PHYSICAL ENVIRONMENT

Climate, geology and soils affect the availability of surface-water and ground-water resources. Climatic factors largely determine the amount of available precipitation in the basin. Geologic and soil factors determine the proportion of precipitation which runs off the land as surface water to that which infiltrates the soil and *percolates* through underlying materials to become ground water. Geology and soils also determine surface drainage characteristics, the vulnerability of *aquifers* to contamination, and the limits of ground-water development.

CLIMATE

Water availability and use in the Maumee River basin are directly linked to the regional climate or the long-term composite of daily weather events. The climate of the basin is broadly classified as temperate continental, which describes areas located within the interior of a large continent and characterized by warm summers, cool winters, and the absence of a pronounced dry season.

The overall climate within the Maumee River basin is fairly consistent, but there is great variability in daily and seasonal precipitation and temperature throughout the basin. This variability is primarily the result of interactions between tropical and polar *air masses*, the passage of low-pressure systems, and the shifting location of the *jet stream*.

Sources of climatic data

Most climatic data for Indiana are collected and analyzed by the National Weather Service (NWS) of the National Oceanic and Atmospheric Administration (NOAA). The agency gathers data from more than 100 Indiana stations belonging to one or more of three networks (climatic, hydrologic or agricultural).

Temperature and precipitation data from the **climatic** network are primarily intended to represent long-term conditions over large areas of uniform terrain and climate. Rainfall intensity data collected from the **hydrologic** network of recording precipitation gages are used for river forecasting, flood forecasting and related planning purposes. Data on precipitation, air and soil temperature, relative humidity and other parameters are collected at **agricultural** stations.

At most NWS stations, precipitation and/or temperature data are collected once daily by observers who typically are employed by water utilities, wastewater facilities, industries, municipalities or agribusiness. More detailed meteorological data are collected at the 24-hour NWS offices at Indianapolis, South Bend, Fort Wayne, and Evansville.

Figure 13 shows the location of official NWS stations in or adjacent to the Maumee River basin in Indiana. Table 7 presents selected information about these stations.

Climatic data collected at NWS stations are published in a variety of formats by NOAA's National Climatic Data Center (NCDC) in Asheville, North Carolina (Hatch, 1983). Most of the data presented in the following pages were obtained from tabular summaries for Indiana stations (National Oceanic and Atmospheric Administration, 1992a, 1992b, 1992c, 1995). The data in these documents encompass the most recent climatic base period, 1961-90. Data for a 30-year period are used by NOAA to evaluate climatic conditions and to calculate climatic normals (National Oceanic and Atmospheric Administration, 1983). The above NCDC data have recently been published in CD-ROM format. The CD-ROM version of Climatological Data is entitled "Cooperative Summary of the Day". Disk 15 in the series includes data for Indiana for the years from beginning of station record through 1993. An annual supplement has been published for 1994 data. A CD-ROM version of Local Climatological Data is published as "Solar and Meteorological Surface Observation Network (1961-1990)". Hourly weather observations for the four Indiana NWS sites are included. Statistical summaries of Hourly LCD data have been published by NCDC on CD-ROM as "International Meteorological Station Climate Summary". More than 50 types of analyses are presented. Most data summaries cover the period 1948 through 1990.

Data are available from the NCDC on a monthly and annual basis in several serial publications, including **Climatological Data**, **Hourly Precipitation Data**, and **Local Climatological Data**. Additional data are available in other serial and periodic publications.

Climatic data are also available from the Midwestern Climatic Center, a federally-funded regional center housed at the Illinois State Water

Survey in Champaign, Illinois. The center collects, analyzes and disseminates climatic data for nine midwestern states, including Indiana.

Unpublished daily and monthly precipitation data are available from the State Climatologist at Purdue University for official and unofficial stations in and near the Maumee River basin.

The unpublished, unofficial daily precipitation data are collected by amateur radio operators as part of a statewide volunteer network which began in 1980 to enhance the NWS river and flood forecasting program. These data are available from the NWS in Indianapolis and from Purdue University. The State Climatologist at Purdue University maintains a computerized archive of the daily reports from October 1989 to present.

Climatic features

Although the climate of the Maumee River basin encompasses variations in wind, clouds, humidity, solar radiation and other elements, the following sections focus on variations in precipitation, temperature, and *evapotranspiration*. Precipitation is the source of fresh water which occurs as surface water and ground water. Temperature defines the frost-free growing season for crops, and largely controls the process of evapotranspiration.

In some regional overviews of climate, data are grouped and analyzed on the basis of geographic areas which are, as nearly as possible, climatically homogeneous. The U.S. Department of Agriculture has divided Indiana into nine crop-reporting districts, which are identical to the nine climatic divisions defined by NOAA. In the following sections of this report, however, summaries of precipitation in the Maumee River basin are derived primarily from station data near Berne, Decatur, Fort Wayne, and Monroeville. Data are also furnished from a discontinued station near Auburn because of the long data record. The temperature data are from stations at Auburn, Berne, and Fort Wayne.

Because there are no evaporation stations in the Maumee River basin, evaporation data included in this report are from nearby Kendallville and Prairie Heights.

Precipitation

Precipitation events can vary widely in duration and intensity within the Maumee River basin and are typically interspersed among several dry days. Geographic and temporal variations in daily precipitation are produced by the passage of frontal systems and by daytime *convection*.

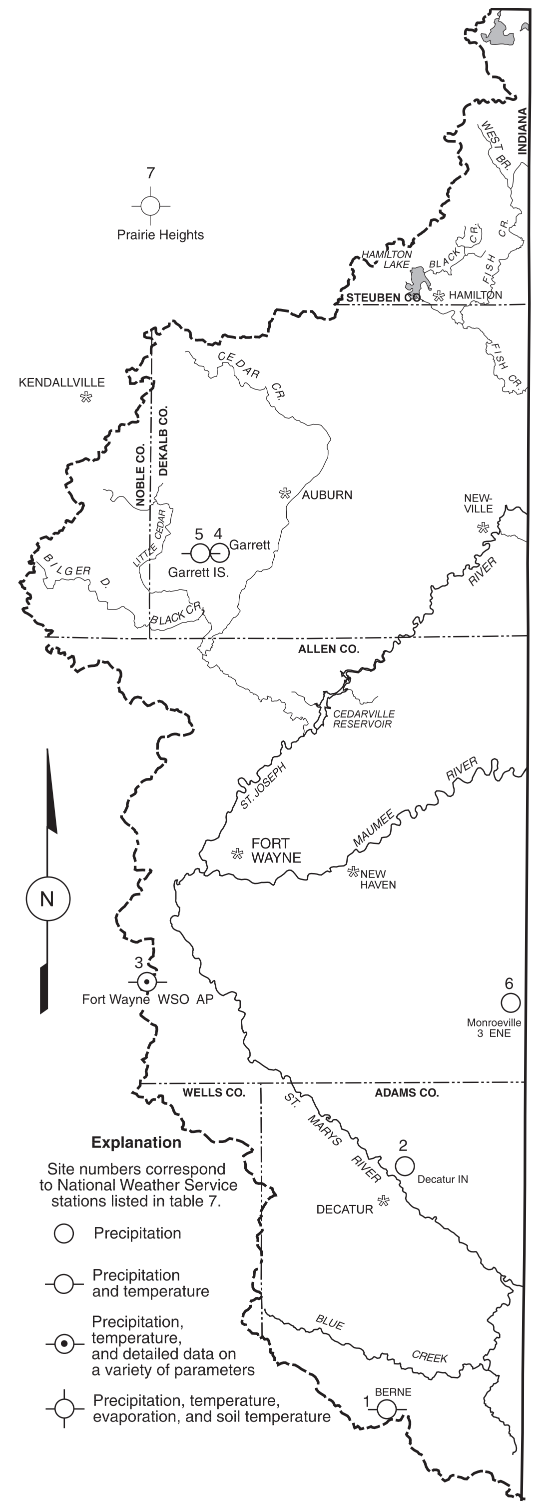

Figure 13. Location of climate stations in and near the Maumee River Basin

Table 7. National Weather Service stations in and near the Maumee River basin

Map number: Station locations are shown in figure 13.
Station: Only active stations are tabulated. Historical data for discontinued stations in and near the basin are available for Auburn and Kendallville.

Data network: A, climatological network and/or B, hydrologic network (National Weather Service); AG, agricultural network (Purdue University).

Data type: P, precipitation; T, temperature; E, evaporation and wind; S, soil temperature; D, detailed data on a variety of parameters.

Publication, ongoing: Precipitation and/or temperature data are published monthly and annually by the National Oceanic and Atmospheric Administration in the following reports — CD, Climatological Data (precipitation amounts are from non-recording gages); HP, Hourly Precipitation Data (precipitation amounts are from recording gages); LCD, Local Climatological Data (detailed data published).

Publication, periodic: Climatological summaries are published every 10 years, generally at the end of a 30-year period.

Period of record: Approximate total length of precipitation record, through 1990 inclusive. Years of record are taken from 1990 annual summaries of Climatological Data and Hourly Precipitation Data. Hourly precipitation data may not be available for all years of record at hydrologic (B) network stations.

Map no.	Station name	Data Network	Data Type	Publication Ongoing	Period of Record	
					Years	Dates
1.	Berne[1]	A,B	P,T	CD	81	1910-
2.	Decatur 1 N[1]	B	P	CD	60	1931-
3.	Fort Wayne WSO AP[1]	A,B	P,T,D	CD,HP,LCD	107	1884-
4.	Garrett[2]	A	P	HP	31	1960-
5.	Garrett 1 S[2]	A	P,T	CD	2	1989-
6.	Monroeville 3 ENE[1]	B	P	CD	51	1940-
7.	Prairie Heights[1,*]	B,AG	P,T,E,S	CD	17	1968-

[1] From Ken Scheeringa, Indiana State Climotologist, written communication, 1995
[2] From Roger Kenyon, Cooperative Program Manager, National Weather Service, written communication,1995
* Within 10 miles of basin boundary (located near LaGrange and Steuben County Line)

Most rainfall in late spring and throughout the summer is produced during localized thundershowers generated by the passage of cold fronts or by daytime convection. Local thunderstorms occasionally become severe, and are accompanied by strong winds, large hail, frequent lightning, funnel clouds or tornadoes.

Precipitation during spring and autumn, which typically is associated with the passage of frontal systems, often occurs in the form of slow, steady rains over large areas. However, in September 1950, Fort Wayne received its greatest 24-hour precipitation amount of 4.6 inches (National Oceanic and Atmospheric Administration, 1995).

Normal **daily** precipitation amounts calculated for Fort Wayne range from 0.05 inch in January, which is the driest month, to 0.12 inch in June, the wettest month. Normal daily precipitation amounts are *interpolated* values which do not reflect typical daily random patterns, but they can be used to compute normal precipitation over selected time intervals (National Oceanic and Atmospheric Administration, 1992b).

Normal **monthly** precipitation at Auburn, Berne, Decatur, Fort Wayne, and Monroeville ranges from 1.53 inches in February to 4.23 inches in June (table 8). The lowest normal monthly precipitation in the basin occurred in Auburn; whereas, the highest occurred in Berne. In general, total monthly rainfall amounts are more variable during the warm season than during the cool season.

Normal **seasonal** precipitation in the basin averages 10 inches in spring (March thru May), 10 inches in summer (June thru August), 8 inches in fall (September thru November), and 6 inches in winter (December thru February).

Normal **annual** precipitation at Auburn, Berne, Decatur, Fort Wayne, and Monroeville averages 34.5 inches for the period 1961-1990 (table 8). Normal annual precipitation in the basin ranges from a high of approximately 37 inches at Berne to a low of approximately 32 inches at Monroeville.

Table 8. Normal monthly, seasonal and annual precipitation for the period 1961-90

{All values are in inches; monthly data are obtained from National Oceanic and Atmospheric Administration, 1992a}

Month	Auburn 2 SSE	Berne	Decatur 1 N	Fort Wayne-WSO AP	Monroeville 3 ENE
SPRING					
March	2.51	3.16	2.82	2.9	2.52
April	3.26	3.7	3.29	3.38	2.99
May	3.77	3.61	3.67	3.44	3.27
Seasonal	9.54	10.47	9.78	9.72	8.78
SUMMER					
June	3.91	4.23	3.34	3.59	3.26
July	3.68	3.47	3.56	3.45	3.4
August	3.13	3.32	3.15	3.37	2.79
Seasonal	10.72	11.02	10.05	10.41	9.45
AUTUMN					
September	3.19	3.14	2.98	2.67	2.74
October	2.45	2.45	2.33	2.49	2.23
November	2.91	3.03	2.84	2.79	2.75
Seasonal	8.55	8.62	8.15	7.95	7.72
WINTER					
December	2.74	2.9	2.6	2.89	2.56
January	1.64	1.96	1.77	1.87	1.79
February	1.53	2.08	1.54	1.91	1.66
Seasonal	5.91	6.94	5.91	6.67	6.01
ANNUAL	34.72	37.05	33.89	34.75	31.96

Annual probability data for Fort Wayne and Auburn, show a 90 percent chance that the annual precipitation over a long period of time will average 27 inches or greater (National Oceanic and Atmospheric Administration, 1992c). Conversely, there is only a 10 percent chance that the annual precipitation will average 42 inches or greater. At Berne, there is a 90 percent chance that the annual precipitation will average 30 inches or greater and a 10 percent chance that it will be 44 inches or greater.

Temperature

The normal **annual** temperature averages 50º F (degrees Fahrenheit) at Auburn, Berne, and Fort Wayne. Normal **seasonal** temperature in the basin averages 49º F in spring, 72º F in summer, 53º F in autumn, and 26º F in winter (National Oceanic and Atmospheric Administration, 1992a).

Spring and autumn months generally are characterized by moderate temperatures, although brief periods of unusually cool or warm temperatures may occur. Summer months bring warm, humid conditions and occasional periods of oppressive heat. Winter months are characterized by short periods of extreme cold alternating with several days of milder temperatures.

January, the coldest month, has an average temperature of 23º F and an average monthly minimum of 16º F (National Oceanic and Atmospheric Administration, 1992a). Typically Fort Wayne experiences 5 days in January which have a minimum of less than 0º F (National Oceanic and Atmospheric Administration, 1995).

July, the warmest month, has an average temperature of 74º F and an average maximum temperature of 85º F. July typically has 6 days which have maximum temperatures of at least 90º F.

Table 9. Normal seasonal maximum and minimum temperatures for the period 1961-90

{Values, in degree F, are derived from monthly station normals published by the National Oceanic and Atmospheric Administration, 1992a}

	Spring		Summer		Fall		Winter	
Station	max	min	max	min	max	min	max	min
Auburn 2 SSE	59.8	37.5	82.5	58.5	63	42	34	17.7
Berne	60.4	39.5	83.2	61.1	63.6	43.7	35	19.2
Fort Wayne WSO AP	59.1	38.8	82.6	61.1	62.6	43.4	33.3	18.2

The range in **daily** temperature is generally least in winter, and greatest in summer. The average difference between normal daily maximum and minimum temperatures in the Maumee River basin is 16º F in winter, 20º F in the fall, 21º F in the spring, and 23º F in the summer.

According to comparisons of monthly and seasonal normal temperatures at climatic stations in and near the Maumee River basin, Auburn has the greatest average temperature fluctuations, whereas Fort Wayne has the least (table 9).

Typically the last freeze in the spring occurs in Fort Wayne in late April; in the fall, the first freeze occurs in mid-October. Therefore, the average freeze-free period is 173 days. (National Oceanic and Atmospheric Administration, 1995). The length of the growing season provides favorable conditions for a large variety of crops and vegetables.

