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 Region. Geologic and soil factors determine the proportion of precipitation which runs off the land to become surface water, as opposed 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 Lake Michigan Region is directly linked to the regional climate, which is the long-term composite of daily weather events. The climate of the Region is broadly classified as temperate continental, which describes areas located in the interior of a large continent and characterized by warm summers, cool winters, and the absence of a pronounced dry season. The continentality is partially modified near Lake Michigan, where the climate can take on semi-marine characteristics when *air masses* that have passed southward over the lake move inland.

Precipitation and temperature throughout the Region vary considerably on a daily, seasonal and yearly basis. 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, a powerful air current about 6 miles above the land surface. Localized weather modifications attributable to the presence of Lake Michigan and the Gary-South Chicago metropolis are superimposed on this regional variability.

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 primarily are 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. (About two-thirds of these recording gages are co-located with non-recording gages belonging to the climatic network.) Data on precipitation, air and soil temperature, relative humidity and other parameters are collected at agricultural stations. All but two of these **agricultural** stations also belong to the climatic or hydrologic networks, or both.

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 four 24-hour NWS offices (including an office at South Bend) and at the Midwest Agricultural Weather Service Center at Purdue University.

Figure 13 shows the location of official NWS stations in or adjacent to the Lake Michigan Region in Indiana. Table 4 presents selected information for these stations and additional stations located within 8 miles of the Region boundary. The 8-mile limit was selected primarily for convenience rather than meteorological considerations.

Climatic stations in and near the Illinois and Michigan portions of the Region are not listed in table 4 or shown in figure 13. However, precipitation and temperature data are available for several stations in Berrien County, Michigan and Cook County, Illinois, including the NWS forecast office at Chicago's O'-Hare International Airport.

An array of climatic data and climate-related data products for Indiana is available from NOAA's National Climatic Data Center in Asheville, North Carolina (Hatch, 1983). Climatic data also are available from the Midwestern Climate 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. Climatic summaries for stations in Berrien County, Michigan are available from the Michigan Department of Agriculture as part of a series of climatological publications (Michigan Department of Agriculture, 1989).

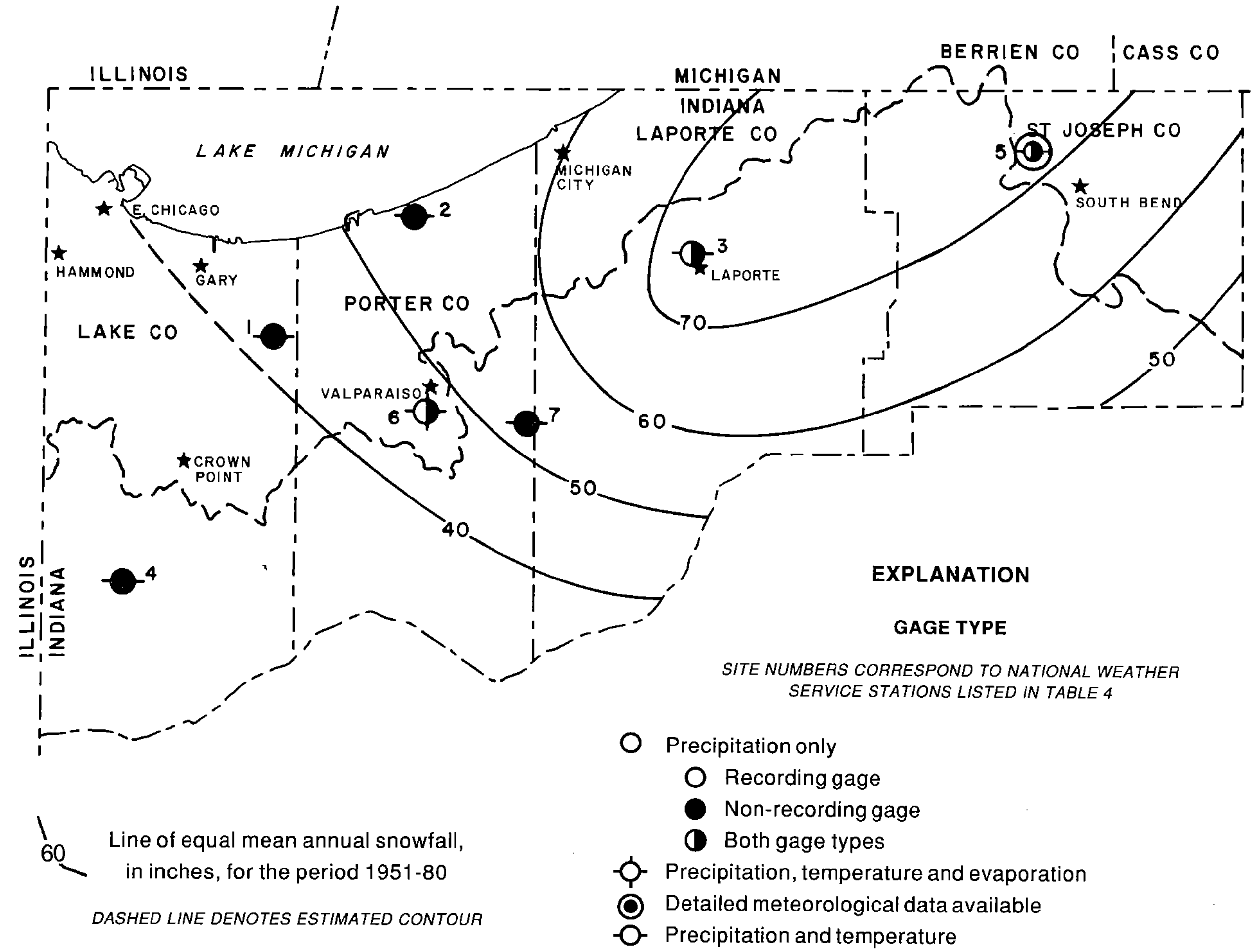

Figure 13. Location of National Weather Service stations and mean annual snowfall in and near the Lake Michigan Region

In the Indiana part of the Region, unpublished precipitation data are collected at the South Bend wastewater-treatment plant and at several unofficial NWS stations. Data from the unofficial stations are collected once daily by amateur-radio operators as part of a statewide volunteer network used to enhance the NWS river and flood forecasting program. Data from this network would be of limited use for most water management applications because the network is modified often and the data are filed only on a temporary basis.

The IDNR Division of Water operates a network of precipitation stations in Indiana, including a station in Merrillville in the Lake Michigan Region. Precipitation records from Merrillville are filed for an indefinite period at the division.

Climatic features

Although the climate of the Lake Michigan Region 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 occurring on or below the land surface. Temperature defines the frost-free season, and largely controls the process of evapotranspiration, which accounts for about 70 percent of the average annual precipitation in northern Indiana.

In some regional overviews of climate, data are grouped and analyzed on the basis of geographic areas having homogeneous climate. 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 and temperature in the Lake Michigan Region are derived primarily from station data for Gary, Hobart, Ogden Dunes, and Valparaiso. Some data for LaPorte and South Bend also are included, because of the long data record and their proximity to the Region boundary.

Lake and urban effects

The presence of Lake Michigan produces unique climatic conditions in parts of northwestern Indiana, as described by Changnon (1968a), Changnon and Jones (1972), and Eichenlaub (1979). Although modifications of climate are most pronounced within a mile or two of the shore, several lake-effect features extend about 25 miles inland. This broad area of lake influence encompasses the entire Lake Michigan Region in Indiana.

In general, the Region can experience warmer falls, cooler springs, higher humidity, more frequent lakeshore fogs, increased winter cloudiness, and greater amounts of snow compared to nearby regions of similar latitude. The most critical factor producing these

Table 4. National Weather Service stations in and near the Lake Michigan Region

Map number: Station locations are shown in figure 13.

Station: Only active stations are tabulated. Historical data for discontinued stations in Indiana are available from Gary, Michigan City, and the University of Notre Dame.

Data network: A, climatological network; 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. Numbers refer to footnotes.

Period of record: Approximate total length of precipitation record, through 1980 inclusive. Years of record are taken from 1980 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		Period of record	
				Ongoing	Periodic	Years	Dates
1	Hobart	A	P,T	CD	*1,2,3*	61	1920-
2	Indiana Dunes National Lakeshore[4]	A	P,T	CD	*2,3*	29	1952-
3	LaPorte[5]	A,B	P,T	CD,HP	*1,2,3*	86	1895-
4	Lowell[5]	A	P,T	CD	—	18	1963-
5	South Bend NWSO[5,6]	A,B,AG	P,T,D	CD,HP,LCD	*2,7*	93	1888-
6	Valparaiso Waterworks	A,B	P,T,E	CD,HP	*2,3*	81	1900-
7	Wanatah[5]	A,AG	P,T,S	CD	—	20	1961-

1 National Oceanic and Atmospheric Administration, 1976.
2 ______1982a, 1983a.
3 ______1985.
4 Located at Ogden Dunes until May 1989.
5 Within 8 miles of Region boundary in Indiana.
6 NWSO, National Weather Service office.
7 National Oceanic and Atmospheric Administration, 1982b.

climate modifications is the slower change of the lake's water-surface temperature relative to the change of the adjacent land-surface temperature.

The slower change in water temperature tends to moderate extremes in air temperature, a feature which typically is ascribed to a semi-marine climate rather than a continental climate. Because the lake retains some of its summer warmth until midwinter, minimum air temperatures near the lake during fall and early winter are several degrees warmer than in areas farther south. Conversely, because the lake retains its winter chill long after the land has thawed, areas near the lake experience maximum springtime temperatures that are cooler than those expected for the given latitude.

Local lake breezes reaching a mile or two inland further moderate temperature extremes along the immediate lakeshore. For example, summer lake breezes can reduce maximum air temperatures along the lakeshore by several degrees, whereas land breezes help maintain warmer minimums.

Lake-induced changes in cloud cover are associated with changes in air temperature and humidity. A reduction in summer cloudiness may extend 20 miles inland when westerly winds blow across the lake and advect colder off-lake air onto the eastern shore (Changnon and Jones, 1972); however, summer clouds are most noticeably reduced over the lake and along the immediate lakeshore.

