels, and portions of the northern channel near and east of Lake Everett are also underlain by outwash at depth. Variably thick sections of silt and clay also are widespread, and appear to have been deposited in lakes and ponds that formed as the flow of meltwater diminished. A test hole drilled by IGS in the southernmost meltwater channel near Arcola penetrated 68 feet of lacustrine clay before bottoming out in till.

The vertical sequence beneath large parts of the Arcola plain is characterized by thick till sections that contain widely scattered sand and gravel bodies. In most places, a substantial portion of this sequence is composed of loam till of the Trafalgar Formation, which directly underlies the clayey surface till of the Lagro Formation in most places and is commonly 75 to 100 feet thick. Pre-Wisconsin till units up to 150 feet thick underlie the Trafalgar Formation in some places, particularly in buried bedrock valleys, where the aggregate thickness of all till units can be as great as 250 to 300 feet. Sand and gravel bodies within this till sequence have a limited distribution, and tend to be localized along several horizons. Relatively shallow sand and gravel units of small areal extent are associated with the buried feather edge of the Huntertown Formation in the northern part of the region, and with the intersequence zone between the Lagro and Trafalgar Formations further to the south. Somewhat larger and more persistent sand and gravel units occur at greater depths, chiefly at the base of the Trafalgar Formation and along the bedrock surface, particularly in buried bedrock valleys.

Maumee Lacustrine Plain

The Maumee Lacustrine Plain (for simplicity, referred to hereafter as the "lake plain") occupies most of the east-central part of the county (fig. 9, pl. 5). This low-lying and poorly drained landscape contains even less relief than the Arcola plain. It represents the former bottom of ancestral Lake Erie during the Maumee phase (fig. 7). The lake plain is bisected by the small valley of the Maumee River, which was discussed earlier under alluvial valleys.

Three somewhat different terrain subregions can be identified within the lake plain region. The first includes all of the lake plain south of the Maumee River. This is the flattest part of the lake plain, and other than a few small beach ridges and bars, has virtually no relief of any kind. The southern lake plain is underlain by laminated lacustrine mud as much as 10 feet thick that overlies tills of the Lagro and Trafalgar Formations, respectively. Depth to the limestone bedrock is relatively shallow over large parts of this area and ranges from less than 30 feet to more than 70 feet. Other than a thin veneer of beach sand atop the bars and beach ridges, bodies of sand and gravel are virtually absent below this part of the lake plain.

The second subregion includes much of the lake plain north of the Maumee River. Although relatively flat, this area exhibits a gentle, but noticable, southward slope. A slightly greater amount of local relief is also present in the form of more numerous beach ridges, bars, and small stream valleys. Small blankets of beach sand, generally less than 5 feet thick, are present over many parts of the land surface. The sequence of glacial deposits is similar to the southern area but is generally thicker, being about 40 to 60 feet thick just north of the river, and as much as 150 feet thick near the northern edge of the lake plain. The marked northward thickening of unconsolidated deposits is due to two factors:

1) the elevation of the land surface gradually rises by about 40 feet between the river and the northern edge of the lake plain; and
2) the elevation of the bedrock surface falls sharply in the same direction.

The greater thickness of the glacial deposits is partly accounted for by a corresponding increase in the thickness of the Trafalgar Formation, which contains larger and more numerous bodies of sand and gravel to the north, particularly along its base. Also contributing is the appearance of a northward-thickening wedge of lacustrine sand and silt between the Trafalgar and Lagro Formations (pl. 4), which represents the distal edge of the Huntertown Formation.

The third subregion includes the extreme northern margin and western apex of the lake plain, and represents a major swash zone. It is characterized by numerous large beach ridges, spits, and bars, as well as a sizable dune field that was derived from adjacent beach deposits. The northern limit of the lake plain is sharply defined by a large complex of beach ridges that extends along the entire reach between the head of the Wabash-Erie Channel and the Ohio state line (fig. 9, pl. 5). The largest ridges are up to 30 feet tall. In most places, they are composed mostly or entirely of wave-deposited sand and gravel, although in some ridges the beach deposits form a veneer only a few feet thick over wave-stripped benches of till. A persistent blanket of beach sand up to 10 feet thick is widely present directly in front (lakeward) of the beach ridge complex in a band up to a mile wide. Large bodies of lacustrine sand and silt of the Huntertown Formation, some up to 50 feet thick, underlie thin till of the Lagro Formation throughout much of this northern beach zone. In a few places where wave erosion has removed the Lagro Formation, these older lacustrine deposits are present directly below the newer beach deposits. Otherwise, the vertical sequence and depth to bedrock below the swash zone are generally comparable to the rest of the northern half of the lake plain.

In and east of the City of New Haven, the apex of the lake plain is covered by an extensive blanket of beach sand up to 20 feet thick, which is locally covered by sand dunes as high as 25 feet (pl. 5). East of New Haven, these deposits overlie fine-grained lacustrine sediments and discontinuous till of the Lagro Formation, but closer to New Haven they lie directly on the Trafalgar Formation. Throughout this area, small- to medium-sized bodies of sand are common along several horizons within and between both till units.

Wabash-Erie Channel

The Wabash-Erie Channel represents the principal outlet of the Maumee phase of ancestral Lake Erie. It is generally a flat-bottomed valley as much as two miles or more wide that extends from the apex of the Maumee Lacustrine Plain to the west county line (fig. 9, pl. 5). The bottom of the valley is very poorly drained and contains remnants of a once vast wetland that has since been extensively drained. Sediments below the floor of the outlet are highly variable from place to place, and vertical sequences can be categorized only in the broadest terms.

Several distinct segments of the channel can be identified based on bottom elevation and morphology. The head of the channel has been referred to as the "Fort Wayne Outlet" (Bleuer and Moore, 1974; 1978) because it is cut through the Fort Wayne Moraine between the lake plain and downtown Fort Wayne. This segment, which is now occupied by the upper part of the Maumee River Valley, has a bottom (floodplain) elevation of between 740 to 750 feet.

West of the St. Marys River, the channel is as much as 2.5 miles wide and has two distinct, parallel halves separated by a low ridge. Just west of the confluence of the St. Joseph, St. Marys, and Maumee Rivers, the flat floor of the north half of the channel rises gently to about 755 feet and forms a drainage divide about a mile west of the St. Marys River. The southern half of the channel is more irregular, and contains the remnants of an Erie Lobe outwash fan as well as several large sand dunes. Elevations range from less than 760 feet along the narrow floor of this half to as much as 790 feet on outwash terraces and dunes.

West of the St. Marys River, the two halves of the channel gradually merge into a single 2-mile-wide channel near the boundary between Wayne and Aboite Townships (figs. 4 and 9). West of here, the channel maintains a near-perfectly flat profile, narrowing in width to just over a mile and falling almost imperceptibly in elevation to about 750 feet at the west county line.

The surficial geology and vertical sequences below the outlet (pl. 5) are among the most variable and complex of any terrain region in Allen County. In general, most vertical sequences consist of one or more assemblages of outwash and(or) post-glacial sediments deposited atop the scoured surface of the Trafalgar Formation (pl. 4). The composition of the Trafalgar Formation ranges from all till to all sand and gravel. Thick sections of sand and gravel below some parts of the outlet appear to be channel deposits within the Trafalgar that were exhumed during the meltwater torrent that scoured out the channel.

Surficial sediments are even more variable. A large, thick body of Erie Lobe outwash underlies much of the channel between the Fort Wayne Outlet and the drainage divide west of the St. Marys River, and a second body of outwash occupies the head of the southern half of the channel as well as some of the intervening ridge between the northern and southern halves. Elsewhere there are complex assemblages of alluvial, lacustrine, and palustrine sediments. These sediments are composed of different proprtions of silt and sand and are up to 35 feet thick where they fill the more deeply scoured parts of the channel. Sand dunes, organic sediments, and modern alluvium cap the sequence in many parts of the channel. The depth to limestone bedrock is generally less than 50 feet below much of the channel.

HYDROGEOLOGIC FRAMEWORK AND PRINCIPLES

by Anthony H. Fleming and William J. Steen

OVERVIEW

There are few published studies concerning ground water in Allen County, and most of these are related chiefly to generalized ground-water availability (Planert, 1980; Herring, 1969; Pettijohn and Davis, 1973). Selected geochemical characteristics of ground water were described by Foley and others (1973). There are no published studies that relate the occurrence, movement, or protection of ground water to a well-documented stratigraphic framework. The purpose of this chapter is to fill that gap by identifying the hydrogeologic framework of Allen County as it relates to the bedrock and glacial sequences described in the preceding chapter.

Ground water is produced in Allen County from the limestone bedrock as well as sand and(or) gravel bodies in the glacial deposits (table 4). Productive zones and units within these formations are generally referred to as **aquifers**. Aquifers in the bedrock and glacial deposits are commonly separated from one another by less permeable materials called **confining units**. Glacial till, lacustrine mud, and shale are the principal confining units in Allen County.

The particular origin and geometry of aquifers and confining units determines the degree to which individual aquifers are directly interconnected to form an **aquifer system**. In some places, aquifers are geographically isolated from each other or are hydraulically isolated by thick sections of fine-grained glacial till, lacustrine sediment, or shale. In other instances, however, permeable deposits have coalesced on a large scale to form regionally extensive aquifer systems, such as the Huntertown aquifer system of northwestern Allen County. An aquifer system usually shows a well-defined ground-water **flow system** with one or more characteristic regional flow directions as well as recharge and discharge areas.

This chapter describes these major hydrogeologic elements and their relationships to the geologic framework of Allen County. Emphasis is placed on the identification of and interaction between a number of key hydrogeological factors that affect the rate of ground-water movement, recharge rates, ground-water availability (well yields), and the sensitivity of aquifers to contamination.

AQUIFER CHARACTERISTICS

The term "aquifer" has traditionally been defined to mean any body of rock or unconsolidated sediment capable of producing ground water to a well in an economically useful amount (Maxey, 1964). From a slightly different perspective, an aquifer could also be defined as any unit capable of transmitting contaminants at a rate significantly greater than surrounding materials. This is in contrast to a "confining unit," which generally restricts ground-water flow, helps to retard contaminant migration, and typically is not capable of yielding significant amounts of water to a well. An important point is that *all* the geologic materials in Allen County contain and are capable of transmitting at least a limited quantity of ground water, albeit some much more slowly than others.

The ease with which ground water can flow through any particular geologic material is generally referred to as the **hydraulic conductivity** of that material. The similar term "**permeability**" is probably better known to most people, and although its meaning differs from "hydraulic conductivity" in a strictly technical sense, it is used in a roughly equivalent way in this report.

Aquifers of various types, shapes, and thicknesses are present in Allen County, and can be classified into two general categories according to their geology. The first includes productive beds and zones within the limestone and dolomite bedrock. Such zones are generally present in the bedrock throughout the county. The bedrock is used extensively as a source of ground water by industry, municipalities, and individual homeowners, particularly in the southern half of the county. The second basic aquifer group consists of the various sand and gravel units contained within the glacial deposits. Some of these units are present locally at the land surface, but in most places they typically occur below the clayey till of the Lagro Formation.

Limestone Bedrock

Ground water within the bedrock occurs along planar openings such as bedding planes and fractures, which may become enlarged over a long period of time to form **solution features** (see sidebar, **Karst: Characteristics and Origin**, page 16). Landscapes typified by a large number of well-developed solution features, such as sinkholes and caves, are referred to as **karst**. Karst areas are well known for their characteristically great ability to transmit large volumes of ground water, and where saturated, they represent one of the most productive kinds of aquifers.

The buried surface of the carbonate bedrock in Allen County appears to at least partly represent a karst landscape that existed prior to glaciation. Joints and bedding planes observed in most exposures of the bedrock commonly show some enlargement, and a variety of other somewhat larger solution features are locally present. Small caves in the bedrock have also been reported by drillers during the construction of several water wells. In Allen County, most of the known solution features are concentrated in the upper 20 to 30 feet of the bedrock.

Abrupt and unpredictable spatial variations in the number and size of water-bearing openings in the carbonate bedrock can cause large differences in the yield of wells from place to place. The amount of ground water available to a particular well in the bedrock depends on the size and number of open fractures and solution features intersected by the borehole. Wells that penetrate an interconnected network of fractures and solution features will generally yield more water than those tapping only an isolated fracture. Yields may also be greater in places where the bedrock is directly overlain by sand and gravel, which can release large quantities of water from storage to parts of the fracture network that intersect the bedrock surface.

Major supplies of ground water are available from the carbonate bedrock in many parts of the county, and it is not uncommon for properly constructed large-diameter wells to yield 100 to 600 gallons per minute (gpm) or more. On the other hand, localized areas of limited ground-water availability from the bedrock also occur in some parts of the county. It is difficult to predict the locations of such areas in advance, but some generalizations about the productivity of bedrock aquifers can be made at the scale of the entire county (fig. 10a).

It might be reasonable to assume that well yields will be greater in areas underlain by the Devonian carbonates, because they are mainly limestone and thus more soluble than the Silurian rocks, which are mainly dolomite. Contrary to this expectation, however, there does not appear to be a strong relationship between well yield and the distribution of carbonate bedrock formations (pl. 2), because all of these units contain both high- and low-yielding areas. Instead, well yields appear to show a more pronounced relationship to the gross morphology of the bedrock surface, and may be controlled more by geography than by stratigraphy. Solution features appear to be more numerous and well yields are generally somewhat greater in western and northwestern Allen County than elsewhere. In contrast, fewer karst features have been reported on water well records from areas further east, and some areas in the extreme eastern part of the county, such as near the City of Woodburn, have experienced problems in developing high-capacity wells.

Several factors could be contributing to these broad geographic differences, but the more prominent possibilities include better pre-glacial karst development as well as differing degrees of karst preservation due to differential intensity of glacial erosion along the bedrock surface. For example, the bedrock surface in eastern Allen County lay along the axis of ice flow out of the Huron-Erie Basin and

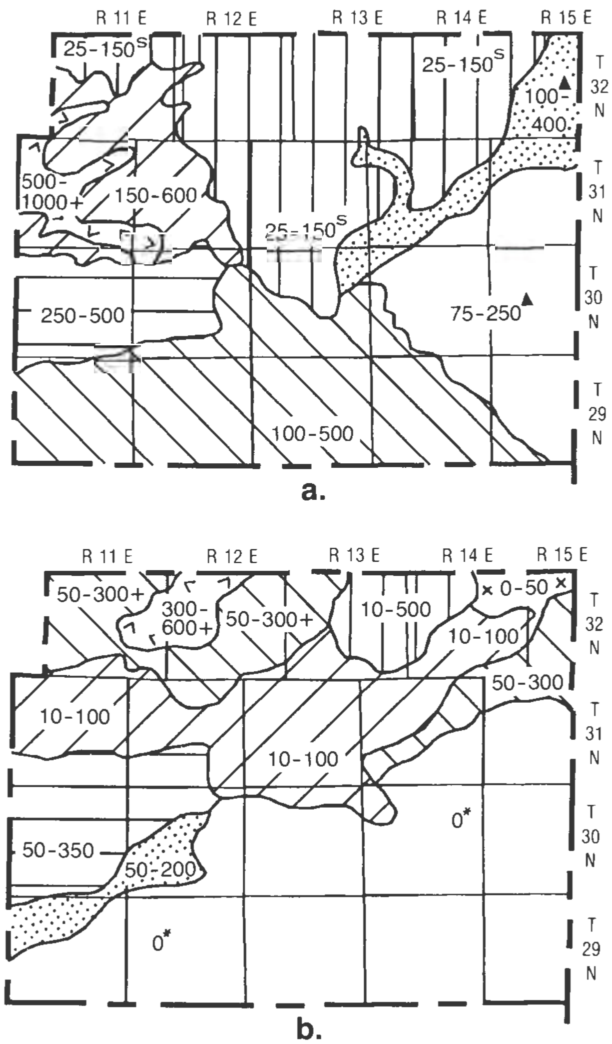


Figure 10. Generalized ground-water availability in Allen County, in gallons per minute (gpm): a) bedrock aquifer system; b) sand and gravel aquifers. [Symbols: * = sand and gravel aquifers are generally absent over this region, although a few widely scattered sand and gravel units on the bedrock surface may locally yield up to 200 gpm; + = much larger yields are documented from some parts of these regions; ▲ = localized areas of limited ground-water availability are known from these regions, and ground water typically contains some hydrogen sulfide; s = hydrogen sulfide is common in ground water from this region.]

was severely scoured, not only during the late Wisconsin glacial advances, but presumably during several pre-Wisconsin glaciations as well. The repeated scouring removed an unknown, but probably large thickness of weathered and karsted bedrock from the pre-glacial surface in this area. In contrast, the bedrock over much of western and northwestern Allen County is overlain by deposits that may be pre-Wisconsin in age, but in any event are significantly older than the late Wisconsin Trafalgar and Lagro Forma-

Table 4. Geology and nomenclature of aquifers and aquifer systems in Allen County and the map units used to identify them on Plate 6. Some of these sand and gravel units also occur as geographically isolated aquifers that are not part of one of the mapped aquifer systems.

Aquifer System	Aquifer Geology	Map Unit (plate 6)
Huntertown aquifer system	Outwash in Eel River, Cedar Creek, St. Joseph River	Os, Oh, O/h
	Ice-contact stratified deposits, Huntertown Formation	Hbi, Hfc
	Basal outwash sand, Huntertown Formation	Hb, Hbi
	Fan-deltas, Huntertown Formation	Hd
	Lacustrine sand, Huntertown Formation	Is, Im
Aboite aquifer system	Erie Lobe outwash in Wabash-Erie Channel, locally coalesced with subjacent sand and gravel units	Os, Otc
	Intersequence unit	I
	Sand and gravel in aprons and channels (Trafalgar Formation)	Tx, Tc
	Basal outwash sand and gravel (Trafalgar Formation)	Tb
	Pre-Trafalgar sand and gravel (northern part only)	ts
	Limestone bedrock (southern part only)	b
Bedrock aquifer system	Sand and gravel on bedrock surface and in buried bedrock valleys	Tb, ts, b
	Fractured and karsted limestone and dolomite	b

tions. This relationship indicates that this part of the bedrock surface did not undergo any scouring by the Huron-Erie Lobe or the Erie Lobe during the late Wisconsin Age, resulting perhaps, in better preservation of pre-glacial karst features.

It is possible, however, that pre-glacial karst features in western and northwestern Allen County were better developed to begin with by virtue of the presence of the deeply-incised Metea Bedrock Valley and its numerous tributaries (pl. 2). Although the configuration and characteristics of the pre-glacial hydrogeologic regime are largely unknown, it does seem almost certain that these large valleys formed major ground-water discharge areas. If this was the case, then it is also reasonable to assume that the water table in the adjacent valley walls would have been substantially lowered for a considerable distance away from the valleys themselves, at least relative to pre-glacial "uplands" far from the valleys. Such a condition would have been highly conducive to deep karst development and could help explain the seemingly greater yields of wells drilled into bedrock in the general vicinity of this bedrock valley system. At least one bedrock well in that area had an estimated yield in excess of 1,500 gpm, but data are currently insufficient to conclusively evaluate the effect of this bedrock valley system on overall ground-water availability.

Sand and Gravel Aquifers

Ground water within sand and gravel occurs in the spaces between individual rock and mineral particles. These spaces, known as pores, vary considerably in size, shape, and degree of interconnection, depending on conditions particular to the geologic environment in which the sediment was deposited. In general, three conditions collectively determine the relative ability of sand and gravel to store, transmit, and release water to a well:

1) Particle size and shape: With progressively larger particle sizes, the sizes of individual pores and the degree of interconnection between them are correspondingly greater, which results in a greater ability to transmit water. Likewise, the more nearly round the particles, the larger and more uniform the pore spaces are;
2) Sorting: The more alike in size the grains in a sediment are, the more uniform and well-connected are the pores. In contrast, sand and gravel that contains a significant quantity of relatively finer sediment (for example, silt, clay, or a much finer sand size) will be characterized by reduced permeability, because smaller particles will partially fill pore spaces between the larger grains and thus obstruct ground-water flow; and
3) Size and shape of the sand and gravel body: The overall ability of a particular sand and gravel body to store and transmit ground water is directly proportional to its thickness and lateral continuity.

Because of the complex nature of the glacial depositional environment, individual bodies of sand and gravel can exhibit a considerable range in the above properties within short distances. Fine sand deposits may abruptly grade into coarse sand and gravel, or be reduced to paper-thin layers interbedded with silt, till, or other fine-grained material. Despite this variation, however, a number of generalizations can be made regarding the characteristics of sand and gravel units formed in different depositional environments. Sand and gravel deposited as outwash in large, high-energy meltwater channels or fans draining the front of an ice margin tends to be coarse, well-sorted, and laterally extensive. In contrast, sand and gravel associated with ice-contact stratified deposits or lakes is more likely to be muddy, of limited lateral extent, and(or) interbedded with lenses of fine-grained mudflow sediments, till, or lake mud. Sand and gravel deposited in ice-walled channels (for example, those of the Trafalgar Formation in western Allen County) are coarse and well sorted in many places, but also contain poorly sorted materials and lenses of fine-grained sediment, especially near the former walls of the channel.

Many sand and gravel aquifers in Allen County are associated with the Trafalgar and Huntertown Formations (pl. 6), with the largest bodies occurring as outwash at the base of each formation. The basal outwash of the Trafalgar Formation (unit Tb, pl. 6) forms small to large bodies of coarse sand and gravel that are widely distributed throughout the county. The unit commonly rests on the carbonate bedrock in the southern half of the county. It attains thicknesses in excess of 30 feet in parts of western Allen County, where it is locally overlain by thick channel deposits.

Throughout much of western Allen County, as well as in scattered locations elsewhere, the horizon between the Trafalgar Formation and the overlying Lagro Formation is also marked by a pervasive sheet of outwash (unit I, pl. 6). This intersequence unit tends to be composed of coarse sand and some gravel in western Allen County, and forms an integral part of the Aboite aquifer system in that area. In many places it coalesces with large, thick channel-like bodies of sand in the underlying Trafalgar Formation, some of which extend completely to bedrock. In contrast, the intersequence unit in eastern Allen County mostly occurs as small, isolated bodies that appear to have been deposited in lakes and ponds as part of the Lagro Formation. They are composed chiefly of fine sand, are locally interbedded with finer materials, and are generally less productive aquifers.

Outwash at the bottom of the Huntertown Formation is composed chiefly of sand, and is present over a substantial part of northwestern Allen County (pl. 6). The distribution and thickness of this unit are in large part controlled by the topography of the buried Trafalgar surface (pl. 4). The unit forms a small outwash plain over the gently undulating Trafalgar surface in the vicinity of Huntertown. To the south and east, however, Saginaw Lobe meltwater evidently occupied several prominent southeast-trending valleys which are now filled by outwash deposits that locally attain thicknesses in excess of 40 feet. Several of these valleys lead into the basin of ancestral Lake Erie, and the outwash grades into progressively finer sand that was presumably deposited as deltas where the meltwater channels emptied into the lake. Overall, the basal outwash is the most persistent and productive aquifer of the Huntertown Formation.

Ice-contact stratified sediments in the upper and middle part of the Huntertown Formation also form locally prominent aquifers, especially where they occur in relatively large fans along former ice margins (unit Hfc, pl. 6). Some of the larger fans are superposed directly on the basal outwash, forming large composite sand and gravel aquifers 60 or more feet thick. In many places, however, the ice-contact stratified deposits are more discontinuous and irregularly interstratified with finer sediments (unit Hbi, pl. 6), and their hydraulic properties are generally less uniform and predictable than those of the basal outwash. The basal outwash aquifer is generally present below all the ice-contact stratified units, and is typically the aquifer of choice for most water well installations in northwestern Allen County.

A variety of surficial sand and gravel bodies are present in several parts of the county, particularly in low-lying parts of the landscape (pl. 5). Examples include outwash in terraces and river valleys, dune sand, beach sand and gravel, and medium- to coarse-grained alluvium. Although many of these bodies are well sorted and commonly occur under saturated conditions, they are rarely of sufficient thickness or lateral extent to form significant water supply aquifers. Because these bodies are considerably more permeable than most of the other surficial sediments in the county, however, they do represent potential conduits for the migration of contaminants, especially where they are interconnected to larger aquifers at depth.

Of the surficial deposits, only the outwash bodies within the Eel and St. Joseph River Valleys are of sufficient thickness and extent to constitute useful water supply aquifers. These deposits typically attain saturated thicknesses of 30 to 60 feet, and can be expected to yield moderate amounts of water up to about 200 gpm, particularly if wells are properly constructed. In many places these units are less than 50 feet thick, however, which limits their potential for high-capacity wells. On the other hand, localized areas of significantly greater productivity in both of these valleys can usually be attributed to the presence of older sand and gravel aquifers directly below the surficial outwash.

Sand and gravel aquifers associated with the Aboite and Huntertown aquifer systems offer good potential for high-yielding wells (fig. 10b), as do a number of deep intertill aquifers (unit ts, pl. 6) in northern Allen County. It is not uncommon for large diameter wells screened in the thicker portions of these systems to yield from 150 to 500 gpm, especially in the northern and northwestern parts of the county, where large bodies of sand between 20 and 80 feet thick are prominent in the Huntertown aquifer system. Areas near Huntertown and westward exhibit excellent potential for ground-water supply development, and a few very thick (>100 feet) sand and gravel units in these areas could be expected to yield up to 500 to 1,000 gpm. Ground-water availability is discussed in greater detail in connection with the hydrogeologic regions described in Chapter 4.

CONFINING UNITS

The principal confining units in Allen County include the Antrim Shale, several glacial till units, and various fine-grained lacustrine deposits. Most of the fine-grained lacustrine units occur in eastern Allen County, where they are closely associated with the Lagro Formation. The Antrim Shale and the glacial tills are more extensive and are the focus of this section.

Antrim Shale

The Antrim Shale lies atop the carbonate bedrock over a sizable portion of northern Allen County. No exposures of the unit are known in northeastern Indiana and there are few data concerning its hydrogeologic characteristics. However, the physical and hydrogeological properties of the unit are likely to be similar to those of its correlative to the south, the New Albany Shale (Gray, 1982). The New Albany is generally a poorly bedded, non-fissile, weakly fractured shale. Well yields are generally low and ground water from the New Albany tends to be highly mineralized, indicating a long residence time and low permeability (Branam and others, 1991; Ripley and others, 1990; Shaffer and others, 1988; Shaffer and Yarling, 1991).

Available data for the Antrim Shale generally indicate similar characteristics. A few widely scattered domestic wells are developed in the Antrim Shale in northern Allen County. All these are reported to yield less than 15 gpm and most are less than 5 gpm. The highest yields appear to be associated with the lower part of the formation, which contains some interbedded limestone, particularly to the northwest. Several of the well logs reported a strong sulfur odor or other objectionable qualities of the water. During this study, several of the local water well drillers indicated that they bypass the shale because it commonly yields no water or poor-quality water.

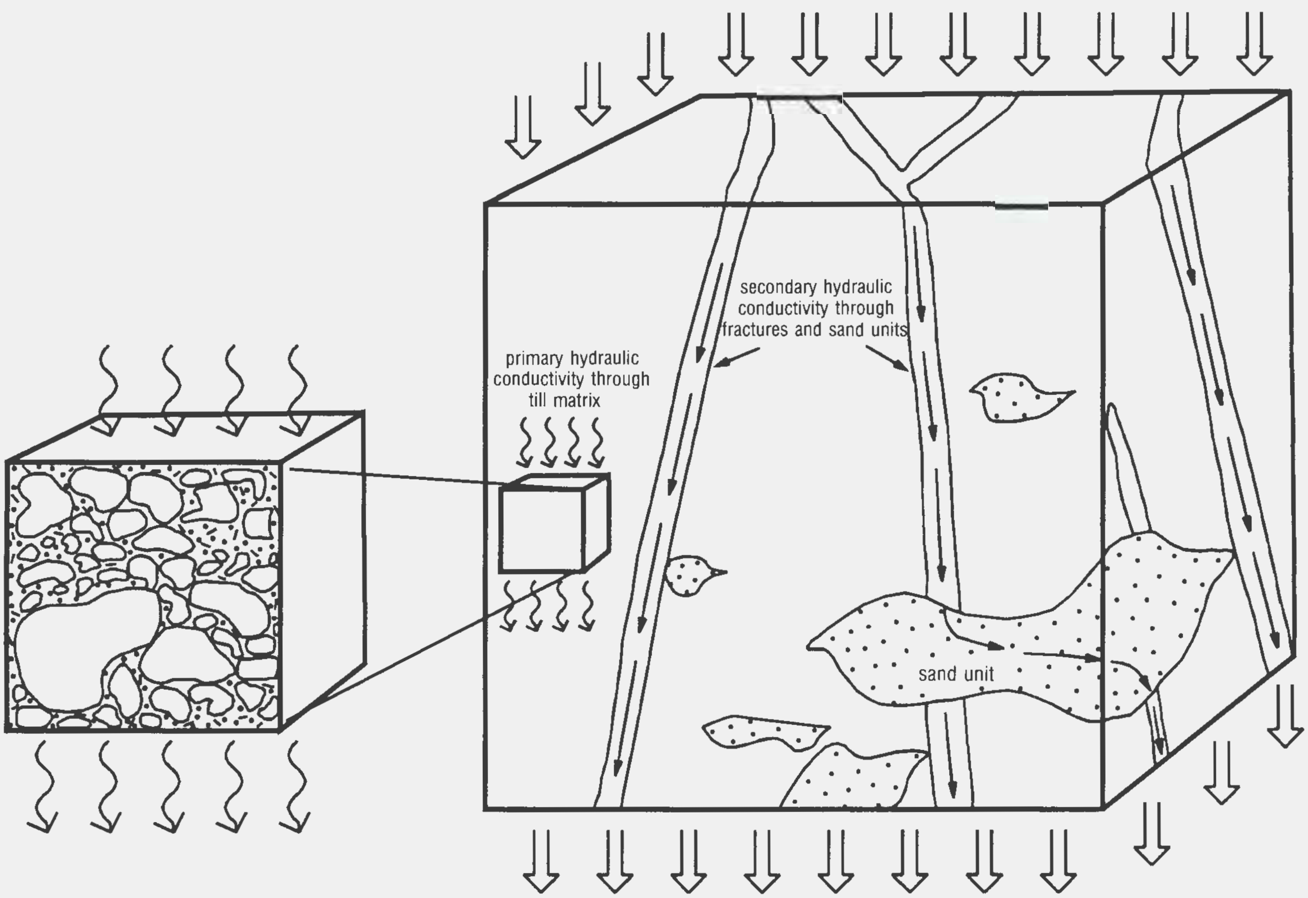
Although mostly inferential, the above evidence strongly suggests that the Antrim Shale is an effective confining unit. The degree to which the lower, limestone-bearing part of the formation is affected by solution features is unknown but is probably not great. Ground-water flow into and out of the underlying carbonate rock is likely to be severely limited in northeastern Allen County, where the shale is consistently 40 or more feet thick (pl. 2). A strongly confined condition in this area is suggested by highly mineralized ground water from the limestone, and by a generally consistent relationship of low well yields in the limestone to greater thicknesses of the shale.

Till Confining Units

Glacial till is the most common type of confining unit in Allen County. Several distinct till units are present, each occurring in a particular stratigraphic position with respect to each other and the principal aquifers, and each having a particular set of physical characteristics that determine its hydraulic integrity as a confining unit.

The most important confining unit is the clayey till that forms the bulk of the Lagro Formation. The till is present immediately below the land surface over more than three-fourths of the county and is likely to be the first material encountered by infiltrating precipitation or by contaminants released at or near the surface. Moreover, the till is the

Hydraulic Conductivity of Glacial Till and its Measurement



Bulk hydraulic conductivity

The hydraulic conductivity of glacial till can be of several types, depending on both the mode of deposition and postdepositional history of the particular unit in question, as well as the scale of measurement. Till is composed of an unsorted mixture of particles that range in size from clay to boulders. Till is deposited directly by glacier ice and is characteristically **overconsolidated**, due to the great weight of the overlying ice. Depending on the particular dynamics of the glacier during till deposition (stagnant or active) and the distribution of meltwater within the glacier, till may contain sand and gravel bodies that range from tiny layers a few millimeters thick to extensive channels tens of feet thick and hundreds of feet in length. In general, most till units contain some sand and gravel bodies, but in most places they are commonly small and isolated from one another.

The **primary hydraulic conductivity** is attributable to the matrix of the till. Because of its poorly sorted and overconsolidated nature, the primary hydraulic conductivity of fine-grained till is typically among the lowest of all unconsolidated sediments. This attribute has made till an attractive target for waste disposal sites because it is widely believed that the low primary hydraulic conductivity will prevent or at least greatly limit the migration of contaminants from these sites.

Hydraulic conductivity is scale-dependent, however, and many tills exhibit appreciable **secondary hydraulic conductivity** related to the presence of more permeable zones within it. Perhaps the best-known cause of secondary hydraulic conductivity is fractures. The origin of fractures in till is debatable, but in some units they form a well-connected network that essentially controls the majority of ground-water movement. The hydraulic conductivity of fractured tills ranges from ten to as much as 10,000 times greater than their unfractured counterparts (Stephenson and others, 1988). Secondary hydraulic conductivity may also be attributable to very small layers and seams of sand within the till, some of which may be difficult to see without careful inspection. Although the sand seams represent a different and better sorted material, they typically originated with the till during deposition and, for all practical purposes, are an integral part of the till unit.

The combination of primary hydraulic conductivity and secondary hydraulic conductivity associated with all of the fractures and sand seams within a large (many cubic meters) volume of till represents the **bulk hydraulic conductivity**. The value of bulk hydraulic conductivity usually falls somewhere between primary and secondary hydraulic conductivity. If the sand seams and fractures are large and collectively form a well-interconnected network that extends completely through the volume of till, then bulk hydraulic conductivity will be similar to secondary hydraulic conductivity. On the other hand, if the secondary features are small and essentially act only as isolated reservoirs, then the bulk hydraulic conductivity will more closely approximate primary hydraulic conductivity.

Hydraulic conductivity is measured in a variety of ways, all of which are scale-dependent. The most common laboratory method employs a device known as a **permeameter**, which places a hydraulic gradient across a small sample of till within a cylinder, and measures either the rate of water flux or the hydraulic head differential. There are several variations on this device; probably the most useful of these is a flexible-wall permeameter, which can measure the permeability of a relatively large, undisturbed block of material, which is likely to be more representative of actual field conditions. In contrast, many permeameter measurements are made on disturbed samples derived by disaggregating a block of till and then repacking it into a fixed-wall cylinder. This procedure typically underestimates the hydraulic conductivity because it does not take into account any secondary features and may also misrepresent the original arrangement of grains in the till matrix.

A common field technique is the slug test, which measures the response at a single well to adding or subtracting a known volume (slug) of water. Although it has certain limitations, the larger scale of this method is more likely to detect secondary hydraulic conductivity, which is usually associated with features too large to be represented in a typical laboratory sample. A wholly different type of field method operates at a much larger scale by utilizing measurements of selected natural and manmade radioactive isotopes (such as radiocarbon, oxygen, tritium) to estimate the age of ground water at different depths. Under favorable conditions, this approach yields very precise estimates of vertical hydraulic conductivity because the time of recharge of ground water at different depths is known. This geochemical technique is probably the most representative measure of bulk hydraulic conductivity, because it averages the effects of both primary and secondary hydraulic conductivity over a scale of tens or hundreds of cubic meters.

principal, and in many places the only material confining large parts of the Huntertown and Aboite aquifer systems. Its hydraulic properties are, therefore, of fundamental importance in determining the potential recharge and sensitivity to contamination of underlying aquifers.

The Lagro till is typically very stiff, contains very few sand bodies, and is composed of at least 35 percent clay. Consequently, it can be expected to have very low primary permeability (see sidebar, **Hydraulic Conductivity of Glacial Till and its Measurement,** pages 44-45). Laboratory tests conducted by IGS on large, undisturbed blocks of the till indicate that the matrix permeability is typically on the order of about 0.00003 feet per day (10^{-8} centimeters per second) or less (table 3). In addition, the high clay content of the till should provide a very good capacity to **attenuate** contaminants through cation exchange and other sorption reactions.

Fine-grained deposits such as the Lagro till are usually only slowly permeable, thus they tend to retard the downward movement of water. Consequently, if the permeability of a particular deposit is uniformly low, the ground water within it should become progressively older with increasing depth, reflecting correspondingly older times of recharge. Exposed sections of the till, however, commonly exhibit a pervasive system of vertical fractures that show abundant evidence for water movement, such as large oxidation haloes, and deposits of calcite and oxides of manganese and iron. The fractures can be expected to significantly increase the **secondary permeability** of the till (see sidebar, **Hydraulic Conductivity of Glacial Till and its Measurement**, pages 44-45), at least within the upper 20 feet of the unit, where they are mostly concentrated. By providing preferred pathways of greater permeability that allow water and contaminants to bypass the slowly permeable matrix of the till, the presence of well-developed secondary permeability can reduce the ability of the till to protect underlying aquifers from contaminants. Evidence for such pathways usually appears in the form of anomalously young ground-water ages or other unexpected chemical characteristics in the ground water at depth in or below the till.

Hydrogeologic and geochemical data from wells installed within a thick section of the Lagro Formation in southwestern Allen County indicate that water within the till is mostly of modern origin (post-1953) to a depth of at least 20 feet (Ferguson, 1992; Ferguson and others, 1991; 1992). The same data also suggest that some modern water is being recharged to depths of up to 40 feet. The presence of modern water at either of these depths would not be expected based solely on the low laboratory permeability values cited above, but it is consistent with the presence of a systematic set of vertical fractures. On balance, the geochemical and well recovery data from this site suggest a bulk vertical permeability of between 0.03 and 0.0003 feet per day (10^{-5} to 10^{-7} cm/sec) (IGS, unpublished data). This is in accord with results of IGS laboratory tests on blocks of fractured till, and with published values in the literature for other fractured tills (Hendry, 1982; 1988; Grisak and Cherry, 1975; Stephenson and others, 1988). Not surprisingly, the geochemical data tend to confirm field observations indicating that the bulk of the fractures are concentrated in the first 20 feet of the till below the ground surface.

The above characteristics suggest that the fractured till of the Lagro Formation may act as a leaky confining unit, at least where the formation is less than about 20 feet thick. Based on current information, however, there is no indication that significant numbers of fractures extend to depths much greater than this, and all of the physical and geochemical characteristics suggest that greater thicknesses of the till are likely to form an excellent confining unit. The till exceeds 40 feet in thickness over large regions of the county, especially along the north limbs of the Wabash and Fort Wayne Moraines, where thicknesses of 60 to 80 feet are not uncommon (pl. 5). Recharge to subjacent aquifers through such a thickness of fine-grained till is likely to be minimal, possibly being less than 2 inches (5 cm) per year based on the data given above.

Sandy loam to loam till of the Huntertown Formation locally occurs below the Lagro Formation in the northern part of the county. The till is commonly broken by numerous, small to large sand bodies, and its thickness is known to change by tens of feet over short distances. In many places, the till occurs as irregular discontinuous bodies up to 50 feet thick within the sand and gravel deposits of the Huntertown Formation.

No permeability data are available for the till of the Huntertown Formation. However, there appears to be little, if any, difference in water levels in adjacent wells screened in aquifers immediately above and below bodies of the till. This relationship suggests that the till is very leaky, presumably because of its discontinuous nature and(or) the abundant sand units within it, both of which provide numerous hydraulic connections between higher and lower aquifers. For this reason, the till is not interpreted as a regional confining unit. It is instead considered to act as a leaky confining unit within the Huntertown aquifer system that locally separates the shallower and deeper parts of the system.

Overconsolidated loam till of the Trafalgar Formation is widespread in the subsurface throughout the county. The till locally attains thicknesses in excess of 100 feet, especially to the northeast, and large parts of the till appear to be free of large or extensive sand and gravel bodies. The till confines the bedrock aquifer system and deep sand and gravel bodies, such as the basal outwash in the Trafalgar Formation.

Permeability data for the Trafalgar till (table 3) show a considerable range and are indicative of the importance of very small sand seams in transmitting ground water through the unit. Laboratory tests performed on large, undisturbed blocks of till with no apparent sand seams yielded permeabilities in the range of 0.0003 feet per day (10^{-7} cm/sec). Blocks with small (<0.1 inches thick) sand seams yielded permeabilities as great as 0.03 feet per day (10^{-5} cm/sec), especially when water flow was directed along the near-horizontal fabric of the till, parallel to the sand seams. Geochemical data and water level recovery rates for wells in the till in southwestern Allen County also suggest that the unit has an appreciably greater permeability where small sand seams are present (Ferguson and others, 1991; 1992).

Comparison of the data for tills of the Lagro and Trafalgar Formation (table 3) indicate comparable ranges of permeability and suggest that the sand seams in the Trafalgar have a similar overall effect on the rate of ground-water movement as the fractures do in the Lagro. However, these effects differ in two critical respects. First, the abundance, size, and distribution of the sand seams are less predictable, whereas the geometry of the fractures is at least somewhat better known (see section on **General Setting**, page 11). More importantly, the great majority of fractures in the Lagro are oriented near-vertical and therefore tend to increase the vertical component of ground-water flow, whereas the sand seams are predominantly horizontal or gently inclined and probably have a much greater effect on horizontal ground-water flow. This comparison would, at face value, suggest that the ability of the Trafalgar till (with small sand seams) to retard downward leakage of water and contaminants into subjacent aquifers may be greater than that of a similar thickness of fractured Lagro till.

Over sizable areas the Trafalgar till generally appears to act as an effective confining unit, because water levels in shallow aquifers above the till are commonly somewhat different than those in the bedrock or sand and gravel aquifers below, indicating that the two aquifer zones are hydraulically isolated by the till. A significant deviation from this condition occurs in western Allen County, however, where the Trafalgar forms a system of buried moraines and contains a large complex of sand and gravel bodies (pl. 4). The sand and gravel is commonly in the form of deep, narrow channels that cut completely through the till, and it also forms numerous smaller bodies at several different horizons in the till. Near these channels, water levels in aquifers above the till are virtually identical to those in the bedrock below, lending support to the supposition that the bedrock in that area is hydraulically well interconnected to most of the larger sand and gravel units. The localized discontinuity of the till confining unit in this area results in all of these aquifers behaving as one system, which is shown on Plate 6 as the Aboite aquifer system (see following section on **Aquifer Systems**).

Over much of the northern third of the county, the Trafalgar Formation rests directly on one or more sheets of presumably much older till. The combined thickness of the Trafalgar and older till units locally reaches 150 feet or more. The disparity between water levels in the Huntertown aquifer system, which is above this till sequence, and those in the bedrock or deep sand and gravel below suggests that these tills collectively form an effective confining unit that isolates the shallow Huntertown aquifers from those below.

AQUIFER SYSTEMS

An aquifer system is defined as "a heterogeneous body of permeable and poorly permeable materials that functions regionally as a water-yielding unit; it consists of two or more aquifers separated at least locally by confining units that impede ground-water movement, but do not affect the overall hydraulic continuity of the system" (Poland and others, 1972). Using this definition, three distinct aquifer systems can be recognized in Allen County (table 4, pl. 6):

1) the **Huntertown aquifer system** of northwest and north-central Allen County, which is formed by an array of sand and gravel units deposited by Saginaw Lobe meltwater, and their lacustrine equivalents to the southeast (the Huntertown Formation);
2) the **Aboite aquifer system** of western Allen County includes sand and gravel units at several horizons that have coalesced to form a large complex that is commonly in hydraulic connection with the limestone bedrock. This relationship is best developed in Aboite Township (fig. 4); and
3) the **bedrock aquifer system** includes the limestone and dolomite that underlies all of the county at depths of 30 to 300 or more feet. The bedrock is immediately overlain in many places by coarse gravel or bedrock rubble and in other places is cut by buried valleys that locally contain sand and gravel. All of these sand and gravel bodies are hydraulically connected to the bedrock and are considered to be part of the bedrock aquifer system. In the northeastern part of the county, the limestone bedrock is overlain by up to 90 feet of low-permeability Antrim Shale.

The boundaries of these aquifer systems are generally defined by thick, regionally extensive sheets of glacial till that so restrict flow that water levels and flow patterns between adjacent or subjacent aquifer systems are substantially different. Each aquifer system is characterized by a distinct pattern of ground-water flow, including significant recharge and discharge areas (pls. 7 and 8). This pattern is referred to as a regional **flow system**, and determines the prevailing direction of both vertical and horizontal ground-water flow at different places within the aquifer system.

Contour lines (pls. 7 and 8) represent the **potentiometric surface** of the aquifer system, or lines of equal water levels in wells developed in the system. The term "potentiometric surface" applies only to confined aquifers, and can be thought of as representing the elevation to which water will rise in a well drilled into the aquifer system at any given location. In most places, the potentiometric surface elevation is higher than the top of the aquifer system. This is in contrast to the term **water table**, which represents the top of the **saturated zone** in an unconfined aquifer or in a near-surface confining unit. It is possible for an aquifer or aquifer system to be confined in some places and unconfined (under water table conditions) in others. On a regional scale, ground water moving through the aquifer system flows down the slope of the potentiometric surface (or water table) at right angles to the contours. The rate of flow is partly determined by the slope, or gradient, of this surface and partly by the permeability of the aquifers themselves. In general, the configuration of the potentiometric surface or water table is a subdued image of the land surface above, and indicates the predominant horizontal components of ground-water flow within the system.

Ground-Water Recharge and Discharge

Ground-water flow is not limited to the horizontal dimension, however, especially in fine-grained materials. Vertical components of flow are predominant in some places, and are responsible for recharge and discharge areas (pls. 7 and 8), as well as flow between aquifers at different horizons. Vertical flow components are generally difficult to define clearly without detailed water level measurements made in adjacent monitoring wells installed at several different depths in the system. Like horizontal flow, the strength of the vertical component is expressed as a gradient. In most systems, different combinations of horizontal and vertical flow components are present in different places, depending on the geologic framework and position in the landscape. In general, however, the vertical flow component is usually predominant across fine-grained confining units, which tend to retard water movement, whereas horizontal flow predominates in thick, uniform aquifers. In the absence of detailed well data, the presence of upward or downward hydraulic gradients must usually be inferred from the regional configuration of the potentiometric surface and from the relationship between surface water elevation and the potentiometric surface. In recharge areas, the former is usually higher, whereas in discharge areas, the potentiometric surface may be equal or higher in elevation relative to surface water.

Aquifers are recharged directly by precipitation and, more rarely, by surface water, that move through the soil profile and downward into the underlying geologic materials. While the exact mechanisms are not well defined, much of the recharge to aquifers in Allen County is interpreted to be of local origin or to occur at distances not far away. Recharge rates are difficult to quantify, and they are affected by a host of both climatic and geologic variables. The type of soil and the nature of the underlying geologic material are probably the most significant geologic factors in determining the amount of recharge that takes place.

It is widely believed that the greatest recharge occurs where aquifers are unconfined and overlain by thin, sandy soils (see Aller and others, 1987; Fetter, 1988; Freeze and Cherry, 1979; and references therein). Under such conditions, recharge can occur very rapidly following a precipitation event, and potential recharge may be as much as 10 inches per year or more in a humid climate. The presence of even a small thickness of permeable materials at the land surface can greatly increase the amount of precipitation that infiltrates to the subsurface. However, if the permeable surficial material is hydraulically isolated from an underlying aquifer by a till confining unit, much of the water that infiltrates may not actually recharge the aquifer, but will instead flow laterally along the top of the till until it discharges along a nearby slope or surface drainage. Such shallow flow is generally ephemeral in nature and represents one kind of **local flow system.** Flow directions in such localized systems are determined mainly by local topography and surface drainage, hence, they are commonly complex and may differ significantly from the regional pattern exhibited by the underlying confined aquifer system.

In contrast, recharge in areas underlain by fine-grained soils and thick clayey till may be minimal. For example, the typical field permeabilities of soils developed on the Lagro Formation are among the slowest of all the soil series mapped in Allen County (Kirschner and Zachary, 1969). As little as 2 inches per year or less of recharge may reach underlying aquifers via very slow diffuse leakage through the low permeability till cap. Thus some confined aquifers may receive significant recharge only in isolated places where the till confining unit is thin or absent. Similarly, many deep sand and gravel bodies may receive recharge chiefly through channels or other interconnections with higher aquifers that are more susceptible to recharge. Large areas in which most or all aquifers are well confined by thick till are characteristic of much of Allen County. Such hydrogeologic settings are neither recharge or discharge areas, and are referred to as "intermediate areas" (pls. 7 and 8).

Discharge areas are found in low positions in the landscape, where the potentiometric surface of an aquifer system is at, near, or above the land surface. Topographic position and soil patterns can be indicators of probable discharge areas, but discharge conditions are most reliably determined on the basis of potentiometric surface maps, relative water levels, and ground-water flow patterns. River valleys and their major tributaries tend to be significant ground-water discharge areas. Two general kinds of ground-water discharge can be identified. The first includes small springs and diffuse seepage emanating from saturated materials exposed along valley walls, steep slopes, or in low spots (the latter may form wetlands). Such discharge is commonly ephemeral and of local origin, being restricted primarily to wet periods. Regional discharge, in contrast, is characterized by upward flow of ground water from subjacent aquifers and occurs in the vicinity of major river valleys and lake basins. At some places, the subjacent aquifer is in full hydraulic connection with the surface water body, but elsewhere, the subjacent aquifer(s) may be separated from the surface water by a confining unit. In the first instance, a large volume of water actually discharges to the surface, whereas in the second case, discharge occurs only as slow upward seepage across the slowly permeable confining unit.

Huntertown Aquifer System

Of the three aquifer systems, the Huntertown may be the most clearly defined in terms of both geologic framework and ground-water flow system. The aquifer system is present over a broad region in northwest and north-central Allen County that corresponds almost precisely with the distribution of the Huntertown Formation (pl. 6). The principal aquifers that make up this system include the basal outwash, ice-contact stratified deposits, and lacustrine sand units of the Huntertown Formation, as well as the surficial outwash within the Eel and St. Joseph River Valleys (table 4). The lower boundary of the aquifer system is defined by the hard till at the top of the Trafalgar Formation, whose typically great thickness in northern Allen County tends to limit hydraulic communication with deeper aquifers such as the bedrock. The Huntertown aquifer system is confined by the Lagro Formation over much of its extent. It is unconfined along the St. Joseph River, and ranges from poorly confined to unconfined in the broad interlobate region in and near the Eel River Valley (fig. 9, pl. 6).

The St. Joseph River bisects the aquifer system into two geographically distinct parts. The continuity and thickness of the aquifer system are greatest west of the river, where it is dominated by thick and extensive units of basal outwash and ice-contact stratified deposits. Bodies of sandy loam till, till-like sediment, and lesser lacustrine mud within the Huntertown Formation separate the aquifers from one another in some places, but these confining units are typically leaky and of localized extent, especially west of the St. Joseph River. Consequently, the individual aquifers are well interconnected over most of the western part of the system, a condition that is reflected hydrologically by similar or identical water levels in wells developed at different depths within the system.

The eastern part of the aquifer system (pl. 6) is considerably thinner and less continuous, and is interrupted in several places by buried ridges on the underlying surface of the Trafalgar Formation (pl. 4). The aquifers that make up the eastern part of the system are dominated by lacustrine sand and lesser fan deposits whose geometry is greatly influenced by the topography of the Trafalgar surface on which they were deposited. Sand bodies deposited in relatively broad basins tend to be of large thickness and areal extent (pl. 4) and consequently form excellent aquifers. On the other hand, those bodies deposited on more undulating parts of the Trafalgar surface are much less predictable and frequently pinch out abruptly or are interbedded with lacustrine mud.

The Huntertown aquifer system is characterized by a well-defined flow system with relatively distinct recharge and discharge areas (pl. 8). Ground water within the Huntertown aquifer system enters the northwestern corner of Allen County and flows southeast toward the Town of Huntertown and the Eel River Valley under a gradient of about 10 to 15 feet per mile. Over a broad area in the vicinity of Huntertown, the potentiometric surface flattens out considerably, which suggests the presence of a significant vertical flow component. In this area, a downward gradient is indicated by the relationship between the water table, represented by large peat bogs and other wetlands, and the potentiometric surface of the aquifer system, whose elevation appears to be as much as 10 to 15 feet lower (pl. 10) (see sidebar, **Near-Surface Hydrogeology of the Huntertown Interlobate Area**, page 70-71). The landscape is composed of ridges and hummocks of clayey till separated by enclosed depressions of various sizes, and appears to be almost entirely internally drained. Runoff from the steeply sloping hummocks collects in the depressions, where the aquifer system is unconfined and commonly overlain by highly permeable outwash and peat. The wetlands in these depressions gradually release some of their water to the aquifer system. The hydrogeology of much of this region is characteristic of a regional recharge area and suggests that the aquifer system is receiving abundant infiltration derived directly from precipitation, surface water, or both. Recent analyses of hydrogen and oxygen isotopes in the Huntertown aquifer system confirm the presence of modern (post-1953) ground water in this part of the system, and suggest that evaporation from open water occurred prior to recharge, which is consistent with recharge from peat bogs.

A variety of more localized areas having an elevated **recharge potential** are also present in this flow system (pl. 8). These areas differ from the regional recharge area primarily in being of small areal extent. Consequently, they tend to have little or no expression in the potentiometric surface, and it is difficult to estimate the magnitude of recharge that may be occurring. Downward gradients are not likely to be as pronounced, and the bulk of any recharge that does occur is probably to the shallowest part of the aquifer system.

These local recharge areas are identified by one or both of two conditions:

1) the aquifer system is poorly confined over small areas; and(or)
2) permeable surficial sediments having a relatively greater ability to absorb large amounts of precipitation are present.