Evapotranspiration

Precipitated water is continually being returned to the atmosphere as vapor through the processes of evaporation and plant transpiration. The combined processes of evaporation from water, soil, snow, ice, vegetation and other surfaces are commonly referred to as evapotranspiration. In the annual water-use budget, evapotranspiration is the largest climatological consideration. Approximately 70 percent of annual precipitation in Indiana is consumed by evapotranspiration (Newman, 1981).

Measurements of evaporation from the water surface in a shallow, circular pan can be used to estimate the maximum water loss possible from shallow lakes or saturated soils. Pan evaporation stations are usually operated between May and October, the frost-free growing season for most crops. In general, evaporation pans are not operated between November and April because frequent ice cover produces erroneous measurements.

Pan evaporation stations used in this study are located near Kendallville and Prairie Heights. These two stations are outside the Maumee River basin, but within 10 miles of the boundary. In addition, there are estimates derived for Fort Wayne (table 10).

Table 11 presents the monthly and seasonal pan evaporation averages at Kendallville and Prairie Heights. Differences in station exposure, observational techniques, and years of data record may largely account for the considerable variations among the average values. Mean monthly pan evaporation for Prairie Heights during the growing season ranges from an average of 7.4 inches in June and July to 3 inches in October. Estimated monthly means of pan evaporation at Fort Wayne show that less than 25 percent of the annual total pan evaporation occurs during the 6-month winter period (Farnsworth and Thompson, 1982b).

A reasonable estimate of lake or free-water evaporation can be obtained by multiplying total pan evaporation by a factor of 0.7 to 0.75 (Farnsworth and Thompson, 1982a); hence, the estimated mean monthly lake evaporation at Fort Wayne from May to October is about 4.16 inches. Whereas, the mean monthly lake evaporation at Kendallville and Prairie Heights averages about 3.8 and 4.1 inches, respectively.

Estimates of lake or free-water evaporation are important in reservoir design, rainfall-runoff modeling, and various water-supply studies. In most applications, the free-water value represents **potential** evaporation, which is the maximum water loss expected to occur from a shallow water body, saturated soil, or an adequately watered vegetative surface with an unlimited supply of water. Lake evaporation is a good index of maximum consumptive use of water by evaporation and transpiration.

Table 10. Estimated mean monthly pan evaporation at Fort Wayne

{Monthly values, from Farnsworth and Thompson (1982b), are averages of estimated pan evaporation derived from hydrometeorological measurements using a form of the Penman equation.}

Month & season	Estimated evaporation in inches (1956-70)
Warm Season	
May	6.27
June	7.45
July	7.51
August	6.5
September	4.64
October	3.25
Seasonal Total	35.62
Cool Season	
November	1.6
December	0.9
January	0.86
February	1.17
March	2.23
April	4.03
Seasonal Total	10.79
ANNUAL TOTAL	46.41

In theory, it can be assumed that when soil moisture is not limiting to vegetation growth, the potential evapotranspiration is the same as the actual evapotranspiration. Because the availability of moisture for evapotranspiration varies continually in time and space, actual evapotranspiration often occurs at less than the potential rate.

Evapotranspiration during the summer months commonly exceeds total rainfall, producing a seasonal deficit in available precipitated water. During the winter, when precipitation far exceeds evapotranspiration, water supplies are replenished in the form of increased ground-water and surface-water levels and increased soil moisture. In dry years, the amount of moisture available from precipitation may be less than the potential maximum moisture needs for evapotranspiration. The moisture deficit in a dry year can be considered a conservative index of the amount of water that must be applied through irrigation to supplement precipitation. However, the actual amount of water needed would depend on many variables, including local rainfall, soil type and soil moisture conditions.

Variations in temperature and other climate factors can produce significant variations in evapotranspiration from year to year. Several methods are used for estimating evapotranspiration rates based on average environmental temperature. Newman (1981) used a modified Thornthwaite method to estimate potential evapotranspiration for Indiana's nine climatological and crop-reporting districts. The method is based on estimated environmental energy available to evaporate water.

The northeastern part of the state, which covers nine counties and includes the Maumee River basin, is referred to as Region 3 in the Newman classification.

Table 11. Warm-season mean monthly pan evaporation at Kendallville and Prairie Heights

{Monthly values, in inches, are obtained from Ken Scheeringa, Indiana State Climatologist, 1995}

Station	May	June	July	August	September	October	Total
Kendallville (1961-71)	5.8	6.77	6.98	6.14	4.25	2.9	32.84
Prairie Heights (1972-90)	6.5	7.14	7.69	6.02	4.64	3.15	35.14

Note: Both Kendallville and Prairie Heights evaporation stations lie outside the basin. Observations are not continuous during the stated period of record.

According to regional estimates, which were based on 1941-70 climatic data, the potential evapotranspiration (PET) for Region 3 ranges from 16.2 to 38.6 inches per year. These values were based on a -10º F to +10º F deviation from the mean temperature during the months of March through November. When there is no deviation from mean temperature, an annual mean of 26.43 inches PET is estimated for Region 3. Evaluation of more recent climatic data might produce slightly different PET estimates. Actual annual evapotranspiration is probably less than the estimated potential evapotranspiration in normal years.

Because the average annual precipitation in the Maumee River basin is about 34.5 inches, it can be concluded that there is, on average, more than 8 inches of potential water surplus in years of normal precipitation.

Climatic extremes

Extreme climatic events such as droughts and flood-producing storms are infrequent but can have far-reaching economic impacts. In the Maumee River basin, economic losses caused by floods and drought have been most widespread in urban and residential areas. In recent years, Fort Wayne experienced flooding in 1982 and drought in 1988.

Heavy rainstorms can be described statistically using rainfall frequency analysis. Rainfall frequency data are used primarily to develop design criteria for drainage, flood-control and water-supply projects. To achieve an economic balance between the average cost of damages from occasional floods and the cost of protecting facilities against larger, less frequent floods, water-control projects generally are designed for flood events of selected magnitude and frequency.

Three reports published by NOAA summarize rainfall frequency data for selected durations from 5 minutes to 10 days and *return periods* from 1 to 100 years (Hershfield, 1961; U.S. Weather Bureau, 1957, 1964; National Oceanic and Atmospheric Administration, 1977). Other reports provide data on probable maximum precipitation (Schreiner and Riedel, 1978; Ho and Riedel, 1980) and rainfall intensity-duration-frequency (U.S. Weather Bureau, 1955). A report by the Indiana Department of Natural Resources (1994a) summarizes the NOAA data for Indiana and provides interpolated estimates of rainfall values.

In addition to the above publications, the Midwestern Climate Center in Illinois has updated the heavy-rainfall frequency values for midwestern states (Huff and Angel, 1992). The analyses, which utilize data from NWS stations, provide values on a more detailed scale than values published by Hershfield in 1961.

The term **drought** is generally associated with a sustained period of abnormally low water or moisture supply. Drought, unlike a flood, is not a distinct event because its onset and termination are difficult to recognize. Moreover, the variation in duration, severity and spatial extent leads to a wide variation in environmental and socioeconomic impacts.

Although the most well-known droughts encompass large areas, the variability of rainfall in combination with other factors can produce localized drought conditions in areas having an overall water surplus.

Because of its complex nature, drought can be defined in several ways. Terms referring primarily to the physical conditions of moisture deficiency include **meteorologic drought**, which focuses on deficiencies of precipitation, and **hydrologic drought**, which explains drought in terms of reduced stream flow, ground-water levels, or reservoir storage.

Terms referring to impacts of below-normal precipitation on sectors of society include **agricultural drought** and **urban** or **water-supply drought**. Agricultural drought is defined as a continued period of moisture deficiency so serious that crops, trees and other vegetation fail to develop and mature properly. In a water-supply drought, water shortages lead to adjustments in water-supply management, such as the implementation of conservation measures or the use of alternate water supplies.

One well-known measure of the severity and extent of meteorologic drought is the Palmer Drought Severity Index (PDSI), which is one of three Palmer indices (Palmer, 1965; Alley, 1984, 1985). Values of the Palmer Index for climatic divisions of each state are reported monthly, and sometimes weekly, in documents published jointly by the U.S. Departments of Commerce and Agriculture. Monthly tables and maps of PDSI for all climatic divisions in the United States for the years 1895 through 1989 have been published by NCDC on a CD-ROM entitled "National Climate Information Disc-Volume 1".

Other drought indices are based on cumulative precipitation deficits, reservoir storage, stream flows, ground-water levels, or other hydrologic factors relevant to water supply and agricultural activities.

It is crucial that the drought severity indices selected provides a representative assessment of drought conditions because these indices are commonly used to indicate drought response activities such as water conservation measures and financial assistance. Researchers at Purdue University have worked with the Indiana Department of Natural Resources, Division of Water to investigate the use of various hydrologic parameters as potential regional drought indicators for Indiana (Delleur and others, 1990).

In the Purdue study, the state was divided into three Drought Regions which roughly correspond to the northern, central, and southern thirds of the state. Drought indicator time-series analyses were performed on precipitation for 3-, 6-, 9-, and 12-month intervals; on high temperatures for 1-, 2-, 3-, and 4-month intervals; and on monthly average river flows. Reservoir and ground-water levels and regional Palmer Hydrologic Drought Index (PHDI) were also examined.

Based on the time-series analyses, it was determined that river flow, 3-month precipitation, and PHDI appear to be the most consistent drought indicators for Indiana. River flow and 3-month precipitation time-series were found to be the most useful indicators for short-term duration droughts; whereas, the PHDI series were demonstrated to be the most useful indicators of long-term drought.

Using the drought time series, the Purdue researchers established three levels of drought severity: **drought watch**, **drought warning**, and **drought emergency**. A drought watch requires close monitoring and a few conservation measures; a drought warning could require stringent measures; and a drought emergency necessitates very stringent conservation measures.

Applying the Purdue drought time series indicators to historical streamflow data indicates that drought conditions were present for Region 1, which includes the Maumee River basin, for March and April of 1987 and for May to September of 1988. A **drought watch** existed for March and April of 1987, a **drought warning** for May of 1988, and a **drought emergency** for June through August of 1988.

During the 1988 drought period, it was necessary for the City of Fort Wayne to release water from the Hurshtown upland reservoir to supplement its public water supply from the St. Joseph River.

Additional information about drought and drought planning in Indiana may be found in the following reports. A report by Fowler (1992) describes the effects of the 1988 drought on ground-water levels, stream flow, and reservoirs in Indiana. Reports by the former Indiana Drought Disaster Preparedness Committee (1977), the former Indiana Drought Advisory Committee (1988), the Great Lakes Commission (1990), and the Indiana's Water Shortage Plan (Indiana Department of Natural Resources, 1994b) discuss drought preparedness and planning for Indiana.

GEOLOGY

Geology of the Maumee River basin affects water resource availability by influencing the distribution of precipitation between surface-water and ground-water regimes. Near-surface geology greatly influences *topography* and soil development that, in turn, control runoff and *infiltration* of precipitation. Geology also helps control movement and storage of surface water and ground water.

Perhaps the largest single geologic influence upon the availability of the water resource in the Maumee River basin has been that of glaciation. During the Pleistocene Epoch (Ice Age), *glacial lobes* repeatedly entered Indiana from at least three directions (figure 14). The glacial episodes altered all aspects of the area's hydrology and hydrogeology. Because each successive advance and retreat of glacial ice caused erosion and redeposition of earth materials, glacial sediments and their hydrogeologic properties are very complex.

Little is known about the basin's oldest glacial deposits or the glacial episodes which produced them. This report, therefore focuses on the most recent glacial episodes. Most of the landforms in the basin were produced by these recent glacial and subsequent events. These recent deposits contain most of the readily available ground-water resources.

In the northern portion of the basin most ground-water resources occur in unconsolidated aquifers of glacial origin; whereas in the southern portion these resources occur in carbonate bedrock. Significant areas of overlap exist in the central part of the basin.

Sources of geologic data

Basic geologic data and numerous geologic studies

(see **Selected References** chapter) were used to prepare this section and the **Ground-water hydrology** chapter of this report. The basic geologic data include water well records, oil and gas records, engineering borings, *seismic* studies, geophysical logs, and *exposure* descriptions.

Much of the information about aquifer systems, *lithology*, and bedrock topography in the basin was derived from water well records. More than 10,000 Maumee River basin water well records are on file with the IDNR, Division of Water, Ground Water Section. Since 1959, water well drilling contractors have been required to submit to the IDNR a record of all water wells drilled in the state, including information about the geologic materials penetrated. Although these records are not always complete and the quality of the data varies, these water well records are the most comprehensive set of subsurface geologic and hydrogeologic data existing for the basin.

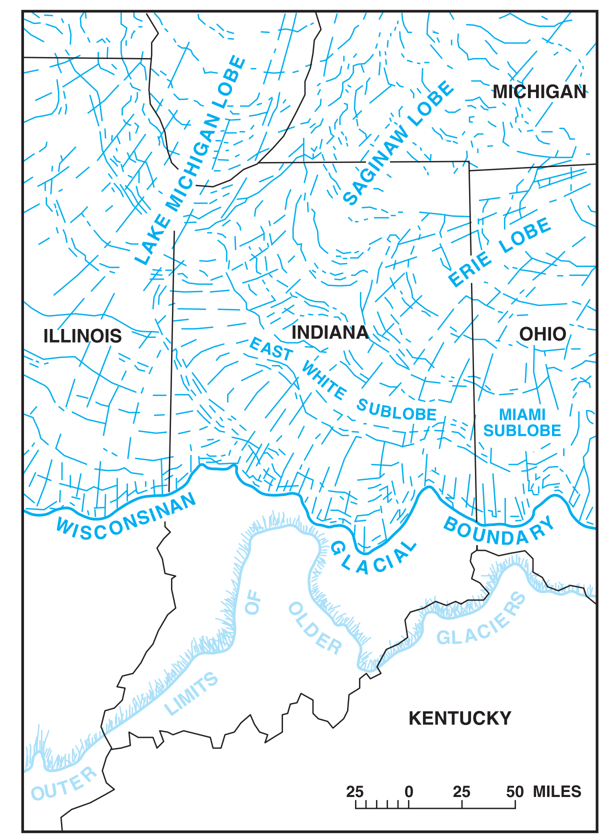

Figure 14. Extent of major ice lobes in Indiana during the Wisconsinan glaciation
(adapted from Wayne, 1965)

A significant portion of the geologic information for Allen County was derived from a report by Fleming, 1994. In addition, an unpublished paper by Fleming provided most of the interpretation of the glacial geology for the entire basin.

Oil and gas records and maps from the IDNR, Division of Oil and Gas and the Indiana Geologic Survey, although of limited value to the overall study, provided basic information necessary to identify major *lithologic* sequences and areas of petroleum exploration.

Regional physiography

The modern landscape of northeastern Indiana reflects a predominance of glacial depositional processes and is characterized by strongly constructional topography. Consequently, the overall *physiography* of the Maumee River basin is strongly *lobate* in character, reflecting the positions of ice lobes at various points in time and space. This pattern is accentuated by relative differences in surface elevations across the basin. Both the northern and southern parts of the basin constitute relatively elevated, broadly *arcuate* uplands that surround a central region of much lower elevation. Factors that have contributed to the formation of the landscape to the north differ markedly from those that affected the landscape to the south.

Upland elevations in the southern part of the basin are generally about 780 to 870 feet above mean sea level (m.s.l.). This part of the basin forms a broadly rolling, intermittently ridged plain characterized by subdued local relief. The southward rise in surface elevation, accentuated by local ridges and other upland areas of glacial derivation, generally parallels a regional rise in the elevation of the bedrock surface. Many of the far southern parts of the basin lie along the northern edge of a broad buried bedrock upland that appears to generally control regional surface elevation.

