GROUND-WATER HYDROLOGY

Ground-water supplies are obtained from *aquifers*, or subsurface formations of rock saturated with water. The hydrologic characteristics of aquifers and natural chemistry of ground water determine the availability and suitability of regional ground-water resources for specific uses.

GROUND-WATER RESOURCES

Ground water is the part of precipitation which enters the ground and continues to move downward through openings in soil and bedrock until it reaches the water table (figure 49). The water table is the elevation below which all openings in the rock or soil are filled with water. Water entering the saturated zone is called *recharge*.

In a general way, the configuration of the water table approximates the overlying topography (figure 49). At a depression where the land surface intersects the water table, water is discharged from the ground-water system to become part of the surface-water system.

The interaction between ground water and surface water can moderate seasonal water-level fluctuations in both of these systems. During dry periods, ground-water discharge can help maintain water levels in streams. Conversely, surface water can recharge ground water through soils saturated by flooding or through streambeds during periods when the water table falls below the elevation of the water surface in a stream.

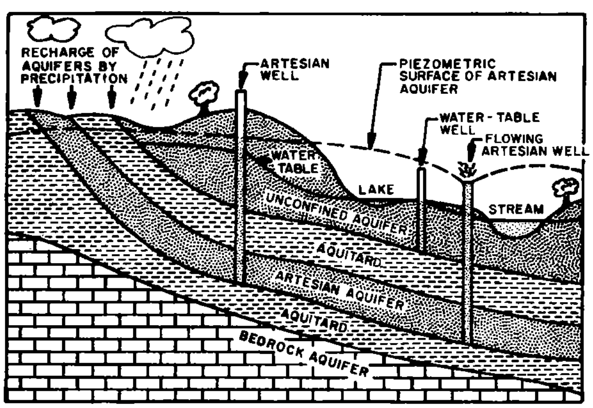


Figure 49. Aquifer types and ground-water movement

Porosity and *permeability* are the most important hydraulic properties affecting ground-water availability. Porosity is the amount of open space in rock and soil. Permeability is the degree to which pores are connected and determines how quickly water moves through the material.

In bedrock, pores occur as fractures, solution openings, and openings between grains composing the rock. In unconsolidated deposits, all of the pores are intergranular, but fine-grained deposits such as clays or silts may have secondary porosity in the form of fractures.

The size and sorting of material determines the amount and interconnection of intergranular pores. Sand and gravel deposits have a high proportion of pore space and high permeability, whereas fine-grained or clay-rich deposits have a greater proportion of pores, but a lower degree of permeability.

Aquifers have high porosity and permeability so that they may absorb, store and transmit water in usable quantities. Materials with low permeability, called *aquitards*, restrict ground-water movement. An aquitard overlying an aquifer may limit the recharge to the aquifer but may also protect an aquifer from surface contamination.

Where an aquitard overlies an aquifer, the water in the aquifer may be under *hydrostatic pressure*. The aquifer is said to be confined or artesian because the aquitard prevents or restricts upward movement of water from the aquifer. In an artesian well, the water level will rise to an elevation higher than the elevation of the top of the aquifer (figure 49). In a flowing artesian well, the water level in the well rises above the land surface. The level of water in wells in a confined aquifer is known as the potentiometric or *piezometric surface* (figure 49).

As a well discharges water from an aquifer, the water level is lowered around the well. This depression in the water level, called *drawdown*, causes ground water around the well to flow toward the well to compensate for water pumped from the aquifer. A greater pumping rate causes a greater depression in the water level and induces recharge to the aquifer; however, the recharge rate may be limited by the permeability of the aquifer and surrounding formations.

Ground-water levels

Ground-water levels fluctuate in response to rainfall, evapotranspiration, barometric pressure, and ground water recharge, discharge and pumpage. However, the response time for the ground-water level fluctuations is controlled predominantly by the local and regional geology.

To study natural or man-induced stresses in an aquifer, an observation well is completed in the aquifer of interest and the *static water level* is monitored periodically. The static water level in an observation well represents the local *hydraulic head* in the aquifer, and it may not be an indication of the hydraulic head in more shallow or deeper aquifers. Significant fluctuations in the static water level in the observation well may be an indication of natural or man-induced stresses in the aquifer.

The observation well monitoring program in the Lake Michigan Region was started in 1956 by the U.S. Geological Survey (USGS) in cooperation with the Indiana Department of Natural Resources (IDNR). By 1957, the observation well network consisted of six wells, five in Lake County and one in Porter County (table 21). At the present, the network includes six discontinued wells and one active observation well, Lake 13, which is located in northwestern Lake County (figure 50). Records on all of the active and discontinued observation wells in Indiana are kept on file at the Division of Water, IDNR. Observation wells in the Lake Michigan Region are categorized into three groups: 1) unaffected by pumping, 2) affected by pumping, and 3) special purpose. The seven observation wells in the Lake Michigan Region include two wells classified as unaffected, two wells classified as affected, and three wells classified as special purpose (table 21).

The two observation wells that are classified as unaffected by pumping are Porter 8 and Lake 13. Because the records of water levels in both wells are discontinuous, the hydrographs of the two wells, as well as pertinent hydrologic data such as river stage and precipitation are presented for **selected** water years only (figures 51 and 52). Hydrologic data are often presented in water years (October to September) instead of calender years (January to December) because the annual peak in river stage, which commmonly occurs from December to June, can be interpreted as two annual peaks in two calender years if a major precipitation event occurs from late December to early January.

The hydrograph of Porter 8 for the 1960 water year (Oct. 1959 to Sep. 1960) shows static water level fluctuations during a period of average rainfall (figure 51). The static water levels in Porter 8, which corresponded to the local hydraulic head in a *confined* sand and gravel aquifer in northern Porter County, were monitored from 1956 to 1974 (table 21).

Observation well Lake 13, which has been active since 1986, has an automatic water-level recorder that monitors the local static water levels in a shallow *unconfined* aquifer. In the vicinity of the well, annual rainfall was above and below normal for the last few years. Rainfall was above average during the 1987, 1989 and 1990 water years, but was considerably less than average during the 1988 water year. For the 1990 water year (Oct. 1989 to Sep. 1990), static water level fluctuations in Lake 13 showed a correlative response to daily rainfall (figure 52). This type of response is expected and common in shallow *water-table* aquifers.

The hydrographs of both Porter 8 (figure 51) and Lake 13 (figure 52) indicate that the temporal trends in the ground-water levels are normal. Ground-water levels in the aquifers are highest during the wet season of spring, and decline during summer and fall because of increased evapotranspiration and reduced recharge. Fluctuations in the ground-water levels in both Porter 8 and Lake 13 average 3 to 4 feet annually. The fluctuations are the result of natural stresses, and thus may indicate trends in the natural rates of ground-water recharge to and discharge from the aquifers.

Observation wells Lake 4 and Lake 5, active from 1956 to 1971, and 1956 to 1961, respectively, were used to monitor the static water levels in a confined sand and gravel aquifer in northern Lake County. The static water levels in both wells were affected by nearby pumping (table 21) and the water level fluctuations could not clearly show any indication of natural recharge to and discharge from the aquifer.

Special-purpose observation wells in the Lake Michigan Region include Lake 8, Lake 9 and Lake 10. Data collected from these wells were not available, and therefore could not be analyzed.

Piezometric Surface

Water exists under different pressures in unconfined and confined aquifers. Water in unconfined aquifers exists under atmospheric pressure, and wells that are

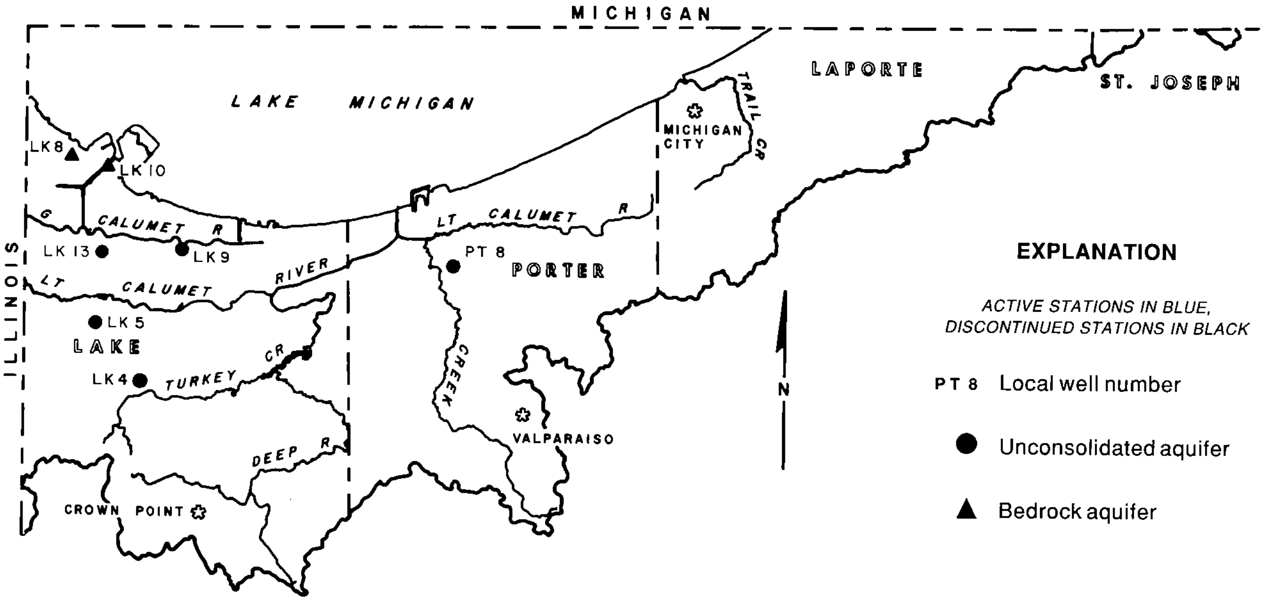


Figure 50. Location of observation wells

Table 21. Summary of active and discontinued observation wells

Well number: U.S. Geological Survey county code and well number. Well locations are shown in figure 50.
Period of record: Refers to calender year, whether or not data encompasses entire year.
Aquifer system: Cal, Calumet; LP, Lacustrine Plain; COS, Cambrian-Ordovician-Silurian carbonates and sandstones; Sil, Silurian;
Aquifer type: LS, Limestone; DOL, Dolomite; SS, Sandstone; SG, Sand and Gravel; S, Sand.
Aquifer classification: A, affected by pumpage; UA, unaffected by pumping; SP, special purpose.