Lake-related increases in cloud cover are common throughout the Lake Michigan Region, especially during the fall and early winter when the lake is warm relative to land. Winter fog may form over the lake when cold air from the north initially contacts the warm water. As the air continues to pass southward over the lake, convection and turbulence transport the acquired moisture aloft to form clouds, rain or snow. Cloud and precipitation development may be further enhanced by the lack of winter icepack on most of the lake, except in nearshore and harbor areas.

As the warmed off-lake air reaches the shoreline, upward currents can become stronger because of the increased friction over land, thereby increasing the potential for cloud and snow development. An additional impetus may be provided by *orographic lifting* as the air ascends the elevated Valparaiso Moraine (figure 16), whose crest is as much as 300 feet higher than the lake surface. It also is possible that the additional warmth and the urban-related increases in ice-forming nuclei from the Chicago-Gary metropolis may help create or intensify downwind lake-effect snows (Eichenlaub, 1979).

Lake-effect snows of the Great Lakes region are unique because only a few areas of the world experience this *mesoscale* feature (Eichenlaub, 1979). In Indiana, lake-effect snows are most common in Lake, Porter, LaPorte and St. Joseph Counties.

North or northwest winds sweeping over Lake Michigan can acquire large amounts of warmth and moisture before crossing the downwind shoreline; consequently, the major snowbelt of southern Lake Michigan is located about 5 to 25 miles inland of the southeast shore. This snowbelt encompasses an area roughly bounded by Michigan City, LaPorte and South Bend, Indiana, and extends into Berrien County, Michigan (figure 13).

Annual snowfall in the snowbelt averages as much as 70 inches, which is twice the annual amount normally received elsewhere in northern Indiana. In some years, snowfall amounts may exceed 100 inches, largely due to the frequency of moderate to heavy lake-effect snows. Eichenlaub (1970) estimated that lake-effect snowfall accounts for 30 to 50 percent of the total snowfall in the Lake Michigan snowbelt.

The climate of the Lake Michigan Region is modified not only by the presence of Lake Michigan but also by the Chicago-Gary metropolis of northeast Illinois and northwest Indiana. In general, large cities and their environs experience higher average temperatures than rural areas, more clouds, haze, and local fog, and more summer convective storms. Many of these differences are due to the "heat island" effect of urban-industrial centers and the increased presence of atmospheric pollutants and particles which serve as nuclei for the formation of tiny water droplets and/or ice crystals. Reports by Changnon (1971, 1980a, 1980c), Huff and Changnon (1972, 1973), Lyons (1974), Changnon and Semonin (1978, 1979), and Changnon and others (1979a, 1979b) present the results of detailed climatic studies in the Chicago area.

Inadvertent weather modification by the Chicago-Gary metropolis has been cited as a possible cause of increased summer rainfall and severe storm events recorded at LaPorte from the mid-1930s to the mid-1960s (Changnon, 1968b, 1980b; Maxwell, 1975; Changnon and Huff, 1977; Clark, 1979). However, the validity of an urban-induced anomaly centered at or near LaPorte has been questioned by those who attributed the unusual precipitation record to poor gage exposure or observer error (Holzman and Thom, 1970;

Holzman, 1971a, 1971b; Machta and others, 1977). A water-resources report for the Kankakee River Basin (Indiana Department of Natural Resources, 1990) contains a summary of the rainfall anomaly.

Precipitation

Most precipitation in the Lake Michigan Region is derived from air masses that have passed over the Gulf of Mexico, although Lake Michigan can be the principal moisture source for some precipitation events, particularly snows. The geographic and temporal variability in precipitation is produced by daytime convection and the passage of frontal systems.

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 can become severe, and may be accompanied by strong winds, large hail, or frequent lightning. Funnel clouds, tornadoes, and offshore *waterspouts* are rare near Lake Michigan, perhaps because the relatively cool water of the lake has a stabilizing effect on atmospheric processes during spring and early summer.

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. One exception occurred on October 9-11, 1954, when heavy storms produced record-breaking rainfall at many locations in northwest Indiana, including Hobart, Valparaiso, and Ogden Dunes in the Lake Michigan Region (National Oceanic and Atmospheric Administration, 1985; Daniels and Hale, 1955; Huff and others, 1955).

Precipitation events typically are interspersed among several dry days and can vary widely in intensity and duration. Although daily normal values *interpolated* from monthly normals do not exhibit the daily random patterns, normals can be used to compute average precipitation for selected time intervals (National Oceanic and Atmospheric Administration, 1982b). Normal daily precipitation amounts calculated for South Bend range from 0.07 inch in February, the driest month, to 0.14 inch in April and June, the wettest months.

Monthly precipitation during the frost-free season commonly ranges from about 2 to 5 inches (see National Oceanic and Atmospheric Administration, 1985), but monthly extremes recorded in the Region range from trace amounts to about 14 inches. Normal seasonal precipitation at Gary, Hobart, Ogden Dunes, and Valparaiso averages 5.8 inches in winter, 10.1 inches in spring, 11.4 inches in summer, and 9.0 inches in fall (table 5). In general, total monthly rainfall amounts are greater and more variable during warm months than during cool months.

Normal annual precipitation at Gary, Hobart, Ogden Dunes and Valparaiso averages 36.2 inches for the period 1951-80 (see table 5). Total annual precipitation recorded for this period ranges from about 23 inches to nearly 50 inches.

Annual probability data (National Oceanic and Atmospheric Administration, 1983a) show that there is a 9-in-10 chance that the annual precipitation over a long period of time will average 28 inches or greater. There is only a 1-in-10 chance that the annual precipitation will average 44 inches or greater.

Annual snowfall is quite variable in the Region because of the lake effect. Annual averages range from about 35 inches near the Indiana-Illinois state line to about 70 inches in the lake-related snowbelt. The predominant snow season is from November to March, but snowfall has occurred as early as September and as late as May. On average, snowfall constitutes 10 percent of the annual precipitation in the Region's western portions, and 19 percent of the annual precipitation in the snowbelt.

Temperature

The normal annual temperature averages 50° F (degrees Fahrenheit) at Gary, Hobart, Ogden Dunes, and Valparaiso, and 49° F at South Bend, Indiana and Eau Claire, Michigan. Normal seasonal temperature in the Indiana part of the Region averages 49° F in spring, 72° F in summer, 54° F in autumn, and 27° F in winter (National Oceanic and Atmospheric Administration, 1982a).

Spring and autumn months generally are characterized by moderate temperatures, although brief periods of unusually cool or warm temperatures may occasionally 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 normal monthly temperature of 23° F and an average normal

Table 5. Normal monthly, seasonal and annual precipitation for the period 1951-80

{All values in inches; monthly data are from the National Oceanic and Atmospheric Administration, 1982a}

Month	Gary	Hobart	LaPorte[1]	Ogden Dunes	South Bend	Valparaiso
SPRING						
March	2.7	2.4	3.2	2.8	3.1	2.9
April	3.8	3.8	4.3	3.8	4.1	4.3
May	3.7	3.3	3.2	3.2	2.8	3.6
Seasonal	10.2	9.5	10.7	9.8	10.0	10.8
SUMMER						
June	3.8	3.8	4.2	4.0	3.9	4.1
July	3.8	3.8	4.5	3.8	3.7	4.0
August	3.6	3.5	4.1	3.4	3.9	4.0
Seasonal	11.2	11.1	12.8	11.2	11.5	12.1
AUTUMN						
September	3.4	3.5	3.8	3.4	3.2	3.7
October	2.9	2.9	3.8	3.1	3.2	3.4
November	2.3	2.4	2.8	2.3	2.8	2.6
Seasonal	8.6	8.8	10.4	8.8	9.2	9.7
WINTER						
December	2.4	2.2	3.1	2.4	3.0	2.6
January	1.7	1.7	2.4	2.0	2.5	2.0
February	1.4	1.5	2.2	1.6	2.0	1.6
Seasonal	5.5	5.4	7.7	6.0	7.5	6.2
ANNUAL	35.5	34.8	41.6	35.8	38.2	38.8

[1] Base data may be anomalous

daily minimum of 15° F. On average, about 3 or 4 days in January have minimum daily temperatures less than 0° F.

July, the warmest month, has an average normal monthly temperature of 73° F and an average normal daily maximum of 84° F. Maximum temperatures of at least 90° F typically occur on about 5 or 6 days.

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 Lake Michigan Region is 16° F in winter, 20° F in spring and fall, and 21° F in summer (table 6). Due to the moderating effect of Lake Michigan, these average temperature fluctuations are about 3 degrees less than average fluctuations elsewhere in northern Indiana.

According to comparisons of monthly and seasonal normal temperatures at climatic stations in and near the Lake Michigan Region (National Oceanic and Atmospheric Administration, 1982a), Hobart has the greatest average temperature fluctuations, and Gary has the least (table 6). A combination of the lake effect and urban-related heating probably explains the warmer average spring and summer minimums at Gary, whereas the lake effect probably is responsible for maintaining warmer average minimums during fall and winter at Ogden Dunes (table 6).

Because the presence of Lake Michigan reduces the risk of early fall frosts and unusually late spring frosts, the frost-free season within about 10 miles of the lakeshore generally is 2 to 3 weeks longer than the season elsewhere in northern Indiana. In the Lake Michigan Region, the frost-free season typically lasts from late April or early May to the middle of October.

Table 6. Normal seasonal maximum and minimum temperatures for the period 1951-80

{Values, in degrees F, are derived from monthly normals published by the National Oceanic and Atmospheric Administration, 1982a}

Station	Spring		Summer		Fall		Winter	
	max	min	max	min	max	min	max	min
Gary	57.5	39.2	81.9	62.1	62.9	44.6	33.9	18.7
Hobart	60.1	38.4	83.6	60.3	65.2	43.4	35.4	18.9
LaPorte	59.0	38.0	82.8	60.1	63.0	42.7	33.8	18.3
Ogden Dunes	58.1	38.5	81.9	61.3	63.6	44.9	34.4	19.7
South Bend	57.6	38.1	81.1	60.4	61.8	43.3	33.4	19.0
Valparaiso	59.1	37.9	81.8	59.6	63.2	42.6	34.0	17.9

The average number of consecutive frost-free days ranges from about 175 days near the lakeshore to about 165 days near the Region's southern boundary (National Oceanic and Atmospheric Administration, 1985). A season of this length is comparable to the season typically found in much of central and south-central Indiana; however, the season length near Lake Michigan changes rapidly within short distances, as opposed to a more gradual change in central and southern Indiana (Schaal and Newman, 1981).