Although various combinations of these conditions are possible, the local recharge areas can be broadly grouped into two categories according to the general nature of the glacial terrain above the aquifer system (pls. 5 and 8). The first case includes areas where the aquifer system is or may be locally unconfined or poorly confined, such as along beach ridges, abandoned meltwater channels, and below large sand bodies within the Lagro Formation (unit p, pl. 8). In all these situations there is a distinct possibility that the clayey till that normally confines the aquifer system has been breached or greatly thinned by wave or meltwater action and replaced by more permeable materials. The likelihood of a continuous sequence of permeable sediments between the land surface and the top of the aquifer system increases the recharge potential in these areas.

The second case includes areas where permeable sediments of uncertain thickness are present at the land surface and may lead to higher rates of surface infiltration relative to surrounding till-capped areas (units W and S, pl. 8). The degree to which this increased infiltration actually recharges the aquifer system depends on the presence and thickness of the Lagro Formation below the surface sediments, which is usually not well known. Many of these bodies of permeable surficial sediments are of limited areal extent, and some occur in places where the Lagro is generally quite thick, such as in depressions along end moraines (compare pls. 5 and 8). In such places, the Lagro is more likely to have continuity below the surficial sediments and will limit the recharge to underlying aquifers. Accordingly, most of the increased infiltration attributable to the permeable surface sediments is likely to feed very localized flow systems in the permeable surficial sediments and in the upper, fractured part of the till, or to simply remain ponded in wetlands. On the other hand, considerable recharge may be associated with some bodies of permeable surficial sediments that occur in low places in the landscape or in other situations where there is a greater possibility of the aquifer system being poorly confined. Large peat-filled depressions within a broad tract of extremely hummocky topography just west of the Town of Leo, near the center of T32N, R13E, are a good example of this type of situation (fig. 4). A comparison of the distribution of local recharge areas (pl. 8) with the thickness of the Lagro till (pl. 5) affords a general idea of the relative degree of recharge that may be taking place in these areas.

The St. Joseph River is the principal discharge area for the Huntertown aquifer system (pl. 8). The overall configuration of the potentiometric surface is essentially oriented about the river valley, and the course of the river coincides with a prominent valley in the potentiometric surface. The elevation of the potentiometric surface is equal to or greater than river level, indicating that the aquifer system is discharging upward into the river or into the outwash in the bottom of the channel.

A secondary discharge area for the aquifer system is the northern part of the Maumee Lacustrine Plain (pl. 8), which primarily receives discharge from the eastern part of the system. At least a dozen **flowing artesian wells** have been reported from this area, and the potentiometric surface elevation is at or above the land surface throughout some of this region. These conditions indicate the presence of strong upward gradients within the flow system and that the northern lake plain is a regional discharge area. Cedar Creek and several other smaller streams represent local discharge areas where small amounts of ground-water discharge from the upper part of the aquifer system.

Bedrock Aquifer System

The bedrock aquifer system consists of fractured and karsted limestone and dolomite that underlie the glacial deposits throughout the county. The Antrim Shale overlies the carbonates and separates them from overlying glacial deposits in northeastern and north-central Allen County. Bodies of sand and gravel of various ages are present in many places along the bedrock surface and in buried bedrock valleys. Where the Antrim is absent, these granular units typically are hydraulically connected to the flow system in the carbonate bedrock and are thus considered to be part of that system.

Virtually all of the ground water within the carbonate bedrock moves along bedding planes, joints, and solution features via a process known as **fracture flow**. Observations from quarries and other bedrock exposures in northeastern Indiana indicate that the majority of the Silurian rocks (pl. 2) are very massive dolomite that contains few open bedding planes and virtually no intergranular porosity. Thus, ground-water flow in these rocks is almost entirely through joints and solution features. In contrast, the Devonian carbonates are typically well bedded and locally exhibit considerable solution along bedding planes as well as along joints.

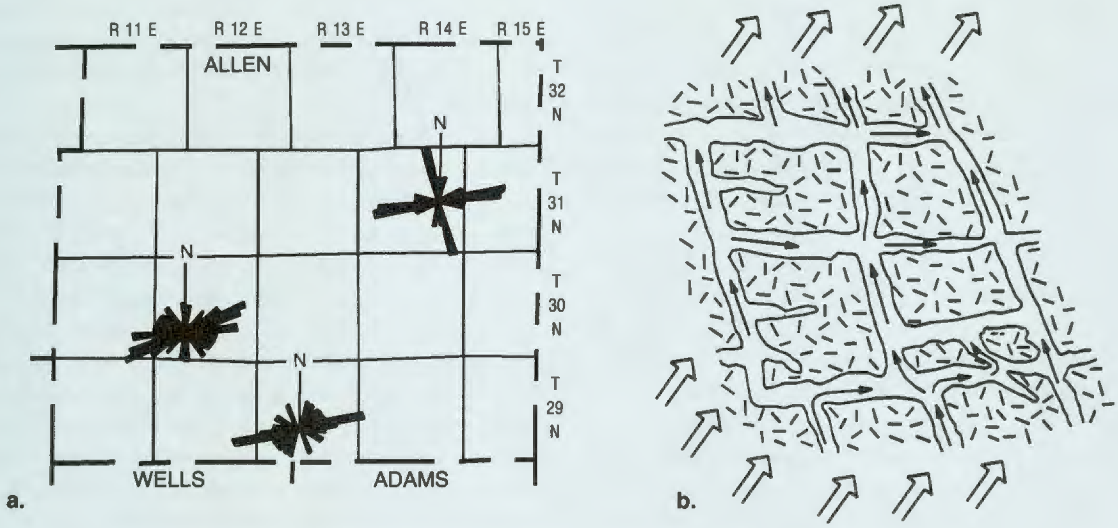
Measurements of the orientations of bedrock joints in local quarries (see sidebar, **Ground-water Flow in Fractured and Karsted Carbonate Rocks**, page 51) indicate that the great majority occur in sets that exhibit strong preferred orientations (Ault, 1989). At any particular location, the direction of ground-water flow in the carbonate bedrock will parallel the preferred joint orientations. Consequently, in places where the slope of the potentiometric surface in the bedrock (pl. 7) lies at a high angle to the preferred joint orientations, the local direction of ground-water flow may be very different from the regional direction of flow indicated by the potentiometric surface. This situation can result in fairly tortuous and complex local ground-water flow systems at a site-specific scale (see sidebar, **Ground-water Flow in Fractured and Karsted Carbonate Rocks**, page 51), even though the orientation of the regional flow system may be fairly uniform. Indeed, determination of ground-water flow patterns in fractured and karsted carbonates represents one of the most challenging types of hydrogeological problems.

The relationship between the potentiometric surfaces (pls. 7 and 8) of the major aquifer systems indicates that flow in the bedrock aquifer system is not as strongly influenced by near-surface conditions as the more shallow sand and gravel systems, whose potentiometric surface closely mimics the surface topography. This difference is probably attributable to the much more strongly confined condition of the bedrock aquifer system. In the south, the bedrock is commonly overlain by between 50 to more than 100 feet of fine-grained tills of the Lagro and Trafalgar Formations, whereas to the north, till thicknesses of 150 to 250 feet are typical. Given this degree of confinement, recharge to the bedrock over most of Allen County is probably minimal and occurs mainly by slow leakage through till confining units. In a few instances, the bedrock may receive some recharge from shallow sand and gravel aquifers or, more rarely, directly from the land surface itself (pl. 7). This situation could occur where the bedrock is directly overlain by large bodies of sand and gravel that extend upward to the land surface or that are hydraulically connected to stratigraphically higher aquifers.

The potentiometric surface of the bedrock aquifer system shows a strong relationship to the elongated lowland defined by the Maumee River and Wabash-Erie Channel, which are the principal discharge areas (pl. 7). Ground water flows into these discharge areas from both north and south under a relatively gentle horizontal gradient of 10 feet per mile or less. In both of these regions, the elevation of the potentiometric surface is close to ground elevation, suggesting that upward flow of ground water out of the bedrock is occurring. Several flowing artesian wells have been reported from the bedrock in the northern part of the Maumee Lacustrine Plain, indicating some upward leakage of ground water from the bedrock into the unconsolidated deposits is occurring within this part of the regional discharge area. There is little evidence to suggest the occurrence of appreciable ground-water discharge from the bedrock directly into other surface water courses. Sizable potentiometric valleys are present below the St. Marys River, St. Joseph River, and several of the largest creeks (unit D3, pl. 7). In all of these cases, however, the elevation of the potentiometric surface is well below that of the bottoms of the valleys. This relationship suggests that ground water in the bedrock mostly moves as **underflow** in a down-valley direction, and does not physically discharge upward into the valleys.

The configuration of the potentiometric surface of the bedrock aquifer system in Allen County (pl. 7) suggests that a large amount of ground water within the system is derived

Ground-Water Flow in Fractured and Karsted Carbonate Rocks



a) Map of Allen County with rose histograms showing preferred orientations of bedrock joints measured in three local quarries (from Ault, 1989); b) plan view contrasting the regional direction of ground-water flow (large arrows) with local flow directions in open joints (small arrows) in rock with preferred joint orientations.

Fractured rocks in general, and karst terrains in particular, represent one of the most complex types of hydrogeologic settings. Ground-water flow patterns are typically of a highly localized nature and depend on the characteristics of specific features that act as permeable conduits within the otherwise solid rock. In Allen County, the fractured and karsted limestone bedrock is well confined and thus believed to be saturated throughout its entire thickness. This condition results in a relatively uniform regional flow pattern and a somewhat slower rate of ground-water flow than might be the case if the aquifer system was unconfined.

The regional flow system in the bedrock aquifer system appears to be relatively uniform and does not show as strong a response to surface topography as that in the shallow sand and gravel units. Thus, over a large area, the regional ground-water flow direction through the bedrock is relatively predictable. On the other hand, fractures in the bedrock and the solution features developed along them typically show one or more strong preferred orientations based on measurements in local quarries (fig. a). On a highly localized scale, ground-water flow directions are likely to parallel the orientations of the fractures, which may differ considerably from the regional flow direction (fig. b). Consequently, determining the local direction of ground-water flow in the bedrock at the scale of a specific site is commonly problematic and may require elaborate instrumentation, monitoring, and dye tracing to identify the major conduits through which ground water is moving.

from outside of the county. Immediately to the south, in Adams and Wells Counties, the bedrock crops out or is less than 25 feet below the land surface over a relatively large area, particularly in the vicinity of the Wabash River Valley (Gray, 1983; IGS, unpublished data). Direct recharge to the bedrock in this area probably contributes to the northward flow of ground water into Allen County through the bedrock aquifer system. Few data are available concerning the regional flow system in the limestone bedrock north of Allen County, but the aquifer system is known to be confined by the Antrim Shale as well as by younger rocks of low permeability (Gray and others, 1987). Ground water from the bedrock in northern Allen County also tends to be highly mineralized (see sidebar, **Origins of Sulfur in Ground Water**, page 53). These characteristics suggest that much of the ground water within the bedrock aquifer system in the northern part of the county is relatively old and is gradually moving southward out of the Michigan Basin.

Aboite Aquifer System

The Aboite aquifer system consists chiefly of a complex of small to very large sand and gravel bodies that occur at several horizons between the base of the Lagro Formation and the bedrock surface. The principal sand and gravel aquifers are generally in, atop, or directly below the Trafalgar Formation, and include basal outwash, large channels, the intersequence unit, and a variety of irregular to sheetlike bodies at other horizons. In a few places within the northern part of the system, deeper sand and gravel bodies that appear to be well below the base of the Trafalgar Formation are also included.

The Aboite aquifer system is present over a wide area in west-central and southwest Allen County, and can be divided into two general parts based on the geologic framework of the aquifers within it (pl. 6). The northern part lies entirely north of the Wabash-Erie Channel, and consists only of sand and gravel aquifers. In this part of the system, there appears to be little, if any, hydraulic connection with the limestone bedrock, which is separated from the sand and gravel by between 10 and more than 100 feet of till. Although large channels are present sporadically within the Trafalgar Formation and act to interconnect the various sand and gravel aquifers, they do not commonly appear to extend to bedrock in the northern part of the system.

The southern part of the aquifer system lies on either side of, and is bisected by the Wabash-Erie Channel (pl. 6). It differs significantly from the northern half in that the Trafalgar Formation contains numerous large channels that bottom out on the limestone, resulting in well-developed hydraulic communication between the bedrock and most of the higher sand and gravel aquifers. In addition, the overall thickness of unconsolidated deposits is considerably less over most of the southern part of the system (compare pls. 3 and 6), and a greater proportion of those deposits are sand and gravel. Consequently, there is little, if any, distinction between the potentiometric surface elevation and regional flow direction in the bedrock and that in the sand and gravel units. For this reason, the bedrock is essentially considered to be part of the Aboite aquifer system in this southern area. The southern area also contains the Wabash-Erie Channel, within which the Lagro Formation has been largely stripped off, leaving a heterogeneous assemblage of surficial sediments atop till, poorly confined sand and gravel units, and relatively shallow bedrock.

Plate 8 shows the potentiometric surface of sand and gravel aquifers within the Aboite aquifer system. Because of extensive hydraulic connection between sand and gravel aquifers and the bedrock, the overall configuration of the flow system in the southern part of the system is very similar to that in the bedrock (pl. 7). For all practical purposes, there is little distinction in potentiometric surface elevation between the two. Potentiometric contours for the sand and gravel aquifers do show a more pronounced relationship to surface drainage, which is presumably attributable to their generally lesser degree of confinement. Vertical flow between sand and gravel aquifers and the bedrock could be significant in some places, but is difficult to document without more detailed data. Some downward flow might be expected below the largest upland areas, whereas upward flow is likely to predominate in the low-lying discharge areas (pl. 8).

The Wabash-Erie Channel is the main discharge area for the Aboite aquifer system. The potentiometric surface to both the north and south slopes steeply into the channel. In several places within the channel, thick sand and gravel units are unconfined or very poorly confined, and the contours in those areas represent the elevation of the water table. In fact, over most of the channel bottom, no clear distinction can be made between the elevation of the potentiometric surface and the water table, which generally lies within a few inches to a few feet of the land surface. An unknown, but probably considerable amount of ground water is interpreted to discharge along the base of the channel walls, where extensive bodies of intersequence sand and gravel are truncated. Some upward discharge is also interpreted to occur between deeper sand and gravel units below the floor of the channel and the surficial sediments and wetlands. The original hydrogeologic regime of the channel bottom is difficult to interpret, however, especially in and adjacent to Fort Wayne, because of extensive ditching of wetlands and large-scale ground-water withdrawals by quarries and high-capacity wellfields. These activities have greatly altered the pattern of surface drainage and the configuration of the potentiometric surface, and in some cases have locally reversed the hydraulic gradients.

The potentiometric surface of the Aboite aquifer system also shows a large amount of deflection around the deeply incised valleys of Aboite Creek and its tributaries. These valleys receive discharge from truncated aquifers in the upper part of the aquifer system. Discharge from aquifers below the valley floor may also occur, especially in the lower reaches of Aboite Creek. Some discharge from the upper part of the aquifer system may also be occurring along the Spy Run-Covington sag, particularly in the lower reaches of Spy Run and Covington Creeks, which are cut below the base of the Lagro Formation.

With the exception of the discharge areas noted above, the Aboite aquifer system is generally well confined over most of its extent. Consequently, the identification of clearly defined recharge areas is problematic and much of the recharge the system does receive may be in the form of slow leakage through the Lagro Formation. However, there is some suggestion that recharge may be occurring to a somewhat greater extent in the northern part of the Arcola plain, particularly in the vicinity of Lake Everett (pl. 8). The potentiometric surface in that area is relatively elevated and

Origins of Sulfur In Ground Water

Sulfur is a natural constituent in the ground water throughout Allen County and adjacent areas, but is especially pervasive in the northern part of the county. In that area, high sulfur concentrations are most commonly found in the bedrock aquifer system, but they also occur to a lesser extent in sand and gravel aquifers. The characteristic odor of ground water pumped from these aquifers is due to hydrogen sulfide, a noxious gas formed by the reduction of sulfate in the ground water. Sulfur concentrations are commonly strong enough to be objectionable for most ground-water uses, and some form of treatment may be required to remove the sulfur.

The geochemical processes responsible for the high levels of sulfur in this area are not well documented, but there are at least two potential sources of the sulfur. The most likely possibility is calcium sulfate, which occurs abundantly in the Devonian limestones, and to a lesser extent in the Silurian rocks, as the evaporite minerals gypsum and anhydrite. The sulfate minerals are particularly abundant in the Devonian bedrock north of Allen County and upgradient in the regional flow system. Fragments of the evaporite-bearing rocks were also incorporated into the ice sheets as they advanced over the bedrock surface, and are thus present in some sand and gravel units. Dissolution of these minerals produces ground water that contains abundant calcium sulfate. Geochemical conditions in parts of the aquifer system cause some of the sulfate to be reduced by bacteria to hydrogen sulfide. This gas remains dissolved under pressure until the ground water discharges to a well or land surface, whereupon the gas comes out of solution.

A second possibility is the presence of the mineral pyrite (iron sulfide) in the Antrim Shale. Oxidation of the pyrite releases both iron and sulfate into solution in the ground water. This process is likely to contribute to the high sulfate concentrations observed in some shallow sand and gravel aquifers. Some of these aquifers contain abundant fragments of Antrim Shale, and their relatively shallow depths are likely to promote oxidizing conditions. The role of pyrite oxidation in these aquifers is further suggested by relatively high iron concentrations accompanying the sulfur (IGS, unpublished data).

Ground water with a noticeable sulfur odor can be found in widely scattered locations in the bedrock throughout Allen County, although this condition is clearly most severe, if not commonplace, in the northeastern part of the county. This distribution suggests an important relationship between sulfur concentrations and the age of ground water in the bedrock. Ground-water age is, in turn, partly a function of the degree of confinement as well as the regional pattern of ground-water flow. Regional ground-water flow in the bedrock is southward, out of the Michigan Basin, where the carbonates are confined by thick sections of low-permeability rocks. It seems likely that at least some of the ground water that enters northern Allen County in the bedrock has been residing in the limestone deep within the basin for thousands of years, which has allowed it to dissolve large amounts of gypsum and anhydrite. Over much of Allen County north of the Maumee River, the Silurian and Devonian limestone is confined by the Antrim Shale, which tends to restrict interchange with younger, less mineralized ground water in the glacial deposits. Consequently, the chemical composition of ground water extracted from the bedrock aquifer system north of the edge of the Antrim Shale is likely to reflect a long residence time and be enriched in sulfur and other dissolved constituents.

In contrast, the limestone bedrock in southern Allen County is not confined by the shale and interacts hydraulically with the overlying glacial deposits. Ground water flows northward into southern Allen County from Wells and Adams Counties. Over sizable parts of those counties, the carbonate rocks crop out or are relatively close to the land surface and are thus likely to receive abundant modern recharge. Consequently, even though sulfur-bearing minerals are locally abundant in the bedrock south of the Maumee River, the shorter residence time of the ground water, coupled with mixing of ground water from the glacial deposits, tend to limit the severity and extent of sulfur problems in that area.

forms a prominent flow system divide between the Huntertown aquifer system to the north and the Aboite aquifer system to the south. The Lagro Formation appears to be thin or absent below several segments of an extensive abandoned meltwater channel system that includes the basin of Lake Everett (pl. 5), and the surface sediments over large parts of this landscape consist of permeable outwash and peat. The level of the lake (approximately 740 feet), as well as the elevation of the water table, as defined by wetlands within the meltwater channels and nearby depressions, are higher than the potentiometric surface, which suggests that some downward leakage is occurring to several shallow sand and gravel aquifers (pl. 8). However, the level of Lake Everett has been artificially raised in the past, and its present relationship to the flow system is not entirely clear (see sidebar, **The Hydrogeology of Lake Everett**, page 55).

Highly localized areas that have an elevated recharge potential can be identified in a few places (pl. 8). These areas are almost entirely associated with one of the following conditions:

1) the Lagro Formation has been removed by erosion, and sand and gravel aquifers are present at the land surface;
2) the Lagro Formation contains channels that may act as conduits to carry water from the land surface to the intersequence zone; and
3) permeable surficial sediments having a relatively greater capacity to absorb precipitation are present.

The first type of situation is restricted to low places in the landscape, such as Aboite Creek and portions of the Wabash-Erie Channel (pl. 5). Most of these settings are discharge areas characterized by neutral or upward vertical gradients. Nonetheless, the absence of any confining unit over the system means that a higher percentage of precipitation is likely to infiltrate into at least the near-surface part of the aquifer system.

In the second situation, channel-like sand bodies within the Lagro Formation may act in a conduit-like fashion to allow percolating surface water to bypass the clayey till that would otherwise retard recharge. In many cases, the data are too sparse to clearly define the geometry of the channels, but in at least some places these bodies appear to extend to the base of the till. Most of the channels do not appear to extend all the way to the land surface, however, and are usually capped by less than 20 feet of till and till-like sediment, which will retard infiltration. Thus, it seems probable that many of the channels will act more like drains, allowing relatively more rapid downward percolation of water that slowly seeps out of the enclosing till.

The third condition is typical of the Arcola plain, which overlies a broad area of the aquifer system in the north. That region is characterized by numerous peat-filled depressions and small outwash terraces, as well as several larger meltwater channels with thicker accumulations of these relatively permeable sediments. The water table appears to be very shallow over almost all of the plain, and most of the surficial sediments are saturated, at least seasonally. In many places, however, the shallow water table within the permeable surficial sediments is perched atop a substantial thickness of slowly permeable Lagro till (pl. 5). Till thicknesses between 40 and 60 feet are common throughout the plain and subsurface data indicate the till to be uniformly dense and clayey. It seems unlikely that appreciable recharge to underlying aquifers could occur under these conditions. Consequently, ground water within the permeable surficial sediments is likely to comprise a perched system characterized by highly localized flow patterns completely distinct from those of the Aboite aquifer system.

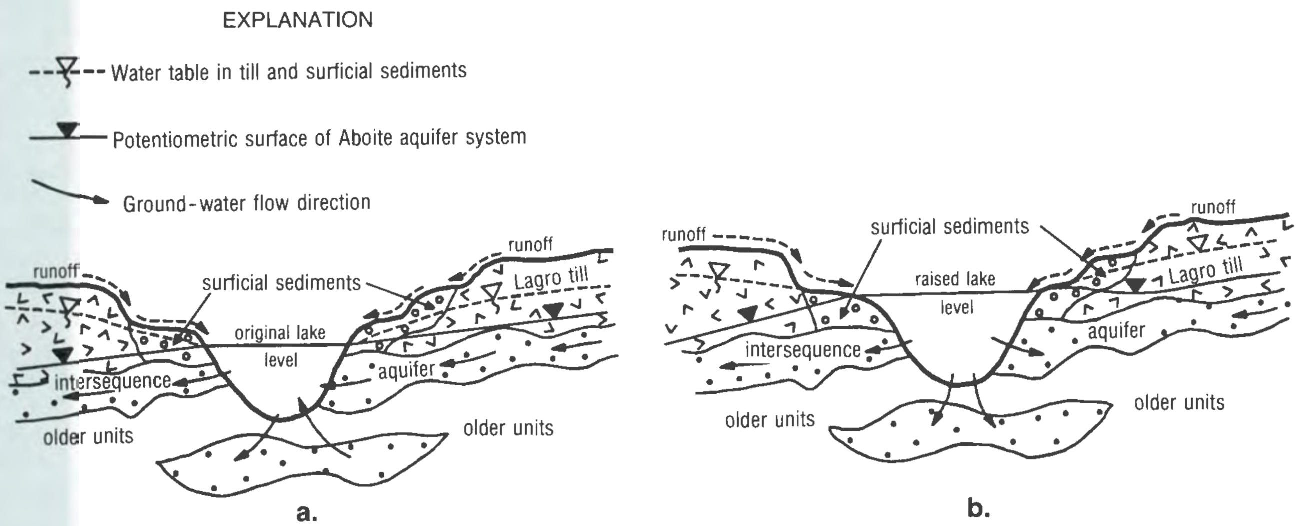
Ground Water-Surface Water Interaction

There is a close relationship at several scales between surface drainage and the pattern of ground-water flow throughout Allen County. In general, regional ground-water flow is toward the major surface drainages, with the St. Joseph, St. Marys, Little, and Maumee Rivers receiving the bulk of the discharge (pls. 7 and 8). The St. Joseph River receives a substantial amount of ground-water discharge, even during extremely dry conditions. For example, about 14 million gallons per day are discharged to the river, mainly by the Huntertown aquifer system, between the stream gauge near Cedarville and the Fort Wayne gauging site (Arvin, 1989) (pl. 8). In contrast, the St. Marys River receives a much smaller contribution of ground water and, in fact, may actually be losing flow to the ground-water system in some places. Ground-water discharge to the Maumee River is also substantial, but is somewhat less than that received by the St. Joseph River. Ground-water discharge to all three rivers maintains base flow during those times when surface runoff is lacking.

Most of the other streams in the county are also fed by ground-water discharge. The volume of discharge may be considerable for the larger streams, such as Aboite and Cedar Creeks, whose valleys are incised into shallow sand and gravel aquifers. Smaller streams that cross upland areas flow mainly on the fine-grained till of the Lagro Formation. These receive much lesser ground-water discharge, which is primarily of a local and ephemeral character, being derived mainly from very shallow flow systems in the weathered and fractured upper part of the till.

An important point from a water quality standpoint is that there may be considerable interchange between surface water and shallow ground water in some places. This is likely to be the case where streams and rivers flow across outwash, thick alluvium, or unconfined areas of shallow aquifers. Several instances where this situation is likely to occur can be inferred from the surficial geology (pl. 5) and aquifer characteristics (pl. 6). Good examples include the St. Joseph River, which flows on thick outwash, and Cedar Creek, which is incised into the upper part of the Huntertown aquifer system. Even very small areas below any size stream where confinement of underlying aquifers is limited or lacking have the potential to lose surface water to the flow system under certain conditions, especially during prolonged dry periods when the water table may decline to below stream level. This type of interaction can have implications for ground-water quality.

The Hydrogeology of Lake Everett



Lake Everett is located in the northern part of the Arcola plain, a mostly flat and poorly drained landscape that was pervasively washed by meltwater discharged from the Erie Lobe when it stood at the Wabash Moraine, just to the east (pl. 5). The lake occupies a large ice-block depression, known as a **kettle**, adjacent to an extensive system of abandoned meltwater channels. The channels are filled with thick deposits of peat and some outwash, and contain vast wetland areas that have locally been ditched and drained. The bathymetry of the lake (Churubusco 7.5-minute quadrangle) indicates that its bottom is well below the base of the Lagro Formation and is in contact with intersequence sand and gravel, and possibly with subjacent aquifers as well (fig. a). Originally, lake level was probably similar to the potentiometric surface elevation of adjoining parts of the Aboite aquifer system (pl. 8), but it has since been artificially raised by approximately 10 feet. The lake may have originally been a **flow-through lake**, which received ground water on the upgradient side (in this case, probably the north side) and discharged water back to the flow system on the downgradient side.

Raising of lake level has altered this regime. The lake is fed mostly by surface runoff and by localized ground-water discharge from very shallow flow systems within the permeable surficial sediments and fractured till that surrounds it. The lake discharges some water via a surface outlet on its east side, but relative levels of the lake and the potentiometric surface suggest that the lake now loses water to subjacent aquifers (fig. b). Thus, the lake itself may constitute a recharge area of sorts for the northern part of the Aboite aquifer system.

Ground-Water Withdrawals

An important type of ground-water discharge is represented by the tens of thousands of wells in Allen County that withdraw water from the various aquifers. The long-term effect of these withdrawals on water levels in each aquifer system is not precisely known, but is probably small. Historical water levels appear to have declined significantly in only a few places, most of which are associated with **high-capacity wells** or dewatering operations.

The pumping of every well, no matter how small or large, causes the water table or potentiometric surface to decline in the area immediately around the well. The depth, radius, and longevity of this **cone of depression** depend on the depth and capacity of the well, the duration of the pumping, and the hydraulic characteristics of the aquifer being pumped. In some instances the interaction between these factors can be quite complex, and it may be difficult to make *a priori* predictions without detailed knowledge of specific conditions. However, a number of more generalized observations can be made with reasonable confidence.

Small domestic wells typically pump at rates of less than 10 gpm and operate on a discontinuous schedule. They tend to produce small, ephemeral cones of depression that recover rapidly each time the pump is shut off. In contrast, some large, high-capacity wells may be in nearly continuous

General Characteristics of Ground-Water Contaminants

On a nationwide basis, hundreds of contaminants have been found in ground water (U.S.E.P.A., 1980). However, the majority of documented ground-water contamination cases involve a far smaller number of relatively common chemicals and pathogens. Most of the chemical contaminants belong to a few distinctive chemical families. The compounds within each family generally have similar attributes in terms of their physical and chemical behavior but may differ dramatically from those in other families. Thus, a wide range is possible in the ways the various contaminant groups behave in ground water. What follows is an extremely simplified overview of some common categories of contaminants and the complications that their differing behaviors in ground water can pose in attempting to characterize the sensitivity of different hydrogeologic environments.

Most of the major contaminants occur as liquids or end up in liquid form by dissolving in or mixing with water. A variety of chemical and physical properties affect the manner in which they migrate through the hydrogeologic environment. Some contaminants dissolve readily in water and will move in a fashion comparable to the natural flow of ground water, whereas others are insoluble and will migrate as a separate phase. In many instances, contaminants are only partially soluble, and may migrate in solution and as a separate phase. Pesticides, metals, and most inorganic constituents (such as road salt, nitrate) are among the better-known examples of contaminants that are relatively soluble and tend to migrate more or less parallel to the prevailing direction of ground-water flow.

If a contaminant is introduced in a more or less concentrated form from a point source, it will tend to migrate as a distinct **plume**. The plume can enlarge in both length and width via a process known as **diffusion**, in which the concentration at the center of the mass is reduced as molecules of the contaminant move outward across chemical gradients toward and beyond the fringe of the plume. A variety of reactions between contaminants and the minerals composing the aquifer are also possible and can either reduce or increase the concentration of the contaminant, or transform it into a different compound. These reactions are specific to individual contaminants and commonly are dependent on existing ground-water chemistry.

For largely insoluble contaminants, one of the most important physical properties is its density relative to that of water. For example, petroleum products are lighter than water and tend to float on the water table, whereas many widely used organic solvents are heavier and will sink to the bottom of the aquifer. The latter are frequently referred to as "DNAPLS" (dense, non-aqueous phase liquids), and they commonly migrate by sinking through an aquifer until they encounter a dense, fine-grained confining layer. The DNAPLS may simply pool on the top of the low-permeability layer or, if the confining layer is sufficiently sloping, they will migrate downslope along the top of the unit, even if that direction is counter to the prevailing flow direction of the aquifer. Heavier-than-water contaminants pose a particularly insidious threat to ground water because they can penetrate deep into an aquifer system even in areas where strong upward gradients are present. Their migration through the system is often unpredictable, being controlled more by local vagarities in the configuration of permeable and nonpermeable units rather than the local ground-water flow direction.

operation and withdraw several million gallons of ground water each day. Depending on the size and permeability of the pumped aquifer, the cone of depression around such a well can be tens or even hundreds of feet deep and may have a radius of several thousand feet. If the aquifer is not receiving large amounts of recharge in the immediate vicinity, the cone of depression may not completely recover when the well is shut off over a short period of time and may continue to enlarge over time as pumping continues. In general, cones of depression tend to be smaller and to recover more rapidly in extensive unconfined aquifers, such as thick bodies of glacial outwash, whereas they tend to be larger and of more prolonged duration in confined aquifers.

Large-scale dewatering operations, such as those at quarries, gravel pits, or large construction sites, can produce the same effect as a high-capacity well. In the case of a quarry, for instance, the excavation acts essentially like a very large diameter well, and the floor and walls of the quarry are analogous to the water-producing zone in a well. Large and expanding drawdowns in bedrock aquifers surrounding quarries are well documented in Allen County and elsewhere. The effect on an aquifer system of several large water withdrawal operations localized within a relatively small area are usually quite complex. Such is the case in and near part of the Wabash-Erie Channel (pl. 7), where as many as nine high-capacity wellfields and quarry dewatering operations may be or historically may have been withdrawing ground water from the limestone bedrock. In one or two highly localized parts of this general area, water levels in the bedrock appear to have declined by 50 to 100 feet or more, but a more pervasive decline of lesser magnitude may be occurring over a much broader part of the channel. Unfortunately, the lack of detailed and evenly distributed historical water level data makes it virtually impossible to determine the rate and severity of the decline, much less accurately map the ever-changing elevation and configuration of the potentiometric surface of the bedrock aquifer system. Consequently, much of this area is shown as a large, composite cone of depression of uncertain magnitude on Plate 7.

More rarely, localized water level declines of a few feet may correspond to large concentrations of mostly small, domestic wells developed in confined aquifers of limited areal extent or hydraulic capability. Although this condition appears to be rare and difficult to document in Allen County, it may be the case for some sand and gravel aquifers in the northern part of the Maumee Lacustrine Plain from the Town of Harlan southeast to the Maumee River (pl. 8). A number of water well records from the late 1950s through the 1960s reported flowing artesian conditions in bodies of lacustrine sand as well as some sand and gravel units in the Trafalgar Formation in that area (pl. 6). More recent well records report such conditions far less commonly, if at all. A plausible interpretation of this historical difference is that pumping of these confined aquifers by an increasing number of widely distributed small-capacity wells has led to a decline in water levels to the point where artesian conditions no longer occur. Unfortunately, the absence of detailed and historical water level data collected under controlled conditions precludes a definitive explanation for the apparent decline in water levels in this area.

It should be evident from the above discussion that the drawdown associated with ground-water withdrawals, particularly those of high capacity, will lead to strong downward hydraulic gradients within the cone of depression. Depending on a number of geologic factors, such gradients can greatly increase the amount of water that leaks downward from overlying strata or from surface water bodies into the pumped aquifer. Pumping of unconfined aquifers is likely to induce the greatest amount of additional leakage, especially where the cone of depression extends beneath surface water bodies, whereas leakage into aquifers confined by thick, fine-grained material may be much less. Clearly, however, potential for more rapid downward movement of water causes portions of aquifers affected by a cone of depression to be more sensitive to potential contamination. The idea of protecting parts of aquifers that contribute to high-capacity public wellfields by protecting the land surface above is known as **wellhead protection**, and is discussed in greater detail in the following section.

SENSITIVITY OF GROUND WATER TO CONTAMINATION

Contaminant hydrogeology is a complex subject involving not only numerous geologic and hydrogeologic variables, but a myriad of potential contaminants as well. It is well known that the behavior of many contaminants in ground water is determined as much by their particular chemical and physical characteristics as by the hydrogeology of the affected aquifer (see sidebar, **General Characteristics of Ground-Water Contaminants,** page 56). Consequently, it is problematic to make an assessment of ground-water contamination potential without *a priori* knowledge of which contaminants are present and pose a potential threat to ground water.

Some of the terminology employed to describe the subject of actual or potential contamination of ground water (or aquifers) can be confusing or misleading, and a brief clarification is in order. A few of the most common terms include *ground-water vulnerability*, *aquifer sensitivity*, *susceptibility to contamination*, and *potential for ground-water contamination*. These terms are frequently used interchangeably when, in fact, they have quite different connotations, as illustrated by the following example.

Certain hydrogeologic environments are clearly more conducive to the migration of contaminants into aquifers than others. It is difficult to argue, for example, that an unconfined sand and gravel aquifer in which the water table lies 2 feet below the land surface is not more readily accessible to potential contaminants than an otherwise similar aquifer separated from the land surface by 200 feet of dense glacial till. In this case, the combination of geologic and hydrogeologic factors causes the first aquifer to have a naturally greater *sensitivity*, or *susceptibility*, to contamination than the second. However, the unconfined aquifer is not unnecessarily more *vulnerable* to contamination than the confined aquifer. An aquifer cannot be "vulnerable" unless a source of potential contaminants is present above it and the particular disposition of those contaminants could threaten ground-water quality. Extending the same logic, there is little potential for ground-water contamination if no potential contaminants are present above the aquifer. On the other hand, the confined aquifer, with its inherently low sensitivity, could become vulnerable if a potential contaminant happened to be released near one or more improperly abandoned wells. It seems most appropriate, therefore, to use the terms *aquifer sensitivity* or *ground-water sensitivity* when referring to relative susceptibility attributable strictly to geologic or hydrogeologic factors, unless an inventory of potential contaminants has also been made, in which case *vulnerability* or *potential for contamination* are acceptable terms.

The above distinction may appear to be an exercise in semantics, but due to the vagaries of public perception, it is terribly important. There is commonly a widespread misperception by the public and the media who, upon hearing (or seeing on a map) that ground water in a particular area is "vulnerable" or has a high "potential for contamination," tend to assume that contamination is imminent or has already occurred. Although pollution of ground water has indeed occurred in some such areas, it is not necessarily as pervasive as some media reports would lead us to believe. In fact, the ground water beneath many so-called "vulnerable" areas has not been impacted by contamination. Part of the misconception may stem from the word "vulnerable," which implies that there already is a problem when, in reality, none may exist. The terms "sensitive" and "susceptible" carry the appropriate sense of urgency, but with less implication that the dreaded event has already taken place. Rather, they imply that such an event *could* occur, but only if inappropriate practices are allowed to take place.

It is equally important to bear in mind that terms such as "high sensitivity" or "low sensitivity" are valid only in a comparative sense. As used in this discussion, these terms represent a range of conditions and should only be interpreted relative to one another, rather than as absolute indicators of ground-water sensitivity. In most cases, it is problematic and probably misleading to say that a particular hydrogeologic region has an absolute "high sensitivity" or "low sensitivity." On the one hand, a number of conditions can be identified that are *likely* to lead to greater sensitivity, but there is usually sufficient variation in those conditions within a particular region to cause sensitivity to also vary considerably from place to place. In some hydrogeologic settings within Allen County, subsurface data are sufficiently lacking in either quality or quantity to allow subtle variations in geologic conditions to be detected or mapped at a fine enough scale. For example, an aquifer system generally overlain by a thick till confining unit may contain localized areas where the till is thin or absent, but which go undetected because no subsurface data or diagnostic landforms exist in these localities. Moreover, hydrogeologic regions that appear to have a "high" sensitivity relative to other regions within Allen County might be interpreted as having a "low" or "moderate" sensitivity when compared to other hydrogeologic settings outside of the county. For all these reasons, when any ground-water sensitivity description (for example, "high sensitivity") is given in this report, it is with the understanding that it derives its meaning only by comparison with other regions in Allen County.

Before proceeding to a discussion of specific hydrogeological factors and conditions, several general statements can be made regarding the overall sensitivity of aquifers in Allen County. Wide areas of the land surface are underlain by relatively thick clay-rich glacial till of the Lagro Formation, which restricts the ability of contaminants to migrate into aquifers, especially where the till is more than 40 feet thick. Thus, approximately two-thirds of the county is characterized by hydrogeologic regions having relatively lesser sensitivities. Only a small fraction of the county, perhaps as little as 10 percent, is characterized by hydrogeologic regions where the sensitivity of ground water to contamination appears to be generally high. Ground-water protection efforts should primarily be directed toward these regions, and to localized small areas within other regions whose sensitivities appear to be relatively greater than the region as a whole.

The remainder of this chapter, as well as the discussions of hydrogeologic regions in Chapter 4, emphasize those *naturally occurring* geologic and hydrogeologic conditions that generally control ground-water sensitivity by:

1) influencing the movement of most potential contaminants into the ground-water system from a source at or near the land surface; and
2) affecting the overall impact of the contaminant on ground-water quality.

The following discussion is intended only for a general ground-water sensitivity analysis at the scale of the hydrogeologic regions presented on Plate 9. Although the general principles are applicable to site-specific situations, the latter almost always require a relatively detailed knowledge of the chemical characteristics and aqueous behavior of the specific contaminant(s) involved, as well as a more exacting analysis of the hydrogeologic framework of the site.

At any given point in the landscape, the sensitivity to contamination of a particular aquifer is a function of the total hydrogeologic setting. The hydrogeologic setting is, in turn, composed of several interdependent factors, each of which exerts an influence on ground-water sensitivity. Several factors are judged to be of primary importance in controlling the relative sensitivity of aquifers in Allen County:

1) the composition and permeability of each aquifer;
2) the degree of confinement of the aquifer, and the geologic characteristics of the confining unit(s);
3) position in the ground-water flow system, with particular emphasis on recharge or discharge conditions at different points within the system;
4) the ability of the soil to restrict the downward migration of contaminants, either through physical, chemical, or biological processes; and
5) near-surface drainage characteristics, which include depth to the water table and the relationship between surface drainage and shallow ground water.

Aquifer Characteristics

The composition and geometry of an aquifer are the principal determinants of the impact of a contaminant once it has already entered the aquifer. These characteristics control the rate at which the contaminant can migrate through the aquifer, as well as the ability of the aquifer material to filter or chemically attenuate the contaminant. In general, aquifers uniformly composed of relatively finer grained materials (fine sand, for example) will have lower permeability and greater filtering ability, because pore size is reduced and contact between the geologic material and the pore fluids (namely, water and(or) contaminants) is maximized. Both conditions are likely to retard contaminant migration and thus reduce the impact on water quality in an areal sense. Likewise, aquifers or aquifer systems that contain appreciable fine-grained sediment, such as lenses of silt

Table 5. Aquifers mapped on Plate 6 listed in order of relative abilities to attenuate or restrict the migration of contaminants.

Type of Aquifer (Map Symbol on Plate 6)	Relative Attenuation Ability
Limestone bedrock, generally karsted (b)	LEAST
Large channel complexes in the Trafalgar Formation (OTc, Tc)	
Other, mostly coarse sand and gravel units in the Trafalgar Formation (Tb, Tx)	
Intersequence unit, Aboite aquifer system, mainly coarse sand and gravel (I)	
Deep intertill aquifers, sand and gravel (ts)	
Unconfined outwash and ice-contact stratified deposits of the Erie Lobe, chiefly sand and some gravel (Os, Oh, O/h, Leh)	
Huntertown aquifer system, ice-contact stratified deposits, chiefly sand and some gravel (Hbi, Hfc)	
Huntertown aquifer system, fan-deltas, sand and some gravel (Hd)	
Huntertown aquifer system, basal outwash sand (Hb)	
Huntertown aquifer system, fine lacustrine sand (ls)	
Intersequence unit, eastern Allen County, mainly fine sand (I)	
Huntertown aquifer system, mixed lacustrine sediments (lm)	MOST

and clay, will have a greater capacity to chemically react with contaminants than aquifers composed exclusively of coarse-grained materials. In contrast, permeability is relatively more rapid, and attenuation capacity correspondingly less in fractured bedrock or coarse sand and gravel aquifers.

Most aquifers in Allen County (table 5) fall somewhere in between these extremes. Moreover, the distribution of permeability is rarely uniform in most geologic materials. Many aquifers commonly contain zones of higher permeability, such as lenses of coarse gravel within a body of sand, or large solution features within fractured limestone. These geologic **heterogeneities** typically form significant water-producing zones within the aquifer and represent pathways through which contaminants could migrate more rapidly than in the aquifer as a whole. On the other hand, some kinds of heterogeneities may have the opposite effect. For example, zones of fine sand or silty sand deposited in localized areas of lesser meltwater velocity commonly occur in otherwise coarse-grained outwash bodies. If large enough and properly situated with respect to the contaminant plume, the finer-grained material is likely to retard contaminant migration. Similarly, tabular lenses of fine-grained material within an aquifer can retard or even altogether prevent the downward movement of a contaminant that originates above the lens. From the standpoint of aquifer sensitivity, then, it follows that the more heterogeneous a particular aquifer is, the greater the likelihood that contaminants could migrate farther and faster along preferred pathways, and the more difficult it will be to predict the distribution of those contaminants.

The least favorable type of aquifer for restricting contaminant migration in Allen County is represented by the karsted limestone and dolomite bedrock, in which potentially rapid ground-water flow occurs via definite conduits (fractures or solution features). The aquifer media is solid rock having little or no ability to either filter or chemically react with contaminants, and the concentration of ground-water flow along discrete conduits greatly reduces the opportunities for interaction between fluids and the aquifer material. In contrast, the lacustrine sand aquifers of the Huntertown aquifer system may have the best qualities in this regard, since they are composed chiefly of relatively uniform, fine to very fine sand, and are locally interbedded with silt and clay.

Degree of Confinement

The relative degree of confinement of aquifers in Allen County may well be the single most important factor affecting their sensitivity to contamination. The principal confining units are composed of fine- to medium-grained glacial till characterized by low primary hydraulic conductivities (table 3). Ground-water flow through these confining units is generally very slow unless secondary permeability is developed along such features as fractures and interconnected sand seams. Such features also represent heterogeneities that can act to facilitate the vertical movement of contaminants across one or more confining unit(s). Although it is difficult to predict the specific locations of individual features that may enhance the permeability of confining units, the general occurrence of fractures and sand bodies and their relationship to specific till units was identified and discussed previously.

The most important confining unit in Allen County is the fine-grained till of the Lagro Formation. In many places, this unit is likely to be the first geologic material contaminants will come in contact with because it directly underlies the land surface over most of the upland areas in the county. The high clay content of the unit contributes to its low primary permeability (table 3) and greatly increases its ability to attenuate contaminants. Because most fractures appear to be concentrated in the upper 20 feet of the unit, the till affords a less certain degree of protection to underlying aquifers where it is less than this thickness. Likewise, the few large bodies of sand and gravel that are known to cut the till in the northern part of the county (pl. 5) also locally diminish the effectiveness of the till as a confining unit. The till is the only confining unit over several important shallow sand and gravel aquifers of the Huntertown and Aboite aquifer systems (pls. 6 and 10). Hydrogeologic regions containing these aquifers are mapped according to the thickness range of the Lagro, and their relative sensitivities vary accordingly (pl. 9).

The deeper aquifers in many parts of the county (pl. 6), such as the bedrock (b), deep intertill sand and gravel units (ts), and the basal outwash of the Trafalgar Formation (Tb) are confined by one or more additional till units below the Lagro. These lower till units are generally loamy in texture and include tills of the Trafalgar Formation as well as older sequences. The aggregate thickness of this lower till sequence reaches 200 feet in parts of northern Allen County, but elsewhere a thickness range of 40 to 75 feet is more typical. Although these tills are significantly less clayey than the Lagro and therefore may not possess the same ability to attenuate contaminants, they are typically highly overconsolidated and appear to be characterized by low vertical ground-water flow rates (table 3). The added thickness of low permeability material below the Lagro till thus represents additional protection for the deep aquifers.

In some places the Trafalgar Formation contains large channel-like sand and gravel bodies that cut partially or completely through the enclosing till. Such features are particularly abundant in parts of the Aboite aquifer system in western and southwestern Allen County (pl. 6). They represent high-permeability vertical conduits that interconnect aquifers at different horizons and that may act to recharge the bedrock and other deep aquifers. Where such features are present in abundance or on a large scale, they diminish the degree of confinement and afford a direct pathway for the migration of potential contaminants into deeper aquifers. In the valley of Aboite Creek and the Wabash-Erie Channel, the tops of some of these channels are at or close to the land surface and essentially are unconfined. Deep aquifers, which are normally well protected in most places, are considerably more sensitive in this type of hydrogeologic setting, because the channels afford a direct connection between the near-surface environment and the bedrock surface.

The limestone bedrock in northern Allen County is confined by as much as 90 feet of Antrim Shale, which effectively isolates the bedrock from ground water in any of the overlying glacial units. The shale is likely to retard the downward migration into the limestone of any contaminants that might reach the deeply buried bedrock surface. Ironically, the added "protection" provided by the Antrim Shale actually may work to the detriment of the bedrock aquifer system by restricting flow into the system by younger water. Consequently, water in the limestone in that area is commonly of too poor quality for domestic consumption unless treated, reflecting the high amounts of iron, sulfate, and other constituents naturally present in the relatively old, mineralized water.

Some protection of shallow aquifers is provided locally by fine-grained lacustrine and stream sediments, which are composed of various assemblages of silt, clay, and fine sand.

These sediments occur chiefly in three distinct hydrogeologic situations. In the first, massive to laminated lacustrine silt up to 20 feet thick locally overlies and is interbedded with fine lacustrine sand aquifers of the Huntertown aquifer system (pl. 6). The fine-grained sediments afford additional protection for the sand aquifers, especially where the overlying Lagro Formation is thin or absent, and they create low-permeability zones within the aquifer system that could retard potential contaminants. The other two confining units are composed of surficial sediments associated with ancestral Lake Erie and its outlets. One unit forms a veneer of laminated silt and clay that caps the surface of the lake plain in eastern Allen County (pl. 5). The unit is typically less than 5 feet thick, but the thickness increases to more than 10 feet in some parts of the lake plain. The silt and clay directly overlies the till of the Lagro Formation and is included in the till thickness contours shown on Plate 5.

The third unit occupies the floor of the Wabash-Erie Channel in several areas (pl. 5). The unit ranges from less than 5 feet to more than 35 feet thick, and can generally be subdivided into two sub-units, the first composed chiefly of massive to laminated sand, silty fine sand, and lesser sandy silt, and the second composed mainly of silt, sandy silt, and lesser fine sand. In some places, lenses of fine to coarse sand of uncertain shape and extent are locally present within the surficial sediments and form localized aquifers. Overall, however, these sediments probably behave as a semi-confining unit relative to underlying aquifers. Additional discussion of the origin and characteristics of this problematic unit can be found in the section on the **Wabash-Erie Channel** hydrogeologic region in the next chapter.

Position in the Ground-Water Flow System

As noted previously, some contaminants can behave differently than ground water in the subsurface geologic environment and can move independently of the prevailing ground-water flow direction. However, for the majority of contaminants, position in the flow system has an important bearing on aquifer sensitivity as well as the volume of aquifer potentially impacted by the contamination.

Contaminants released at the ground surface within or near regional discharge areas may, in some cases, be prevented from reaching underlying confined aquifers by upward hydraulic gradients, and the contaminants may simply discharge into a nearby surface water body (fig. 11). This is also true to an extent for local discharge areas, since the shallow ground water underlying these areas is typically discharging into surface water. In any event, the spread of the contamination is likely to be limited by the proximity to the ground-water discharge area. In contrast, the sensitivity of aquifers in recharge areas is considerably greater, and contamination may occur relatively rapidly following a release at the land surface, because of the downward hydraulic gradients and permeable geologic sequences that characterize these areas. Likewise, the overall severity and extent of contamination events could be greater in regional recharge areas because these areas are typically located high in both the landscape and the ground-water flow system and far from major discharge areas.

In at least one type of hydrogeologic setting, it is possible to have both regional discharge and local recharge occurring simultaneously. This situation occurs along the

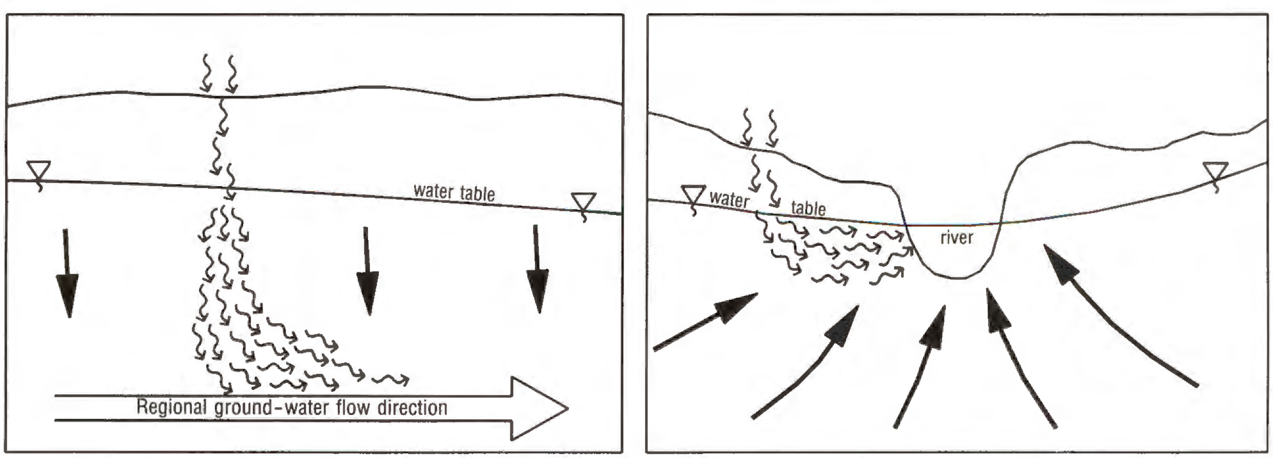


Figure 11. Schematic diagram comparing the possible effects of vertical gradients (heavy arrows) on the migration of contaminants (small arrows) in a recharge area (left) and a discharge area (right) of an idealized water table aquifer. Note that the directions of contaminant migration are hypothetical and apply only to those substances that are soluble in and of the same density as water, and thus move with the flow of ground water as a dissolved phase. Heavy contaminants are likely to sink through the aquifer regardless of the direction of any vertical gradients present, whereas lighter contaminants are likely to float on the water table.

St. Joseph River Valley, and possibly in portions of the other major river valleys, where unconfined glacial outwash or other permeable surficial sediments overlie a deeper aquifer of more regional extent. The St. Joseph River is the regional discharge area for the Huntertown aquifer system, which is in a semi-confined state and discharging upward. However, the top of the unconfined outwash that forms the floor of the valley is characterized by high infiltration rates and receives abundant recharge. Under such conditions, the outwash is considerably more sensitive to contamination than the deeper aquifer.