County	Well no.	Period of record	Aquifer System	Aquifer Type	Aquifer Condition	Well Diameter (in.)	Well Depth (ft.)	Aquifer Class
Lake	LK13	1986-	Cal	S	Unconfined	6	23	UA
	*LK4	1956-1971	LP	SG	Confined	12	82	A
	*LK5	1956-1961	LP	SG	Confined	10	39	A
	*LK8	1957-1958	COS	LS/SS	Confined	8	1228	SP
	*LK9	1957-1967	Cal	SG	Unconfined	600	30	SP
	*LK10	1957-1968	Sil	LS/DOL	Confined	8	550	SP
Porter	* PT8	1956-1974	LP	SG	Confined	10	80	UA

* Discontinued wells

completed in these aquifers have water levels that correspond to the local water table. In contrast, water in confined aquifers exists under hydrostatic pressure which exceeds atmospheric pressure. Wells completed in confined aquifers have water levels that rise above the water-bearing formation until the local hydrostatic pressure in the well is equal to the atmospheric pressure (figure 49).

The composite piezometric surface map of the Lake Michigan Region (plate 1) shows elevations of the water table in unconfined aquifers and elevations of the static water level in wells that penetrate confined aquifers. However, depths to the piezometric surface **do not** represent appropriate depths for water wells. Instead, wells must be completed in the water-yielding formation, with depth into the aquifer based primarily

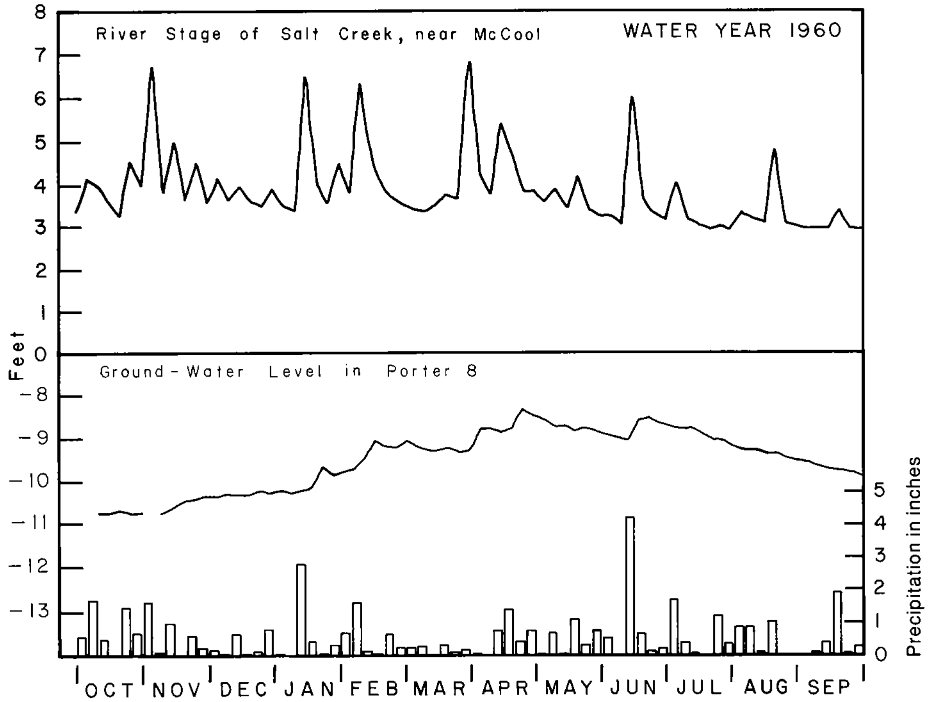


Figure 51. Comparison of river stage, precipitation, and water-level fluctuations in a confined aquifer

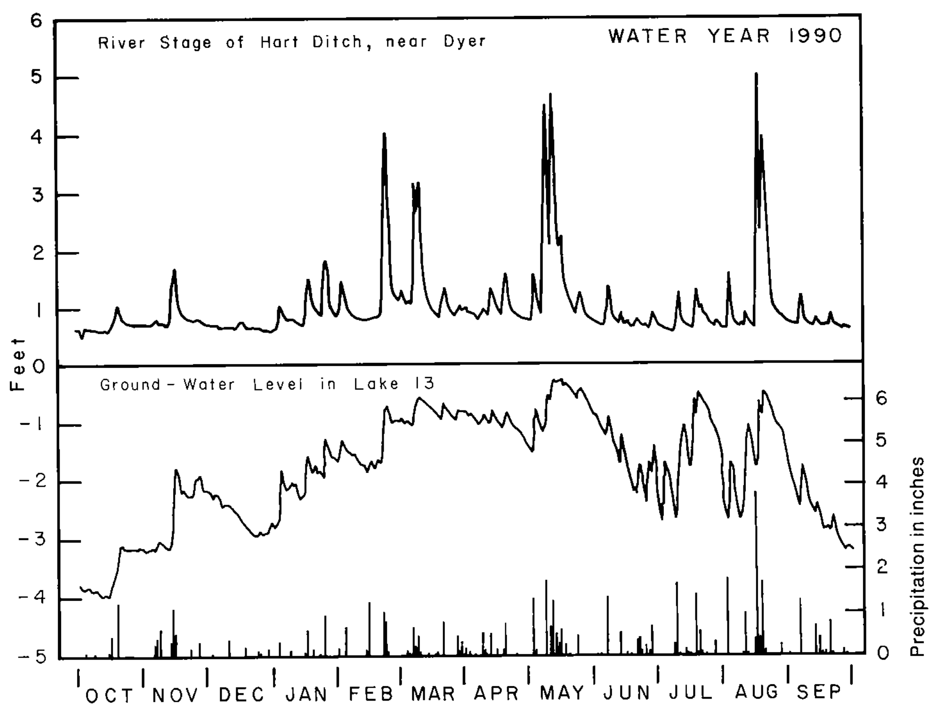


Figure 52. Comparison of river stage, precipitation, and water-level fluctuations in an unconfined aquifer

on local geologic conditions, such as thickness and lateral extent of the aquifer.

The piezometric surface map of the Lake Michigan Region (plate 1) can be used to indicate probable directions of regional ground-water flow, areas of ground-water recharge and discharge, and preferential paths for contaminant migration in regions that are dominated by horizontal ground-water flow. In natural, shallow ground-water flow systems, the piezometric surface is highest in elevation along drainage divides and lowest in elevation along *effluent streams.* Probable ground-water flow paths are perpendicular to the piezometric contour lines of decreasing values. However, heterogeneity of the deposits can affect local ground-water flow directions.

The piezometric surface in the Lake Michigan Region generally reflects the overlying topography throughout most of the region. In the eastern part of the basin in northern Porter and LaPorte Counties, the piezometric surface ranges in elevation from about 625 to 675 feet (190 to 206 meters) above m.s.l. (mean sea level) in the Lacustrine Plain *Aquifer system* and from about 675 to 775 feet (206 to 236 meters) above m.s.l. in the Valparaiso Moraine Aquifer system (plate 1).

Flowing wells (figure 49) are present in some parts of Porter and LaPorte County where the piezometric surface of the Valparaiso Moraine and the Lacustrine Plain Aquifer systems is above the land surface. The local hydrostatic pressures in these aquifer systems are generated by the high *hydraulic heads* that are present along the crest of the Valparaiso Moraine in the eastern and central parts of the Lake Michigan Region.

Hydraulic heads in the western part of the Valparaiso Moraine are not as high as in the eastern and central parts because the moraine decreases in elevation toward the west. In northern Lake County the piezometric surface ranges in elevation from about 600 to 625 feet (183 to 190 meters) above m.s.l. in the Lacustrine Plain Aquifer system and from about 625 to 675 feet (190 to 206 meters) above m.s.l. in the Valparaiso Moraine Aquifer system (plate 1).

Water-levels in most of the unconfined Calumet Aquifer system range in elevation from approximately 580 feet (177 meters) above m.s.l. at the shores of Lake Michigan to just over 600 feet (183 meters) above m.s.l. along the southern boundary of the aquifer system (plate 1). The surficial sands of the Calumet Aquifer system permit discharge of ground water from the aquifer to Lake Michigan, and the Little Calumet and Grand Calumet Rivers.