The longer frost-free season, in combination with the moderate temperatures, higher humidity, rolling terrain, and loamy or clayey soils on and north of the Valparaiso Moraine produce an environment suitable for the growing of frost-sensitive fruit crops such as apples, pears, peaches, grapes and berries. Fruit production is especially common in northern LaPorte County, Indiana and in Berrien County, Michigan.

During the warm season when Lake Michigan is cool relative to land, local lake breezes may limit extremely high temperatures within a mile or two of the shore. Conversely, land breezes at night help maintain temperatures that are warmer than those farther inland; hence, 24-hour temperature averages are not significantly modified by local lake winds.

Extreme temperatures recorded in the Lake Michigan Region range from -23° F to 104° F for the period 1951-80. Very hot weather typically occurs when tropical air masses reach the region from the south without first passing over Lake Michigan. Record high temperatures occurred at several stations during the summer drought of 1988, when southerly winds predominated.

Winter cold snaps generally are less severe in the Lake Michigan Region than in other areas of northern Indiana, but northeast winds not moderated by the lake influence can occasionally bring extremely low temperatures.

Evapotranspiration

Precipitated water is being returned continually to the atmosphere as vapor through the processes of evaporation and plant *transpiration*. 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 typically are operated between May and October. In general, evaporation pans are not operated between November and April because frequent ice cover would produce erroneous measurements.

At South Bend and Valparaiso, mean monthly pan evaporation during the frost-free season ranges from an average of about 6 inches in June and July to about 3 inches in October (table 7). Estimated monthly means of evaporation at South Bend show that nearly 25 percent of the annual total pan evaporation occurs during the 6-month winter period (Farnsworth and Thompson, 1982b).

A reasonable estimate of potential evapotranspiration can be obtained by multiplying total pan evaporation by a factor of 0.75 (see Farnsworth and Thompson, 1982a); hence, potential evapotranspiration at South Bend and Valparaiso averages about 30 inches. This amount is a generalized index of the maximum annual consumptive use of water by evaporation and transpiration.

Because the availability of moisture for evapotranspiration varies continually in time and space, actual evapotranspiration often occurs at less than the poten-

Table 7. Mean monthly pan evaporation at South Bend and Valparaiso

{Values, in inches, are from Farnsworth and Thompson (1982b) unless otherwise indicated.}

Month and season	South Bend, estimated (1956-70)	Valparaiso, measured (1960-79)
WARM SEASON		
May	5.63	5.38
June	6.73	6.14
July	6.64	5.94
August	5.93	4.92
September	4.26	3.23
October	3.17	2.95
Season total	32.36	28.56
COOL SEASON		
November	1.61	1.48[1]
December	0.88	0.93[1]
January	0.83	0.83[2]
February	1.00	1.00[2]
March	2.08	2.58[1]
April	3.80	3.84[1]
Season total	10.20	10.66
Annual total	42.56	39.22

[1] From Indiana Department of Natural Resources, 1988.
[2] Estimated values for South Bend; no measured data available.

tial rate. Studies in central Illinois revealed that average annual evapotranspiration is approximately 84 percent of the average annual potential evapotranspiration during years of normal or above-normal precipitation (Schicht and Walton, 1961). If annual potential evapotranspiration in the Lake Michigan is assumed to be 30 inches, then annual evapotranspiration is approximately 25 inches. An estimate of 25 to 26 inches for northwest Indiana was obtained by different methods by Jones (1966) and Newman (1981).

The loss of at least 25 inches (more than 70 percent) of the average annual precipitation to evaporative processes represents the single largest consumptive use of water in the Lake Michigan Region. Although the remaining 11 inches of water is considered adequate with respect to the Region's overall water budget, the spatial and temporal variability of rainfall from year to year and its uneven distribution during any given year can occasionally limit crops and water supplies.

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.

The exact amount of evaporation from Lake Michigan is unknown; however, average annual evaporation has been estimated to be 30 inches (Richards and Irbe, 1969). More recent studies have involved modeling efforts for forecasting and simulation applications (Croley, 1989a, 1989b).

Climatic extremes

Extreme climatic events such as droughts and flood-producing storms are infrequent but can have far-reaching economic impacts. In the Lake Michigan Region, economic losses caused by flooding and high lake levels are most widespread in urban and residential areas.

Heavy rainstorms can be described statistically by rainfall frequency analysis. 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 (1982c) summarizes the NOAA data for Indiana and provides interpolated estimates of rainfall values.

The Midwestern Climate Center in Illinois has updated heavy-rainfall frequency values for midwestern states. The analyses, which utilize data from NWS stations, provide values on a more detailed scale than values published by NOAA. A preliminary report was available in early 1990 (J. Angel, Illinois State Water Survey, personal communication, 1990).

The term "drought" generally is associated with a sustained period of abnormally low water levels or moisture supply. Drought-severity indices may be based on cumulative precipitation deficits, reservoir storage, stream flows, ground-water levels, or other hydrologic factors relevant to water supply and agricultural activities.

Because drought-severity indices commonly are used to initiate drought-response activities such as water-conservation measures and financial assistance, it is crucial that the selected indices provide a representative assessment of drought conditions. Researchers at Purdue University are working cooperatively with the IDNR Division of Water to develop regional drought indicators for Indiana (Delleur and others, 1990).

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), and the Great Lakes Commission (1990) discuss drought preparedness and planning for Indiana. Reports by Changnon and others (1982), Changnon (1987), Easterling and Changnon (1987), and Changnon and Easterling (1989) are four among many publications by staff of the Illinois State Water Survey that address drought climatology, impacts and preparedness in Illinois, including the Chicago-Gary area.

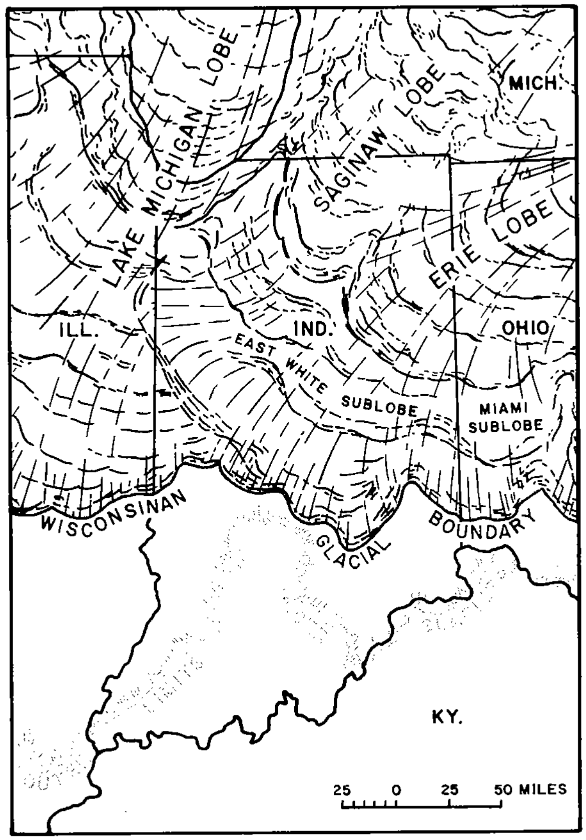

Figure 14. Extent of major ice lobes in Indiana during the Wisconsinan glaciation
(Adapted from Wayne, 1965)

GEOLOGY

Ground-water resources are strongly influenced by geology. Surficial geology greatly influences *topography* and soil development which, in turn, control runoff and *infiltration* of precipitation. Ground-water storage and rate of flow are controlled by the geology of the underlying unconsolidated and bedrock formations.

In northwestern Indiana, herein called the Lake Michigan Region, the most important *aquifers* consist of glacial, *glaciofluvial*, and *glaciolacustrine* deposits. These unconsolidated sediments were associated directly or indirectly with the advance and retreat of the Lake Michigan lobe of ice into and out of northwestern Indiana (figure 14).

Sources of geologic data

Hydrogeologic information for the Lake Michigan Region comes primarily from water-well records, an observation-well monitoring program, *lithologic* descriptions from oil- and gas-well records, engineering borings, *seismic* studies, *gamma-ray logs*, and local hydrogeologic projects.

Information on the shallow *aquifer systems* in the Lake Michigan Region comes mainly from water-well records. Approximately 4,500 water well records, kept on file at the Division of Water- Indiana Department of Natural Resources (IDNR), were analyzed for the ground-water assessment portion of this study. Since 1959, water-well drilling contractors have been required to submit to the IDNR a complete record of any water well drilled in the state.

Hydrogeologic information on the deep unconsolidated formations in the Lake Michigan Region was obtained during a cooperative drilling project that was conducted by the Division of Water and the Indiana Geological Survey (IGS) in 1987-88. This information was helpful in determining aquifer characteristics and the depositional history of the unconsolidated sedi-