Upland elevations in the northern part of the basin are generally about 900 to 1000 feet m.s.l. and can exceed 1100 feet m.s.l. Unlike topographic elevations in the southern part of the basin, elevations in the northern part of the basin show no relation to the underlying bedrock. For example, some of the most elevated areas in the northern portion of the basin overlie an extensive bedrock lowland in northern

DeKalb County. Instead, surface elevations in the northern basin are attributable to a significant thickening and stacking of glacial sequences from different source areas, which is indicative of the fundamental *interlobate* nature of glacial processes in that area (see sidebar, **Summary of Late Wisconsin glacial events**. This process is partly responsible for the northern region being typified by rugged local relief, abundant basins of internal drainage, and a preponderance of irregular hummocks, blind valleys, and enclosed depressions that host a myriad of lakes and wetlands. The configurations of some of these topographic features appear inconsistent to known ice flow directions, *meltwater* channels, and other oriented structural features associated with the latest sequence of Erie Lobe deposits. Instead, the configurations of topographic features of the north reflect the structure of buried surfaces of older unconsolidated sequences at depth, thereby suggesting that some elements of this landscape may be *palimpsest*, or inherited. Thus, the uppermost deposits are locally only a veneer, draped over the topography of one or more underlying landscapes.

The central part of the basin is a lake plain that is bisected by the Maumee River. Elevations across most of the plain range from 750 to 765 feet m.s.l., whereas elevations along the Maumee River valley range from about 700 to 750 feet m.s.l.

The contrasts in topographic form in the Maumee River basin are reflected in the definitions of the three broad *physiographic regions* (Malott, 1922; Schneider, 1966) whose juncture lies within the basin (figure 15):

* the **Tipton *Till Plain***, an extensive region of very low relief that covers a large part of central Indiana and generally corresponds to the southern part of the basin;

* the **Maumee Lacustrine Plain**, a flat, nearly featureless lake bottom in east-central Allen County that generally corresponds to the central core of the basin; and

* the **Steuben Morainal Lake Area**, characterized by low- to high-relief, *hummocky* ridges and uplands, numerous enclosed depressions commonly occupied by lakes and wetlands, and a generally deranged drainage pattern throughout. The larger, northern part of the basin falls into this region.

Each of these broader physiographic regions contains various internal terrain elements that are identified on the basis of topographic form and composition of the underlying sequence. The Steuben Morainal Lake Area contains numerous, highly varied terrains, each having its own distinctive characteristics that reflect a particular, and commonly localized, history of interaction among the ice lobes. Fewer individual terrains are recognizable within the Tipton Till Plain, whereas the Maumee Lacustrine Plain appears to be a single terrain.

Overview of glacial history

The Maumee River basin is characterized by a variety of landscapes and unconsolidated deposits. The great majority of glacial deposits in the basin represent the most recent period of glacial activity, known as the late *Wisconsin Age*, which took place between about 22,000 and 13,000 years ago. Consequently, this was one of the last parts of Indiana to become ice-free. The configurations of individual landforms on the comparatively fresh landscape tend to directly reflect the general shapes and styles of sediment bodies deposited by these latest glaciers and their meltwaters.

The relationship between landforms and underlying depositional sequences can be represented by the concept of *glacial terrains*. A glacial terrain is a geographically-defined feature characterized by a particular type of landform or group of related landforms, and a closely associated sequence of sediments that constitute said landforms. Based on this definition, both the landforms and the underlying sediments in a terrain are indicative of a particular type of depositional environment. A glacial terrain is therefore expected to possess a characteristic range of physical properties that strongly influence surface water hydrology, the movement of ground water, soil development, and a host of other environmental attributes. Definition and analysis of glacial terrains thus provide a basis for understanding the geologic history of the basin as well as the distribution and character of a variety of important hydrogeologic parameters.

Over the course of the Ice Age (commonly called the *Pleistocene Epoch* by geologists), the continental ice sheets in the upper Midwest became increasingly differentiated into *glacial lobes* whose axes and regional flow directions corresponded closely in time and space to the carving of the Great Lakes and their

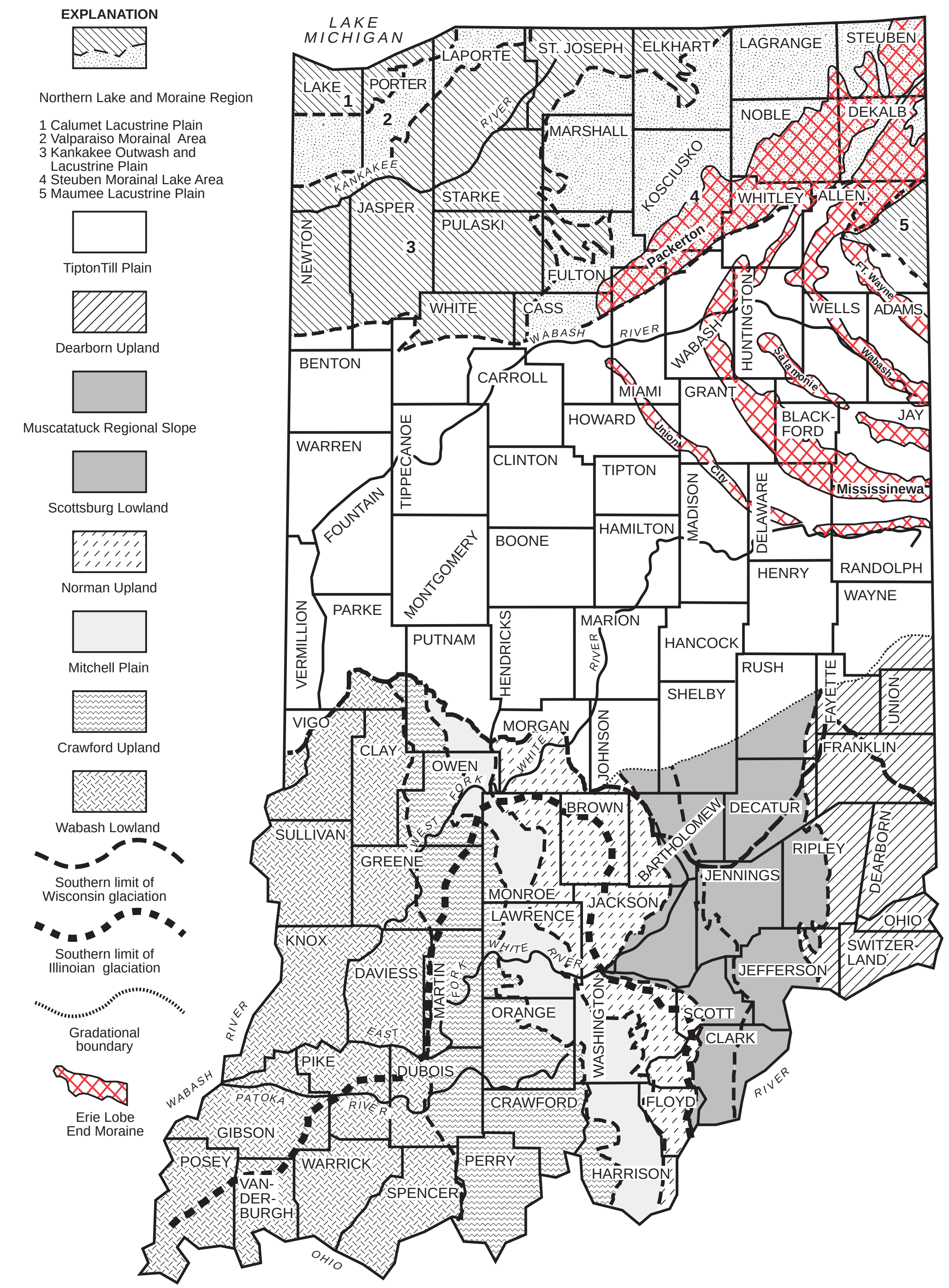

Figure 15. Physiographic regions and Erie Lobe end moraines
(after Malott, 1922; modified by Wayne, 1956) (adapted from Schneider, 1966; modifed by Fleming, written communication, 1994)

Summary of Late Wisconsin glacial events

Northeastern Indiana was repeatedly invaded by ice sheets from both the north and east during the past 1 to 2 million years. Most of the glacial sequences in the Maumee River basin, as well as virtually all of the modern landforms, result from the latest events of the Wisconsin Age, and are generally between about 22,000 and 13,000 years old.

The earliest known Wisconsin glaciers entered the basin about 22,000 ybp (years before present) from the east-northeast (Huron-Erie Lobe) and possibly also from the north-northwest (Saginaw Lobe) and probably covered the entire basin several times. Representative deposits from these advances are restricted to the subsurface within the Maumee River basin. Subsurface relations in northwestern Allen County indicate pinkish clay-loam till of the Saginaw Lobe that may or may not be of Wisconsin age, underlying at least two sheets of grey loam till of the Huron-Erie Lobe. Saginaw Lobe till has not been observed in the southern or far eastern parts of the basin, where these earliest Wisconsin events are marked only by eastern source till. These sequences appear to be draped over a pre-existing upland composed of pre-Wisconsin tills and outwash in the northern part of the basin, but the Huron-Erie Lobe tills and associated outwash were deposited directly on the bedrock in most of the southern part of the basin.

The buried surface of the Huron-Erie Lobe sequence exhibits considerable relief in some places, particularly in west-central Allen County, where it appears to comprise a buried morainal landscape composed of a series of till ridges and associated *meltwater* channels. These uplands effectively blocked meltwater drainage from the central part of the basin and led to the development of a series of regionally extensive glacial lakes that developed episodically in the lowlands to the east. These meltwater-fed lakes represent phases of ancestral Lake Erie and they profoundly influenced later glacial events in the central core of the basin and beyond.

Latest Wisconsin glaciers entered the Maumee basin from the north and east at several times between about 17,000 and 15,000 ybp. The deposits of these advances include brown, sandy, coal- and sandstone-bearing till and outwash of the Saginaw Lobe, and light grey, silty to clayey tills of the Erie Lobe that contain sparse fragments of black shale and *gypsiferous* limestone as well as deformed rafts of lake mud. Regional terrain relations suggest that the two lobes were acting independently and that major periods of ice-margin advance of one lobe were not generally synchronous with those of the other. In general, a tongue of the Saginaw Lobe appears to have preoccupied the northern part of the basin as far south as northern Allen County. Collapse of this ice tongue produced extensive areas of irregular *ablation* topography and large blocks of stagnant ice that subsequently inhibited the northward progress of the Erie Lobe, contributing to the compressed and asymmetrical character of Erie Lobe moraines in that area. The pattern of glacial dynamics and resulting terrain configuration in the **interlobate** northern part of the basin are thus fundamentally different from those to the south, which resulted from extensive advances of the Erie Lobe over relatively smooth terrain.

Sandy till of the Saginaw Lobe is typically present in the subsurface in widely scattered localities throughout the northern basin. It is well-represented in northern Allen and southern DeKalb Counties, where it commonly overlies a persistent zone of basal outwash and is locally capped by a variety of ablation and ice-contact stratified deposits. This sequence generally becomes increasingly finer-grained to the southeast and grades into fan-deltas and other glacio-lacustrine sediments associated with the margin of ancestral Lake Erie in north-central Allen County. The latter stage of the glacial activity that produced this sequence appears to have been characterized by general zonal stagnation and irregular ice margin retreat, in which large blocks of stagnant ice became buried in their own debris, including several ice-contact outwash fans. Deposition was focussed at or near the southern margin of the glacier in Allen and southern DeKalb Counties where the sequence attains its greatest thickness and continuity, whereas these deposits become much less prominent and more internally variable northward in DeKalb County.

Sandy till-like sediments of similar aspect also occur in northern Steuben County, but they appear to belong to a younger, outwash-dominated depositional sequence. This sequence probably forms the buried eastern edge of a line of massive outwash fans (the Angola, Sturgis, and Brighton fans) and associated fan-marginal channels (Pigeon and Fawn River troughs) that are exposed at the surface beyond the Erie Lobe overlap just west of the basin divide. These deposits appear to be inset into a "hole" or depositional basin left by the collapse of earlier Saginaw Lobe ice; they may represent a distinctly younger ice advance or they could be the result of reactivation of the formerly stagnating central ice mass. Their relationship in time to Erie Lobe events is problematic because the three outer Erie Lobe moraines so evident to the south are completely attenuated into one broad upland in Steuben County. The best available evidence suggests that they may be approximately contemporaneous with deposition of the Mississenewa Moraine.

The grey, fine-grained tills of the Erie Lobe comprise the principal surficial sediment throughout the basin. Incorporation of lacustrine mud as the ice advanced through the bed of ancestral Lake Erie overwhelmed the coarser parts of the sediment load and led to deposition of tills that are commonly about 90 percent silt and clay and only rarely contain appreciable sand lenses. The earliest Erie Lobe advance(s) extended as far as 50 miles south of the central basin and left a relatively uniform sheet of clay-loam till in their wake. In contrast, ice flowing northward out of the lake plain was impeded by the irregular Saginaw Lobe ablation drift and dead ice and probably took much longer to reach less distant terminal positions. The landscape associated with the Erie Lobe till in this part of the basin locally exhibits structural patterns that more closely resemble the likely orientations of crevasses and ice marginal features of the underlying Saginaw Lobe. This strongly palimpsest topography resulted from the melting of buried Saginaw Lobe ice masses and subsequent collapse of overlying materials. Not surprisingly, the earliest Erie Lobe deposits in the northern basin are more variable in their texture and structure than elsewhere and are locally associated with small ice-contact sand and gravel bodies.

Erie Lobe tills present within the Wabash Moraine and points inward (eastward) are predominantly thick silty-clay to silty-clay loams, and contain remarkably few large clasts. The finer texture could have resulted from a change in the sediment source during the same advance that produced the earlier tills, but the abrupt contrast across the outer edge of the Wabash argues against this possibility. A more likely possibility is that the ice front retreated eastward sufficiently far to allow another lake phase to develop in the lake basin and accumulate lake clays. These clays were subsequently incorporated into the ice as it readvanced to the Wabash Moraine. The moraine is generally a massive physiographic feature, especially in the northern basin, and the ice front probably remained at this position for a substantial period. Meltwater draining the northern part of the ice sheet cut tunnel valleys such as Cedar Creek Canyon, which in turn fed the ice-marginal Eel River. Outwash bodies also become increasingly prevalent within the moraine northward from Allen County, culminating in the large Fish Creek fan that forms the morainal front in eastern Steuben County. The northernmost part of the moraine thus may partly be a complex of overridden outwash fans.

The formation and subsequent catastrophic drainage of glacial Lake Maumee during the late Wisconsin Age represent the final events in the development of the Maumee basin. Fine-grained lake sediments and gravelly beach ridges can be traced far into Ohio, indicating that the lakebed covered several thousand square miles and may have had a maximum water depth approaching 75 feet in some places. Perhaps in response to ice-margin fluctuations further east in the Erie Basin, the level of glacial Lake Maumee appears to have overtopped a sag in the Fort Wayne Moraine near what is now downtown Fort Wayne, unleashing a massive volume of water often referred to as the **Maumee Torrent**. This catastrophic event scoured out a 1- to 2-mile wide outlet known as the **Wabash-Erie Channel** that is one of the most striking topographic features in the basin. Following the drainage of glacial Lake Maumee, regional surface drainage continued to flow southwest through the Wabash-Erie Channel for hundreds, or perhaps thousands, of years until the Erie Basin became ice-free and an eastward drainage route was opened. The record of this early stage of post-glacial drainage is well preserved in the bottom of the Wabash-Erie Channel near Fort Wayne. There, as much as 30 feet of fine sand, silt, and organic sediments were deposited in a complex fluvial-lacustrine-palustrine environment during the interval following the cutting of the outlet and leading up to the complete capture of surface drainage by the Maumee River. The course of the Maumee River generally follows the route of an earlier subglacial channel, but the modern, eastbound drainage system did not become established until headward erosion by the river captured the St. Joseph and St. Marys Rivers.