AQUIFER SYSTEMS

The ground water resources of the Lake Michigan Region are mapped and described as regional aquifer systems. Lack of data and complexity of the deposits preclude detailed aquifer mapping.

The unconsolidated and bedrock aquifer systems of the Lake Michigan Region form a single but complex hydrologic system. Three major and three minor unconsolidated aquifer systems are defined according to the hydrologic characteristics and hydrogeologic conditions of the deposits, and two bedrock aquifer systems are defined on the basis of hydrologic and lithologic characteristics. Overall, ground water supplies in the Lake Michigan Region are obtained mainly from unconsolidated aquifers, although bedrock aquifers are utilized as an important source of water in parts of Lake County.

Unconsolidated aquifer systems

The Valparaiso Moraine, Lacustrine Plain and Calumet Aquifer systems are recognized as the major unconsolidated aquifer systems in the Lake Michigan Region. Small parts of the Valparaiso *Outwash Apron*, Kankakee, and the St. Joseph Aquifer systems extend into the southern and eastern areas of the Lake Michigan Region (plate 2).

Sediments that comprise these aquifer systems were deposited in complex environments associated with the Lake Michigan lobe and ancestral Lake Michigan. Boundaries of the unconsolidated aquifer systems are gradational, and individual aquifers may extend across aquifer systems boundaries.

Unconsolidated aquifers in the Lake Michigan Region are utilized primarily in the interior portions of Porter and LaPorte Counties, and in north-central and east-central Lake County. Highly-productive zones within the unconsolidated aquifer systems are encountered where thick, coarse-grained deposits occur (figure 53).

Valparaiso Moraine Aquifer System

The Valparaiso Moraine Aquifer system consists of a heterogeneous layer of outwash sand and gravel with intermixed clay and silt lenses. The aquifer system, which lies along the central parts of Lake, LaPorte and

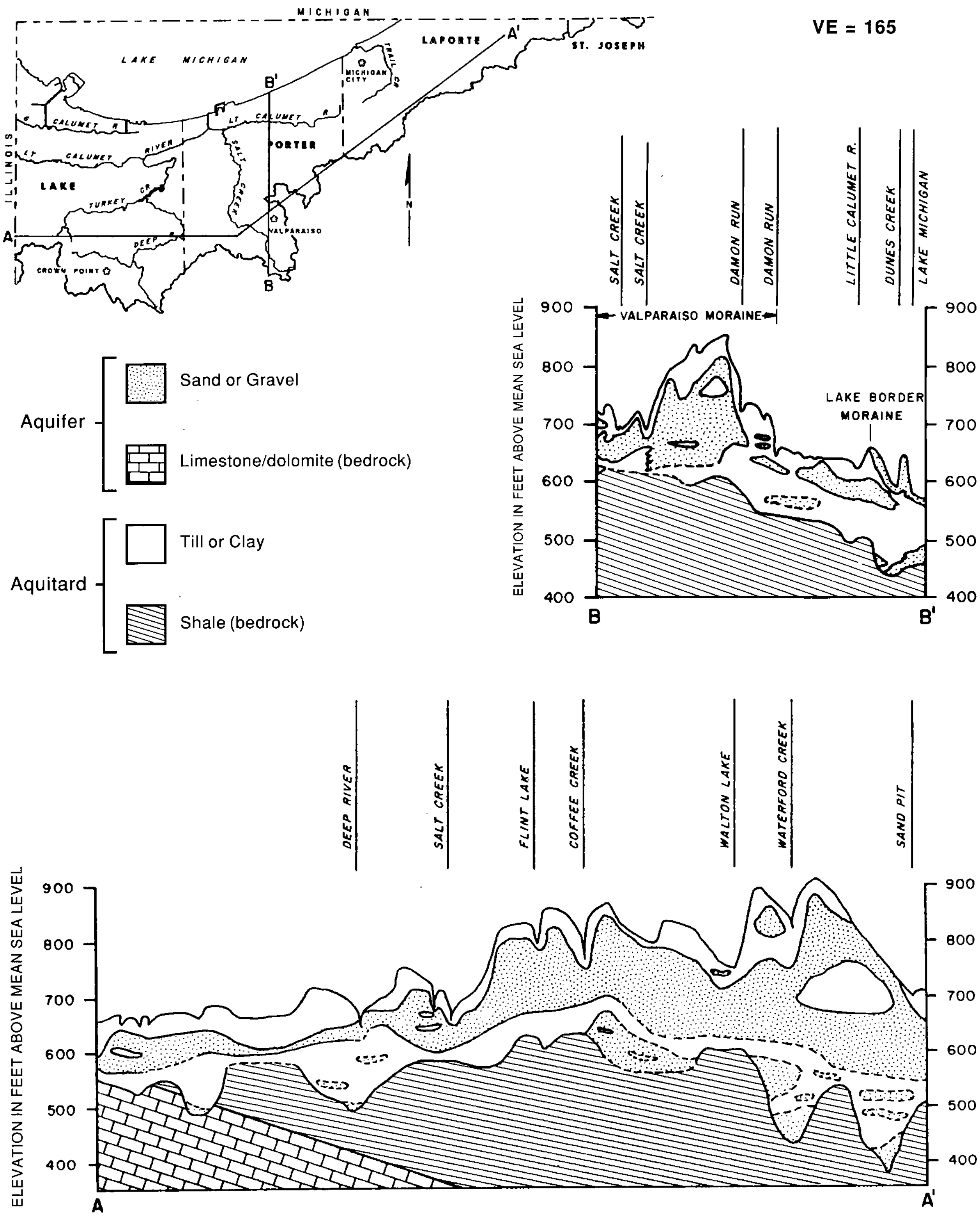


Figure 53. Generalized cross sections of unconsolidated aquifer systems

Porter Counties, is overlain by a till that is present as surficial ground and terminal moraine. The aquifer system was previously defined as the confined part of Unit 3 of the unconsolidated deposits of Lake, LaPorte and Porter Counties (Rosenshein and Hunn 1968a; 1968b). However, the aquifer system is unconfined in small isolated areas in Porter County where surficial tills are absent.

In the Lake Michigan Region, the upper surface of the Valparaiso Moraine Aquifer system lies about 10 to 100 feet (3 to 30 meters) beneath the surface of the Valparaiso Moraine. Elevations of the top of the aquifer system generally range from 638 to 700 feet (194 to 213 meters) above m.s.l. in Lake County and 675 to 740 feet (206 to 226 meters) above m.s.l. in LaPorte and Porter Counties.

The Valparaiso Moraine Aquifer system typically ranges in thickness from about 10 to 130 feet (3 to 40 meters). However, the geometry and extent of the aquifer system varies from east to west along the crest of the morainal complex (figure 53). In most of Porter County, the outwash sand body is laterally extensive, and exceeds 100 feet (30 meters) in thickness in the north-central part of the county. However, toward the western part of the Lake Michigan Region, the Valparaiso Moraine Aquifer system becomes thinner and less permeable. In some parts of western Lake County, the aquifer system is less than 10 feet (3 meters) thick or absent.

Sand-and gravel-filled outwash channels of limited saturated thickness are present in Lake and western Porter Counties at elevations ranging from 670 to 775 feet (204 to 236 meters) above m.s.l. These coarse-grained but poorly-sorted outwash channel deposits have an average thickness of about 26 feet (8 meters) and directly overlie the major aquifer body. However, the channel deposits may be locally separated from the major aquifer by a 10- to 20-foot (3 to 6 meter) thick clay.

In parts of the Valparaiso Moraine Aquifer system, artesian conditions exist because the overlying till behaves as an aquitard (figure 53). Water levels in the artesian wells that are completed in the aquifer system seldom rise to the surface, except in parts of LaPorte and Porter Counties where flowing artesian wells are found. However, despite the artesian conditions, static water levels in most of the Valparaiso Moraine Aquifer system are relatively deep, generally ranging from 25 to 80 feet (8 to 24 meters) below the morainal surface.

Production from wells that are completed in the main aquifer body are commonly more than adequate for domestic use. Yields from 2- and 4-inch domestic wells typically range from 10 to 25 gpm, although yields may vary from 5 to 60 gpm (table 22). In general, high capacity wells can produce as much as 800 gpm which is adequate for some municipal supplies. However, higher yields are possible from wells completed in the thicker portions of the Valparaiso aquifer in parts of LaPorte and Porter Counties.

The Valparaiso Moraine Aquifer system is an important source of water in the Lake Michigan Region. However, drawbacks in obtaining water from this aquifer system include the relatively deep drilling depths required and problems in obtaining adequate yields where the aquifer consists of fine- to very fine-grained sand. Where these less permeable zones are encountered, wells tap the underlying Silurian and Devonian bedrock aquifers.

Surficial outwash sands along the southern margin of the Lake Michigan Region in parts of LaPorte and Porter Counties are not considered part of the Valparaiso Moraine Aquifer system. Instead, these areas are mapped as the Kankakee and the Valparaiso Outwash Apron Aquifer systems (plate 2). Hydraulic connections among these aquifer systems are considered good.

Valparaiso Outwash Apron Aquifer System

The Valparaiso Outwash Apron Aquifer system is a wedge of outwash sediments that form the southern slope of the Valparaiso Moraine. The outwash apron consists of interbedded sand and fine gravel, and has clay lenses and zones of shale-rich gravel. In the Lake Michigan Region, these deposits are present near the crest of the Valparaiso Moraine just south of the town of Valparaiso in Porter County and exceed 100 feet (30 meters) in thickness.