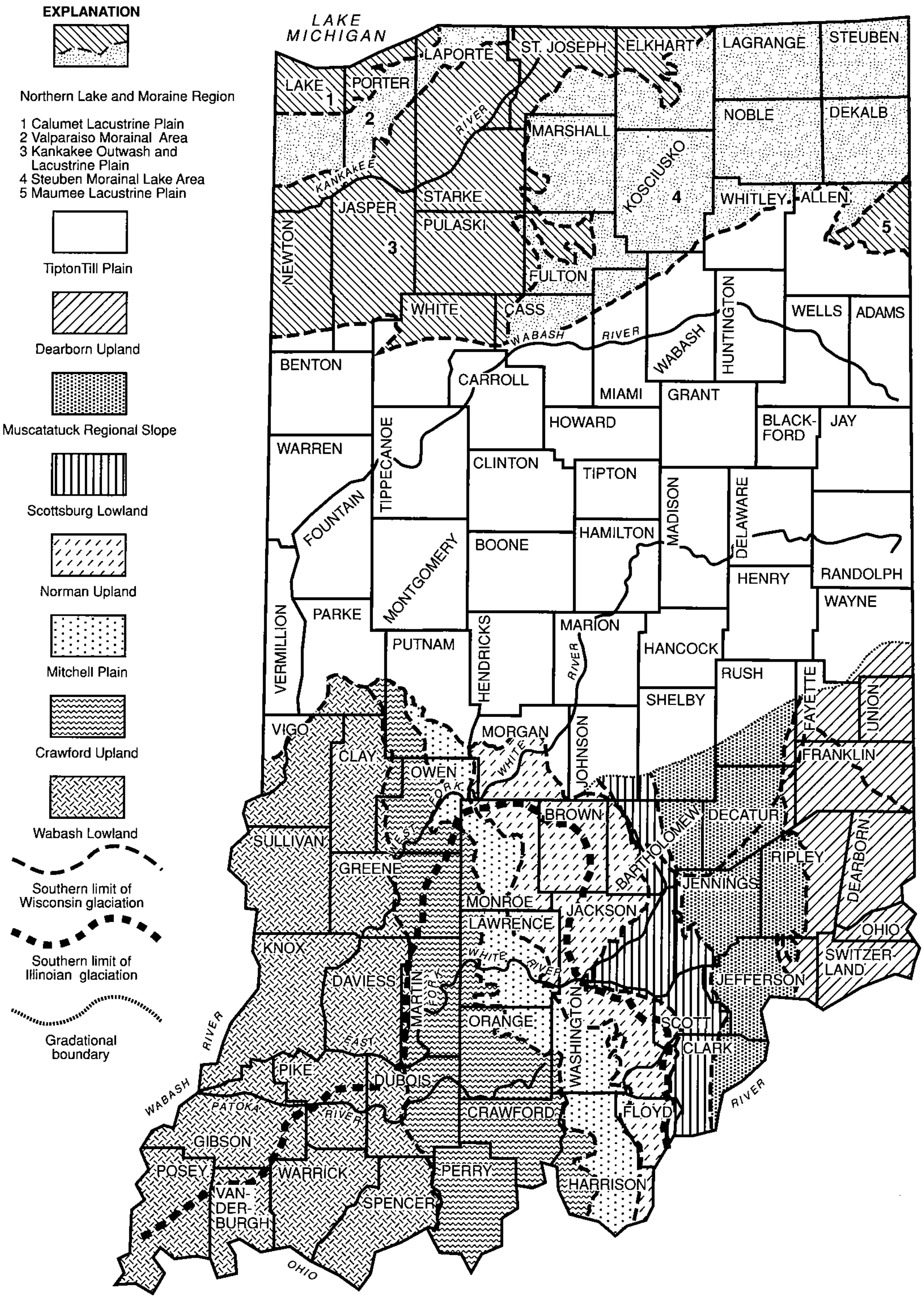

Figure 15. Physiographic regions of Indiana
(After Malott, 1922; modifed by Wayne)

ments in the region. Much of the interpretation of the glacial geology of the southern part of the Lake Michigan Region comes from an unpublished report by Bleuer and Fraser, Indiana Geological Survey.

Physiography

Malott (1922) divided Indiana into nine *physiographic regions* according to topography and the effect of glaciers on the landscape. The Lake Michigan Region lies within the extreme northwestern part of the Northern Lake and *Moraine* Region and includes the northern part of the **Valparaiso Morainal Area** and the entire **Calumet *Lacustrine* Plain** (figure 15).

The physiography of the southern part of the Lake Michigan Region is mostly the product of late Wisconsinan glacial advances of the Lake Michigan lobe. Subsequent retreat of the Lake Michigan lobe from the morainal area and development of ancestral Lake Michigan were responsible for most of the physiography in the northern part of the region.

The Valparaiso Morainal Area

The Valparaiso Morainal Area is comprised of the Valparaiso, Tinley and Lake Border Moraines (figure 16). These *end moraines* mark the limits of glacial advances by the Lake Michigan lobe during the late Wisconsinan glacial period.

The **Valparaiso Moraine** is the largest and oldest end moraine in the Lake Michigan Region. The crest of the moraine forms most of the drainage divide between the Kankakee River Basin to the south and the Lake Michigan Region to the north. A topographic sag near the town of Valparaiso in Porter County divides the moraine into two segments. Topographic expression and areal extent of both segments are distinctly asymmetrical.

The eastern segment of the Valparaiso Moraine is a ridge having maximum elevations which vary from about 850 feet (259 meters) to more than 950 feet (290 meters) above mean sea level (m.s.l.) near Springville in LaPorte County. The crest and northern slopes of the morainal ridge are underlain by a veneer of *debris-flow tills*. Numerous ice-block depressions called *kettle holes* are present in areas of rugged relief along the northern slopes of the moraine from Valparaiso to the Michigan state line. Large kettle depressions are presently occupied by lakes, and the smaller depressions are filled with a complex mix of sediment, including considerable amounts of *peat* and *muck.*

The western segment of the Valparaiso Moraine is comprised of two ridges capped by *basal tills.* The western segment of the moraine is much broader than the eastern segment, and maximum elevations seldom exceed 800 feet (244 meters) above m.s.l. The morainal surface is highly irregular and contains numerous basins of internal drainage and areas of irregular and deranged drainage patterns. Stream channels are flat-floored and deeply *incised* into the till surface. Evidence of *mass movements* from the margins into the axes of the channels suggest that the surficial till was deposited from thick ice that was drained by deep *englacial channels* or *tunnel valleys.*

The **Tinley Moraine** is the northernmost of the three morainal ridges in the western segment of the Valparaiso Morainal Area. The Tinley Moraine represents a readvance of the Lake Michigan Lobe after it had retreated an unknown distance from the Valparaiso Moraine (Schneider, 1968). The Tinley Moraine generally trends eastward from the Indiana-Illinois state line near the town of St. John, through Lake County, and into western Porter County. The moraine has local relief of less than 50 feet (15 meters), but maximum elevations of the moraine exceed 730 feet (222 meters) above m.s.l. at its western edge and 700 feet (213 meters) above m.s.l. at its eastern edge.

A shallow trough lying between 690 and 700 feet (210 and 213 meters) above m.s.l. separates the Tinley Moraine from the Valparaiso Moraine. The trough is presently drained by West Creek in the extreme west-central part of Lake County and the upper reach of Deep River in central and east-central Lake County. Considerable deposits of peat, muck and organic-rich *colluvium* are found in ice-block depressions along the trough.

An upland *till plain* located north of the eastern extent of the Tinley Moraine (figure 17) probably represents the terminal zone of Tinley ice (Schneider, 1968). This upland probably joins northward with the Lake Border Moraine (Todd Thompson, Indiana Geological Survey, personal communication).

The **Lake Border Moraine** in the Lake Michigan Region is an end moraine complex of low relief that is located north of the eastern segment of the Valparaiso Moraine (figure 16). The Lake Border Moraine consists of several linear ridges that parallel the long axis of the moraine. In northwestern LaPorte County, the

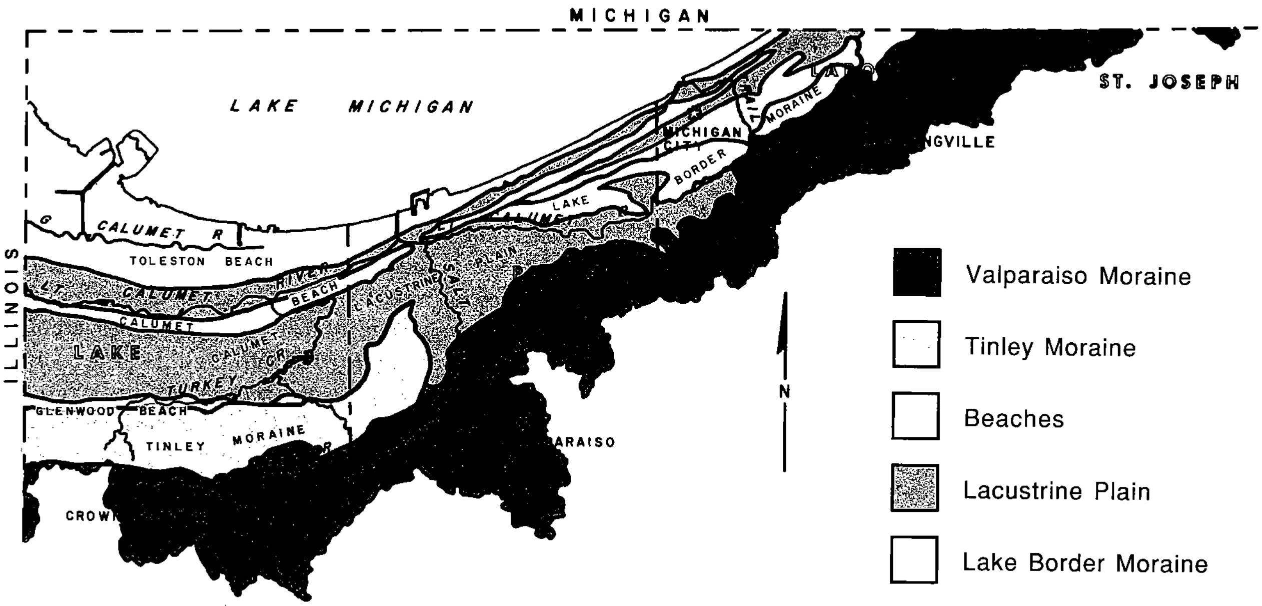

Figure 16. Major physiographic features

moraine is approximately 2.5 miles (4 kilometers) wide and ranges in elevation from 630 to 670 feet (192 to 204 meters) above m.s.l. Toward the west, the moraine thins to less than 0.25 mile (0.4 kilometers) in width and ranges in elevation from 650 to 690 feet (198 to 210 meters) above m.s.l. in north-central Porter County (Thompson, 1987).

The Calumet Lacustrine Plain

The Calumet Lacustrine Plain lies between the Valparaiso Morainal Area and Lake Michigan (figure 16). The plain ranges in elevation from about 580 feet (177 meters) at the present shoreline of Lake Michigan to as much as 760 feet (232 meters) above m.s.l. at dune-capped beach ridges. In the western part of the plain, the natural character of the landscape has been altered considerably as a result of industrialization and urbanization. The following description of the major physiographic features in the Calumet Lacustrine Plain is based on studies conducted primarily at the Indiana Dunes National Lakeshore and the Indiana Dunes State Park in the extreme northern part of Porter County. The natural physiography of the plain has remained relatively unaltered in these areas.

The predominant topographic expressions in the Calumet Lacustrine Plain are three *relict* dune-capped beach ridges separated by extensive interridge marshes. The relict beaches mark semi-stable shorelines of ancestral Lake Michigan during its late *Pleistocene* and *Holocene* history.