Sequence of events

ERIE LOBE	ANCESTRAL LAKE ERIE	SAGINAW LOBE
	Minor readvance of ice further east in Lake Erie causes lake level to overtop sag in Fort Wayne Moraine, resulting in catastrophic drainage via *Wabash-Erie Channel*	Melting of buried ice masses in northern basin creates classic *knob-and-kettle topography* and numerous lakes and wetlands
General ice margin retreat. Deposition of *Fort Wayne Moraine* during stillstand. Ice retreats back into Ohio	Opening of lake basin in front of receding ice and development of *Glacial Lake Maumee.* Deposition of lake mud in central basin and beach deposits along shorelines	
		Zonal stagnation and general retreat
Readvance of ice front to *Wabash Moraine* (*silty-clay and silty clay-loam inner tills of the Lagro Fm*) (**event 6**)	Closing of lake basin, incorporation of lake clays into overriding ice	
General retreat of ice front eastward into Lake Erie Basin. Formation of *Mississinewa Moraine* during minor readvance (*clay-loam outer tills of the Lagro Formation*) (**event 5**)	Proglacial lake develops in Erie Basin. Accumulation of *lake clays* derived from recently deglaciated landscape to north and south	Ice front readvances into northern Steuben and Lagrange Counties. Deposition of outwash fans (*Brighton, Sturgis, Angola fans*) and ice-marginal channels (*Fawn and Pigeon River troughs*) mainly just west of Maumee Basin (**event 4**)
Ice overrides lake basin and spreads both north and south from core of basin, ultimately reaching terminal position south of basin at *Union City Moraine* while abutting and eventually overriding large dead-ice landforms and stagnant ice masses of the Saginaw Lobe to north (*clay-loam to silt loam outer tills of Lagro Formation*) (**event 3**)	Catastrophic(?) drainage of lake to southwest	
Erie sublobe begins advancing through western Ohio, incorporating abundant lake mud into base of ice	Area of lake basin becomes attenuated while meltwater input increases from both ice lobes	General collapse and zonal stagnation (*ice-contact fans; hummocky ablation complex; dead-ice landforms*)
Ice front retreats far back into eastern Great Lakes (*Erie Interstadial*)	Large proglacial lake impounded between morainal complex to west and ice front to east. (*deltaic silt, sand, and waterlain till from retreating Huron-Erie Lobe; sand and silt in fan-deltas from Saginaw Lobe meltwater streams*)	Southern edge of lobe advances to terminal position in northern Allen County (*proglacial outwash, sandy loam till, fan-deltas*) (**event 2**)
		General recession or zonal stagnation
Main advances of Huron-Erie Lobe into central Indiana. Formation of complex of buried recessional moraines in western and central Allen County (*grey loam tills of the Trafalgar Formation*) (**event 1b**)		Ice advances across preexisting upland in Noble and DeKalb Counties reaching at least to northwestern Allen County (*pinkish clay loam till*)(may be pre-Wisconsin age) (**event 1a**)

major bays (figure 14). During the late Wisconsin Age, northeastern Indiana was repeatedly covered by ice from two such lobes—the Saginaw Lobe from the north, and the Huron-Erie Lobe from the east. However, the shapes and regional distributions of landforms suggest that the Huron-Erie Lobe became increasingly dominated by ice flow from the Erie Lowland during the late Wisconsin glaciation. Hence, the *provenance* of latest eastern source deposits is referred to as "Erie Lobe", whereas the earlier eastern source deposits in the basin are commonly referred to as "Huron-Erie Lobe".

The distinct geologic and topograhic differences within the basin are directly related to the glacial history of the region. The glacial terrains in the southern and central parts of the basin were mainly produced during the most recent advances of the Erie Lobe, and are characterized by a relatively narrow range of depositional sequences and regionally extensive but relatively simple landforms. In contrast, the northern half of the basin constitutes a much more complex, composite region formed by several overlapping advances of the Huron-Erie, Saginaw, and Erie Lobes (see sidebar on **Summary of Late Wisconsin glacial events**). These two strongly contrasting regions, and the glacial terrains within them, provide a convenient and logical basis for describing the history and physical properties of the glacial deposits at various places within the basin.

Overview of glacial deposits

The unconsolidated deposits in the Maumee River basin are primarily the result of glacial activity during the Ice Age. The great variability in thickness of the unconsolidated sediments in the southern and northern parts of the basin, 50 to 100 feet and 150 to 400 feet, respectively (figure16), is an indication of the differences in glacial activity in the northern and southern parts of the basin.

Most deposition associated with glaciers takes place at or near the ice margin. The particular type of deposit and its expression as a landform depend on the dynamics of the glacier, the mechanics of sediment transport within the glacier and the method of sediment deposition. In general, materials deposited by a robust, active ice sheet tend to be more uniform in both thickness and sediment type than those deposited from stagnant or sluggish ice. Both styles of deposition appear to have operated at different times during

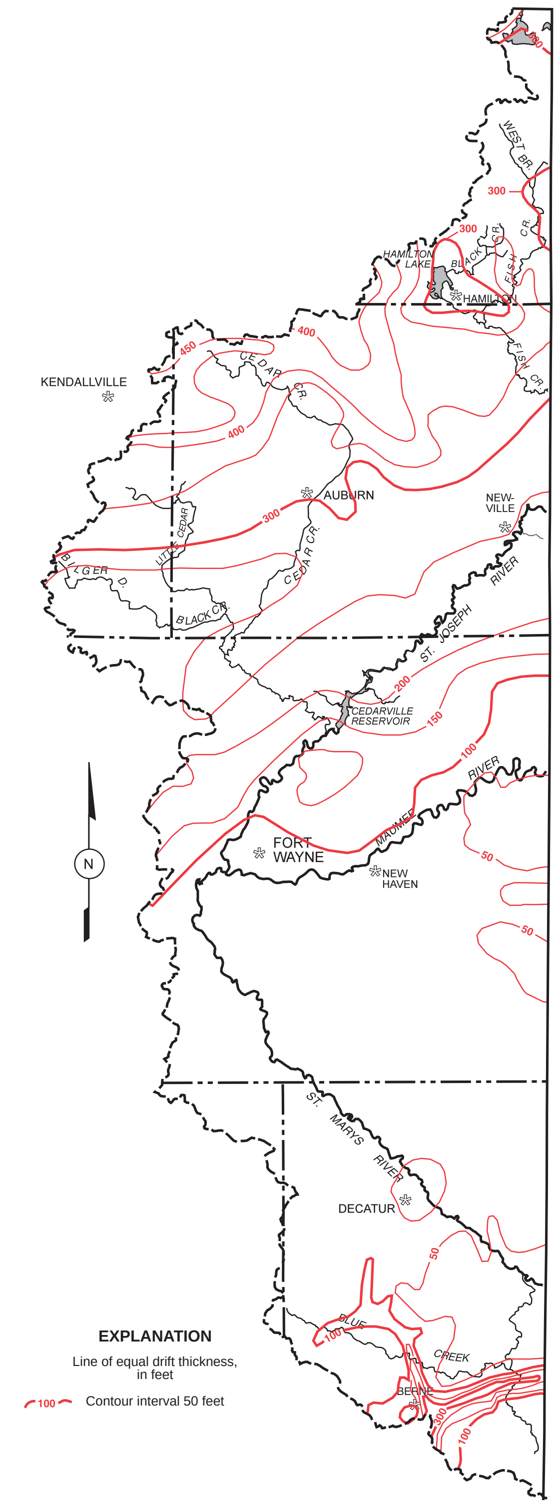

Figure 16. Thickness of unconsolidated deposits
(adapted from Gray 1983)

the glacial history of the basin.

Through time, accumulation of ice toward the center of a glacier is balanced by melting at and near the margin. This equilibrium has two important consequences. First, the outward flow of ice within the glacier transports sediment to the ice margin where it is deposited by a variety of processes. Second, the melting ice front feeds meltwater streams that flow both away from and parallel to the ice margin. The high energy typical of most meltwater streams results in the removal of silt and clay from the glacial debris. This process commonly concentrates sand and gravel in the form of *outwash* deposits. Within a depositional system, the relative coarseness of the outwash sediments tends to decrease with increasing distance from the ice front. Outwash bodies range from narrow and discontinuous channels to broad, regionally extensive plains and *fans*. The detailed geometry of outwash bodies depends on such factors as the configuration of the landscape over which the meltwater flows, the size and location of meltwater outlets from the ice front, the sediment load each meltwater stream carries, and the behavior and duration of the ice front at a particular location.

Outwash constitutes several landforms within the Maumee River basin (figure 17). It forms small *valley trains* along the St. Joseph River and Cedar Creek, as well as broader *aprons* and fans in the vicinity of Huntertown (northwestern Allen County), western Fort Wayne, and Fish Creek (eastern Steuben County). Large buried outwash bodies also occur at many places within the basin, notably in northern Allen County and northern Steuben County. Some of the buried outwash units in northern Allen County appear to comprise an extensive *outwash plain* that was deposited as the Saginaw Lobe advanced down a preexisting regional slope into the basin of ancestral Lake Erie (Fleming, 1994). The outwash plain was partially eroded during subsequent glacial events and is now buried by as much as 50 to 100 feet of younger sediments.

The land surface over the greater part of the Maumee River basin is underlain by glacial *till*, a fine- to medium-grained, poorly-sorted sediment that was transported near the base of the glacier and deposited directly by ice with minimal reworking by meltwater and *mass movement*. Most till contains scattered rock fragments set in an *overconsolidated* fine-grained matrix. Each ice advance tends to produce a characteristic till sheet that can usually be distinguished from other till sheets on the basis of grain-size distribution, combinations of rock and mineral fragments unique to a particular source area, and other diagnostic attributes. The relative proportions of sand, silt, and clay that form the matrix of any particular till unit depend on the *source area* of the glacier as well as on the kinds of processes that release the sediment from the ice. These processes, together with the prevailing conditions at the bed of the glacier during and after till deposition, strongly influence the geotechnical properties of a particular till unit (see appendix 4 for a discussion on geotechnical properties of Erie Lobe till units).

The surface till in most of the Maumee River basin is part of the Lagro Formation (Wayne, 1963) and is typically clay-rich, reflecting the abundance of both lake mud and shale bedrock in the source area of the Erie Lobe east of the basin. In contrast, tills of the Saginaw Lobe, which underlie Erie Lobe tills in many places in the northern part of the basin, are sandy due to the combination of coarse-grained bedrock and abundant outwash in the source area. Somewhat older Huron-Erie Lobe tills (the Trafalgar Formation of Wayne, 1963) present in the subsurface throughout the basin, are silty or loamy in texture and are dominated by particles derived from a mixed bedrock source.

Debris flow deposits are a significant component of the glacial sediments in the Maumee basin. Although a variety of processes can be involved in the formation of these mass movement deposits, most debris flows of glacial origin form when the loss of supporting ice induces the slumping and sliding of recently thawed supersaturated sediments. Many debris flow deposits closely resemble glacial till and are sometimes referred to as *flow tills* and *mud flows*. Because of their similarity, the distinction between debris flows and true glacial till can be problematic in Pleistocene deposits. This is especially true where the two occur together in the subsurface within the same depositional sequence. It is best in such instances, therefore, to refer to the entire assemblage as *till-like sediment*, which acknowledges the variety of processes and sediment types represented.

Debris flows can be formed from almost any kind of pre-existing sediment and are widely scattered throughout the Maumee basin. However, flowage of glacial sediments was most commonly triggered by the melting of adjacent or *subjacent* ice blocks. Hence, debris flows are most abundant in the northern half of the basin, where they are associated with bodies of *ice-contact stratified drift*. The latter are composed mainly of sand and gravel deposited by meltwater in, on, or against disintegrating ice. Subsequent melting of the surrounding ice caused these sediments to collapse, giving them their characteristically irregular form. Common types of ice-contact stratified deposits include narrow, linear, and commonly sharp-peaked ridges of sand and gravel referred to as *eskers*; and irregular masses of sand, gravel, and till-like sediment known as *kames*, that range in shape from semi-conical mounds to broad-crested, hummocky ridges.

Ice-contact stratified deposits, debris flows, small bodies of outwash in channelized form, and localized pond sediments commonly occur together as *ablation complexes* formed during the melting of an ice sheet. Ablation complexes can be quite thick and widespread when large debris-covered parts of an ice lobe become stagnant and melt via the process of downwasting. In the northern part of the basin, large-scale ablation deposits occur within which individual sediment bodies commonly have little homogeneity and extent.

Deposits formed in glacial lakes are also widespread in the Maumee basin, particularly along former ice margins where meltwater was impounded by ice or debris. Because these ice margins shifted over time, most of the glacial lakes were ephemeral features with generally little accumulation of *lacustrine sediments*. However, in the eastern part of the basin topographic and ice margin conditions were favorable for the establishment of large and relatively long-lived *proglacial* lakes in which thick widespread blankets of lacustrine sediments accumulated. This area, known as the **Maumee Lacustrine Plain** (figure 15), represents the former bottom of **ancestral Lake Erie**. The lakebed covers a large part of eastern Allen County and extends across northwestern Ohio to Lake Erie. Sediments deposited in the ancestral lake range from silt and clay, laid down in quiet water in the central portions of the lake, to coarse sand and gravel associated with high-energy shorelines. Much older sequences of lake sediments are found at depth in this same general part of the basin, and are thought to date from one or more earlier phases of Lake Erie that predated the latest advances of the Erie Lobe. Clay-rich lake sediments can be found beneath the surface tills at many places throughout the Lake Erie basin and are generally believed to have furnished the abundant clay to the ice sheets that deposited these tills.

Glacial terrains

The previous sections dealt mainly with regional aspects of basin physiography and unconsolidated deposits. The following discussion emphasizes the relationships between internal sequence elements, landscape characteristics, and geologic processes within specific glacial terrains (figure 17) to provide a context for evaluating the availability of ground water and its relationship to surface water and to human activities at the land surface.

Morainal highland

The morainal highland that characterizes the northern part of the Maumee River basin is one of the most topographically varied and geologically diverse regions in the state. A large part of this morainal highland corresponds to what has classically been described as the **interlobate** region of the Saginaw and Erie Lobes (e.g., Chamberlin, 1883; Dryer, 1889, 1893, 1894; Leverett and Taylor, 1915; Malott, 1922). This area generally represents the onlap of a succession of Erie Lobe *end moraines* onto preexisting deposits and perhaps ice of the Saginaw Lobe. The region is characterized by a preponderance of irregular mounds, hummocky ridges, closed depressions, and dead-end channels, which attest to deposition within and atop abundant masses of stagnant ice. Large parts of the landscape are internally drained and are dotted with numerous lakes and wetlands, many of which are underlain by significant accumulations of peat and marl.

Many of the ridges and hummocks in the region consist of clayey till-like sediments of the Erie Lobe, but the till-like sediments range widely in thickness from more than 100 feet to a thin veneer only a few feet thick. The Erie Lobe deposits are plastered atop an older, hummocky surface that is at least partly developed on latest till, outwash, and ice-contact stratified deposits of the Saginaw Lobe, but also on somewhat earlier Huron-Erie Lobe sequences as well.