Lacustrine clays and channel sands are present beneath the outwash apron. The clays are of unknown lateral extent and vary up to 20 feet (6 meters) in thickness. The thickness of the channel deposits ranges from zero where the lacustrine clays rest on bedrock to more than 100 feet (30 meters) in deep bedrock valleys. Although the lacustrine clays separate the outwash apron deposits and the deeper channel deposits in places, the two permeable units are considered to be one aquifer system.

Most wells are completed in the upper aquifer unit

Table 22. Hydrologic characteristics of unconsolidated aquifer systems

Aquifer System	Aquifer thickness (ft)		Range of pumping rates (gpm)		Expected high-capacity yield(gpm)	Hydrologic condition
	Range	Common	Domestic	High-capacity		
Valparaiso Moraine	0 - 100+	40 - 60	5 - 60	100 - 800	100 - 600	Confined Unconfined
Valparaiso Outwash Apron	10 - 100+	50	15 - 60	100 - 1100	150 - 600	Unconfined
Kankakee	20 - 150	30	15 - 50	100 - 1500	100 - 1200	Unconfined
St. Joseph	10 - 100+	10 - 60	8 - 60	500 - 1500	500 - 1000	Unconfined Confined
Lacustrine Plain	0 - 90+	20 - 30	5 - 50	80 - 500	50 - 150	Confined
Calumet	0 - 40	20 - 30	5 - 20	30 - 150	20 - 100	Unconfined

and have depths ranging from 30 feet (9 meters) to more than 100 feet (30 meters). Wells completed in the lower aquifer unit have depths that typically exceed 50 feet (15 meters), but may also exceed 150 feet (46 meters). Static water levels are typically less than 20 feet (6 meters) deep, but can exceed 40 feet (12 meters) in depth in areas of higher surface elevation.

Yields in the upper and lower aquifer units are similar, typically ranging from 15 to 60 gpm for domestic wells and 100 to 600 gpm for large-diameter wells (table 22). Yields up to 1100 gpm are reported for some areas. However, special well construction techniques may be necessary because of the dominance of fine-grained sand.

Kankakee Aquifer System

The Kankakee Aquifer system is an unconfined deposit of sand in the floodplain of the Kankakee River and some of its tributaries. Almost all of the aquifer lies within the Kankakee River Basin, but small parts of the aquifer extend into the Lake Michigan Region along glacial drainageways which dissected the Valparaiso Moraine just east and west of the community of Rolling Prairie in LaPorte County (Indiana Department of Natural Resources, 1990a). Some of the glacial drainageways are presently occupied by tributaries of the Kankakee River.

The Kankakee Aquifer system overlies clay or bedrock. Most of the sediments of the aquifer system that lie in the tributary valleys are well-sorted fine- to medium-grained sands that are interbedded with gravel. The aquifer is as much as 150 feet (46 meters) thick in the Little Kankakee River valley. In the tributary valleys, depths to the water table may exceed 50 feet (15 meters), and well depths may exceed 150 feet (46 meters).

Domestic wells usually produce from 15 to 50 gpm, and high-capacity wells may produce 100 to 1200 gpm (table 22). Yields up to 1500 gpm may be possible in areas which have thick, coarse-grained deposits such as the Little Kankakee River valley in LaPorte County.

St. Joseph Aquifer System

The St. Joseph Aquifer system consists of thick deposits of outwash sand and gravel. Large meltwater rivers sorted and deposited thick beds of coarse-grained sand and gravel. These deposits are as much as 129 feet (39 meters) thick, but are commonly from 10 to 60 feet (3 to 18 meters) thick.

In the small part of St. Joseph County that lies in the Lake Michigan Region, the St. Joseph Aquifer system is interbedded with outwash deposits of the Kankakee

Aquifer system. Locally interspersed with the deposits that comprise the St. Joseph Aquifer system are thin clay or till units of limited areal extent.

Shallow wells ranging from 40 to 90 feet (12 to 27 meters) in depth are common in this aquifer system because of the presence of thick, near-surface sands and gravels. Overall, well depths range from 30 to 145 feet (9 to 44 meters). Static water levels range from 4 to 70 feet (1 to 21 meters) deep, but commonly are between 10 and 30 feet (3 and 9 meters) deep.

Aquifer yields in the part of the St. Joseph Aquifer system that lies in the Lake Michigan Region are not reliably known. Reported yields from the aquifer system range from 100 to 1500 gpm.

Lacustrine Plain Aquifer System

The Lacustrine Plain Aquifer system consists of a series of confined aquifers present beneath the Calumet Lacustrine Plain (figure 16). The southern boundary of the aquifer system is only an approximation (plate 2) and aquifers that comprise the Lacustrine Plain Aquifer system may interconnect with and be hydraulically connected to the Valparaiso Moraine Aquifer system. The northern part of the Lacustrine Plain Aquifer system contains aquifers that are separated from the surficial Calumet Aquifer by a clay and till unit that in places exceeds 100 feet (30 meters) in thickness.

The Lacustrine Plain Aquifer system consists of fine-to medium-grained glaciolacustrine sand, and coastal sand and gravel capped by either lacustrine clay or till. Thickness of the individual aquifers averages 24 feet (8 meters), but frequently ranges from 7 feet (2 meters) to as much as 90 feet (27 meters) in areas where sediment accumulations were localized in bedrock valleys.

Of the many individual aquifers that comprise the Lacustrine Plain Aquifer system, two aquifers of significant areal extent have been identified beneath the Lake Border Moraine. Although one aquifer underlies the central part of the Lake Border Moraine and the other aquifer underlies the western part of the moraine, both aquifers may be hydraulically connected near the Porter-LaPorte County line (Dave Cohen, U.S. Geological Survey, personal communication, 1993).

The aquifer that underlies the central part of the Lake Border Moraine is located in northwestern LaPorte County at depths ranging from 40 to 60 feet (12 to 18 meters) below the surface. The aquifer consists of fine- to medium-grained sand with minor amounts of silt and gravel. Aquifer thickness is variable but exceeds 150 feet (46 meters) in the vicinity of Michigan City's municipal airport.

The aquifer beneath the western part of Lake Border Moraine in northeastern Porter County lies about 25 to 70 feet (8 to 21 meters) below the surface. The aquifer has a common thickness of about 40 feet (12 meters) but thins to the east. Fine- to medium-grained sands comprise most of the aquifer, but gravel is present in appreciable amounts in the central and eastern extent of the aquifer.

Depths to static water levels are highly variable in the many aquifers of the Lacustrine Plain Aquifer system. In western Lake County, static water levels can be more than 60 feet (18 meters) below the surface, but in some parts of La Porte County flowing artesian wells are present. Artesian heads in the eastern part of the Lacustrine Plain Aquifer system strongly suggest local hydraulic connection between the Lacustrine Plain and Valparaiso Moraine Aquifer systems.

Wells completed in the Lacustrine Plain Aquifer system can typically produce about 5 to 20 gpm (table 22), more than sufficient for domestic use. In areas where wells penetrate coarse sand and gravel, yields of 40 to 50 gpm have been reported. Yields from high-capacity wells range from 80 to as much as 500 gpm for some municipal well systems. However, because of variations in thickness, lateral extent and localized hydraulic connections of the individual aquifers, sustained yields from the Lacustrine Plain Aquifer system vary.

Calumet Aquifer System

The Calumet Aquifer system is mainly a water-table aquifer located in the northern parts of Lake, LaPorte and Porter Counties (plate 2). The aquifer system is bordered to the north by Lake Michigan, and roughly to the south by the Little Calumet River in Lake County and the northern slopes of the Lake Border Moraine in northwestern LaPorte and northeastern Porter Counties.

The Calumet Aquifer system consists of fine- to medium-grained sand with dispersed lenses of beach gravel. The aquifer system is capped by dunal sands in many places. However, beds of interlaminated silt and clay, and deposits of peat and muck confine the aquifer system in small areas across the Lake Michigan Region. The aquifer system is underlain by a relatively impermeable clay and till unit that in places exceeds 100 feet (30 meters) in thickness. Aquifers that lie beneath the clay and till unit are considered part of the Lacustrine Plain Aquifer system.

Static water levels in the Calumet Aquifer system vary accordingly to surface elevation. Areas of subdued relief in northern Lake and northwestern Porter Counties have static water levels that are frequently less than 15 feet (5 meters) below the surface. However, static water levels can be as much as 100 feet (30 meters) below the crests of high dunes in northern LaPorte and northeastern Porter Counties. Ponds and marshes in the interdunal depressions define areas where the water-table intersects the ground surface.

Saturated thickness of the Calumet Aquifer system ranges from less than 5 feet (2 meters) along its southwestern extent to about 40 feet (12 meters) in areas containing broad water-table mounds. Watson and others (1989) identified water-table mounds between the Little Calumet and Grand Calumet Rivers, and between Gary Harbor and the Indiana Harbor Canal.

Development of the Calumet Aquifer system has not been significant because of the proximity of Lake Michigan, an abundant surface-water source. However, the aquifer system is utilized as a source of water by a few domestic and small commercial facilities. Domestic wells typically produce about 5 to 20 gpm, and high-capacity wells can be expected to produce up to 100 gpm (table 22). Higher sustained-withdrawal rates are difficult to achieve in many parts of the aquifer system because of the predominance of fine-grained sand.

