

GROUND-WATER HYDROLOGY

Ground-water supplies are obtained from *aquifers*, which are subsurface units of rock and unconsolidated sediments capable of yielding water in usable quantities to wells and springs. The hydrologic characteristics of aquifers and natural chemistry of ground water determine the availability and suitability of ground-water resources for specific uses.

GROUND-WATER RESOURCES

Ground water is the part of precipitation that enters the ground and percolates downward through unconsolidated materials and openings in bedrock until it reaches the *water table* (figure 48). The water table is the surface below which all openings in the rock or unconsolidated materials are filled with water. Water entering this zone of saturation is called *recharge*.

Ground water, in response to gravity, moves from areas of recharge to areas of discharge. In a general way, the configuration of the water table approximates the overlying topography (figure 48). In valleys and depressions 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 systems. During dry periods, baseflow or ground-water discharge to streams, can help maintain minimum stream flows. Conversely, during flood stages surface water can recharge the ground-water system by vertical recharge on the water-covered flood plain and bank storage through streambed sediments. The net effect of ground-water recharge is a reduction in flood peaks and replenishment of available ground-water supplies.

Aquifer properties which affect ground-water availability include aquifer thickness and the size, number, and degree of interconnection of pore spaces within the aquifer material. These properties affect the ability of an aquifer to store and transmit ground water. *Porosity*, the ratio of void space to unit volume of rock or soil, is an index of how much ground water the aquifer can store. The *permeability*, a property largely controlled by size and interconnection of pore spaces within the material, affects the fluid-transmitting capacity of materials.

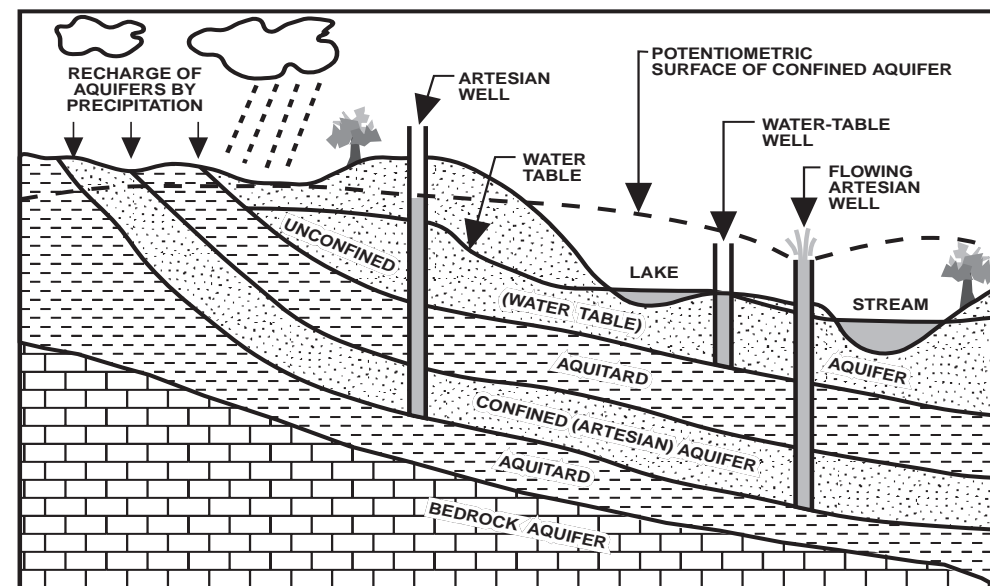


Figure 48. Aquifer types and ground-water movement

The water-transmitting characteristics of an aquifer are expressed as *hydraulic conductivity* and *transmissivity*. Hydraulic conductivity is a measure of the rate that water will move through an aquifer; it is usually expressed in gallons per day through a cross section of one square foot under a unit *hydraulic gradient*. Transmissivity is equal to the hydraulic conductivity multiplied by the saturated thickness of the aquifer. The storage characteristic of an aquifer is expressed as the *storage coefficient*.

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

The size, shape, and sorting of material determine 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 porosity and permeability sufficient to absorb, store and transmit water in usable quantities. *Aquitards* consist of materials with low permeability which restrict ground-water movement. An aquitard overlying an aquifer may limit the recharge to the aquifer but may also protect the aquifer from surface contamination.

Where an aquitard overlies an aquifer, the water in the aquifer is said to be *confined* because the aquitard prevents or restricts upward movement of water from the aquifer. Such an aquifer is referred to as a confined or *artesian* aquifer. Water in confined aquifers exists under *hydrostatic pressure* which exceeds atmospheric pressure; and 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. Such wells may or may not be flowing wells (figure 48). A measure of the pressure of water in a confined aquifer is referred to as the *potentiometric level*.

In contrast, water in an *unconfined* aquifer exists under atmospheric pressure; and wells that are completed in such aquifers have water levels that correspond to the local water table. An unconfined aquifer is also referred to as a water table aquifer, and the spatial distribution of water levels in wells in unconfined aquifers is shown on a water table map. Water level

maps for confined and unconfined aquifers are typically referred to as potentiometric surface maps (plate 1).

As a well discharges water from an aquifer the water level drops in the well. The drop in water level, which is called *drawdown*, creates a hydraulic gradient and causes ground water around the well to flow toward the well. If an unconfined or confined aquifer is being pumped, an overall lowering of either the water table or the potentiometric surface, respectively, occurs around the well. The zone being influenced by pumpage is called the *cone of depression*. An increase in the pumping rate usually creates a larger cone of depression which may induce more recharge to the aquifer. However, the rate of recharge to confined aquifers is limited by the thickness and hydraulic properties of the confining layers.

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 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 or may not be equal to 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 Maumee River basin was started in 1944 by the U.S. Geological Survey (USGS) in cooperation with the Indiana Department of Natural Resources (IDNR). Records for active and discontinued observation wells in Indiana are kept on file at the IDNR, Division of Water. Basic information for the discontinued and active observation wells in and near the Maumee River basin is presented in table 22.

Currently, the observation well network in the Maumee River basin includes five discontinued wells and four active wells. In addition, three active observation wells are located just beyond the basin bound-

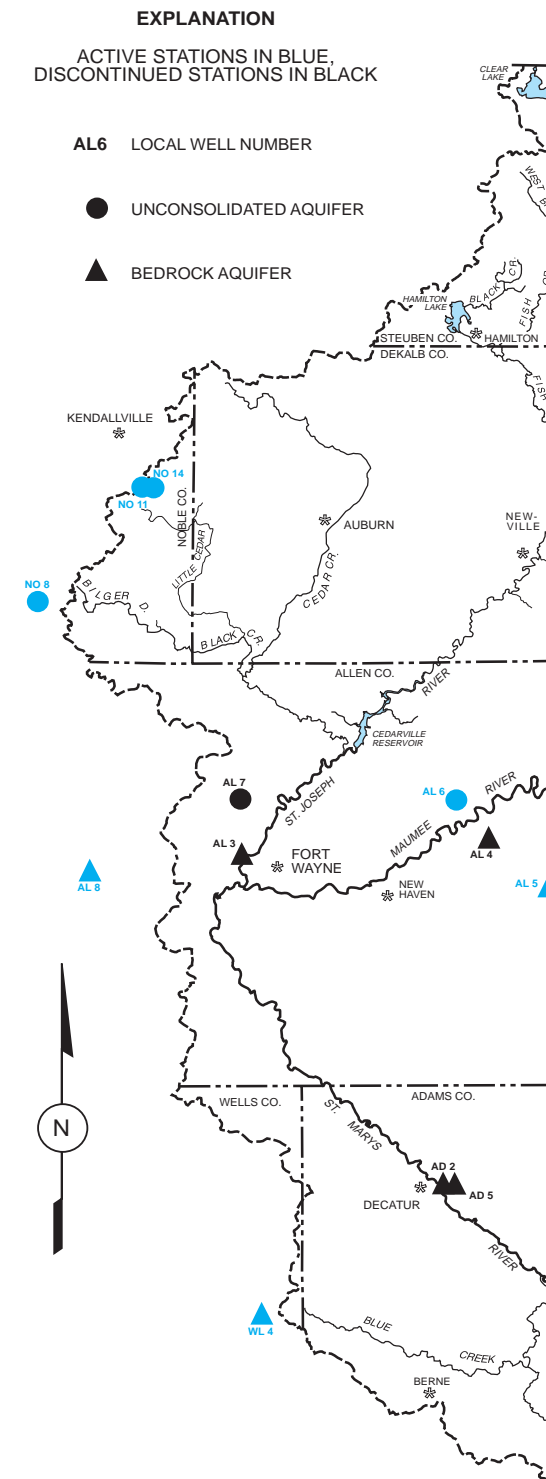


Figure 49. Location of observation wells

ary (figure 49). Of the four active observations wells in the basin, two are *nested* near the basin boundary in Noble County. The remaining two are located in east-central Allen County.

Observation wells in the Maumee River basin are categorized into two groups: 1) unaffected by pumping and 2) affected by pumping. However, classification can be difficult in cases where the observation well has a short period of record.

Hydrologic data are often presented in water years (October through September) instead of calendar years (January through December) because the annual peak in river *stage*, which commonly occurs from December to June, can be interpreted as two annual peaks in two calendar years if a major precipitation event occurs from late December to early January.

The hydrograph of Allen 5 (AL5) for the period 1962 to 1966 (figure 50) shows how nearby pumping caused a ground-water level decline of almost 30 feet. However, pumpage has long ceased and the ground water is now at near-normal levels.

The hydrographs of both Allen 5 (AL5) and Allen 6 (AL6) for the period October 1992 through September 1994 show static water level fluctuations during a period of abnormally high and abnormally low rainfall (figure 51). Rainfall was above normal during the 1992 and 1993 water years and below normal during the 1994 water year.

Normal temporal trends in the ground-water levels are illustrated by the hydrograph of Allen 6 (figure 51). Ground-water levels in aquifers are highest during the wet season of spring, and decline during summer and fall because of increased evapotranspiration and reduced recharge. However, the hydrograph of Allen 5 (figure 51) indicates that a delayed effect of recharge can occur in the ground-water levels of bedrock wells where fine-grained unconsolidated sediments overlie bedrock.