Although not a naturally occurring element of the ground-water flow system, large water withdrawals from high-capacity wellfields and dewatering of quarries and excavations are an important consideration for aquifer sensitivity. Intense downward gradients commonly associated with such withdrawals lead to **induced recharge** to the pumped aquifer, and may also induce contaminants to migrate into aquifers at potentially faster rates than they otherwise might. Depending on specific hydrogeologic characteristics and pumping schedules, the cone of depression associated with some large wellfields may be quite extensive, involving more than 100 feet of drawdown at each well and having a lateral extent as much as 2 to 3 square miles. The land area directly above a cone of depression is sometimes referred to as the "zone of influence" and is at increased risk because most of the water (and contaminants) that infiltrate this area will be "captured" by the cone of depression, and will eventually be drawn into the well (fig. 12). Additionally, ground-water recharge derived from land areas upgradient of the cone of depression also can contribute to the well. This situation clearly has the greatest implications for municipal wellfields that serve many water users.

The recognition that the sensitivity of aquifers is likely to be considerably elevated in the vicinity of large-capacity wells has led to the establishment of **wellhead protection areas** (WHPA) for an increasing number of public water supplies in the U.S. (U.S.E.P.A., 1991a). The loss of public water supplies through ground-water contamination is extremely costly; costs to treat the water or to replace the supply commonly run into millions of dollars, and the water supplies and potentially the health of a large population may be jeopardized. In contrast, the cost of implementing a wellhead protection program for public water supplies is minimal by comparison (U.S.E.P.A., 1991a). Wellhead protection programs can use a variety of both regulatory and nonregulatory approaches tailored to meet the geological conditions and socioeconomic needs of a particular community (U.S.E.P.A., 1991a; 1991b; 1991c). The general steps involved in such a program are:

1) conducting a relatively detailed hydrogeologic investigation of the wellfield and adjacent areas to define the geologic framework and to delineate a number of hydraulic parameters (fig. 12), such as the zone of influence and distances corresponding to the 5-, 10-, and 20-year travel times (U.S.E.P.A., 1991b);
2) identifying potential and actual sources of contamination within the wellhead protection area; and
3) taking appropriate steps to prevent and(or) mitigate ground-water contamination within the area.

Approximately 50 high-capacity wellfields in Allen County are registered with the Indiana Department of Natural Resources, Division of Water. Eight of these are municipal wellfields serving large fixed populations and another eight are smaller community systems serving mobile home parks and public schools (table 6). The remainder are privately owned wellfields that provide water for irrigation, energy production, and industrial purposes. The rated capacities of these wellfields range from about 70 gpm (the minimum pumping rate needed to require registration as a **significant water withdrawal facility** under IDNR rules) to more than 2,000 gpm, which translates into daily withdrawals of close to 3 million gallons. Although aquifers below all of the high-capacity wellfields in the county could be regarded as being somewhat more at risk than surrounding areas, the public water supplies are particularly worthy targets for ground-water protection efforts.

Soil Characteristics

Soils represent the upper few feet of material below the land surface that has been most strongly affected by chemical and physical weathering as well as a variety of biological activities. Soils are the first line of defense against contaminants released at the land surface, and they host many processes that help to restrict further contaminant movement. Processes and characteristics that affect contaminants as they move through soils can be broadly grouped into three types: physical, chemical, and biological. The distinctions between these categories are commonly blurred and the effects of one type of process can enhance or reduce the effectiveness of another.

In general, the physical rate at which water and(or) contaminants can move through the soil is controlled by soil permeability. The permeability of any given soil is a function of two characteristics. The first is grain size and shape, with fine-grained, compact soils generally being characterized by lesser permeabilities than coarse-grained, loose soils. The second is the abundance of **macropores**, which is partly a function of soil structure and includes root casts, animal burrows, cracks associated with shrinking and swelling, and other relatively large linear and planar openings that may increase soil permeability. A system of large, well-connected macropores can allow some contaminants to bypass the soil zone altogether. Macropores tend to be most abundant in fine-grained soils with high shrink-swell potential.

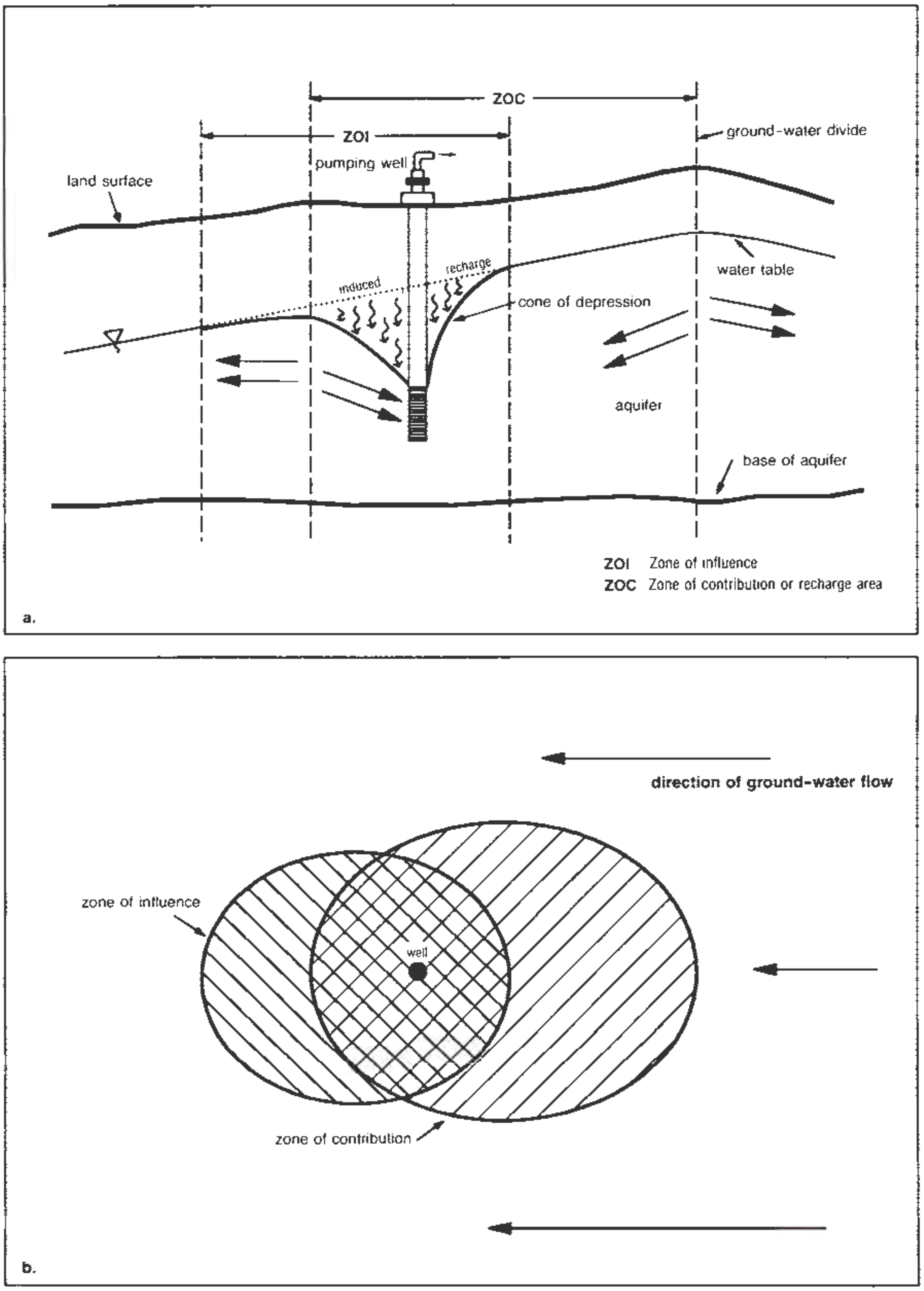


Figure 12. (a) Schematic cross section and (b) map illustrating hydrogeologic features associated with a high-capacity wellfield in an idealized unconfined aquifer.

Table 6. Public water supplies served by wellfields in Allen County. (Source: Indiana Department of Natural Resources, Division of Water.)

Municipal Wellfields

Name/Operator	Location	Capacity (gpm)	Pumped Aquifer[1]
Huntertown Utilities	SR 3, Huntertown	1220	Hb
City of Woodburn	Woodburn	484	b
Town of Monroeville	Monroeville	600	b
Town of Grabill	Grabill	460	ts
Utility Center, Inc.	St. Joseph Twp.	1500	ts
Utility Center, Inc.	Aboite Twp.[2]	3620	b
Utility Center, Inc.	Washington Twp.	1475	ts, hfc

Community Wellfields

Name/Operator	Location	Capacity (gpm)	Pumped Aquifer[1]
Somerdale Mobile Home Park	Lafayette Twp.	135	b
Harlan Mobile Home Park	Town of Harlan	100	ls
East Allen County Schools	Leo High School	205	ts
East Allen County Schools	Leo Elementary School	85	ts
East Allen County Schools	Hoagland Elementary School	85	b
East Allen County Schools	Heritage High School, Madison Twp.	80	b
East Allen County Schools	Harlan Elementary School	145	ls
Country Court Estates	Marion Twp.	250	b

[1]Corresponds to aquifer units on Plate 6.
[2]Operates two wellfields in Aboite Township.

Numerous bacteria are present in soil and are capable of digesting or transforming a variety of pollutants into less toxic or less mobile forms. Most soil bacteria require oxygen (namely, unsaturated conditions) and a supply of organic matter, such as humus, to carry out these functions. The organic matter itself is also capable of forming complexes with many kinds of contaminants and holding them in the soil. Likewise, many clay minerals are electrochemically active and can bind a variety of contaminants, keeping them from migrating further. The depth to the water table, or the presence of a seasonally perched water table is critical to these processes. In soils characterized by high water tables, contaminants will not only reach the ground water faster, but chemical and biological processes that require aerated conditions will be limited. In general, well-drained mineral soils characterized by abundant humus and a relatively deep water table are the most effective at retarding the migration of contaminants.

The soil series mapped and described in the Soil Survey of Allen County (Kirschner and Zachary, 1969) were evaluated in terms of their relative abilities to restrict contaminant migration. The evaluation was based on a comparison of published characteristics, including grain-size distribution, shrink-swell potential, water table depth, organic matter content, and field permeability. The major soil associations exhibit a clear relationship to the distribution of surficial geologic materials (pl. 5). Consequently, most of the hydrogeologic regions of the county are characterized by well-defined soil associations whose properties closely parallel those of the underlying geologic material. In general, most of the soils developed on fine-grained glacial till and lake sediments have many of the characteristics favorable to retarding the migration of contaminants, whereas soils developed on outwash and peat are less effective in this regard. A more detailed description of the process used to rate the soils, and the ratings themselves, can be found in Fleming (1992).

Near-Surface Drainage Characteristics

As used here, the term "near-surface drainage" includes several important and interrelated elements of surface and shallow subsurface water movement, including how well drained the land surface and soils are, nature of surface water bodies and their interaction with the water table, and the thickness of the **unsaturated zone**. These characteristics can affect ground-water sensitivity in a number of direct and indirect ways, chiefly by influencing whether and how quickly a contaminant enters the zone of saturation, which in turn controls the effectiveness of a variety of attenuation processes that take place above the water table. The near-surface drainage characteristics are intimately related to other sensitivity factors, specifically position in the ground-water flow system and soil characteristics, and the effects of the different factors may at times be difficult to distinguish.

The drainage of the land surface may have a bearing on the initial fate of a contaminant released at or near the surface. Water that falls on a well-drained part of the landscape does not remain on that landscape very long, and is removed by a combination of relatively rapid surface runoff and soil drainage. Most well-drained landscapes are moderately to strongly sloping and are characterized by well-drained soil types and a relatively deep water table. A contaminant released in this setting is more likely to be degraded relatively rapidly by attenuation processes or to simply run off into a surface water body, rather than moving directly into the ground water. Poorly drained landscapes, in contrast, are typically flat or low-lying or both, and water tends to remain on or near the land surface for long periods of time. Soils are commonly waterlogged and the water table may be at very shallow depth, sometimes within a few inches of the land surface. Attenuation processes are likely to be less effective in this type of setting, and the immediate fate of contaminants is more likely to be determined by the interaction between surface water and ground water.

The importance of water table depth as a factor in aquifer sensitivity has been mentioned in earlier sections, notably in the context of soil characteristics and position in the ground-water flow system. Many of the biological and chemical processes that act to attenuate contaminants are effective only under unsaturated conditions. Consequently, the closer the water table is to the land surface, the less opportunity there is for these processes to operate, and potential contaminants can enter ground water more rapidly and perhaps in a more concentrated form.

A shallow water table is characteristic of many regions in Allen County, but its presence may be due to different causes in different places and is not necessarily related directly to the potentiometric surface of underlying confined aquifers (fig. 13). For example, a shallow water table is common in many upland areas of the county and is attributable to the slow permeability of the underlying Lagro Formation, which contributes to poor landscape drainage. The shallow water table may or may not represent the top of a continuous zone of saturation (it may be perched in some places), but in any event it is quite distinct both in origin and elevation from the potentiometric surface. The low-permeability till greatly inhibits direct interaction between ground water near the water table and that in confined aquifers at depth. Consequently, although attenuation processes are likely to be limited by the shallow water table in this setting, the bulk of the contaminants that do reach the water table are likely to remain in the shallow ground water within the till, and any downward movement into underlying aquifers will occur at a very slow rate.

In many large low-lying areas, on the other hand, the water table is typically within 1 to 3 feet of the land surface and may represent the top of a continuous zone of saturation in an unconfined or semi-confined aquifer. For all practical purposes, the water table in these areas is continuous with, and indistinguishable from, the potentiometric surface in adjacent or subjacent areas where the aquifer is confined (fig. 13). Such areas may or may not be regional discharge areas depending on their positions within the ground-water flow system (pl. 7 and 8), but the proximity of the water table to the land surface will reduce the effectiveness of attenuation processes and could allow contaminants to enter the top of the regional flow system relatively rapidly.

Interaction of Factors

All of the factors that influence ground-water sensitivity commonly exhibit a predictable and generally interdependent pattern within a specific hydrogeologic setting, and the effects of the different factors may at times be difficult to distinguish. The patterns of local and regional-scale geographic variations in each of the factors show a marked parallelism to one another that is readily explained by their direct and unifying relationship to the landscape and sequence elements of particular glacial terrains. Surface morphology, for example, is usually a good indicator of the range of variation in the type of underlying vertical sequences, the quality of surficial confining units, soil associations, and other factors that can significantly affect the sensitivity of underlying aquifers. It should also be apparent from the preceding discussion that the nature of the interaction between the individual factors, as well as the relationship between the factors as a whole and ground-water sensitivity, are specific to individual hydrogeologic regions because each region is characterized by a relatively distinct set of glacial terrain elements. These specific relationships are explored further in the discussions of the individual hydrogeologic regions in Chapter 4.

The net effect of the factors as a group is reflected in the relative sensitivity of ground water below different hydrogeologic regions (pl. 9). The explanation of each hydrogeologic region is accompanied by a generalized ground-water sensitivity range based on all these factors. These ranges are relative, and are generally indicated as "low," "moderate," and "high." Certain conditions in parts of some hydrogeologic regions make it difficult to assign a specific sensitivity range. For example, aquifers may occur at different depths below the same general area and may be under different hydrogeologic regimes, and thus be interpreted to have differing sensitivities. Sensitivities are given as a correspondingly broad range in the explanation of these areas, and the existence of a dual or "tiered" system of aquifers is explicitly cited. In other regions the geographic variation of one or more factors may be so great as to cause a wide range in sensitivity over very small areas relative to the map scale. The sensitivity of such areas is again stated as a relatively wide range, and the cause cited specifically in the explanation.

The sensitivity ranges shown on Plate 9 are not entirely the product of qualitative interpretation. During the compilation of 1:24,000 hydrogeologic quadrangle maps of Allen County (Fleming, 1992), a numerical aquifer sensitivity index was formulated based on weights and ratings of the individual factors and characteristics described above. Each factor was assigned a weight that indicates its importance for aquifer sensitivity relative to other factors. Specific ranges of conditions within each factor (for example, thickness

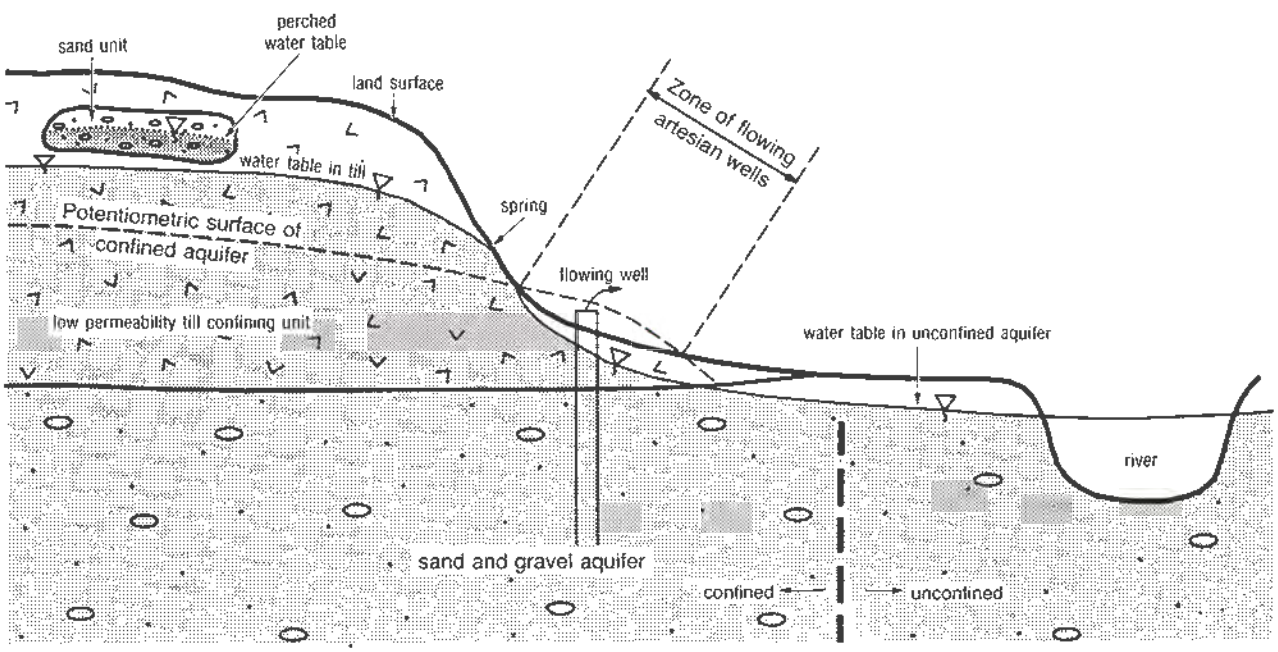


Figure 13. Schematic cross section showing the relationship between the water table, perched water table, potentiometric surface, and zone of saturation (shaded) in confined and unconfined parts of a sand and gravel aquifer and the overlying till confining unit. The zone of flowing artesian wells occurs where the potentiometric surface of the confined sand and gravel aquifer is at a higher elevation than the land surface. Similar conditions occur locally along the extreme northern part of the Maumee Lacustrine Plain in eastern Allen County.

ranges of till confining units) were given numerical ratings based on their effect (negative or positive) on ground-water sensitivity. Using this approach, a sensitivity index range was derived for every hydrogeologic region by summing the products of factor weights and ratings, both on an areal basis and for selected individual water wells. The results of this procedure generally confirmed the qualitative interpretation of sensitivity and provided a semiquantitative basis for comparing the effects on aquifer sensitivity as certain conditions changed across the landscape. Although the sensitivity index does not specifically appear in the sensitivity ranges shown on Plate 9, it did serve as a "logic check" in evaluating the sensitivities of the different hydrogeologic regions.

CHAPTER 4

HYDROGEOLOGIC REGIONS OF ALLEN COUNTY

by Anthony H. Fleming
(Sections on ground-water availability by Anthony H. Fleming and William J. Steen)

OVERVIEW

In the preceding chapter, the principal geological formations and depositional sequences that underlie Allen County provide a useful context for describing a variety of hydrogeologic terms and concepts. This context, or hydrogeologic framework, relates the hydrogeologic behavior of the predominant geologic units to their specific physical and chemical properties on a broad countywide scale. It should be evident from the preceding chapters, however, that none of these geologic materials are uniform in their properties and attributes, nor are the larger stratigraphic sequences and landscapes they occur within. Even relatively subtle geographic variations in one or more characteristics of a particular formation, in the configuration of the landscape, or in the arrangement of a stratigraphic sequence can sometimes lead to very large differences in gross hydrogeological behavior from one area to the next.

Nearly all of the geographic variation in hydrogeologic characteristics observed in Allen County can be directly related to one or more of three main causes:

1) changes in the physical attributes of the major geologic materials;
2) differences in the stratigraphic arrangement of materials with contrasting properties; and
3) differences in landscape characteristics.

Collectively, these three features are the consequence of the particular series of geologic events specific to a geographic region. They are also the principal elements that make up and distinguish the glacial terrain regions described previously in Chapter 2.

The relationships noted above suggest that the predominant kind of hydrogeologic setting that characterizes each of the different geographic regions within Allen County is essentially a manifestation of a particular type of glacial terrain. Although a certain amount of variation in hydrogeologic behavior can always be found within each terrain region, the range of hydrogeologic conditions within a particular region is typically much less than that between different regions. In view of this relationship, it is not surprising that each of the eleven major glacial terrain regions in Allen County is typified by a specific association of hydrogeologic conditions that differ in one or more significant ways from conditions in adjoining regions. Stated slightly differently, each of the glacial terrains can also be defined as a hydrogeologic region characterized by a relatively distinct set of aquifers, confining units, ground-water flow system characteristics, and near-surface drainage characteristics.

This chapter examines the hydrogeologic framework of Allen County from a more localized perspective based on the 11 glacial terrains/hydrogeologic regions identified in Chapter 2. In the following sections, the defining hydrogeologic characteristics of each of these regions are described in detail using as many specific examples as possible. The hydrogeologic regions are particularly useful for discussing such practical considerations as ground-water availability and the sensitivity of aquifers to contamination. These gross hydrogeologic parameters are a function of the total hydrogeologic environment of each region and they tend to exhibit a distinct pattern that closely parallels the range of hydrogeologic conditions specific to each region.

HUNTERTOWN INTERLOBATE REGION

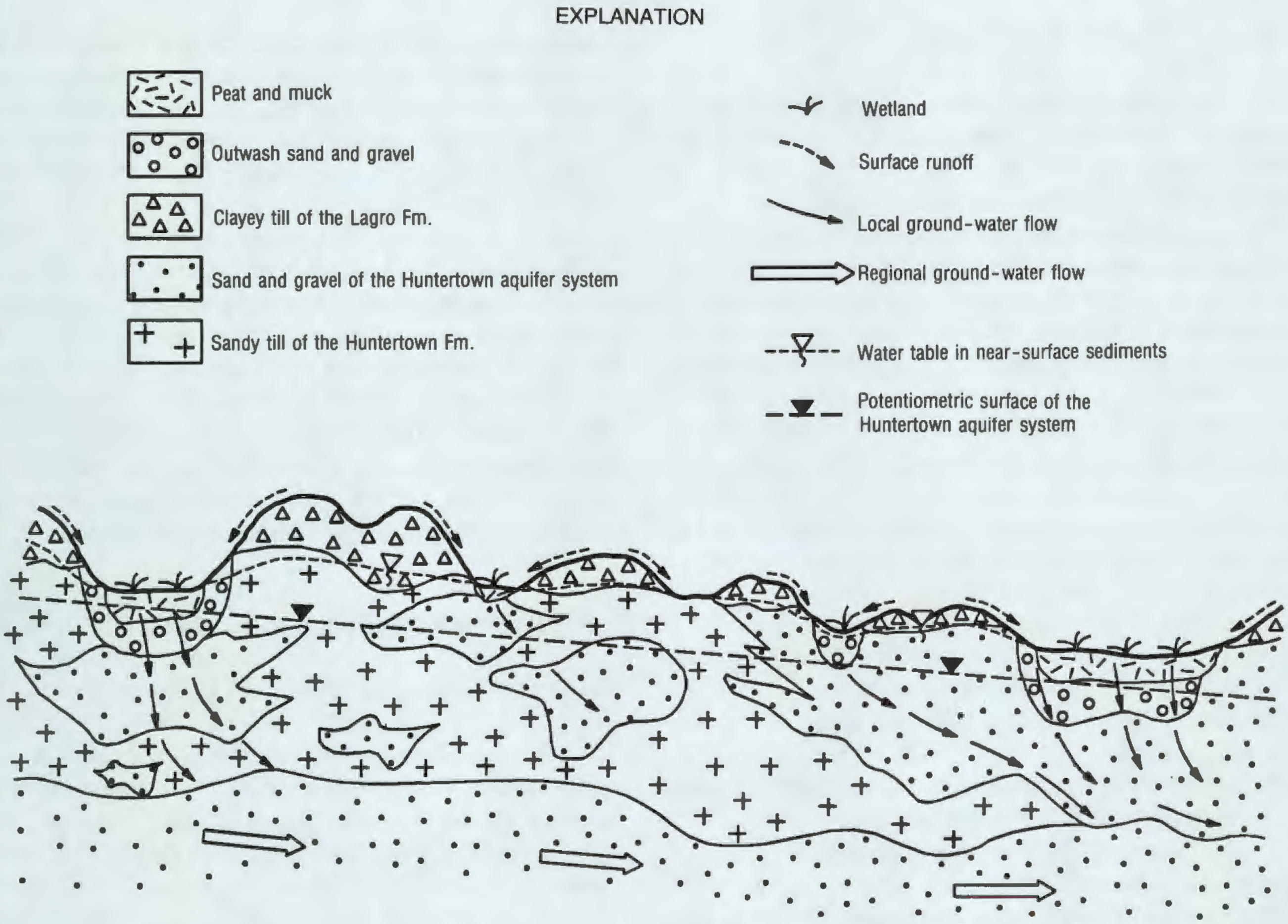
General Characteristics

The Huntertown interlobate region comprises an elongate, northeast-to-southwest-trending belt that extends over most of the northwestern corner of the county (pl. 9). It contains the Eel River Valley, which is discussed in the next section as a separate but related hydrogeologic region. The Huntertown interlobate region includes some of the most productive aquifers in the county, but many of the same qualities that contribute to high productivity also lead to a relatively elevated sensitivity to contamination for much of the region.

The typical stratigraphy of the Huntertown interlobate region consists of a discontinuous confining unit of clayey to loamy till of the Lagro Formation draped over a thick sequence of ice-contact stratified deposits, discontinuous loamy till, and outwash sand that make up the Huntertown aquifer system in this area. The ice-contact stratified deposits are commonly 30 or more feet thick and have locally coalesced with the underlying outwash to form exceptionally thick sections of sand and gravel.

The predominant feature that sets this region apart from all others is its characteristic hummocky, internally-drained landscape. The distinctive surface morphology of this region exerts a strong influence on the hydrogeologic regime

Near-Surface Hydrogeology of the Huntertown Interlobate Region



The soils on most of the hummocks and other uplands in this region are moderately well drained to somewhat poorly drained silty-clay loams of the Morley and Blount Series (Kirschner and Zachary, 1969). These soils formed on the Lagro Formation and are characterized by limited permeability and moderately to strongly sloping topography, which is likely to lead to a considerable amount of surface runoff into adjacent low-lying areas. The latter areas are underlain by much more permeable soils developed on peat and sand and gravel, and are characterized by water table depths as little as a few inches. There are few through-flowing surface drainages in the region and most of the low areas are enclosed or semienclosed depressions and abandoned channels occupied by peat bogs or other wetlands. The wetlands collect, store, and filter runoff from the adjacent uplands before gradually releasing it into the aquifer system below.

The soils present below the wetlands are chiefly saturated peat and muck of the Carlisle Series (Kirschner and Zachary, 1969), which have limited ability to attenuate contaminants via the kinds of processes that typically operate in soils under aerobic conditions. Considerable attenuation is possible, however, within the wetlands themselves. Many wetland plants are well known for their great ability to absorb contaminants and purify wastewater, consequently an increasing number of communities are utilizing natural and artificial wetlands to treat sewage in several ways (see sidebar, **Near-Surface Hydrogeology of the Huntertown Interlobate Area**, pages 70-71). The degree of confinement of the Huntertown aquifer system is directly related to the continuity and thickness of the Lagro Formation, which is in part a function of surface morphology. The till is thickest and most continuous below the largest hummocks and uplands, where it locally reaches thicknesses of 25 to 30 feet. In contrast, the till is largely absent from the bottoms of the many large depressions and meltwater channels within the region, and is thin and discontinuous along adjacent hummocky slopes. Peat, outwash, sandy till, and sand and gravel in the upper part of the Huntertown aquifer system are the typical surficial materials in areas where the Lagro is absent.

This situation gives rise to a distinctive drainage pattern that appears to be unique to this region and which is indicative of the close relationship between landforms, soil type, and surficial geology. Runoff from hummocks and ridges collects in peat bogs in low-lying areas, where it seeps directly into the underlying aquifer system. The water table in these wetlands is typically at or within a few inches of the land surface, although the potentiometric surface of progressively deeper parts of the aquifer system is as much as 10 feet lower. This results in a relatively pronounced downward hydraulic gradient through the aquifer system, which suggests that a substantial amount of water released by peat bogs eventually recharges deeper parts of the aquifer system. Artificial drainage of some of these wetlands is likely to have a negative effect on recharge rates, however, and could end up dewatering the uppermost part of the aquifer system near large drainage ditches.

effluent. It seems likely, therefore, that the wetlands in the Huntertown interlobate region may play an important role in maintaining the quality of water that is recharged to the aquifer system below.

A considerable number of peat bogs and other wetlands in northwestern Allen County have been artificially drained via ditching of existing creeks and the installation of new ditches that connect previous isolated depressions. Drainage of these areas can have several effects, some may have negative implications for ground-water recharge and water quality. The principal effect is the lowering of the water table, which eliminates wetlands and causes the upper part of the peat to dry out and blow away. Runoff from uplands adjacent to drained areas may be carried away as surface water via the ditches, reducing the amount of water available to recharge subjacent aquifers. Loss of wetlands also reduces the purification of runoff, which may alter the quality of that part of the runoff that does become ground water, particularly if the runoff is derived from agricultural areas where pesticides and fertilizers are employed. An incidental effect of artificial drainage is the potential dewatering of the top of the aquifer system along segments of ditches excavated into sand and gravel aquifers. All of these effects alter the natural hydrogeologic regime in both subtle and obvious ways, but the long-term implications for both the quality and quantity of ground water in the aquifer system as a whole may not become evident for decades.

Ground-Water Availability

The primary source of ground water is the Huntertown aquifer system, which is composed chiefly of thick sand units and lesser sand and gravel bodies deposited by the Saginaw Lobe and its meltwaters (pl. 6). These units rest on a surface of variable relief developed chiefly on till of the Trafalgar Formation (pl. 4). The combined thickness of all saturated sand and gravel units in this aquifer system is typically between 30 and 80 feet in most of the Huntertown interlobate region. In a few very small and widely scattered locations, these deposits are too thin to serve as reliable water-supply aquifers, and wells are made in sand and gravel units in or below the underlying Trafalgar Formation.

Ground-water availability in the Huntertown aquifer system in general, and the interlobate region in particular, is among the best in the county. Although the productivity of individual wells shows a considerable range across the region, yields are consistently adequate to meet even the largest domestic needs as well as most high-capacity uses. The basal outwash sand of the Huntertown Formation is the most widely used aquifer, but the overlying ice-contact stratified deposits are locally important aquifers as well. These aquifers are used chiefly by households, scattered industries, and the Huntertown municipal wellfield.

The yields that can be expected in any given part of the region show a direct relationship to the geology of the underlying aquifers and, to a lesser extent, to the degree of confinement. The capability of the basal outwash aquifer can be limited in a few places because the sand is locally fine. Yields of 10 to 50 gpm, however, appear to be common, and much larger yields are possible where this aquifer contains a greater proportion of gravel or is overlain directly by thick, gravelly ice-contact stratified deposits. Somewhat greater yields might also be expected where the aquifer system is unconfined or poorly confined, but most of these areas correspond to wetlands or other low-lying places with few wells. The above interpretation is based on a comparison with yields from the Eel River Valley, where the geology is generally comparable to smaller unconfined areas within the Huntertown interlobate region.

Ground-Water Sensitivity

The type of glacial terrain particular to the Huntertown interlobate region results in a coincidence of several factors that contribute to a generally high sensitivity to contamination:

1) a shallow aquifer system characterized by large, productive sand and gravel aquifers at different depths that have locally coalesced to form very thick granular sections;
2) numerous areas characterized by little or no confinement of the aquifer system;
3) shallow water table, waterlogged soils, and permeable surficial sediments, especially in low-lying areas; and
4) internally drained landscape with high recharge potential.

It is difficult to single out any one of these conditions as being the primary reason for the relatively high sensitivity of the region because the different factors are closely related and tend to reinforce each other. For example, parts of the aquifer system lacking a confining unit (unit Ho, pl. 9) almost always occur in low-lying parts of the landscape which essentially collect and transmit runoff from the surrounding landscape to the aquifers below. In these places, soils are waterlogged and surficial sediments are permeable, thus any contaminants that might be introduced are likely to move directly and rapidly into the aquifer system with little or no attenuation. On the other hand, ground water below the largest upland areas within the region (unit H2, pl. 9) is likely to be somewhat less sensitive due to a slightly thicker and less broken till cover, better soil characteristics, and greater water table depth. The least sensitive parts of the region are those where the Huntertown aquifer system is thin or discontinuous (unit Hd, pl. 9) and the principal ground-water production is from well-confined sand and gravel aquifers at depths generally greater than 100 to 150 feet.

The sensitivity of each of the different subregions of the Huntertown interlobate region (pl. 9) is shown as a range, which is partially attributable to variations in the factors described above that are too localized to show at the published map scale. Some of the variation in sensitivity, however, is attributable to different aquifer configurations that occur within the Huntertown aquifer system (fig. 14). Comparison of Plates 6 and 9 helps to illustrate how different aquifer geometries can affect the sensitivity range within a particular subregion. Subregion H (pl. 9), for example, is generally characterized by less than 20 feet of locally discontinuous Lagro till confining the aquifer system as a whole. However, aquifer unit Hb (pl. 6) is likely to be less sensitive to contamination than unit Hbi, which in turn might be expected to be less sensitive than Hfc, because there is a progression from a relatively thick local till confining unit *within* the aquifer system in unit Hb to a situation where virtually the entire thickness of the aquifer system is composed of sand and gravel in unit Hfc.

EEL RIVER VALLEY

General Characteristics

The Eel River Valley is a narrow, southwest-to-northeast-trending abandoned meltwater channel that roughly parallels the front of the Wabash Moraine and sharply demarcates the northwestern corner of the county (pl. 9). The Eel River Valley is located almost entirely within the Huntertown interlobate region and shares several important similarities with that region. The part of the Huntertown aquifer system below the Eel River Valley is perhaps the most productive, as well as the most sensitive to contamination, of any hydrogeologic region in Allen County.

The typical sequence below much of the Eel River Valley consists of thick, coalesced sand and gravel bodies of different ages and origins. In most places, the upper 10 to 40 feet of the section is Erie Lobe outwash, which was deposited atop one or more large ice-contact fans of the Huntertown Formation. The thickest sections of sand and gravel are located just north and west of Huntertown, and are locally in excess of 100 feet thick. Elsewhere, the sand and gravel is typically in the range of 30 to 80 feet thick, being thickest where ice-contact fans (unit Hfc, pl. 6) are present below the valley. Thin till confining units of limited areal extent are present in a few places within the sand and gravel of the Huntertown Formation.

The Eel River Valley in Allen County is an ancient glacial sluiceway that is now predominantly an upland landscape with little natural through-flowing surface drainage. The upper reaches of the valley, as well as the valley margins further downstream are underlain by outwash that is locally pitted. The outwash also forms a few terraces outside of the main trunk of the valley. Further downstream, the axis of the valley contains extensive peat lands where as much as 35 feet of peat is present above the sand and gravel. The water table is typically shallow and is within a few inches of the land surface in peat-filled areas. Soils are generally highly permeable and at least seasonally waterlogged. Much of the region is a wetland, parts of which have been extensively drained and modified, chiefly for agricultural purposes. The valley contains a major surface drainage divide between the Eel River, which is part of the Wabash River system (Mississippi River drainage) to the west, and Cedar Creek, which drains into the Maumee River system (Lake Erie drainage) to the southeast.

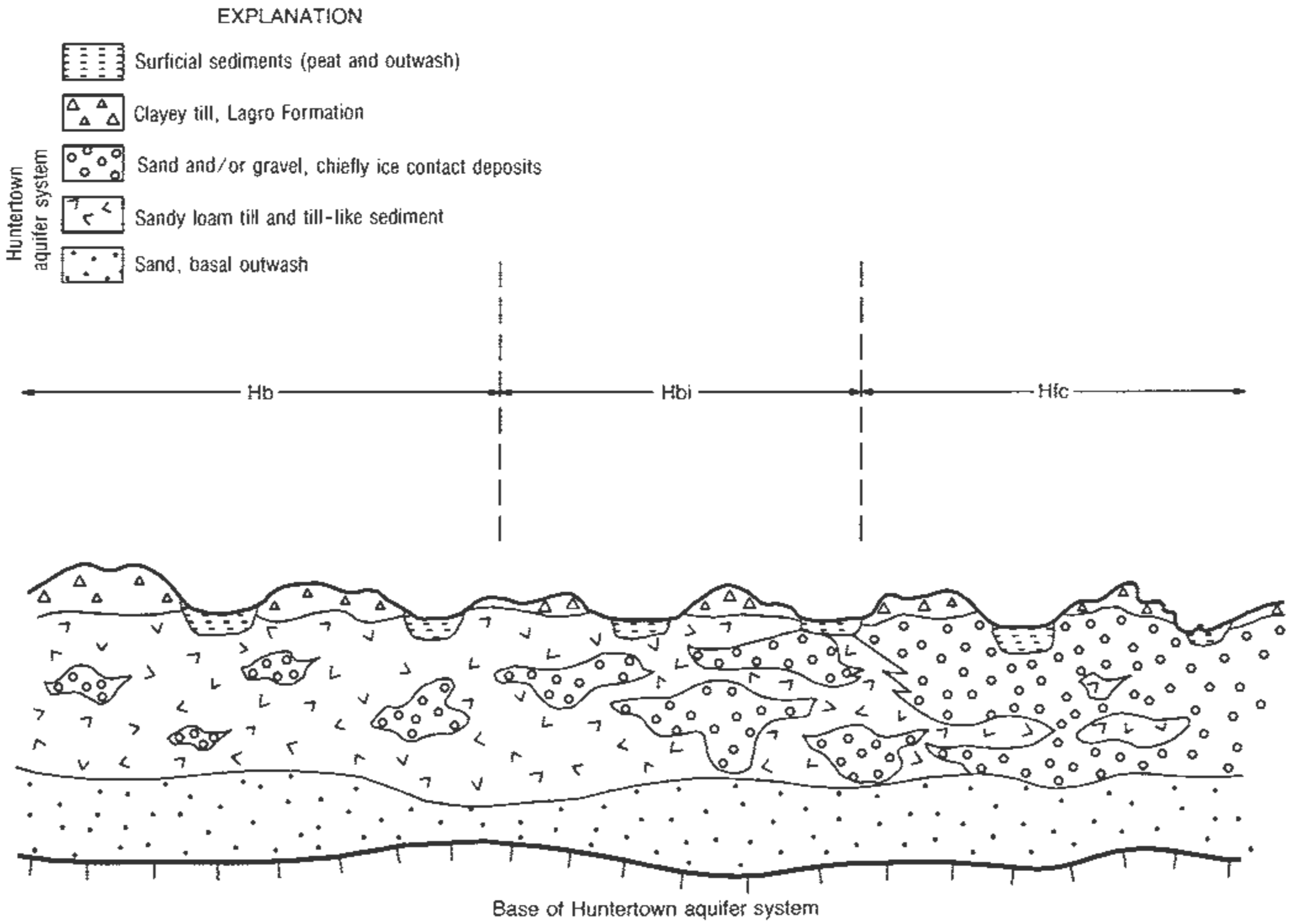


Figure 14. Schematic cross section across the Huntertown interlobate region showing how different aquifer geometries affect the sensitivity of the Huntertown aquifer system to contamination under otherwise similar terrain conditions. Segments of the cross section denoted as "Hb," "Hbi," and "Hfc" correspond to aquifer map units on Plate 6.

A complex shallow ground-water flow system is present within the peat and outwash below the virtually flat floor of the valley. The surface wetlands receive abundant runoff from small ravines and ditches draining adjacent till-capped areas, as well as some ground-water discharge from the near-surface sediments that flank the valley. The general absence of surface streams within much of the valley itself causes the water to become ponded within the extensive wetlands that occupy the drainage divide. An unknown but probably large percentage of the water thus accumulated moves downward into the unconfined aquifer system below the valley. Downward hydraulic gradients between the water table and deep parts of the aquifer system strongly suggest that the entire aquifer system receives large amounts of recharge below the valley. The thick sections of unconfined or poorly confined sand and gravel that characterize the valley essentially function as a hydraulic "window" through the entire thickness of the Huntertown aquifer system.

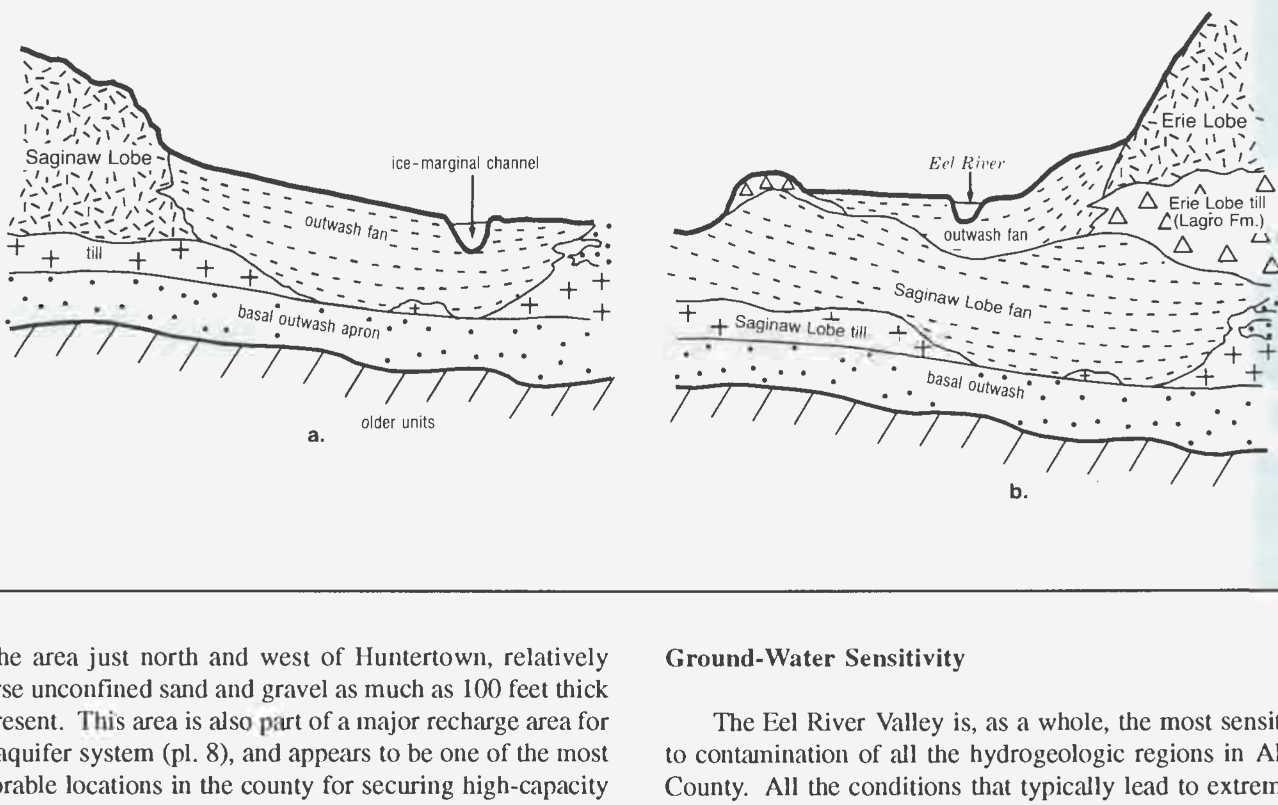
Ground-Water Availability

Ground water in this hydrogeologic region is produced almost entirely from the Huntertown aquifer system, which includes the Erie Lobe outwash that caps the valley. Most wells are developed in the deeper part of the sand and gravel, which is in some places semi-confined and separated from the surficial outwash by sandy till of the Huntertown Formation. Ground-water availability is generally excellent throughout the valley, and domestic well yields greater than 20 gallons per minute (gpm) are to be expected in most places.

Evolution of Large-scale Sand and Gravel Aquifers Below the Eel River Valley

The Eel River Valley is an excellent example of how several bodies of sand and gravel that are otherwise distinct in form and origin can become coalesced on a very large scale to form one very large aquifer. In most places, the Huntertown aquifer system consists of sand and gravel aquifers situated at as many as three distinct horizons in the Huntertown Formation (see fig. 14). The basal sand aquifer originated as a proglacial outwash apron in front of the advancing Saginaw Lobe, whereas aquifers higher in the system generally represent various types of ice-contact stratified bodies formed during disintegration of the ice. The largest of these occur as ice-contact fans and associated channels that appear to have been deposited in places where the retreating ice front became stabilized for some extended length of time. The largest such fan complex known in Allen County extends southeast under the central segment of the Eel River Valley from its apparent head along the Dekalb County Line north of Huntertown. Meltwater associated with the deposition of this fan evidently removed most of the till and other fine-grained material that may have once capped the basal outwash sand, resulting in the coalescing of sand and gravel bodies on a very large scale (fig. a). Some parts of this coalesced body just north of the Eel River Valley are 80 to 100 feet thick.

This sand and gravel body was entirely covered by clayey till of the Lagro Formation during the initial advance of the Erie Lobe. However, subsequent large-scale meltwater discharges from the Erie Lobe at the Wabash Moraine cleaned out the till from the valley floor and deposited still more sand and gravel atop the exhumed Saginaw Lobe complex (fig. b). The result of these events is a thick section of coalesced sand and gravel bodies that is unconfined in the Eel River Valley and that extends back under the Lagro till to the north and south (fig. b). Hydrogeologically, this section acts as a large-scale interconnection between sand and gravel aquifers at various horizons within the Huntertown aquifer system, and thus serves to recharge the entire aquifer system.



In the area just north and west of Huntertown, relatively coarse unconfined sand and gravel as much as 100 feet thick is present. This area is also part of a major recharge area for the aquifer system (pl. 8), and appears to be one of the most favorable locations in the county for securing high-capacity sand and gravel wells. Potential well yields of between 300 and 600 gpm, or greater, are likely in this part of the aquifer system.

Ground-Water Sensitivity

The Eel River Valley is, as a whole, the most sensitive to contamination of all the hydrogeologic regions in Allen County. All the conditions that typically lead to extremely high sensitivity are present in this region and can be directly attributed to the geologic history of the valley (see sidebar, **Evolution of Large-Scale Sand and Gravel Aquifers**

Below the Eel River Valley, page 74). The fact that the valley functions as a regional recharge area for the Huntertown aquifer system and is located high in the ground-water flow system could increase the severity of any contamination that might occur. Instead of being restricted to a small area in the upper part of the aquifer system, a contaminant whose presence remains undetected for any appreciable length of time is likely to migrate into deeper portions of the aquifer system and could spread over a relatively larger area of the system downgradient of the recharge area. Similarly, nonpoint source contaminants introduced in the valley, such as pesticides, fertilizers, or septic effluent could have a more systemic impact on ground-water quality within the aquifer system downgradient of the sources. Finally, large, unbroken sections of sand and gravel are at particular risk from contaminants that are heavier than water. Such contaminants could pollute the entire column of ground water in the aquifer system as they sink to the bottom of the sand and gravel. Once there, cleanup might be virtually impossible and the heavy liquids would thus constitute a continuous and permanent source of contamination to deeper parts of the Huntertown aquifer system, which are otherwise the least likely to become polluted.

INTERLOBATE MORAINAL REGIONS

General Characteristics

Interlobate morainal regions are defined as Erie Lobe end moraines that overlie hummocky, morainal topography of the Saginaw Lobe. They occur in two separate locations in the county (pl. 9). The first corresponds to the north limb of the Wabash Moraine in Perry and Cedar Creek Townships (fig. 4), whereas the second encompasses the Salamonie Moraine in the extreme northwestern part of the county. For simplicity, these two areas are referred to respectively as the "Wabash Moraine" and "Salamonie Moraine," with the understanding that the former term refers only to the interlobate portion of the Wabash Moraine as shown on Plates 5 and 9. The interlobate morainal regions represent an extension of the Huntertown interlobate region, but differ in several important respects.

The typical stratigraphy of these regions consists of between 20 and 60 feet of clayey to loamy till of the Lagro Formation confining a variable sequence of ice-contact stratified deposits, discontinuous loamy till, lacustrine deposits, and outwash sand that make up the Huntertown aquifer system (pl. 6). Below the Wabash Moraine, the ice-contact stratified deposits are generally not as thick or well developed as they are in the Huntertown interlobate region, but large ice-contact fans up to 80 feet thick are present in a few places and have locally coalesced with the underlying basal outwash to form exceptionally thick sections of sand and gravel. The sandy Saginaw Lobe till that locally separates the basal outwash aquifer from higher aquifers in the system appears to be somewhat more persistent below the Wabash Moraine than elsewhere. Similarly, the Lagro Formation is greater than 60 feet thick in several places along the Wabash Moraine.

In contrast, the Salamonie Moraine is much more similar to the Huntertown interlobate region. The Lagro Formation is rarely greater than 40 feet thick and its thickness varies abruptly over short distances as the underlying surface of the Huntertown Formation changes in elevation. Small- to medium-size ice-contact stratified deposits are widespread within the Huntertown aquifer system below the Salamonie Moraine and are commonly between 10 and 30 feet thick. The sandy Saginaw Lobe till is locally thin or absent and large coalesced bodies of coarse sand and gravel up to 40 or more feet thick are common in this area.

The land surface in the interlobate morainal regions is a somewhat more subdued version of that in the Huntertown interlobate region. The crestal areas of the Erie Lobe moraines generally do not form sharply defined ridges, but instead appear as rather irregular belts of hummocky topography that may be inherited from the buried surface of the Saginaw Lobe deposits. The **palimpsest** character of the surface topography is suggested by the fact that the hummocky topography is sharpest where the Lagro Formation is thinnest, and by the highly irregular nature of the underlying buried surface.

The landscape and soils of the interlobate morainal regions are largely formed on the fine-grained till of the Lagro Formation. Ridges, hummocks, and other uplands tend to be well drained, but abundant depressions and meltwater channels commonly contain wetlands underlain by peat of variable thickness. The till confining unit may be absent from some of these low-lying areas, and peat may directly overlie the Huntertown aquifer system. Internal drainage is well developed in some places, and is likely to contribute to increased recharge in places where the Lagro Formation is thin or absent.

Ground-Water Availability

Nearly all of the ground water in these regions is produced from various sand and gravel aquifers of the Huntertown aquifer system. Ground-water availability is generally good throughout the region, but is greatest in the Salamonie Moraine to the west. There, large aquifers are commonly present at relatively shallow depths and typically contain coarse, gravelly zones capable of yielding large quantities of water. At least one high-capacity well in this region has a reported yield greater than 400 gpm.

Most of the region associated with the Wabash Moraine is characterized by aquifers composed chiefly of thick sand, the most extensive of which is the basal outwash aquifer. Some sand aquifers of lacustrine origin may also be present in the extreme southern and eastern parts of the region. The capability of the sand aquifers can be somewhat limited because some sand bodies are locally fine. These aquifers are used chiefly by households and yields of 10 to 50 gpm appear to be common. Much larger yields are possible, however, where aquifers contain a greater proportion of gravel. For example, the drilling of three high-capacity irrigation wells was observed in the northern part of the region. All the wells are developed in thick, gravelly fan deposits that appear to coalesce with the basal outwash sand, and each well yields 500 to 600 gpm. These results indicate that large yields can be expected for properly constructed wells located in appropriate hydrogeologic settings within the region.

Ground-Water Sensitivity

The sensitivity of ground water below the interlobate morainal regions ranges from moderately low to moderately high and is largely dependent on the thickness of the Lagro Formation. Aquifers confined by clayey till more than 60 feet thick (unit MH6, pl. 9) have the lowest sensitivities relative to other settings within the region, whereas those with less than 20 feet of till (unit MH1) may have somewhat elevated sensitivities. Most of the thin-till areas are located along deeply entrenched stream valleys and in large depressions. The till appears to be absent in a few of these places, all of which are too small to be shown at the published map scale. Consequently, unit MH1 (pl. 9) should be regarded with some caution. Most of the interlobate morainal regions, however, are capped by between 20 and 60 feet of till, which should be sufficient in most cases to limit the downward movement of contaminants from the land surface.

Large channels composed chiefly of sand are present in several places within the Lagro Formation (unit MHc, pl. 9). These are generally capped by a thin veneer of till-like sediment and in some places cut completely through the till to the Huntertown aquifer system below. Although it is usually problematic to determine the precise geometries and depths of the channels, it is likely that they afford a direct conduit for the downward migration of potential contaminants. Subjacent aquifers are thus more sensitive to contamination wherever these features are present.

Other factors that contribute to elevated ground-water sensitivity in some of the regions discussed previously are typically not as severe in the interlobate morainal regions, where soils generally have favorable attenuation characteristics and the depth to the water table is considerable, especially below ridges and other upland parts of the landscape. Although internal drainage is well developed in some places, it is likely to lead to increased recharge to underlying aquifers only where the Lagro Formation is less than 20 feet thick and locally breached. Only a few small areas in the Salamonie Moraine fit this description. For the most part, the downward migration of runoff and contaminants that drain into peat bogs is likely to be retarded considerably by the clayey till below.