Bedrock aquifer systems

The occurrence of bedrock aquifers in the Lake Michigan Region depends on the original composition of rocks and post-depositional changes which can influence hydraulic properties. Erosion has removed layers of bedrock in the Lake Michigan Region, which lies along the northeastern flank of the Kankakee arch (figure 19). Subsequent weathering and solution activity have increased the permeability of the rocks at the bedrock surface.

In bedrock aquifers, the upper units are usually the most productive zones because permeability is greatest at the bedrock surface. Rock types present at the bedrock surface in the Lake Michigan Region (plate 2) range from poorly productive shales to fairly productive carbonates. The yields of bedrock aquifers depend on the hydraulic characteristics of the bedrock units and the nature of the overlying deposits. Recharge rates to bedrock aquifers are largely influenced by the overlying strata.

Where shale or till overlies a bedrock aquifer, recharge to the underlying aquifer is generally limited by the overlying material of low permeability.

In general, bedrock aquifers are not utilized in the central and eastern parts of the Lake Michigan Region because of the predominance of unproductive shales at the bedrock surface and the availability of water from the overlying glacial deposits. In parts of Lake County, the unconsolidated deposits do not contain significant aquifers and therefore bedrock aquifers are utilized. Carbonate aquifers are used in parts of western Lake County, and shale is used as a source of water in some areas in central Lake County despite low yields.

Silurian-Devonian Carbonate Aquifer System

Silurian and Devonian carbonate rocks form the most utilized bedrock aquifer system in the Lake Michigan Region. However, water-yielding capabilities of this aquifer system are not uniform throughout its extent. Differences in *porosity* and variations in the degree of enhanced permeability have made it necessary to subdivide the Silurian-Devonian Carbonate Aquifer system into the Silurian Aquifer and the Devonian Carbonate Aquifer.

The **Silurian Aquifer** in the Lake Michigan Region consists of reef and interreef carbonate rocks of the Salina Group. Pre-middle Devonian chemical and physical weathering have produced considerable solution features in the rocks of the Wabash Formation which form the upper part of the bedrock aquifer.

Permeability of the Silurian carbonates decreases significantly with depth and only the upper 100 feet (30 meters) of the unit can be considered transmissible (Rosenshein and Hunn, 1968a). Reef rocks of the Salina Group have porosity values ranging from 5 to 25 percent and are quite permeable, but bank and interreef rocks have significantly lower porosities and permeabilities. Reefcore rocks may be less permeable than rocks of the inner flanks (John Rupp, Indiana Geological Survey, written communication, 1988).

Approximately 80 to 170 feet (24 to 52 meters) of unconsolidated material overlies Silurian bedrock in western Lake County. Water wells are drilled to an average depth of about 230 feet (70 meters) and the static water levels range from about 11 to 70 feet (3 to 21 meters) below the land surface. Most wells penetrate the upper 50 feet (15 meters) of bedrock.

The Silurian Aquifer is the most utilized bedrock aquifer in the Lake Michigan Region. The aquifer can be a reliable source of water for users requiring about 10 to 200 gpm. However, large-diameter wells drilled into the most tranmissible zones of the Silurian carbonates can produce as much as 500 gpm if constructed and developed optimally.

The **Devonian Carbonate Aquifer** overlies the Silurian Aquifer subsystem in most of the Lake Michigan Region, except in western Lake County where Silurian rocks are present at the bedrock surface (plate 2). The Devonian Carbonate Aquifer is comprised of limestone and dolomitic rocks of the Muscatatuck Group. The aquifer is utilized as a minor source of water in the western part of the Lake Michigan Region where it forms the bedrock surface. However, shale overlies Muscatatuck rocks in some areas. Porosity of the Devonian carbonates ranges from 0 to 14 percent, but permeability is highly variable (John Rupp, Indiana Geological Survey, written communication, 1988). The following hydrogeologic information on the Devonian Carbonate Aquifer is based on the records of water wells that are completed in areas where the Devonian carbonates are present at the bedrock surface. However, in areas where the Devonian carbonates are thin, some of the water wells may be completed in the underlying Silurian carbonates. The Devonian Carbonate Aquifer is overlain in most places by about 125 feet (38 meters) to more than 230 feet (70 meters) of unconsolidated material. The majority of water wells that penetrate the Devonian Carbonate Aquifer are completed in the upper 70 feet (21 meters) of bedrock, which is the most transmissible part of the aquifer. In general, static water levels in the Devonian Carbonate Aquifer are highly variable, ranging from about 25 to 90 feet (8 to 27 meters) below the surface.

Compared to water removal from Silurian carbonates, sustained yields from water wells that penetrate Devonian carbonates are much lower. The Devonian carbonates in the Lake Michigan Region can be used as a possible source of water for domestic and farm purposes requiring no more than 100 gpm. For maximum yields, wells should have large diameters (at least 8 inches or 20 centimeters) and should be properly developed. Low-yield wells are not uncommon and may be unavoidable in areas where shale is present at the bedrock surface.

Devonian Shale Aquifer

The Devonian-age Antrim Shale is used as the primary source of water in a few isolated areas in the Lake Michigan Region. These localities lie to the immediate north and north-east of the town of Crown Point, where the unconsolidated deposits do not contain any significant aquifers and the Antrim Shale forms the bedrock surface. In some instances, wells are completed in the underlying carbonate rocks in areas where the Antrim Shale is relatively thin, but the water may be of poorer quality.

Water wells that tap the Antrim Shale penetrate approximately 100 to 150 feet (30 to 46 meters) of unconsolidated material, and some of the wells are completed into more than 50 feet (15 meters) of shale. However, only the upper 25 feet (8 meters) of the shale has been made permeable due to post-Devonian weathering, jointing and fracturing. Static water levels in the shale range from 40 to 80 feet (12 to 24 meters) below the surface.

The Antrim Shale can be a possible source of water for users requiring about 10 gpm or less, which is adequate for most domestic and farm supplies. Water extracted from the Antrim Shale has been reported to contain a slight amount of natural gas.

The Upper Devonian to Lower Mississippian Ellsworth Shale is present at the bedrock surface along the southern boundary of the Lake Michigan Region (plate 2). However, the Ellsworth is not utilized as a source of water in the Lake Michigan Region because unconsolidated aquifers are abundant in the overlying deposits.

GROUND-WATER DEVELOPMENT POTENTIAL

The development or potential yield of an aquifer depends on aquifer characteristics (*transmissivity, hydraulic conductivity*, and storage), aquifer thickness, areal extent, ground-water levels and recharge. The aquifer system in the Region which has the greatest potential for ground-water development is the Valparaiso Moraine along the southern boundary in eastern Porter and western LaPorte Counties where permeable deposits are thick and extensive (figure 53). Of the Region's bedrock aquifers, the Silurian reef rocks which are overlain directly by outwash deposits have the highest potential for development.

Transmissivity

Transmissivity is a measure of the water-transmitting capability of an aquifer. It is defined as the product of the hydraulic conductivity and thickness of an aquifer. Each of the various methods developed to compute aquifer transmissivity establishes a mathematical relationship between the pumping rate and the resultant *drawdown* in the aquifer. The three methods used to estimate aquifer transmissivity in the Lake Michigan Region, listed in order of decreasing reliability, include the use of 1) graphical plots based on aquifer-test data, 2) specific capacity data based on adjusted drawdown, and 3) specific capacity data based on unadjusted drawdown.

The graphical approach can only be used when extensive data have been collected from aquifer tests. In most aquifer tests, water levels are recorded simultaneously at observation wells while the test well is being pumped. The response of the aquifer is monitored over an areal extent that is determined by the spatial distribution of the observation wells. Graphical plots of time versus drawdown and distance versus drawdown can yield reliable estimates of the hydraulic parameters of the aquifer. However, unless an extensive well field is being developed, an aquifer test is not warranted because the cost of installing observation wells is too high.