Potentiometric surface maps

Ground-water level measurements can provide important information about the local ground-water resources. For example, ground-water availability and estimates of aquifer yield are determined by analyzing changes in water levels related to pumpage. Also, because differences in water-level elevation provide potential for flow, spatial mapping of water-level elevations can permit identification of regional ground-

Table 22. Summary of active and discontinued observation wells

Well number: U.S. Geological Survey county code and well number. Well locations are shown in figure 49.
 Period of record: Refers to calendar year, whether or not data encompasses entire year.
 Aquifer system: SD, Silurian-Devonian carbonates; KEN, Kendallville; NH, New Haven
 Aquifer type: LS, limestone; SG, sand and gravel; S, sand.
 Aquifer classification: A, affected by pumping; UA, unaffected by pumping.

County	Well number	Period of record	Aquifer System	Aquifer Type	Aquifer Condition	Well Diameter (in.)	Well Depth (ft.)	Aquifer Class
Adams	*AD2	1945-66	SD	LS	Confined	6	250	A
	*AD5	1950-66	SD	LS	Confined	6	144	A
Allen	AL5	1962- ¹	SD	LS	Confined	4	97	A
	AL6	1966-	NH	SG	Confined	6	84	UA
	AL8 ²	1988-	SD	LS	Confined	6	193	A
	*AL3	1944-66	SD	LS	Confined	8	400	A
	*AL4	1962-71	SD	LS(?)	Confined	4	44	A
	*AL7	1980-82	KEN	S	Confined	5	148	UA
Noble	NO8 ³	1966-71;74-	KEN	SG	Confined	6	149	UA
	NO11	1987-	KEN	SG	Confined	6	216	UA
	NO14	1987-	KEN	SG	Confined	6	145	UA
Wells	WL4 ⁴	1967- ⁵	SD	LS	Confined	6	79	UA

* Discontinued wells.
¹ No record 1972.
² Outside Maumee River basin boundary, approximately 3 miles.
³ Outside Maumee River basin boundary approximately 1/2 mile.
⁴ Outside Maumee River basin boundary approximately 1 mile.
⁵ Semi-annual tape-down readings only, September 1971 to December 1981.

water flow direction, as well as areas of recharge and discharge.

The potentiometric surface map of the Maumee River basin (plate 1) depicts the elevation to which water levels will rise in wells. The map is created by plotting elevations of the static water level and then generating contours or lines of equal elevation. Static water levels used to develop the potentiometric surface map are from wells completed at various depths and under confined and unconfined conditions.

In general, the composite potentiometric surface follows the overlying land-surface topography and intersects the land surface at major streams. The expected flow path is downslope or perpendicular to the potentiometric surface contours. Natural ground-water flow is from areas of recharge toward areas of discharge. Depths to the potentiometric 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 on local geologic conditions, such as thickness and lateral extent of the aquifer, in combination with the potentiometric surface.

The generalized potentiometric surface map of the Maumee River basin displays contours for two separate aquifer types, unconsolidated aquifers in the north, and bedrock in the south. In Allen County, where both aquifer types are used, overlapping contours are displayed. In regions where the unconsolidated and bedrock aquifer systems overlap, ground-water levels generally occur at similar elevations.

Ground-water level elevations for unconsolidated aquifers in the Maumee River basin range from 1050 feet m.s.l. (mean sea level datum) near Clear Lake in the northern tip of the basin to less than 725 feet m.s.l. where the Maumee River enters Ohio. These respec-

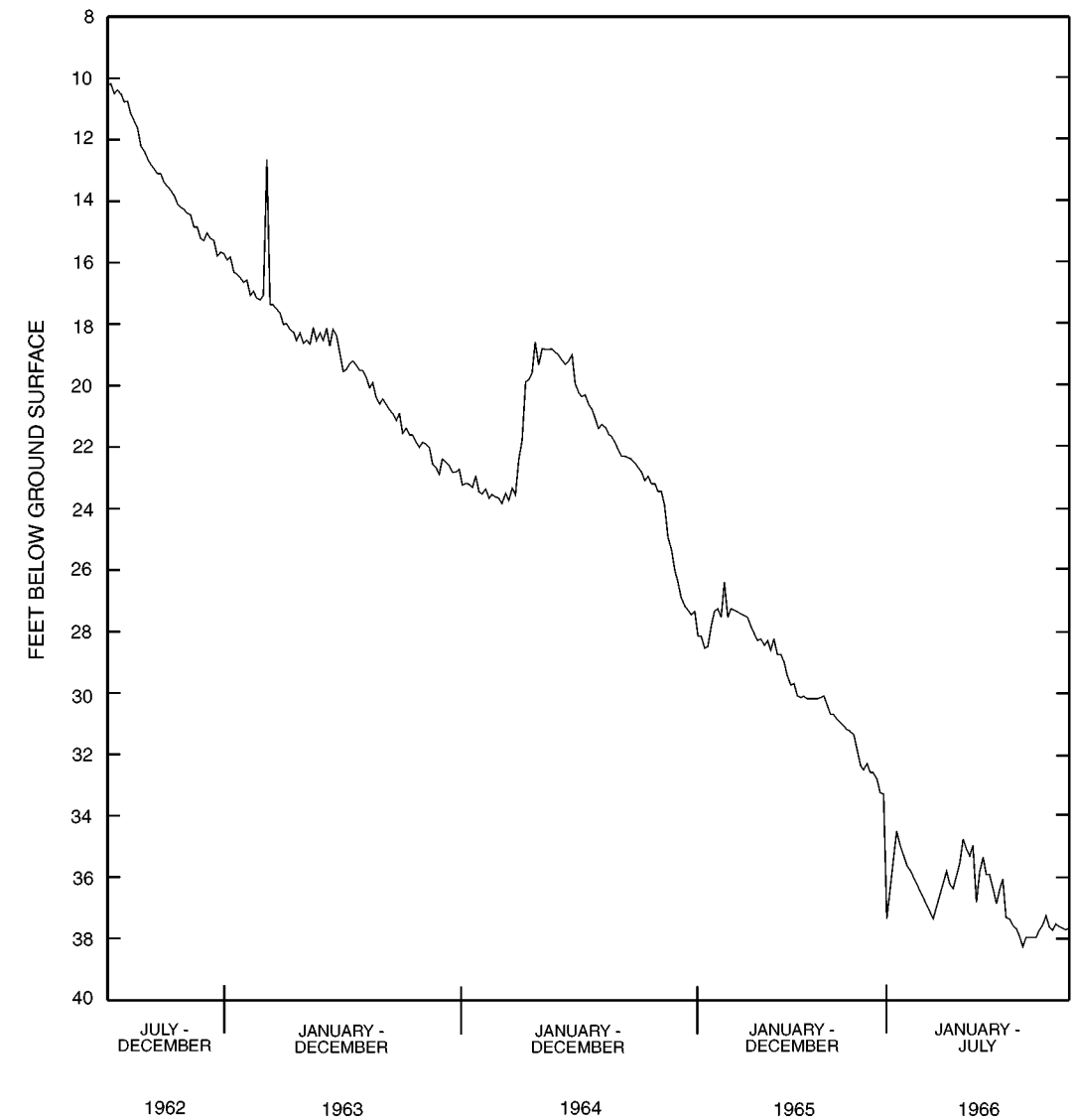


Figure 50. Water-level decline in observation well affected by nearby pumpage

tive water-level elevations correspond closely to the topographic highs of more than 1,100 feet m.s.l. in northeastern Steuben County and the topographic lows of almost 700 feet m.s.l. along the lowest reaches of the Maumee River.

Ground-water level elevations in the bedrock aquifers range from approximately 825 feet m.s.l. at the southern tip of the basin to less than 725 feet m.s.l. where the Maumee River leaves the state. Maximum elevations of the ground-water levels in the bedrock

aquifers generally coincide with the bedrock surface topographic highs in southern Adams County (see figure 21).

Regional ground-water flow for both aquifer types follows the same general direction as the Maumee River and its major tributaries. Ground-water flow in the unconsolidated sediments is away from the drainage divide in the north and west and toward the south and east. Regional ground-water flow in the bedrock is primarily from the south and west, toward