CEDAR CREEK CANYON

General Characteristics

Cedar Creek Canyon is a state scenic river that cuts across the north limb of the Wabash Moraine between the Eel River Valley east of Huntertown and the St. Joseph River at Cedarville (pl. 9). The canyon is located entirely within the interlobate morainal region and is deeply incised into the Huntertown aquifer system along much of its length. Although the geologic history and hydrogeology of the canyon differ considerably from the surrounding region, the canyon itself represents a remarkable window into the subsurface stratigraphy of northern Allen County.

Cedar Creek Canyon as we now know it originated as a northwest-flowing tunnel valley when the Erie Lobe stood at the Wabash Moraine. The size of the canyon suggests that the tunnel valley drained meltwater from a large part of the ice sheet. The locally precipitous walls of the canyon are characterized by as much as 80 feet of relief. The stratigraphy shown in the canyon walls is identical to that in the adjacent interlobate morainal region, with 20 to 70 feet of clayey till overlying sand, gravel, and till of the Huntertown Formation. Numerous seeps and springs are present along the canyon walls, particularly where bodies of sand and gravel crop out.

The canyon floor is vastly different, however, in both form and stratigraphy. The floor is generally quite smooth and flat, and is essentially an alluvial valley confined by walls. Small terraces of outwash are present in several places throughout the canyon. A veneer of fine-grained alluvium, derived chiefly from the clayey till of the canyon walls, blankets floodplains in the lower parts of the floor. In the northwestern segment of the canyon, the alluvium overlies Erie Lobe sand and gravel deposited in the tunnel valley, which in turn is cut into the Huntertown aquifer system. Several large, thick fan deposits appear to extend under this part of the canyon, resulting in composite sand and gravel bodies close to 100 feet thick in some places.

The southeastern segment of the canyon is less precipitous, and the Erie Lobe outwash is thinner. Fewer large sand and gravel bodies are present below the canyon, which appears to be cut into a combination of lacustrine sediments, till, and ablation sediments of the Huntertown Formation.

The soils within the canyon are formed chiefly on alluvium or outwash. The water table, represented by the elevation of Cedar Creek, is generally within a few inches of the surface along the lowest parts of the canyon floor, and the soils are correspondingly waterlogged. Water table depth

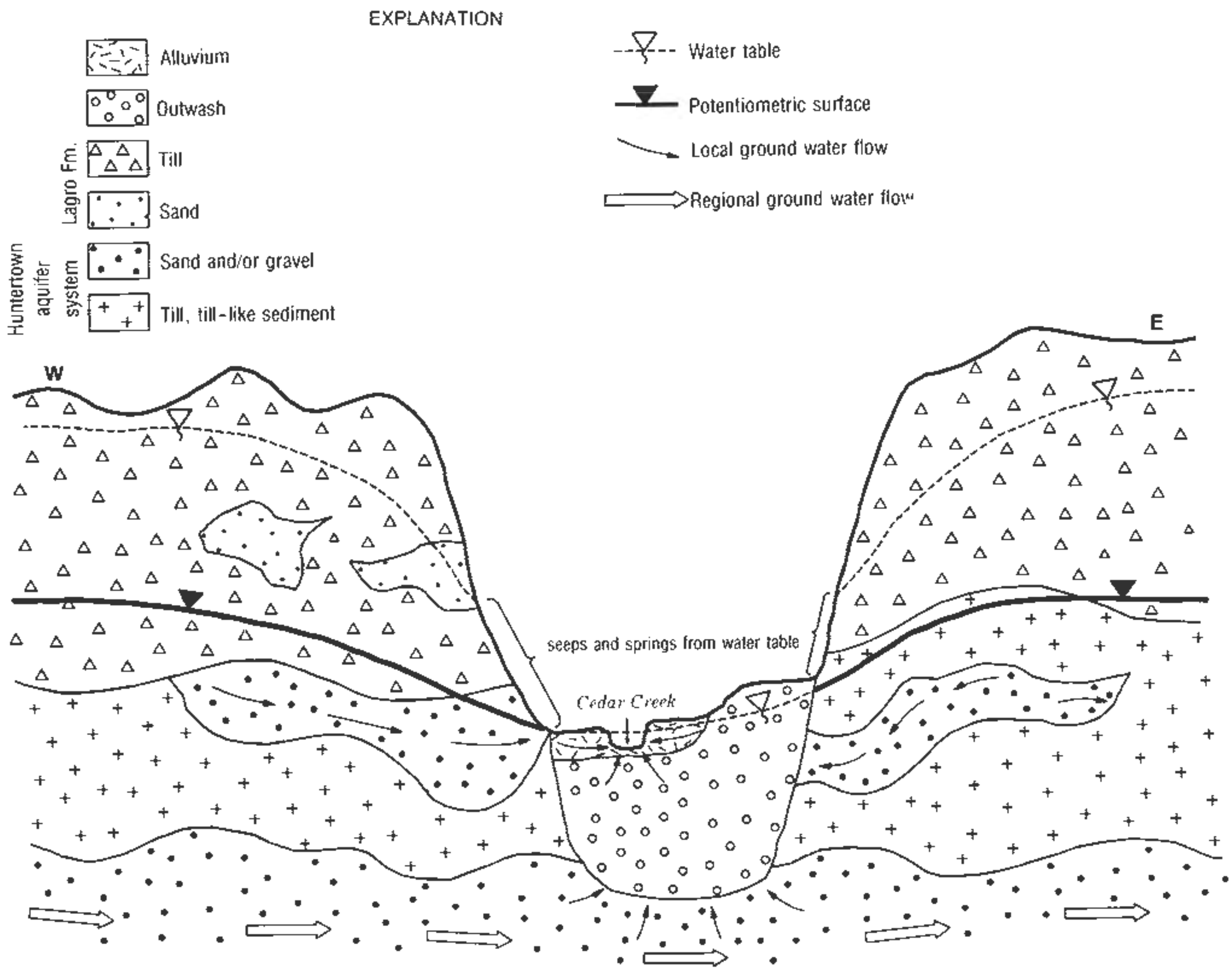


Figure 15. Generalized east-west cross section across the northwestern part of Cedar Creek Canyon in the vicinity of Interstate 69, showing inferred ground-water flow pattern associated with the Huntertown aquifer system and overlying units.

is greater, and soil drainage correspondingly better, below the outwash terraces and footslopes of the canyon walls. The canyon is generally a discharge area for aquifers in the upper part of the Huntertown aquifer system, and for local ground-water flow systems in the overlying till that are truncated by the near-vertical canyon walls. However, ground-water flow patterns are likely to be complex, and will depend on the specific degree of confinement of aquifers at depth below the canyon as well as regional and local flow system characteristics (fig. 15).

Ground-Water Availability

Most of Cedar Creek Canyon is a protected natural area, consequently there are only a very few wells installed within the confines of the canyon walls. Aquifers below the northwestern segment of the canyon are similar to those in the adjacent interlobate morainal region, with the main difference being the lack of confinement within the canyon. It is probably reasonable to expect that well yields will be similar to those described for the adjacent interlobate morainal region, with greater yields associated with the thickest and coarsest sections of sand and gravel. Further to the southeast, the Huntertown aquifer system is generally thinner and finer-grained, and water wells adjacent to that part of the canyon are developed in a variety of sand and gravel aquifers at different depths. Well yields may vary accordingly in this area.

Ground-Water Sensitivity

Cedar Creek Canyon shares many of the same attributes as the Eel River Valley, consequently ground water below the floor of the canyon is highly sensitive to contamination.

Thick sections of unconfined sand and gravel underlie a considerable segment of the canyon. These sections represent surficial outwash that has coalesced with exhumed sand and gravel bodies of the Huntertown aquifer system. Many of the latter extend for considerable distances away from the canyon walls and are directly interconnected with other aquifers elsewhere in the system.

Only a thin veneer of alluvium overlies the sand and gravel in most places. Although the alluvium is fine-grained, it is neither thick enough or sufficiently continuous to be able to effectively retard downward migration of potential contaminants. Shallow water table depth and soils that are commonly waterlogged contribute to the severely limited attenuation capacity in this setting. The fact that the canyon is a discharge area may help to limit the spread of some contaminants beyond the canyon walls, at least those contaminants that are soluble in, or lighter than water. However, any release of heavy liquids capable of sinking through water could have a severe impact. Such substances would tend to sink through the thick sections of unconfined sand and gravel to the first confining unit they encountered, which could be the bottom of the aquifer system at some places. In the process, the entire column of ground water within the section could become polluted. Once there, the contaminants would be virtually impossible to clean up and would represent a long-term, continuous source of pollution for the aquifer system. Fortunately the above scenario is made less likely by the protected status of much of the canyon, with the principal concern being spills associated with the few transportation corridors that cross the canyon.

ST. JOSEPH RIVER VALLEY

General Characteristics

The St. Joseph River occupies a deeply entrenched valley that separates the north limbs of the Fort Wayne and Wabash Moraines (pl. 9). It flows southwest for approximately 18 miles across the northern half of Allen County before joining the St. Marys River at the headwaters of the Maumee River in downtown Fort Wayne. This course spans a wide range of hydrogeologic conditions, in terms of both ground-water availability and sensitivity.

Unlike the other two major rivers in the county, the St. Joseph River Valley is associated with a significant outwash train. The outwash was derived from the Erie Lobe when it stood at the adjacent Fort Wayne Moraine. Before and during outwash deposition, meltwater erosion stripped the Lagro Formation from the bottom of the valley at most places along its length. Although a large volume of outwash has been removed by post-glacial valley incision, the outwash that remains below some parts of the river appears to be as much as 60 feet thick and generally thickens to the south. In addition to underlying the valley, the outwash also forms sizable terraces in many places above both sides of the valley, and it forms the valley walls themselves in some places.

The stratigraphy below the outwash is highly variable. In the northern half of the valley, the outwash was generally deposited over till, lacustrine sediments, and a few sand and gravel bodies of the Huntertown Formation. Much of the valley further to the south also appears to be cut into lacustrine sediments as well as till and some sand and gravel of the Trafalgar Formation. Thick sections of lacustrine sand underlie the valley in the vicinity of Fort Wayne (pl. 4).

The St. Joseph River is the regional discharge area of the Huntertown aquifer system and upward gradients are present in the system below the outwash. There is likely to be considerable interaction, however, between the river and shallow ground water in the outwash. The water table depth ranges from a few inches below the low-lying floodplains immediately adjacent to the river to perhaps as much as 10 to 15 feet below some of the higher outwash terraces that adjoin the floodplain within the valley. Soils are primarily formed on alluvium or reworked outwash, and are commonly very poorly developed and locally waterlogged.

Ground-Water Availability

Most of the St. Joseph River Valley is a floodplain, hence there are few establishments and water wells within the valley itself. Consequently, ground-water availability information for the valley is largely inferred from the hydrostratigraphy of the valley and from water well characteristics in immediately adjacent parts of neighboring hydrogeologic regions.

The St. Joseph River Valley marks a basic change in the Huntertown aquifer system from the relatively large and continuous basal outwash and ice-contact stratified aquifers to the northwest, to a preponderance of lacustrine sediments with smaller and more widely scattered sand bodies to the southeast (pl. 6). This change is clearly reflected by the wide range of well depths present in the vicinity of the valley. In general, however, wells in the northern half of the valley are most commonly developed in relatively shallow sand and gravel of the Huntertown aquifer system, whereas those in the southern half tend to be developed in deep sand and gravel aquifers at or near the bedrock surface. A small number of domestic wells are developed in the surficial outwash.

With few exceptions, most of the shallow sand and gravel aquifers, including the lacustrine units, are relatively fine-grained and are less than 20 feet thick. Many of these aquifers are small tabular lenses of fine and medium sand that are enclosed in till and(or) fine-grained lacustrine sediment. These characteristics limit the hydraulic capabilities of the shallow aquifers. Well yields from these aquifers are typically on the order of 10 to 20 gpm, which is more than adequate for most domestic needs. Larger yields are generally unlikely, however.

Somewhat larger well yields are possible from the surficial outwash below the valley, which attains saturated thicknesses of 30 to 60 feet. The outwash can be expected to yield moderate amounts of water up to about 200 gpm, particularly if wells are properly constructed. However, the thickness of the outwash, generally less than 60 feet, limits its potential for high capacity wells. The thickness of unconfined sand and gravel is greater, and the potential for high capacity wells correspondingly better, below the southernmost part of the valley in Fort Wayne, where the outwash has coalesced with a thick body of lacustrine sand.

The largest well yields in and near the valley are obtained from deep sand and gravel aquifers at or near the bedrock surface. Although the available data are generally too widely scattered to characterize the geometry of these bodies, some of the deep aquifers appear to be as thick as 20 to 40 feet and to be composed of relatively coarse sand and gravel. High-capacity wells near Leo and further to the south exhibit relatively good yields (300 to 500 gpm) from such bodies. However, the presence of such high-yielding deep sand and gravel aquifers appears to be localized and difficult to predict (see discussion on **Ground-Water Availability** under Morainal Regions).

Ground-Water Sensitivity

Ground water below the St. Joseph River Valley has a relatively high sensitivity to contamination. The valley floor is directly underlain by saturated glacial outwash. The water table is almost everywhere less than 15 feet deep, and in many places is within a foot or two of the land surface. The weakly developed alluvial soils are coarse-grained and commonly waterlogged. The permeable character of the soil and outwash means that they are capable of receiving a large amount of direct recharge, both from precipitation and from the river. Consequently, there is little attenuation potential and contaminants are likely to migrate rapidly into and through the outwash aquifer. There is also likely to be a relationship between ground-water quality in the shallow outwash and water quality of the river.

The sensitivity of other aquifers below the outwash is likely to vary according to the degree to which they are interconnected with the outwash. Relatively shallow sand aquifers of the Huntertown aquifer system are locally coalesced with the outwash in the northern part of the valley. The fact that the valley is the regional discharge area for the aquifer system may help to limit migration of some types of contaminants into these aquifers but will have little effect on heavy contaminants that sink through aquifers. For this reason, the Huntertown aquifer system is interpreted to be relatively sensitive to contamination within the valley.

Aquifers at greater depth are generally more protected from contamination, for two reasons. First, they are likely to be confined or semi-confined by at least some thickness of till and(or) fine-grained lacustrine sediments. The fine-grained sediments isolate the deeper aquifers from the outwash and minimize direct hydraulic interaction. Second, the valley is also a discharge area for the deep aquifers, so there are likely to be upward hydraulic gradients across the confining units which will limit or prevent the downward migration of contaminants that move with the prevailing direction of ground-water flow. Such gradients can be readily reversed, however, in the vicinity of high-capacity wells. The strong downward gradients associated with such facilities typically induce considerable recharge into the pumped aquifer from overlying materials and(or) surface water, especially if the pumping is continuous over months or years. In summary, the valley is characterized by a two-tiered aquifer sensitivity that is related directly to the recharge potential of individual aquifers. The unconfined glacial outwash and immediately subjacent shallow aquifers receive abundant recharge, interact strongly with the river, and are extremely sensitive, whereas deeper aquifers are discharging upward across confining units, do not interact with surface water, and are therefore much less sensitive.

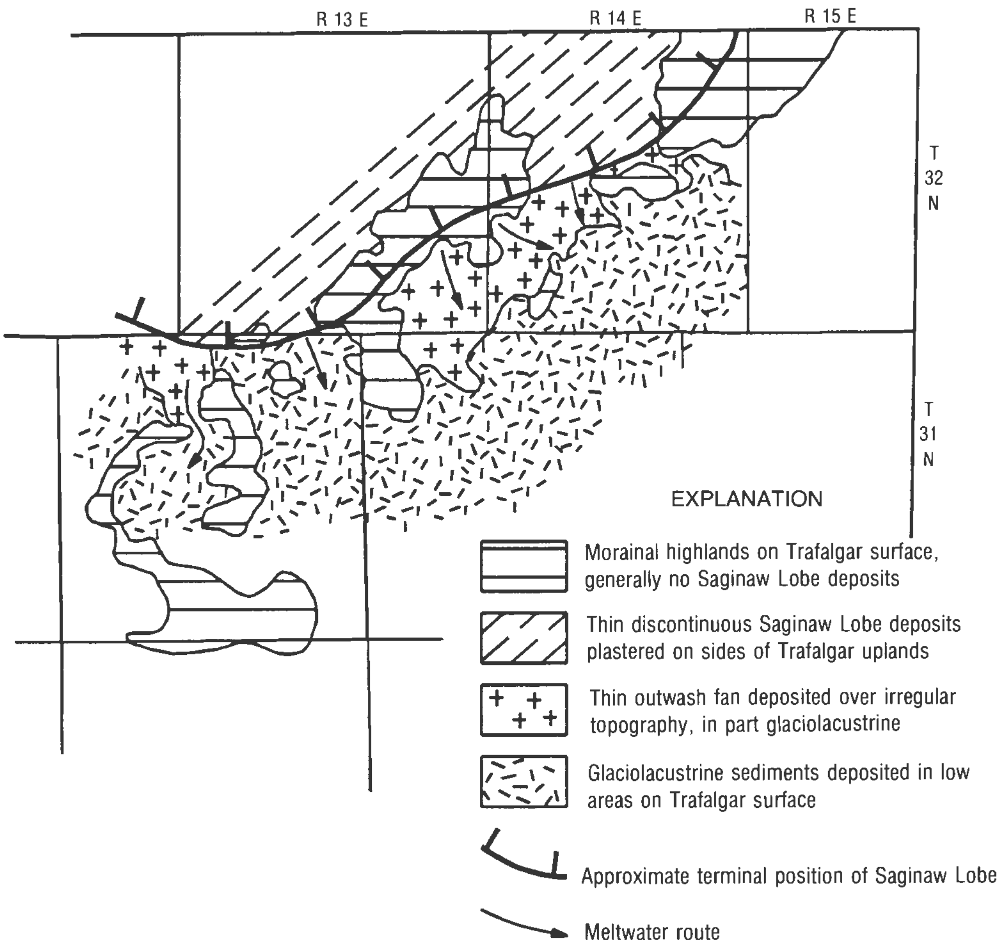
MORAINAL REGIONS

General Characteristics

The morainal regions of Allen County (pl. 9) include all of the Fort Wayne Moraine and most of the Wabash Moraine. Collectively, the two moraines cover about 21 percent of the county, making this the most extensive type of hydrogeologic region in the county. Their great extent, however, spans a wide range of hydrogeologic conditions, making the morainal regions the most varied of all the different types of regions. Both moraines are separated into northern and southern limbs by the Wabash-Erie Channel and Maumee Lacustrine Plain (pl. 5). This geomorphic division also corresponds to a significant hydrogeologic boundary based on different ground-water conditions in their northern and southern limbs. Only the southern half of the northern limb of the Wabash Moraine (pl. 9) is considered in this section. The northernmost part of that moraine was discussed previously under "Interlobate Morainal Regions."

The morainal regions are generally characterized by strongly rolling to hummocky topography developed on thick sections of glacial till. The Lagro Formation is typically between 20 and 60 feet thick, but over large areas along the crests of the moraines, it is between 60 and 100 feet thick, especially to the north (pl. 5). Although the stratigraphy and landscape of the morainal regions are similar in general aspect throughout the county, there are important distinctions between the northern and southern limbs.

Influence of the Buried Trafalgar Surface on Aquifer Geometry Along the Edge of the Huntertown Aquifer System



The geometry of the Huntertown aquifer system below the northern limb of the Fort Wayne Moraine is a good example of how sand and gravel deposition (and consequently, ground-water availability) can be affected on a regional scale by substrate topography. The Huntertown aquifer system in this area consists chiefly of small sand bodies deposited near the stagnating terminal margin of the Saginaw Lobe and in the adjacent basin of ancestral Lake Erie. The substrate upon which these sediments were deposited is represented by the buried surface of the Trafalgar Formation (pl. 4). There appears to be a strong inverse relationship between the elevation of the Trafalgar surface and the presence of sand bodies deposited by Saginaw Lobe meltwater, and the general configuration of that surface was a useful guide for constraining the approximate locations and sizes of shallow sand and gravel aquifers along the edge of the Huntertown aquifer system (pl. 6) in places where subsurface data are more scattered.

The buried Trafalgar surface below Allen County contains several prominent ridges which appear to represent a morainal complex of some type. The northeastern end of this complex extends below the Fort Wayne Moraine and is particularly irregular and elevated relative to surrounding parts of the buried surface. Northwest of the St. Joseph River, in contrast, the buried Trafalgar surface is generally subdued, slopes gently to the southeast, and contains several sizable southward-draining valleys. Consequently, when the Saginaw Lobe advanced into northwestern Allen County, the flow of ice and outwash-bearing meltwater to the southeast were readily facilitated, resulting in thick deposits of outwash, till, and a variety of ice-contact stratified deposits that formed in thick, stagnant ice.

The apparent terminus of the Saginaw Lobe in northeastern Allen County is generally marked by an abrupt thinning of northern-source deposits as well as a change in character from terrestrial deposits to a predominance of glacio-lacustrine deposits. These changes correspond closely to where the ice would have encountered the morainal complex on the underlying Trafalgar surface. The Saginaw Lobe appears to have stagnated on the buried morainal complex below the crestal area of the modern Fort Wayne Moraine. The ice does not appear to have been able to surmount the complex in most places, thus the majority of Saginaw Lobe deposits, including basal outwash aquifers, are localized on the north side of the buried ridges. Moreover, the morainal complex appears to have acted as a meltwater drainage divide, having few or no major valleys available to carry meltwater away from the ice margin and localize outwash deposition. As a result, most of the Saginaw Lobe deposits generally form small bodies plastered on the north sides of Trafalgar uplands. A few relatively thin fan deposits occur between Harlan and Grabill (pl. 6) where the ice margin briefly overtopped the drainage divide and meltwater drained into the Fort Wayne phase of ancestral Lake Erie.

The distribution of lacustrine depositional basins proximal to the Saginaw Lobe terminus was also localized by Trafalgar surface topography (pl. 4). Although the depth of this phase of ancestral Lake Erie is not known, it is clear that the largest and thickest bodies of lacustrine sediments are localized in broad low areas on the Trafalgar surface. These local basins contain bodies of lacustrine sand which are interpreted to have been deposited by meltwater in deltas, and which form the most productive shallow aquifers in the region. In contrast, former "uplands" on the Trafalgar surface contain little or no evidence of lacustrine sediments. The higher ridges on the surface may or may not have extended above lake level but in any event did not receive sediment-laden meltwater discharged from the Saginaw Lobe, which instead was localized in low gaps and basins adjacent to the ice margin.

The southern limbs of both moraines are similar in both form and stratigraphy. They form broad rolling ridges with some internal drainage that are generally only moderately higher in elevation than the adjacent till plains. In both southern limbs, a thick section of clayey till overlies overconsolidated loam till of the Trafalgar Formation. Sand and gravel bodies are typically small, widely scattered, and generally not employed for water supply purposes. Virtually all ground water is produced from the limestone bedrock, which underlies the Trafalgar Formation. The total thickness of unconsolidated deposits (chiefly till) above the bedrock in the southern limbs of the moraines ranges from less than 80 feet to more than 120 feet (pl. 3).

The northern limb of the Wabash Moraine forms a prominent ridge that rises noticeably above adjoining regions. The surface of the moraine is strongly rolling and contains numerous hummocks and a few enclosed depressions. The Lagro till is typically greater than 60 feet thick over most of the moraine, and thicknesses more than 80 feet are not uncommon. A thick sequence of older tills is typically present below the Lagro, and includes the Trafalgar Formation, the feather edge of the Huntertown Formation in the northernmost part of the region, as well as pre-Wisconsin tills below the Trafalgar. The aggregate thickness of all till units in this region is commonly greater than 200 feet, and reaches 300 feet in a few places. Shallow sand and gravel aquifers are also common in the Wabash Moraine (pl. 9). Most of these belong to the intersequence unit or the edge of the Huntertown aquifer system, and are present directly below the Lagro Formation. Sand and gravel aquifers at greater depth are common in other places, but some parts of the region are characterized by thick till sections over limestone bedrock.

The northern limb of the Fort Wayne Moraine is similar to the Wabash Moraine in landscape characteristics in that it forms a broad, robust ridge that is as much as 100 feet higher than the adjacent lowlands of the Maumee Lacustrine Plain and the St. Joseph River Valley. Much of the landscape is strongly rolling, but some areas are intensely hummocky and have abundant enclosed depressions and well-developed internal drainage, particularly to the northeast. The stratigraphy of the moraine is characterized by thick till sections over shale bedrock, which lies at a depth between 120 and 250 feet (pl. 3). Till units include the Lagro Formation (typically 40 to 60 feet thick), exceptionally thick sections of the Trafalgar Formation (up to 120 or more feet), and some pre-Wisconsin units. Sand and gravel units tend to be small and widely scattered (pls. 6 and 9). Some of these are shallow bodies associated with the edge of the Huntertown aquifer system, but many occur within or below the Trafalgar Formation.

The rolling landscapes of all the morainal regions are typically accompanied by well-developed surface drainage relative to many of the other regions. Soils also tend to be well developed and possess many favorable attenuation characteristics, and the water table may be as much as 40 feet deep in some areas. Waterlogged soils and poorly drained landscapes occur only within enclosed depressions or along stream valleys that dissect the moraines.

Ground-Water Availability

Ground-water availability differs considerably among the various morainal regions described above. It also differs to a lesser extent within each region. These differences reflect the particular distribution and characteristics of specific types of aquifers within each region. These characteristics vary from region to region because of important differences in the geologic histories of different parts of the county.

Ground-water availability is generally similar for the southern limbs of both moraines, and depends on the abundance of fractures and solution features in the bedrock aquifer system. Ground water from this aquifer system is generally more than adequate for most household needs, and yields of 100 to 500 gpm may be obtained by high-capacity wells. Well depths normally range from 90 to 150 feet, but wells as deep as 300 or more feet are required in some places to obtain sufficient water supplies.

Several small buried bedrock valleys are found in the southern part of the county (pl. 2) and may locally contain deposits of sand and gravel. These deposits, as well as sand and gravel bodies elsewhere on the bedrock surface, can significantly increase yields to wells completed in the adjacent and underlying bedrock by releasing large amounts of ground water from storage. Locally, the thickness of sand and gravel within the bedrock valleys may be adequate to provide water for wells needing up to 100 gpm.

A variety of sand and gravel aquifers as well as the bedrock aquifer system are typically present below the northern limb of the Wabash Moraine, leading to generally excellent ground-water availability in this region. In the northern part of the region, wells are commonly developed in relatively shallow sand and gravel aquifers below the Lagro Formation or in deeper sand and gravel bodies within or below the Trafalgar Formation. Many of these aquifers are thick and extensive (pl. 6). Reported well yields are commonly in the range of 10 to 25 gpm, although much greater yields (>100 gpm) may be possible from some of the deeper aquifers, which appear to be composed of coarse sand and gravel as much as 40 feet thick. Even in areas where sand and gravel aquifers are thin or absent, ground water is readily available from the bedrock aquifer system, where reported yields range from 25 to 600 gpm. The bedrock below much of this region appears to be conducive to productive large-diameter wells, which may in part be due to deeper pre-glacial karst development near the Metea Bedrock Valley and its tributaries, several of which are present below the region (pl. 2). Large bodies of sand and gravel may be present in some segments of this valley system and would be expected to be extremely productive, but data are currently too sparse to draw any firm conclusions regarding their distribution or potential yields.

Ground-water availability below the northern limb of the Fort Wayne Moraine is highly variable and difficult to predict from place to place. The wide range of well depths, from 40 to more than 250 feet, is indicative of the diverse conditions that characterize this hydrogeological region. Bodies of relatively shallow sand and gravel are generally thin and irregularly distributed over much of the region. The Huntertown aquifer system becomes increasingly discontinuous southeast of the St. Joseph River, mainly because numerous irregularities and elevated areas on the underlying Trafalgar surface (pl. 4) restricted sand and gravel deposition to highly localized areas along the terminus of the Saginaw Lobe (see sidebar, **Influence of the Buried Trafalgar Surface on Aquifer Geometry Along the Edge of the Huntertown Aquifer System**, pages 80-81). The primary type of shallow aquifer in the region consists chiefly of fine lacustrine sand of the Huntertown aquifer system. The sand forms several large bodies up to 30 or more feet thick along the southern edge of the region, but elsewhere it is generally restricted to relatively small lenses within fine-grained lacustrine sediments (pl. 6). These aquifers are used chiefly for domestic purposes because the prevalence of fine sand limits their yields to less than 15 gpm in most cases. The larger bodies, some of which contain gravelly zones, may be capable of yields greater than 50 gpm.

Coarse sand and gravel bodies are present locally at depth throughout the region. These bodies are mainly associated with the lower part of the Trafalgar Formation and(or) older units (pl. 6) and tend to occur near the bedrock surface. Some parts of these aquifers are characterized by thicknesses of 20 to 40 feet, and high-capacity wells exhibiting good yields (300 to 500 gpm) are present in Grabill and the southwestern part of St. Joseph Township. Although many of these bodies appear to be of limited extent, they are the most reliable type of aquifer in the region in terms of consistently yielding large quantities of high-quality water.

The discontinuous nature of potential sand and gravel aquifers below the Fort Wayne Moraine creates erratic ground-water conditions in several areas east of the St. Joseph River, where well yields and water quality can vary widely. There are localized areas where thick (125 to 200 feet) sections of glacial till containing only thin, discontinuous, and(or) poorly sorted lenses of sand are present above the bedrock. Securing an adequate quantity of water from the unconsolidated deposits may be difficult in these localities.

Securing a good supply of high-quality water from the bedrock in this area is even more problematic, however, because of its characteristically high sulfur content. A relatively thick section of gypsum-bearing Devonian limestone is present in the upper part of the bedrock aquifer system throughout this region (pl. 2), and the chemistry of ground water in the bedrock suggests a long residence time. Consequently, ground water from the limestone almost always contains objectionable amounts of hydrogen sulfide, or "sulfur water," and usually requires some form of treatment. The bedrock aquifer system in this region is confined by 20 to 90 feet of black shale, which is thickest in the northern part of the region (pl. 2). Although the limestone is locally a source of water for high-capacity wells, it generally has lower yields than in other regions of the county, particularly where overlain by the thickest sections of shale. In such instances, yields from the limestone are generally in the range of 25 to 150 gpm. In contrast, in the Maumee Lacustrine Plain to the south, where it is generally not overlain by thick shale, the limestone may yield 100 to 400 gpm.

Ground-Water Sensitivity

The sensitivity of ground water below the morainal regions is generally low, although localized conditions may cause shallow aquifers to be somewhat more sensitive to contamination under certain circumstances. Aquifers below most of these regions are typically well confined by thick till, and soil and water table conditions are characteristically favorable for restricting contaminant migration. It is chiefly in those places where the Lagro Formation is thin or broken and shallow sand and gravel aquifers are present that elevated sensitivity may occur.

Over most of the morainal regions, the Lagro Formation exceeds 40 feet in thickness, and contaminants are unlikely to migrate rapidly through the till. The least sensitive aquifers are the bedrock and deep sand and gravel bodies because they are protected by till sections well over 100 feet thick that include one or more lower tills in addition to the Lagro. Shallow aquifers such as the intersequence unit (pl. 6) are somewhat more sensitive by virtue of being closer to the land surface, but are still relatively well protected by the Lagro Formation. The shallow and deep aquifers of the Aboite aquifer system are commonly well interconnected below the Wabash Moraine in southwestern Allen County (pl. 6). In this instance, the sensitivity of the bedrock and deep sand and gravel, although still relatively low, is similar to that of the shallow aquifers because water quality changes in the shallow aquifers could eventually affect the deep aquifers as well, given the high degree of interconnection.

Sensitive locations within the morainal regions are associated with stream valleys or abandoned meltwater channels where the Lagro Formation is less than 20 feet thick (or perhaps locally absent) over shallow sand and gravel (units M1s and Mms, pl. 9). Large modern stream valleys are uncommon because the morainal regions are uplands that act as local or regional drainage divides. The till is known to be completely breached in only a few small, widely scattered locations, which are generally restricted to very small reaches of the largest streams that cross these regions.

On the other hand, large abandoned meltwater channels such as the Six-Mile Creek Channel (Trier Ditch) and the Spy Run-Covington sag are more problematic. These features were cut by large meltwater torrents and subsequently filled in by outwash and(or) post-glacial alluvium and lacustrine sediments. The degree to which the Lagro till has been removed or breached is difficult to determine. However, it is reasonable to assume that the till has been removed from at least some parts of the largest meltwater channels. Shallow aquifers known or inferred to be present below these channels should thus be regarded as being sensitive to contamination. Deeper aquifers are less likely to be affected because they are separated from the bottom of the channels by additional till units. Most of these channels contain wetlands developed on assorted outwash, alluvium, and lacustrine sediments. Local ground-water flow systems within these sediments are sensitive to pollution by virtue of being close to the land surface and in situations where little attenuation of contaminants is likely to occur above the water table.

A second situation in which sensitivity may be greater in some of the morainal regions occurs where channels are present within the Lagro Formation. The channels are composed chiefly of sand and are only known to be present in several places in the northern limbs of the moraines (units Mc and Mcs, pl. 9). They are generally capped by a thin veneer of till-like sediment, and in some places they extend completely through to the base of the till. Although it is usually problematic to determine the precise geometries and depths of the channels, it seems likely that they afford a direct conduit for the downward migration of potential contaminants. Shallow aquifers are thus more sensitive to contamination wherever these features are present. The effect of the channels on sensitivities of deeper aquifers is likely to be minor, due to the additional till confining units below the Lagro Formation that protect the deep aquifers.

TILL PLAINS

General Characteristics

Till plains are nearly flat to gently rolling landscapes developed on clayey till of the Lagro Formation. They comprise three geographically distinct regions which are all located in the southern half of the county (pl. 9). The largest till plain is located between the southern limbs of the Wabash and Fort Wayne Moraines, while a slightly smaller unit lies between the Fort Wayne Moraine and the Maumee Lacustrine Plain. A much smaller till plain of more rolling aspect is situated west of the Wabash Moraine, mainly in Aboite Township (fig. 4). The three till plains collectively account for about 15 percent of the area of the county, making them one of the more extensive kinds of hydrogeological regions.

The stratigraphy of the three till plains is generally similar and predictable. Between 20 and 50 feet of Lagro till makes up the top of the sequence. A thin granular or silty unit almost invariably separates the Lagro from the underlying loam till of the Trafalgar Formation, which in turn rests on limestone bedrock. Mappable sand and gravel bodies are rare in the two eastern till plains, and consist chiefly of small bodies of intersequence sand and somewhat larger aprons of sand, gravel, and boulders along the bedrock surface at the base of the Trafalgar Formation. More rarely, narrow, linear channels occur within the Trafalgar Formation. These channels frequently extend completely through the formation to the bedrock surface, but their true shapes and trends are rarely traceable due to their narrow profiles and sparse data.

The situation at depth in the most westerly till plain is somewhat different due to the presence of the Aboite aquifer system (pl. 6). Large sand and gravel bodies are locally abundant and include the intersequence unit, basal outwash of the Trafalgar Formation, and large channels that commonly interconnect the first two types with the bedrock. The intersequence and basal Trafalgar aquifers are up to 30 feet thick in some places and commonly contain a large proportion of coarse sand and gravel. The channels in the Trafalgar Formation attain their best development in this area, and in some places the entire formation is composed of sand and gravel, resulting in stratigraphic sections where the Lagro Formation is the only confining unit over one massive aquifer composed of coalesced sand and gravel bodies on limestone. The abundance of sand and gravel units carries southward across the Wabash-Erie Channel and includes the northern part of the western till plain in Lafayette Township and the northwest corner of the till plain immediately east of the Wabash Moraine.

Much of the till plain landscape is poorly drained and is characterized by numerous ablation hummocks, most of which are less than 5 feet tall. Very broad, shallow depressions of similar relief are also present. Soils are commonly poorly drained and the water table depth is usually less than 10 feet. A seasonally perched water table at an even lesser depth in the low-permeability till is common, especially in spring, resulting in waterlogged soils in most low places in this landscape. Somewhat better landscape drainage is present in the till plain in Aboite Township, which is more rolling and dissected than the others.

Ground-Water Availability

Ground water is produced almost entirely from the bedrock aquifer system in all of the till plains, with the exception of the northern part of Aboite Township where intersequence sand and gravel of the Aboite aquifer system is also exploited. A few wells in that area also produce water from sand and gravel aquifers in and below the Trafalgar Formation. Ground-water availability is generally good throughout all the till plains, and might be considered exceptional in the Aboite Township area.

Ground water in the two till plains east of the Wabash Moraine is generally available in sufficient quantity from the bedrock aquifer system to meet most needs. In most locations, yields of 100 to 500 gpm may be obtained by large-capacity wells. Well depths normally range from 60 to 150 feet, but wells as deep as 300 or more feet are required in some places to obtain sufficient water supplies. Several small buried bedrock valleys are found below the till plains (pl. 2). Sand and gravel contained within the bedrock valleys, as well as bodies elsewhere along the bedrock surface can significantly increase yields to wells completed in the underlying bedrock by releasing large amounts of ground water from storage.

High-yielding wells are common throughout the till plain in Aboite Township, particularly those developed in bedrock aquifers. Most of the sand and gravel aquifers in this region are generally expected to yield small amounts of water in the range of 10 to 25 gpm; however, in localized areas where they attain saturated thicknesses of 50 or more feet and contain a greater percentage of gravel, the yields to large-diameter wells could be 50 to 350 gpm. These sand and gravel units are commonly bypassed by water well drillers in favor of the underlying limestone. The bedrock is the most utilized source of water in the region and it appears to contain numerous solution features and other evidence of a well-developed karst system. Yields on the order of 250 to 500 gpm are readily available to high-capacity wells drilled over most of the region. Well yields from the bedrock are enhanced by the locally thick sections of sand and gravel above, which can release large volumes of water from storage when the bedrock is pumped.

Well depths in the Aboite till plain vary substantially, depending on topographic position, the type of aquifer utilized, and the amount of water withdrawn. Wells as shallow as 50 feet are present in some places, but some high-capacity wells are as much as 400 to 500 feet deep. Bedrock wells in the area typically obtain water from within 10 to 30 feet of the bedrock surface, presumably from abundant karst features.

Ground-Water Sensitivity

The sensitivity of ground water below the till plains ranges from moderately low to high depending on the nature of underlying aquifers, the thickness of the Lagro Formation and subjacent till units, as well as other factors that may affect contaminant migration and attenuation. Attenuation ranges from poor to fair and is likely to be limited by wet soils and shallow water table depths. Where these surface conditions occur over thick till, however, there is little likelihood that the contaminants can migrate into subjacent aquifers.

The thickness of the Lagro Formation ranges from 20 to 50 feet across the till plains and is typically about 25 to 35 feet in most places, which should afford a reasonable amount of protection to underlying aquifers. In general, the bedrock and deep sand and gravel aquifers are the least sensitive to contamination because of their depth and degree of confinement. Shallow aquifers, such as the intersequence unit, are somewhat more sensitive but should still be relatively well protected as long as the till is greater than 20 feet thick. In parts of Aboite Township, the large-scale coalescing of sand and gravel bodies of the Aboite aquifer system and their common hydraulic connection with the limestone bedrock (pl. 6) means that the sensitivity of the bedrock aquifer system is essentially that of the shallow aquifers, because contaminants could migrate from shallow aquifers to deeper ones fairly readily over time.

The sensitivity of shallow aquifers is considerably heightened in places where the Lagro Formation may be thin or absent, such as in abandoned meltwater channels (unit Pms, pl. 9) or stream valleys (unit P1s, pl. 9). In some of these places, holes in the till could allow contaminants to move unimpeded into the aquifers, especially if downward gradients are present. Even where some till cover is present, shallow ground water within the surficial sediments (such as alluvium, small outwash bodies) in some of the larger valleys and meltwater channels may itself be fairly sensitive to contamination because it is close to the land surface and has little or no protection from overlying materials.

ARCOLA PLAIN

General Characteristics

The Arcola plain is a nearly flat to very gently rolling tract situated in front of the north limb of the Wabash Moraine in western Allen County (pl. 9). This region covers nearly all of Lake Township and extends into the northern edge of Aboite Township. The characteristic feature of the region is the very poorly drained and pervasively washed appearance of the landscape. The distinctive landscape of this region, together with a number of related hydrogeologic characteristics, make the Arcola plain a decidedly distinct hydrogeologic region and cause it to differ sharply from the till plains described previously.

The Arcola plain in general is characterized by some of the thickest unconsolidated deposits in the county (pl. 3). This condition is partly related to the highly dissected bedrock surface below this region (pl. 2), which contains the south branch of the Metea Bedrock Valley and its confluence with several large tributaries. Unconsolidated sediment thicknesses greater than 250 feet are common near the bedrock valleys, which are in part filled by exceptionally large thicknesses of pre-Wisconsin deposits. Even on buried bedrock uplands, however, the unconsolidated materials are only rarely less than 200 feet thick, and these relatively thinner sections are restricted to the southern quarter of the region.

The stratigraphy of the Arcola plain is dominated by thick, locally monotonous sections of till that locally contain small to large bodies of sand and gravel. The unconsolidated deposits overlie limestone of Devonian age. The uppermost of the till units is the Lagro Formation, which is particularly clayey and interfingers with locally thick sections of lacustrine clay. These clay-rich sediments are commonly between 40 and 60 feet thick in this area, except in the largest abandoned meltwater channels, where lesser till thicknesses are characteristic. The northern and central parts of the region contain the discontinuous feather edge of the Huntertown Formation. Where present, the unit consists chiefly of very thin (5 to 20 feet) sandy till and small bodies of sand. South of Lake Everett, the Huntertown Formation is progressively more discontinuous and is difficult to distinguish from similar materials of the underlying Trafalgar Formation. The hard loam tills of the Trafalgar Formation appear to be as much as 150 feet thick in some parts of the region, although the distinction between the Trafalgar and some of the pre-Wisconsin units is locally problematic. A variety of sediments of possible pre-Wisconsin age are present at depth, including pinkish-gray clay-loam till of northern (Saginaw Lobe) source, gray-brown loam till of uncertain source, and pink to red lacustrine silt and clay in the Metea Bedrock Valley. The distributions of these units and their relationships to one another are not well known. The collectively large thickness of all these fine-grained confining units suggests that recharge to the bedrock and deep sand and gravel aquifers may be severely limited in most of this region.

Bodies of sand and gravel, some of which are quite large, are present along several different stratigraphic horizons in limited parts of the region (pl. 6). The largest bodies occur at depth in two general settings. Thick sections of sand and gravel occur in some places along or near the bedrock surface and are presumably of pre-Wisconsin age. Some of these bodies are reportedly more than 50 feet thick, especially in and near the Metea Bedrock Valley, but their configuration is poorly known due to a dearth of deep subsurface data. Another group of sand and gravel units are concentrated along the base of the Trafalgar Formation and help to identify the top of the pre-Wisconsin sediments.

Other bodies of sand and gravel occur in the upper part of the Trafalgar Formation (unit Tx, pl. 6) and along the intersequence horizon between the Trafalgar and Lagro Formations. Most of these bodies are somewhat thinner than the deeper units, although several of the upper Trafalgar bodies in the Arcola area appear to have considerable extent and are locally significant aquifers. The nature of the intersequence sand and gravel bodies in the northern and central parts of this region is problematic. Some of these bodies may in fact represent the Huntertown Formation along its feather edge. However, the lack of identifiable northern-source till or diagnostic pebble samples associated with these bodies precludes a definitive determination, and they are simply mapped as intersequence unit by virtue of their stratigraphic position.

The landscape and associated near-surface sediments of the Arcola plain are unlike those of any other region in Allen County, and they contain a distinct shallow ground-water flow system that is closely related to the surface hydrology (fig. 16). The geologic history of this landscape appears to involve a complex series of events that generally involved scouring and outwash deposition by large-scale meltwater discharges from the Erie Lobe, followed by widespread ponding and infilling of meltwater channels and depressions. Some of the meltwater flow was channelized, as evidenced by the two large abandoned meltwater channels that cross the region, but much of the meltwater flowed across the landscape as a sheet, judging from the outwash terraces that are widespread in the region. The main consequence of these events was the deposition of a heterogeneous assemblage of permeable and poorly permeable surficial sediments atop the Lagro Formation. These sediments include outwash sand and gravel up to 30 feet thick; sand, silt, and clay of lacustrine origin; and abundant peat in depressions and channels. The distribution of these sediments is difficult to predict, because infilling of channels and depressions by lacustrine sediments and peat has left a remarkably smooth landscape which is generally characterized by less than 5 feet of local relief.

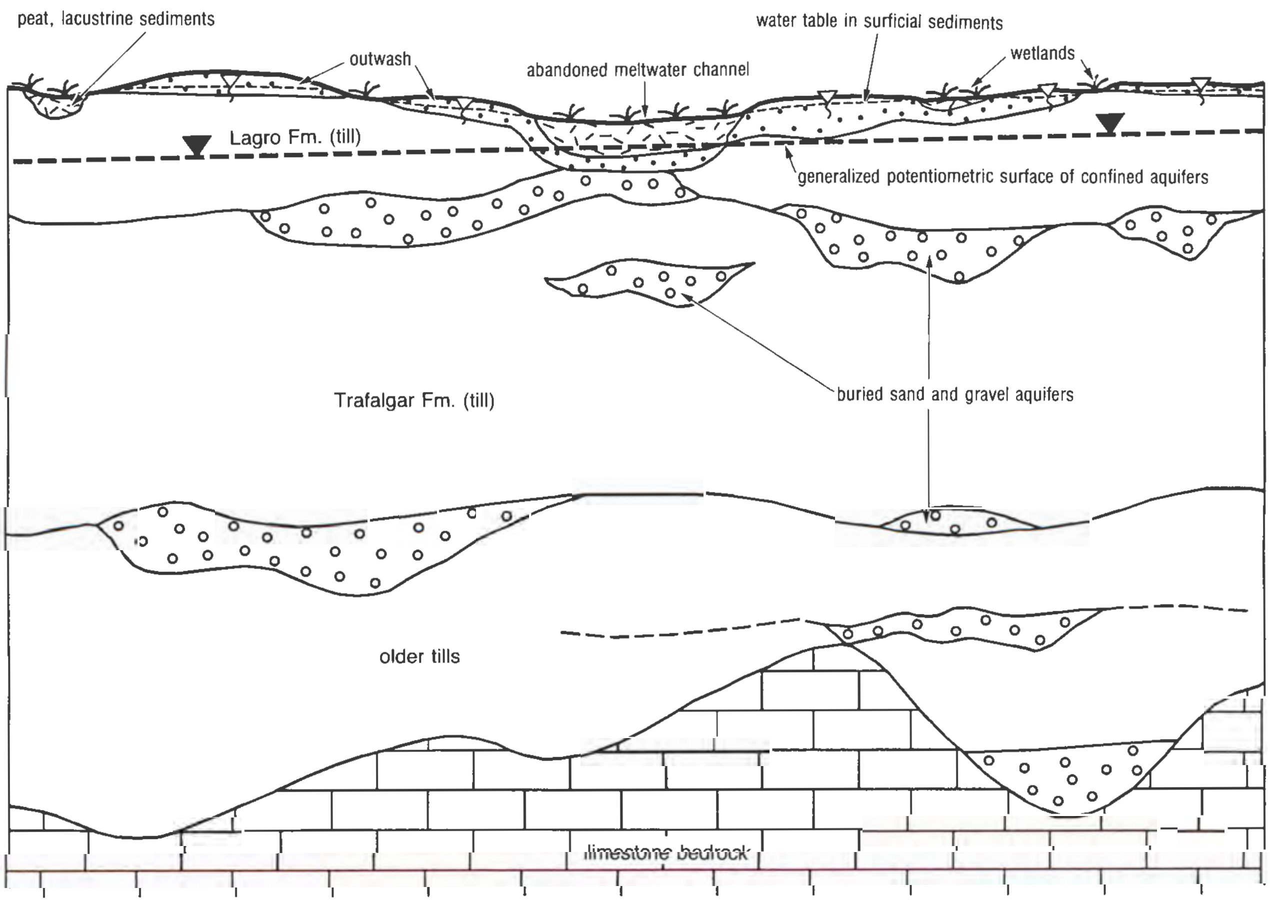


Figure 16. Schematic diagram showing typical hydrostratigraphy of the Arcola plain and the relationship between surficial sediments, shallow water table, and the potentiometric surface. In general, the shallow ground-water flow system associated with the surficial sediments is entirely distinct from that in the deeper aquifers, although the two systems may be locally connected below parts of large abandoned meltwater channels where the Lagro Formation is absent.

The entire landscape is generally very wet. Most low areas are wetlands, and standing water can be found in many parts of the landscape. The water table, which may be perched on the underlying Lagro Formation, is typically within a few inches of the land surface in the most low-lying areas, and generally within 2 to 3 feet elsewhere. The great majority of the soils mapped in the region are poorly drained or very poorly drained mucks and clays (Kirschner and Zachary, 1969) and are usually waterlogged for most of the year. A shallow ground-water flow system is present in the surficial materials and is the primary means for assimilating and conducting precipitation and surface runoff. The shallow flow system discharges into the many wetlands in the region, although at certain times, the reverse may also be true. There are no natural surface streams whatsoever in this region, although several areas have been extensively ditched for agricultural purposes, including the wetlands at the headwaters of Aboite Creek. The creek now artifically extends to the Town of Arcola in the south-central part of the region.

Ground-Water Availability

Ground-water availability in the Arcola plain is typically quite good. More than half of the wells are developed in the limestone bedrock and the remainder are screened in sand and gravel aquifers. Well depths range from about 50 feet to as much as several hundred feet.

Large parts of the Arcola plain appear to contain fewer sand and gravel aquifers than many of the other hydrogeologic regions in the county, with the possible exception of some of the morainal regions and the Maumee Lacustrine Plain. For this reason the bedrock aquifer system is the most reliable and heavily utilized source of ground water for the region as a whole. Reported yields for the bedrock are consistently good throughout the region and should generally range from 150 to 600 gpm or more for large-diameter wells. As noted in previous sections, an increased incidence of karst features in this region may be associated with the Metea Bedrock Valley and its tributaries. This condition could result in even greater yields from the bedrock near the valley walls, especially where large sand and gravel bodies rest directly on the bedrock. One practical manifestation of greater karst development is that most domestic wells in this region generally do not need to be drilled far below the bedrock surface to obtain adequate amounts of ground water.

The greatest number of sand and gravel aquifers are in the northern part of the region, near Lake Everett and in the south, near the Town of Arcola. The northern part of the region contains the feather edge of the Huntertown aquifer system and forms the transitional boundary with the sand and gravel-rich Eel River Valley and Huntertown interlobate region. The variability of these deposits is great, however, and is exemplified by conditions near Lake Everett where there are locally thick units of sand at several horizons that appear to have little continuity or areal extent. Many of the sand and gravel aquifers utilized in the northern part of the Arcola plain typically occur in lenses which are mostly less than 10 feet thick. Expected yields range from less than 10 gpm for small sand lenses to over 100 gpm for the larger bodies.

A few sand and gravel aquifers of somewhat larger extent occur in and just below the Trafalgar Formation in the vicinity of Arcola. These units represent the transitional northern edge of the Aboite aquifer system and are more characteristic of conditions further to the south. Other sizable sand and gravel bodies are also reported within the confines of the Metea Bedrock Valley System and are associated with the pre-Wisconsin sequences. Expected yields for these somewhat larger sand and gravel bodies is on the order of 50 to 300 gpm. Significantly greater yields may be possible from the bodies in the Metea Bedrock Valley, but data pertaining to these deeply buried sand and gravel aquifers are too sparse to draw any firm conclusions at this time.

Ground-Water Sensitivity

With few exceptions, the sensitivity to contamination of aquifers that serve as the principal sources of water supply in the Arcola plain is uniformly low. In most places, these aquifers are well confined by one or more sheets of fine-grained till whose thickness and low permeability are likely to greatly retard recharge and contaminant migration. The bedrock and deep sand and gravel aquifers are the least sensitive because they are typically confined by more than 200 feet of till, whereas the sensitivity of shallow aquifers such as the intersequence unit is slightly greater.

The principal exceptions to the above generalization are associated with the two large abandoned meltwater channels that cross the region in an east-to-west direction (units Am and Ams, pl. 9). One of the channels is located in the vicinity of Arcola and the other encompasses a chain of large, peat- and outwash-filled depressions that includes Lake Everett. Both channels are characterized by a marked thickening of post-glacial surficial sediments, which appear to be as thick as 60 feet in some parts of the Arcola channel and at least 30 feet thick east of Lake Everett. The thickening of these locally permeable sediments occurs at the expense of the Lagro Formation, which appears to be completely removed by meltwater erosion below some segments of the channels. Consequently, the sensitivity of the intersequence unit and other aquifers located close below the base of the Lagro Formation is moderately to strongly elevated where they are present below the bottoms of the channels. It also seems likely that there is considerable interaction in these settings between surface water held in wetlands within the channels, local ground-water flow systems in the surficial sediments, and ground water in the intersequence unit below the channels. Consequently, it is possible that some segments of the channels may function as local recharge areas.

Very shallow ground-water flow systems in the surficial sediments may also be sensitive to contamination because of their proximity to the land surface. The surficial sediments generally appear to be saturated in most places and, where thicker than a few feet, are likely to contain a significant amount of ground water. The surficial sediments are thickest and probably contain the most robust shallow flow systems within the confines of the two large channels noted above. In these locations there may be little distinction between this very shallow ground-water flow system and the somewhat deeper system in the intersequence unit. Outside of the two meltwater channels, however, contaminants introduced into ground water within the surficial sediments are relatively unlikely to migrate into drinking water aquifers below the Lagro Formation due to the thickness of the till confining units below the surficial sediments.