The **Glenwood Beach** is the highest dune and beach complex in the Lake Michigan Region. The relict beach is present as a discontinuous ridge on the lakeward slopes of the Lake Border and Tinley Moraines. The crest of the dune and beach complex has an average elevation of about 650 feet (198 meters) above m.s.l. However, the *foreshore* deposits, which represent the paleoshoreline, are present in places between 620 and 630 feet (189 to 192 meters) above m.s.l. (Thompson, 1987). The poorly-developed beach consists predominantly of dune sand capping till which suggest that the beach was probably covered by ice for most of the year.

The **Calumet Beach** is lakeward of the Glenwood Beach, but truncates the Glenwood Beach at the western tip of the Lake Border Moraine near the town of Tremont in Porter County. Dune-capped areas of the Calumet Beach have an average elevation of about 630 feet (192 meters) above m.s.l., and the foreshore deposits have an average elevation of 607 feet (185 meters) above m.s.l. (Thompson, 1987). Calumet deposits consist of *dune* sediments overlying beach and *nearshore sediments.*

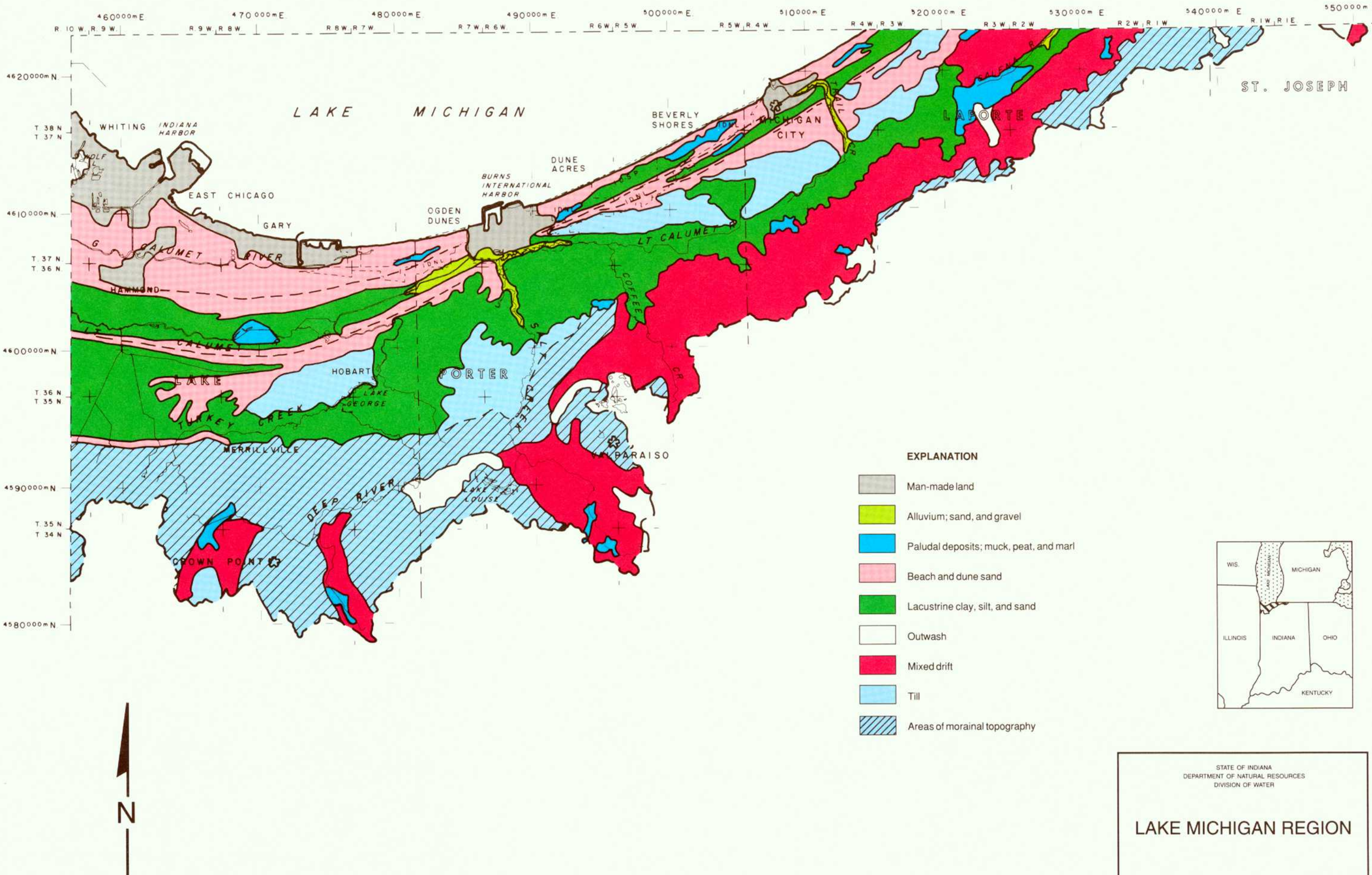

Figure 17. Surficial geology
(modified from Gray, 1989)

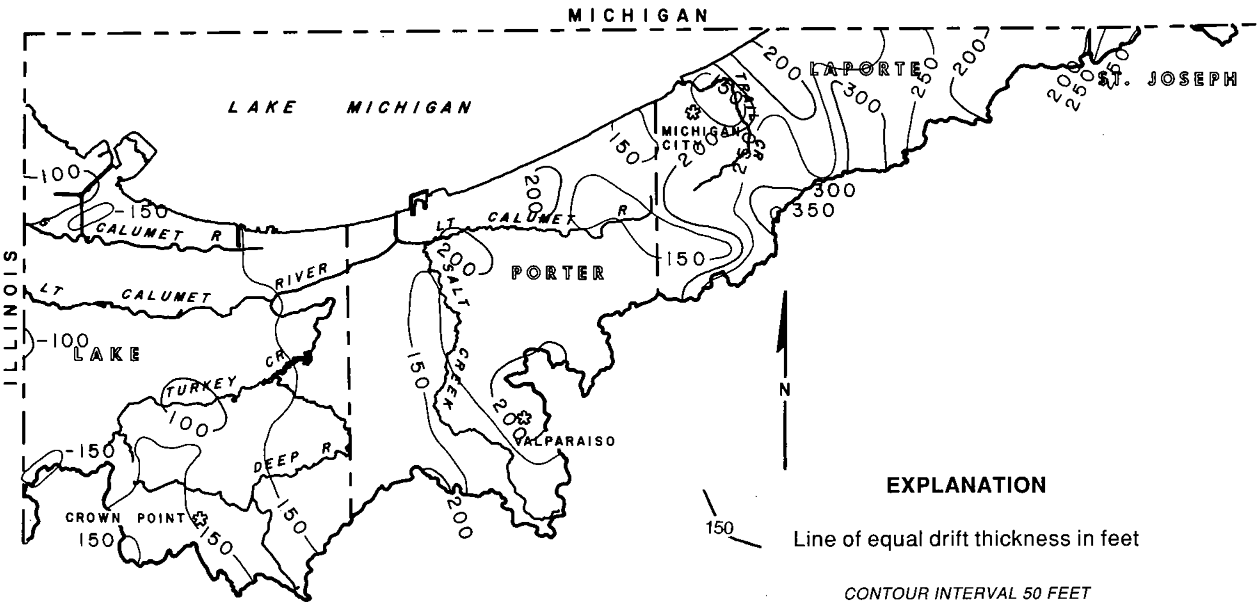

Figure 18. Thickness of unconsolidated deposits
(Adapted from Gray 1983)

The **Toleston Beach** is the youngest dune and beach complex in the Lake Michigan Region. The landward part of this complex consists of linear ridges of coalesced *parabolic* dunes separated by interdunal swamps, and the lakeward portion is comprised of large dome-shaped and small parabolic dunes (Thompson, 1987), as well as over 150 beach ridges in its western part. Elevations at the top of large domal dunes are as much as 750 feet (229 meters) above m.s.l. Foreshore, *upper shoreface* and *back-barrier* lacustrine deposits occur in the internal core of the complex. The top of the foreshore sequence of the Toleston Beach ranges from 597 to 603 feet (182 to 184 meters) above m.s.l. (Thompson, 1987). Modification of the Toleston Beach is still occurring in the eastern part of the Lake Michigan Region because of the reorientation of dominant wind direction across Lake Michigan.

Wetlands of considerable size are present in the interridge depressions in the eastern part of the Lake Michigan Region. An unnamed marsh lies between the Glenwood and the Calumet Beaches, and **Great Marsh**, which includes **Cowles Bog**, lies between the Calumet and the Toleston Beaches. *Palustrine* sediments are abundant in these interridge wetlands.

Areas of gentle relief in the Calumet Lacustrine Plain are capped by lacustrine and palustrine sediments (Gray, 1989). These areas are drained by sluggish rivers which empty into Lake Michigan. However, extensive *channelization* of the Little and Grand Calumet Rivers and industrialization in neighboring areas have altered the physiography and the hydrology of the Region.

Surficial geology

Surficial deposits overlie bedrock throughout the Lake Michigan Region. The deposits in the region are directly and indirectly related to the latest Wisconsinan glacial events of the Lake Michigan lobe.

The surficial deposits in the southern part of the Region are primarily the result of glacial processes, but the deposits in the northern part of the Region are the result of glacial, lacustrine, coastal and *eolian* sedimentation (figure 17). The unconsolidated deposits in the Lake Michigan Region ranges in thickness from about 100 feet (30 meters) to more than 350 feet (107 meters) (figure 18).

In general, the *stratigraphy* of surficial deposits controls the occurrence of ground water within the deposits. Important factors that control the hydraulic characteristics of an aquifer include grain size, grain shape, degree of sorting, and extent and arrangement of the deposits. The occurrence of these hydrogeologic elements in the surficial deposits of the Lake Michigan Region is the result of a complex interplay of depositional processes in various sedimentary environments.

Valparaiso Morainal Complex

The *lithofacies* of the Valparaiso and Tinley Moraines can be classified into five groups: 1) lacustrine muds, 2) *outwash* sands, 3) shale-rich gravels, 4) basal tills and 5) debris-flow tills. The vertical sequence of the deposits suggests that most of the complex was probably deposited during a time of ice advance.