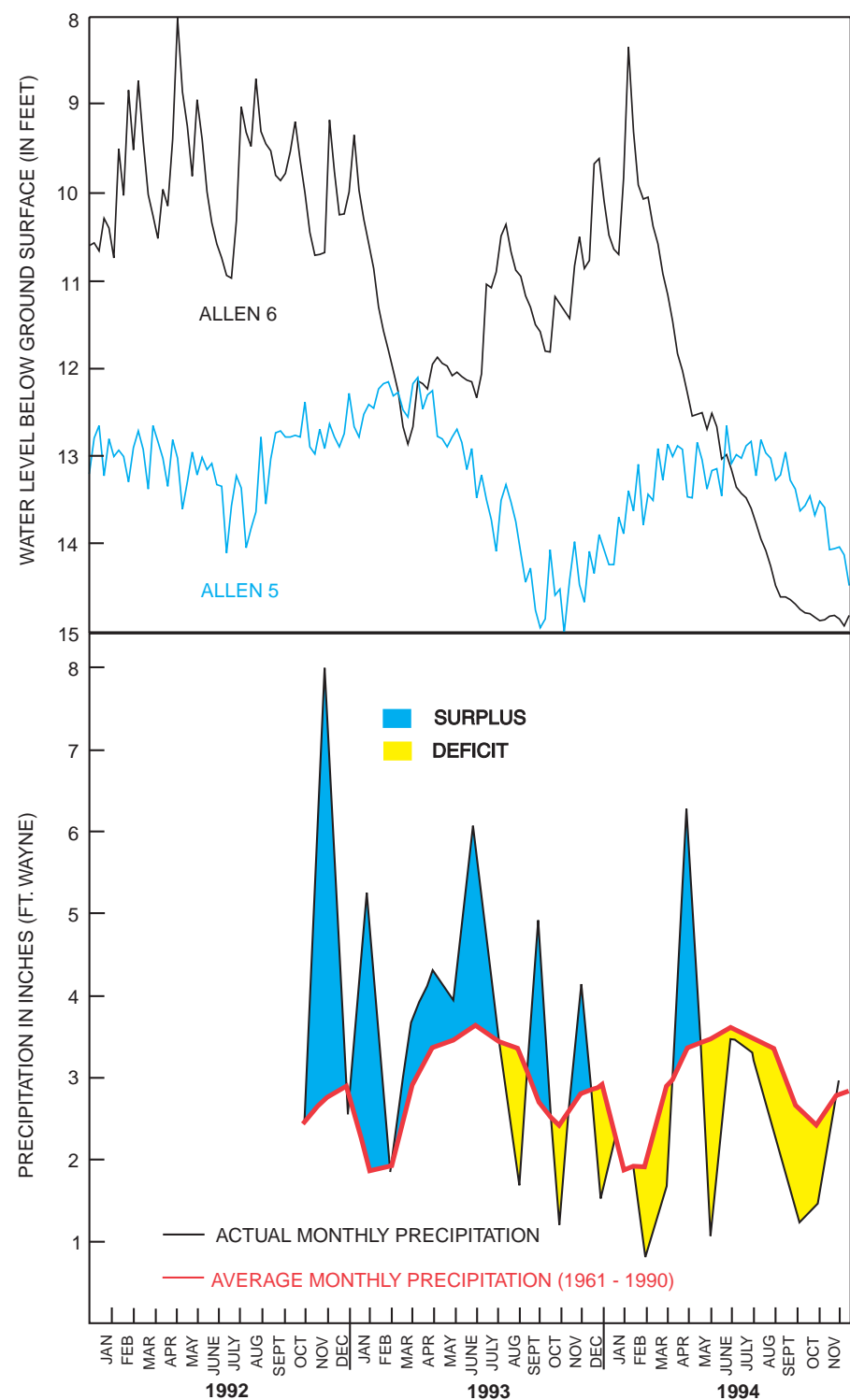


Figure 51. Comparison of normal and actual monthly precipitation and water-level fluctuations in an unconsolidated and a bedrock well

the north and east.

AQUIFER SYSTEMS

In this report, the ground-water resources of the Maumee River basin are mapped and described as regional aquifer systems (plate 2). Lack of data in many parts of the basin and complexity of the deposits preclude detailed aquifer mapping. Much of the discussion of general ground-water conditions in the Maumee River basin is adapted from interpretations made by Herring (1969); but mapping and discussion of specific aquifer systems are based on additional data and interpretation. For Allen County, more detailed information is available in a report by Fleming (1994).

The unconsolidated and bedrock aquifer systems of the Maumee River basin form a single but complex geohydrologic system. Ground-water supplies in the basin are generally derived from three principal aquifer groups: 1) valley train, outwash plain, and discontinuous sand and gravel deposits; 2) bedrock of Silurian and Devonian age; and 3) sand and gravel deposits in and above buried bedrock valley systems.

The most important aquifers in the northern part of the basin, which comprises about 60 percent of the total area, consist of valley train, outwash plain, and discontinuous sand and gravel deposits of *Pleistocene* age. These deposits vary in thickness and extent, but are sufficiently widespread to serve as primary aquifers. In most of the southern part of the basin, Silurian and Devonian carbonates form the principal aquifer, although sand and gravel deposits in and above buried bedrock valleys are important in southern Adams County.

Seven unconsolidated aquifer systems are defined in this report according to hydrologic characteristics of the deposits and environments of deposition (plate 2). Table 23 summarizes various hydrologic characteristics of the unconsolidated aquifer systems. Bedrock aquifer systems are defined on the basis of hydrologic and lithologic characteristics; however, not all of the bedrock formations are productive aquifers.

Unconsolidated aquifer systems

The primary unconsolidated aquifer systems in the Maumee River basin include the Kendallville, Aboite,

Hessen Cassel, New Haven, Cedarville, Eel River-Cedar Creek and the Teays Valley and Tributary Aquifer systems. Sediments that comprise these aquifer systems were deposited by glaciers and their meltwaters during the Ice Age. Boundaries of the aquifer systems are gradational and individual aquifers may extend across aquifer system boundaries.

In the northern part of the Maumee River basin, unconsolidated aquifer systems are the primary source of ground water. Highly productive zones within the unconsolidated aquifer systems are encountered where thick, coarse-grained sand and gravel deposits occur.

Kendallville Aquifer System

The Kendallville Aquifer system consists of sand and gravel lenses at various depths within a till and mixed drift complex containing appreciable fine-grained sediments. The aquifer system encompasses a significant part of northeastern Indiana and possibly part of northwestern Ohio and southern Michigan. In Indiana, the aquifer system extends into most of the northern part of the Maumee River basin (plate 2) and parts of southeastern St. Joseph River basin (Indiana Department of Natural Resources, Clendenon and Beaty eds., 1987).

Sediments of the till and mixed drift complex were deposited by distinct glacial advances resulting in local accumulations of more than 350 feet in thickness. Individual aquifers, consisting of discontinuous sand and gravel bodies, generally thicken northward where local outwash accumulations may attain up to 95 feet in thickness. However, the common thickness of the sand and gravel deposits ranges from 5 to 30 feet. Wells that penetrate the Kendallville Aquifer system vary widely in depth. Although the overall range in depth is from 26 to 385 feet, well depths between 40 and 180 feet are common across most of the aquifer system. Wells commonly exceed 150 feet in depth along the west edge of the basin near the drainage divide and in north-central Allen County.

Static water levels are highly variable across the aquifer system. Under typical conditions, static water levels range from about 10 to 50 feet in depth. Extreme levels range from above ground at flowing artesian wells near the lake areas in the northern part of the basin, to as much as 138 feet deep along the

Table 23. Hydrologic characteristics of unconsolidated aquifers

Aquifer System	Range of Aquifer Thickness (ft)	Common Aquifer Thickness (ft)	Range of pumping rates (gpm)		Expected high capacity yeild(gpm)	Hydrologic condition
			Domestic	High-capacity		
Teays Valley	3-80	10-30	10-50	500-2100	500-1000	Confined
Teays Valley Tributary	2-42	5-10	10-40	*	200-400	Confined
Hessen Cassel	3-40	5-10	10-30	75-100	50-100	Confined
Kendallville	5-95	5-30	10-50	500-2250	200-600	Confined
Eel River-Cedar Creek	0-120	20-55	10-60	300-600	600-1000	Confined/ Unconfined
Cedarville	3-96	10-30	10-60	200	400-600	Confined/ Unconfined
Aboite	5-60	5-20	10-50	225-1000	200-600	Confined
New Haven	1-30	5-10	5-20	100-250	100-150	Confined

* Indicates limited to no data

western basin boundary in Noble County.

Ground-water availability in the Kendallville Aquifer system is considered good. Most of the wells that penetrate the aquifer system are domestic supply wells that yield about 10 to 50 gpm. Large diameter high-capacity wells commonly yield from 70 to 1000 gpm, although yields up to 2250 gpm have been reported at test wells (table 23). Local geologic conditions within this aquifer system cause great variability in potential yield. One area within the system that has a greater than average potential for production is the Hometown interlobate area (see figure 17 and accompanying discussion in the **Physical Environment** chapter, **geology** section).

Aboite Aquifer System

The Aboite Aquifer system consists of sand and gravel deposits that occur at several horizons within thick, clayey till deposits in the west-central part of Allen County (plate 2). The aquifer system is comprised of two distinct parts which exhibit somewhat different geohydrologic characteristics.

In the northern part of the aquifer system, the sand and gravel bodies are separated from the underlying carbonate bedrock by till which ranges from 10 to 100 feet in thickness. Large channel deposits are sporadic.

However, in the southern part of the aquifer system, coarse-grained bodies are more abundant, and many large channel deposits which directly overlie bedrock valleys form well-developed hydraulic connections with the carbonate bedrock (Fleming, 1994). Common thickness of the individual aquifers that comprise the Aboite Aquifer system ranges from about 5 to 20 feet.

Wells penetrating the Aboite have depths which generally range from 20 to 80 feet, but depths approaching 220 feet are not uncommon. In general, conditions for deep wells are more likely to occur in the northern portion of the Aboite Aquifer system than in the southern part. Overall, static water levels range from 30 to 70 feet below the land surface. Yields from domestic wells range from 10 to 50 gpm. The unconsolidated deposits of the Aboite Aquifer system are generally bypassed in favor of the bedrock for development of high-capacity wells.

Hessen Cassel Aquifer System

The Hessen Cassel Aquifer system consists of scattered lenses of glacial outwash amidst thick sequences of tills and, along its northeastern extent, some fine-grained *glaciolacustrine* deposits. The aquifer system extends across most of the southern part of the basin

(plate 2); but the overall scarcity of productive zones of sand and gravel in this aquifer system is apparent from the number of ground-water wells completed in the underlying Silurian-Devonian carbonate bedrock.

The sand and gravel lenses are commonly 5 to 10 feet thick and are either confined within glacial till materials, or are overlying bedrock. Wells that penetrate the Hessen Cassel Aquifer system range from about 50 to 90 feet in depth, and have static water levels that range from 10 to 20 feet below the ground surface.

Of the few high-capacity wells that occur within the Hessen Cassel Aquifer system, yields from 75 to 85 gpm are common from locally-thick outwash deposits. Yields from domestic wells within the system typically range from 10 to 30 gpm.

New Haven Aquifer System

The New Haven Aquifer system consists of outwash plain sediments confined by varied sequences of till and glaciolacustrine deposits. However, the aquifer is relatively continuous across its extent in north-central Allen County (plate 2). North from the Maumee River, depth to bedrock increases and the accumulation of unconsolidated deposits thickens.

The aquifer, which commonly ranges from 5 to 10 feet in thickness, directly overlies bedrock in some places. Depth to the New Haven Aquifer ranges from about 30 feet near the Maumee River to about 80 feet at the northward extent of the aquifer. In general, wells penetrating the aquifer have static water levels that range from 5 to 40 feet below the ground surface.

Yields from domestic wells range from 5 to 20 gpm. From the few high-capacity wells that penetrate locally-thick outwash deposits (up to 30 feet), yields from 100 to 250 gpm are common.