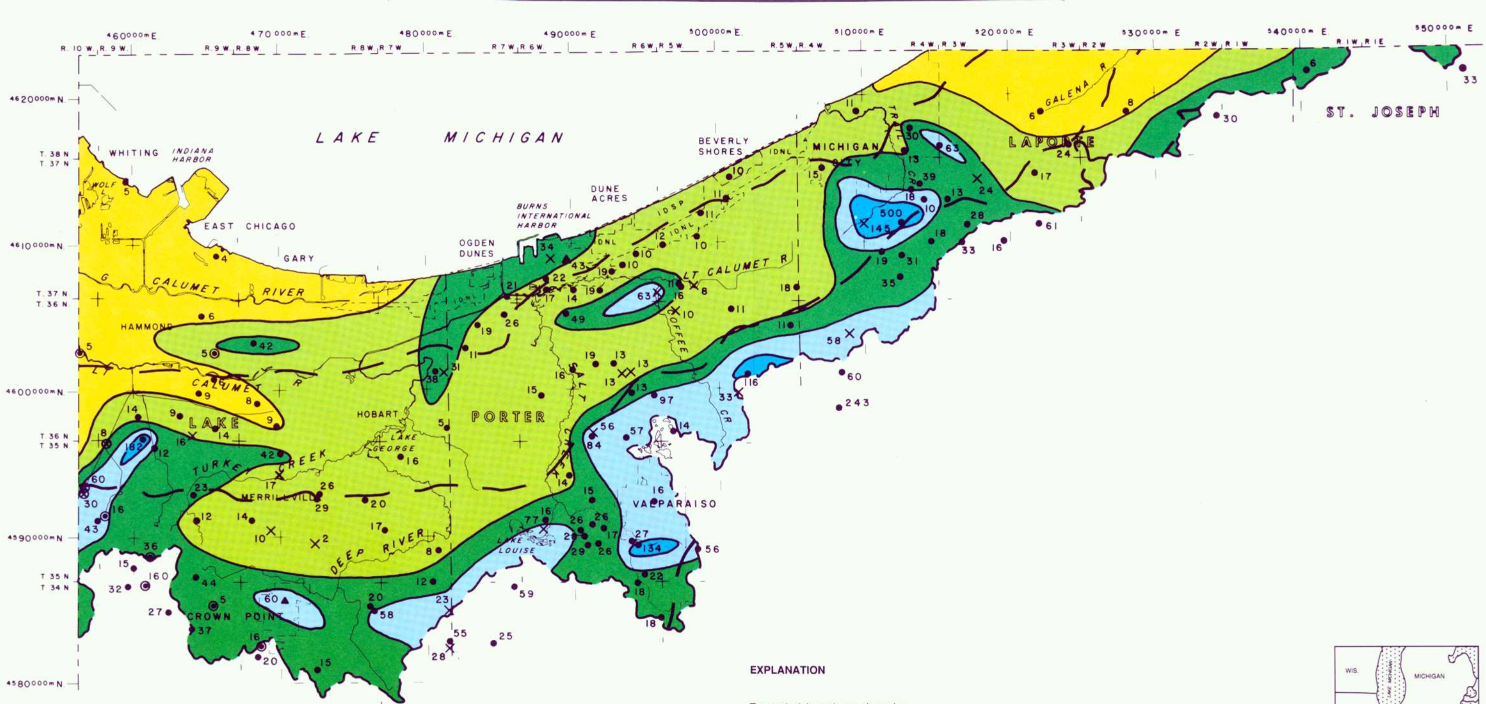
Specific capacity tests are less expensive than aquifer tests because drawdown is measured only at the test well while it is being pumped. After the completion of a water well, the driller conducts a specific capacity test to determine the potential yield of the well. As the length of the test increases, continued drawdown in the well causes a decrease in specific capacity, which is defined as the rate at which water can be pumped from a well under unit decline in drawdown. In reconnaissance ground-water investigations, useful estimates of aquifer transmissivity can be based on specific capacity data (Walton, 1970).

Consistent estimates of aquifer transmissivity in the Lake Michigan Region were efficiently generated from specific capacity data by using a computer program called "Tguess" (Bradbury and Rothschild, 1985). The computer program can adjust drawdown values from specific capacity tests to accommodate for well loss, partial penetration and dewatering of the aquifer. In most cases, these factors tend to cause lower estimates of specific capacity (Walton, 1970). However, if a well penetrates an aquifer of unknown thickness, drawdowns from specific capacity tests cannot be accurately adjusted. In this case, aquifer thickness is assumed to be equal to the thickness of aquifer that is penetrated by the well. The computed transmissivity of the aquifer, which is referred to as transmissivity based on unadjusted drawdown, can be considered to represent a local minimum transmissivity of the aquifer.

Regional estimates of aquifer transmissivity in the Lake Michigan Region (figure 54) were based on specific capacity tests that were conducted predominantly at high-capacity wells. At most of these facilities, wells fully penetrate the aquifer and are developed properly. However, in areas where regional hydrogeologic information was sparse or unreliable, transmissivity estimates based on unadjusted drawdown were used as supplemental data for the regional transmissivity map of the Lake Michigan Region (figure 54).

Estimates of transmissivity in the Lake Michigan Region typically range from 10,000 to 25,000 gallons per day per foot (124 to 311 square meters per day) in the Calumet Aquifer system, 10,000 to 50,000 gpd/ft (124 to 621 sq. meters/day) in the Lacustrine Plain Aquifer system, and 25,000 to 50,000 gpd/ft (311 to 621 sq. meters/day) in the Valparaiso Moraine Aquifer system (figure 54). Variations in transmissivities are probably the result of local changes in the lithofacies, thickness, and depth of the aquifer, and local differences in the nature of the surficial deposits. In the northwestern part of the Calumet Aquifer system, where fine-grained sands are predominant, transmissivity estimates are commonly much less than 10,000 gpd/ft (124 sq. meters/day) (figure 54). In contrast, thick coarse-grained deposits occur in localized areas within the Lacustrine Plain and Valparaiso Moraine Aquifer systems. In some of these areas, transmissivities exceed 100,000 gpd/ft (1242 sq. meters/day) (figure 54).

Bedrock aquifers in the Lake Michigan Region are utilized in small areas in Lake County, and therefore transmissivities of the bedrock systems could not be mapped on a regional scale. Transmissivities of the Silurian-Devonian Carbonate Aquifer system are highly



EXPLANATION

(yellow)	< 10,000 gpd/ft
(light green)	10,000 - 25,000 gpd/ft
(dark green)	25,000 - 50,000 gpd/ft
(light blue)	50,000 - 100,000 gpd/ft
(blue)	> 100,000 gpd/ft

Transmissivity estimates based on

- ● Specific capacity of a domestic well completed in unconsolidated deposits
- × Specific capacity of a high-capacity well completed in unconsolidated deposits
- ▲ Pump test conducted in unconsolidated deposits
- ⊙ Specific capacity of a domestic well completed in bedrock
- ⊗ Specific capacity of a high-capacity well completed in bedrock
- Aquifer boundary

Regional estimates of transmissivity are based on specific capacity tests conducted in both high-capacity and domestic wells. In areas containing few water wells, regional estimates of transmissivity were based on the thickness and extent of the major aquifers interpreted from maps showing bedrock topography, saturated thickness, and surficial geology.

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DEPARTMENT OF NATURAL RESOURCES
DIVISION OF WATER

LAKE MICHIGAN REGION

Figure 54. Regional estimates of aquifer transmissivity
(unconsolidated materials only)

variable, but commonly range from 1,000 to 10,000 gpd/ft (12 to 124 sq. meters/day). In general, the Silurian carbonates are more transmissive than Devonian carbonates in the Lake Michigan Region. Localized transmissivities of the Silurian carbonates are as much as 60,000 gpd/ft (745 sq. meters/day) near Dyer in Lake County. In the few areas of the Lake Michigan Region where the Antrim Shale is used as a source of water, transmissivities of the shale are less than 5,000 gpd/ft (62 sq. meters/day).

Recharge

Aquifer yield is dependent upon aquifer permeability and saturated thickness and on the number, spacing and diameter of the wells that tap the aquifer. Although the development potential of an aquifer is determined by the total recharge to the aquifer, water quality, and well yields must be considered when ground-water systems are being appraised.

The ground-water development potential of the aquifer systems in the Lake Michigan Region is based on the rate of recharge (derived chiefly from *infiltration* of direct precipitation) and areal extent of the aquifer systems (figure 55). Estimates of natural recharge rates to the aquifer systems of the Lake Michigan Region were based on the permeability, areal extent and thickness of the deposits overlying the aquifer systems, and on regional climate (mainly precipitation and temperature).

Estimated recharge rates to the aquifers in the Lake Michigan Region are highest in the unconfined Calumet Aquifer system (figure 55). Infiltration of direct precipitation to the Calumet Aquifer system is high because of thinly developed soils on the thick surficial sands. The Calumet Aquifer system, which has an average recharge rate of about 500,000 gallons per day per square mile (26.7 centimeters per year), accounts for more than 50 percent of the total recharge to aquifers in the Lake Michigan Region despite occupying only 21 percent of the areal extent of the region (figure 55). However, estimates of recharge to the Calumet Aquifer must be viewed with caution because the high degree of industrialization and urbanization affect the local surface and subsurface hydrology to a considerable extent.

Rates of recharge to the Valparaiso Moraine Aquifer system are considerably lower than rates of recharge to the Calumet Aquifer system (figure 55) because the surficial tills and steeper gradient of the Valparaiso morainal surface promote runoff. Rates of recharge to the Valparaiso Moraine Aquifer system vary from 125,000 gpd/sq mi (6.7 cm/yr) in the west to 200,000 gpd/sq mi (10.7 cm/yr) in the east. Recharge rates to the western part of the aquifer system are lower because the surficial tills are thicker and finer grained than to the east.