The late Wisconsin deposits are draped over a much older tableland composed of a thick sequence of *pre-Wisconsin* tills (figure 18). Sporadic, thin sand and gravel lenses occur within this older sequence, which locally attains thicknesses approaching 350 feet and may be responsible for much of the overall elevation of the northern part of the basin. This great mass of

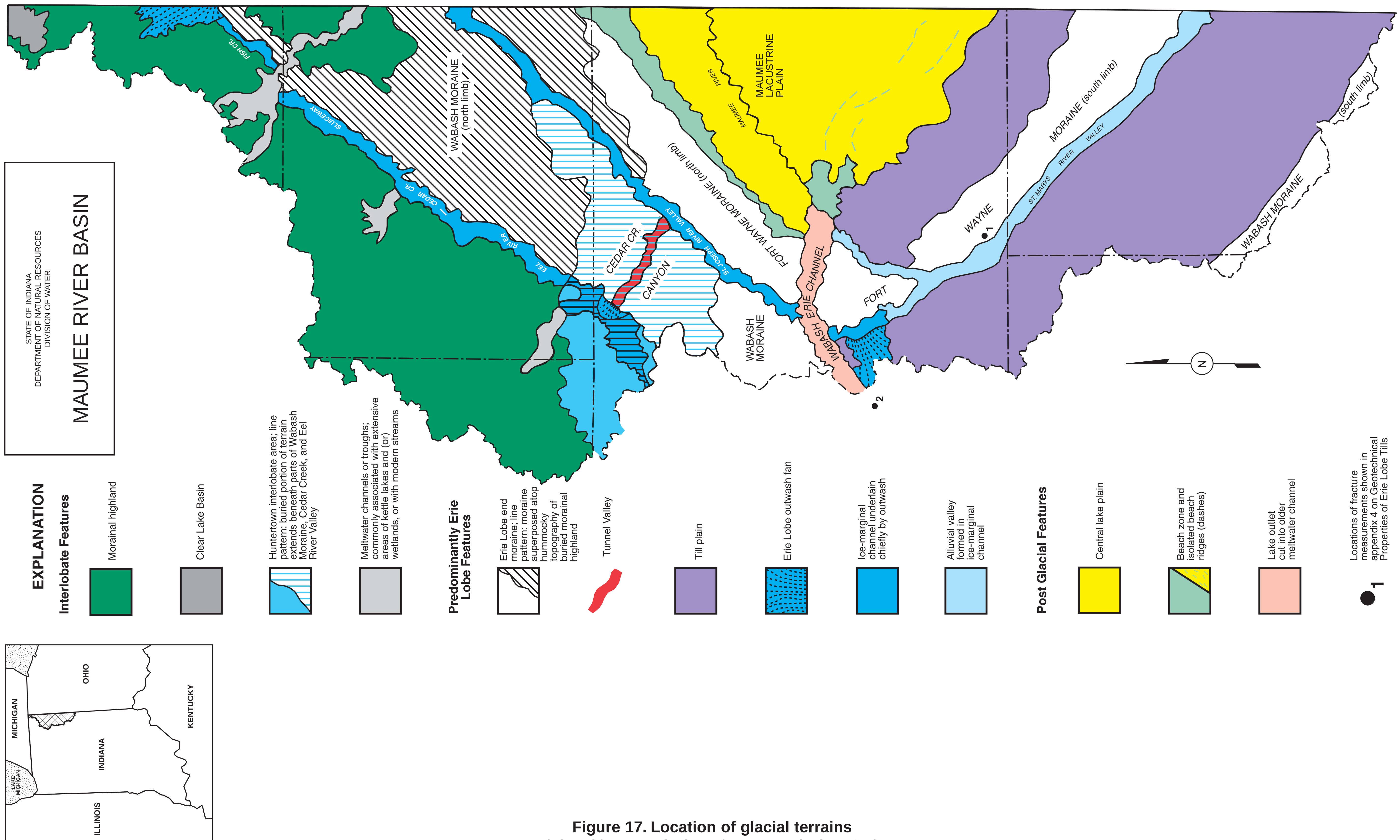

Figure 17. Location of glacial terrains
(adapted from A. H. Fleming, written communications 1994)

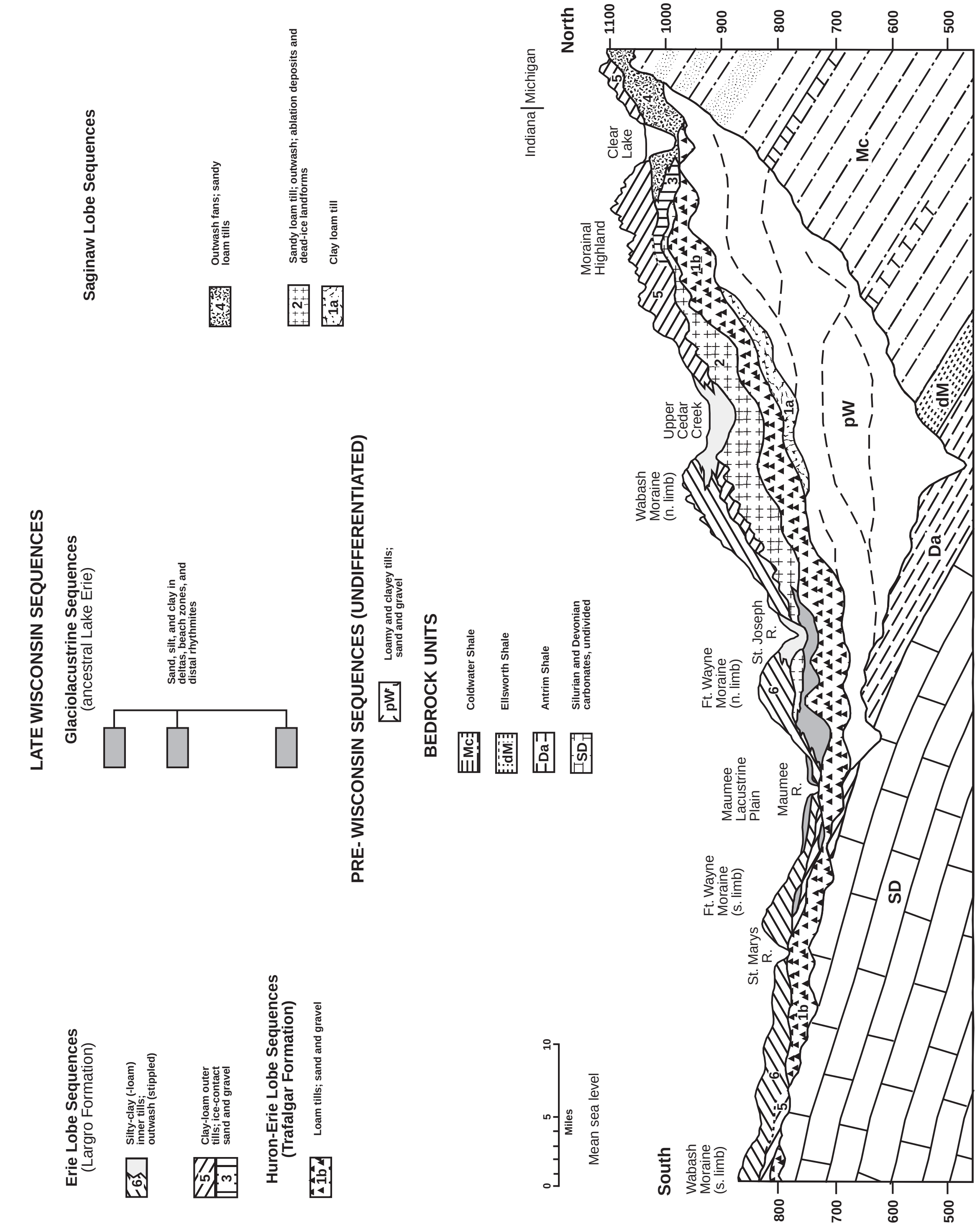

Figure 18. Schematic cross section of unconsolidated sequences and near-surface bedrock geology
(adapted from A.H. Fleming, written communication, 1994)

older drift lies in the lee of a major, south-facing bedrock *escarpment* that rises to elevations in excess of 1,100 feet m.s.l. a few miles north of the Michigan state line. The elevation of the pre-Wisconsin deposits falls sharply south of central DeKalb County and a corresponding thickening of late Wisconsin sequences occurs.

The distribution of well-developed knob-and-kettle topography is commonly thought to parallel the former extent of the Saginaw Lobe, and may indicate the presence of buried ice-contact stratified drift and other hummocky deposits of that lobe. In areas characterized by high densities of large depressions, *kettle lakes* are common.

Huntertown interlobate area

Although a detailed and systematic analysis of Saginaw Lobe deposits has not been made for the entire region, a local terrain in northern Allen County, referred to as the **Huntertown interlobate area** (figure 17), may indicate the potential range of depositional *facies* and the relationship to overlying landforms. The Saginaw Lobe deposits in the Huntertown interlobate area range from less than 20 feet to more than 100 feet thick and occur in distinct *facies tracts.* The distribution of the facies tracts partly reflects the nature of the surface over which the sequence was deposited, as well as changes in glacial dynamics during deposition. The lower part of the sequence, which consists of an extensive blanket of proglacial outwash capped by sandy till, was produced as ice advanced into the area. The outwash is composed chiefly of medium to coarse sand that was deposited in an outwash plain over a gently undulating to channeled surface on older Huron-Erie Lobe till. At any given location, the outwash generally coarsens upward, reflecting increasing proximity to the advancing ice during deposition. Stacked channel-fill deposits composed of coarse sand and some gravel fill former valleys on the underlying till surface, whereas finer-textured sequences of fine sand and silt occur in *fan-deltas* where the meltwater entered the northern extremities of ancestral Lake Erie further to the southeast (Fleming, 1994).

The recession of the Saginaw Lobe in the Huntertown area was characterized by general *zonal stagnation* and localized deposition of *ice-contact fans* along ephemeral ice margins. In this process, large masses of stagnant ice were rapidly buried by outwash and debris flows, effectively insulating them for long periods. The largest fans were deposited along the most long-lived of these ice margins, and were accompanied by arcuate *fan-marginal channels* that outline the position of the lobe during temporary pauses in the glacial retreat process.

The Saginaw Lobe deposits and the buried ice blocks were subsequently overridden by the Erie Lobe and further buried by clayey till. The buried ice ultimately melted, causing the overlying sediments to collapse, thereby creating enclosed depressions. Because the buried ice blocks were commonly lined up along fan heads, marginal channels, and other structural trends particular to the Saginaw Lobe, the orientations of the resulting collapse features generally bear little relation to the surficial Erie Lobe tills or latest ice movements, but are instead indicative of a *palimpsest* condition. At many places in the Huntertown interlobate area where collapse features are present, surficial tills are thin or absent and the top of the Saginaw Lobe deposits are exposed. Peatlands subsequently developed in many of the enclosed depressions and are an important element of the modern internal drainage (Fleming, 1995).

Till plains

Till plains are the predominant terrain in the southern extent of the basin, where they form the very gently rolling to virtually flat landscapes typical of large parts of Adams, Wells, and southern Allen Counties. The elevation of the till plains typically ranges from about 780 to 840 feet m.s.l., gradually rising southward. A few small areas of similar aspect also occur within the northern basin but are regarded as local variants of the dominant morainal terrains in that area.

All of the major till plains in the basin developed on clayey till of the Lagro Formation. A thin veneer of *ablation* deposits—mainly fine-grained sediments reworked by meltwater and mass movement during the final melting of the Erie Lobe—is also present in some places and imparts a minor amount of local relief in the form of subtle *ablation hummocks.* Other than a few stream valleys that locally dissect the till plains, there is little internal relief. Many parts of this landscape are very poorly drained, and drainage ditches are commonly employed to carry away runoff and to lower the characteristically shallow water table within the slow-draining till.

The till plains exhibit a relatively consistent stratigraphy that consists of one or more clayey Erie Lobe tills of the Lagro Formation atop loamy Huron-Erie Lobe tills of the Trafalgar Formation (Wayne, 1963). The clayey, upper till sequence is mostly between 20 and 40 feet thick and is composed primarily of moderately *overconsolidated* basal till deposited at the base of an actively moving ice sheet. Consequently, it shows a very pronounced *fabric* in many exposures, marked by steeply dipping shear planes and deformed rafts of lake sediment. The till commonly contains a well-developed system of near-vertical fractures that extend to a depth of about 20 to 25 feet.

The till sequences overlie a somewhat irregular, but generally southward-rising erosional surface on carbonate bedrock that lies at depths ranging from more than 100 to less than 40 feet (figure 18). Small, tabular sand and gravel bodies are scattered between the tills and along the bedrock surface.

Erie Lobe end moraines

Two prominent *end moraines* of the Erie Lobe, known respectively as the **Fort Wayne Moraine** and the **Wabash Moraine**, are largely responsible for defining the lobate form and overall extent of the Maumee River basin (figure 17). They constitute broadly arcuate, ridged uplands composed of a thick sequence of very clayey till-like sediments. The end moraines represent the positions along which the Erie Lobe margin became stationary for extended periods during its final advance into northeastern Indiana. The Wabash Moraine is thought to be a *terminal moraine*, which marks the maximum extent of this latest ice advance, whereas the Fort Wayne Moraine is probably a *recessional moraine* deposited where the ice margin stabilized for some time during its overall retreat.

Both moraines are generally composed of thick till that appears to have been deposited predominantly by passive meltout of clayey sediment from repetitively sheared stacks of debris-rich ice. Fine-grained debris flows and very small lenses of fine sand are also common. The fine-grained deposits in the cores of these moraines generally range from about 50 to 75 feet in thickness, but they locally exceed 100 feet in the Wabash Moraine northwest of Fort Wayne. Small bodies of lacustrine silt and a few ice-contact stratified deposits are also present in the northern parts of both moraines.

Exposures, borehole information, and surface samples in and behind the Wabash Moraine locally indicate a thick upper sequence of silty-clay to silty-clay loam tills in sharp contact with a lower clay-loam till unit (figure 18; Fleming, 1994). Deformed lenses of lacustrine mud are locally present between the two sequences and within the upper sequence. These relationships suggest that the increased clay content of the inner tills may have been derived from another phase of ancestral Lake Erie that formed during a brief retreat of the Erie Lobe, although detailed radiocarbon age dating of the two till sequences would be desirable to corroborate this possibility.

Both the Fort Wayne and Wabash moraines have distinct north and south limbs that lie on opposite sides of the basin (figure 17). The north and south limbs differ appreciably in their topographic expression and, to a lesser extent, internal composition. The southern limbs of both moraines are considerably more subdued than their northern counterparts and tend to form broad, rolling uplands only moderately higher than the surrounding till plains. Crest elevations of the south limbs range between 825 and 870 feet m.s.l., or about 30 to 60 feet higher than the adjacent till plains. Both south limbs are typically somewhat asymmetric in cross section, with their outer faces generally being more steeply sloping than their gradual, ramp-like inner sides. The south limb of the Wabash Moraine is sufficiently robust, however, to control the position of the surface divide that forms the southern boundary of the basin. The stratigraphy beneath the south limbs of both moraines is comparable to that of the adjacent till plains, differing mainly in the greater thickness of the Erie Lobe tills. The south limbs of both moraines are associated with modern river valleys that originated as *ice-marginal channels* that drained the meltwater issuing from the ice front during moraine deposition.

The north limbs of the Fort Wayne and Wabash moraines are considerably broader, taller, and more topographically varied than the south limbs. Over much of the northern basin, they are separated from each other only by the relatively narrow valley of the St. Joseph River, and they collectively form a broad, more or less continuous belt of morainal topography that covers a large part of the northern basin (figure 17). Both north limbs contain appreciable internal relief in the form of enclosed depressions, irregular hummocks, and small, linear ridges that parallel the regional trends of the moraines. The north limb of the Wabash Moraine is a particularly prominent feature, consisting of a series of bold ridges that locally stand more than 100 feet above adjacent areas. North of Allen County, both moraines appear to be *superposed* atop the northward-rising morainal highland of the northern basin. Consequently, the crest elevations of both moraines also rise northward, with the Wabash experiencing the greatest elevation gain from about 880 feet m.s.l. in northern Allen County to about 1,000 ft m.s.l. at the Ohio state line in southeastern Steuben County.