In areas where the New Haven Aquifer system has adequate sand and gravel, the unconsolidated deposits appear to be the preferred source of water. However, in some locations within the system, high-capacity wells must be completed in the underlying Devonian carbonate bedrock.

Cedarville Aquifer System

The Cedarville Aquifer system is comprised primarily of surficial valley train sediments and deeper

outwash deposits in the St. Joseph River valley region of the Maumee River basin (plate 2). Although a thin till cap may be present locally, the valley train deposits commonly extend from the ground surface to depths ranging from about 10 to 30 feet.

Most wells that are completed in the Cedarville Aquifer system penetrate the deeper outwash deposits rather than the valley train deposits. The deep aquifers, which commonly range from 20 to 40 feet in thickness, are afforded some protection against contamination from surficial sources by overlying tills of variable thickness. In DeKalb County, valley train sediments typically coalesce with underlying outwash deposits to form total aquifer thickness up to 96 feet.

Wells that are completed in the Cedarville Aquifer system commonly have depths that range from 25 to 60 feet, but some have depths of 100 to 140 feet. Static water levels in wells penetrating the aquifer system range from 10 to 30 feet below the surface.

Yields from domestic wells range from 10 to 60 gpm, but no known high-capacity well is completed in the aquifer system.

Eel River-Cedar Creek Aquifer System

The Eel River-Cedar Creek Aquifer system (plate 2), like the Cedarville, consists of surficial valley train sediments and deeper outwash plain deposits occurring beneath a major river valley. The surficial sediments consist of sand and gravel deposits which are present from the ground surface to various depths and are either underlain by tills, or coalesce with older outwash deposits.

In areas where intervening layers of till are present, most wells are completed in the deeper outwash deposits which occur beneath the surficial sand and gravel aquifer. The susceptibility of the outwash deposits to contamination from surface sources is generally lowered by the presence of the overlying till which retards the downward movement of chemical contaminants. In general, the outwash deposits commonly range from 20 to 30 feet in thickness.

Wells that penetrate the Eel River-Cedar Creek Aquifer system range from 20 to 120 feet in depth. However, along the northern boundary of Allen County and in parts of DeKalb County, typical wells have depths which range from 40 to 55 feet. Static water levels commonly occur between 10 and 30 feet below the surface. Yields from domestic wells range

from 10 to 60 gpm. High-capacity wells generally yield 300 to 600 gpm.

Teays Valley and Tributary Aquifer System

The Teays Valley is a buried pre-glacial bedrock valley in the southern portion of Adams County. During valley development, layers of bedrock ranging from Silurian limestone and dolomite to Ordovician limestone and shale were dissected to create an entrenched valley having a width that varies from one to two miles. Subsequent glacial advances covered the bedrock surface with unconsolidated sediments of variable thickness. In some places, the till and outwash sediments occurring above the buried bedrock valley may exceed 385 feet in thickness. Outwash deposits consisting of sand and gravel range from 5 to 182 feet in thickness.

Valley development along pre-glacial tributaries was not as extensive as along the mainstem of the Teays Valley network. However, a significant but narrow tributary valley was cut into Silurian carbonates. The tributary valley, which entered the Teays mainstem near present-day Berne in Adams County, trends in a general north-south direction from Allen County (plate 2). Appreciable outwash sediments occur in the glacial deposits overlying the tributary valley.

Wells in the Teays Valley are completed at depths ranging from 65 to 295 feet, although well depths ranging from 135 to 250 feet are most common. Static water levels in the wells range from 20 to 40 feet below the ground surface. Domestic wells typically yield from 10 to 50 gpm; but as reported for the Berne well field in Adams County, high-capacity wells may yield as much as 2100 gpm.

The Tributary Valley deposits are penetrated by wells that range from 55 to 245 feet in depth. The static water levels are also variable, ranging from 15 to 70 feet below the surface. Yields from domestic wells range from 10 to 40 gpm. No known high-capacity wells tap the tributary valley of the Teays.

Bedrock aquifer systems

The occurrence of bedrock aquifers depends on the original composition of the rocks and subsequent changes which influence the hydraulic properties. *Post depositional* processes which promote jointing,

fracturing, and solution activity of exposed bedrock generally increase the *hydraulic conductivity* of the upper portion of bedrock aquifer systems. Because permeability is usually greatest near the bedrock surface, the upper bedrock units are generally the most productive aquifers. In the Maumee River basin, rock types exposed at the bedrock surface range from unproductive shales to highly productive limestones and dolomites.

Bedrock aquifer systems in the basin are overlain by glacial deposits of varying thickness (see figure 16). South of Fort Wayne, bedrock is generally covered by less than 100 feet of glacial drift. North of the Maumee River, drift thickness increases to a maximum of more than 400 feet in north central DeKalb County. Most of the bedrock aquifers in the basin are under *confined* conditions. In other words, the water level (*potentiometric* surface) in wells completed in the aquifer rises above the top of the aquifer.

The yield of a bedrock aquifer depends on its hydraulic characteristics and the nature of the overlying deposits. Shale and glacial till act as aquitards, restricting recharge to underlying bedrock aquifers. However, fracturing and/or jointing may occur in aquitards which can increase recharge to the underlying aquifers. The shale in the Maumee River basin is most likely to be fractured where it occurs as a relatively thin covering on the carbonate bedrock, a situation that exists near the subcrop of the shale in northern and central portions of Allen County. Although usually penetrating less than 20 feet below the surface, jointing within till units will increase the bulk hydraulic conductivity of the unit, thus allowing increased recharge to the underlying strata (Fleming, 1994).

In this report, two primary bedrock aquifer systems are identified for the Maumee River basin based on bedrock surface lithology, the Silurian-Devonian Carbonate Aquifer system and the Devonian and Mississippian Shale Aquifer system (plate 2 and figure 21). Ordovician shales, although present at the bedrock surface in a small area at the base of a buried bedrock valley in southern Adams County (figure 21), are not discussed in this section because they are not aquifers in this area. Although this type of two-dimensional mapping is useful, it should be remembered that the Silurian-Devonian Carbonate rocks extend beneath the Devonian and Mississippian Shale Aquifer system (figure 21) and are used as a water supply within its boundaries. The Silurian-Devonian

Carbonate Aquifer system occurs in most of the southern half of the basin, and the Devonian and Mississippian Shale aquifer system is in the north. Hydraulic properties within the two aquifer systems are highly variable.

In addition to the two bedrock aquifer systems identified on plate 2, other bedrock units capable of transmitting water are present in the basin, but the "aquifers" have water quality that is not acceptable for many uses (appendix 5). A brief discussion of some of these non *potable* aquifers is included.

In general, bedrock aquifers are not used in the northern half of the Maumee River basin because ground water is available from the unconsolidated materials overlying the bedrock and because there is a predominance of unproductive shales. In the southern part of the basin, a thin mantle of unconsolidated materials and the presence of thick, highly productive carbonate aquifers favor the development of bedrock aquifers.

In places, sand and gravel aquifers are located immediately overlying the bedrock surface. Many of these materials are found in association with buried bedrock valleys but do occur elsewhere along the bedrock surface. Where unconsolidated aquifers are in contact with the carbonate system, the two aquifers are hydraulically linked and have very similar *hydraulic gradients*.

Silurian-Devonian Carbonates

The carbonate aquifer system of the Maumee River basin is composed of limestone, dolomitic limestone, and dolomite ranging in age from lower and middle Silurian in Adams County to middle Devonian in Allen County (figure 21 and plate 2). Ground-water flow in this system occurs predominately along bedrock joints, fractures, and bedding planes as well as along *solution* features (see sidebar, **Ground-water flow and the dissolution of carbonate rocks**).

Because ground-water flow through carbonate rock is controlled by the geometry of its joints and fractures, the direction of site specific or local flow may differ from that of the regional ground-water flow path. Ground-water flow in these rocks can be complex because the type of fracturing and fracture patterns in a specific carbonate rock in a specific location are determined by many factors. In the Maumee River basin, the original fracture patterns in the carbonate

rocks are altered by pre-Pleistocene ground-water flow; solution features are one result (Fleming, 1994). In addition to complexities introduced by pre-Pleistocene events, Pleistocene erosion, weathering, and deposition have caused additional alterations to the carbonate aquifer system in the basin. All of these factors result in very complex local ground-water flow.

Water well data indicate that the most productive part of the carbonate aquifer occurs within the upper 100 feet, and in many places, within a few feet of the bedrock surface. However, other zones of relatively high permeability do occur at greater depth. The deeper zones are most likely to be penetrated by large diameter, high-capacity wells in an attempt to increase available drawdown in the well and obtain maximum yield. Yields of the large-diameter wells generally range from 100 to 500 gpm, but higher-yielding wells may be possible where several feet of sand and gravel are directly overlying the bedrock surface.

In Adams County, depth to the bedrock ranges from 25 to 128 feet below the land surface; and static water levels in bedrock wells typically occur at 15 to 50 feet below the surface. Domestic water wells, typically 2 to 6 inches in diameter, penetrate about 45 feet into the bedrock and yield from 7 to 63 gpm. High-capacity wells, generally 6 to 12 inches in diameter and having depths of 200 to 400 feet below ground level, have reported yields up to 400 gpm.

In bedrock wells in Allen County, static water levels typically occur at 10 to 70 feet below the surface. Two- to 6-inch diameter domestic wells, penetrating up to 90 feet of bedrock, have depths that range from 60 to 300 feet below land surface and reported yields of 10 to 60 gpm. The six- to 12-inch high-capacity bedrock wells, which may penetrate more than 350 feet of the bedrock, have depths exceeding 550 feet.

In the northern part of the basin, including northern Allen County, the carbonate aquifer is overlain by shales and is generally not considered a significant ground-water source. However, little is known about the ground-water potential for the carbonate aquifer system in this area. Because the aquifer system occurs at great depth and because the overlying unconsolidated aquifers provide an adequate ground-water supply, very few water wells are drilled into the bedrock system.