Lacustrine muds, consisting of laminated silt, silty *loam*, and silty clay loam underlie the morainal complex in many places. These basal muds were probably deposited in a *proglacial* lake that covered almost the entire Kankakee River Basin. The lake formed when the Lake Michigan lobe retreated from a terminal position at the Iroquois Moraine south of the Region. The basal lacustrine muds are thickest beneath the western part of the Valparaiso morainal complex. Thin, less extensive sequences of lacustrine muds occur in the upper parts of the morainal complex. The muds, which are commonly interbedded with debris-flow tills or sand in abbreviated *deltaic sequences*, probably originated as *ice karst*, kettle holes or other irregular basins of internal drainage.

Medium-grained outwash sands overlie the basal lacustrine muds throughout most of the complex. The outwash sands were deposited by *meltwater* streams emanating from the Lake Michigan lobe. Thick outwash deposits occur as stacked channel fills with erosional *basal contacts* or as coarsening-upward deltaic sequences. The sand deposits form the Valparaiso Moraine *Aquifer system* and are extensive and thought to be continuous beneath most of the morainal complex. The outwash sands are generally thinner toward the west.

Black shale gravels are common in the Valparaiso morainal complex. The gravels are present in channel deposits throughout the central part of the morainal complex, and also make up a significant portion of the *outwash fan* toward the east. Thinning and fining-upward sequences in the channel deposits indicate channel abandonment, while thickening and coarsening-upward sequences indicate *progradation* of depositional lobes away from the advancing ice front. Gravels that were deposited outside of channels may be coarser-grained and thicker-bedded upward in the sequence.

Tills overlie most of the outwash sands in the Lake Michigan Region and extend to the surface. However, the thickness and texture of the surficial tills are not uniform across the morainal complex.

Thick basal tills cover the surface of the western segment of the Valparaiso morainal complex. The tills, mostly of clay loam texture, were deposited directly from ice as the Lake Michigan lobe overrode its outwash fan.

A **veneer of *debris-flow tills*** is present along the northern slopes and crest of the eastern part of the Valparaiso morainal complex indicating that glacial ice did not override the outwash fan in this area. The debris-flow tills are coarser grained than the basal tills to the west, and are usually in the form of silty loam and sandy silty loam. In a few places along the crest of the eastern part of the morainal complex, no tills are present and outwash deposits occur at the top of the sequence (figure 17).

The surface of the Valparaiso morainal complex contains isolated pockets of palustrine sediments (figure 17). The organic-rich sediments accumulated in *kettle holes* which are scattered throughout the morainal surface.

Lake Border Moraine

Surficial sediments of the Lake Border Moraine were deposited during the final glacial advances of the Lake Michigan Lobe. Thompson (1987) subdivided the deposits beneath the morainal surface into three *lithostratigraphic units*: 1) interbedded sand, gravel, clay and till, 2) till and glaciolacustrine clay capped by outwash sand and gravel, and 3) till.

Randomly **interbedded sand, gravel, clay and till** overlie shale and limestone bedrock in the northern part of the moraine. Lithologic variability, random distribution and poor preservation of the basal sediments prohibit interpretation of age and origin (Thompson, 1987).

Till and glaciolacustrine clay directly overlie the basal sediments of the Lake Border Moraine. Glaciolacustrine deposits predominate in the northward part of the unit, whereas tills are common in the central part of the unit (Thompson, 1987). The till and glaciolacustrine clay unit averages about 50 feet (15 meters) in thickness, and extends under Lake Michigan. Outwash sand and gravel overlie the glaciolacustrine clay and form the internal core of the morainal complex. The coarse-grained deposits commonly range in thickness from about 40 to 60 feet (12 to 18 meters). In some areas where the coarse-grained sediments are underlain by broken rock, local thickness of the sediments may exceed 150 feet (46 meters). Thick, localized accumulations of outwash material may indicate *tunnel valley fills* and/or isolated *outwash cones* at tunnel exits (Ned Bleuer, Indiana Geological Survey, personal communication).

A relatively impermeable **till** overlies the sandy core of the Lake Border Moraine and extends to the surface. The upper part of the till is yellow to brown but becomes blue-gray in the lower part. *Lenticular* bodies of sand and gravel, which probably formed as beach ridges, are present at the contact between the upper and lower parts of the till (Thompson, 1987). The surficial till of the Lake Border Moraine can be traced westward beneath the surficial sands of the Calumet Lacustrine Plain (Ned Bleuer, Indiana Geological Survey, personal communication).

Calumet Lacustrine Plain

Formation and development of the Calumet Lacustrine Plain began after the Lake Michigan lobe retreated northward from a terminal position at the Lake Border Moraine. The southern extent of the plain is marked by the Glenwood Beach, a discontinuous relict dune-capped beach ridge present along the northern slopes of the Lake Border and Tinley Moraines (figure 16). The deposits of the Calumet Lacustrine Plain can be subdivided into three lithostratigraphic units: 1) stratified lacustrine sand, silt and clay, 2) till and glaciolacustrine clay, and 3) lacustrine, dunal and coastal sands.

Stratified lacustrine sand, silt and clay overlie shale and limestone bedrock in the Calumet Lacustrine Plain. Gamma-ray logs of wells drilled in northern Lake and northwestern Porter Counties indicate the lacustrine sequence is generally upward-coarsening with intermixed silt and clay layers (Ned Bleuer, Indiana Geological Survey, unpublished data). This unit may be similar to the lowest unconsolidated unit of the Lake Border Moraine.

A relatively impermeable **till and glaciolacustrine clay** unit overlies the lacustrine sediments in the Calumet Lacustrine Plain. The unit consists predominantly of thick basal tills and thinner sequences of *ablation* tills. The unit exceeds 100 feet (30 meters) in thickness in many places.

Fine-grained lacustrine and dunal sands, and medium-grained coastal sands form most of the surficial deposits of the Calumet Lacustrine Plain. The lacustrine sands were deposited during the formation and development of ancestral Lake Michigan. Coastal and dunal sands comprise the relict beach ridges which mark the ancient shorelines of the lake. The surficial sand deposits of the Calumet Lacustrine Plain commonly range from about 30 to 50 feet (9 to 15 meters) in thickness, but can be much thicker along the dune-capped beach ridges.

Lacustrine clays and palustrine sediments are present at the surface in small areas throughout the plain (Gray, 1989). The lacustrine clays were deposited in the low-energy environments of ancestral Lake Michigan, and the palustrine sediments accumulated in basins of restricted or internal drainage and in poorly-drained interridge lowlands. Extensive accumulations of palustrine sediments which are found in Great Marsh, including Cowles Bog, are preserved in the Indiana Dunes National Lakeshore and the Indiana Dunes State Park. In the industrialized part of the Calumet Lacustrine Plain and lakeshore areas, slag and dunal sands were used to fill in the depressions and interridge lowlands, creating a relatively featureless plain.

Bedrock geology

Bedrock in the Lake Michigan Region consists of more than 4,000 feet of *sedimentary* rocks overlying a *granitic Precambrian basement*. The bedrock units consist primarily of sequences of **Cambrian** through **Mississippian** sandstone, limestone, dolomite and shale. In the Lake Michigan Region, bedrock is not exposed at the surface.

Regional bedrock structure in the Lake Michigan Region is controlled by two principal features: the **Kankakee Arch** to the southwest and the **Michigan Basin** to the northeast (figure 19). Sedimentary rocks dip away from the northern flank of the Kankakee Arch toward the Michigan Basin at an average rate of about 35 feet per mile (6.6 meters per kilometer) (Pinsak and Shaver, 1964). The gradient of the lower surface of the bedrock units is significantly higher than the gradient

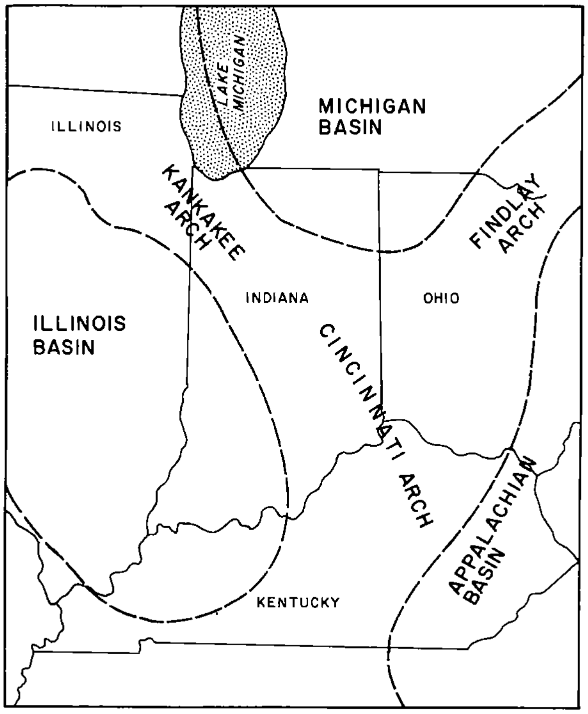

Figure 19. Regional bedrock structure

of the upper surface because the units thicken toward the Michigan Basin. Erosional truncation of bedrock along the Kankakee Arch has left Silurian rocks at the bedrock surface in western Lake County and progressively younger rocks toward the east.

Bedrock physiography

Bedrock relief in the Lake Michigan Region is probably the result of bedrock structure, lithology, differential erosion by streams and glaciers, and variations in the orientation and direction of glacial advances. The bedrock surface has greater relief in the eastern part of the Lake Michigan Region than in the western part of the region (figure 20).

Bedrock highs are present along the southern margin of the Lake Michigan Region. Maximum elevations developed on the bedrock surface range from about 575 feet (175 meters) above m.s.l. in southwestern Lake County to more than 675 feet (206 meters) above m.s.l. in east-central Porter County (figure 20). In most of the areas where maximum bedrock elevations exceed 600 feet (183 meters) above m.s.l., the Antrim and Ellsworth Shales form the bedrock surface (figures 20 and 21).

Major **bedrock valleys** in the Lake Michigan Region frequently originate near or beyond the southern margin of the Region and generally trend northward into Lake Michigan (figure 20). The bedrock valleys in northern Lake and northwestern Porter Counties are broad and have gently-sloping walls along most of their extent. These valleys are developed on rocks which range from Silurian carbonates to Mississippian shales (figures 20 and 21). In contrast, the deep bedrock valleys with steep walls in northeastern Porter and northern LaPorte Counties are developed on shales (figures 20 and 21).