Although the north limbs of both moraines are composed predominantly of fine-grained till up to 100 feet thick, sand and gravel are common within the Wabash Moraine. The granular material occurs primarily in the form of outwash, but also as other kinds of bodies. The distribution and form of the sand and gravel units are related to the nature of meltwater drainage at different places within and in front of the ice sheet when it stood at the moraine. Tabular to irregularly-shaped sand and gravel bodies of uncertain continuity appear to be relatively common in the widest part of the Wabash Moraine in DeKalb County; they are consistently present within or beneath the clayey till at depths ranging from about 20 to 40 feet. The tabular to irregularly-shaped granular units locally comprise more than half of the Erie Lobe sequence in the core of the moraine, and are thought to consist of a complex of small *outwash fans* that were deposited as the ice initially advanced to the position of the moraine. The capping tills were deposited when the ice subsequently advanced onto its own outwash.

The **Fish Creek fan** is a large, *ice-contact fan* located along the front of the Wabash Moraine in extreme eastern Steuben County and adjacent parts of Ohio. The strongly collapsed head and intensely pitted surface of this fan indicate that it was deposited up against the front of the glacier. Sand and gravel forms the surface of most of the fan, and only the *fan head* is capped by till-like sediment, indicating that the ice did not advance far over the body of the fan. The valley of Fish Creek lies at the toe of the fan and probably originated as a *fan-marginal channel*, draining the meltwater that emanated from the growing fan. Small, high-level *outwash terraces* occur as much as 30 feet above the modern stream level and attest to the amount of incision that has occurred since the outwash was deposited.

Ice-marginal channels

The present surface drainage network of the Maumee River basin contains several former ice-marginal channels, including the St. Marys and St. Joseph Rivers and Cedar Creek. These channels drained meltwater issuing from the ice front during the deposition of the Erie lobe end moraines.

The **St. Marys River Valley** is a small, alluvial valley that follows the toe of the south limb of the Fort Wayne Moraine. Other than widely scattered, high-level outwash terraces, there is little sand and gravel associated with the St. Marys River, which is typically underlain by as much as 15 or 20 feet of modern *alluvium* that generally rests atop a stripped surface on hard loam till of the Trafalgar Formation.

The **St. Joseph River Valley** (figure 17) originated as the ice-marginal channel in front of the north limb of the Fort Wayne Moraine. The St. Joseph River forms a deep narrow *sluiceway* flanked by numerous high-level outwash terraces that mark former levels of the river before downcutting to the present channel level. As much as 60 feet of outwash sand is present below some of these terraces, particularly in the lowest reaches of the valley in and near Fort Wayne. Sequences of sand and silt deposited in *fan-deltas* that predate the latest Erie Lobe tills underlie the outwash at some places and suggest that some segments of the valley are situated over fingers or localized lake basins associated with the earliest phases of ancestral Lake Erie (Fleming, 1994).

The upper valley of **Cedar Creek** and the **Eel River Valley** to the west constitute the major ice-marginal channel system for the north limb of the Wabash Moraine. This system contains a significant amount of outwash and originally comprised a unified, southwest-flowing sluiceway known as the **ancestral Eel River** when the Erie Lobe stood at the moraine. Scouring of the sluiceway floor by meltwater resulted in the superposition of Erie Lobe outwash directly atop thick sections of older Saginaw Lobe outwash. In northern Allen County, composite sand and gravel thicknesses as great as 75 to 100 feet occur below parts of the Eel River valley floor.

The outwash and meltwater that shaped the early Eel River were derived from numerous outlets in the Wabash Moraine, now marked by linear sags and flat-bottomed troughs. The most striking of these features is **Cedar Creek Canyon** (figure 17), a remarkably straight, 50- to 100-foot deep, narrow gorge that cuts straight across the moraine. The form of the canyon indicates that it originated as a *tunnel valley*, a type of sub-ice channel cut by meltwater flowing under considerable hydrostatic head. A prominent outwash fan formed across the Eel River Valley where meltwater exited the mouth of the tunnel valley. After the ice front receded from the moraine, meltwater flow became insufficient to mobilize the coarse fan materials, and drainage from the upper Eel was diverted southeast down Cedar Creek Canyon (Bleuer and Moore, 1974). This classic example of *stream piracy* added substantially to the size of the modern Maumee River drainage system and resulted in the paradox of Cedar Creek now flowing in a direction opposite to that which existed when the canyon was cut. This series of events also separated the ancestral Eel River from its headwaters, leaving part of the valley just southwest of Cedar Creek Canyon as an excellent example of an abandoned, high-level valley. Today, this area lies astride the axis of the eastern continental drainage divide separating eastbound Great Lakes drainage (via the Maumee River) from westbound Mississippi drainage (via the Wabash and Ohio Rivers).

Maumee Lacustrine Plain

The virtually flat landscape that characterizes the east-central part of the Maumee River basin is part of the **Maumee Lacustrine Plain** (figure 17). The lake plain represents the bottom of **Glacial Lake Maumee**, the forerunner of modern Lake Erie that formed between the front of the retreating Erie Lobe and the Fort Wayne Moraine. The elevation of the former lake bottom ranges from about 765 feet m.s.l. near its margins, to about 740 feet m.s.l. adjacent to the Maumee River along its axis. Internal relief is minimal, consisting of widely scattered small sand bars, spits, and wave-scoured terraces, most of which are concentrated within a mile of former shorelines. The northern edge of the lake plain is marked by a complex of prominent *beach ridges*. As much as 30 feet of beach sand and gravel are found atop wave-scoured till benches that are *incised* into the lakeward side of the Fort Wayne Moraine.

The lake plain is underlain by a variety of *glaciolacustrine* sequences that were deposited at different times under widely different conditions. A surficial veneer of laminated silt and clay deposited in relatively quiet water is widespread in the central and southern part of the plain, whereas a blanket of fine sand is more characteristic to the north, where water depths were less and depositional energy somewhat greater. These *post-glacial* sediments overlie a highly varied sequence of waterlain tills, debris flows, and small deltas derived from the retreating Erie Lobe.

Older glaciolacustrine sequences are present sporadically beneath the Erie Lobe deposits, particularly in the northern part of the lake plain. They were deposited in a much earlier and larger phase of **ancestral Lake Erie** and can be traced northward beneath parts of the Fort Wayne Moraine to the St. Joseph River (figure 18). Some of these older sequences were derived in part from Saginaw Lobe meltwater that entered the lake from the north and deposited *fan-deltas*. Deltas are composed in part of thick units of fine sand that overlie and grade laterally (lakeward) into extensive bodies of interlayered silt and very fine sand deposited by *turbidity currents* at greater distances from the mouths of sediment-laden meltwater streams. Fan elements are composed mainly of medium or coarse sand, but they locally contain some gravel and debris flows in the northernmost parts of the sequence. Facies relations are quite complex within these sequences but they generally appear to indicate increasing proximity of ice through time, as well as local *progradation* of deltas and infilling of localized embayments in the ancestral lake basin. All of these sequences overlie an irregular surface on loamy and silty till-like materials of the Trafalgar Formation, some of which also appear to be of glaciolacustrine aspect.

The axis of the lake plain is marked by the narrow, straight valley of the **Maumee River**. The valley appears to be sharply entrenched into the surface of the lake plain, and adjacent deposits are uncommonly heterogeneous, containing a variety of bouldery and gravelly meltwater-deposited units. The modern, eastward-flowing river itself is entirely post-glacial, having developed only when the eastern outlet of Lake Erie became ice free. The valley itself, however, as well as the coarse meltwater deposits along it, probably originated as a *sub-glacial* channel when the Erie Lobe stood at the Fort Wayne Moraine. Remnants of a thick outwash deposit immediately north and west of downtown Fort Wayne suggest that the outlet of this westward-flowing channel was located just east of the present confluence of the Maumee, St. Marys, and St. Joseph Rivers, where the Wabash-Erie Channel now lies.

The massive **Wabash-Erie Channel** (figure 17) represents the former outlet of **Glacial Lake Maumee**. The channel was severely scoured by the **Maumee Torrent**, which was unleashed when lake level overtopped the sag channel across the Fort Wayne Moraine. The perfectly flat bottom of the channel (750-755 feet m.s.l.) is well over a mile wide in some places and represents a period of alluvial infilling that followed the catastrophic drainage. It is underlain by as much as 30 feet of organic silt, sand, and some muck deposited in an extensive slackwater environment characterized by low-gradient river channels and oxbow lakes that existed prior to the opening of the Maumee River and the regional drainage reversal that followed. The slackwater sediments overlie the scoured surface of the Trafalgar Formation, which in this area contains several large, southwest-trending, channel-like sand and gravel bodies in addition to hard loam till. The eroded remnants of an Erie Lobe outwash fan also lie within the channel and form the local drainage divide between the Maumee and Little River (Wabash) basins. As much as 40 feet of outwash underlies the highest part of the fan (785-790 feet m.s.l.), which generally occupies the southern half of the channel. The fan appears to be related to the Fort Wayne Moraine and was probably deposited by meltwater emanating from the apex of the ice and from the mouth of the subglacial channel now occupied by the Maumee River valley. Although the fan remnants are currently separated from the moraine by the subsequent valley of the St. Marys River, it seems probable that a sizable mass of outwash may have once filled this part of the Wabash-Erie Channel. Taken together, all of these features indicate that the general course of the Wabash-Erie Channel was established long before the advent of glacial lake drainage, and presumably during the earliest events of the late Wisconsin glaciation.

Bedrock geology

Throughout the Maumee River basin, the bedrock is covered by glacial and/or other unconsolidated sediments and is not naturally exposed at the modern land surface. The unconsolidated sediments were deposited primarily as a result of continental glaciation that

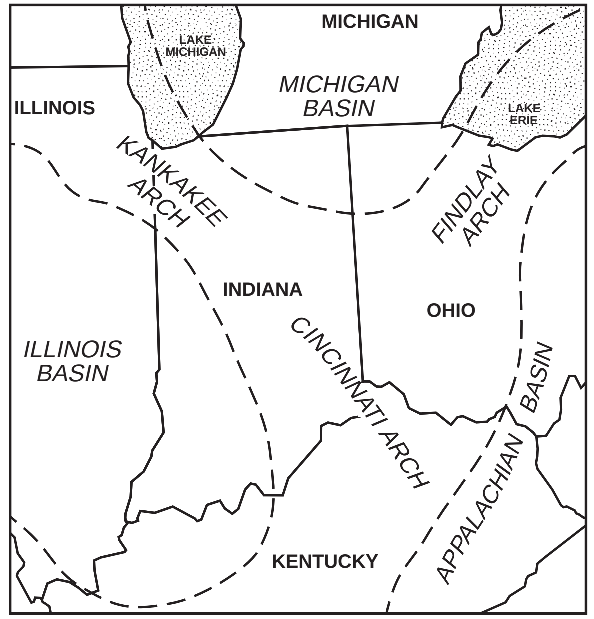

Figure 19. Regional bedrock structure

occurred during the **Pleistocene Epoch** of the **Cenozoic Era**.

Bedrock of the Maumee River basin consists of sedimentary rocks deposited during the **Paleozoic Era** that lie over much older **Precambrian** crystalline rocks (See sidebar on the following page entitled **History of Bedrock Deposition**). The *sedimentary* rocks in the basin were deposited during the **Cambrian** to **Mississippian** periods of the Paleozoic Era, and include *carbonates, sandstone and shales.* Middle Paleozoic rocks form the bedrock surface of the basin. *Unconformities* that represent gaps of several hundred million years in the geologic record are present at both the Paleozoic-Precambrian and the Paleozoic-Pleistocene *contacts.*

A broad uplift known as the **Cincinnati Arch** (figure 19) controls the regional bedrock structure in the Maumee River basin. The axis of the Cincinnati Arch extends north-northwest from Cincinnati, Ohio into Randolph County, Indiana. To the north, the arch splits into two branches, a northwest branch known as the Kankakee Arch that passes through northwest Indiana, and a northeast branch known as the Findley Arch that extends across Ohio to Lake Erie. The Maumee River basin lies on the north-dipping flank of the Cincinnati Arch.

The two branches of the Cincinnati Arch define part

History of bedrock deposition

Deposition of the preserved sedimentary rocks began in the late Cambrian Period as the sea invaded the area which is now the Maumee River basin. Beach sands derived through erosion of the *igneous* basement rocks were deposited to form the Mount Simon Sandstone. As sea level continued to rise through the early Ordovician Period, the depositional environment shifted to one progressively favoring shale and limestone. Toward the end of the early Ordovician period, the shallow sea began to retreat from the area and erosion removed the upper portion of the Knox dolomite (Gutstadt, 1958).

Sea level again rose and reached its maximum extent, known as *transgression*, upon the North American continent. The basal St. Peter Sandstone of the Ancell Group, was sporadically deposited, followed by extensive and fairly uniform limestones. An abrupt change at the end of Trenton Limestone deposition marked the end of widespread *carbonate* deposition. Physical and biological environments changed rapidly as the shallow water in which the Maquoketa Group was deposited alternated between clear and muddy (Gutstadt, 1958).

A period of non-deposition and erosion occurred through the late Ordovician and early Silurian Periods. Land-locked reef-fringed basins developed in the region now occupied by the Great Lakes. As inland seas withdrew at the end of early Paleozoic time, precipitation of *evaporites* such as salt and gypsum occurred within the basins. (Levin, 1988).

Deposition of Silurian and Devonian sediments was largely influenced by local conditions. The subsidence of the Michigan Basin and the expansion of reefs determined the local conditions under which the limestones and shales of the Silurian and Devonian Periods were deposited (Pinsak and Shaver, 1964).

In the region east of the Mississippi Valley, predominant carbonate sedimentation gave way to shales in the middle and late Devonian Period. The change to clastic deposition was a consequence of mountain-building in the Appalachians. Highlands formed during this time were rapidly eroded and clastics were transported westward to form an extensive apron of sediments (Levin, 1988).

Sediment that ultimately became black shale was deposited in a transgressing epicontinental sea that covered much of Indiana. Anoxic conditions caused by lack of water circulation between the epicontinental waters and the open ocean resulted in an accumulation of organic matter as an important part of the sediment.

Partial deposition of upper Paleozoic rock units occurred in the area of the present day Maumee River basin. Erosion throughout the post-Paleozoic Eras, coupled with bedrock structure and lithology, resulted in the total removal of all Paleozoic units deposited in this area above the lower Mississippian shales.

The resulting pre-Pleistocene bedrock topography reflected the drainage associated with the extensive period of post-Paleozoic erosion.