As the shale thickens north of its Allen County *subcrop*, depth to, and confinement of the carbonate system generally increase; whereas, the fracturing,

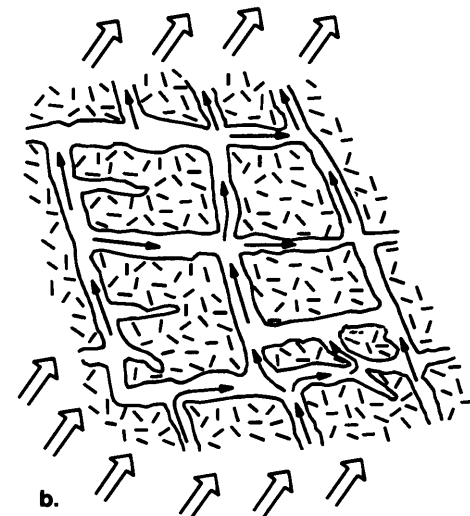
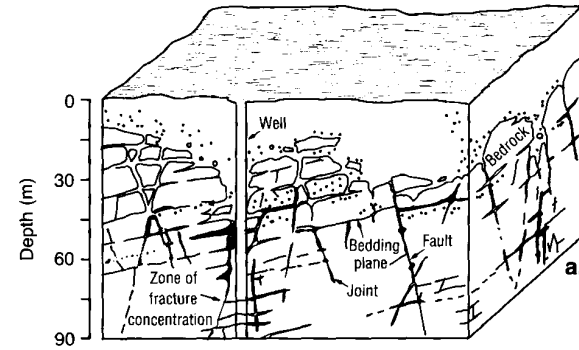
Ground-water flow and dissolution of carbonate rocks

Over a long period of time, limestone and to a lesser extent dolomite, will gradually dissolve in the presence of ground water which was derived from precipitation. Carbon dioxide from the atmosphere and from the soil is incorporated into the precipitation as it changes from atmospheric moisture to ground water. Ground water containing dissolved carbon dioxide forms a mild acid which can slowly dissolve alkaline materials. The alkaline carbonate bedrock units are affected by this process when the slightly acidic ground water moves through the units and is neutralized by the carbonate. A portion of the carbonate unit is dissolved in this neutralization process thus increasing the size of the fracture in which the water is flowing. As this process continues through time larger openings, solution features, form in the rock allowing for increased ground-water flow.

Many types of solution features can result from this process, some subtle and others quite large. The most common features develop along preexisting fractures, joints, and bedding planes, which represent the initial flow path of the water through the rock (fig. a). Over time a variety of larger features can develop leading to cave systems with sinkholes and deep valleys as surface expression.

As this process continued in the southern portion of the Maumee River basin, a very complex system of fractures, solution channels, valleys, and sinkholes probably developed. Glacial events partially eroded the weakened surface of the carbonate rock and then covered the surface with glacial sediments. Consequently no direct surface expression of the probable pre-Pleistocene karst terrain (paleo-karst) currently exists in the Basin.

The resulting near-surface carbonate bedrock aquifer in the Maumee River basin contains a highly variable fractured section which greatly affects ground-water flow through the bedrock. Fractured rock represents one of the most complex types of hydrogeologic systems known. While regional ground-water flow can be very predictable, local flow can be highly varied both in terms of quantity and direction (fig. b). Consequently, determining the local direction of ground-water flow in fractured bedrock at the scale of a specific site may require elaborate instrumentation, monitoring, and dye tracing.



recharge, and productivity of the carbonate decrease. The thickness of glacial drift also increases in the same general area; therefore, the depth to the bedrock aquifer system further increases. All of these factors provide numerous opportunities to develop unconsolidated aquifers overlying the carbonates.

Devonian and Mississippian Shales

For approximately the northern half of the Maumee River basin, the bedrock surface is comprised of Devonian and Mississippian age shales (figure 21). Because these rock units dip to the north toward the Michigan Basin, younger strata appear at the bedrock surface in a northward direction. The units exposed at

the bedrock surface are, from oldest to youngest: the Antrim, Ellsworth, Sunbury, and Coldwater Shales (see **Physical Environment, Bedrock Geology** section of this report).

Very few wells obtain *potable* ground water from the Antrim Shale. Wells that have sufficient yield are generally located near the Devonian carbonate/shale contact at depths ranging from 56 to 135 feet below ground level. Static water levels generally occur at 30 to 35 feet below land surface. Domestic wells in the shale, typically 4 to 6 inches in diameter and penetrating 3 to 16 feet into the bedrock, have yields ranging from 10 to 15 gpm. Unconsolidated materials that overlie the Antrim Shale generally provide sufficient ground-water supplies.

The Ellsworth, Sunbury, and Coldwater Shales occur at the bedrock surface in northern DeKalb

County and Steuben County. There are no known water wells producing from any of these shales, and it is not expected that any of these shales are capable of providing significant yields. In this area in the basin, the bedrock is overlain by thick accumulations of unconsolidated deposits that contain sand and gravel aquifers capable of providing ground-water in usable quantities.

Non Potable Aquifers

Natural water quality within a bedrock aquifer may vary considerably with increasing depth beneath the land surface. Generally, with increasing depth several water-quality parameters degrade resulting in higher total dissolved solids (TDS) values.

Some bedrock aquifers in the Maumee River basin, because of geologic structure, occur near the land surface in part of the basin, but occur at greater depth in other places in the basin (see figures 18 and 19, and discussion in chapter on **Physical Environment, Bedrock geology**). Water quality in the portion of an aquifer located near the surface may be of acceptable quality; whereas, water quality in the same aquifer may be unacceptable in areas where it occurs at greater depth.

Throughout the basin, bedrock aquifers that occur beneath the Silurian/Devonian carbonates have natural water quality unacceptable for potable water supply (appendix 5). Some of these deep, non potable aquifers are being used for disposal of brine or salt water, which is a byproduct of petroleum production in the basin.

The brine, after being pumped to the surface during oil or gas production, is injected into a deep bedrock unit or formation via a USEPA Class II injection well. Such disposal is regulated by the Department of Natural Resources, Division of Oil and Gas.

Formations currently used for brine injection/disposal in the basin include the Knox Supergroup and Black River Group (see appendix 5). Disposal of over 500,000 gallons of brine was reported to have taken place at one well in the Knox in 1994. In addition to the Knox and Black River formations, other formations in the basin have been used for disposal in the past. However, the deepest aquifer identified in the basin, the Mount Simon sandstone, has not been used or tested for brine disposal within the basin.

GROUND-WATER DEVELOPMENT POTENTIAL

The development potential or potential yield of an aquifer depends on aquifer characteristics such as hydraulic conductivity, aquifer thickness, storativity, areal extent, ground-water levels, available drawdown, and recharge. All aquifer properties are important, but three are particularly useful for basin-wide ground-water resource assessment: recharge, storativity, and transmissivity (hydraulic conductivity multiplied by aquifer thickness). If these properties can be determined for aquifer systems, and can be applied with a basic understanding of hydrogeology, a qualitative comparison can be made of ground-water development potential within a basin and between basins. These three aquifer properties are used in digital and analytical ground-water models.

Other factors such as water quality, potential contamination sources, demand, water rights, well design and well location influence actual ground-water development. This section of the report focuses primarily on transmissivity and recharge, two aquifer characteristics important for ground-water development. Water quality and ground-water protection are discussed in the **Ground-water quality** section of this chapter. Demand and water rights are discussed in the chapter titled **Water Resource Development**.

Transmissivity

Transmissivity is a measure of the water-transmitting capability of an aquifer. Expressed as the rate at which water flows through a unit width of an aquifer, transmissivity is defined as the product of the hydraulic conductivity and the saturated thickness of an aquifer. Methods used to compute transmissivity are based upon a mathematical relationship between the pumping rate and the resultant drawdown of the water level in the aquifer for a given set of well and aquifer conditions.

The most reliable method for estimating transmissivity is a graphical approach based on aquifer-test data. 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 at a constant and controlled rate. The response of an 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 often not warranted because the cost of installing observation wells and conducting the test exceed the immediate benefit. There are only a few aquifer tests available for the Maumee River basin.

A method using specific capacity data based on unadjusted drawdown was used to estimate aquifer transmissivity in the Maumee River basin. Specific capacity is defined as the rate at which water can be pumped from a well per unit decline of water level in the well (commonly expressed as gallons per foot) for a specified time period. Specific capacity tests are less expensive than aquifer tests because drawdown typically is measured only once at the pumped well just before the pumping is stopped. These tests are conducted by the driller after completion of a well to determine the potential yield of the well. As the length of the test increases, continued drawdown in the well causes a decrease in the specific capacity. In reconnaissance ground-water investigations, useful estimates of aquifer transmissivity can be based on specific capacity data (Walton, 1970).

Estimates of aquifer transmissivity in the Maumee River basin were generated from specific capacity data of nearly 800 water well logs by using a computer program called "TGUESS" (Bradbury and Rothschild, 1985) (figure 52). 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, drawdown from specific capacity tests cannot be accurately adjusted. In this case, aquifer thickness is assumed to be equal to the thickness of the aquifer that is penetrated by the well. The computed transmissivity of the aquifer (referred to as transmissivity based on unadjusted drawdown) can be considered to represent a local minimum transmissivity for the aquifer. Of the approximately 10,000 well records on file with the IDNR, Division of Water, fewer than 800 were found to be sufficiently complete to estimate and plot transmissivity values. Transmissivity values generated for the basin using "TGUESS" were compared to values

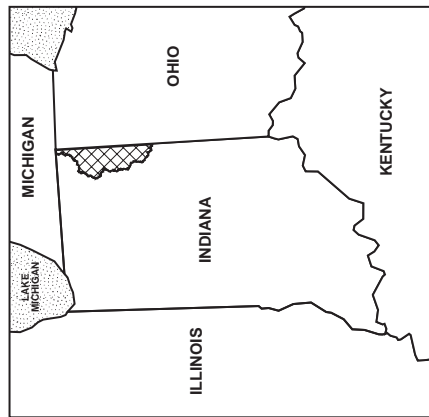
derived from aquifer tests nearby and were found to be conservative although quite variable.