ALLUVIAL VALLEYS

General Characteristics

Alluvial valleys are modern river valleys whose floodplains are underlain by alluvium deposited over a stripped surface of older materials. Alluvial valleys in Allen County include the St. Marys and Maumee Rivers (pl. 9). Although the St. Joseph River, Wabash-Erie Channel, and Cedar Creek all possess some of the major attributes of alluvial valleys, their geologic histories and hydrogeologic characteristics are sufficiently different to warrant defining them as separate hydrogeologic regions. Segments of several of the other larger streams in Allen County, such as Aboite, Flatrock, and Eight-Mile Creeks, are also similar in character to the alluvial valleys described below, but are too small or too short to be mapped as individual alluvial valleys. These streams can generally be characterized adequately in terms of the broader hydrogeologic region(s) that they occur within, although several aspects of the following discussion on alluvial valleys are generally applicable to them.

The St. Marys and the Maumee Rivers both follow relatively small valleys, and their floodplains are rarely more than a quarter of a mile wide. Both rivers have cut through the Lagro Formation and flow on stripped surfaces developed on the hard till of the Trafalgar Formation. The hardness of the till appears to be at least partly responsible for limiting the amount of downcutting by both rivers. The walls of both valleys are relatively gentle and are composed chiefly of the Lagro Formation. Fine- and medium-grained lacustrine sediments are also present in the valley walls along the Maumee River both above and below the Lagro Formation.

The floodplains of both rivers are characteristically underlain by fine- to medium-grained alluvium which is mainly derived from the valley walls and adjacent uplands. The thickness of the alluvium is difficult to predict in any one location, but it is commonly less than 15 feet. Neither valley contains appreciable amounts of outwash, although relatively small terraces of sand and gravel do occur high on the valley walls and on adjacent upland surfaces along both streams.

The depth to limestone bedrock is as little as 30 feet below some river segments. Loam till of the Trafalgar Formation is the principal material between the alluvium and the bedrock, although widely scattered small sand and gravel bodies are also present. The St. Marys River generally parallels a small bedrock valley (pl. 2). Sparse well data indicate that some parts of the bedrock valley contain thick sections of sand and gravel whereas others are filled with till and lacustrine mud, but the distribution of the differing types of sediment is not well defined.

Both rivers are important ground-water discharge areas, especially for the bedrock aquifer system. The Maumee River Valley appears to be the main regional discharge area in Allen County, whereas the St. Marys is more of a local discharge area whose relationship to the ground-water flow system may vary seasonally depending on stream flow and ground-water levels. Strong upward hydraulic gradients are present between the bedrock and the Maumee River, as evidenced by high static water levels and localized flowing artesian wells in the adjacent lake plain. In contrast, vertical gradients appear to be generally neutral or weak below the St. Marys River. Both valleys also receive considerable discharge in the form of seepage from the valley walls, particularly during wet periods. The seepage is derived from local ground-water flow systems in the fractured and weathered upper part of the Lagro till and from small sand and gravel bodies truncated by the valley walls.

Both valleys are characterized by weakly developed wet soils formed on alluvium. The depth to the water table is generally minimal, being as little as a few inches on low-lying floodplains and increasing to several feet below higher terraces close to the valley walls.

Ground-Water Availability

Relatively few wells are developed within the alluvial valleys, which are mostly made up of frequently inundated floodplains that are protected from development. A few widely scattered wells are present along somewhat higher-lying terraces, but most of the nearby wells are on the immediately adjacent uplands. Virtually all these wells are developed in the bedrock aquifer system, with the only exceptions being one or two wells developed in a large sand and gravel body just above bedrock within the buried valley below the St. Marys River.

Well depths are typically between 60 and 200 feet. Overall well yields near the alluvial valleys are typically not as great as in some of the other hydrogeologic regions to the north and west. In general, well yields range from about 10 gpm to as much as 100 gpm, with 10 to 25 gpm being typical for most domestic wells. Well yields appear to be geographically dependent, being somewhat limited in some areas along the Maumee River but generally larger near the St. Marys River. This difference could be partly attributable to an increased instance and depth of solution features associated with the presence of the buried bedrock valley below the latter, as well as the presence of sand and gravel bodies on top of the bedrock within the buried valley.

Ground-Water Sensitivity

Ground water below the alluvial valleys exhibits a dual sensitivity to contamination (fig. 17). Shallow ground water within the alluvium is unconfined and at most only a few feet below the land surface. Attenuation of contaminants is severely limited by the high water table and poorly developed, wet soils. Consequently there is little to prevent contaminants from moving rapidly into the saturated alluvium, resulting in a high sensitivity to contamination.

Several factors may help to limit the impact of any contaminants that do enter the alluvium. Ground water within the alluvium is in direct communication with the river and there is undoubtedly much exchange between the two. Consequently, contaminants are likely to flow through the alluvium for only a short distance before discharging into the river. Because of the limited physical dimensions of the alluvium, most contaminants are likely to remain confined within the valley and will generally move downriver.

In contrast to the alluvium, the sensitivity to contamination of ground water within the bedrock below the alluvial valleys is typically moderate or low. Several factors are likely to prevent the migration of contaminants from the land surface into the bedrock. First, contaminants are likely to be intercepted by the shallow ground water flow system within the alluvium and conducted downriver by the interaction of the shallow system with surface water. Second, the shallow system is typically isolated from the bedrock in most places by a minimum of 20 feet of dense, low-permeability till of the Trafalgar Formation. Unless channels are present in the till, there is little likelihood of migration through the till. Finally, these valleys are regional discharge areas for the bedrock aquifer system. The presence of strong upward gradients in the Maumee River Valley and at least seasonal upward flow in the St. Marys River Valley will hinder the downward movement of contaminants that are lighter than or soluble in ground water. Only heavy contaminants have a significant chance of reaching the bedrock, but only in rare places where the till confining unit has been completely breached.

MAUMEE LACUSTRINE PLAIN

General Characteristics

The Maumee Lacustrine Plain (hereafter referred to as the "lake plain" for simplicity) is a low-lying and locally featureless landscape that occupies all of the east-central section of Allen County (pl. 9). It represents the former

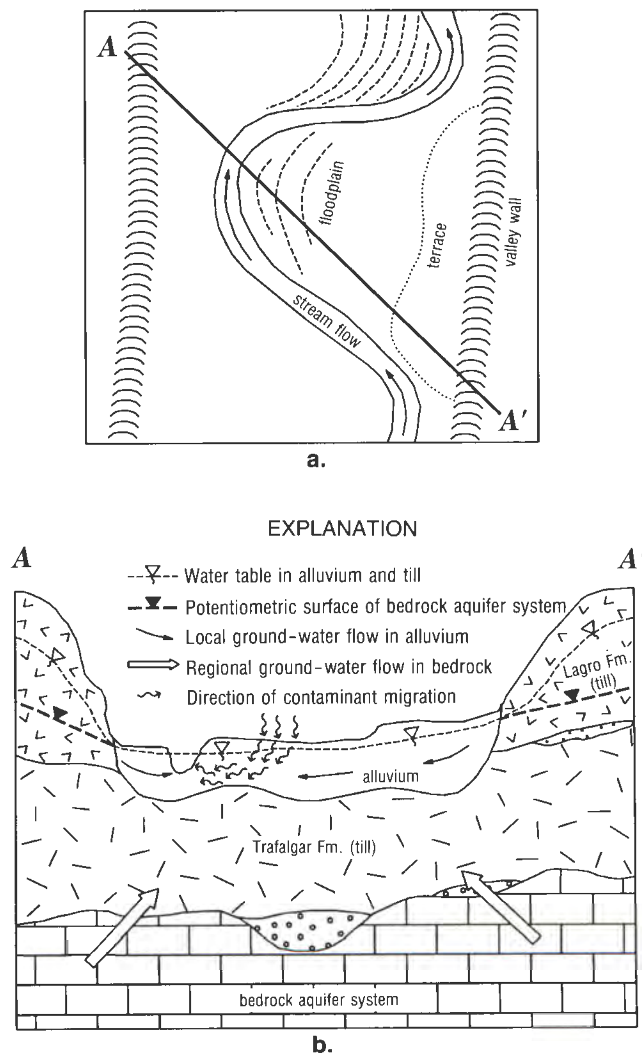


Figure 17. Schematic map (top) and cross section (bottom) illustrating general surface features, subsurface geology, and ground-water flow in an alluvial valley. Contaminants that enter the shallow ground water within the confines of the valley are likely to move laterally in the alluvium before discharging into the river at the next meander downstream. In contrast, the migration of contaminants into the bedrock is less likely because of the upward hydraulic gradient across the subjacent till confining unit.

bottom and adjacent shorelines of ancestral Lake Erie when that lake extended into Indiana following the most recent advance of the Erie Lobe. The lake plain covers about 18 percent of the land surface in Allen County and is the second most extensive type of hydrogeologic region. Other than the more elevated beach deposits, the flat landscape of the lake plain is poorly drained and commonly underlain by a shallow water table and seasonally waterlogged soils that appear to have low to moderate attenuation potential.

The lake plain can be conveniently divided into three somewhat distinct subregions based on both terrain characteristics and hydrogeologic properties (pl. 9). The three subregions form a logical basis for further subdividing the following discussions on the stratigraphic characteristics, ground-water availability, and ground-water sensitivity of the lake plain.

Southern Lake Plain

The first subregion includes all of the lake plain south of the Maumee River and is the flattest area in the county. The only relief in this part of the lake plain is associated with widely scattered small beach ridges and spits, which are locally capped by up to 10 feet of muddy sand and gravel. Otherwise, the stratigraphy of the southern lake plain is very consistent from place to place, having approximately 30 to 70 feet of fine-grained till and post-glacial lacustrine sediments overlying limestone bedrock. The till units belong to the Lagro and Trafalgar Formations, both of which are typically between 20 and 30 feet thick. The tills are separated locally by up to 10 feet of fine- to medium-grained lacustrine sediments deposited in earlier phases of ancestral Lake Erie. More rarely, bodies of fine to medium sand occur between the tills but are seldom more than a few feet thick. The till sequence is capped by from 1 to 15 feet of post-glacial silt and clay deposited in ancestral Lake Erie. The potentiometric surface of the bedrock aquifer system in the southern lake plain is virtually flat and typically lies at an elevation approximately 5 to 15 feet below that of the land surface (pl. 7).

Northern Lake Plain

The second subregion is referred to as the "northern lake plain" and occupies most of the region north of the Maumee River (pl. 9). Although also relatively flat, the northern lake plain is characterized by a gentle but pervasive southward slope and a greater number of beach features (chiefly bars, ridges, and spits) than its southern counterpart. A persistent veneer of beach sand up to 5 feet thick is present near the northern edge of this subregion (pl. 5). From south to north across this area, the unconsolidated deposits thicken markedly and show an increase in the incidence of sand and gravel bodies (pl. 3). The till stratigraphy of this area is similar to the southern lake plain but the individual till units are generally thicker. This is particularly true of the Trafalgar Formation, in which the till appears to attain thicknesses as great as 80 to 100 feet near the northern edge of the region.

The major sand and gravel aquifer in the northern lake plain occurs at the base of the Trafalgar Formation and extends over at least 40 square miles (pl. 6). The unit appears to form a small outwash plain deposited as the Huron-Erie Lobe advanced into Allen County at the beginning of the late Wisconsin Age (see sidebar, **Origin of Buried Sheet-like Sand and Gravel Bodies**, page 91). The southern and eastern parts of this body directly overlie limestone bedrock, but to the north it is separated from the limestone by an increasingly thick section of Antrim Shale and (or) older tills. Other large sand aquifers occur near the northern edge of the region, where they are associated with lacustrine deposits at the southeastern edge of the Huntertown aquifer system (pl. 6).

The northern lake plain is a regional discharge area for bedrock and unconsolidated aquifers, and the potentiometric surfaces of both are commonly at or above the land surface (pls. 7 and 8), resulting in flowing artesian wells in some places. The relationship of the flow system in the Huntertown aquifer system (pl. 8) to the Maumee River is unclear, however, because the aquifer system appears to pinch out several miles north of the river. Some interconnection may exist with sand and gravel aquifers in the subjacent Trafalgar Formation that would allow direct discharge to the river to occur, but such conditions are speculative. It is more likely that the majority of discharge from the Huntertown aquifer system occurs further north in the lake plain by two other mechanisms. First, the direction of the vertical gradient suggests that upward flow of ground water does occur across the slowly permeable clayey till and lake sediments that confine the system. The rate of discharge may be increased by capillary forces in the clayey sediments, as well as by evapotranspiration during the growing season. Second, several small perennial streams are incised into this section of the lake plain and may receive considerable discharge from shallow sand units near the top of the aquifer system.

Beach Zone

The third subregion consists of a series of large beach ridges, spits, bars, and overlying sand dunes concentrated along the northern and western margins of the lake plain (pl. 9). Bodies of sand and some gravel up to 30 feet thick characterize the land surface in this beach zone. The beach deposits generally overlie thin (less than 20 feet thick) till of the Lagro Formation, which has locally been completely stripped by wave action. Bodies of lacustrine sand commonly are present below the Lagro and are locally of considerable thickness and extent. The largest of these are deltas that occur within the Huntertown Formation along the northern edge of the lake plain (pl. 6) and which serve as the principal type of aquifer in that area. The permeable

Origin of Buried Sheetlike Sand and Gravel Bodies

Many of the sand and gravel aquifers in Allen County and elsewhere are referred to as "intertill" sand and gravel because they are localized along discrete horizons between different till units or, in some cases, between a till unit and the bedrock. Most of these aquifers have a tabular form and some have considerable areal extent. This sheetlike geometry is suggestive of an outwash apron deposited by meltwater issuing from a nearby ice margin.

Numerous bodies of this type are associated with the Trafalgar Formation in Allen County and they are one of the most ubiquitous and widely used kinds of sand and gravel aquifers. Although some of these aquifers occur in the middle and upper parts of the formation and appear to be completely enclosed by till (so-called "intra-till" aquifers), the great majority commonly occur at or near the base of the formation and are overlain by the characteristic overconsolidated loam till that makes up the bulk of the formation. Most of these basal sand and gravel aquifers of the Trafalgar Formation are very coarse-grained and commonly contain localized zones of cobble- and boulder-bearing gravel composed chiefly of the local limestone bedrock. Over much of the southern one-half to two-thirds of the county, these gravel units were deposited directly on bedrock.

These characteristics suggest that the basal sand and gravel units represent proglacial outwash aprons deposited by large high-energy meltwater streams directly in front of the Huron-Erie Lobe as it advanced over the pre-Wisconsin landscape. In southern Allen County, this landscape was developed chiefly on weathered limestone bedrock and presumably furnished an abundant supply of easily eroded rock fragments of all sizes that were incorporated into the base of the ice or simply reworked and rounded by the meltwater torrents. It also seems probable that the distribution and geometry of the outwash bodies were strongly influenced by local details of the pre-Wisconsin surface. The largest meltwater streams were likely to have been concentrated in valleys and low-lying plains and away from bedrock uplands. Consequently, although a pervasive sheet of outwash a few feet thick might have blanketed most parts of the bedrock surface, the thickest and most extensive outwash bodies would have been deposited on low-lying, gently sloping parts of the landscape. Unfortunately much of the evidence that might help confirm such a relationship is obscured. Subsequent erosion at the sole of the glacier as it advanced over the region at several different times probably stripped sizable parts of the outwash apron and generally bevelled the bedrock surface severely. Based on the presently known distribution of basal outwash bodies (unit Tb, pl. 6), however, it is not difficult to imagine a proglacial outwash apron that originally extended over a substantially greater area of the pre-Wisconsin surface.

nature of the surficial deposits and the shallow depth to water make this subregion a potential local recharge area for the shallow sand and gravel aquifers.

Ground-Water Availability

Ground-water availability in the Maumee Lacustrine Plain ranges from fair to excellent depending on location. In general, the bedrock aquifer system is not as productive in this region as it is elsewhere, but several productive sand and gravel aquifers locally compensate for this difference. Ground-water availability is generally related to the three subregions, as discussed below.

Southern Lake Plain

The limestone bedrock is the only source of groundwater over nearly all of the southern lake plain. A few sand and gravel bodies lie directly on the bedrock surface at the base of the Trafalgar Formation and locally thicken to as much as 20 feet, but are usually bypassed in favor of the bedrock below. Ground-water supplies from the bedrock in most of the southern lake plain are generally adequate for domestic wells, which are typically between 50 and 150 feet deep. In some parts of this area, however, the limestone appears to be relatively tight and free of significant solution features. In these places, it may be difficult to secure a high-capacity well and greater well depths are typically required for domestic wells. Generally speaking, large diameter wells drilled into the bedrock should yield in the range of 75 to 250 gpm.

Hydrogen sulfide is locally present in ground water from the bedrock aquifer system in this area. The sulfur appears to be derived at least in part from the mineral **gypsum**, which is a common constituent in the Devonian carbonates as well as in glacial till whose source included these rocks. Hydrogen sulfide produces an unpleasant "rotten egg" odor in water and sometimes requires treatment to achieve a potable water supply.

Northern Lake Plain and Beach Zone

Ground-water availability considerations are very similar in the northern lake plain and the beach zone. Hence, the availability of ground water in both subregions is discussed together. The irregular distribution and locally complex geometry of sand and gravel aquifers coupled with changes in the character of the bedrock across the northern part of the lake plain lead to diverse and sometimes unpredictable ground-water availability conditions in this subregion. The equation is further complicated by the persistence of poor water quality in the bedrock. In general, sand and gravel aquifers are larger, more abundant, and therefore the more common source of water to the north, whereas bedrock is most commonly utilized along the southern fringes of the area.

The most widely used sand and gravel aquifer is the extensive body of basal outwash of the Trafalgar Formation that underlies much of the central and southern parts of the northern lake plain (pl. 6). It is over 30 feet thick in many places and is composed chiefly of coarse, well-sorted sand and gravel. Wells yielding between 50 and 100 gpm are common, and yields approaching 300 gpm may be possible in the thickest parts of the aquifer. In the northern and western parts of this subregion, the principal aquifer is the fine lacustrine sand of the Huntertown aquifer system (pl. 6). The largest bodies of lacustrine sand occur in the Harlan area and reach thicknesses of 30 feet or more. The thickest and coarsest portions may be locally capable of yielding as much as 100 gpm, although the prevalence of fine sand suggests that much smaller yields are more typical.

The bedrock aquifer system is typically confined by the Antrim Shale over a large part of the northern lake plain; limestone occurs at the bedrock surface only near the Maumee River and along an irregular zone parallel to the Ohio state line that may be fault controlled (pl. 2). The thickness of the shale increases progressively to the north and west and is as much as 60 feet along the extreme northern edge of the lake plain. Although the limestone is locally a source of water for high-capacity wells, it generally has lower yields than in other regions of the county, particularly where overlain by the thickest sections of shale. In such instances, yields from the limestone are generally in the range of 25 to 150 gpm. In contrast, where it is not overlain by shale, the limestone may yield between 100 to 400 gpm.

A relatively thick section of gypsum-bearing Devonian limestone is present in the upper part of the bedrock aquifer system throughout the northern part of the lake plain. Consequently, ground water from the limestone almost always contains objectionable amounts of hydrogen sulfide, or "sulfur water," and usually requires some form of treatment. The likelihood of encountering poor water quality combined with the considerable well depth that is usually required to penetrate the limestone tend to make sand and gravel bodies the preferred aquifers over most of the northern part of the lake plain. In general, wells are developed in the bedrock only near the Maumee River, where water quality problems are less severe, and in a few places further to the north where no sand and gravel aquifers are available. Such is the case along a narrow belt that stretches from northeast to southwest across the north-central part of the area (pl. 6).

Ground-Water Sensitivity

The sensitivity to contamination of aquifers below the lake plain ranges from very low to high, with the greater part of the region lying somewhere between these two extremes (pl. 9). The distribution of ground-water sensitivity is influenced by factors that are closely related to geologic characteristics particular to the three subregions within the lake plain.

Southern Lake Plain

The sensitivity of the bedrock aquifer system ranges from moderate to moderately high in this subregion, with the differences being related chiefly to the thickness of fine-grained confining units. In most places, these units are collectively between 40 and more than 70 feet thick and are likely to retard significantly the downward migration of most potential contaminants. The most sensitive areas are in the eastern part of the subregion where confining unit thicknesses appear to be considerably less (unit L4, pl. 9). The depth to bedrock is reportedly as little as 25 feet in some parts of these areas, notably in a broad tract east of the City of Woodburn. Although the downward migration of contaminants still will be retarded, the thinness of the confining units means that contaminants could reach the bedrock potentially faster, especially in places where poorly documented or currently undiscovered sand and gravel bodies are present. A few widely scattered wells within these thin till areas reportedly contain moderately thick bodies or zones of sand within the till units. The configurations of these bodies are not well constrained due to the sparse data. Although they are believed to be relatively small, their presence further reduces the effectiveness of the till confining units in an area where these units are already relatively thin.

Northern Lake Plain

The sensitivity of aquifers below the northern lake plain is generally lower than in other parts of the lake plain (pl. 9), for two main reasons. First, in most places the principal aquifers are well confined by fine-grained till and lacustrine sediment which is typically at least 40 feet thick and, in some places, much more. The bedrock is further protected by the Antrim Shale. Second, and perhaps more significantly, strong upward gradients are present between all the aquifers and the land surface over most of the area. These conditions should greatly restrict the downward movement of contaminants. The presence of several medium to large, well-entrenched streams and their tributaries that cross the northern lake plain is another factor that may indirectly contribute to reduced sensitivity in some places. The bottoms of these stream valleys are as much as 20 feet below the prevailing lake plain elevation, which has the effect of lowering the water table in immediately adjacent areas. In addition to increasing the relative travel time of contaminants to the water table, this condition may also help to improve near-surface drainage and in turn increase the attenuation potential of the soils.

Beach Zone

The beach zone has several characteristics that cause it to be the most sensitive subregion to contamination within the lake plain, and among the most sensitive in the county (pl. 9). This area is characterized by an abundance of near-surface granular materials of relatively high permeability. Soils are coarse grained and range from excessively drained to poorly drained depending on their relative elevations. The depth to the water table may be as great as 15 or 20 feet below the highest beach ridges but as little as a few inches in swales. The permeable composition of the soils and near-surface materials greatly increases recharge potential in the beach zone and is highly conducive to the rapid infiltration of contaminants into the subsurface. Under these conditions, any ground water present within the surficial beach deposits is thus highly sensitive to contamination.

As much as two-thirds or more of the beach zone appears to be underlain by sand aquifers at relatively shallow depth (units ls, lm, l, and Tx, pl. 6). In most places there is considerably less than 20 feet of the Lagro till to separate these aquifers from the permeable surficial sediments, and in some places no till is present. The lack of confinement of the shallow aquifers, some of which are within 20 feet of the land surface, means that they are in direct hydraulic connection with the surficial deposits and could be affected relatively readily by events at the land surface. This situation (unit Lb0, pl. 9) occurs in several places, such as near Harlan as well as in and east of New Haven. The shallow sand units are commonly the only unconsolidated aquifers in several parts of the beach zone and northern lake plain, notably in the Harlan area, where the only other source of ground water is the highly sulfated water in the deeply buried bedrock. In such instances, the high sensitivity of the shallow aquifers is of a particularly serious nature, perhaps more than in some of the other highly sensitive areas in the county where high-quality ground water may be available from other aquifers at depth below the more sensitive shallow aquifers.

WABASH-ERIE CHANNEL

General Characteristics

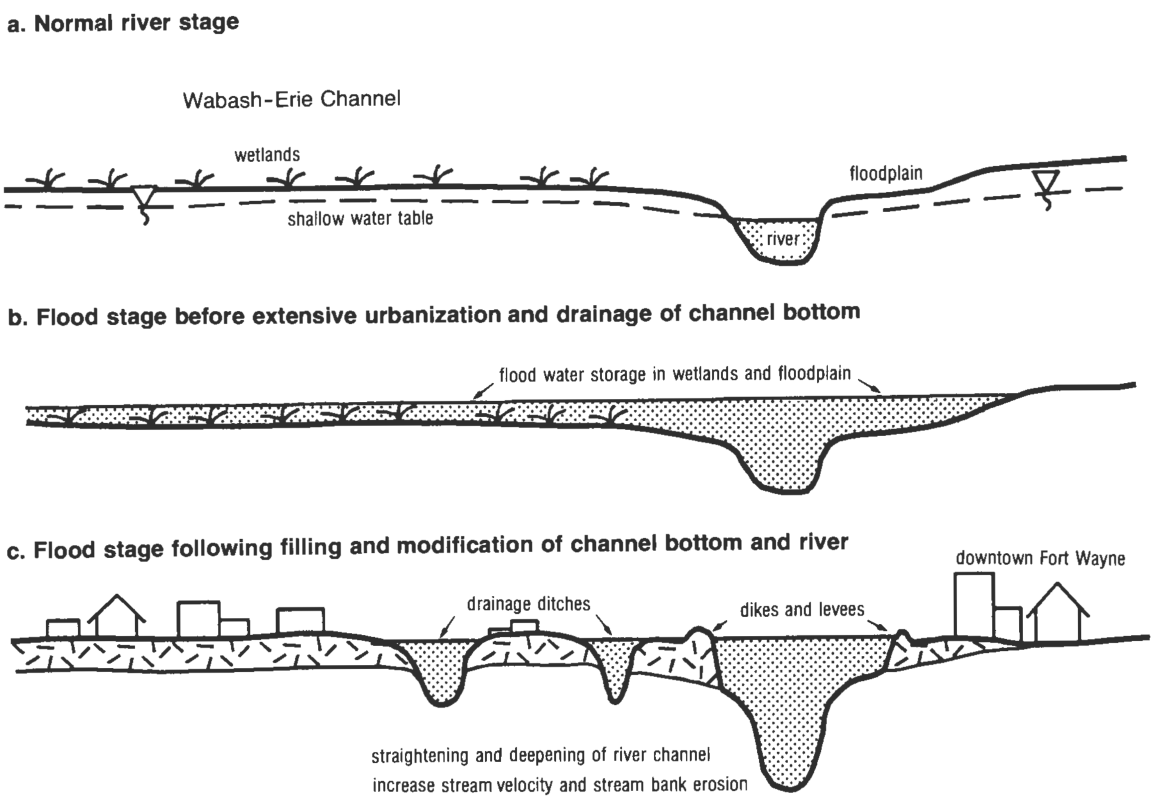
The Wabash-Erie Channel is a flat-bottomed valley as much as a mile or more wide that extends for a distance of approximately 15 miles between the western apex of the Maumee Lacustrine Plain and the west county line (pl. 9). The channel owes much of its present morphology to the catastrophic drainage of ancestral Lake Erie, which appears to represent only one in a complex series of events and depositional environments that have shaped the channel. Several distinct parts of channel can be identified, but for purposes of the following discussion, only the parallel northern and southern halves located west of the St. Marys River are distinguished (fig. 9).

The flat bottom of the channel belies the complex stratigraphy below. The central and western parts of the channel are incised through the heart of the Aboite aquifer system (pl. 6) and are locally underlain at depth by thick, extensive sand and gravel bodies that are part of the Trafalgar Formation. Some of the sand and gravel bodies extend completely to the limestone bedrock, which is at a depth ranging from about 40 to 60 feet below the floor of the channel. Elsewhere the Trafalgar Formation consists predominantly of till.

The Trafalgar Formation lies at a depth of between 5 and 35 feet and is overlain in most places by one or more complex sequences of late-glacial and post-glacial sediments (pl. 5). These sediments include locally thick sections of Erie Lobe outwash in the eastern end of the channel and a heterogeneous assemblage of fine- to medium-grained fluvial, lacustrine, and palustrine sediments. Several small dune fields are present as well.

One of the characteristic features of the Wabash-Erie Channel is the mucky wetland landscape that characterizes much of its flat bottom. In most places the seasonal high water table is within a few inches of the surface except below sand dunes and other locally elevated places. Soils show a wide range of properties, being generally mucky and waterlogged in the lower areas, and sandy and porous elsewhere. The Fort Wayne Outlet at the eastern end of the channel contains the head of the Maumee River Valley, but the part of the channel to the west forms a surface drainage divide and is characterized by a few sluggishly flowing small creeks and artificial ditches. The entire channel is a regional discharge area, and most water discharges into the drainage ditches and the saturated surficial sediments immediately below. As many as nine high-capacity wellfields and quarry dewatering operations have greatly perturbed the potentiometric surface in several places, creating large composite cones of depression and locally reversing both the lateral and vertical hydraulic gradients.

Floodwater Storage in the Wabash-Erie Channel



Although the role of the Wabash-Erie Channel in mitigating flooding on surface streams may not seem to be directly related to the general ground-water oriented theme of this report, it does have some bearing on the shallow ground-water flow system that occurs under water table conditions throughout most of the channel. The Wabash-Erie Channel is a natural area for surface water to collect during periods of severe flooding (fig. a). Nearly all of the channel bottom was formerly a vast wetland, now greatly reduced in size by artificial drainage and urbanization. The wetlands play a vital role in reducing the severity of flooding in nearby rivers and streams by holding excess floodwater and gradually releasing it back to streams and recharging shallow ground water. Several streams that drain adjacent uplands empty into the channel, and the east end of the channel also borders the lowest reaches of the St. Marys River and its confluence with the St. Joseph River at the headwaters of the Maumee River. This "three rivers area," now located near the middle of downtown Fort Wayne, was naturally flood-prone to begin with because of the confined nature of the valley and the large amount of runoff caused by the clay-rich soils that predominate throughout the entire watershed. It seems likely that very large magnitude floods on these rivers spilled over into adjacent parts of the Wabash-Erie Channel because there is only a slight (10 to 15 feet) elevation difference between the bottom of the channel and the rivers (fig. b).

The almost complete urbanization of the eastern part of the channel bottom, however, as well as urban growth in outlying parts of the watershed have contributed to more severe flooding by increasing runoff to streams and rivers while decreasing the area of channel bottom available for floodwater storage (fig. c). Filling and drainage of wetlands and general urban encroachment on floodplains all worsen the situation by eliminating the capacity of the system to store floodwaters. An increasing body of scientific evidence indicates that some so-called "flood control" measures such as straightening and widening river channels or the building of levies, retaining walls, and dikes along stream banks actually worsen the situation by eliminating storage capacity. These measures result in large volumes of water being conducted downstream at unnaturally rapid rates, causing streambank erosion and property damage in downstream areas and necessitating additional "flood control" measures in those areas at considerable expense. In some cases, reduction in the amount of water in storage may also decrease the amount of recharge to shallow aquifers below floodplains and other wetlands.

The vast size of the flat channel bottom, together with the presence of the wetlands, suggest that the Wabash-Erie Channel once performed the critical task of storing flood waters on a very large scale during periods of excessive precipitation. Several small- to medium-sized streams empty into the bottom of the channel, which is mostly less than 10 to 15 feet higher than the channel elevation at the confluence of the St. Marys, St. Joseph, and Maumee Rivers. Excess runoff from all these sources may have once accumulated in the wetlands over extensive parts of the channel and then been gradually released to the St. Marys and Little Rivers or perhaps recharged shallow water-table aquifers in the surficial sediments. Unfortunately, extensive development as well as widespread draining of wetlands over large parts of the channel bottom, particularly within the western part of the City of Fort Wayne, has severely constrained the ability of the channel to perform this essential natural function and has probably exacerbated flooding problems elsewhere (see sidebar, **Floodwater Storage in the Wabash-Erie Channel**, page 94).

Ground-Water Availability

Ground-water use and availability in and near the Wabash-Erie Channel are in flux. Historically, nearly all the wells in this region have derived their water from the bedrock aquifer system, although some wells near the Maumee River between Fort Wayne and New Haven are developed in coarse sand and gravel in the lower part of the Trafalgar Formation. Today, the majority of neighborhoods in and near the channel in Wayne and Adams Townships are served by municipal water supplies derived from the Cedarville Reservoir. In addition, dewatering of part of the bedrock aquifer is occurring west of Fort Wayne, primarily because of deep quarrying activities (pl. 7).

The largest historical users of ground water in and near the channel are represented by high-capacity wellfields constructed to supply industrial or irrigation needs (pl. 7). However, there are a significant number of isolated homes as well as several small neighborhoods that are not connected to the public water supply and therefore rely on domestic wells to provide a water supply. Under normal circumstances, the availability of ground water from the limestone bedrock under the Wabash-Erie Channel has appeared to be more than adequate to satisfy all these users, especially as many of the high-capacity wells have been operated on an intermittent or seasonal basis. Typical yields to domestic wells in this region range from about 10 gpm to as much as 50 gpm. Yields to large-diameter wells are reportedly as great as 1,000 gpm, but are typically on the order of 300 to 600 gpm. These yield data indicate the presence of a well-developed network of large fractures and(or) solution features in the bedrock in this area, which is borne out by observations in quarry exposures. A second factor contributing to large well yields is the presence of thick sections of sand and gravel directly atop the bedrock in several parts of the channel, which can release large volumes of water from storage when the bedrock is pumped.

Currently, the hydrogeologic regime in the central part of the channel is under stress due to long-term dewatering of the bedrock by deep quarrying operations. Some quarrying has been occurring in these locations for at least 45 years, but the excavations have deepened considerably in recent years and are now as much as 200 feet below the original floor of the channel. Although historical water level data are sparse and not uniformly distributed, they are sufficient to suggest a dramatic decline in static water levels in the immediate vicinity of the quarries and a somewhat lesser, but still significant decline, at greater distance. The zone of influence associated with the dewatering is difficult to delineate precisely but appears to extend over perhaps as much as several square miles (pl. 7). The zone of influence is likely to be highly irregular and asymmetric because the drawdown is taking place in fractured rocks (see related discussion under **Bedrock Aquifer System** in Chapter 3).

There are several implications associated with this situation. First, the long-term effects on this part of the aquifer system cannot be forecast precisely, but it seems likely that the zone of influence will continue to deepen and expand as long as quarry operations do the same. There is currently some evidence that suggests the zone of influence may extend beyond the edge of the Wabash-Erie Channel. The extent of such effects are likely to grow. Second, it will be difficult to predict the shape of the zone of influence because it will be controlled entirely by the orientations of interconnected fractures, which may extend for great distances in some directions but not in others. Consequently, the drawdown may be severe in isolated places far from the center of dewatering, but inconsequential or nonexistent at much closer distances elsewhere. Third, a number of domestic wells located within the zone of influence have at least temporarily experienced lowered static water levels in recent years. Most domestic wells are not drilled very far into the bedrock, hence more such events are likely in the future. Finally, both of the solid waste landfills operating in Allen County are less than one mile from quarry operations and the probability is strong that the formerly upward gradients between the bedrock and the land surface have been reversed, negating the major benefits of having the landfills located in a regional ground-water discharge area (see sidebar, **Hydrogeologic Impact of Conflicting Land Uses in the Wabash-Erie Channel**, page 97).

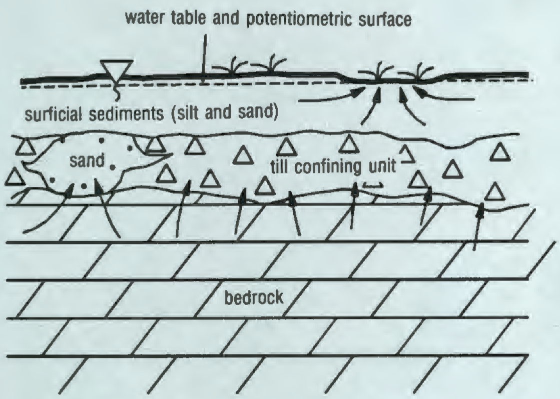
Ground-Water Sensitivity

Ground-water sensitivity in the Wabash-Erie Channel ranges from moderately high to extremely high, and some parts of the channel are among the most sensitive areas in the county. The thick surficial sediments that are nearly everywhere present below the channel bottom contain a complex shallow ground-water flow system characterized by water table depths of 1 to 5 feet in most places and abundant interaction with surface water. The waterlogged landscape provides little capacity to attenuate contaminants before they reach the water table. This shallow system is sensitive to contamination virtually everywhere, but especially where the surficial materials are composed chiefly of saturated sand and(or) gravel (units Wf and Wg, pl. 9; see also pl. 5).

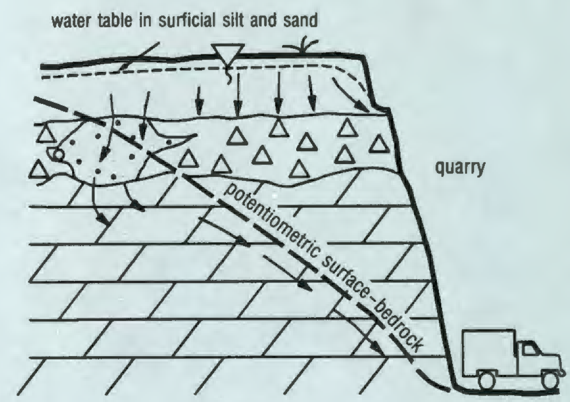
The sensitivity of deeper aquifers, such as the bedrock or sand and gravel within the Trafalgar Formation, is mixed and depends in large part on the nature of the overlying sequence. Where these aquifers are confined by 20 or more feet of Trafalgar till, they have a low degree of sensitivity, but it increases progressively as the thickness of the till is reduced. Similarly, areas where the surficial sediments are predominantly fine-grained will provide some protection for underlying aquifers by inhibiting the downward migration of contaminants. Many of the surficial sediments in unit W on Plate 9 are heterogeneous assemblages that contain bodies of both fine and relatively coarse-grained sediments, and their overall ability to confine and protect underlying aquifers is in many cases uncertain. The deeper aquifers are most sensitive where thick sections of sand and gravel are present between the bedrock and the land surface (unit Wg, pl. 9).

Most or all of the deeper aquifers are generally discharging upward below the channel, although the strength of these gradients is generally weak. Nonetheless, this condition may afford some protection to the deeper aquifers in most parts of the channel because it is difficult for most contaminants to move downward against an upward gradient. This hydraulic regime has been reversed in several places, however, resulting in artificially strong downward gradients that could in fact draw contaminants down into the deep aquifers. At least one of the two landfills west of Fort Wayne, for example, appears to lie within the zone of influence of the deep quarry operations noted in the preceding section. At one time, the (probably accidental) location of these landfills in a ground-water discharge area was advantageous because any leachate seeping from the fill would most likely move laterally and discharge into surface water within a very short distance. Now, however, documented changes in the magnitude and direction of ground-water flow tend to negate the benefits of having the landfills located in a ground-water discharge area and may increase the possibility of downward migration of leachate into the bedrock from the older, unlined parts of these facilities.

Hydrogeologic Impact of Conflicting Land Uses in the Wabash-Erie Channel: An Example of How Large-scale Water Withdrawals May Change Ground-Water Vulnerability



a.



b.

Regional configuration of the potentiometric surfaces of the bedrock and Aboite aquifer systems indicate that the Wabash-Erie Channel is a regional discharge area for both deep and shallow aquifers. In relatively undisturbed parts of the channel, the prevailing hydraulic gradient between the bedrock and the water table in the surficial sediments appears to be weakly upward or neutral, indicating that ground water generally is moving upward out of the bedrock aquifer system and into the shallow water table system and associated wetlands (fig. a). Ground water in the bedrock below the discharge area would generally be considered to have a relatively low sensitivity to contamination, especially if there was some kind of fine-grained confining unit atop the bedrock. Although by no means the only criterion, such discharge conditions represent a particularly desirable attribute of a landfill site, because leachate that seeps out of the fill is not likely to move downward against the prevailing hydraulic gradients, at least not if the leachate is of equal or lesser density than water. Instead, it is likely to migrate within the shallow water table system until it discharges into nearby surface water such as wetlands, where it may receive some natural biological treatment.

Reversal of the hydraulic gradient by long-term pumping can alter the sensitivity of underlying aquifers. This is precisely the situation in the central part of the Wabash-Erie Channel, where dewatering by adjacent quarries has created a sizable cone of depression in the bedrock that now extends below one or possibly two neighboring landfills (fig. b). The strong artificial downward hydraulic gradient creates induced recharge to the bedrock and negates most of the benefits of having the landfills situated within a regional discharge area, at least as far as the bedrock aquifer system is concerned. The bedrock may now be vulnerable to contamination because a potential source of contamination is located directly above a recharge area. The vulnerability of the bedrock in this area ultimately depends on the largely unknown integrity of the fine-grained materials that separate it from the shallow water table system in the surficial sediments. The presence of any large bodies of sand that cut completely through the confining layer could provide a conduit through which contaminants could readily be drawn downwards into the cone of depression in the bedrock below.

CHAPTER 5

SUMMARY AND RECOMMENDATIONS

By Anthony H. Fleming

SUMMARY

Usable amounts of ground water occur chiefly in three major aquifer systems in Allen County:

1) the bedrock aquifer system, composed of fractured and karsted limestone and dolomite, and present at depth throughout the county;
2) the Huntertown aquifer system, which includes outwash, ice-contact sand and gravel, and lacustrine sand deposited by Saginaw Lobe meltwater in northwest and north-central Allen County; and
3) the Aboite aquifer system, which consists of a large, well-interconnected complex of sand and gravel bodies in western Allen County that is locally in direct hydraulic communication with the limestone bedrock.

All three of these systems are variably confined by one or more till sheets and lesser fine-grained lacustrine sediments whose composite thickness ranges from less than 10 feet to more than 250 feet. Other sand and gravel aquifers occur in scattered locations throughout the county under both confined and unconfined conditions.

Over about two-thirds to three-quarters of the county, these aquifer systems are generally well protected by thick, fine-grained till confining units that typically have low permeability and thus retard the downward migration of potential contaminants. The thickness of the clay-rich surface till of the Lagro Formation appears to be the single most important factor in determining the overall sensitivity to contamination of ground water in any particular area. Other important factors include the composition and permeability of individual aquifers, presence and thickness of other till confining units, position in the ground-water flow system, type of soil, water table depth, and interaction between surface water and ground water.

Areas having relatively elevated sensitivity to ground-water contamination typically correspond to one or more of the following hydrogeological conditions:

1) little or no confinement of the aquifer;
2) cut-outs in till confining units caused by channels, beaches, lake outlets, and other features containing coarse-grained, permeable materials;
3) recharge areas;
4) poorly drained landscapes characterized by shallow water-table depth and waterlogged soils; and
5) wellhead protection areas.

Moderate to large areas characterized by these conditions chiefly occur:

1) along river valleys;
2) over most of the county northwest of Huntertown;
3) along the shoreline complex that defines the northern edge of the Maumee Lacustrine Plain; and
4) in the Wabash-Erie Channel.

Small areas with elevated sensitivity attributable to the localized occurrence of one or more of these conditions are also found in widely scattered hydrogeologic settings throughout the county. Overall, only about 10 to 15 percent of the county is characterized by relatively high ground-water sensitivity.

RECOMMENDATIONS

There are several simple and inexpensive steps that can be taken to minimize the possibility of ground-water contamination due to human activities taking place at or near the land surface. Most of these steps should be targeted at areas having the greatest sensitivity or at areas and(or) activities where the consequences of contamination could be extremely severe, such as public water supply wells. Several practical ground-water protection activities are suggested below.

Wellhead Protection Areas: Establish a wellhead protection program for all public water supply wellfields in Allen County. This should involve representatives from: all affected water utilities; county planning, health, and environmental affairs departments; Indiana Department of Environmental Management (IDEM) Drinking Water Branch; Indiana Geological Survey; and public citizens.

Ground-Water Protection Zones: Establish ground-water protection zones in sensitive areas overlying major aquifers, including especially the regional recharge area for the Huntertown aquifer system in northwestern Allen County. Utilize zoning, health ordinances, easements, and other tools to direct development away from these zones. Existing facilities within these zones may be required to provide monitoring, leak detection, and other assurances to protect ground-water quality.

Ground-Water Vulnerability Mapping: The actual vulnerability of ground water to contamination depends on the presence and nature of potential sources of contaminants and their distribution relative to sensitive hydrogeologic areas. Ground water is vulnerable to contamination where such sources coincide with areas characterized by high ground-water sensitivity. Undertake a survey of potential sources of contaminants such as waste disposal sites (see below), bulk storage facilities, underground storage tanks, and other types of facilities and activities that typically store, transport, or dispose of potential contaminants. Such a survey could be undertaken using in-house land-use data, via windshield surveys, or both. Utilize the hydrogeologic maps and information in this report and in Fleming (1992) to construct ground-water vulnerability maps based on actual and potential threats to ground water. It would be logical to begin this process in those hydrogeologic regions and subregions identified in plate 9 of this report as having a relatively high sensitivity to contamination.

Commercial and Industrial Development: Utilize the hydrogeologic maps to direct industrial and commercial development towards areas having relatively less potential for ground-water contamination. Such areas are widely distributed in nearly every part of the county, thus such a policy should not appreciably hinder economic development.

Residential Development: For unsewered residential developments, establish density requirements that reflect both the capacity of the particular soil type to attenuate septic effluent and the sensitivity of the underlying aquifers. Residents of such developments will undoubtedly be using these same aquifers as a water supply, hence it is in their interest to protect their own water quality. At the same time, sewer service should be required of additions served by public water supplies.

Abandoned Water Wells: Improperly abandoned water wells may pose the greatest threat to ground-water quality in Allen County. They provide a direct conduit between the land surface and the aquifers they are developed in. During the field location of water wells for this study, dozens of abandoned wells were identified, and it is likely that these represent only a small fraction of the total number in the county. There are several ways to address this problem, which could be implemented collectively:

1) Establish a county well ordinance that requires *all* unused water wells to be properly plugged from top to bottom by a certified water well contractor;
2) Since public water utilities are continuing to expand their service areas, especially in immediately outlying parts of the City of Fort Wayne, require unused wells to be properly plugged *as a condition for hooking up to a public water supply*. The property owner *must* provide a completed copy of the state well abandonment form to the utility prior to hookup;
3) Expand the inspections of sewer, water, and utility services that are a standard requirement for many property transactions. This process could include a concerted search for abandoned wells that might be located on the particular property in question. The search could employ historical records as well as a physical reconnaissance. Abandoned (unused) wells found during such a search should be properly plugged. This is particularly important when a property is converted to commercial use from agriculture or some other previous use that is likely to have had a drilled or dug well. The new owners/developers may not be aware of the existence of old wells, as illustrated by the apparent bulldozing or burial of old wells on several such properties observed during this study.

New Water Wells: In some hydrogeologic settings, the current state well code may not be adequate to protect aquifers and water well users from potential contaminants derived from the land surface. Under current law, there is a possibility for cross-contamination of aquifers at nearby horizons in some instances. Establish a county well ordinance requiring that the annulus of every new water well be *continuously grouted* between the water-bearing formation and the land surface (current law requires only that the 25 feet above the water-bearing interval be grouted). In addition, the ordinance should require that the well casing project at least one foot above grade, and that the land surface be graded to slope radially away from the well. Although the well casing requirement is currently a state law, well drillers have little control over the ultimate configuration of the land around the well once they leave the site. Finally, the ordinance should require that the well be located *upgrade* of all sources of contamination on the property (for example, septic systems, storage tanks) as opposed to current law, which only establishes a minimum separation distance without respect to relative elevations. **Any county well ordinance should be developed with the full input and cooperation of local water well drillers, who are in the best position to help design a practical and workable set of ordinances and who may be aware of other problems and ideas related to the construction and use of water wells.**

Sole-Source Aquifer Designation: For all practical purposes, the limestone bedrock is the only available source of ground water over most of the southern half of the county as well as in most or all of several counties immediately to the south. It may, therefore, qualify as a sole-source aquifer under Environmental Protection Agency guidelines, which require ground-water protection criteria to be considered when any federally funded development project is under review in the area above the designated aquifer. The possibility of such a designation could be explored, perhaps collectively with Adams and Wells Counties, where much of the recharge that supplies the bedrock aquifer system in southern Allen County is believed to occur.

Abandoned Waste Disposal Sites: Many such sites exist in a variety of hydrogeologic settings in Allen County. Utilize the hydrogeologic maps to evaluate the relative risks these sites pose to ground-water quality. Use the results of this analysis to prioritize the sites for monitoring and remediation.

Active Waste Disposal Sites: There are currently three operating landfills in Allen County, none of which are located in particularly ideal hydrogeologic settings. Current state and federal monitoring rules for landfills are largely based on site-specific results and rarely take into account regional aquifer system characteristics beyond the site boundaries. The county could work with IDEM to determine whether additional monitoring is required, based on the distributions and known ground-water flow patterns of the major aquifers these sites overlie.

Proposed Waste Disposal Sites: Current regulations governing landfills focus almost entirely on engineered approaches that attempt to maintain the so-called "dry-tomb" condition; that is, the principal is to utilize daily soil cover or liners to keep precipitation out of the fill area, and to utilize a system of liners and collection systems below the site to collect any leachate that is generated and prevent it from being released to the ground water below. There are few, if any, specific requirements related to geologic or hydrogeologic characteristics of the proposed site. The county could establish requirements that any new landfill be sited in one of two types of areas with respect to geologic conditions:

1) areas characterized by more than 100 feet of glacial till above the first major aquifer, and located where strong downward gradients do not exist, such as near a local discharge area;
2) regional discharge areas, characterized by strong upward hydraulic gradients and located in proximity to a large stream or river.

The base of a site in a regional discharge area, *after all excavation is completed,* should also be underlain by at least 15 to 20 feet of low-permeability till or other fine-grained material. Any leakage of leachate from a site so located is unlikely to migrate into a subjacent aquifer; more probably it will discharge to the surface a short distance away, rather than potentially impacting a wide area, as a site located directly over a major aquifer in an upland area with downward gradients could do. Several parts of Allen County contain both of these favorable geologic conditions.

Spills and Transportation: Some types of hazardous truck and rail cargo could seriously affect ground-water quality if a spill were to occur in a sensitive area. This is especially true of liquid materials. Two approaches could be implemented to minimize this risk:

1) Establish designated hazardous cargo truck routes that take advantage of high-quality roads that pass through the large parts of the county with low potential for ground-water pollution. Spills are less likely to travel very far in the thick, low-permeability tills that underlie the land surface in these areas. To the extent practical, such routes should attempt to avoid areas where ground water is most sensitive to contamination, such as the Eel River Valley, St. Joseph River Valley, Cedar Creek, and parts of the Wabash-Erie Channel;
2) For spills or other incidents that have the potential to release hazardous chemicals, develop a response plan that takes into account conditions in the different hydrogeologic regions of the county.

For example, foam should be used rather than water to extinguish chemical fires in areas underlain by thick sand and gravel. Even though water may be more readily available as well as chemically acceptable for responding to a particular situation, use of large amounts of water could flush contaminants into the aquifer below.

Public Education: Develop an educational program for county residents and businesses that emphasizes the dependence of the county on ground-water resources and the importance of protecting them. A program consisting of printed materials, public service announcements, and public presentations could highlight the many simple steps individuals can take to protect groundwater. Emphasis on new well owners would be a logical approach for beginning the program.

ACKNOWLEDGMENTS

A study of this scope is not feasible without substantial input and cooperation from numerous individuals and organizations. My understanding of hydrogeologic conditions has been greatly enhanced by numerous discussions with William J. Steen, IDNR–Division of Water, who also is a contributor to Chapters 3 and 4. I also acknowledge the geologic acumen of my colleagues at the Indiana Geological Survey: S. E. Brown, N. K. Bleuer, V. R. Ferguson, H. H. Gray, E. J. Hartke, S. J. Keller, and R. F. Rupp. Many informal discussions with all of these individuals greatly improved this study and sharpened my thinking about the complex nature of the bedrock and glacial deposits and their hydrogeologic characteristics. I am also indebted to V. R. Ferguson for sharing the data from her field studies of the hydrogeology of certain glacial till units in Allen County. The manuscript benefitted from extremely thorough reviews by H. H. Gray, S. E. Brown, V. R. Ferguson, E. J. Hartke, W. J. Steen, and K. R. Bowman.

Significant financial support for field operations was provided by the Allen County Board of Commissioners and the U.S. Geological Survey. Allen County also provided most of the funding for the preparation and publication of the report and maps. I especially acknowledge D. A. Gordon, Executive Director, and K. R. Bowman, Senior and Long-range Planner, of the Allen County Department of Planning Services, for their strong support and many helpful ideas during every phase of this study. I am most grateful to David Meyers of Ball State University for performing much of the field work. The success of the down-hole sampling and gamma-ray logging operation is directly attributable to the long hours Dave spent tracking down water wells and drillers in widely scattered parts of thecounty. All laboratory analyses were performed by S. E. Frushour and T. Chitwood, IGS. The final compilation of several of the plates, as well as the compilation and drafting of numerous 1:24,000 work maps on which these plates are based, was performed by R. F. Rupp.

Finally, I am deeply indebted to the following water well contractors, who freely provided access to the many private water wells used in this study, and who generously gave of their time and expertise: Amstutz Well Drilling; D. G. Bojrab and Sons; Croy Bros. Well Drilling; G & K Well Drilling; Gordon and Sloffer Well Drilling; Hollenbaugh Well Drilling; Kell Drilling; and Killen Drilling. I also thank United Refuse, Chemical Waste Management of Indiana, and National Serv-All for providing access to monitoring wells for gamma-ray logging; and Stone Street Quarries, StoneCo, France Stone, Canyon Sand and Gravel, WW Sand and Gravel, and Pleasant Prairie Products for access to exposures in quarries and gravel pits.