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**	
	TERTIARY	65 MILLION	No deposits in northeastern Indiana	
MESOZOIC	CRETACEOUS	78 MILLION		
	JURASSIC	64 MILLION		
	TRIASSIC	37 MILLION		
PALEOZOIC	PERMIAN	41 MILLION		
	PENNSYLVANIAN	34 MILLION	*Shale, sandstone, mudstone, clay, coal, limestone, and conglomerate.* Not present in northeastern Indiana but extensive in nearby parts of Michigan	
	MISSISSIPPIAN	40 MILLION	*Shale, mudstone, sandstone, limestone, and gypsum.*	
	DEVONIAN	48 MILLION	Upper part: *carbonaceous shale* **100 ft** Lower part: *limestone, dolomite, shale, and gypsum*	
	SILURIAN	30 MILLION	*Dolomite, limestone, siltstone, and shale deposited in regionally extensive reef platform* ***(the Fort Wayne Bank)***	
	ORDOVICIAN	70 MILLION	*Shale and limestone* *Limestone, dolomite, and sandstone*	Not present at the bedrock surface in northeastern Indiana
	CAMBRIAN	65 MILLION	*Sandstone and dolomite*	
PRECAMBRIAN ERAS		4 BILLION	*Granite, marble, gneiss, and other igneous and metamorphic rock types*	

of the southern limit of a large sedimentary basin called the **Michigan Basin**. The oldest rocks at the bedrock surface occur near the crest of the arch and progressively younger rocks are exposed at the bedrock surface in the *down-dip* direction. The angle of dip increases from south to north in the Maumee River basin off the crest of the arch and into the southern flank of the Michigan Basin. The regional dip angle increases from less than 14 feet per mile in Adams County to greater than 24 feet per mile in Steuben County (Rupp, 1991).

The Paleozoic sequence in the Maumee River basin thickens in the down-dip direction, reflecting the subsidence of the Michigan Basin. The coincidence of increasing thickness of individual Paleozoic sedimentary rock formations and increasing angle of dip may indicate basin subsidence and increased deposition during the Paleozoic Era (appendix 5).

Other structural features, including two *faults*, have been mapped recently in the Maumee River basin (Fleming, 1994). Subsurface data was utilized to map one fault that trends north-northeast from approximately 2 miles west of the city of Woodburn to approximately 2 miles east of the northeast corner of Allen County. The southern extension of the **Antrim Shale** into west-central Allen County may be related to the fault, since the fault helps define the eastern side of the extension (Fleming, 1994). The relationship of this fault to the geologic history of the area is not currently understood. The fault may be related to the development of the Michigan Basin, or to other faults that developed along the arch such as the Bowling Green Fault of northwestern Ohio. No evidence for the extension of the fault into the unconsolidated sediments has been found to date (A. H. Fleming, oral commun., 1995).

A second fault, trending east-west in northern Allen County, is indicated by an abrupt increase (approximately 50 feet) in thickness of the Antrim Shale across the inferred fault zone (Fleming, 1994). At this time, little is known of the nature and extent of this feature.

Bedrock physiography

Local bedrock relief in the Maumee River basin is the result of erosion. The bedrock surface is thought to strongly resemble the pre-glacial topography. Erosion throughout millions of years, prior to continental glaciation, established a well developed surface drainage pattern on the underlying bedrock. The period of glaciation removed, through differential erosion, much of the less resistant near-surface materials. Materials and structures affected by the process of erosion included the residual soil profiles, portions of the shale and carbonate bedrock, and portions of the less resistant *karst*ic areas associated with the carbonate bedrock.

The topographical characteristics of the bedrock surface are influenced by the bedrock type (see figures 20 and 21). Beneath the northern half of the basin, **Devonian** and **Mississippian** shales have been eroded into broad sloping valleys and hills. In contrast, **Silurian** and **Devonian** carbonates present in the southern areas have been eroded into low-relief plateaus that exhibit evidence of *karst* and fracture development which predates glaciation (Fleming, 1994).

Total relief on the bedrock surface in the Maumee River basin is more than 300 feet (figure 18 and 20). Bedrock uplands occur in the far northeastern and southeastern corners of the Maumee River basin in Indiana. Bedrock elevations in excess of 800 feet above m.s.l. are developed in the far southeastern corner of the basin on Silurian carbonates and in the extreme northeastern corner on lower Mississippian shale. The increase in elevation of the bedrock surface in the extreme northern portions of the basin is associated with a south-facing *escarpment*. This escarpment is capped by erosion-resistant sandstone and lies just north of the Michigan state line (A. H. Fleming, written commun., 1995).

Topography on the bedrock surface reflects portions of three preglacial drainage systems for the area. A northern dendritic drainage system is incised into the shale bedrock in northern DeKalb County to an elevation of less than 500 feet above m.s.l. The southern drainage system, located in southern Adams County, consists of a deep valley cut into and through Silurian carbonates. A transitional drainage system occupies central and western Allen County, encompassing an area underlain by carbonate bedrock in the south and west and an area underlain by shale in the north. The resulting drainage pattern for the central region is a combination of a dendritic drainage pattern similar to the northern system and the steep-sided valleys of the carbonate plateaus of the southern system.

The southern drainage system is represented by the bedrock valley of a south draining tributary and a small segment of the **Teays River Valley** which drains from the east to the west (Bruns and others, 1985). The Teays was the principal drainage system in central Indiana during the Tertiary period (Wayne, 1956). The Teays River system and its affect on preglacial drainage have been investigated for many years; and although much has been learned, the history of the drainage system and its relationship to glaciation have yet to be fully understood (Melhorn and Kempton, 1991).

Bedrock stratigraphy and lithology

Ordovician shale and limestone of the **Maquoketa Group** are the oldest rocks present at the surface of the bedrock in the Maumee River basin. This Group is found at the base of the Teays River Valley in southern Adams County where it is overlain by more than 250 feet of **Pleistocene** sediment (figures 16 and 21). The Maquoketa is *disconformably* overlain by Silurian age rocks throughout the Maumee River basin (Shaver and others, 1986).

Rocks of **Silurian** age are found at the bedrock surface along the southern portions of Allen County and throughout Adams County, excluding a limited area of Ordovician exposure (figure 21). Rocks of Silurian age attain a thickness of approximately 500 feet near the Devonian contact in Allen County. The oldest

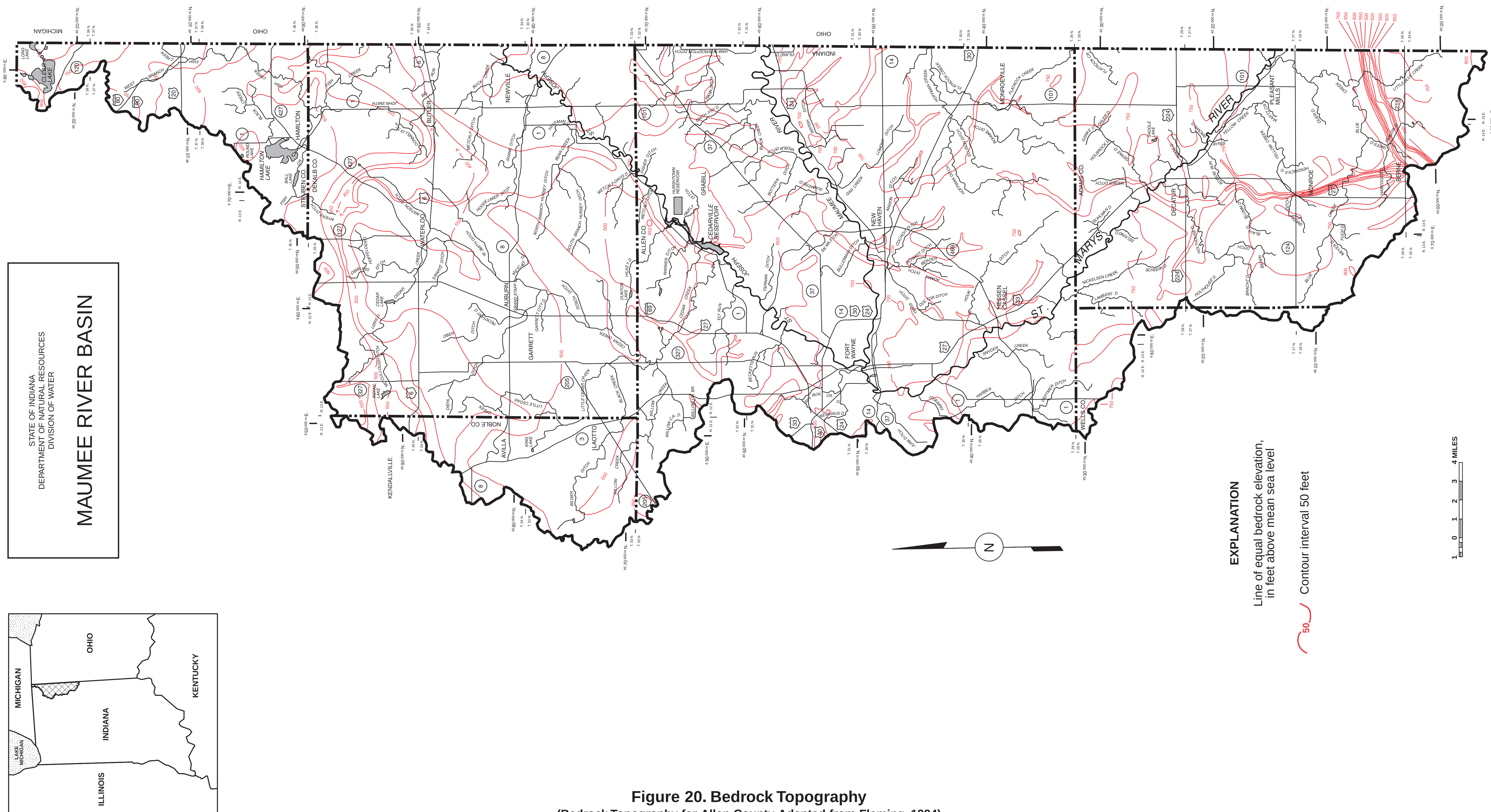

Figure 20. Bedrock Topography

(Bedrock Topography for Allen County Adapted from Fleming, 1994)

Silurian rocks found in the Maumee River basin belong to the **Cataract Formation** and the **Salamonie Dolomite**. These comprise the bedrock surface in southern Adams County. The occurrence of the lower Silurian carbonates at the bedrock surface in this portion of the basin are associated with the Teays Valley and tributary. Typical lithologies within the Cataract are *dolomitic* and *argillaceous* limestones whereas, the overlying Salamonie Dolomite grades into a purer *bioclastic vuggy dolomite* (Shaver and others, 1986). Overlying the Salamonie Dolomite and representing a large portion of the bedrock contact in Adams County are rocks of the **Pleasant Mills Formation** (figure 21). In this area the Pleasant Mills consists of mature reef to non-reef dolomite and dolomitic limestone (Droste and Shaver, 1982). The **Wabash Formation** overlies the Pleasant Mills in a *conformable* and gradational relationship (Shaver and others, 1986). Rocks of the Wabash Formation comprise the upper bedrock contact in northern Adams County and approximately the southern half of Township 29 North in southern Allen County (figure 21). Dolomitic limestones, having varying amounts of argillaceous limestones deposited between areas of *reef* development, are characteristic of the Wabash (Shaver and others, 1986). The term **Huntington *Lithofacies*** has been applied to the reef rock located in the upper Silurian. The reefs often developed across formation boundaries and collectively constitute a vast expanse of reefs known as the **Fort Wayne Reef Bank** (Pinsak and Shaver, 1964).

Carbonate units of middle **Devonian** age, **Muscatatuck Group**, overlie the Silurian rocks in the middle portion of the present Maumee River basin (Gray and others, 1987, and Fleming, 1994). Rocks belonging to the Muscatatuck group make up the bedrock surface throughout a large portion of Allen County and attain a maximum thickness of approximately 100 feet (Rupp, 1991). Lower portions of the group, known as the **Detroit River Formation**, contain *evaporitic deposits* of *gypsum* and *anhydrite* along with purer dolomites (Shaver and others, 1986). The **Traverse Formation** overlies the Detroit River Formation in a gradational relationship. The Traverse is commonly composed of dolomitic limestone and limestone which range from very fine to coarse grained and *fossiliferous*.

A distinct change in the type of rock being deposited occurred in upper Devonian time. Deposition of carbonate ceased and was replaced by deposition of very fine grained *clastic* material that formed the

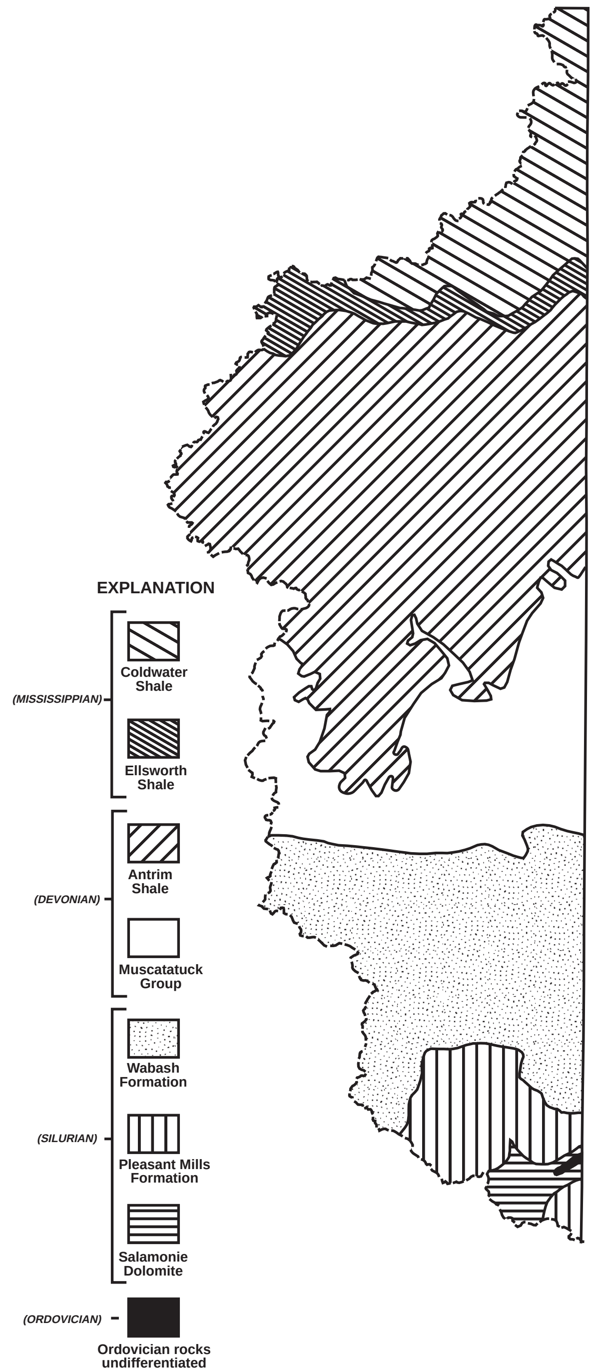

Figure 21. Bedrock geology
(Adapted from Gray and others, 1987 and Fleming, 1994)

Antrim Shale. The Antrim Shale is found at the bedrock surface throughout much of northern Allen County and most of DeKalb County (Gray and others, 1987 and Fleming, 1994). In Steuben County, the Antrim Shale reaches a thickness of 220 feet (Shaver and others, 1986). Brownish-black shale of the Antrim grade upward to the green gray shale of the Ellsworth. Deposition of the **Ellsworth Shale** spanned the **Devonian-Mississippian** age time boundary. The Ellsworth Shale occurs at the bedrock surface as a relatively narrow belt in northern DeKalb County (figure 21) where the unit is more than 40 feet thick (Shaver and others, 1986). A thin black carbonaceous shale, the **Sunbury Shale**, separates the Ellsworth Shale from the **Coldwater Shale** (Shaver and others, 1986) in the northern portion of the Maumee River basin where all the units are present in the subsurface (figure 21). The Coldwater Shale is typically gray to greenish gray, slightly silty shale with some red shale stringers in the lower portions (Shaver and others, 1986). Parts of the unit contain appreciable amounts of siltstone (Fleming, written commun., 1996). The Coldwater Shale is present at the bedrock surface in extreme northern DeKalb County and all of Steuben County in the Maumee River basin where it is also covered by more than 250 feet of Pleistocene sediment (figure 16). The Coldwater Shale attains a thickness of more than 500 feet in Steuben County.