The transmissivity values for the Maumee River basin are highly variable (figure 53). The wide range in values is probably a result of the heterogeneity of the geologic formations and the nature of the data used to obtain the estimates. Data used in the analysis are from different types of wells, ranging from shallow, small-diameter domestic wells to deep, large-diameter high-capacity wells. In addition, the geographic distribution of usable data is haphazard; and multiple water-bearing units are represented, even within individual aquifer systems. Furthermore, there are differences in methods used by drillers to conduct and report specific capacity test results. This variability precludes developing regional transmissivity estimates; however, a few general trends are observed.

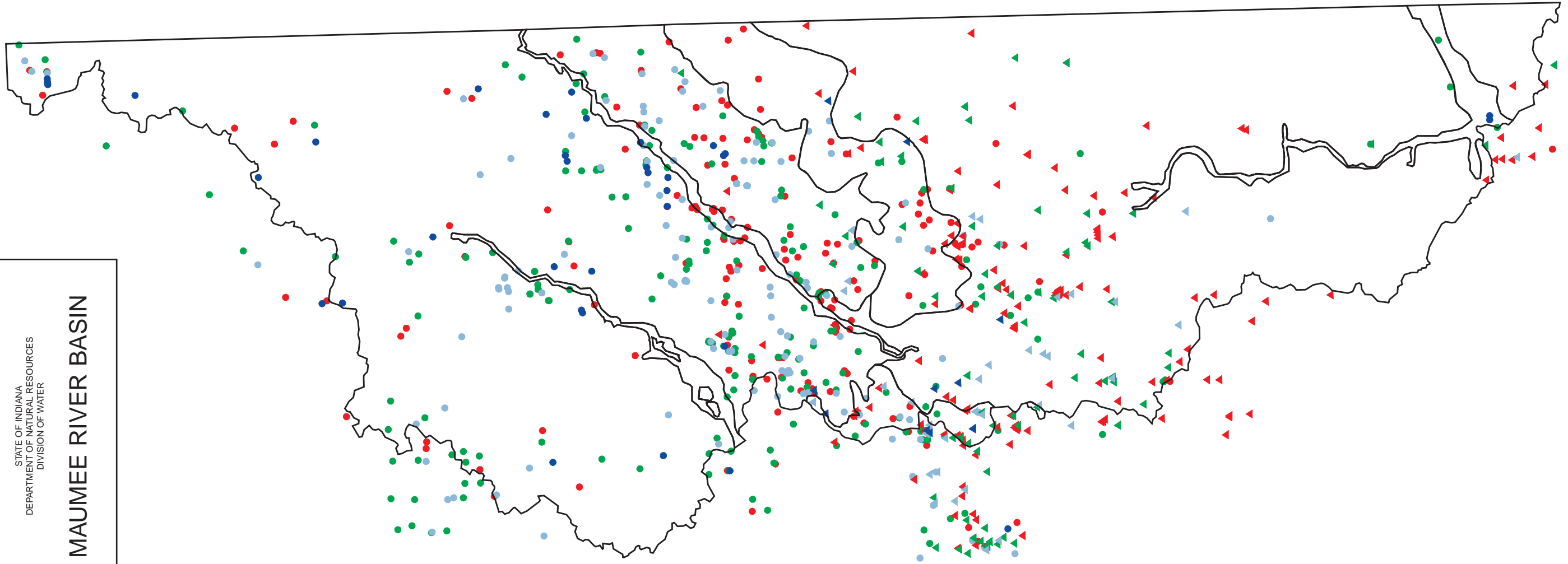
In general, transmissivity estimates for unconsolidated aquifers are less variable and slightly higher than those for bedrock aquifers (figure 53). Approximately 65 percent of the unconsolidated wells have values above 10,000 gallons per day per foot (gpd/ft); whereas, approximately 55 percent of the bedrock wells have transmissivity values of less than 10,000 gpd/ft. Transmissivity values in the unconsolidated aquifer systems range from less than 500 to 558,000 gpd/ft; however, values between 4,000 to 40,000 gpd/ft. are most common (figure 53).

The most transmissive unconsolidated aquifers generally occur in the northern part of the basin where locally-thick outwash deposits are present. In northern Allen and most of DeKalb Counties, highly transmissive zones occur in the valley train and outwash sediments of the Cedarville and the Eel River-Cedar Creek Aquifer systems. Another area of high transmissivity occurs in the extreme northern part of the basin near Clear Lake in Steuben County, where thick outwash fan deposits are present (figure 17). Some unconsolidated deposits associated with the Teays Valley and Tributaries system in the southern portions of the basin also have high transmissivity values.

Within the Kendallville Aquifer system, the Wabash Moraine (figure 17) appears to contain the most transmissive aquifers, having approximately one-third of the wells exhibiting transmissivity values greater than 50,000 gpd/ft. The Fort Wayne Moraine appears to have the least transmissive aquifers, having less than one-fifth of the wells with values greater than 50,000 gpd/ft. Much of the variation between these two moraines may be explained by a general trend of



STATE OF INDIANA
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF WATER
MAUMEE RIVER BASIN



TGUESS values for 794 wells
in thousands GPD/FT



Figure 52. Transmissivity ranges for wells in the Maumee River basin

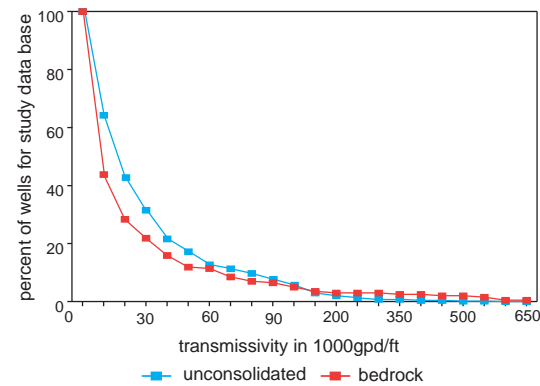


Figure 53. Frequency curves for transmissivity values of unconsolidated and bedrock wells

greater drift thickness to the north. However, sand and gravel deposits are also generally more common in the Wabash Moraine (see **Physical Environment, Geology** section). Data indicate that transmissivity values for the Morainal Highland are much like those for the northern portions of the Wabash Moraine.

Transmissivity values for bedrock aquifers in the basin range from less than 500 to 663,000 gpd/ft; however, values of 3,000 to 30,000 gpd/ft are most common (figure 53). Data are sparse for the Silurian portion of the carbonate aquifer in Adams County. The Devonian carbonate aquifer appears to be slightly more transmissive in the western portions of the basin than in the eastern portions.

Recharge

Aquifer yield is dependent upon aquifer permeability, saturated thickness; available drawdown, areal extent, and upon the number, spacing, diameter, and pumping rates of the wells that tap the aquifer. The ultimate development potential of an aquifer is often equated to the total recharge to the aquifer. However, recharge will vary considerably from year to year due to climatic variations and may vary somewhat with pumping.

The ground-water development potential of the aquifer systems in the Maumee River basin is based on the rate of recharge (derived chiefly from infiltration of direct precipitation) and areal extent of the aquifer systems (figure 54). Estimates of natural

recharge rates to the aquifer systems of the basin were based on several types of analyses. The primary techniques used include base-flow separation and flow duration analysis (see **Surface-Water Hydrology** chapter), aquifer and specific capacity tests to determine the effects of the hydrogeologic and spatial characteristics of the deposits overlying the aquifer systems, and the effects of regional climate (mainly precipitation and temperature).

The highest estimated rate of recharge to aquifers in the Maumee River basin is approximately 500,000 gallons per day per square mile (gpd/sq mi) (table 24). However, these high rates occur in the unconfined parts of both the Cedarville and the Eel River-Cedar Creek Aquifer systems (figure 54), which occupy only 1.6 percent of the basin area. Infiltration of direct precipitation to these two aquifer systems is high because of thinly developed soils on thick, surficial sands.

In contrast to the permeable surficial sediments overlying the Cedarville and the Eel River-Cedar Creek Aquifer systems, sediments overlying the Kendallville Aquifer system consist of surficial tills and mixed drift of rugged topography, factors which promote surface runoff. The rate of recharge to the Kendallville Aquifer system is approximately 250,000 gpd/sq mi. (figure 54). However, the Kendallville Aquifer system occupies approximately 49 percent of the basin area and thereby accounts for about 62 percent of the recharge in the basin.

The southern part of the basin has less rugged topography than the north and surficial sediments are predominantly clay-rich Erie Lobe deposits which limit aquifer recharge to approximately 150,000 gpd/sq mi or less. The Aboite, Hessen Cassel, New Haven and the Teays Valley and Tributary Aquifer systems cover almost 50 percent of the total area of the basin and account for approximately 34 percent of the recharge.

Rates of recharge to bedrock aquifers in the Maumee River basin are low, ranging from less than 50,000 to 100,000 gpd/sq mi. (table 24). Local areas of Silurian and Devonian carbonates that are overlain by outwash sand and gravel are expected to have higher recharge rates than areas of till-covered bedrock.