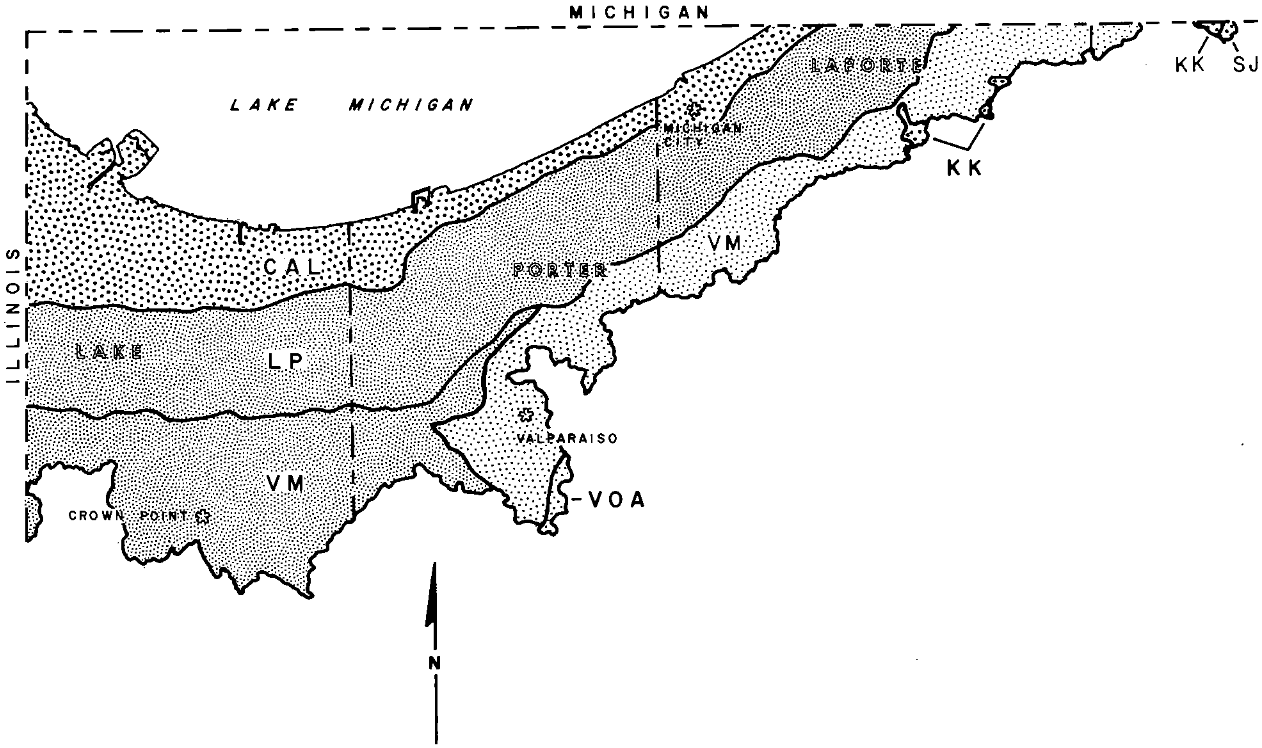
The Lacustrine Plain Aquifer system has the lowest recharge rates of the major aquifer systems in the Lake Michigan Region, averaging about 100,000 gpd/sq mi (5.3 cm/yr) (figure 55). Recharge to the many individual aquifers that comprise the aquifer system is limited by tills and fine-grained lacustrine sediments that surround the aquifers.

Recharge to the bedrock aquifers of the Lake Michigan Region is difficult to determine accurately because of the complex geology of the overlying glacial and lacustrine deposits. Rosenshein (1963) estimated an average recharge rate of 20,000 gpd/sq mi (1.1 cm/yr) for till-covered Silurian carbonates in Lake County. Higher recharge rates to the Silurian and Devonian carbonates are expected in areas where the carbonate bedrock is overlain directly by outwash deposits.

GROUND-WATER QUALITY

Water quality is an important and occasionally deciding factor in determining the utility of the groundwater resources in a given region. The concentrations of various naturally-occurring and artificial chemical constituents define ground-water quality and determine whether the resource, without prior treatment, is suitable for drinking water supplies, industrial purposes, irrigation, livestock watering, or other uses.

The dissolved constituents discussed in the following section are often detected in unpolluted ground waters, where their concentrations are primarily controlled by the composition and physical properties of the geological materials through which the waters circulate. However, under certain circumstances, the concentration of these chemicals in the water of an aquifer can be substantially increased by human activities. Elevated levels of certain naturally-occurring constituents in some areas of the Lake Michigan Region cannot be reconciled with the local geology and may reflect human-induced pollution of the groundwater systems. Chemicals such as organic compounds and heavy metals can also be introduced into ground



Aquifer System	Area (sq. mi)	Area (sq. km)	Recharge rate (gpd/sq. mi)	Recharge rate (cm/yr)	Recharge (mgd)	Recharge (cu. m/day)
Valparaiso Moraine (VM)	230.0	595.7	125,000 - 200,000	6.7- 10.7	37.38	141,651
Valparaiso Outwash Apron (VOA)	2.5	6.5	300,000	16.0	0.75	2,843
Kankakee (KK)	2.4	6.2	500,000	26.7	1.20	4,548
St. Joseph (SJ)	0.5	1.3	500,000	26.7	0.25	948
Lacustrine Plain (LP)	239.8	621.0	100,000	5.3	23.98	90,884
Calumet (CAL)	128.8	333.6	500,000	26.7	64.40	244,076

Figure 55. Estimated recharge rates of unconsolidated aquifer systems

water by human activities. In some areas of the Lake Michigan Region, human-induced aquifer pollution has locally diminished the quality and utility of ground-water resources.

Sources of ground-water quality data

Inorganic chemical analyses of water samples from 297 wells in the Lake Michigan Region were used to characterize the ground-water quality of the aquifer systems defined in this Region. An additional 36 chemical analyses from wells in the adjacent Kankakee River Basin were used to assist in constructing concentration maps of chemical constituents; but the additional data were not included in the statistical analyses. Major data sources include: 1) domestic, commercial and public-supply wells sampled during the fall of 1987 in a cooperative effort between the Division of Water (DOW) and the Indiana Geological Survey (IGS); 2) municipal and other public-supply wells sampled periodically by the Indiana State Board of Health (ISBH) which is now the Department of Health; 3) the Ground-water Strategy Study in Lake and Porter Counties published by ISBH; 4) public supply, industrial, industrial, domestic, and observation wells sampled by the U.S. Geological Survey (USGS); 5) dunes studies published by the USGS.

The intent of the water-quality analysis is to provide a realistic characterization of the natural ground-water chemistry of the Region; specific instances of ground-water contamination are not analyzed in detail. Chemical conditions are likely to be site-specific in cases of contamination, and may not be representative of typical ground-water chemistry in the Region. To minimize possible effects ground-water contamination may have on the characterization and description of the Region's ground-water, available chemical data from identified sites of contamination were excluded from the water-quality data set analyzed in this report. Excluding this data should provide a more reasonable assessment of natural water-quality conditions in the Region.

The location of ground-water chemistry sites used in the analysis are displayed on plate 3. Plate 3 also displays the reported use of the sampled wells, and the group or agency that performed the sampling and chemical analysis. Appendix 9 lists selected data for individual wells used in the analysis for this report.

A ground-water quality study conducted by Indiana University, School of Public and Environmental Affairs (1985) and funded by the U.S. Environmental Protection Agency (USEPA) provided additional nitrate-nitrogen analyses.

A private Indiana cooperative well-water testing program sponsored by the Farm Bureau, Soil and Water Conservation Districts, County Health Departments, Extension Service, and Resource Conservation and Development Districts provided additional information on nitrates, pesticides and herbicides in rural wells in LaPorte County. Information is not yet available for Lake and Porter Counties from this program, but should be in the near future.

Factors in the assessment of ground-water quality

Major dissolved constituents in the ground water of the Lake Michigan Region include calcium, sodium, chloride, sulfate, and bicarbonate. Less abundant constituents include potassium, magnesium, iron, manganese, fluoride and nitrate. Other chemical parameters that are discussed in this report are pH, alkalinity, hardness and total dissolved solids (TDS).

Although the data from well-water samples in the Lake Michigan Region are treated as if they represent the chemistry of ground water at a distinct point, they actually represent the average concentration of an unknown water volume in the aquifer. The extent of aquifer representation depends mostly on the depth of the well, hydraulic conductivity of the aquifer, and rate of pumping. For example, the chemistry of water sampled from high-capacity wells may represent average ground-water quality for a large cone of influence (Sasman and others, 1981). Also, water collected from deep bedrock wells can be a mixture of water from different production zones.

The chemistry of original aquifer water may be altered by contact with plumbing, residence time in a pressure tank, method of sampling and laboratory analysis. Because the degree to which these factors affect original aquifer water is unknown, ground-water analyses generally typify the quality of water at the tap rather than the composition of in-situ aquifer water. In spite of these limitations, results of sample analyses can provide basic information on ground-water quality characteristics of aquifer systems.

Analysis of data

Graphical and statistical techniques were used to analyze the available ground-water quality data from the Lake Michigan Region. Graphical analysis is used to display the areal distribution of dissolved constituents over the Region and to determine the general chemical character of the ground water of each aquifer system. Statistical analysis can provide some useful generalizations about the water quality of the Region, such as the average concentration of a constituent and

FACTORS AFFECTING GROUND-WATER CHEMISTRY

The chemical composition of ground water varies because of many complex factors that change with depth and over geographic distances. Ground-water quality can be affected by the composition and solubility of rock materials in the soil or aquifer, water temperature, partial pressure of carbon dioxide, acid-base reactions, oxidation-reduction reactions, loss or gain of constituents as water percolates through clay layers, and mixing of ground water from adjacent strata. The extent of the effect will be determined in part by the residence time of the water within the different environments.