The most prominent bedrock valley in the Lake Michigan Region is located in northern LaPorte County (figure 20). The valley begins in the vicinity of Pine Lake near the city of LaPorte and generally trends northward to the Michigan state line, where it is overlain by more than 250 feet (76 meters) of unconsolidated material (figure 18). Minimum elevations at the valley floor are less than 350 feet (107 meters) above m.s.l. in the northernmost reach (figure 20). Buried bedrock valleys sometimes contain thick coarse-grained deposits which can form aquifers.

Bedrock stratigraphy and lithology

Cambrian and Ordovician rocks form a large part of the Paleozoic sedimentary sequence in the Lake Michigan Region (appendix 3). However, these lower Paleozoic rocks are not present at the bedrock surface in the Region.

The **Cambrian** sequence in the Lake Michigan Region is comprised of thick sandstone units separated by carbonate, shale, and interbedded shale and carbonate units (appendix 3). The overlying rocks of lower Ordovician age are *conformable* with the upper Cambrian rocks where the stratigraphic sequence is preserved. However, in parts of northwestern Indiana, pre-middle Ordovician erosion has removed lower Ordovician rocks. The **Ordovician** sequence is not as thick as the Cambrian sequence, but consists of relatively thick carbonate units that are separated by a thin sandstone unit and capped by a shale unit (appendix 3).

Rocks at the bedrock surface in the Lake Michigan Region range from **Silurian** to **Mississippian** (figure 21). Detailed discussions on structure, stratigraphy and sedimentology of the rocks may be obtained from

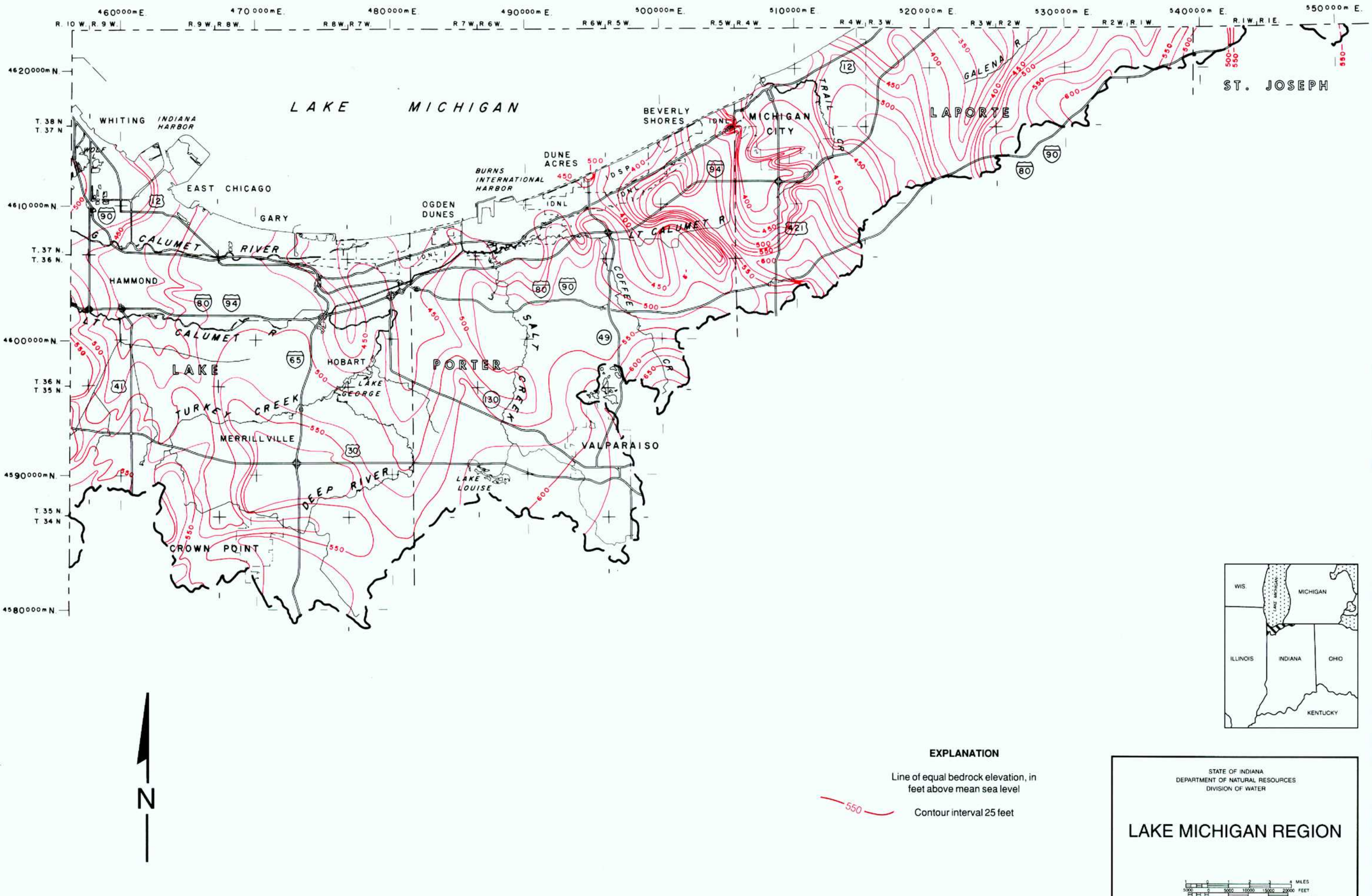

Figure 20. Bedrock topography

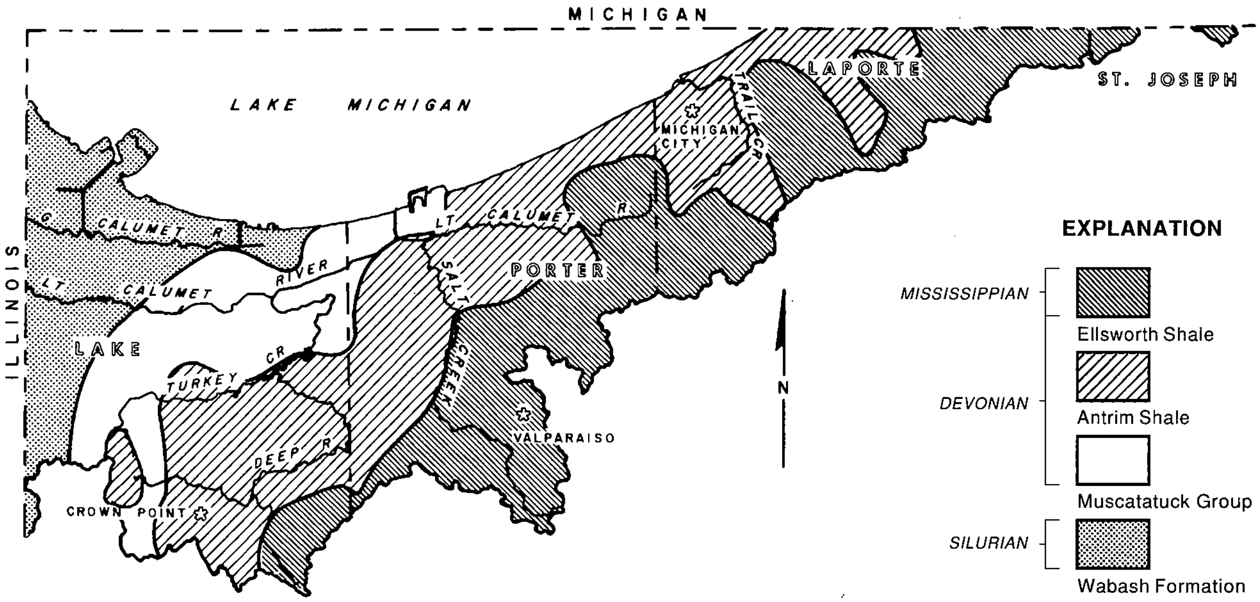

Figure 21. Bedrock geology
(Adapted from Gray and others, 1987)

Doheny and others (1975), Droste and Shaver (1982), and other references cited in the text.

Rocks of the **Silurian Wabash Formation** are the oldest rocks at the bedrock surface in the Lake Michigan Region. Wabash rocks consist of limestone, dolomitic limestone, dolomite and *argillaceous* dolomite. Depositional environments of the Wabash rocks include reef and inter-reef environments, although non-reef facies of the Wabash Formation exist (Droste and Shaver, 1982). The four principal lithologies of the Wabash Formation which are generally characteristic of the Mississinewa Shale Member, Liston Creek Limestone Member, Kokomo Limestone Member and the Huntington Lithofacies intergrade and replace one another spatially within the formation (Shaver and others, 1986). Pre-middle Devonian erosion truncated Wabash rocks differentially, more southward than northward and more eastward than westward (Droste and Shaver, 1982).

The **Devonian Muscatatuck Group** *unconformably* overlies Wabash rocks. The Muscatatuck Group, comprised of the Detroit River and Traverse Formations, occurs at the bedrock surface in the western part of the Lake Michigan Region (figure 21). Rocks of the Muscatatuck Group are predominantly limestone and dolomite, but evaporitic rocks are present in the upper and the lower sections of the Detroit River Formation. Common lithologies of Muscatatuck rocks are described by Shaver and others (1986).

The **Upper Devonian Antrim Shale** *paraconformably* overlies Muscatatuck rocks in the Lake Michigan Region. The Antrim Shale is exposed at the bedrock surface in east-central Lake County and the northern parts of Porter and LaPorte Counties (figure 21). The Antrim consists of brown to black non-*calcareous* shale; however, calcareous shale, limestone and sandstone are present in the lower part of the unit in some areas in LaPorte County (Shaver and others, 1986). The Antrim Shale is largely correlative with the **New Albany Shale** of the Illinois Basin.

The **Ellsworth Shale** ranges from **Upper Devonian** to **Lower Mississippian** in age and conformably overlies the Antrim Shale. The Ellsworth Shale can be found at the bedrock surface along the southern and southeastern margins of the Region in Porter and LaPorte Counties (figure 21). The Ellsworth is characterized by gray-green shale with limestone or dolomite lenses in the upper part and alternating beds of gray-green shale and brown-black shale in the lower part.