GROUND-WATER QUALITY

The geochemistry of ground water may influence the utility of aquifer systems as sources of water. The

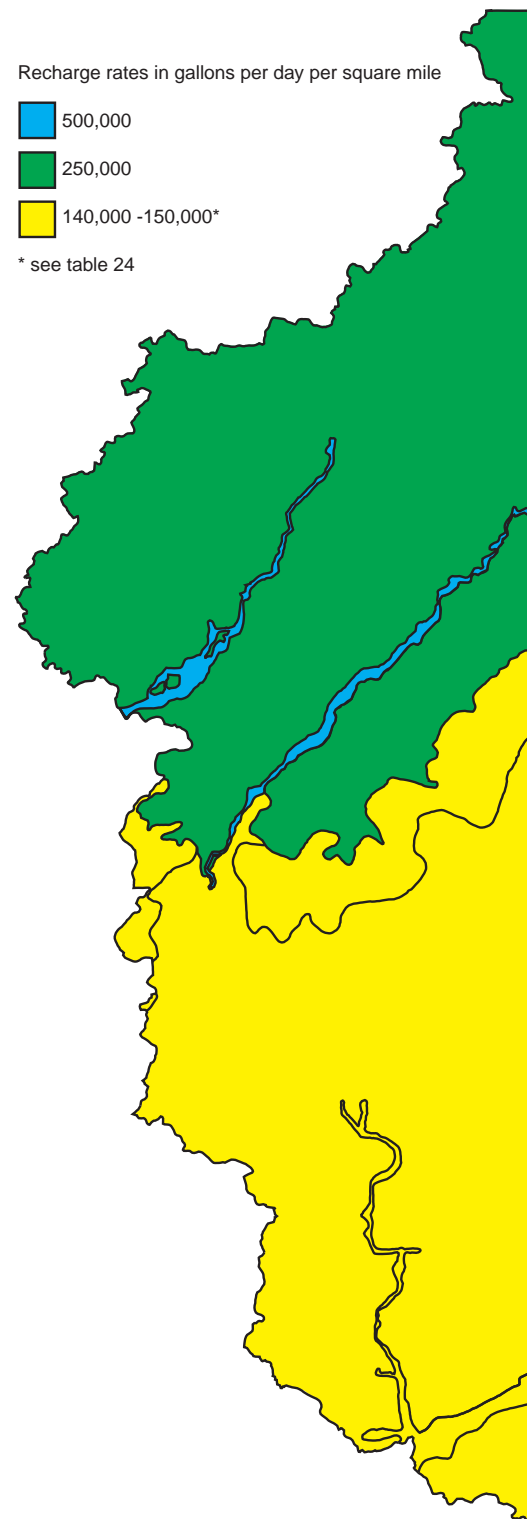


Figure 54. Estimated recharge rates of unconsolidated aquifer systems

types and concentrations of dissolved constituents in the water of an aquifer system determine whether the resource, without prior treatment, is suitable for drinking-water supplies, industrial purposes, irrigation, livestock watering, or other uses. Changes in the concentrations of certain constituents in the water of an aquifer system, whether because of natural or *anthropogenic* causes, may alter the suitability of the aquifer system as a source of water. Assessing ground-water quality and developing strategies to protect aquifers from contamination are necessary aspects of water-resource planning.

Sources of ground-water quality data

The quality of water from the aquifer systems defined in the **Aquifer Systems** section of this chapter is described using selected inorganic chemical analyses from 132 wells in the Maumee River basin. Sources of ground-water quality data are: 1) Ninety-five domestic, commercial or livestock-watering wells sampled during a 1988 cooperative effort between the Indiana Department of Natural Resources, Division of Water (DOW) and the Indiana Geological Survey (IGS); 2) Twenty-four municipal, private, test and observation wells analyzed by the Indiana State Board of Health (presently the Indiana State Department of Health) and private laboratories between 1979 and 1987; and 3) Thirteen private wells in northern Allen County sampled by the Indiana Department of Environmental Management (IDEM) during the spring of 1992. The locations of ground-water chemistry sites used in the analysis are displayed in figure 55, and selected water-quality data from individual wells are listed in appendices 13 and 14.

An additional 33 analyses from wells in the adjacent St. Joseph River basin and Upper Wabash River basin were used for contour-line control during development of chemical concentration maps. Data from these wells, however, were not included in the statistical analysis of water quality. Water-quality data from wells in the St. Joseph River basin and Upper Wabash River basin are available in IDNR Water Resource Assessment 87-1 (Indiana Department of Natural Resources, 1987) and the IDNR, Division of Water files, respectively.

The intent of the water-quality analysis is to characterize the natural ground-water chemistry of the Maumee River basin. Specific instances of ground-

Table 24. Estimated recharge rates for aquifer systems.

Aquifer System	(gpd/sq mi)	Recharge Rate (inches/year)	(cfs/sq mi)	Area (sq mi)	Recharge (MGD)
Teays	150,000	3.15	0.23		
Teays Tributaries	150,000	3.15	0.23	17*	2.55
Hessen Cassel	140,000	2.94	0.22	522	73.08
New Haven	140,000	2.94	0.22	76	10.64
Aboite	150,000	3.15	0.23	15	2.25
Kendallville	250,000	5.25	0.39	632	158.00
Cedarville (St. Joseph R. Valley)	500,000	10.50	0.77	11	5.50
Eel River-Cedar Creek	500,000	10.50	0.77	10	5.00
Total					257.02
Ordovician Limestones and Shales	<50,000	<1.05	<0.08		
Silurian-Devonian Carbonates	100,000	2.10	0.15		
Devonian-Mississippian Shales	<50,000	<1.05	<0.08		

* includes Teays and Teays Tributaries

water contamination are not evaluated. In cases of contamination, chemical conditions are likely to be site-specific and may not represent typical ground-water quality in the basin. Therefore, available data from identified sites of ground-water contamination were not included in the data sets analyzed for this publication. Samples collected from softened or otherwise treated water were also excluded from the analysis because the chemistry of the water was altered from natural conditions.

Factors in the assessment of ground-water quality

Major dissolved constituents in the ground water of the Maumee River basin include calcium, magnesium, sodium, chloride, sulfate and bicarbonate. Less abundant constituents include potassium, iron, manganese, strontium, zinc, fluoride and nitrate. Other chemical characteristics discussed in this report include pH, alkalinity, hardness, lead, and total dissolved solids (TDS).

Although the data from well-water samples in the Maumee River basin are treated as if they represent the chemistry of ground water at a distinct point, they actually represent the average concentration of an unknown volume of water in an aquifer. The extent of aquifer representation depends on the depth of the

well, hydraulic conductivity of the aquifer, thickness and areal extent 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 time elapsed between sampling and laboratory analysis. Because the degree to which these factors alter the original chemistry of a sample is unknown, ground-water analyses may typify the quality of water consumed by the user rather than composition of in-situ aquifer water. In spite of these limitations, results of sample analyses provide valuable information concerning ground-water quality characteristics of aquifer systems.

Analysis of data

Graphical and statistical techniques are used to analyze the available ground-water quality data from the Maumee River basin. Graphical analyses are used to display the areal distribution of dissolved constituents

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 each effect will be determined in part by the residence time of the water within the different subsurface 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. High sodium and chloride levels can result from upward movement of brine from deeper bedrock in areas of high pumpage, from improper brine disposal from petroleum wells, and from the use of road salt (Hem, 1985).

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 that produce hydrogen sulfide 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, 1968; 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 that 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 geological settings.

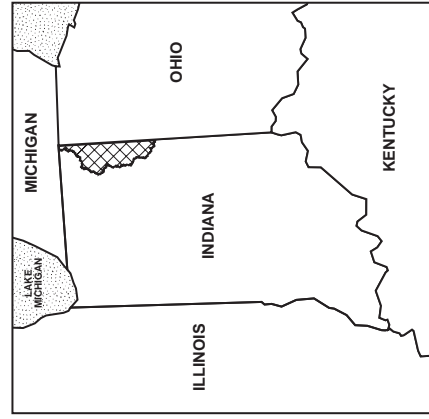
Natural concentrations of nitrate-nitrogen in ground water originate from the atmosphere and from living and decaying organisms. High nitrate levels can result from leaching of industrial and agricultural chemicals or decaying organic matter such as animal waste or sewage.

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-occurring 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.

throughout the basin, and to describe the general chemical character of the ground water of each aquifer system. Statistical analyses provide useful generalizations about the water quality of the basin, such as the average concentration of a constituent and the expected variability.

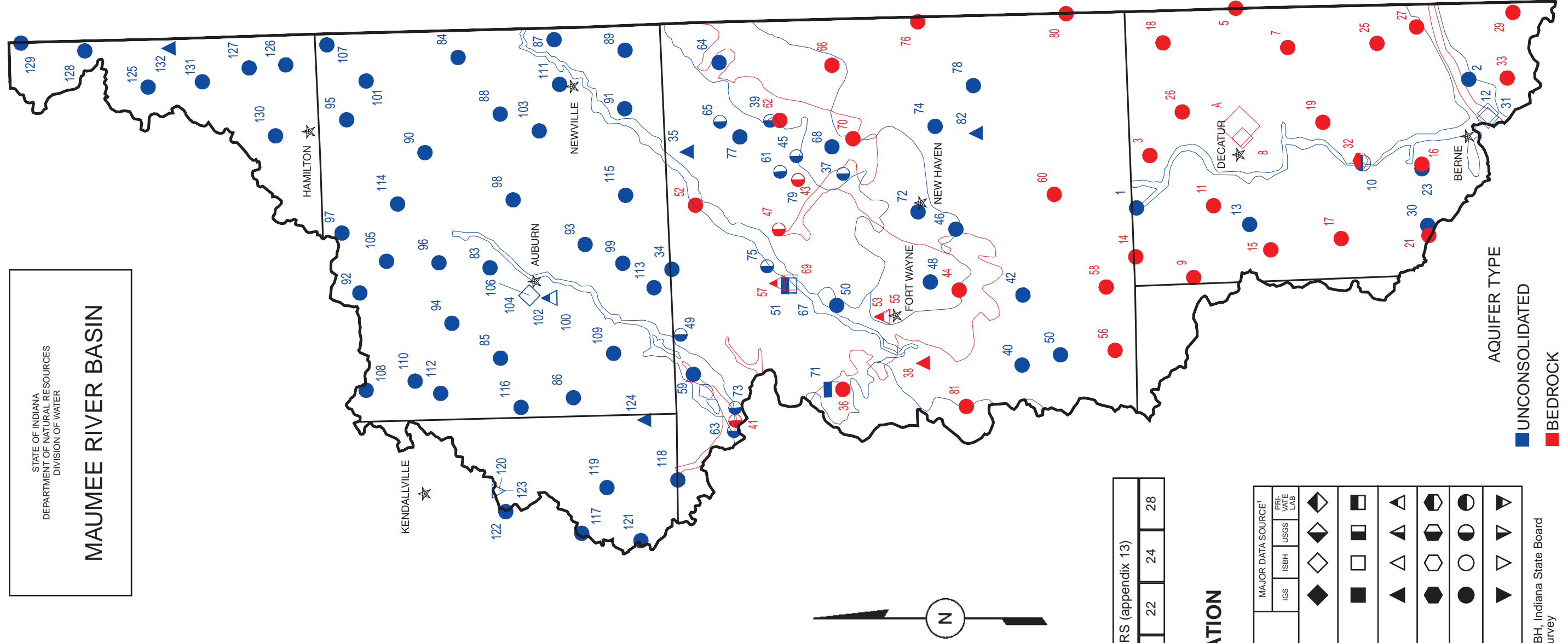
Regional trends in ground-water chemistry can be

analyzed by developing trilinear diagrams for the aquifer systems in the Maumee River basin. Trilinear plotting techniques developed by Piper (1944) can be used to classify ground-waters on the basis of chemistry, and to compare chemical trends among different aquifer systems (see sidebar titled **Chemical classification of ground waters using trilinear diagrams**).