REFERENCES CITED

Aller, L., Bennett, T., Lehr, J., Petty, R., and Hackett, G., 1987, DRASTIC–A standardized system for evaluating ground water pollution potential using hydrogeologic settings: Dublin, Ohio, National Water Well Association, and Washington, D.C., U.S. Government Printing Office, Document EPA 600/2-87-035, 403 p.

Arvin, D. V., 1989, Statistical summary of streamflow data for Indiana: U.S. Geological Survey Open-File Report 89-62.

Ault, C. H., 1989, Map of Indiana showing directions of bedrock jointing: Indiana Geological Survey Miscellaneous Map 52.

Ault, C. H., and others, 1973, Guidebook to the geology of some Ice Age features and bedrock formations in the Fort Wayne, Indiana: Indiana Geological Survey Guidebook, 62 p.

Bleuer, N. K., 1974, Buried till ridges in the Fort Wayne area, Indiana, and their regional significance: Geological Society of America Bulletin, v. 85, p. 917–920.

Bleuer, N. K., and Moore, M. C., 1972, Glacial stratigraphy of the Fort Wayne, Indiana, area and the draining of Glacial Lake Maumee: Proceedings of the Indiana Academy of Science, v. 81, p. 195–209.

Bleuer, N. K., and Moore, M. C., 1974, Buried pinchout of Saginaw Lobe drift in northeastern Indiana: Proceedings of the Indiana Academy of Science, v. 84, p. 362–372.

Bleuer, N. K., and Moore, M. C., 1978, Environmental Geology of Allen County: Indiana Geological Survey Special Report 13, 72 p.

Boulton, G. S., 1970, The deposition of subglacial and meltout tills at the margins of certain Svalbard glaciers: Journal of Glaciology, v. 9, no. 56, p. 231–245.

Branam, T. D., Comer, J. B., Shaffer, N. R., Ennis, M. V., and Carpenter, S. H., 1991, Inorganic ground-water chemistry at an experimental New Albany Shale in situ gasification site: Fuel, v. 70, p. 1317–1323.

Bruns, T. M., Logan, S. M., and Steen, W. J., 1985, Maps showing bedrock topography of the Teays Valley, north-central Indiana: Indiana Geological Survey Miscellaneous Maps 42, 43, 44.

Burger, A. M., Forsyth, J. L., Nicoll, R. S., and Wayne, W. J., 1971, Geologic map of the 1° x 2° Muncie Quadrangle, Indiana and Ohio, showing bedrock and unconsolidated deposits: Indiana Geological Survey Regional Geologic Map 5.

Connell, D. E., 1984, Distribution, characteristics, and genesis of joints in fine-grained till and lacustrine sediment, eastern and northwestern Wisconsin: Madison, University of Wisconsin, unpublished M.S. thesis, 243 p.

Dryer, C. R., 1889, Report on the geology of Allen County: Indiana Department of Geology and Natural Resources Annual Report 16, p. 291–402.

Dryer, C. R., 1894, The drift of the Wabash-Erie region–a summary of results: Indiana Department of Geology and Natural Resources Annual Report 18, p. 83–90.

Ferguson, V. R., 1992, Hydrogeology and hydrogeochemistry of fine-grained glacial till, northeastern Indiana: Bloomington, Indiana University, unpublished M.S. thesis, 75 p.

Ferguson, V. R., Fleming, A. H., and Krothe, N., 1991, Ground water recharge through glacial deposits, northeastern Indiana: Proceedings of the Thirty-sixth Annual Midwest Ground Water Conference, Indianapolis, Indiana, p. 64–65.

Ferguson, V. R., Fleming, A. H., Krothe, N. C., and Steen, W. J., 1992, Hydrogeology and hydrogeochemistry of fine grained glacial till, northeastern Indiana: Proceedings of the Geological Society of America Annual Meeting, v. 24, no. 7, p. 302.

Fetter, C. W., 1988, Applied hydrogeology: Columbus, Ohio, Charles. E. Merrill Publishing Co, 488 p.

Fleming, A. H., 1992. The hydrogeologic framework of Allen County, Indiana: hydrostratigraphic atlas emphasizing subsurface sequence stratigraphy and ground-water contamination potential: Indiana Geological Survey Open File Report 92-14, 55 p. plus 90 maps. Scale 1:24,000

Foley, C. F., Bleuer, N. K., Leininger, R. K., and Herring, W. C., 1973, Strontium and other notable chemical constituents of well water in Allen County, Indiana: Indiana Academy of Science Proceedings, v. 82, p. 274–280.

Forsyth, J., 1965, Contribution of soils to the mapping and interpretation of Wisconsin tills in western Ohio: Ohio Journal of Science, v. 65, no. 4, p. 220–227.

Forsyth, J., 1973, Late-glacial and post-glacial history of western Lake Erie: The Compass of Sigma Gamma Epsilon, v. 51, no. 1, p. 16–26.

Fraser, G. S., and Bleuer, N. K., 1988, Sedimentological consequences of two floods of extreme magnitude on the late Wisconsinan Wabash Valley, *in* Clifton, H. E., ed., Sedimentologic consequences of convulsive geological events: Geological Society of America Special Paper 229, p. 111–125.

Freeze, R. A., and Cherry, J. A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, Inc., 604 p.

Gooding, A. M., 1973, Characteristics of Late Wisconsinan tills in eastern Indiana: Indiana Geological Survey Bulletin 49, 28 p.

Gordon, M. E., and Huebner, P. M., 1983, An evaluation of zone-of-saturation landfills in Wisconsin: Proceedings of the Sixth Annual Madison Waste Conference, Madison, Wisconsin, p. 23–53.

Gray, H. H., 1982, Map of Indiana showing topography of the bedrock surface: Indiana Geological Survey Miscellaneous Map 35.

Gray, H. H., 1983, Map of Indiana showing thickness of unconsolidated deposits: Indiana Geological Survey Miscellaneous Map 37.

Gray, H. H., 1989, Quaternary geologic map of Indiana: Indiana Geological Survey Miscellaneous Map 49.

Gray, H. H., Ault, C. H., and Keller, S. J., 1987, Bedrock geologic map of Indiana: Indiana Geological Survey Miscellaneous Map 48.

Grisak, G. E., and Cherry, J. A., 1975, Hydrologic characteristics and response of a fractured till and clay confining a shallow aquifer: Canadian Geotechnical Journal, v. 12, p. 23–43.

Hendry, M. J., 1982, Hydraulic conductivity of a glacial till in Alberta: Ground Water, v. 20, p. 162–169.

Hendry, M. J., 1988, Hydrogeology of clay till in a prairie region of Canada: Ground Water, v. 26, p. 607–614.

Herring, W. C., 1969, Reconnaissance of the ground-water resources of the Maumee River basin, Indiana Division of Water Report 7 (Open-file report).

Herzog, B. L., Griffin, R. A., Stohr, C. J., Follmer, L. R., Morse, W. J., and Su, W. J., 1989, Investigation of failure mechanisms and migration of organic chemicals at Wilsonville, Illinois: Ground Water Monitoring Review, v. 9, no. 2, p. 82–89.

Johnson, G. H., and Keller, S. J., 1972, Geologic map of the 1° x 2° Fort Wayne Quadrangle, Indiana, Michigan, and Ohio, showing bedrock and unconsolidated deposits: Indiana Geological Survey Regional Geologic Map 8.

Kirschner, F. R., and Zachary, A. L., 1969, Soil Survey of Allen County, Indiana: Washington, D.C., U.S. Department of Agriculture-Soil Conservation Service, 76 p. plus maps.

Leverett, F., 1902, Glacial formations and drainage features of the Erie and Ohio basins: U.S. Geological Survey Monograph 41, 802 p.

Leverett, F., and Taylor, F. B., 1915, The Pleistocene of Indiana and Michigan and the history of the Great Lakes: U.S. Geological Survey Monograph 53, 529 p.

Malott, C. A., 1922, The physiography of Indiana, *in* Handbook of Indiana geology: Indiana Department of Conservation, Publication 21, part 2, p. 59–256.

Maxey, G. B., 1964, Hydrostratigraphic units: Journal of Hydrology, v. 2, p. 124–129.

McGown, A., Anderson, W. F., and Radwan, A., 1975, Geotechnical properties of the tills in west-central Scotland, *in* Proceedings of the symposium on the engineering behavior of glacial materials, University of Birmingham, U.K., p. 89–99.

Mickelson, D. M., Johnson, M. D., Waldemarson, D., and Johansson, H. G., 1981, Jointing in till: An example from south-central Sweden, INQUA Commission on the genesis and lithology of Quaternary deposits, Proceedings of the Symposium on the genesis and lithology of morainic deposits in an alpine environment, Jackson, Wyoming, August 1981.

Nowacki, J., 1991, Karst on the buried Silurian surface in north-central Indiana and the impact on ground water: Proceedings of the Thirty-sixth Annual Midwest Ground Water Conference, Indianapolis, Indiana, p. 80–81.

Pettijohn, R. A., and Davis, L. G., 1973, Water resources of the Maumee River Basin, northeastern Indiana: U.S. Geological Survey Hydrologic Investigation Atlas HA-493.

Planert, M., 1980, Ground-water availability near Fort Wayne, Allen County, Indiana: U.S. Geological Survey Water Resources Investigation 80-34, 60 p.

Poland, J. F., Lofgren, E. E., and Riley, F. S., 1972, Glossary of selected terms useful in studies of the mechanics of aquifer systems and land subsidence due to fluid withdrawals: U.S. Geological Survey Water-Supply Paper 2025, 9 p.

Pye, V. I., and Kelley, J., 1984, The extent of groundwater contamination in the United States, *in* Groundwater Contamination, National Research Council, Studies in Geophysics: Washington, D.C., National Academy Press, p. 23–33.

Ripley, E. M., Shaffer, N. R., and Gilstrap, M. S., 1990, Distribution and geochemical characteristics of metal enrichment in the New Albany Shale, Indiana: Economic Geology, v. 85, p. 1790–1807.

Schneider, A. F., 1966, Physiography, *in* Natural features of Indiana: Indiana Academy of Science Sesquicentennial Volume, p. 40–56.

Shaffer, N. R., Chou, C. L., Frost, J. K., and Coveney, R. M., 1988, Geochemical and petrologic features of phosphate nodules in Paleozoic midwestern black shales: Geological Society of America Annual Meeting, Abstracts with Programs, p. A-212.

Shaffer, N. R., and Yarling, M., 1991, Geochemically anomalous units and their effect on ground water: Indiana Academy of Science, 107th Annual Meeting, Programs and Abstracts, p. 63.

Sharp, J. M., 1984, Hydrogeologic characteristics of shallow drift aquifers in dissected till plains (north-central Missouri): Ground Water, v. 22, no. 6, p. 683–689.

Shaver, R. H., and others, 1986, Compendium of Paleozoic rock-unit stratigraphy in Indiana–a revision: Indiana Geological Survey Bulletin 59, 203 p.

Soil Conservation Service, 1975, Soil taxonomy–A basic system of soil classification for making and interpreting soil surveys: Washington, D.C., U.S. Department of Agriculture, Agriculture Handbook Number 436, 754 p.

Stephenson, D. A., Fleming, A. H., and Mickelson, D. M., 1988, Glacial deposits, *in* Back, W., and others, eds., Hydrogeology: Boulder, Colorado, Geological Society of America, The geology of North America, v. O-2.

U.S. Environmental Protection Agency, 1980, Ground water protection: Washington, D.C., U.S. Environmental Protection Agency Water Quality Management Report, 36 p.

U.S. Environmental Protection Agency, 1989, Wellhead protection programs–tools for local governments: Washington, D.C., Office of Water, Document EPA 440/6-89-0002, April 1989.

U.S. Environmental Protection Agency, 1991a, Protecting local ground-water supplies through wellhead protection: Washington, D.C., Office of Water, Document EPA 570/09/91-007, May 1991.

U.S. Environmental Protection Agency, 1991b, Wellhead protection strategies for confined aquifer settings: Washington, D.C., Office of Water, Document EPA 570/9-91-008, June 1991.

U.S. Environmental Protection Agency, 1991c, Delineation of wellhead protection areas in fractured rocks: Washington, D.C., Office of Water, Document EPA 570/9-91-009, June 1991.

Wayne, W. J., 1956, Thickness of drift and bedrock physiography of Indiana north of the Wisconsin glacial boundary: Indiana Geological Survey Report of Progress 7, 70 p.

Wayne, W. J., 1963, Pleistocene formations in Indiana, Indiana Geological Survey Bulletin 25, 85 p.

Wayne, W. J., 1968, The Erie Lobe margin in east-central Indiana during the Wisconsin glaciations: Proceedings of the Indiana Academy of Science, v. 77, p. 279–291.

Zumberge, J. H., 1960, Correlation of Wisconsin drift in Illinois, Indiana, Michigan, and Ohio: Geological Society of America Bulletin, v. 71, p. 1177–1188.

GLOSSARY OF SELECTED GEOLOGIC TERMS AND NAMES

Aboite aquifer system Complex of sand and gravel aquifers centered on Aboite Township in western Allen County.

ablation Loss of ice in a glacier or ice sheet from melting, sublimation, or calving of bergs into a body of water.

ablation complex Assemblage of sediments deposited during the ablation of a glacier, generally by being let down from at or near the glacier surface by melting of underlying ice.

ablation hummock Mound of till-like sediment deposited in a depression in the ice.The sediment becomes a positive topographic feature after the surrounding ice has melted.

alluvial valley River or stream valley flanked by floodplains that are frequently inundated by seasonal floods and underlain by alluvium.

alluvium Sand, gravel, silt, and clay deposited adjacent to modern streams and derived from erosion of surface sediments elsewhere in the watershed or from valley walls.

annular seal Cement or bentonite clay pumped into the space between the borehole wall and well casing to seal out water and contaminants.

annular space The space between a well casing pipe and the drilled borehole into which the casing is inserted.

aquifer Any body of rock or unconsolidated sediment capable of producing ground-water to a well in an economically useful amount.

aquifer system A heterogeneous body of permeable and poorly permeable materials that functions regionally as a water-yielding unit; it consists of two or more aquifers separated at least locally by confining units that impede ground-water movement, but do not affect the overall hydraulic continuity of the system.

aquitard Slowly permeable stratum that retards water movement into and out of adjacent or underlying aquifers; see **confining unit**.

attenuation The chemical, physical, and(or) biological processes that restrict the migration of contaminants through geologic media.

basal outwash Sand and gravel that were deposited as outwash in front of an advancing glacier and subsequently overridden by the ice and buried by other kinds of deposits. Basal outwash commonly forms the base of glacial depositional sequences such as the Huntertown and Trafalgar Formations.

basal till Glacial till deposited by melting of ice at the base of a glacier and little reworked by meltwater or mass movement.

bedding plane Surface marking the break between two distinct pulses (beds) of sediment deposition.

bedrock Consolidated rock composed of cemented or lithified sediments (such as sandstone, shale, limestone) or crystalline rock such as granite or slate.

bedrock aquifer system All of the limestone and dolomite bedrock below Allen County, which contains both aquifers and local confining units.

bentonite Type of clay derived from weathered volcanic ash that expands when wet; commonly used as well drilling mud and annular seal.

blow count The unit of measure for the standard penetration test and representing the number of blows required to drive a 2-inch diameter core sampler one foot through unconsolidated material by dropping a 140-pound hammer from a distance of 30 inches.

carbonate bedrock Rocks composed of limestone (calcium carbonate) and dolomite (calcium-magnesium carbonate).

channel Typically a linear sag, stream course, or meltwater conduit with a V-shaped or U-shaped cross section. Channels in the glacial environment are commonly filled with sand and gravel deposited by meltwater.

cone of depression Area below a well or dewatering site where the water table or potentiometric surface is drawn down below its natural (static) level due to removal of ground water.

confining unit Rock or unconsolidated material, generally of low permeability, that restricts ground-water flow.

crevasse Large near-vertical fracture open at the surface of a glacier and commonly a route for meltwater flow.

debris flow Mass of rock and(or) sediment that becomes unstable and moves downslope under its own weight.

delta Wedge-shaped mass of sediment deposited where a river or stream empties into a standing body of water such as a lake.

Devonian Period of geologic time from about 410 to 360 million years ago.

diffusion The outward spreading of a plume of liquid or gas from areas of greater concentration to areas of lesser concentration.

discharge area Region where ground water is moving toward, and generally appearing at the land surface or in a surface-water body.

environmental isotope A variety of natural processes cause many elements to occur in two or more atomic weights, known as isotopes, some of which decay into other isotopes by releasing radioactivity. A variety of common elements (for example, oxygen, hydrogen, carbon, nitrogen) occur in different isotopes whose relative abundance in ground water is indicative of the environmental conditions under which the water was recharged or flowed, and are thus referred to as environmental isotopes.

esker Linear type of ice-contact stratified deposit formed in subglacial channels and commonly having a sharply peaked ridgelike profile in cross section.

fabric Structure in a rock or unconsolidated sediment produced by the parallel orientation of individual mineral grains, inclusions, or elongate rock fragments.

fan Wedge-shaped body of sediment (usually sand and gravel) with a roughly semicircular map pattern and a gentle to steep upper surface that slopes away from the head or apex of the body. Usually deposited where a confined river channel loses its confining walls, such as at the mouth of a meltwater channel along an ice margin.

fine-grained Composed chiefly of silt and clay.

flow system The cycle of ground water flow in an aquifer system including recharge, lateral and vertical flow, and discharge. A **regional flow system** generally includes deep ground-water flow that takes place over many tens of years between the highest surface drainage divides and the largest river valleys. A **local flow system** includes mostly very shallow ground-water flow between relatively nearby recharge and discharge areas.

flow-through lake Lake that receives ground water discharge on one side and leaks into the ground water on the other.

flowing artesian well Any well in which the static water level is above the land surface.

fracture flow Ground-water flow controlled predominantly by a network of fractures, bedding planes, or other planar structures in a rock or sediment.

gamma-ray log Geophysical record that indicates vertical changes in the amount of natural gamma radiation in a mass of rock or sediment commonly recorded by pulling a probe up through a borehole.

Glacial Lake Maumee The name historically applied to the phase of ancestral Lake Erie that existed immediately following the retreat of the latest Erie Lobe ice (Dryer, 1889; Leverett and Taylor, 1915).

glacial terrain Geographic region characterized by a distinctive landscape whose morphology reflects a particular series of glacial and post-glacial events and which is underlain by a particular sequence of sediments that are directly related to those events. A **glacial terrain map** depicts the geographic distribution and characteristics of different glacial terrains.

glacier Mass of ice that flows under its own weight by internal deformation of ice, basal sliding, or other mechanisms.

ground water All water present below the surface of the Earth.

grout Material, typically cement or bentonite slurry, used to seal the annular space of a well.

gypsum Mineral composed of calcium sulfate, typically produced in hyper-saline basins characterized by the evaporation of water that causes concentration of salts.

heterogeneity Spatial variation in physical attributes, such as grain-size, of a rock or sediment.

high-capacity well Typically a large-diameter (8 inches or more) well capable of producing more than 70 gallons per minute.

Huntertown aquifer system Complex of sand and gravel aquifers and associated till confining units in northern Allen County, best developed in the general vicinity of the Town of Huntertown.

Huntertown Formation Sequence of outwash sand, till, ice-contact stratified deposits, and lacustrine sediments deposited by the Saginaw Lobe and its meltwaters in northern Allen County.

hydraulic conductivity Ability of a rock or sediment to transmit water under a unit hydraulic gradient. In this report, the term "permeability" is used, since it is more likely to be familiar to the lay person.

hydraulic head The elevation that water rises to in a well open to a specific point in the subsurface. Consists of two components: 1) pressure head, and 2) elevation head.

hydrogeology The science of ground water and its interaction with the geologic environment.

Ice Age The popular name for the most recent period of glacial activity, also known as the Pleistocene Epoch, which began some 2 million years ago and is still in progress.

ice-contact fan Fan deposited against the front of a glacier or atop and amidst blocks of ice.

ice-contact stratified deposits Glacial sediment composed primarily of sand, gravel, and debris flows that were deposited on, against, or within glacier ice.

ice-marginal channel Channel cut by a meltwater stream flowing along the margin of a glacier.

ice-walled channel Channel within a glacier whose walls are largely formed by glacier ice.

induced recharge The increased downward flow of water that occurs above a cone of depression as a result of pumping.

interlobate Located between or affected by two lobes of glacier ice.

intersequence unit System of sand and gravel bodies that commonly define the horizon between the Trafalgar Formation and the overlying Lagro Formation.

joint Crack or fracture in a rock or sediment.

karst Distinctive landscape developed on carbonate rocks that have undergone appreciable solution; commonly marked by numerous sinkholes, caves, blind valleys, and other solution features.

kettle Depression caused by collapse of sediment due to the melting of buried blocks of ice. A **kettle lake** is a kettle that is filled with water.

kettle lake See **kettle**.

Lagro Formation The youngest sequence of glacial deposits in Allen County, composed mainly of clay-rich glacial till deposited during the most recent ice advances out of the Lake Erie basin.

lacustrine (lake) sediment Sediment deposited in lakes. Most commonly composed of silt and clay, but locally may consist of fine sand and gravelly beach sediments. In this report, the term refers chiefly to lakes associated with the margins of glaciers.

late Wisconsin Age The most recent period of major glacial activity during the ongoing Ice Age, from about 22,000 to 10,000 years ago.

lithostratigraphy See **stratigraphy**.

local flow system See **flow system**.

macropore Large opening in a rock or sediment, such as a fracture or root channel that can act as a pipe to conduct ground water.

Maumee Lacustrine Plain The former bottom of ancestral Lake Erie represented by the flat landscape of eastern Allen County and adjacent parts of Ohio.

megasequence Assemblage of sediments associated with one or more successive advances of a particular glacial lobe.

moraine Broadly arcuate to linear hummocky ridge deposited where an ice margin became stationary for a protracted period of time. **Recessional moraines** are formed where the ice margin stabilizes during a general retreat of the glacier, whereas **terminal moraines** mark the maximum extent of the ice margin.

mud flow Unsorted mixture of sediment that ranges from clay to boulders in size, and was deposited by the gravity flowage of unstable, oversaturated sediment. Common in the glacial environment. Because mudflows in glacial sequences frequently resemble glacial till, they are sometimes referred to as "**till-like sediment**."

outwash Sediment deposited by meltwater out in front of an ice margin. Usually composed of sand and(or) gravel.

outwash train Body of outwash sand and gravel in linear form that typically extends along a major river valley that drained one or more former ice margins.

overconsolidated Refers to a sediment that is denser or harder than would be expected based on its depth of burial by younger sediments. For example, glacial till is commonly overconsolidated because of the great weight of the ice that once was above it.

palimpsest Refers to a landscape in which most of the topographic features are not related to the materials at the land surface but are inherited from a buried surface at depth.

permeability The ability of geologic material to transmit water. In this report, the term is used in the same sense as "hydraulic conductivity."

pitted Refers to a landscape composed of outwash with numerous depressions caused by rafted blocks of ice that subsequently melted after being deposited with the outwash.

Pleistocene Geologic epoch corresponding to the most recent ice age, and beginning about 2 million years ago.

plume Mass of liquid or gas moving through a different medium. Most commonly refers to a mass of contaminants or contaminated ground water migrating through the subsurface geologic environment.

potentiometric surface The surface defined by contouring the elevations of water levels tapping a confined aquifer system. This surface represents a map of hydraulic head in the aquifer system and defines the general direction of horizontal ground-water flow.

recessional margin Location where an ice front stood for a significant period of time during the general retreat of the glacier and which is commonly marked by ridges or other accumulations of sediment deposited at the ice margin.

recessional moraine See **moraine**.

recharge area Region where a significant percentage of precipitation and(or) surface water reaches the zone of saturation via infiltration; commonly characterized by some combination of high potentiometric surface elevation, downward hydraulic gradients, and(or) permeable surface sediments.

recharge potential Comparative term that refers to the likelihood or ease with which ground water is likely to be recharged in a particular geologic or geographic region, relative to other regions having different conditions.

saturated zone All of the subsurface below the water table, and characterized by having all of the pore spaces filled with ground water.

secondary permeability Permeability caused by postdepositional modification of a rock or sediment, such as fracturing or the development of solution features.

sensitivity The intrinsic or natural susceptibility of ground water to contamination caused by the combination of geological and hydrogeological conditions particular to a certain location or region.

shale Sedimentary rock composed chiefly of clay and silt.

significant water withdrawal facility Defined by the state of Indiana as any activity or facility that withdraws more than 70 gallons per minute of ground water or surface water.

Silurian Period of geologic time from about 440 to 410 million years ago.

sluiceway Valley or channel that conducted large amounts of glacial meltwater that may or may not be occupied by a modern stream; commonly associated with one or more ice margins.

solution feature Any type of secondary opening in limestone or dolomite caused by the dissolution of the rock in ground water. Caves, enlarged joints, and sinkholes are among the more common forms.

source area Refers to the general geographic region from which a particular glacier flowed and derived certain distinctive rock types. For example, the Saginaw Lobe flowed over central and eastern Michigan, and its deposits contain coal and other rocks diagnostic of that area, whereas the Erie Lobe flowed into Indiana from the east and deposited rock types from Ohio and eastern Ontario.

spring Any place where ground water discharges onto the land surface due to the intersection of the water table with the ground.

Spy Run-Covington sag Major topographic lineament in the northwest part of Fort Wayne that marks a former meltwater channel of complex origin.

stratigraphy The arrangement of geologic materials, and the depositional environments they represent, in both time and space. The term **"lithostratigraphy"** refers to the physical arrangement, in three dimensions, of different geologic materials and formations.

texture The relative proportions of particles of different sizes in a sediment, such as pebbles, sand, silt, and clay.

till Unsorted sediment deposited directly from glacier ice with little or no reworking by meltwater or mass movement. Usually contains particles ranging in size from clay to boulders, and may be partially consolidated depending on the geologic history.

till-like sediment See mudflow.

Trafalgar Formation Assemblage of sediments representing the first known incursion of late Wisconsin ice into northeastern Indiana.

tunnel valley Hummocky to flat-bottomed, linear channel oriented perpendicular to an ice margin and eroded into the substrate below the ice sheet. A tunnel valley typically represents a major route for meltwater draining part of an ice sheet, and exiting the front of that ice sheet.

unconformity Large gap in the rock record, typically represented by a surface that bounds two rock or sediment bodies of vastly different ages.

unconsolidated Refers to sediment that is not generally cemented or otherwise bound together by some type of chemical cement (such as limestone) within the pore spaces or by intense compaction from deep burial.

underflow Ground-water flow that is generally below and parallel to the direction of surface water flow in a river valley.

unsaturated zone All of the subsurface above the water table where pores are filled in part by water and in part by air.

vertical sequence Assemblage of glacial deposits representing a particular depositional history and sequence of events.

Wabash-Erie Channel Very large flat-bottomed valley in southwest Allen County that was in part carved by catastrophic drainage of ancestral Lake Erie and is now abandoned as a major surface water route.

water table The interface between the saturated and unsaturated zones.

well Borehole drilled to produce water for consumption or to monitor water quality.

well casing Plastic or metal pipe used above the water-producing zone of a well to keep the well shaft open and to prevent entry of sediment or contaminants.

well screen Slotted pipe installed in the water-producing zone of a sand and gravel well to allow water to enter the well while keeping sediment out.

wellhead protection area Zone around a public water supply wellfield identified by geologic and hydraulic factors that is managed to prevent contamination of the water supply.

zone of saturation See saturated zone.

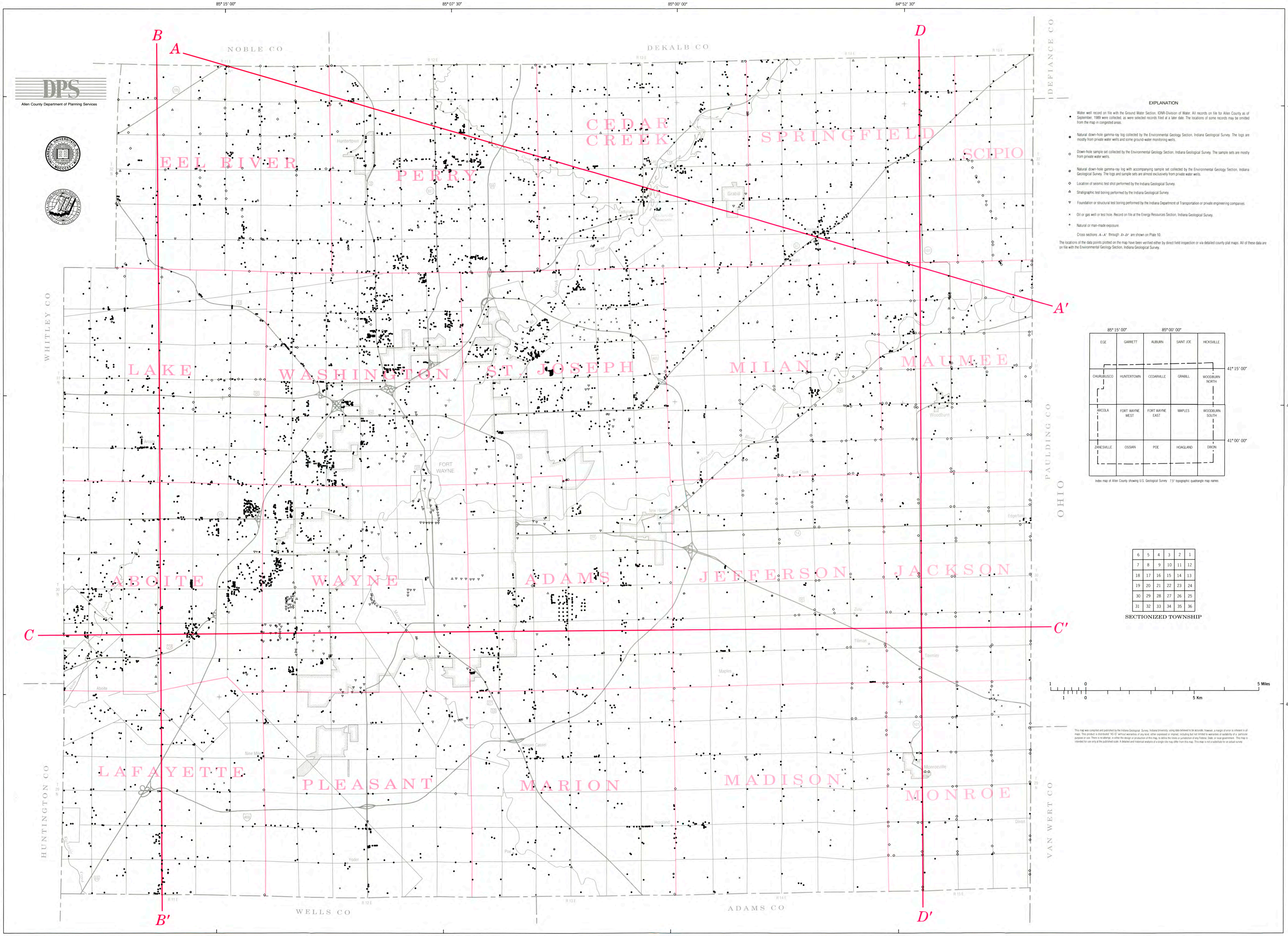
INDIANENSIS UNIVERSITATIS SIGILLUM
LUX ET VERITAS
MDCCCXX

INDIANA GEOLOGICAL SURVEY
INDIANA UNIVERSITY

DPS

OVERSIZED DOCUMENT

The following pages are oversized and need to be printed in correct format.

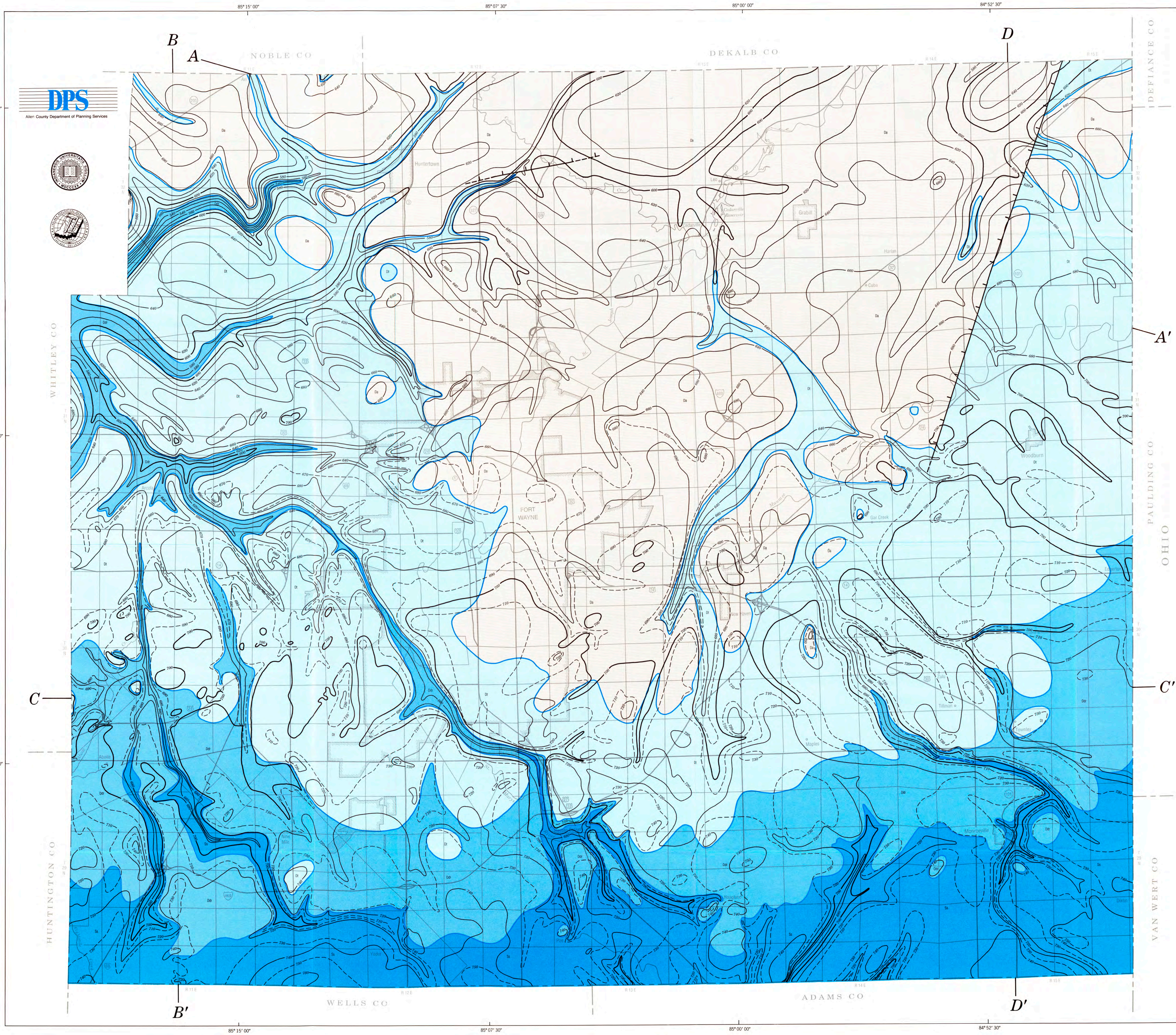


Base from latest U.S. Geological Survey topographic quadrangle maps, scale 1:24,000.

MAP OF ALLEN COUNTY, INDIANA SHOWING DISTRIBUTION OF DATA POINTS

By
Anthony H. Fleming
1994

Drafted by Rea Williams Kersey
Assisted by A. Scott Moonshower
Reprographics by Barbara T. Hill and John Michael Day



MAP DESCRIPTION

Allen County is situated in the basin and arches region of the Midwest and is located in a structural position intermediate between the Cincinnati Arch to the south, and the Michigan Basin to the north (inset 1). The bedrock is composed chiefly of limestone, dolomite, and shale that range in age from Silurian to Upper Devonian. A large flexure in the generally northward-dipping rocks is apparent in the map pattern of the Devonian rocks in the central part of the county. The dip of these rocks in the west central and northwestern part of the county is to the northeast at 10 to 20 feet per mile while the dip of the rocks in the east central and northeastern part of the county is to the northwest at 10 to 30 feet per mile (Doheny and others, 1975).

At least two normal faults can be inferred from several lines of evidence: 1) a steep structural gradient on the top of the Traverse Formation across the fault zones; in northeast Allen County the gradient is marked by an abrupt change in apparent strike and dip angle of the unit on opposite sides of the fault; 2) abrupt changes in the thickness and apparent vertical displacement of the base of the Antrim Shale by as much as 40 feet or more across the inferred fault zones (inset 2); 3) structure contours on the top of the oil- and gas-bearing Trenton limestone indicate a probable fault or flexure (Rupp, 1991) in northeast Allen County; and 4) a prominent aeromagnetic gradient (Henderson and Meuschke, 1950) coincides with the northeastern fault zone. The age of the most recent movement along these faults is unknown.

The bedrock is covered everywhere by unconsolidated Pleistocene sediments, which range from about 30 feet to more than 300 feet thick (Fleming and Rupp, 1994). The configuration of the buried bedrock surface essentially represents the pre-glacial landscape, although it has in places been extensively modified during Pleistocene glaciation. At least one regionally significant drainage divide was present on the pre-glacial landscape (inset 3), and separated the watershed of the Metea Bedrock Valley to the west from the drainage of the Butler Bedrock Valley to the northeast (Wayne, 1956; Gray, 1982). The part of the pre-glacial landscape developed on carbonate rocks generally formed a dissected, northward-sloping karst plateau. A gentle, north-facing slope separates the carbonate plateau region to the south from a broad lowland underlain mainly by Antrim Shale to the northeast. The shale lowland contains the heads of several bedrock valleys that drain northeastward into the large Butler Valley, located in Dekalb County.

References

Bleuer, N.K., 1991, The Lafayette Bedrock Valley System of Indiana; Concept, form and fill stratigraphy, *in* Melhorn, W.N., and Kempton, J.P., eds., Geology and hydrogeology of the Teays-Mahomet Bedrock Valley System: Boulder, Colorado, Geological Society of America Special Paper 258, p. 51-77.

Doheny, E.J., Droste, J.B., and Shaver, R.H., 1975, Stratigraphy of the Detroit River Formation (Middle Devonian) of Northern Indiana: Indiana Geological Survey Bulletin 53, 86 pp.

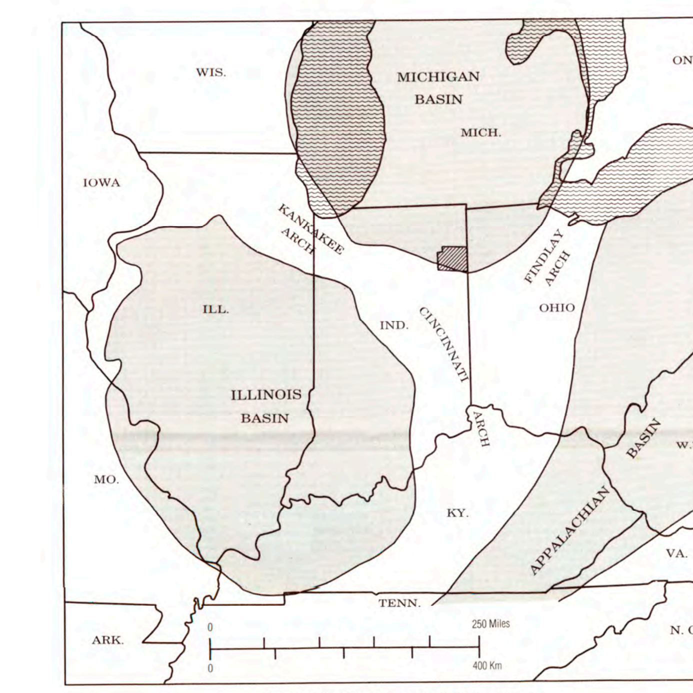
Fleming, A.H., and Rupp, R.F., 1994, Map of Allen County, Indiana showing thickness and general sequence characteristics of unconsolidated deposits: Indiana Geological Survey Miscellaneous Map 57.

Gray, H.H., 1982, Map of Indiana showing topography of the bedrock surface: Indiana Geological Survey Miscellaneous Map 35.

Henderson, J.R., and Meuschke, J.L., 1950, Aeromagentic survey of Allen County, Indiana: U.S. Geological Survey Geophysical Investigations Map GP-21.

Rupp, J.A., 1991, Structure and isopach maps of the Paleozoic rocks of Indiana: Indiana Geological Survey Special Report 48, 106 pp.

Wayne, W.J., 1956, Thickness of drift and bedrock physiography of Indiana north of the Wisconsin glacial boundary: Indiana Geological Survey Report of Progress 7, 70 pp.



Inset 1. Location of Allen County in relation to regional tectonic structure.

EXPLANATION

700 — Line of equal elevation on the bedrock surface. Contour interval: 20 feet.

710 - - Supplemental contour on the bedrock surface. Contour interval: 10 feet. Supplemental contours are employed on the southern and central parts of the map, where data are more numerous. May be omitted in congested areas.

Fault, approximately located. Hachures on downthrown side.

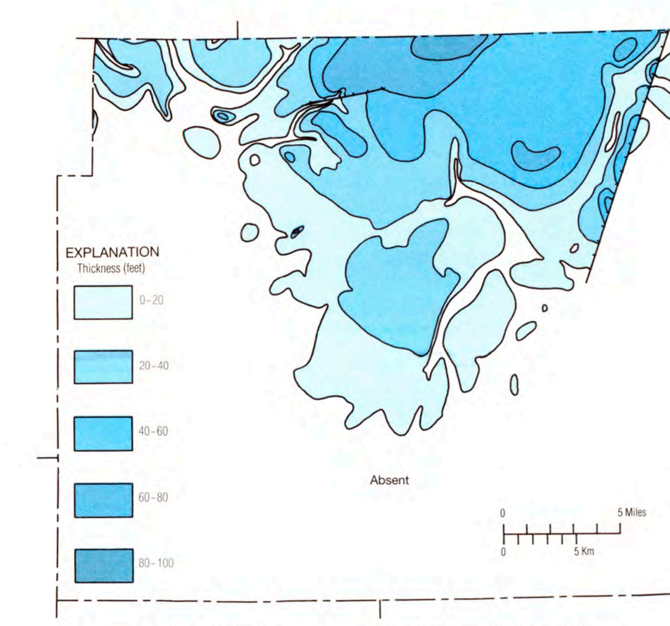
Contact between rock units, approximately located.

Da Antrim Shale (Upper Devonian). Chiefly dark-brown to black, organic-rich shale. At places, the lower 10 to 30 feet of the unit consists of medium- to dark-gray limestone interbedded with calcareous gray shale. Thickness: 0 to 90 feet.

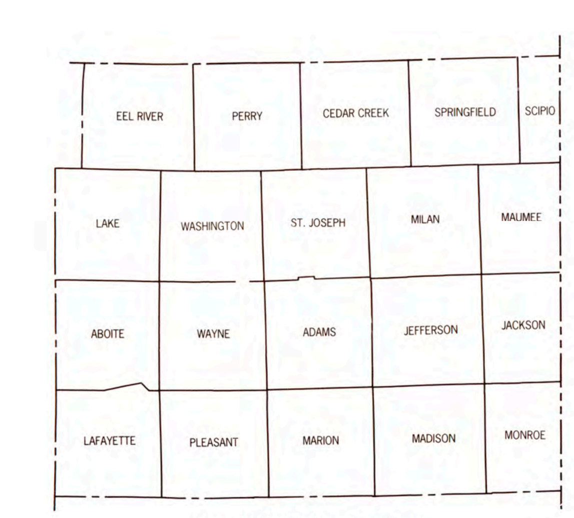
Dt Traverse Formation (Middle Devonian). Thinly bedded, light-gray to brown limestone and lesser dolomite, and much lesser shale. Thickness: 0 to 75 feet.

Ddr Detroit River Formation (Lower and Middle Devonian). Tan to brown dolomite and limestone. Nodules and thin beds of gypsum and anhydrite occur throughout the formation. Base of unit marked by greenish sandy shale. Thickness: 0 to 70 feet.

Ss Salina Group. (Silurian) Chiefly massive light-gray and tan reefal dolomite and lesser limestone and dolomitic siltstone. Contains widely scattered nodules of gypsum. Thickness: 400 to 600 feet.



Inset 2. Map of Allen County showing generalized thickness of the Antrim Shale (Da). Contour interval: 20 feet.

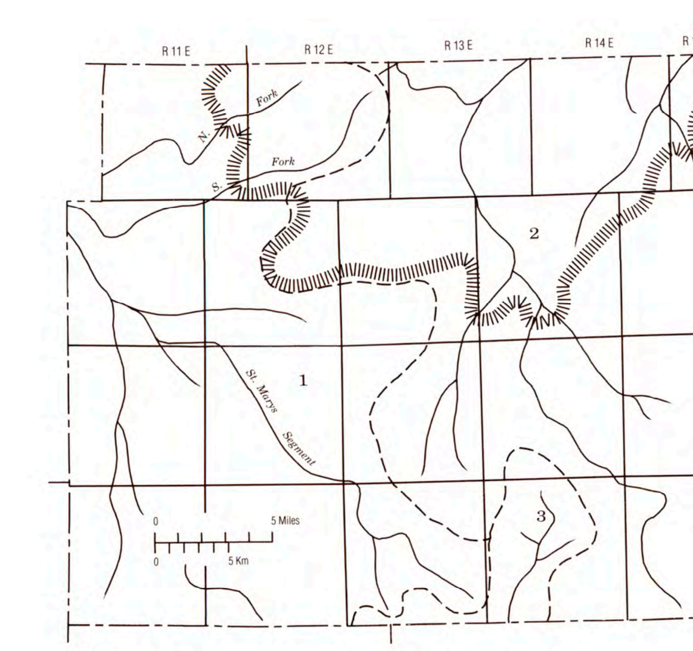


Index map of Allen County showing principal township names

6	5	4	3	2	1
7	8	9	10	11	12
18	17	16	15	14	13
19	20	21	22	23	24
30	29	28	27	26	25
31	32	33	34	35	36

SECTIONIZED TOWNSHIP

1 0 5 Miles
1 0 5 Km



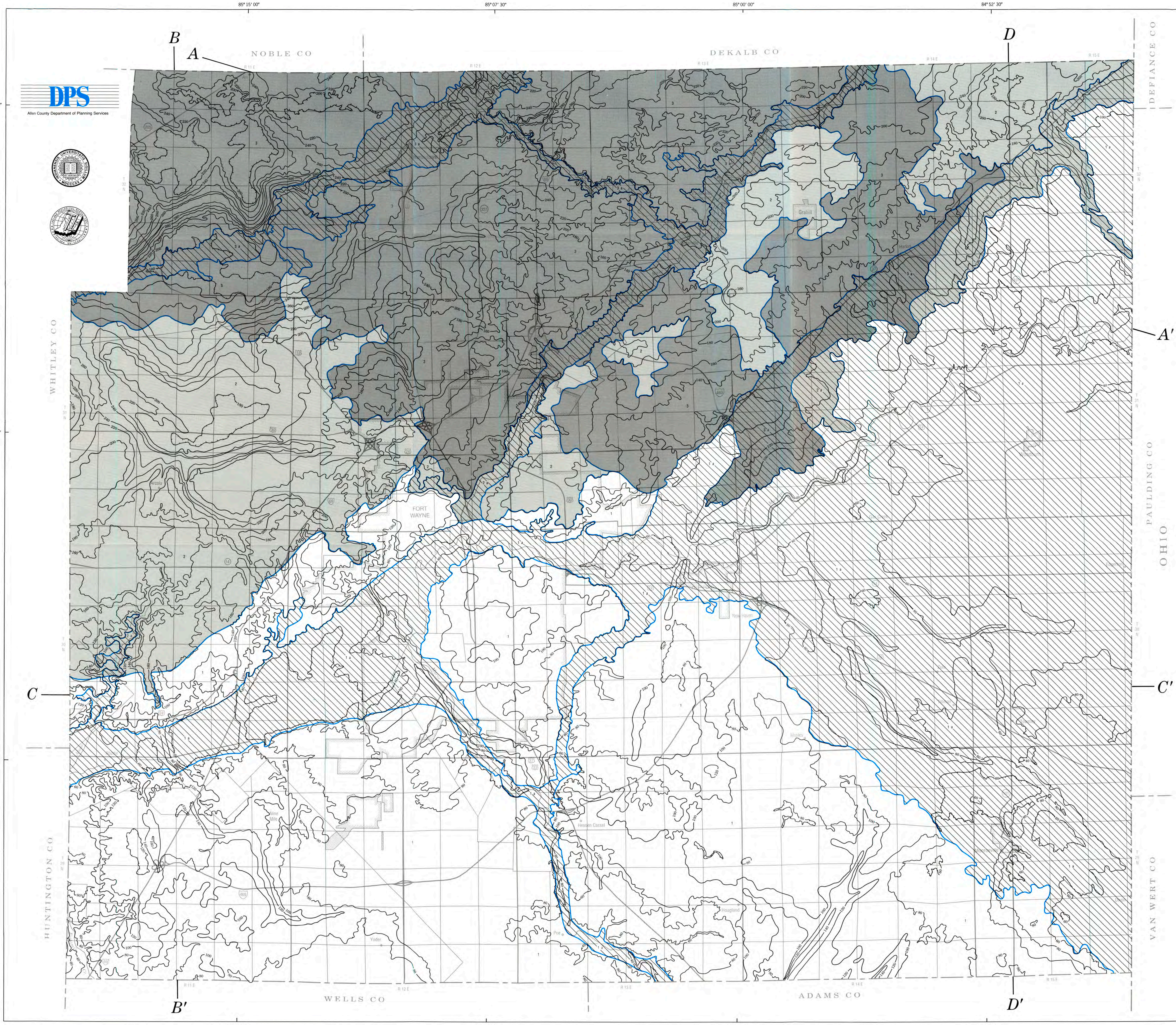
Inset 3.
Map of Allen County showing principal physiographic features and buried valley systems of the bedrock surface. Hachured line marks the approximate location of toe of slope separating lowland developed on shale in the northeast from karst plateau to the south and west. Dashed lines are approximate locations of pre-glacial drainage divides between. 1) the Metea Bedrock Valley (Wayne, 1956), 2) Butler Bedrock Valley (Wayne, 1956), and 3) Lafayette Bedrock Valley System (Bleuer, 1991).

Base from latest U.S. Geological Survey topographic quadrangle maps, scale 1:24,000.

Drafted by Rea Williams Kersey and Roger L. Purcell
Assisted by Kim Hankins Sowder, Kari Lancaster and A. Scott Moonshower
Reprographics by Barbara T. Hill and John Michael Day

MAP OF ALLEN COUNTY, INDIANA SHOWING THE TOPOGRAPHY AND GEOLOGY OF THE BEDROCK SURFACE

By
Robin Frank Rupp, William J. Steen, and Anthony H. Fleming
1994



MAP DESCRIPTION

Unconsolidated deposits of Pleistocene Age underlie all of Allen County and range from about 30 feet to more than 300 feet thick. Differences in thickness are attributable to as much as 200 feet of relief on the bedrock surface as well as to regional variation in the dynamics and amount of glacial deposition. Allen County experienced repeated glacial advances from both the north and east throughout the Ice Age, and deposits ranging in age from late Wisconsin to perhaps as old as pre-Illinoian are present. However, the bulk of the glacial deposits are associated with three glacial episodes of late Wisconsin age (inset 1). The thickest deposits are in northern Allen County, where late Wisconsin sediments deposited by both northern source (Saginaw Lobe) and eastern source (Huron-Erie Lobe, Erie Lobe) ice overlie locally thick sections of pre-Wisconsin age. Deposits are considerably thinner in southern and eastern Allen County, and are almost entirely eastern source sediments deposited during the late Wisconsin Age. In addition to sediments deposited in direct association with glacial ice, a variety of post-glacial deposits are also present, as are extensive bodies of glaciolacustrine sediments associated with several phases of ancestral Lake Erie.

EXPLANATION

120 / 100 — Isopach showing thickness of unconsolidated deposits. Contour interval: 20 feet. Some contours may be omitted in congested areas. Hachures indicate thinning.

Approximate boundary between principal stratigraphic sequences.

Principal Stratigraphic Sequences

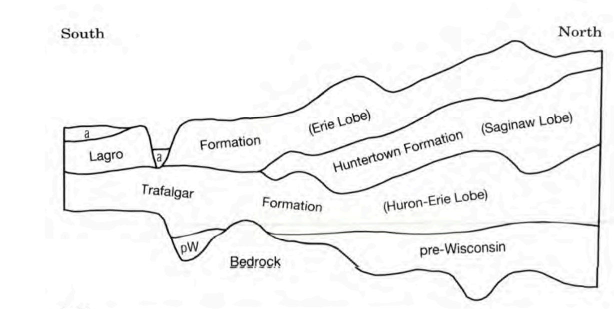
1 — Clayey till of the Lagro Formation over loamy till of the Trafalgar Formation. Widely scattered sand and gravel units are present at the base of both till units and within the Trafalgar Formation. Older sediments of probable pre-Wisconsin age are locally present within buried bedrock valleys (see Plate 2).

2 — Clayey till of the Lagro Formation over loamy till of the Trafalgar Formation over loamy to clayey tills of probable pre-Wisconsin age. Widely scattered sand and gravel bodies occur between the tills and within the Trafalgar and older units.