For a graphic illustration of the various bedrock units which occur in the Maumee River basin see appendix 4, Geologic Column. This geologic column was constructed as a representation of the relative thickness of the various units occurring in northern Steuben County, where all bedrock units in the basin are present.

SOILS

Soils are the end product of various agents acting on unconsolidated and bedrock deposits. The properties of different soils are determined by chemical, physical, and biological processes acting on soil *parent materials* over long periods of time.

Soil properties influence the generation of surface-water runoff and help determine the suitability of an area for crops, pasture, woodland, wildlife habitat, recreational facilities, buildings, roads, and other uses. The type of land use can directly or indirectly modify hydrology, which in turn can further influence land and water development.

In general, soil parent materials and topography in the Maumee River basin differ from south to north. Primarily, moderately fine textured soils occur on subdued local relief and *calcareous*, fine textured Lagro glacial till in the southern portion of the basin. In the nearly featureless lacustrine plain of the east central portion of the basin, very fine to fine textured soils predominate; but soil texture may range from medium and fine textured in central portions of the ancestral lake to moderately coarse and coarse textured along ancient shorelines. Moderate relief, complex geology, and loamy Trafalger till in the northwestern part of the basin produce loam and sandy loam soils. Transecting the till plains and lacustrine deposits are glacial outwash and modern alluvial soils in the valleys of major streams. Soils produced on glacial outwash are predominantly loamy and sandy; whereas, soils formed on modern-day alluvial deposits vary widely in texture and composition.

Soil development in most of the Maumee River basin occurred under a cover of mixed hardwood forest. Some basin soils, however developed under cover of water-tolerant trees and sedges, whereas others formed under prairie grasses. Isolated pockets of organic soils have developed in areas of restricted or internal drainage.

Soil data and basic information on the economy, land use and water resources of major basin counties are presented in soil survey reports (Farmer, 1981 and 1986; Jensen, 1982; Kirschner and Zachary, 1969; McCarter, 1977; and Neely, 1992). Soil maps and related data found in these reports can be used for general planning purposes. The following discussions are based on generalized maps, which provide an even broader overview of basin soils.

Soil associations and hydrologic soil groups

Soils can be classified according to similarities of parent materials, texture, *horizon* characteristics, topography, natural drainage, and special features. A soil series, the most common category used in county soil surveys, allows detailed evaluations of specific tracts of land. For generalized applications, however, a soil association is a commonly used category.

A soil association is a landscape having a distinctive pattern of soil series in relation to similar parent materials, landforms, and slopes. Within a given soil association, each soil series occupies a characteristic position on one of three major landform types: 1) hillslopes, swells, or depressions within broad uplands, 2) terraces, outwash plains, or lacustrine plains, and 3) floodplains or bottomlands (Galloway and Steinhardt, 1984).

A soil association is composed primarily of two to four major soils and a few minor soils, and is named for the major soils. The soils in one association may occur in another, but in a different percentage and pattern. A total of 108 soil associations were identified in a series of generalized county soil maps developed in 1970 by the U.S. Department of Agriculture's Soil Conservation Service (SCS) and Purdue University's Agricultural Experiment Station. A few of the general soil maps were revised slightly when they were later printed with supplementary data tables and a user's guide in 1975 (U.S. Department of Agriculture, 1971: Galloway and others, [1975]). In 1977, the Soil Conservation Service and Purdue University combined the 1971/1975 series of general soil maps to produce a 1:500,000-scale map of Indiana showing major soil associations on a regional basis.

The Natural Resources Conservation Service (formerly SCS) has developed, in cooperation with Purdue University, a computerized soil data base (STATSGO). This geographic data base with its linked attribute data files is used by the Natural Resources Conservation Service (NRCS) to generate the general soils map for the state. Ninety-four soil associations are recognized in the data base. Figure 22, adapted from the STATSGO state soil map, shows the location of major soil associations in the Maumee River basin. Since the STATSGO mapping effort is multi-state, soil series not previously mapped in Indiana are included in the Indiana STATSGO. As older soil surveys are updated, some of the soil series used in adjacent states will be mapped in Indiana.

Figure 22 also shows the regions of similar parent materials into which the major associations are grouped. Figure 22 can be useful in relating basin soils to surficial geology, topography, and vegetation types (see explanatory text accompanying figure 22). A report by Galloway and Steinhardt (1984) discusses the influences of geology, physiography and climate on the formation of soil association, and summarizes the relations among associations occupying specific landscape positions.

Soil survey reports (referenced previously) contain detailed descriptions of soil properties that affect land use, and include tables which outline the potentials and limitations of individual soils for cultivated crops, woodland, urban and recreation uses. Although the map shown in figure 22 is too generalized for such detailed land-use planning, it can be used to compare the suitability of large areas for general land uses.

In addition to its utility in assessing general land uses, the map in figure 22 also can be helpful in examining, on a broad basis, the role of soils in the generation of surface-water runoff. The Soil Conservation Service (now called the Natural Resources Conservation Service) has classified soils into four hydrologic groups (A,B,C,D) according to the tendency of the soil to absorb rainfall and thereby reduce runoff. Classifying bare soils on the basis of their minimum infiltration rate, after an extended period of wetting, reflects the properties of both the surface and underlying soil horizons.

Soils in hydrologic group A have high infiltration rates even when thoroughly wetted, and consist primarily of deep, well- to excessively-drained sands and gravels. These soils also have high transmission rates. The only classified hydrologic group A soils in the basin are the natural, undrained Spinks soils near the Michigan/Indiana state line. Other basin soils may be classified into hydrologic soil group A if artificial drainage measures have improved the ability of the soils to absorb rainfall and thereby reduce runoff; these are Houghton-Adrian-Carlisle soils which occur in southeast Noble County, along Willow Ditch near Huntertown, and west of Fort Wayne (association 19).

Soils in hydrologic group B have moderate infiltration and transmission rates. Well-drained soil series that typify this group in the Maumee River basin include: Genesee, Homer, Lawson, Martinsville, Miami, Oshtemo, Riddles, Sawmill, Tice, and Wawasee. Where artificial drainage has taken place, other group B basin soils include Gilford, Lenawee, Sebewa, and Rensselaer.

Soils in hydrologic group C have slow infiltration and transmission rates. They consist primarily of soils with a layer that impedes downward movement of water, or soils having a moderately fine to fine texture. In the Maumee River basin, soils in this group are the most prevalent hydrologic soil group. Individual soil series within the basin which are within the C hydrologic soil group include: Blount, Darroch, Glynwood, Morley, Strole, Whitaker, Eel, and Crosier. Saranac and Pewamo soils may be classified into hydrologic soil group C where artificial drainage has occurred.

Both the Blount-Glynwood-Morley (4) and the Blount-Pewamo-Glynwood (5) associations fall within this hydrologic soil group. Both associations formed from fine to moderately fine textured glacial till and are found primarily on till plains and moraines.

Soils in hydrologic group D have very slow rates of infiltration and transmission. In the Maumee River basin this group consists primarily of soils having a permanent high water table and/or organic materials. Soil series included in hydrologic group D include Fulton, Latty, Nappanee, Hoytville, and Montgomery. Undrained tracts dominated by Houghton (association 19) soils and undrained depressional areas dominated by Pewamo soils are also classified in soil group D. Undrained Pewamo soils commonly are found in *swales* and drainageways on till plains and moraine. In addition, the Lake Maumee Plain contains soil associations classified in hydrologic group D: Hoytville-Nappanee-Blount (32) and Montgomery-Stole-Lenawee (33).

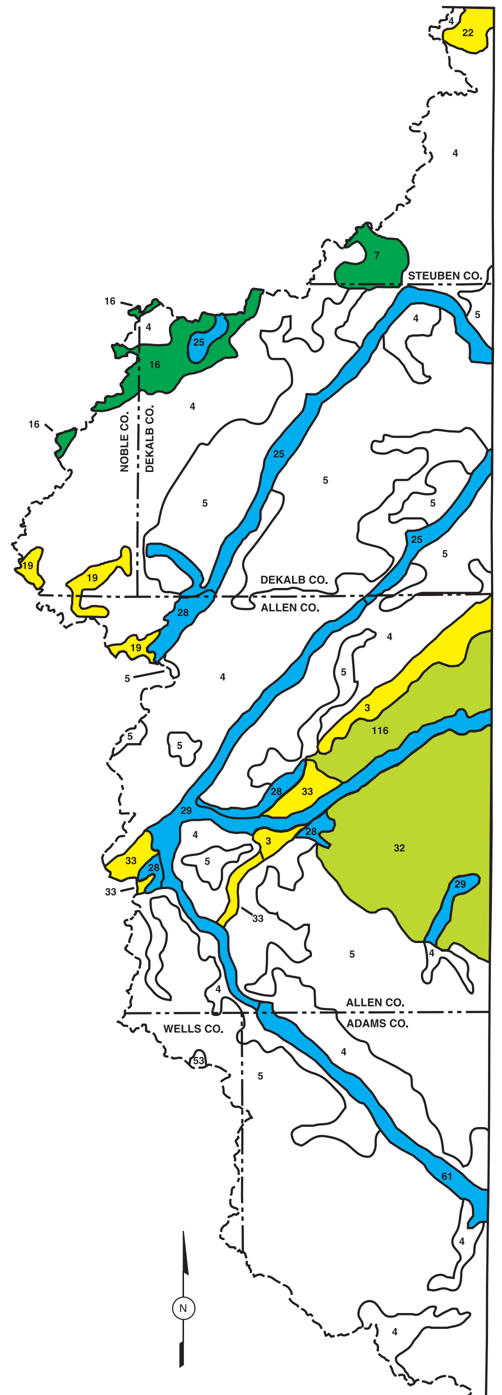

Figure 22. Location of major soil associations
(adapted from U.S. Department of Agriculture, 1982 and Natural Resource Conservation Service STATSGO data 1995)
NOTE: Soils of Regions 2, 4, 5, and 8-13 are not located in the Maumee River Basin

REGION 1 - SOILS FORMED IN SANDY AND LOAMY LACUSTRINE AND EOLIAN SAND DEPOSITS

The nearly level, very poorly drained soils of the **Houghton-Adrian-Carlisle** association (19) formed in organic materials deposited in depressions on uplands or outwash plains, and developed under a cover of trees, shrubs and sedges. These soils frequently occur as small, scattered muck pockets; however, four mappable areas occur in the Maumee River basin along its western boundary. The mapped areas occur in southeastern Noble County, along Willow Ditch near Huntertown, and along the drainageway of an unnamed ditch in west Fort Wayne.

Soils of the **Spinks-Houghton** association (22) occur in Steuben County near the Michigan/Indiana state line. Sandy, well drained Spinks soils occur on dunes and outwash plains. The nearly level, very poorly drained Houghton muck occurs in depressions and former drainageways or along streams and lakeshores.

On the stream terrace along the northern edge of the Lake Maumee Plain, the loamy soils of the **Rensselaer-Darroch-Whitaker** association (3) predominate. The very poorly drained Rensselaer soils occupy swales and broad flat areas, and the somewhat poorly drained Whitaker and Darroch soils occur on convex swells.

Silty clay and silty clay loam soils of the **Montgomery-Strole-Lenawee** association (33) occur on uplands, drainageways and stream terraces near New Haven and along the Trier Ditch drainageway. The nearly level or depressional Montgomery and Lenawee soils are very poorly drained. The gently sloping Strole soils are somewhat poorly drained.

REGION 2 - SOILS FORMED IN SILTY AND CLAYEY WISCONSINAN AND ILLINOIAN LACUSTRINE DEPOSITS

The silty clay, silty loam, and silty clay loam soils of the **Hoytville-Nappanee-Blount** association (32) occur on the uplands of the Lake Maumee Plain. The very poorly drained, nearly level or slightly depressional Hoytville soils are found in swales; whereas, the somewhat poorly drained Nappanee and Blount soils occur on swells.

Soils of the **Latty-Fulton-Nappanee** association (116) are found in the Lake Maumee Plain north of the Maumee River. The very poorly drained Latty and Fulton soils occur in depressional areas; whereas, the somewhat poorly drained, silty loam Nappanee soils occur on swells.

REGION 3 - SOILS FORMED IN ALLUVIAL AND OUTWASH DEPOSITS

The nearly level alluvial soils of the **Saranac-Eel-Tice** association (61) occur in bottomlands in Adams County. The clayey Saranac soils, which occur in depressional areas that are subject to frequent flooding, are very poorly drained. Loamy Tice soils, which appear in slightly higher areas than Saranac soils, are somewhat poorly drained. Loamy Eel soils are moderately well drained.

Loamy and sandy loam soils of the **Sebewa-Gilford-Homer** association (25) were formed in glacial outwash and are underlain by sand and gravel. Soils in this association may be found along Cedar Creek, Little Cedar Creek, and St. Joseph River in DeKalb County. The nearly level Sebewa and Gilford soils, which occur in depressional areas, are very poorly drained. Homer soils, occupying flats between depressions, are somewhat poorly drained.

Sandy loam and loamy soils of the **Martinsville-Whitaker-Rensselaer** association (28) are located on terraces along major streams, on beach ridges in the Lake Maumee Plain, and on outwash plains in uplands near Huntertown. The nearly level to moderately sloping Martinsville soils are well drained. Whitaker soils, which occupy somewhat lower landscape positions than Martinsville, are somewhat poorly drained. Rensselaer soils, found on flats and in depressions, are very poorly drained.

Soils of the **Sawmill-Lawson-Genesee** association (29) occur along the drainageways of the St. Joseph, Maumee, and St. Marys Rivers in Allen County. Loamy clay Sawmill soils, which are very poorly drained, and loamy Lawson soils, which are well drained, are located on floodplains. Silty loam Genesee soils are nearly level and well drained bottomland soils.

REGION 6 - SOILS FORMED IN LOAMY GLACIAL TILL

Loamy soils of the **Miami-Wawasee-Crosier** soil association (16) occur along the northwestern basin boundary on till plains with swell-and-swale topography, on rolling areas near streams dissecting the till plain, and on end moraines. The three soils in this association are similar. The Miami and Wawasee soils, however, occur on convex slopes and are well drained; whereas the Crosier soils occur lower on the landscape and are somewhat poorly drained. In addition to slope differences, Miami soils contain more clay in the subsoil and substratum than Wawasee soils.

Loamy and sandy loam soils of the **Riddles-Crosier-Oshtemo** association (7) occur near the northwestern basin boundary in Steuben County. The well drained soils of the Riddles and Oshtemo soils occur on ridges, knolls, and side slopes of till plains and moraines. Somewhat poorly drained Crosier soils are found on toe slopes and nearly level areas of swells.

REGION 7 - SOILS FORMED IN CLAYEY GLACIAL TILL

The silty, clayey, and loamy soils of the **Blount-Pewamo-Glynwood** association (5), characterized by a very gradual swale-and-swell topography and occasional areas that have frequent changes of slope, occur on till plains and moraines. In depressional areas, the nearly level very poorly drained Pewamo soils occur. On relatively higher lying broad flats and slight rises, the nearly level somewhat poorly drained Blount soils appear. Glynwood soils, which are gently sloping moderately well drained soils, are located on yet higher convex side slopes.

Silty, loamy, and clayey soils of the **Blount-Glynwood-Morley** association (4) occur on till plains and moraines. Nearly level and gently sloping Blount soils occur on a slightly lower position on the landscape than the Glynwood soils and are somewhat poorly drained. The Glynwood soils, which are moderately well drained, are similar and adjacent to Blount and Morley soils, but have slopes ranging from 3 to 6 percent. Well drained Morley soils, which generally appear higher on the landscape than Glynwood soils, occur on the more dissected areas of the landscape.