SOILS

Soil development is controlled to a large extent by climate, topography, biota, *parent material* and time. Surficial geology and physiography are important factors that influence soil texture. In the Lake Michigan Region, the distribution of the major soil types is closely related to the physiographic terrains of the Region: namely, clayey or loamy soils found in the Valparaiso Morainal Area, and sandy soils found in the Calumet Lacustrine Plain.

Soils on the end moraines of the Valparaiso Morainal Area (see figure 16) have been developed primarily in clay-rich glacial till. Loamy soils are more common in the eastern part of the morainal area, where stratified mixed drift of the Valparaiso Moraine are present in northern LaPorte County. The soils that are formed on morainal swells and slopes are well-drained, but the soils in plains, ice-block depressions and relict glacial drainageways are poorly-drained.

In the Calumet Lacustrine Plain, sandy soils occur on dune and beach complexes and on lacustrine and coastal deposits. The well-drained soils occur on the dune and beach ridges, whereas the poorly-drained soils are present in interridge depressions, drainageways and lake-plains.

Soil development in most of the Lake Michigan Region occurred under a cover of mixed hardwood forest; however, some soils in Lake and Porter County developed under prairie grasses (figure 22). Isolated pockets of organic soils have developed in areas of restricted or internal drainage. At several industrial and urban sites along the Lake Michigan shore, alteration of the landscape has resulted in substantially modified soil.

Soil data of major Region counties are presented in soil survey reports (Persinger, 1972; Furr, 1981 and 1982). 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 Region 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; namely, 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 pattern.

A total of 108 soil association were identified in a series of generalized county soil maps developed in 1970 by the U.S. Department of Agriculture's Soil Conservation Service 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 broad basis. Figure 22, adapted from a 1982 revision of the state map (U.S. Department of Agriculture, 1982), shows the location of major soil associations in the Lake Michigan Region.

Figure 22 also shows the regions of similar parent materials into which the major associations are grouped. Figure 22 can be useful in relating Region soils to surficial geology, topography and vegetation types (see explanatory text accompanying figure 22). A report by Galloway and Steinhart (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

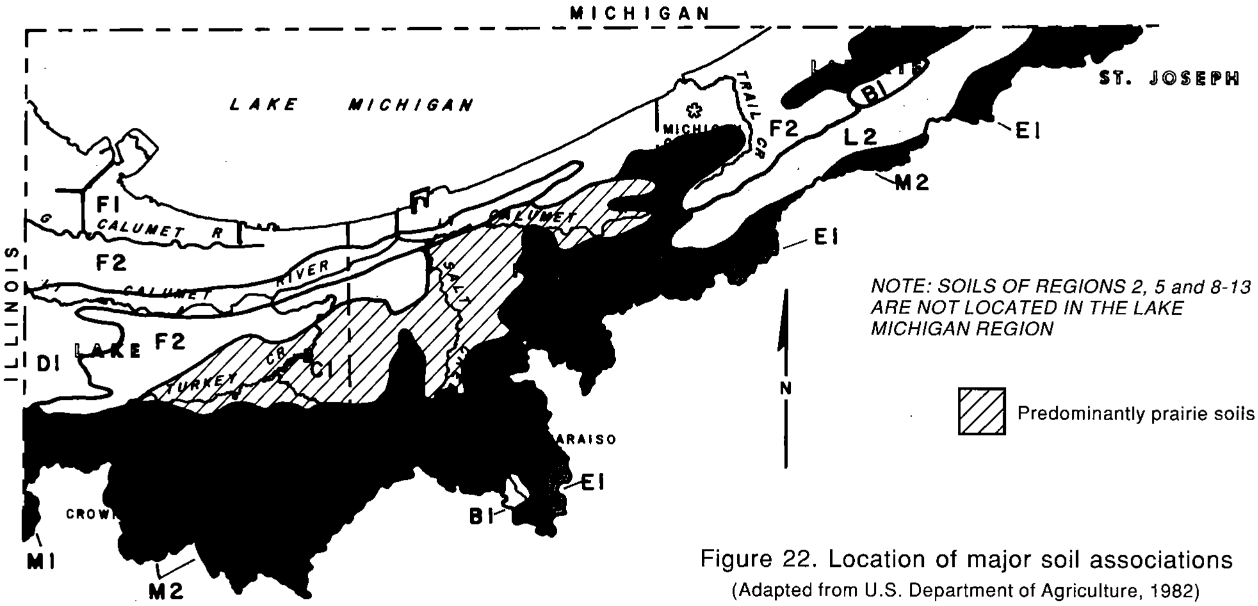

Figure 22. Location of major soil associations
(Adapted from U.S. Department of Agriculture, 1982)

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

The nearly level, very poorly drained soils of the Houghton-Adrian association (B1) formed in organic materials deposited in ancient lakes, and developed under a cover of trees, shrubs and sedges. These soils frequently occur as small, scattered muck pockets; however, two mappable areas occur in the region. One is located in LaPorte County near the headwaters of the Galena River, the other is south of Valparaiso. Loamy soils in the Rensselaer-Darroch-Whitaker association (C1) predominate on the nearly level lacustrine plains of the Lake Michigan Region. The very poorly drained Rensselaer soils occur in swales and broad, flat areas. Somewhat poorly drained Whitaker and Darroch soils are found on convex swells in the lake plain. Whitaker and Rensselaer soils formed under a cover of mixed hardwoods, whereas Darroch soils developed under prairie grasses. Soils of the Milford-Bono-Rensselaer association (D1), located in the west central part of the region, are very poorly drained. The native vegetation was mainly water-tolerant mixed hardwood and grass species. The parent materials are calcareous, silty, clayey and loamy lacustrine deposits.

REGION 3 - SOILS FORMED IN ALLUVIAL AND OUTWASH DEPOSITS

Well-drained soils of the Tracy-Door-Lydick association (E1) occupy the pitted outwash fan which extends from eastern Porter County to northwest St. Joseph County. Only two small areas of this association occur near the southeastern boundary of the Lake Michigan Region. The parent materials are loamy and sandy outwash deposits that were high in sulfur-containing shale particles and which weathered to form acid soils. The native vegetation on Tracy soils was mainly oak; on Door it was prairie grasses; and on Lydick, it was a mixture of the two vegetation types. Tracy soils are found on 0 to 12 percent slopes. Lydick and Door soils are mainly on 0 to 2 percent slopes.

REGION 4 - SOILS FORMED IN EOLIAN DEPOSITS

At the south end of Lake Michigan Oakville-Adrian (F1) association soils are found on the high sand dunes and the lower sandy ridges and wet swales. Oakville soils, formed from dune sand or beach sand, are on dunes and beach ridges. Comprised of fine sand throughout, the Oakville soils are well-drained. Native vegetation was mainly oak trees. Adrian, a very poorly drained soil, formed in 16 to 50 inches of organic material over sands, is found in the swales between the ridges. Soils of the Plainfield-Maumee-Oshtemo association (F2) developed in *eolian* sands and sandy outwash deposits. Well-drained Plainfield soils have a fine sand texture throughout and typically are found on 2 to 12 percent slopes on sand dunes, where the native vegetation was mainly white and black oak. Very poorly drained Maumee soils, which are fine sand or loamy fine sand throughout, occupy the level, low-lying areas around the dunes. Oshtemo soils, located on outwash plains, are well drained and are comprised of loamy sands or sandy loams.

REGION 6 - SOILS FORMED IN LOAMY GLACIAL TILL

Well-drained soils of the Riddles-Tracy-Chelsea (L2) association are mainly found on 2 to 18 percent convex slopes of the Valparaiso Moraine in LaPorte County. Parent materials are glacial till and outwash and native vegetation was hardwood trees.

REGION 7- SOILS FORMED IN CLAYEY GLACIAL TILL

Soils of the Markham-Elliott-Pewamo (M1) and Morley-Blount-Pewamo (M2) associations are found on the Valparaiso Moraine in Lake, Porter and western LaPorte Counties. The parent material is calcareous silty clay loam or clay loam till. Soils of the Markham-Elliott-Pewamo association developed under prairie grasses, whereas soils of the Morley-Blount-Pewamo association formed under beech, oak and maple forests. Well-drained Markham and Morley soils are found on 2 to 12 percent slopes. The somewhat poorly drained Elliott and Blount soils occupy nearly level areas. Very poorly drained Pewamo soils are found in drainageways and swales.

generation of surface-water runoff. The Soil Conservation Service has classified soils into four hydrologic groups (A,B,C,D) according to the soil's ability to absorb rainfall and thereby reduce runoff. Classifying bare soils on the Region 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 chiefly of deep, well to excessively drained sands and gravels. These soils also have high *transmission* rates. Plainfield and Oakville soils, which are found on sand dunes and ridges just south of Lake Michigan (associations F1 and F2 in figure 22) and Chelsea (association L2) which is found on the Valparaiso Moraine in LaPorte County, are the major soils of the region which naturally fall into hydrologic soil group A. Maumee, Houghton and Adrian soils, found primarily in level, low-lying areas around dunes or river valleys (associations F2 and B1), may be classified into hydrologic soil group A after artificial drainage measures have improved their ability to absorb rainfall and reduce runoff.

Soils in hydrologic group B have moderate infiltration and transmission rates. Well-drained soils that typify this soil group include those that have formed in loamy glacial till of the Valparaiso Moraine in LaPorte County (L2). Other soils classified into hydrologic soil group B include those that formed on outwash-plain deposits, such as soils of the Tracy-Door-Lydick association (E1).

Soils in hydrologic group C have slow infiltration and transmission rates. These soils consist chiefly of soils with a layer that impedes downward movement of water, or soils having a moderately fine to fine texture. In the Lake Michigan Region, these soils are found primarily on the Valparaiso Moraine (associations M1 and M2), where soils have formed on clayey glacial till deposits in Lake and Porter Counties. Other areas of C-group soils are found on the nearly level lacustrine plains of the Region (association C1).

Soils in hydrologic group D have very slow rates of infiltration and transmission. In the Lake Michigan Region, this soil group consists chiefly of soils having a permanent high water table and/or organic materials, or soils having a clay layer at or near the surface. Undrained tracts dominated by Maumee, Houghton or Adrian, Bono or Milford soils (associations F2, B1, and D1, respectively) are included in this hydrologic soil group. Undrained depressional areas dominated by Pewamo soils also are classified in soil group D. Undrained Pewamo soils commonly are found in *swales* and drainageways on the Valparaiso Moraine (associations M1 and M2).