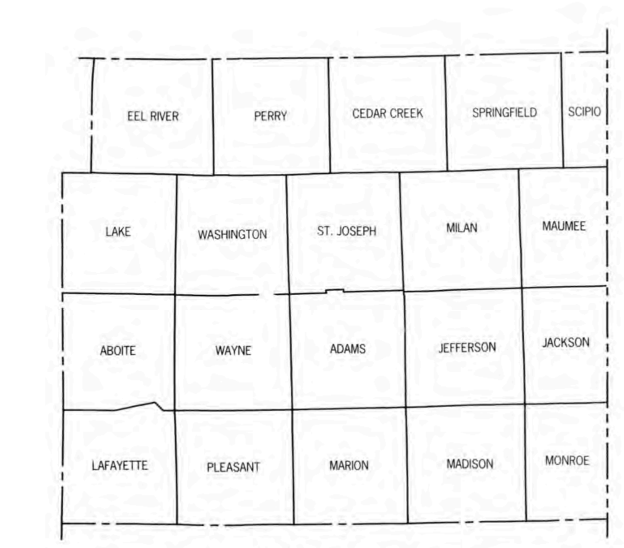
3 — Clayey till of the Lagro Formation over sand, gravel, and sandy till of the Huntertown Formation over loamy till of the Trafalgar Formation over loamy to clayey tills of probable pre-Wisconsin age. Widely scattered sand and gravel bodies occur within and between the Trafalgar and older units.

Modified Sequences

a — Late glacial or post-glacial sediments of fluvial, lacustrine, palustrine, and/or glaciofluvial origin form the upper part of the stratigraphic sequence. At some places, these sediments simply cap the principal stratigraphic sequence that is present in adjacent areas. In some of these areas, however, the Lagro Formation is thin or absent, particularly in former meltwater channels, where the latest sediments may be inset into the upper part of the Huntertown Formation (northern Allen County) or the Trafalgar Formation (southern Allen County). The distribution and thickness of the Lagro Formation, and its relationship to glacial terrains, are shown in detail on Plate 5.



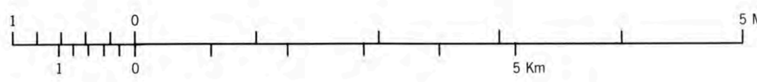
Inset 1.
Generalized lithostratigraphic diagram showing relationships between depositional sequences associated with late Wisconsin and older glacial episodes.



Index map of Allen County showing political township names

6	5	4	3	2	1
7	8	9	10	11	12
18	17	16	15	14	13
19	20	21	22	23	24
30	29	28	27	26	25
31	32	33	34	35	36

SECTIONIZED TOWNSHIP

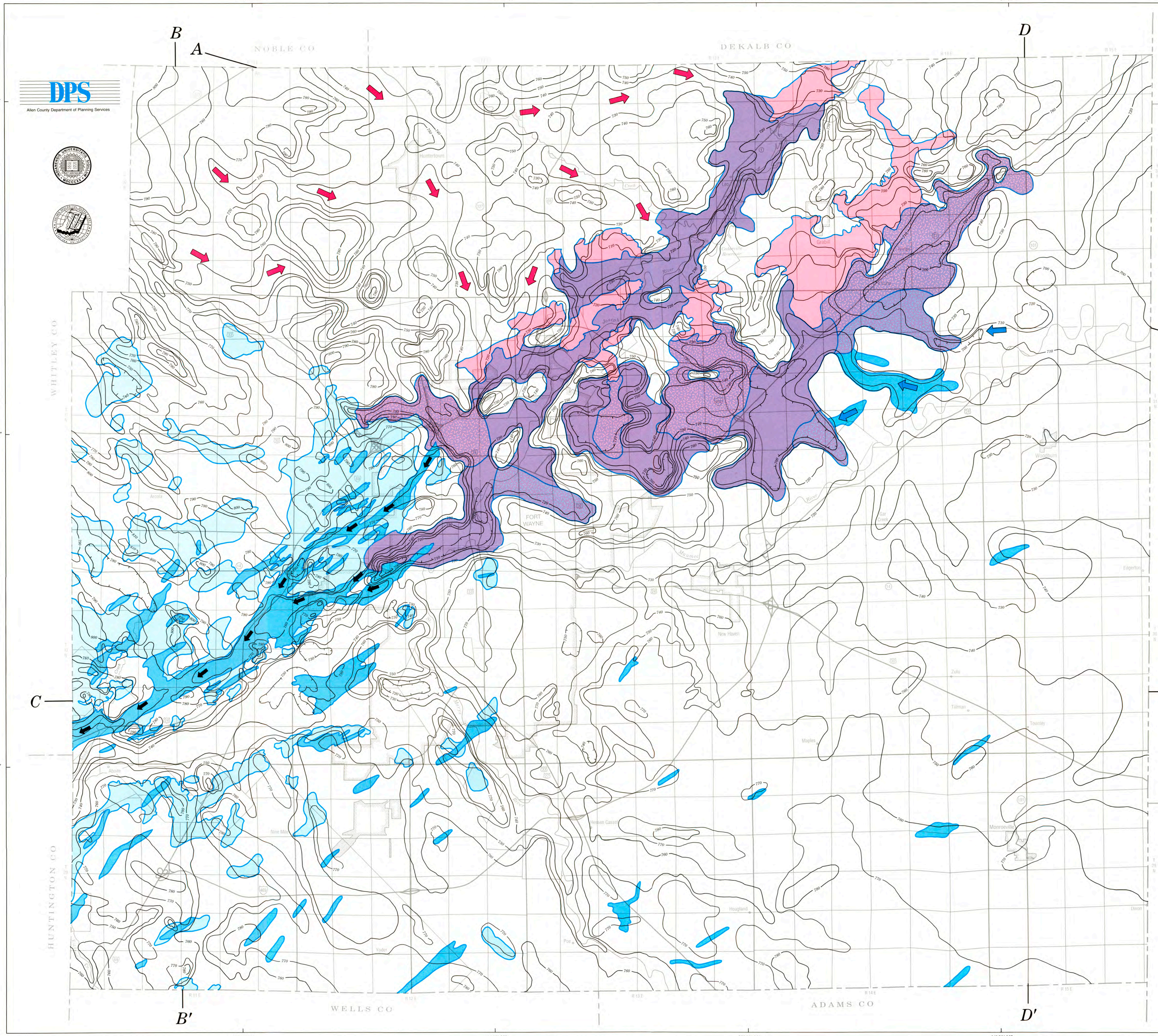


Base from latest U.S. Geological Survey topographic quadrangle maps, scale 1:24,000.

MAP OF ALLEN COUNTY, INDIANA SHOWING THICKNESS AND GENERAL SEQUENCE CHARACTERISTICS OF UNCONSOLIDATED DEPOSITS

By
Anthony H. Fleming and Robin Frank Rupp
1994

Drafted by Rea Williams Kersey and Roger L. Purcell
Assisted by Kim Hankins Sowder, Kari Lancaster and A. Scott Moonshower
Reprographics by Barbara T. Hill and John Michael Day



MAP DESCRIPTION

The Trafalgar Formation consists of severely overconsolidated loam-textured till, debris flows, and locally abundant sand and gravel bodies that were deposited during several advances of the Huron-Erie Lobe during the first part of the late Wisconsin glaciation. The apparent age of the base of the formation in Allen County is about 21,500 ybp (Indiana Geological Survey, unpublished data). The till is extremely difficult to excavate without blasting, consequently the depth of the buried surface below the modern land surface (inset 1) is a significant geotechnical consideration.

A prominent feature of the buried Trafalgar surface is an arcuate complex of irregular ridges and hills that surrounds the east-central portion of the county and attains elevations in excess of 810 feet in western Allen County. In and near the western part of this complex, the Trafalgar Formation contains abundant sand and gravel, which mainly forms two types of bodies: 1) fan-like aprons draped over a hummocky till surface, and 2) linear, southwest-trending channels that locally cut completely through the enclosing till and are commonly between 50 and 100 feet thick. The largest of these channels is nearly 15 miles long and several thousand feet wide. This complex is interpreted to be a partially eroded system of buried end moraines, with many of the channels representing tunnel valleys or other meltwater conduits that drained the margin of the Huron-Erie Lobe (inset 2a).

The surface of the Trafalgar Formation greatly influenced the character and distribution of the deposits of subsequent advances of the Saginaw and Erie Lobes that now bury it. In particular, the morainal complex blocked meltwater drainage and impounded a large lake basin that became the Fort Wayne phase of ancestral Lake Erie (inset 2b). The basin initially received meltwater and sediment from the retreating Huron-Erie Lobe, but meltwater and deltaic sediments derived from the advancing Saginaw Lobe became increasingly important through time (inset 2c). The locations of sluiceways that conducted Saginaw Lobe meltwater into the basin are readily evident as valleys and broad, low-lying plains on the Trafalgar surface. The Saginaw Lobe eventually reached the northern margin of the basin where it deposited a series of fans and deltas as well as finer-grained sediments in more distal parts of the basin. The Fort Wayne phase ultimately covered much of eastern Allen County and northwestern Ohio, and a veneer of lacustrine silt and clay is regionally widespread along the top of the Trafalgar surface. These sediments were probably considerably thicker prior to the advance of the Erie Lobe following the Erie Interstade, but much of the lake mud was incorporated into the Erie Lobe to form the fine-grained till of the Lagro Formation. As the basin became compressed by the rapidly advancing Erie Lobe (inset 2d), drainage of the Fort Wayne phase may have taken place catastrophically through the large meltwater channel that trends across the apex of the morainal complex, and which appears to lead away from the western edge of the basin in two places.

EXPLANATION

710 / 700 — Line of equal elevation on the Trafalgar surface. Contour interval: 10 feet.

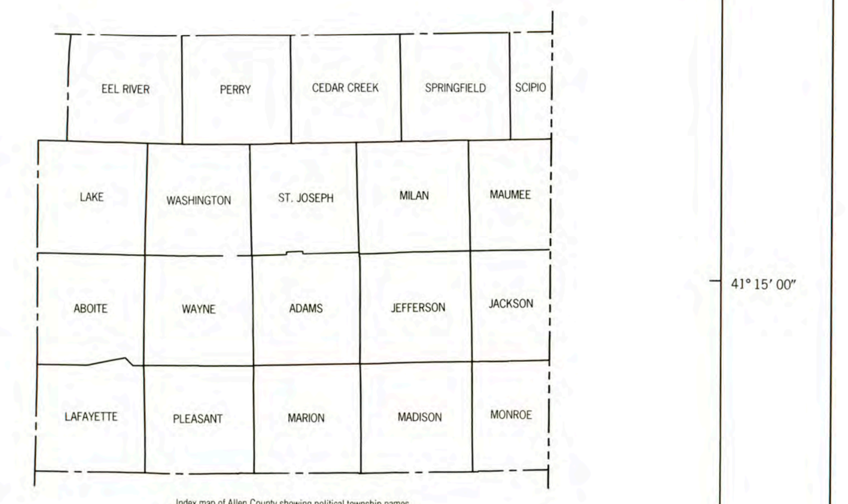
Contact of sand and/or gravel units, approximately located; approximate boundary of lacustrine basins.

Composition of the Trafalgar surface

- Mostly loam till and till-like sediment that contains small lenses of silt and sand. Thickness: 10 to 100 or more feet.
- Mostly sand and gravel in outwash fans and aprons up to 30 feet thick, deposited over loam till. Some of these bodies contain sand and gravel deposited during a later advance of the Erie Lobe (intersequence unit).
- Mostly coarse sand and lesser gravel between 30 and 100 feet thick that formed in meltwater channels. Locally capped by up to 10 feet of loam till and till-like sediment of the Huron-Erie Lobe and/or by sand and gravel deposited atop the Trafalgar surface during a later advance of the Erie Lobe.

Glaciolacustrine and Glaciofluvial Features Formed on Top of the Trafalgar Surface

- Parts of the lake basin that commonly contain well-preserved sequences of fine- to medium-grained lacustrine sediments of undifferentiated Huron-Erie, Saginaw, and Erie Lobe sources deposited during the Fort Wayne phase of ancestral Lake Erie. Chiefly subequal laminated silt and fine sand that locally contain rainout debris and a variety of till-like sediments. A thin, discontinuous veneer of similar sediments (not shown) is present on the Trafalgar surface throughout eastern Allen County. Thickness: 10 to 70 feet.
- Major sluiceways for Saginaw Lobe meltwater. Many of these valleys are now filled with as much as 60 feet of Saginaw Lobe outwash, and several lead into the heads of deltas and fans to the southeast.
- Deltaic and fan deposits mostly associated with the Saginaw Lobe and its meltwater. Stippled pattern: chiefly fine sand deposited in sub-aqueous deltas. Solid pattern: chiefly fine to coarse sand and lesser gravel deposited in sub-aerial and sub-aqueous fan-deltas. Thickness: 10 to 50 feet.
- Bodies of fine to medium sand derived chiefly from the Huron-Erie Lobe and deposited in small sub-aqueous deltas. Adjacent arrows, where present, indicate probable meltwater conduits leading away from the receding Huron-Erie ice front. Thickness: 10 to 60 feet.
- System of large channels that probably formed the principal outlet of the Fort Wayne phase of ancestral Lake Erie.

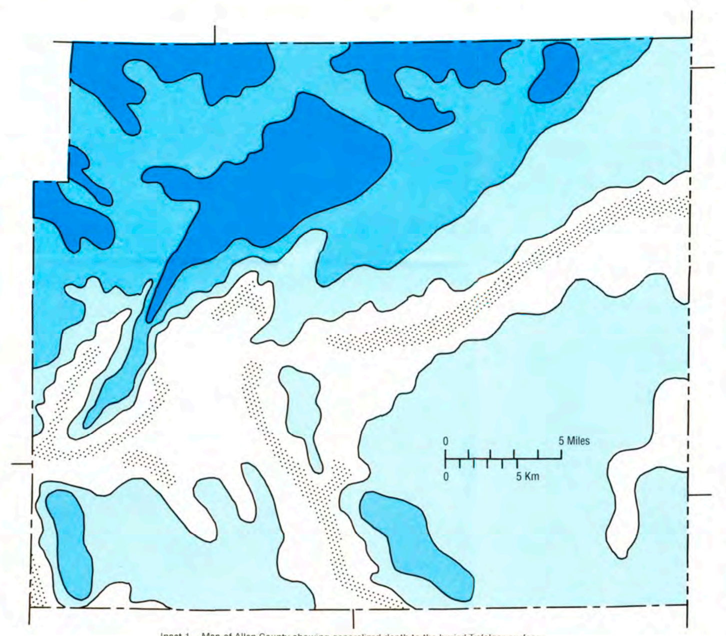


Index map of Allen County showing political township names

6	5	4	3	2	1
7	8	9	10	11	12
18	17	16	15	14	13
19	20	21	22	23	24
30	29	28	27	26	25
31	32	33	34	35	36

SECTIONIZED TOWNSHIP

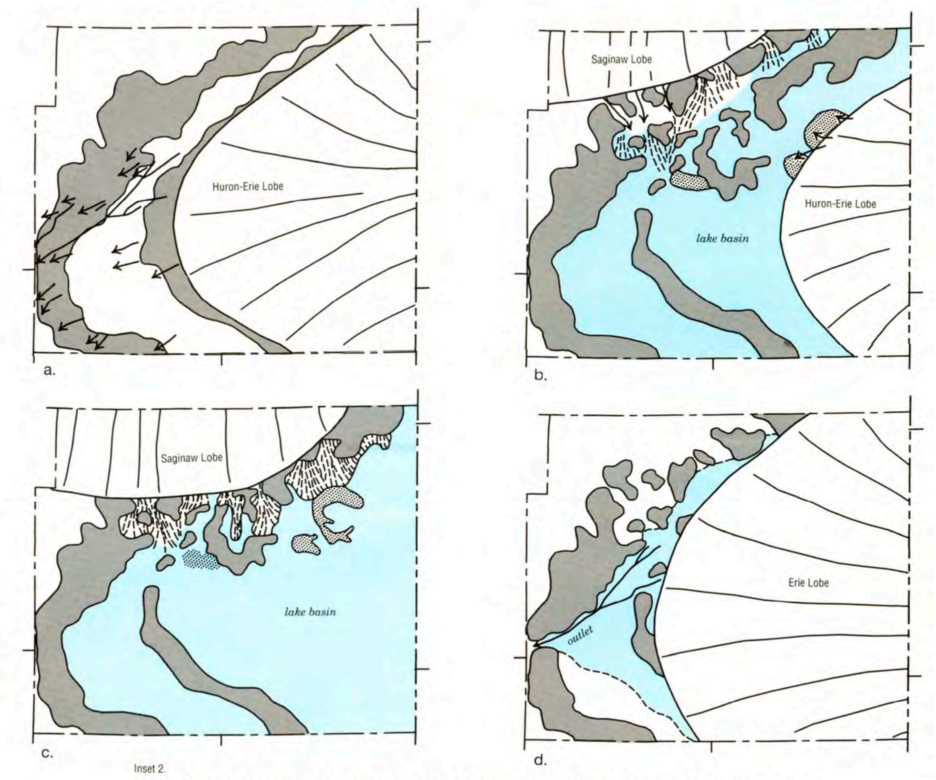
1 0 5 Miles
1 0 5 Km



EXPLANATION
Depth (feet)

- Area where the Trafalgar surface is commonly at or within a few feet of the land surface.
- 0-25
- 25-50
- 50-100
- >100

Inset 1. Map of Allen County showing generalized depth to the buried Trafalgar surface.



Inset 2.

Evolution of lake basin and depositional history of the Fort Wayne phase of ancestral Lake Erie: a) formation of morainal complex (shaded) and meltwater channels (arrows) by Huron-Erie Lobe; b) meltwater from retreating Huron-Erie Lobe dammed by morainal complex. Sand bodies of eastern source (stippled) deposited along ice margin, while advancing Saginaw Lobe contributes meltwater (arrows) and sediment (dashed lines) to the northern part of the basin; c) lake basin reaches its greatest extent. Saginaw Lobe reaches terminal position in and along northern edge of basin and deposits fan-deltas (line pattern); d) advance of Erie Lobe compresses area of lake basin while increasing meltwater input. Morainal dam is breached along former Huron-Erie Lobe meltwater channel, causing the lake to drain catastrophically.

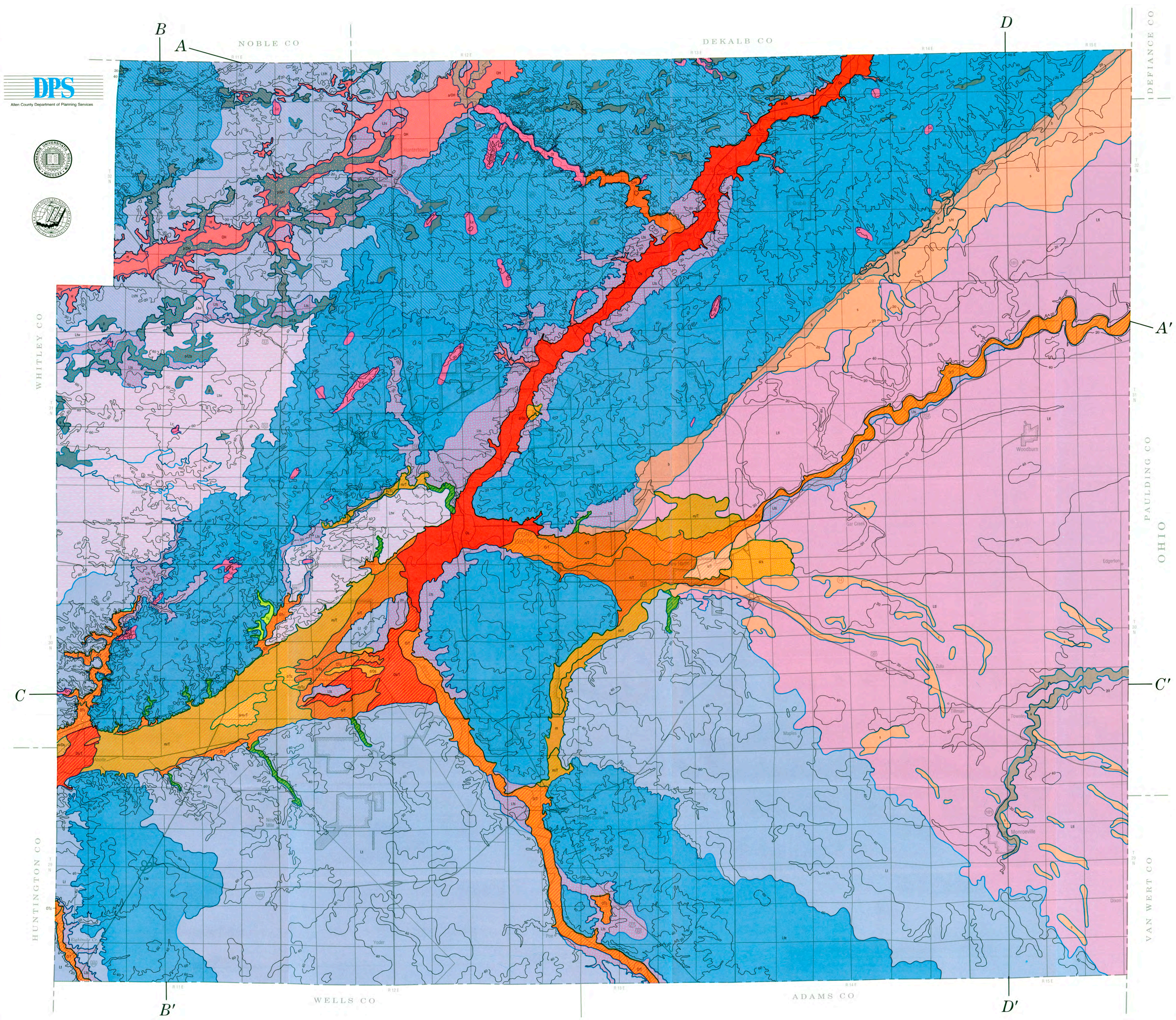
Base from latest U.S. Geological Survey topographic quadrangle maps, scale 1:24,000.

MAP OF ALLEN COUNTY, INDIANA SHOWING THE ELEVATION AND GEOLOGY OF THE BURIED SURFACE OF THE TRAFALGAR FORMATION AND ASSOCIATED FEATURES

By
Anthony H. Fleming

1994

Drafted by Rea Williams Kersey and Kim Hankins Sowder
Assisted by Roger L. Purcell, Kari Lancaster and A. Scott Moonshower
Reprographics by Barbara T. Hill and John Michael Day



MAP DESCRIPTION

Glacial terrains are composed of two elements: 1) sequences of glacial and post-glacial sediments that reflect a particular series of depositional events; and 2) landscape elements associated with the sequences. Major glacial terrain regions and related features are shown on inset 1, whereas Plate 5 shows the distribution and material characteristics of the depositional sequences. Plate 5 emphasizes relatively near-surface depositional sequences associated with the Lagro Formation, the surface till of northeastern Indiana produced by the most recent of three late Wisconsin glacial episodes. Where this unit is absent, other types of sequences and materials are depicted, some of which normally underlie the Lagro Formation elsewhere. The effective depth of Plate 5 ranges from as little as 20 feet to more than 100 feet depending on the specific sequences that are present. In some locations, the entire mapped sequence consists of tills and related sediments of the Lagro Formation, but sequences in many other places commonly contain one or more types of sediments above, below, or instead of the Lagro. Sequences composed of two or more mappable units are indicated by labels in which each stratigraphic unit is separated from the one below by a slash. For example, the unit d/m/T is composed of sand dunes (d) atop fluvial sand and silt (m), which in turn rests on till of the Trafalgar Formation (T).

EXPLANATION

Post-Glacial Sediments

a | a/OH

Alluvium in modern river and stream valleys. Composition ranges from sand and gravel to silt and clay, and reflects texture of surrounding and underlying materials as well as stream processes. Present in most modern streams, but not mapped separately where less than 5 feet thick. a, overlies the Lagro Formation; a/OH, overlies outwash of mixed source in the Eel River Valley.

p | p/Lts | p/Os | p/OH | p/H

Muck and peat in depressions and abandoned sluiceways. Thickness ranges from a few inches to about 35 feet. p, overlies clayey till of the Lagro Formation; p/Lts, overlies washed surface on outwash and till of the Lagro Formation; p/Os, overlies Erie Lobe outwash; p/OH, overlies mixed outwash in the Eel River Valley; p/H, overlies the Huntertown Formation.

d | d/s | d/Os | d/Tc | d/m/T

Sand dunes. Mainly fine sand up to 30 feet thick. Commonly associated with outwash deposits and other sources of windblown sand. d, overlies the Lagro Formation; d/s, overlies lacustrine sand; d/Os, overlies Erie Lobe outwash; d/Tc, overlies channel deposits in the Trafalgar Formation; d/m, overlies slackwater deposits.

n/T | n/Tc

Slackwater deposits composed of sand, silty sand, and lesser silt up to 30 feet thick deposited in the Wabash-Erie Channel following the drainage of ancestral Lake Erie. Commonly mucky near the top. Overlies stripped surface on loam till (n/T) or channel deposits (n/Tc) of the Trafalgar Formation.

m | m/Os | m/T | m/Tc

Slackwater deposits composed of silt, sandy silt, and lesser sand up to 35 feet thick deposited in the Wabash-Erie Channel and Six Mile Creek Channel following the drainage of ancestral Lake Erie, and in the Spy Run-Covington sag. Commonly mucky near the top. m, overlies the Lagro Formation; m/Os, overlies Erie Lobe outwash; most commonly overlies stripped surface on loam till (m/T) or channel deposits (m/Tc) of the Trafalgar Formation.

s | s/H | s/T

Fine to medium sand deposited in spits, bars, and small beach ridges in and near shorelines of ancestral Lake Erie. The unit is typically less than 10 feet thick and overlies wave-stripped surfaces on: s, the Lagro Formation; s/H, glaciolacustrine sediments of the Huntertown Formation; s/T, loam till of the Trafalgar Formation.

b | b/H

Sand, gravel, and lesser mud up to 30 or more feet thick associated with the northern shoreline of ancestral Lake Erie. Typically forms a prominent set of beach ridges. b, overlies the Lagro Formation; b/H, overlies glaciolacustrine sediments of the Huntertown Formation.

Outwash Associations (chiefly Erie Lobe)

O/T | O/H

Predominantly thin discontinuous bodies of Erie Lobe outwash sand and gravel in stream valleys, terraces, and abandoned high-level meltwater channels. The outwash is commonly less than 20 feet thick and is capped by or laterally contiguous with Recent alluvium of varied composition. O/T, overlies stripped surface on loam till of the Trafalgar Formation; O/H, overlies undifferentiated sediments of the Huntertown Formation along Cedar Creek.

OTc

Similar to unit O above, but the Erie Lobe outwash overlies older sand and gravel that forms thick channel deposits in the underlying Trafalgar Formation. Total sand and gravel thickness ranges from 30 to 100 feet.

Os/T | Os

Erie Lobe outwash sand and gravel in fans and valley trains. Typically 20 to 60 or more feet thick and locally capped by medium- to coarse-grained alluvium. Os/T, overlies stripped surface on loam till of the Trafalgar Formation; Os, substrate unknown or highly variable, includes older sand and gravel units, till, and glaciolacustrine sediments of the Trafalgar and Huntertown Formations, and bedrock in a few places.

Ot

Erie Lobe sand and gravel deposited in the Cedar Creek tunnel valley. Thickness ranges from less than 10 feet to more than 100 feet where coalesced with older sand and gravel of the underlying Huntertown Formation. Commonly capped by thin, fine- to medium-grained alluvium.

OH

Erie Lobe outwash deposited in the Eel River valley atop ice-contact fans, channel deposits, and other sand and gravel bodies of the Huntertown Formation. Discontinuous lenses of Saginaw Lobe till are present at depth. Total sand and gravel thickness ranges from 30 to more than 100 feet.

Lagro Formation (Erie Lobe)

40
20

The Lagro Formation is composed chiefly of light-gray, stiff to hard, silty-clay to clay-loam till and till-like sediment with lesser lenses of sheared lacustrine silt and clay and much lesser small bodies of sand. The till is well jointed in the upper 20 feet and is commonly very foliated. Contours show thickness of till and till-like sediments, and include overlying *lacustrine silt and clay in the Arcola plain and Maumee Lacustrine Plain. Contour interval: 20* feet. Some contours may be omitted in congested areas. Hachures indicate thinning.

Le | Lc

Ice-contact stratified sand and gravel. Le: eskers exposed at land surface; Lc: other channel-like bodies enclosed in till.

Lt

Till and till-like sediment in flat to gently rolling till plains.

Lte

Till and till-like sediments in end moraines. Commonly very hard at depth. Contains localized bodies of dense silt and fine sand.

Lagro Formation (Erie Lobe), continued

Lts | Ltw | c

Lts, till and till-like sediments, commonly capped by outwash that ranges from a thin veneer or gravel lag on uplands to as much as 30 feet thick in large terraces and meltwater channels. Typically underlies smooth or locally streamlined landscapes that have been pervasively washed by meltwater. Ltw, till and locally abundant lacustrine silt and clay underlying extremely flat, well-washed landscape of the Arcola plain and the rolling, streamlined landscape south of the Spy Run- Covington sag. Small terraces and veneer of outwash are present in places. c, complex of large, deeply scoured meltwater channels now filled with thick lake mud overlying till and flanked by extensive outwash terraces.

Lt/H

Interlobate landscape with till and till-like sediments of clay-loam to loam texture draped over strongly hummocky Saginaw Lobe topography. Small bodies of ice-contact stratified sediments present in some places.

Lte/H

Interlobate landscape with till and till-like sediments of clay-loam texture in end moraines superposed upon strongly hummocky Saginaw Lobe topography. Contains localized bodies of dense silt and sand.

Ltl

Wave-scoured till and till-like sediments in the Maumee Lacustrine Plain. Locally capped by lacustrine silt and clay up to 15 feet thick.

Huntertown Formation (Saginaw Lobe)

H

Undifferentiated sand, gravel, sandy loam to loam till and till-like sediments in the northwest, with increasingly abundant glaciolacustrine silt and sand to the south and east. Constitutes the principal subsurface unit in northern Allen County, widely exposed at the surface in the interlobate landscape near the Eel River Valley.

Trafalgar Formation (Huron-Erie Lobe)

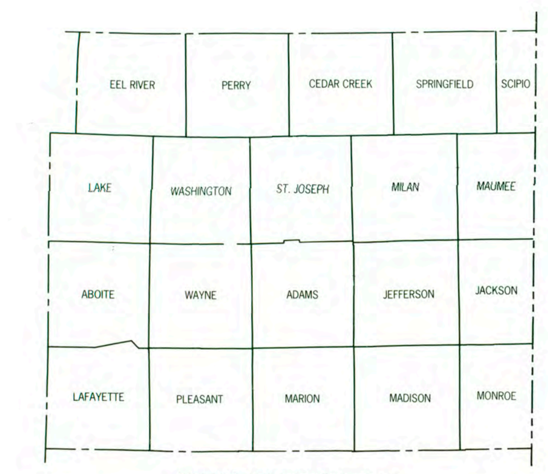
Tc

Sand and gravel in narrow, linear channels 30 to 100 feet thick. These bodies are mostly restricted to the subsurface but are locally exhumed along major Erie Lobe meltwater channels in southern Allen County.

T

Chiefly light grayish-brown, severely overconsolidated loam till and lesser sand. Occurs in the subsurface throughout Allen County, locally exhumed along major meltwater channels and larger valleys in the southern and central parts of the county.

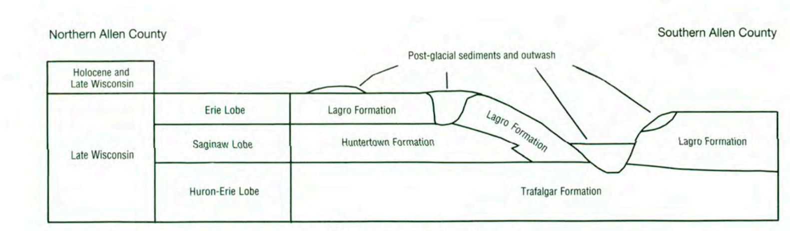
Sequence boundary, approximately located



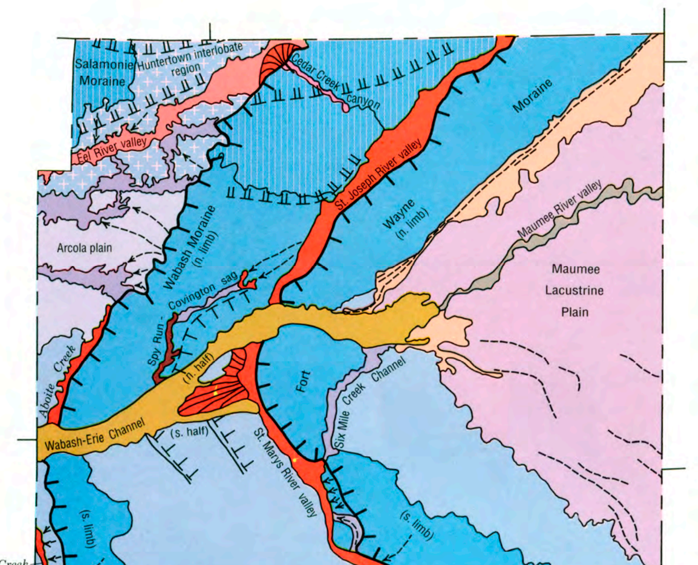
Index map of Allen County showing political township names

6	5	4	3	2	1
7	8	9	10	11	12
18	17	16	15	14	13
19	20	21	22	23	24
30	29	28	27	26	25
31	32	33	34	35	36

SECTIONIZED TOWNSHIP



Inset 2. Stratigraphic relationships of map units



Inset 1. Map showing major glacial terrain regions of Allen County

EXPLANATION

Interlobate Features

- Significant buried Saginaw Lobe ice-marginal position
- Complex interlobate meltwater channel
- Interlobate hummocky topography

Ancestral Lake Erie

- Lake plain formed in deep water
- Swash zone; line pattern - beach ridges
- Outlet
- Post-glacial river valley cut along subglacial meltwater channel

0 5 Miles
0 5 Km

Erie Lobe Features

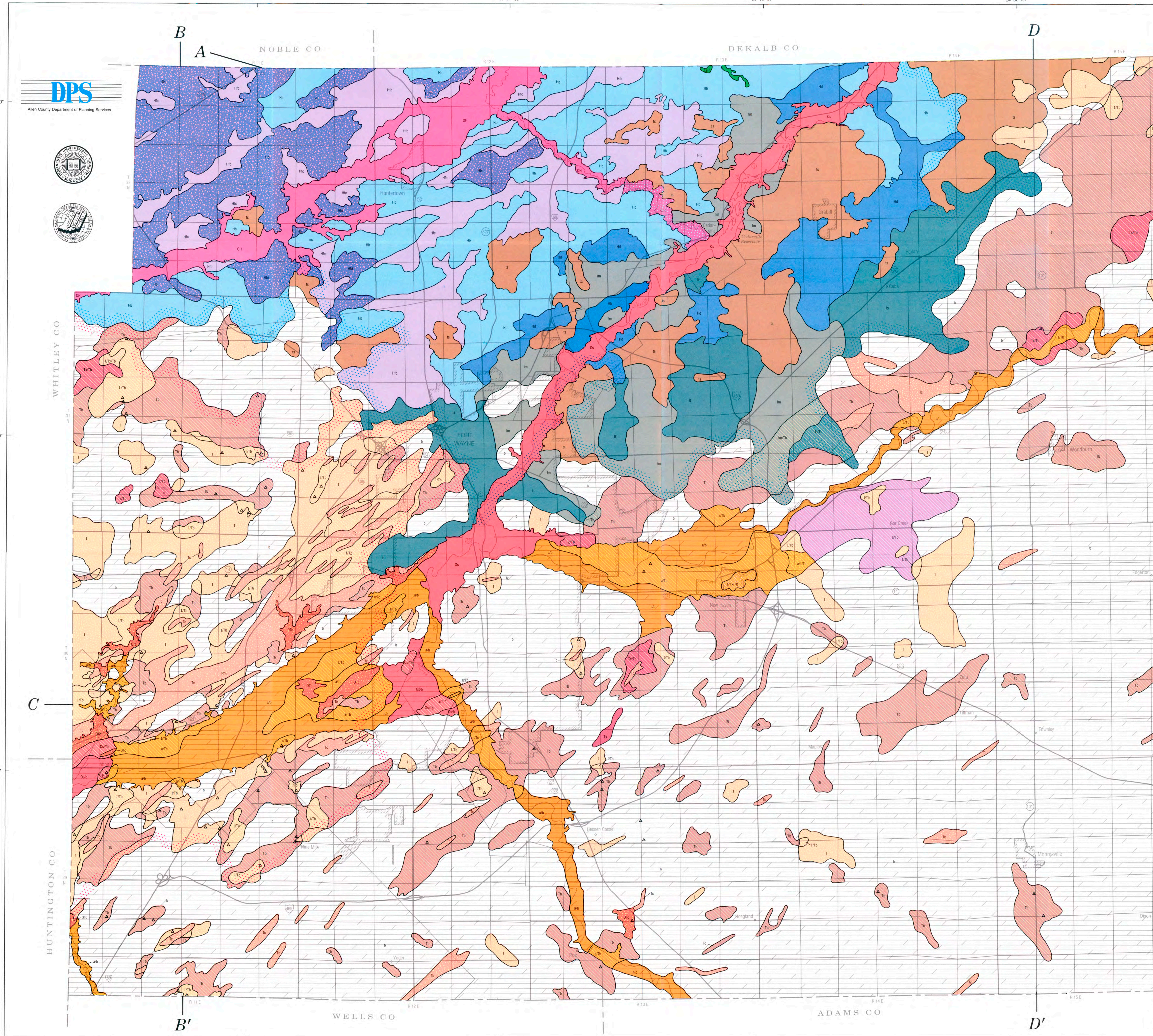
- End moraine; line pattern - topography partly inherited from buried Saginaw Lobe hummocky topography
- Rolling to flat till plain
- Meltwater channel occupied by modern stream
- Abandoned high-level meltwater channel
- Flat till/lacustrine plain washed by meltwater torrents
- Outwash fan
- Tunnel valley
- Meltwater flow direction
- Small ice-marginal channel
- Major ice-marginal position
- Local ice-marginal position

Base from latest U.S. Geological Survey topographic quadrangle maps, scale 1:24,000

MAP OF ALLEN COUNTY, INDIANA SHOWING NEAR-SURFACE GLACIAL SEQUENCES

By
Anthony H. Fleming
1994

Drafted by Rea Williams Kersey and Roger L. Purcell
Assisted by Kim Hankins Sowder, Kari Lancaster and A. Scott Moonshower
Reprographics by Barbara T. Hill and John Michael Day



MAP DESCRIPTION

This map shows the principal aquifers of Allen County according to their stratigraphic position (inset 1). Additional details concerning the stratigraphic sequences can be found in *The Hydrogeologic Framework of Allen County, Indiana* (Fleming, 1994) and on plates 2, 4, and 5. Principal aquifers are defined as bodies of sand and gravel or limestone bedrock that serve as important sources of ground-water supplies, or that are sufficiently thick and permeable to transmit large quantities of ground water and to afford potential pathways for contaminant migration. A slash is used in several places to indicate the presence of two or more superjacent aquifers separated by a till confining unit.

EXPLANATION

Unconfined Surficial Aquifers

a — Undifferentiated surficial sediments that typically contain at least some sand and/or gravel units and are locally saturated. Includes outwash sand and gravel, dune sand, beach sand, lacustrine sand, and alluvium of varied composition. Thickness: 5 to 30 feet. The surficial sediments generally comprise minor aquifers and are mapped along with principal underlying confined aquifer(s).

Os — Outwash deposited by the Erie Lobe in sluiceways and fans. Sand and gravel. Thickness: 10 to 60 feet.

OH — Coalesced Erie Lobe outwash and large ice-contact stratified units of the Huntertown aquifer system. Upper part is sand and gravel, lower part chiefly sand and lesser gravel. Thickness: 30 to 100 feet.

O/H — Erie Lobe outwash over undivided till and granular units of the Huntertown aquifer system. Chiefly sand. Thickness: 20 to 80 feet.

OTc — Coalesced Erie Lobe outwash and thick granular units in channelized form within the Trafalgar Formation. Upper part is sand and gravel. Lower part ranges from sand to cobble gravel. Thickness: 40 to 100 feet.

LeH — Coalesced Erie Lobe ice-contact stratified deposits and granular units of the Huntertown aquifer system. Chiefly sand. Thickness: 30 to 80 feet.

Huntertown Aquifer System

The Huntertown aquifer system is composed of sand and gravel bodies deposited by the Saginaw Lobe and its meltwater, and a laterally equivalent complex of glaciolacustrine sediments to the southeast that were deposited in the basin of ancestral Lake Erie. In most places, the aquifer system is confined by clayey sediments of the Lagro Formation. The aquifer system is divided into two geographically and hydrogeologically distinct parts by the St. Joseph River valley (inset 2). The western part is dominated by bodies of outwash sand and ice-contact fans that are generally thick and relatively continuous over large areas. The individual aquifers are separated by leaky, localized confining units, but at many places they are coalesced on a large scale to form a hydraulically well-interconnected system. In contrast, the eastern part is characterized by a mix of outwash and lacustrine deposits that have less continuity and are generally thinner than aquifers in the western part of the system. Aquifers are draped over a rolling to irregular surface on the underlying Trafalgar Formation, resulting in numerous discontinuities and variable aquifer thicknesses.

Generalized aquifer system boundary.

Hfc — Chiefly ice-contact fans and associated channel deposits localized along buried Saginaw Lobe margins. Commonly coalesced with basal outwash sand (unit Hb, below). Chiefly sand and lesser gravel. Thickness: 40 to 80 feet.

Hbi — Small- to medium-sized ice-contact stratified deposits enclosed in sandy till overlying basal outwash sand (unit Hb, below) Chiefly sand and lesser gravel. Thickness of ice-contact deposits: 5 to 30 feet.

Hb — Outwash aprons and channels capped by sandy till that contains widely scattered ice-contact stratified deposits. Unit forms bottom of aquifer system in most places and locally grades into lacustrine sand (unit ls) in the eastern part of the aquifer system. Chiefly sand, commonly gravelly at base. Thickness: 5 to 40 feet.

Hd — Chiefly fan-deltas and associated channel deposits localized along the northern edge of ancestral Lake Erie (Fort Wayne phase). Locally grades into lacustrine deposits (units ls and Im) to the southeast. Chiefly sand and some gravel. Thickness: 10 to 30 feet.

ls — Deltaic bodies deposited in the northern part of the basin of ancestral Lake Erie (Fort Wayne phase). Chiefly fine sand and sparse sand and gravel. Upper part of unit includes minor amounts of laminated silt, clay, and fine sand. Thickness: 5 to 50 feet.

Im — Mixed deltaic and slackwater sediments deposited in the northern part of the basin of ancestral Lake Erie (Fort Wayne phase). Chiefly laminated silt, clay, and fine sand with scattered larger bodies of fine sand. Thickness of sand bodies: 5 to 20 feet.

Aboite Aquifer System and Trafalgar Formation

The Aboite aquifer system is a complex of small to very large sand and gravel bodies that occur at several horizons between the base of the Lagro Formation and the bedrock surface in western Allen County. Most of the bodies are within the Trafalgar Formation, and are hydraulically well interconnected with each other and, at many places, with the bedrock. The aquifer system can be subdivided into two parts (inset 2), based on characteristics of the sand and gravel bodies and their relationship to the underlying limestone bedrock. The northern part is characterized by very thick unconsolidated deposits (125 to 300 feet). Sand and gravel aquifers are present over about half of the area and, although locally interconnected with each other by thick channel deposits, they are generally separated from the bedrock aquifer system by till confining units. In the southern part of the system, unconsolidated deposits are generally somewhat thinner (50 to 125 feet). Sand and gravel aquifers are present over most of the area and are commonly interconnected with each other and the limestone bedrock. All of the individual sand and gravel bodies that collectively constitute the Aboite aquifer system in western Allen County also occur as isolated aquifers elsewhere in the southern and central parts of the county, where they are mapped as part of the Trafalgar Formation or intersequence unit.

Generalized aquifer system boundary.

I — Intersequence unit. Aprons, blankets, and associated channel sediments deposited chiefly as outwash along the contact between the Trafalgar and Lagro Formations. Mostly sand and gravel in western Allen County. Mostly sand in east. Thickness: 5 to 40 feet.

Tx — Sheetlike bodies deposited as outwash blankets and small channel deposits within the upper 10 to 25 feet of the Trafalgar Formation. Chiefly sand and gravel. Thickness: 5 to 20 feet.

Tc — Deep, relatively narrow to very wide, wedge- or channel-like bodies that commonly extend from the intersequence horizon or upper part of the Trafalgar Formation to the bedrock surface. Most bodies appear to have been deposited in high-energy meltwater channels or tunnel valleys. Chiefly sand and lesser gravel, locally with cobbles and boulders. Thickness: 30 to 100 feet. Symbol (Δ) indicates isolated data point or points showing thick channel-like features, trend unknown.

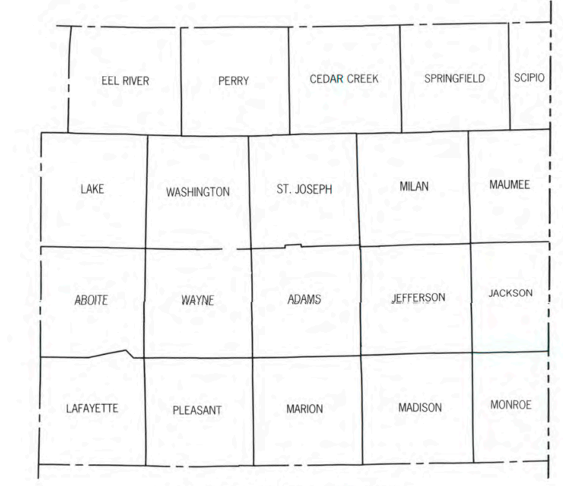
Tb — Outwash aprons and channel deposits at the base of the Trafalgar Formation. Commonly deposited directly on bedrock in southern Allen County, and on older till units to the north. Chiefly sand and gravel. Thickness: 5 to 30 feet.

ts — Undifferentiated sand and gravel in the Trafalgar Formation and older units. Shown only in the northern part of the county, in places where shallower aquifers are absent. Stratigraphic control is usually poor in these areas. The sand and gravel forms moderate to large tabular bodies and channel deposits within and below thick till sequences. Thickness: 10 to 40 or more feet.

Bedrock Aquifer System

Bedrock aquifers are present below the glacial deposits throughout Allen County but are shown only where unconsolidated aquifers are absent or of limited productivity (e.g., unit a, above). Although the bedrock virtually everywhere will yield small to moderate amounts of ground water, the most productive bedrock aquifers consist of karsted limestone and dolomite. The bedrock aquifers are confined by as much as 90 feet of Antrim Shale in the northern part of the county, which may limit recharge and contribute to objectionable levels of sulfur and other minerals.

b — Limestone and dolomite with sparse to numerous fractures and solution features. Includes widespread bouldery sand and gravel deposited directly on the bedrock surface. Sand and gravel aquifers at other horizons appear to be sparse or absent where this unit is mapped.



Index map of Allen County showing political township names

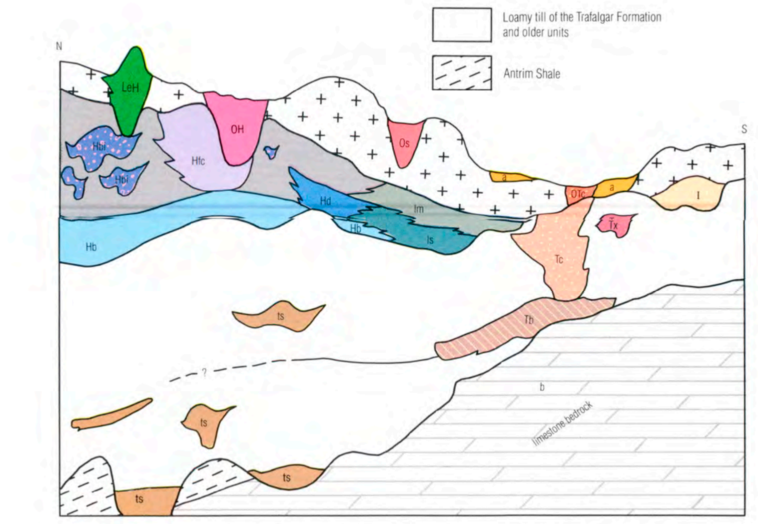
6	5	4	3	2	1
7	8	9	10	11	12
18	17	16	15	14	13
19	20	21	22	23	24
30	29	28	27	26	25
31	32	33	34	35	36

SECTIONIZED TOWNSHIP

1 0 5 Miles
1 0 5 Km

EXPLANATION OF CONFINING UNITS

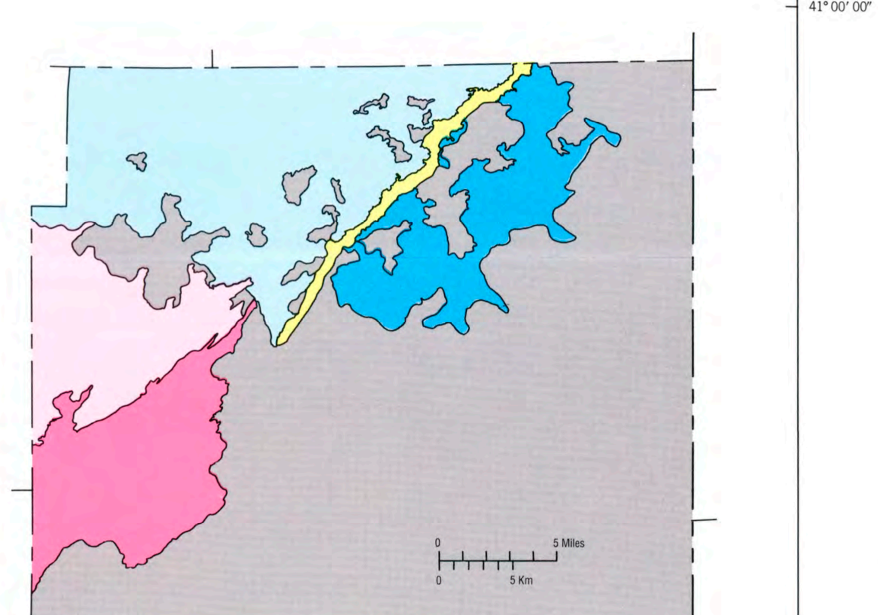
- Clayey till of the Lagro Formation
- Sandy till of the Huntertown Formation
- Loamy till of the Trafalgar Formation and older units
- Antrim Shale



Inset 1. Schematic diagram showing stratigraphic relationships of the aquifer units shown on this plate and major confining units

EXPLANATION

- Huntertown aquifer system, western part
- Huntertown aquifer system, eastern part
- St. Joseph River valley, regional discharge area for the Huntertown aquifer system
- Aboite aquifer system, northern part
- Aboite aquifer system, southern part
- Bedrock aquifer system, includes deep sand and gravel aquifers in northern Allen County



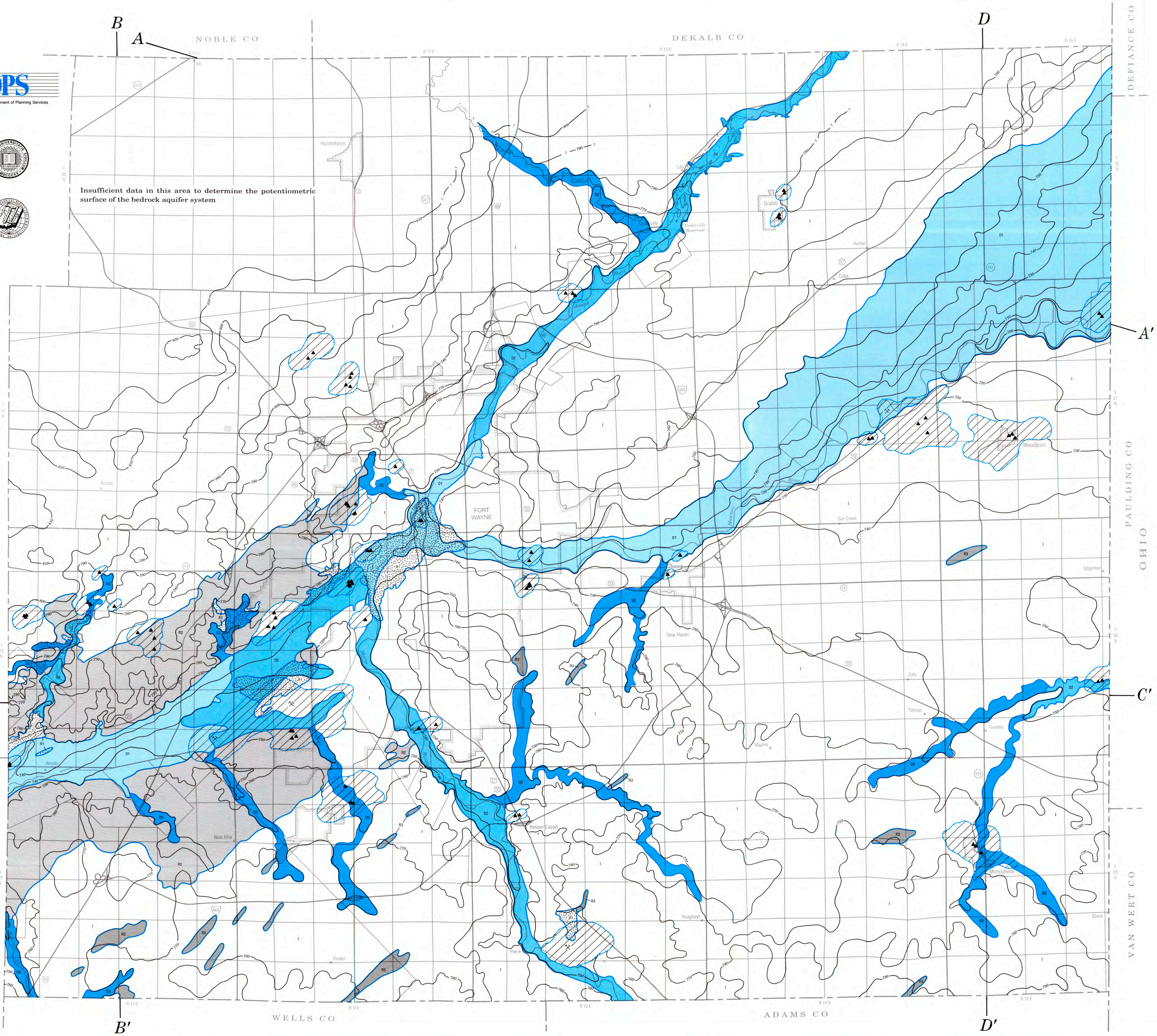
Inset 2. Map of Allen County showing generalized geographic distribution of aquifer systems

Base from latest U.S. Geological Survey topographic quadrangle maps, scale 1:24,000.