Rain and snow are the major sources of recharge to ground water. They contain small amounts of dissolved solids and gases such as carbon dioxide, sulfur dioxide, and oxygen. As precipitation infiltrates through the soil, biologically-derived carbon dioxide reacts with the water to form a weak solution of carbonic acid. The reaction of oxygen with reduced iron minerals such as pyrite is an additional source of acidity in ground water. The slightly acidic water dissolves soluble rock material, thereby increasing the concentrations of chemical constituents such as calcium, magnesium, chloride, iron, and manganese. As ground water moves slowly through an aquifer the composition of water continues to change, usually by the addition of dissolved constituents (Freeze and Cherry, 1979). A longer residence time will usually increase concentrations of **dissolved solids**. Because of short residence time, ground water in recharge areas often contains lower concentrations of dissolved constituents than water occurring deeper in the same aquifer or in shallow discharge areas.

Dissolved carbon dioxide, bicarbonate, and carbonate are the principal sources of **alkalinity**, or the capacity of solutes in water to neutralize acid. Carbonate contributors to alkalinity include atmospheric and biologically-produced carbon dioxide, carbonate minerals, and biologically-mediated sulfate reduction. Noncarbonate contributors to alkalinity include hydroxide, silicate, borate, and organic compounds. Alkalinity helps to buffer natural water so that the **pH** is not greatly altered by addition of acid. The pH of most natural ground waters in Indiana is neutral to slightly alkaline.

Calcium and **magnesium** are the major constituents responsible for **hardness** in water. Their presence is the result of dissolution of carbonate minerals such as calcite and dolomite.

The weathering of feldspar and clay is a source of **sodium** and **potassium** in ground water. Sodium and **chloride** are produced by the solution of halite (sodium chloride) which can occur as grains disseminated in unconsolidated and bedrock deposits. Chloride also occurs in bedrock cementing material, connate fluid inclusions, and as crystals deposited during or after deposition of sediment in sea water (Hem, 1985). High sodium and chloride levels can result from upward movement of brine from deeper bedrock in areas of high pumpage.

Cation exchange is often a modifying influence of ground-water chemistry. The most important cation exchange processes are those involving sodium-calcium, sodium-magnesium, potassium-calcium, and potassium-magnesium. Cation exchanges occurring in clay-rich semi-confining layers can cause magnesium and calcium reductions which result in natural softening.

Concentrations of **sulfide**, **sulfate**, **iron**, and **manganese** depend on geology and hydrology of the aquifer system, amount of dissolved oxygen, pH, minerals available for solution, amount of organic matter, and microbial activity.

Mineral sources of sulfate can include pyrite, gypsum, barite, and celestite. Sulfide is derived from reduction of sulfate when dissolved oxygen concentrations are low and anaerobic bacteria are present. Sulfate-reducing bacteria derive energy from oxidation of organic compounds and obtain oxygen from sulfate ions (Lehr and others, 1980).

Reducing conditions which produce hydrogen sulfide may occur in deep wells completed in carbonate and shale bedrock. Oxygen-deficient conditions are more likely to occur in deep wells than in shallow wells because permeability of the carbonate bedrock decreases with depth, and solution features and joints become smaller and less abundant (Rosenshein and Hunn, 1968a; Bergeron, 1981; Basch and Funkhouser, 1985). Deeper portions of the bedrock are therefore not readily flushed by ground water with high dissolved oxygen. Hydrogen sulfide gas, a common reduced form of sulfide, has a distinctive rotten egg odor which can be detected in water containing only a few tenths of a milligram per liter of sulfide (Hem, 1985).

Oxidation-reduction reactions constitute an important influence on concentrations of both iron and manganese. High dissolved iron concentrations can occur in ground water when pyrite is exposed to oxygenated water or when ferric oxide or hydroxide minerals are in contact with reducing substances (Hem, 1985). Sources of manganese include manganese carbonate, dolomite, limestone, and weathering crusts of manganese oxide.

Sources of **fluoride** in bedrock aquifer systems include fluorite, apatite and fluorapatite. These minerals may occur as evaporites or detrital grains in sedimentary rocks, or as disseminated grains in unconsolidated deposits. Ground waters containing detectable concentrations of fluoride have been found in a variety of geologic settings (Hem, 1985).

Natural concentrations of **nitrate-nitrogen** in ground water originate from the atmosphere and from living and decaying organisms. High nitrate levels can result from leachates of industrial and agricultural chemicals or decaying organic matter such as animal waste or sewage.

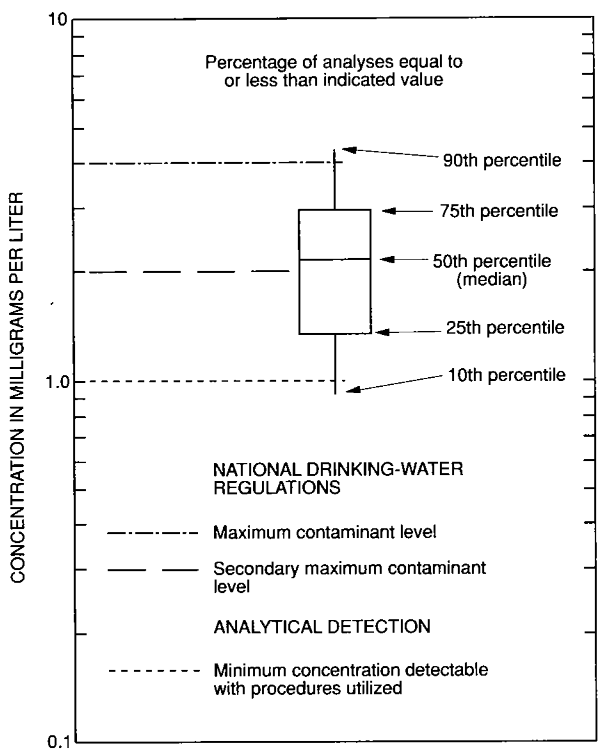
The chemistry of **strontium** is similar to that of calcium, but strontium is present in ground water in much lower concentrations. Natural sources of strontium in ground water include strontianite (strontium carbonate) and celestite (strontium sulfate). Naturally-occuring **barium** sources include barite (barium sulfate) and witherite (barium carbonate). Areas associated with deposits of coal, petroleum, natural gas, oil shale, black shale, and peat may also contain high levels of barium.

the variability that can be expected.

Only wells screened deeper than 25 feet below the surface are included in the data analysis. Most of the wells screened below 25 feet are developed for domestic use, municipal supply, or other water-supply purposes. The majority (83 percent) of wells less than 25 feet deep are USGS monitoring wells in the Calumet Aquifer system, which do not provide water for domestic or municipal use.

Major regional trends in ground-water chemistry were determined by developing trilinear diagrams for the larger aquifer systems in the Lake Michigan Region. Trilinear plotting of ground-water chemistry was popularized by Piper (1944) as a graphical technique to chemically classify ground waters and to compare chemical trends in aquifer systems (see insert, page 165).

In order to graphically represent variability in ground water chemistry, box plots (figure 56) were prepared for selected ground-water constituents. Box plots are useful for depicting descriptive statistics, showing the overall variability in constituent levels occurring in an aquifer system, and making general chemical comparisons among aquifer systems. Unfortunately, statistical analyses of some aquifer systems in the Lake Michigan Region are complicated by a limited number of samples. This is especially true of the Lacustrine Plain Aquifer system underlying the Calumet and the Silurian and Devonian Bedrock Aquifer system, from which only 11 and 12 samples were available, respectively. This limited sampling may not be representative of the chemistry of these two aquifer systems; moreover, the possibility exists that variations in the box plots for the two systems are exaggerated by a few abnormally high or low measurements.



CAL	Calumet Aquifer system
LAC	Lacustrine Plain Aquifer system
LPC	Lacustrine Plain Aquifer system underlying the Calumet
VM	Valparaiso Moraine Aquifer system
SD	Silurian and Devonian Bedrock Aquifer system

Figure 56. Explanation and legend for box-and-whisker plots

The areal distribution of most major constituents is mapped according to aquifer systems using Arc/Info, a Geographic Information System (GIS) (figures 57 to 66). The maps are shown with box plots of corresponding chemical parameters. Several sampling and geologic factors complicate the development of chemical concentration maps for the Region. The locations of sampling sites are not evenly distributed in the Region, but are clustered around towns, industry and developed areas (plate 3). Data points are also scarce in areas utilizing surface water supplies. Lateral and vertical variations in geology can also influence the chemistry of subsurface water. Therefore, the maps presented in the following discussion represent only approximate concentration ranges.

Where applicable, ground-water quality is assessed in the context of National Primary and Secondary Drinking-Water Standards (see box on next page). The secondary drinking water standard referred to in this report is called the secondary maximum contaminant level (SMCL). The SMCL reflects the maximum concentration limit of a constituent that may adversely affect aesthetic properties, such as taste, odor or color, of drinking water. Some chemical constituents (such as fluoride and nitrate) are also considered in terms of their *maximum contaminant level* (MCL); the concentration at which a constituent represents a threat to human health. The MCL is a legally enforceable primary drinking water standard for public water supplies. General water-quality criteria for irrigation and livestock and standards for public supply are given in appendix 6. Note that MCLs and SMCLs are not defined for every dissolved constituent commonly encountered in ground water.

Trilinear diagram analysis

The trilinear diagrams developed from the Lake Michigan Region ground-water chemistry data are presented in appendix 10. The water chemistry of Lake Michigan Region aquifers, excluding the Lacustrine Plain Aquifer system underlying the Calumet and the Silurian and Devonian Bedrock Aquifer system, is shown by the trilinear analyses to be dominated by bicarbonate, calcium and magnesium.