MAP OF ALLEN COUNTY, INDIANA SHOWING AQUIFER DISTRIBUTION AND CHARACTERISTICS

By
Anthony H. Fleming
1994

Drafted by Rea Williams Kersey and Kim Hankins Sowder
Assisted by Kari Lancaster, Roger L. Purcell and A. Scott Moonshower
Reprographics by Barbara T. Hill and John Michael Day



MAP DESCRIPTION

The bedrock aquifer system includes fractured and karsted limestone and dolomite of Silurian and Devonian age, as well as sand and gravel units that lie directly on the bedrock surface and are in hydraulic contact with bedrock aquifers. These aquifers are widely used as a source of domestic, municipal, irrigation, and industrial water and are present at depth throughout the county. They are generally well-confined by between 40 feet and more than 250 feet of fine-grained unconsolidated sediments. Approximately 3,500 data points (mainly water-well records) were used to construct the potentiometric contours. Nearly all of the data are concentrated in the southern three-quarters of the county, consequently it was not possible to map the potentiometric surface in the far north. Recharge-discharge relations are based on the configuration of the potentiometric surface, its relationship to surface-water elevations, and the distribution and characteristics of unconsolidated materials that overlie and confine the bedrock aquifer system.

EXPLANATION

Boundary between areas having different recharge-discharge relationships.

750 / 740 — Potentiometric contour showing line of equal water-level elevation for wells developed in the bedrock aquifer system and sand and gravel units on the bedrock surface. Contour interval: 10 feet.

D1 — Regional discharge area characterized by moderate or strong upward hydraulic gradients, water levels at or near the land surface, and large potentiometric valleys. Flowing artesian wells locally occur north of the Maumee River. Ground water from the bedrock aquifer system in these areas generally discharges to surface water, near-surface unconsolidated aquifers, or both.

D2 — Regional discharge area characterized by neutral or weak upward hydraulic gradients, water levels at or near the land surface, and large potentiometric valleys. Flowing wells are not known from these areas and ground water from the bedrock generally discharges into shallow unconsolidated aquifers.

D3 — Local discharge area characterized by neutral or very weak upward hydraulic gradients, water levels below the land surface, and small potentiometric valleys. Some ground water from the bedrock may discharge into shallow unconsolidated aquifers but ground-water flow is predominantly down the potentiometric valleys toward regional discharge areas.

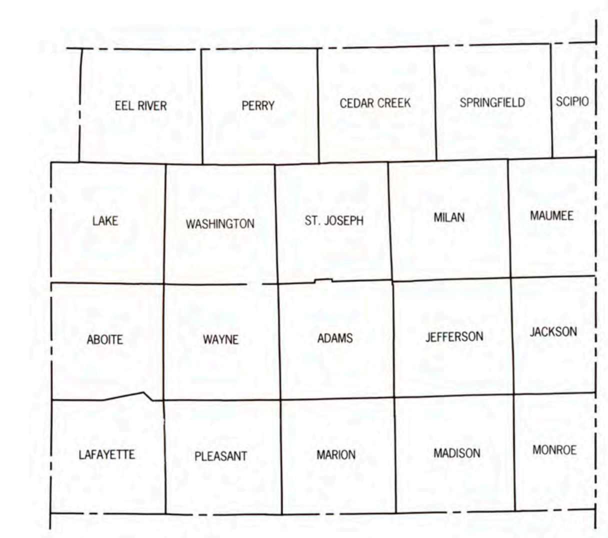
R1 — Local recharge area characterized by thick, unconfined sand and gravel directly overlying the bedrock surface. Most of these areas are in low positions in the landscape in or near regional discharge areas , hence the amount of recharge received by the bedrock is uncertain. However, high infiltration rates are likely to characterize the overlying sand and gravel, and the absence of confining units above the bedrock suggests that some recharge could occur, especially where this sequence occurs in uplands adjacent to the regional discharge areas.

R2 — Local recharge area characterized by thick sections of sand and gravel that hydraulically connect the bedrock with shallow confined sand and gravel aquifers of relatively large extent. These areas occur in uplands where downward gradients are likely to predominate, hence the bedrock may receive considerable recharge from the overlying sand and gravel, especially during pumping.

R3 — Localized area characterized by thick sections of well-confined sand and gravel atop the bedrock. These areas occur in uplands where downward gradients are likely to predominate. The sand and gravel deposits are not known to be interconnected with more extensive shallow sand and gravel aquifers. Although the sand and gravel might provide some additional recharge to the bedrock, the main effect may be to release ground water from storage when the underlying bedrock aquifer system is pumped.

I — Intermediate area characterized by thick sections of glacial till and other fine-grained confining units above the bedrock. Although downward gradients are likely to predominate, only a minimal amount of recharge is likely to reach the bedrock in these settings, primarily by slow, diffuse leakage through the confining units.

Approximate zone of influence of high-capacity well(s) (▲) or quarry (⚒) developed in bedrock or in sand and gravel units along the bedrock surface. Extent and depth of cone of depression are uncertain and may vary seasonally and/or with changes in pumping rate or schedule.



Index map of Allen County showing political township names

6	5	4	3	2	1
7	8	9	10	11	12
18	17	16	15	14	13
19	20	21	22	23	24
30	29	28	27	26	25
31	32	33	34	35	36

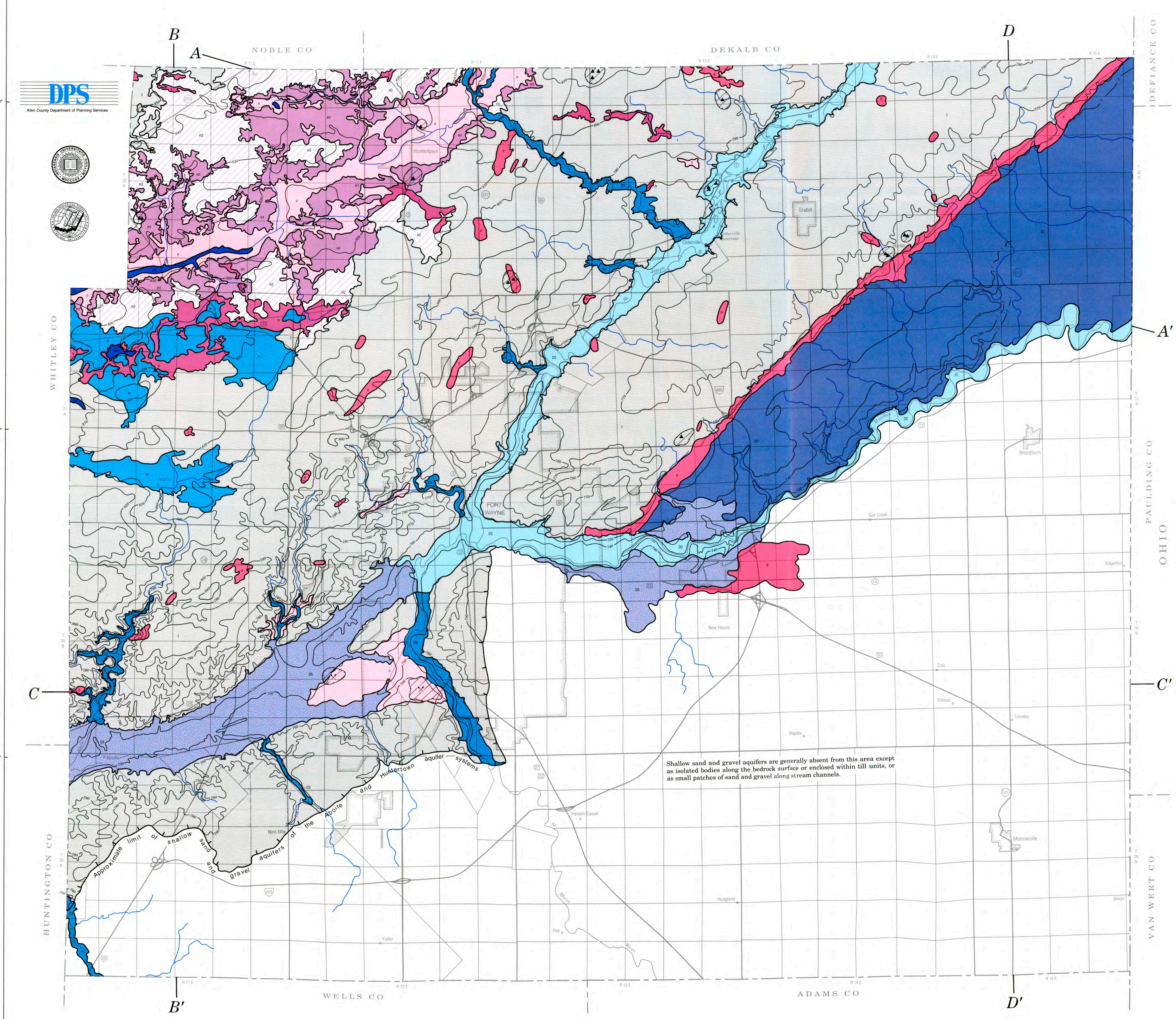
SECTIONIZED TOWNSHIP

Base from latest U.S. Geological Survey topographic quadrangle maps, scale 1:24,000.

MAP OF ALLEN COUNTY, INDIANA SHOWING THE POTENTIOMETRIC SURFACE AND RECHARGE-DISCHARGE RELATIONS OF THE BEDROCK AQUIFER SYSTEM

By
Anthony H. Fleming
1994

Drafted by Rea Williams Kersey and Roger L. Purcell
Assisted by Kim Hankins Sowder, Kari Lancaster and A. Scott Moonshower
Reprographics by Barbara T. Hill and John Michael Day



MAP DESCRIPTION

Shallow sand and gravel aquifers occur as isolated bodies and as part of the Huntertown aquifer system of northern Allen County and the Aboite aquifer system of western Allen County (for distribution of shallow aquifers, see Plate 6). These aquifers are the predominant source of domestic, municipal, and industrial ground water in northern Allen County. They range from completely unconfined to being confined by as much as 100 feet of glacial till, with the principal confining unit being clayey till of the Lagro Formation. The shallow aquifers are generally characterized by flow systems that are distinct from those in deeply buried sand and gravel aquifers and in bedrock, and which commonly exhibit a close relationship to the configuration of the land surface and to surface water bodies.

Approximately 3,000 data points (mainly water well records) were used to construct potentiometric and water table contours, and were supplemented by topographic maps and other data that indicate the configuration and elevation of the land surface and surface water bodies. The great majority of sand and gravel aquifers are concentrated in the northern and western parts of the county, consequently there is no distinct shallow aquifer system or associated potentiometric surface in the southeastern part of the county. Recharge-discharge relations are inferred from the configuration of the potentiometric surface, its relationship to surface water elevations, *and* the distribution and characteristics of fine-grained unconsolidated materials that overlie and confine the sand and gravel aquifers.

EXPLANATION

Location of stream gauging station referred to in report.

790
800

Contour showing potentiometric surface elevation in confined sand and gravel aquifers and water table elevation in unconfined aquifers. Contour interval: 10 feet.

Boundary between regions having different recharge-discharge relationships.

D1

Regional discharge area characterized by strong upward hydraulic gradients, water levels at or above the land surface, and a potentiometric surface that slopes strongly toward the Maumee River. Flowing artesian wells occur in some places. Map unit forms a broad area in the Maumee Lacustrine Plain north of the Maumee River. Shallow aquifers are confined by between 10 and 30 feet of clayey till and appear to pinch out north of the river. Ground water from the shallow aquifers discharges into several small- to medium-sized creeks and possibly by upward seepage and evapotranspiration across confining units.

D2

Regional discharge area characterized by weak to strong upward hydraulic gradients at depth, water levels at or near river level, and large potentiometric valleys. Unit occurs in the valleys of St. Joseph and Maumee Rivers. Bodies of unconfined outwash commonly present directly atop exhumed sand and gravel aquifers below the St. Joseph River and as flanking terraces in both valleys. Ground water from the Huntertown aquifer system discharges to surface water, unconfined outwash and alluvium, or both, whereas the unconfined outwash receives abundant local recharge from precipitation and surface water. Contours within this map unit represent water table elevation.

D3

Local discharge area characterized by neutral or weak upward hydraulic gradients, water levels at or near stream level, and medium to large potentiometric valleys. Unit occurs in stream valleys which are locally incised into the tops of sand and gravel aquifers. Ground water from subjacent aquifers discharges into surface water, alluvium, or both. A large component of ground-water flow is also directed down the potentiometric valleys below these streams. A potentially high rate of local recharge is possible where extensive bodies of permeable sediments occur above the water table. Contours within this map unit represent the water table.

D4

Local discharge area characterized by neutral hydraulic gradients, water levels at or near stream level, and small potentiometric valleys or deflections. Unit occurs immediately adjacent to small perennial upland creeks, lakes, and large ditches. In some places, these surface water bodies lie above weakly confined parts of aquifer systems, but in other areas, no shallow aquifers are present. Some ground water from subjacent aquifers discharges by slow upward flow across confining units, but most discharge is from till, alluvium, and other sediments adjacent to surface water. Magnitude of discharge may be seasonal, and some stream segments may lose water during some times of year.

D5

Mixed area characterized by broad, flat wetlands, nearly flat water table within a few inches of the land surface, and surrounded by broad potentiometric valley. Map unit occurs along Six-Mile Creek, in the extreme western apex of the Maumee Lacustrine Plain, and in the Wabash-Erie Channel, where it forms a discharge divide between the Maumee River and the Little River. The geology in these areas is generally a complex mix of permeable and poorly permeable alluvial and lacustrine sediments that overlie till and variably truncated sand and gravel aquifers. Ground water is believed to discharge from deeper sand and gravel aquifers into surficial sediments, and thence into wetlands and ditches. Appreciable local recharge may also occur where surficial sediments are permeable. Contours within this map unit represent the water table in surficial sediments.

H1

Part of regional recharge area for the Huntertown aquifer system. Hummocky landscape characterized by strongly developed internal drainage, downward hydraulic gradients, shallow water table, thin (<20 feet) and commonly broken till confining units, permeable soils and surficial sediments, and flat or weakly mounded potentiometric surface. Recharge occurs directly from precipitation and surface runoff collected in depressions.

H2

Part of regional recharge area for the Huntertown aquifer system. Generally similar to map unit H1 above, but till confining unit is typically somewhat thicker and more continuous. Recharge occurs primarily from surface runoff from till-capped hummocks into depressions underlain by more permeable sediments or thin till.

u

Upland areas characterized by thick unconfined sand and gravel. May form local recharge area or part of larger regional recharge area depending on location with respect to other map units. Recharge occurs directly from precipitation and collected surface runoff.

s

Potential local recharge areas associated with abandoned meltwater channels in uplands. Characterized by permeable surficial peat and/or outwash, uncertain thickness or continuity of till confining units, and high water table. Ephemeral or perennial discharge from water table into ditches and creeks may occur in some places, but recharge to shallow aquifers from peatlands may be great where till confining unit is thin or absent.

w

Potential local recharge area associated with portions of the Arcola plain. Characterized by very poorly drained landscape and shallow water table in outwash and peat. The surficial sediments are up to 20 or more feet thick, and overlie till with localized discontinuities. The water table in the surficial sediments receives abundant recharge directly from precipitation and generally constitutes a hydraulic system distinct from the underlying Aboite aquifer system. Recharge to the Aboite aquifer system from peatlands may be greater where the till confining unit is thin or absent.

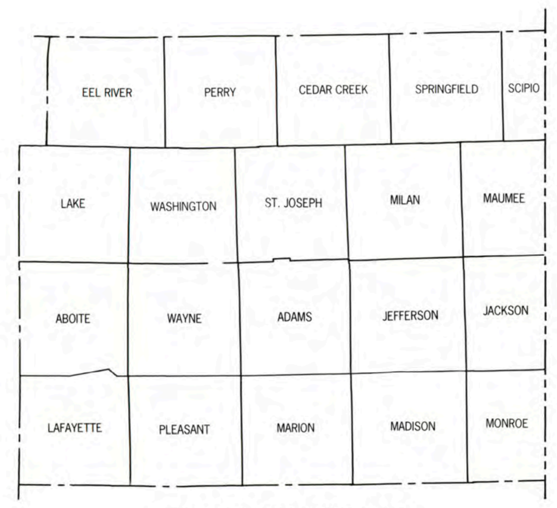
p

Potential local recharge areas associated with sequences of permeable surficial sediments above otherwise confined sand and gravel aquifers. Characterized by landforms composed of sandy or gravelly sediments (e.g., beach ridges, dunes) or by zones of increased permeability within the till confining unit, such as channels and ice-contact stratified deposits. Thickness and continuity of till confining unit unknown or ranges widely. Recharge occurs directly from precipitation and may be substantial where the till is thin or absent.

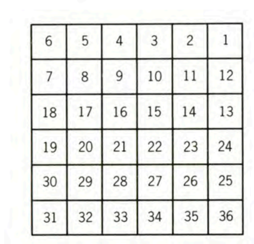
I

Intermediate area characterized by 20 to more than 100 feet of glacial till and other fine-grained confining units above sand and gravel aquifers. Although downward gradients are likely to predominate, only a limited amount of recharge is likely to reach the aquifers in these settings, primarily by slow, diffuse leakage through the confining units.

Approximate zone of influence of high-capacity well(s) (▲) or large gravel pits (⚒) developed in sand and gravel aquifers. Extent and depth of cone of depression are uncertain and may vary seasonally and/or with changes in pumping rate or schedule.



Index map of Allen County showing political township names



SECTIONIZED TOWNSHIP

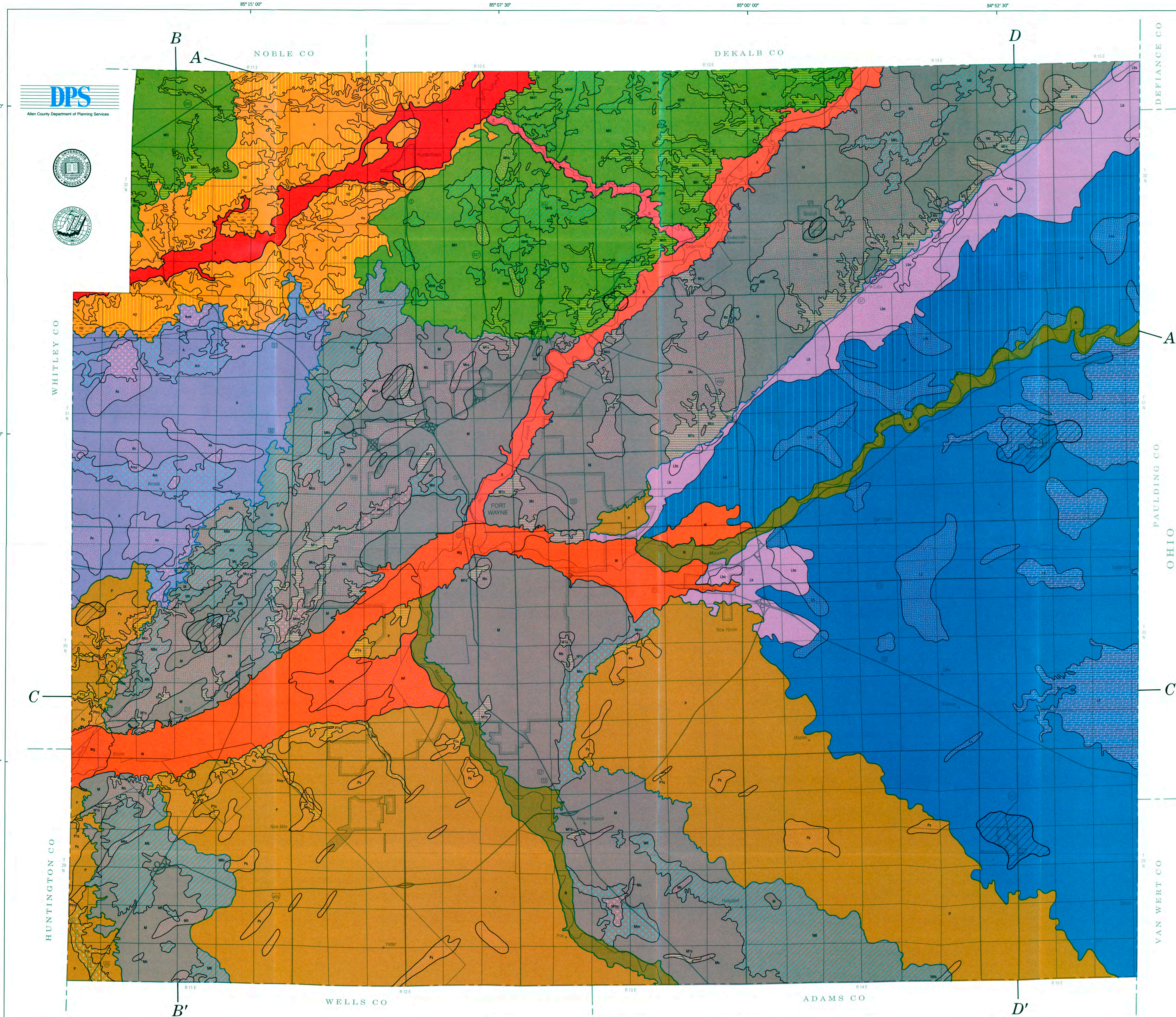
1 0 5 Miles
1 0 5 Km

Base from latest U.S. Geological Survey topographic quadrangle maps, scale 1:24,000.

Drafted by Rea Williams Kersey and Roger L. Purcell
Assisted by Kim Hankins Sowder, Kari Lancaster and A. Scott Moonshower
Reprographics by Barbara T. Hill and John Michael Day

MAP OF ALLEN COUNTY, INDIANA SHOWING THE POTENTIOMETRIC SURFACE AND RECHARGE-DISCHARGE RELATIONS OF THE HUNTERTOWN AND ABOITE AQUIFER SYSTEMS AND OTHER SHALLOW SAND AND GRAVEL AQUIFERS

By
Anthony H. Fleming
1994



MAP DESCRIPTION

Hydrogeologic regions and the range of conditions they represent are closely related to the distribution of glacial terrains, hence the boundaries of the eleven major hydrogeologic regions shown on this map correspond to major terrain boundaries (see Plate 5). Each of these regions is characterized by a distinctive set of landscape elements and a typical hydrostratigraphic sequence or sequences. The nature of the hydrostratigraphic sequence determines the presence, characteristics of, and relationships between specific types of aquifers and confining units, whereas surface morphology is indicative of the characteristics and distribution of surface soils, determines the nature of surface drainage and its interaction with ground water, and is often indicative of variations in the thickness and other physical characteristics of near-surface aquifers and confining units. Within each of the major hydrogeologic regions, one or more sub-regions are defined based on consistent patterns of mappable hydrostratigraphic and/or morphologic characteristics that appear to influence the availability of ground water and its sensitivity to contamination, such as the thickness of the clayey surface till of the Lagro Formation.

The sensitivity of ground water to contamination at any given locality in Allen County is a function of all the above sequence and landscape characteristics, which control the rate at which contaminants can migrate into the saturated zone in general as well as into specific aquifers that comprise important sources of drinking water. On this map, the sensitivity of ground water to contamination is illustrated by the hierarchical system of hydrogeologic regions and sub-regions (inset 1), each of which generally reflects a particular range of conditions with respect to the factors that influence ground-water sensitivity.

EXPLANATION

Map unit labels consist of up to three characters, which are always used as follows. The major hydrogeologic region is identified by one or two upper case letter(s) at the beginning of the label. Sub-regions are identified by any lower case letters or numbers that follow. Numbers always refer to the thickness of till confining units. The major characteristics are described in the first paragraph of the explanation covering each region. Sub-regions are explained in subsequent paragraphs, which describe any significant differences from the major hydrogeologic region within which they occur.

Boundary between major hydrogeologic regions.

Boundary between hydrogeologic subregions.

Hydrogeologic Regions and Subregions

H — **Huntertown Interlobate Region:** Hummocky, internally drained landscape characterized by numerous enclosed depressions and abandoned meltwater channels underlain by peat and outwash, and hummocks cored by clayey till generally less than 20 feet thick. This terrain forms the regional recharge area for the Huntertown aquifer system, which is semi-confined and is the principal ground-water source over the entire region. Ground water below much of this region is highly sensitive to contamination.

Ho — Abandoned meltwater channels, large coalesced depressions, and other low parts of the landscape where the Huntertown aquifer system is unconfined. This unit is characterized by permeable surface sediments, very shallow water table, and high recharge potential. The sensitivity to contamination is very high.

H2 — Ridges, hummocks, and other upland areas where the Huntertown aquifer system is consistently confined by 20 or more feet of clayey sediments of the Lagro Formation. Small depressions and other low areas where the till is thinner or locally absent are commonly present within this unit. The sensitivity to contamination is moderately high.

Hd — Area below which sand and gravel of the Huntertown aquifer system is locally thin or absent; ground water is derived principally from deep sand and gravel aquifers or limestone bedrock. The sensitivity of these aquifers to contamination is moderately low.

E — **Eel River Valley:** Flat to pitted outwash plain underlain in most places by Erie Lobe outwash atop sand and gravel of the Huntertown aquifer system. The sand and gravel ranges from 30 to 100 feet thick and locally contains discontinuous lenses of Saginaw Lobe till. Thick sections of peat overlie the outwash along the axis of the valley. The valley contains extensive wetlands within a surface drainage divide, and is part of the regional recharge area for the Huntertown aquifer system. Ground water below this region is extremely sensitive to contamination.

MH — **Interlobate Morainal Region:** Moderately to strongly hummocky, ridged landscape developed on Erie Lobe end moraines superposed on strongly hummocky Saginaw Lobe topography. The clayey till within the moraines ranges between 20 and 60 feet thick. Much of the region is characterized by internal drainage into depressions filled with peat. The Huntertown aquifer system is the principal source of ground water over the entire region and is moderately sensitive to contamination.

MH1 — Stream valleys, depressions, and high-level meltwater channels characterized by less than 20 feet of clayey till over sand and gravel of the Huntertown aquifer system. Till may be absent in a few places. The sensitivity to contamination is moderately high.

MHc — Channel-like bodies of sand and/or gravel that cut the Lagro Formation. Most of these bodies are capped by thin till; however, they typically penetrate completely through the lower part of the till and afford an avenue of communication between the near surface and the underlying Huntertown aquifer system. The sensitivity to contamination is moderately high.

MH6 — Broad rolling ridges along the moraine crest characterized by thick clayey till that ranges from 60 to about 95 feet thick. Lenses of dense silt and some sand are locally common within the till. The sensitivity to contamination is moderately low.

A — **Arcola Plain:** Flat to very gently rolling, poorly drained landscape that was pervasively washed by meltwater when the Erie Lobe stood at the Wabash Moraine. The surficial materials consist of a patchwork of thin outwash terraces, fine-grained lacustrine sediment, and numerous peat bogs overlying clayey till of the Lagro Formation which ranges from 20 to 60 feet thick. Much of the region is characterized by till sections 100 to 200 or more feet thick. Ground water is produced chiefly from limestone bedrock or deep sand and gravel aquifers, whose sensitivity to contamination is uniformly low. However, the shallow water-table system present within the permeable surficial sediments is sensitive to contamination.

As — Sub-region within which shallow sand and gravel bodies of the Aboite aquifer system are consistently present directly beneath the Lagro till. Thicker parts of these shallow aquifers are widely utilized for ground-water supplies. The sensitivity of these aquifers to contamination is moderate.

Am — Large abandoned meltwater channels containing small lakes, ponds, and expansive wetlands that are underlain and flanked by sections of sand, gravel, and peat ranging from 20 to more than 40 feet thick. The hydrogeologic characteristics of this sub-region are otherwise similar to region A, above. Although not generally exploited for water-supply purposes, the permeable surficial sediments within the meltwater channels are saturated and have a high sensitivity to contamination.

Ams — Identical to subregion Am above, but shallow sand and gravel of the Aboite aquifer system is present and is locally in direct hydraulic connection with surface water and the water-table system within the surficial sediments. The sensitivity to contamination is high.

M — **Morainal Regions:** Rolling to hummocky morainal ridges composed of clayey till of the Lagro Formation which ranges from 20 to 60 feet thick. The landscape ranges from well-drained to somewhat poorly drained. A shallow perched water table may be present seasonally, but a thick unsaturated zone is usually present in the till. Forty to more than 200 feet of older tills are commonly present under the Lagro, and most ground water is produced from deep sand and gravel aquifers or the limestone bedrock. The thick section of fine-grained till severely limits the potential for recharge to these deep aquifers, hence their sensitivity to contamination is low.

Ms — Sub-region within which shallow sand and gravel bodies of the Aboite or Huntertown aquifer systems are consistently present directly beneath the Lagro till. Thicker parts of these shallow aquifers are widely utilized for ground-water supplies. The sensitivity of these aquifers to contamination is moderately low.

Mc / Mcs — Channel-like bodies of sand and/or gravel that cut the Lagro Formation. Most of these bodies are capped by thin till; however, they typically penetrate completely through the lower part of the till and may afford an avenue for contaminants to bypass the clayey till of the Lagro. The presence of these channels considerably elevates the sensitivity to contamination of shallow sand and gravel aquifers (unit Mcs) directly below the Lagro, but has only a nominal effect on the sensitivities of deeper aquifers (unit Mc). Ground water within the channels themselves is also sensitive to contamination.

M1s — Stream valleys, depressions, and high-level meltwater channels characterized by less than 20 feet of clayey till over sand and gravel of the Huntertown or Aboite aquifer systems. Till may be absent in a few places. The sensitivity to contamination is moderately high.

M6 / M6s — Broad rolling ridges along the moraine crest characterized by thick clayey till that ranges from 60 to 110 feet thick. Lenses of dense silt and some sand are locally common. The sensitivity of shallow aquifers directly below the Lagro is low (unit M6s) and is very low for deep aquifers (unit M6).

Mm / Mms — Large abandoned meltwater channels that locally contain extensive wetlands and are in places underlain and flanked by sections of outwash, alluvium, or palustrine sediments. Till of the Lagro Formation is generally absent from these areas. Unit Mms: shallow sand and gravel units are present below the surficial sediments and locally extend to bedrock; unit Mm: thick till sections are typically present below the surficial sediments. Although not generally exploited for water-supply purposes, the permeable surficial sediments within the channels are saturated and have a high sensitivity to contamination, as do shallow sand and gravel aquifers of unit Mms. The sensitivity of deep aquifers in unit Mm is moderate to moderately low.

P — **Till Plains:** Mostly gently rolling to nearly flat, somewhat poorly to very poorly drained landscapes developed on clayey till of the Lagro Formation which ranges from 20 to 50 feet thick. A shallow water table in the till is characteristic. Thick sections of loam till of the Trafalgar Formation are commonly present below the Lagro, and ground water is typically produced from the limestone bedrock. The potential for contamination of bedrock aquifers is moderately low.

Ps — Sub-region within which shallow sand and gravel aquifers are present directly beneath the Lagro till. Thicker parts of the shallow aquifers are locally utilized for ground-water supplies in the far western part of the county. The sensitivity of the shallow aquifers to contamination is moderate.

P1s — Stream valleys and other dissected areas characterized by less than 20 feet of clayey till over shallow sand and gravel aquifers. Till may be absent in a few places. Sensitivity to contamination is moderately high.

Pm / Pms — Abandoned meltwater channels that typically contain small- to medium-sized surface streams and are in places underlain and flanked by small bodies of outwash sand and gravel or alluvium. Till of the Lagro Formation is generally absent from these areas. Unit Pms: sand and gravel units of the Aboite aquifer system are present below the stream sediments and locally extend to bedrock; unit Pm: thick till sections are typically present below the surficial sediments. Although not generally exploited for water supplies, permeable surficial sediments within the channels are saturated and have a high sensitivity to contamination, as do the underlying sand and gravel aquifers of unit Pms. The sensitivity of deep aquifers in unit Pm is moderately low.

Hydrogeologic Regions and Subregions, continued

S — **St. Joseph River Valley:** Narrow, deeply entrenched valley flanked by large outwash terraces and underlain by outwash that ranges from less than 20 feet thick near the edges of the valley to more than 60 feet thick elsewhere. Outwash below the valley is locally in direct contact with the Huntertown aquifer system. The surface of the valley tends to be poorly drained due to the very shallow water table. The valley is the regional discharge area for much of the Huntertown aquifer system, and upward hydraulic gradients occur at depth. The sensitivity of the outwash to contamination is extremely high.

C — **Cedar Creek Canyon:** Narrow, very deeply incised gorge formed as a sub-ice channel beneath the Erie Lobe. Underlain by very thick (50 to 100 feet) sand and gravel in some places and capped by fine-grained alluvium derived from erosion of canyon walls. The canyon is locally incised into large sand and gravel bodies of the Huntertown aquifer system and forms a local discharge area. The canyon bottom is very poorly drained and the water table is typically less than a foot below ground. Ground water under the canyon is highly sensitive to contamination.

R — **Alluvial River Valleys:** Narrow, somewhat entrenched valleys of the St. Marys and Maumee Rivers. These valleys are locally flanked by small outwash terraces but generally contain only small outwash deposits within their actual confines. The predominant material within the valleys is alluvium, which overlies a stripped surface on till of the Trafalgar Formation. Both valleys are significant discharge areas, especially the Maumee River, where strong upward hydraulic gradients are characteristic. Limestone bedrock is the chief source of ground water adjacent to these valleys and has a moderate to moderately low sensitivity to contamination. Shallow ground water within the alluvial deposits has a moderately high sensitivity to contamination.

W — **Wabash-Erie Channel:** Broad, flat, very poorly drained abandoned outlet of ancestral Lake Erie. Formerly a major wetland area that has been extensively drained. Capped by a heterogenous assemblage of outwash, fluvial and palustrine sediments, and scattered sand dunes. These sediments are as much as 35 feet thick and lie atop a stripped surface developed on till and some sand and gravel of the underlying Trafalgar Formation. Ground-water supplies are obtained from the limestone bedrock, which lies at a depth of about 50 to 60 feet. The sensitivity of bedrock aquifers to contamination is moderate to moderately high, whereas the shallow water-table system within the surficial sediments is highly sensitive to contamination.

Wf — Gently rolling to fluvially streamlined landscape developed on outwash fan deposited by the Erie Lobe at the apex of the Fort Wayne Moraine. The fan consists of up to 40 feet of sand and gravel overlying a stripped surface of till and some sand and gravel of the Trafalgar Formation. Small dune fields are locally present but much of the fan surface has been extensively modified by urbanization and gravel excavation. The few water wells in this area utilize the limestone bedrock, which is at a depth of 60 to 80 feet and is moderately sensitive to contamination. The sensitivity of ground water within the outwash fan is high.

Wg — Areas characterized by abundant sand and gravel as much as 60 feet thick between the land surface and bedrock. These composite sand and gravel units represent a variety of Erie Lobe outwash units that were deposited directly atop sand and gravel in channelized form within the underlying Trafalgar Formation. Large sand dunes are locally present and the water table is commonly within a few feet of the surface. The sand and gravel units and the bedrock in this subregion essentially comprise a single thick aquifer that is highly sensitive to contamination.

Maumee Lacustrine Plain: Flat, low-lying, very poorly drained landscape on the former bottom of ancestral Lake Erie. The edges of the region are locally marked by sand dunes and beach ridges.

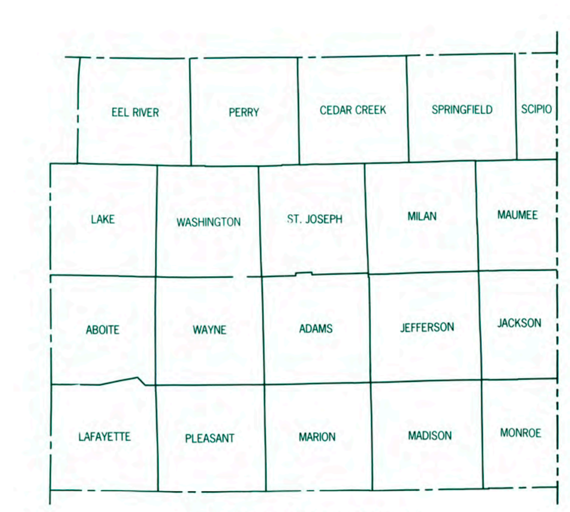
L / L4 / Ls — The lacustrine plain south of the Maumee River Valley, characterized by a veneer of fine-grained lake sediment over tills of the Lagro and Trafalgar Formations, respectively. The water table is usually within 5 feet of the land surface and the landscape is often swampy where it is not artificially drained. Hydraulic gradients are neutral or weakly upward, with most ground water discharging into the Maumee River. Ground-water supplies are derived exclusively from the limestone bedrock, which is at a depth of between 40 and 70 feet and is moderately sensitive to contamination (unit L). The sensitivity is moderately high where the bedrock and any immediately overlying sand and gravel are confined by less than 40 feet of fine-grained sediment (unit L4). Sand and gravel units are rare in the southern part of the lacustrine plain. These include a few bodies of intersequence sand and gravel (unit Ls), which are generally not utilized as a water supply and have a moderately high sensitivity to contamination.

Ln / Lns — The lacustrine plain north of the Maumee River Valley. Landscape is similar to the southern lacustrine plain and slopes gently from north to south and is commonly capped by a gravelly or sandy veneer of beach sediment. This sub-region is a regional discharge area and is characterized by moderate to strong upward hydraulic gradients between the bedrock and the land surface. Flowing artesian wells are numerous in places. Parts of this region are characterized by thick till sections 60 to 100 or more feet thick over bedrock or large sand and gravel aquifers along or near the bedrock surface (unit Ln), and have a low sensitivity to contamination. Small and large sand aquifers are also present near the base of the Lagro Formation, mainly in the northern and western parts of the subregion (unit Lns) and have a moderate sensitivity to contamination.

Lb / Lbs / Lbo — Large beach ridges, sand bars, and spits that form the northern and western margins of the Maumee Lacustrine Plain. The beach deposits are composed mostly of sand and gravel up to 35 feet thick, although wave-stripped benches on till of the Lagro Formation occur locally. Although they are not known to be employed for water supplies, the coarse beach deposits are commonly saturated and have a high sensitivity to contamination. In some places (unit Lb), the beach deposits overlie thick (80 to 150 feet) till sections and most ground water is produced from deep sand and gravel aquifers or from the bedrock, which have a very low sensitivity to contamination. In other places, the beach deposits overlie large bodies of lacustrine sand of the Huntertown aquifer system. These bodies are up to 50 feet thick and are the primarily used aquifer wherever they occur. The lacustrine sand aquifers are typically separated from the beach deposits by 10 to 30 feet of clayey till of the Lagro Formation and underlying lake mud, and have a moderately high sensitivity to contamination (unit Lbs). In a few places, however, there are no intervening fine-grained materials between the coarse-grained beach deposits and the lacustrine sand aquifers and the sensitivity to contamination is very high (unit Lbo).

Other Features

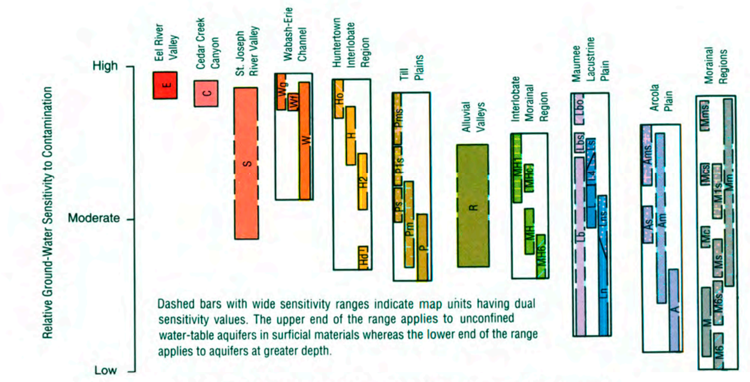
Approximate zone of influence surrounding public water supply wellfield.



Index map of Allen County showing political township names

6	5	4	3	2	1
7	8	9	10	11	12
18	17	16	15	14	13
19	20	21	22	23	24
30	29	28	27	26	25
31	32	33	34	35	36

SECTIONIZED TOWNSHIP



Inset 1. Ranking of map units according to their relative sensitivity to ground-water contamination

1 0 5 Miles

1 0 5 Km

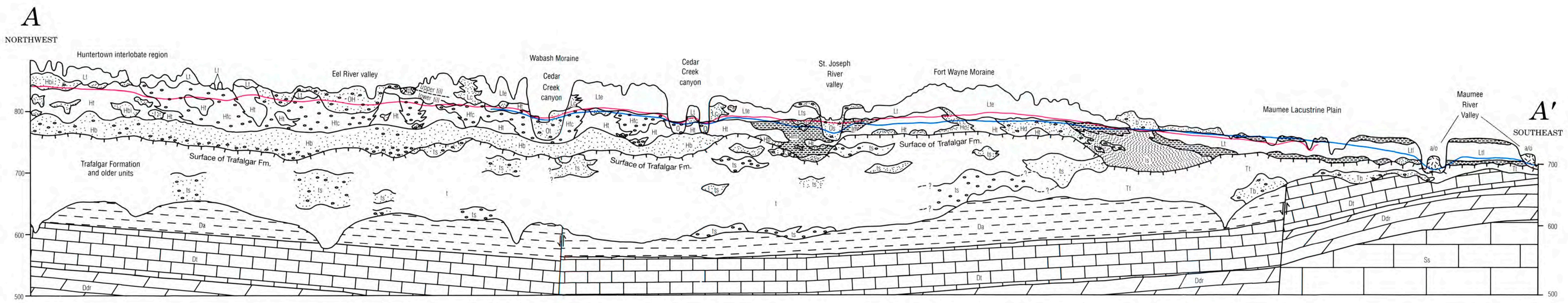
Base from latest U.S. Geological Survey topographic quadrangle maps, scale 1:24,000.

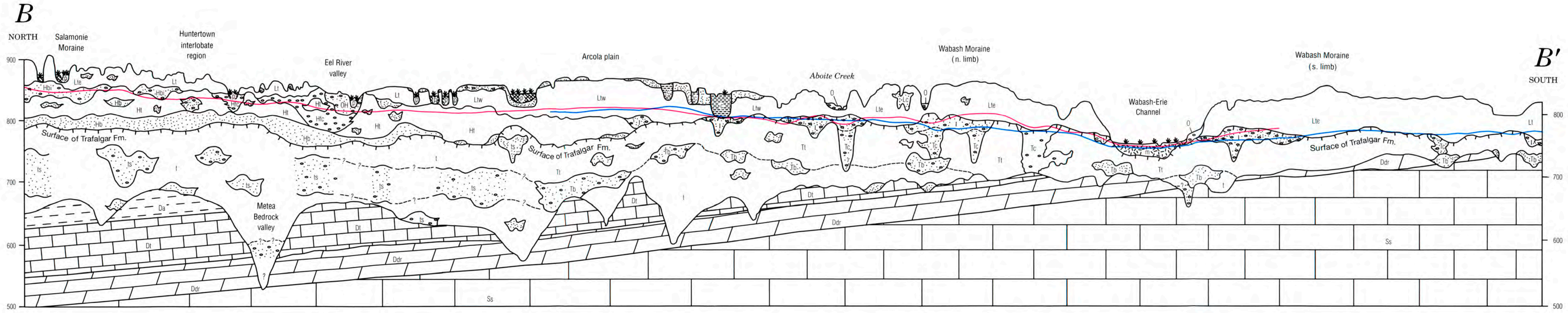
Drafted by Rea Williams Kersey and Roger L. Purcell
Assisted by Kim Hankins Sowder, Kari Lancaster and A. Scott Moonshower
Reprographics by Barbara T. Hill and John Michael Day

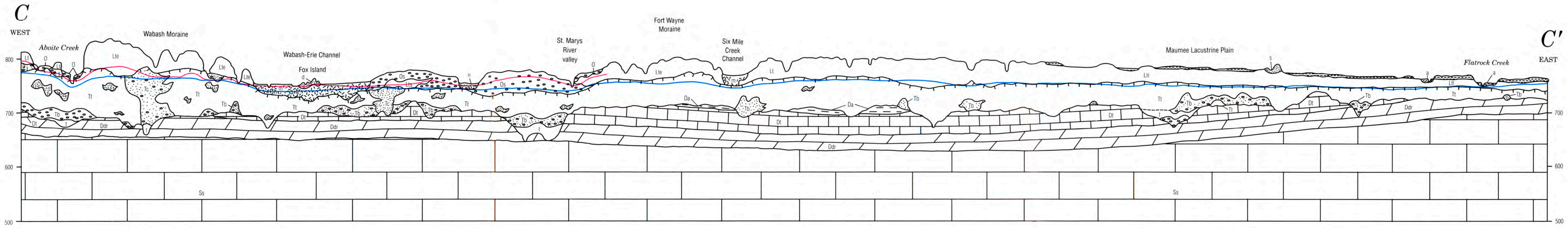
MAP OF ALLEN COUNTY, INDIANA SHOWING HYDROGEOLOGIC REGIONS AND THEIR SENSITIVITY TO CONTAMINATION

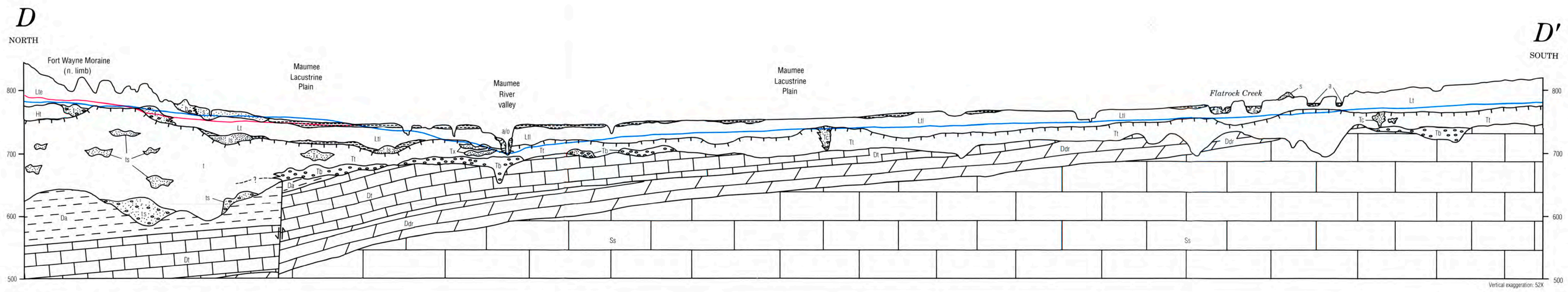
By
Anthony H. Fleming

1994









1 0 5 Miles

1 0 5 Km

The map and cross-sections were compiled by the Indiana Geological Survey, Indiana University, using data believed to be accurate; however, a margin of error is inherent in all maps and cross-sections. This product is distributed "AS-IS" without warranties of any kind, either expressed or implied, including but not limited to warranties of suitability of a particular purpose or use. There is no attempt, in either the design or production of the map and cross-sections, to define the limits or jurisdiction of any Federal, State, or local government. The map and cross-sections are intended for use only at the published scale. A detailed and historical analysis of a single site may differ from the map and cross-sections. The map and cross-sections are not a substitute for an actual survey.

GENERAL DESCRIPTION

The distributions and geometries of geologic map units and major buried surfaces illustrated by the cross-sections are derived directly from plates 2, 4, 5, and 6, and the labels for these units on the cross-sections are the same as those used on their respective plates. In addition, certain granular units and bedrock formations are patterned to indicate their general lithologic composition. The potentiometric surfaces of the bedrock aquifer system and the shallow sand and gravel aquifers are from plates 7 and 8, respectively.

EXPLANATION

CROSS-SECTION UNITS

Post-Glacial Sediments

- a — Alluvium
- p — Peat
- n — Chiefly sand and lesser silt (slackwater deposits)
- m — Chiefly silt and lesser sand (slackwater deposits)
- d — Fine to medium sand in dunes
- c — Lacustrine silt and clay in abandoned meltwater channels
- s — Fine to medium lacustrine sand
- b — Sand and gravel in beach ridges
- a/o — Alluvium over thin or discontinuous outwash

Lagro Formation (Erie Lobe)

- Os, OH, Ot, O — Outwash sand and gravel
- Lc — Sand in channels within till
- Lt, Lte, Ltw, Ltl, Lts — Till and till-like sediment, clay loam to silty clay in till plains, end moraines, and lake plains

Huntertown Formation (Saginaw Lobe)

- Hbi — Ice-contact stratified sand and gravel
- Hfc — Sand and gravel in ice-contact fans and channels
- Hb — Sand and lesser gravel, basal outwash
- Hd — Sand and lesser gravel, fan-deltas
- Ht — Till and till-like sediment, sandy loam
- ls — Fine lacustrine sand, deltaic
- lm — Lacustrine silt with sand lenses

Trafalgar Formation and older units

Trafalgar Formation (Huron-Erie Lobe):
- I — Sand and gravel, intersequence unit
- Tx — Sand, intertill blankets and aprons
- Tc — Sand and gravel, channels
- Tb — Sand and gravel, basal outwash
- Tt — Till and till-like sediment

Trafalgar Formation and older units, undifferentiated:
- t — Till and till-like sediment, mostly loam
- ts — Sand and gravel

Bedrock Units

- Da — Antrim Shale
- Dt — Traverse Formation
- Ddr — Detroit River Formation
- Ss — Salina Group

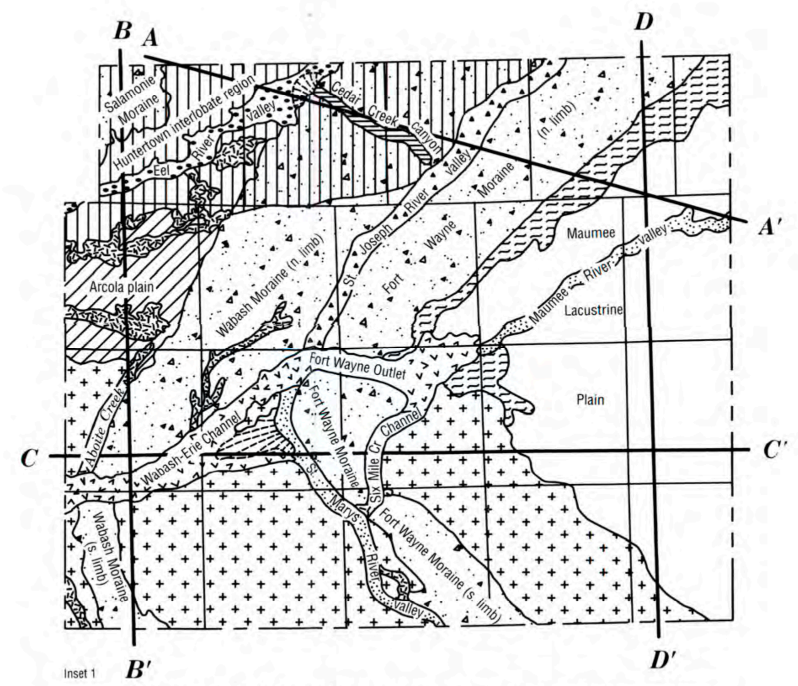
LITHOLOGY

- Peat
- Silt and sand
- Lacustrine mud
- Sand
- Sand and gravel
- Till and till-like sediment
- Black shale, limestone at base
- Limestone and dolomite
- Dolomite and limestone, some gypsum
- Dolomite and limestone, some dolomitic siltstone

CROSS-SECTION SYMBOLS

- Contact; queried where doubtful
- Top of the Trafalgar Formation
- Base of the Trafalgar Formation
- Fault, arrows indicate relative sense of vertical offset
- Potentiometric surface of the bedrock aquifer system
- Potentiometric surface of the Huntertown and Aboite aquifer systems

DPS
Allen County Department of Planning Services



Inset 1

Generalized glacial terrain map of Allen County showing location of cross-section lines A-A' through D-D'. Cross-section lines are shown at a larger scale on Plate 1. End points of cross-section lines are shown on plates 2 through 9.

EXPLANATION

GLACIAL TERRAINS

- Huntertown interlobate region
- Arcola plain
- Eel River valley
- St. Joseph River valley
- Interlobate morainal regions
- Cedar Creek canyon
- Morainal regions
- Alluvial river valleys
- Till plains
- Wabash-Erie Channel
- Maumee Lacustrine Plain (beach zone)

OTHER FEATURES

- Outwash fan
- Meltwater channel

HYDROGEOLOGIC CROSS SECTIONS OF ALLEN COUNTY, INDIANA SHOWING PRINCIPAL BEDROCK AND UNCONSOLIDATED AQUIFERS, CONFINING UNITS, AND POTENTIOMETRIC SURFACES

By
Anthony H. Fleming
1994

Drafted by Kari Lancaster and Rea Williams Kersey
Assisted by A. Scott Moonshower
Reprographics by Barbara T. Hill and John Michael Day