STATE OF INDIANA
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF WATER

MAUMEE RIVER BASIN



CODE	WELL NUMBERS (appendix 13)							
	4	6	20	22	24	28		
A								

EXPLANATION

WELL TYPE	MAJOR DATA SOURCE ¹			
	IGS	ISBH	USGS	PRIV- VATE LAB
Municipal	◆	◇	◇	◇
Public supply	■	□	■	□
Industrial or commercial	▲	△	▲	△
Irrigation	●	○	●	○
Domestic	●	○	●	○
Observation and test	▼	▽	▼	▽

¹IGS, Indiana Geological Survey; ISBH, Indiana State Board of Health; USGS, U.S. Geological Survey

■ UNCONSOLIDATED
■ BEDROCK

AQUIFER TYPE

Figure 55. Locations of ground-water chemistry sites for bedrock and unconsolidated deposits of the Maumee River Basin

To graphically represent variation in ground-water chemistry, box plots (appendix 15) are prepared for selected ground-water constituents. Box plots are useful for depicting descriptive statistics, showing the general variability in constituent concentrations occurring in an aquifer system, and making general chemical comparisons among aquifer systems.

Symmetry of a box plot across the median line (appendix 15) can provide insights into the degree of skewness of chemical concentrations or parameter values in a data set. A box plot that is almost symmetrical about the median line may indicate that the data originate from a nearly symmetrical distribution. In contrast, marked asymmetry across the median line may indicate a skewed distribution of the data.

The areal distribution of selected chemical constituents is mapped according to bedrock or unconsolidated aquifer system (figures 56 to 65). Several sampling and geologic factors complicate the development of chemical concentration maps for the Maumee River basin. The sampling sites are not evenly distributed in the basin, but are clustered around towns and developed areas (figure 55). Data points are generally scarce in areas where surface-water sources are used for water-supply. Furthermore, lateral and vertical variations in geology can also influence the chemistry of subsurface water. Therefore, the maps presented in the following discussion only represent approximate concentration ranges.

No ground-water quality data are available from any bedrock units north of the Allen/DeKalb County line. Therefore, the chemical concentration maps for the bedrock aquifer systems are not extended north of the Allen/DeKalb County line.

Where applicable, ground-water quality is assessed in the context of National Primary and Secondary Drinking-Water Standards (see sidebar titled **National Drinking-water Standards**). The secondary standard referred to in this report is the secondary maximum contaminant level (SMCL). The SMCLs are recommended, non-enforceable standards established to protect aesthetic properties such as taste, odor, or color of drinking water. Some chemical constituents (including fluoride and nitrate) are also considered in terms of the *maximum contaminant level* (MCL). The MCL is the concentration at which a constituent may represent a threat to human health. Maximum *contaminant* levels are legally-enforceable primary drinking-water standards that should not be exceeded in treated drinking-water distributed for public supply.

General water-quality criteria for irrigation and livestock and standards for public supply are given in appendix 9.

Because of data constraints, ground-water quality can only be described for selected aquifer systems as defined in the **Aquifer Systems** section of this chapter. Aquifer systems analyzed include the unconsolidated Kendallville, Hessen Cassel, New Haven, and Teays Valley and Tributary Aquifer systems, and the Silurian-Devonian bedrock aquifer system. There was only one ground-water sample analyzed from a well completed in Devonian shale; therefore the analysis was not included in the set of bedrock wells. However, the results for that well are presented in appendices 13 and 14. There were no chemical analyses available for the Aboite, Cedar Creek-Eel River, or the Cedarville Aquifer systems.

Trilinear-diagram analyses

Ground-water samples from aquifer systems in the Maumee River basin are classified using the trilinear plotting strategy described in the sidebar titled **Chemical classification of ground water using trilinear diagrams**. Trilinear diagrams developed with the available ground-water chemistry data are presented in appendix 16. Only 112 of the 132 ground-water samples available for this report are used in the trilinear plotting of the data. Not all of the samples could be used because some were not analyzed for concentrations of one or more major ions (appendix 13).

Trilinear analysis indicates that most of the available ground-water samples are chemically dominated by alkali-earth metals (calcium and magnesium), bicarbonate, and sulfate. Sodium concentrations do not exceed 50 percent of the sum of major cations in any sample, but variations in sodium levels are observed among samples. Chloride concentrations account for less than 10 percent of the sum of major anions in most samples.

Trilinear analysis suggests that the ground-waters from the Kendallville Aquifer system and the Teays Valley and Tributary Aquifer system belong to distinct hydrochemical *facies* (appendix 16). Most samples from the Kendallville Aquifer system are chemically dominated by calcium and bicarbonate. Sulfate comprises less than 10 percent of the sum of major anions in about two-thirds of all ground-water samples from the Kendallville Aquifer system, and only one sample

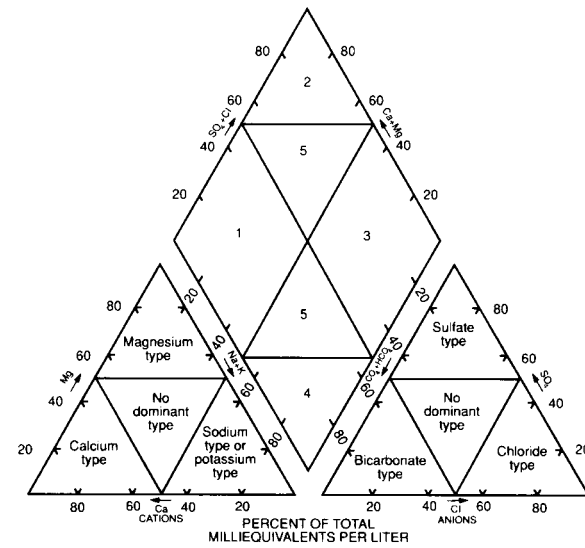
Chemical classification of ground waters using trilinear diagrams

Trilinear plotting systems have been used in the study of water chemistry and quality since as early as 1913 (Hem, 1985). The type of trilinear diagram used in this report, independently developed by Hill (1940) and Piper (1944), has been used extensively to delineate variability and trends in water-quality. The technique of trilinear analysis has contributed extensively to the understanding of ground-water flow, and geochemistry (Dalton and Upchurch, 1978). On conventional trilinear diagrams sample values for three cations (calcium, magnesium and the alkali metals- sodium and potassium) and three anions (bicarbonate, chloride and sulfate) are plotted relative to each other. Because these ions are generally the most common constituents in unpolluted ground waters, the chemical character of most natural waters can be closely approximated by the relative concentration of these ions (Hem, 1985; Walton, 1970).

Before values can be plotted on the trilinear diagram the concentrations of the six ions of interest are converted into milliequivalents per liter (meq/L), a unit of concentration equal to the concentration in milligrams per liter divided by the equivalent weight (atomic weight divided by valence). Each cation value is then plotted, as a percentage of the total concentration (meq/L) of all cations under consideration, in the lower left triangle of the diagram. Likewise, individual anion values are plotted, as percentages of the total concentration of all anions under consideration, in the lower right triangle. Sample values are then projected into the central diamond-shaped field. Fundamental interpretations of the chemical nature of a water sample are based on the location of the sample ion values within the central field.

Distinct zones within aquifers having defined water chemistry properties are referred to as hydrochemical facies (Freeze and Cherry, 1979). Determining the nature and distribution of hydrochemical facies can provide insights into how ground-water quality changes within and between aquifers. Trilinear diagrams can be used to delineate hydrochemical facies, because they graphically demonstrate relationships between the most important dissolved constituents in a set of ground-water samples.

One simple system for describing hydrochemical facies with trilinear diagrams is based on the concept of "dominant" cations and anions. The dominant cation of a water sample is the positively charged ion whose concentration exceeds 50 percent of the summed concentrations of major cations in solution. Likewise, the concentration of the dominant anion exceeds 50 percent of the total anion concentration in the water sample. If no single cation or anion in a water sample meets this criterion, the water has no dominant ion in solution. In most natural waters, the dominant cation is calcium, magnesium or alkali metals (sodium and potassium), and the dominant anion is chloride, bicarbonate or sulfate (see figure above). Distinct hydrochemical facies are defined by specific combinations of dominant cations and anions that plot in certain areas of the central, diamond-shaped part of the trilinear diagram. Four basic hydrochemical facies are defined with



these criteria:

1. Combined concentrations of calcium and/or magnesium, and bicarbonate and/or carbonate exceed 50 percent of the total dissolved constituent load in meq/L. Such waters are generally considered hard and are often found in limestone aquifers or unconsolidated deposits containing abundant carbonate minerals.
2. Combined concentrations of sulfate and/or chloride, and magnesium and/or calcium exceed 50 percent of total meq/L. Waters that have dissolved gypsum ($\text{CaSO}_4 \cdot 2(\text{H}_2\text{O})$) may be classified into this hydrochemical facies.
3. Combined concentrations of alkali metals, sulfate and chloride are greater than 50 percent of the total meq/L. Very concentrated waters of this hydrochemical facies may be considered brackish or (in extreme cases) saline.
4. Combined sodium, potassium and bicarbonate concentrations exceed 50 percent of the total meq/L. These waters generally have low hardness in proportion to their dissolved solids concentration (Walton, 1970).

Additional information on trilinear diagrams and a more detailed discussion of the geochemical classification of ground waters is presented in Freeze and Cherry (1979) and Fetter (1988).

contains sulfate as the dominant anion. In contrast, all available ground-water samples from the Teays Valley and Tributary Aquifer system can be characterized as calcium, magnesium and sulfate dominated.

Ground-water samples from the Silurian and Devonian bedrock aquifer appear to originate from two distinct hydrochemical facies. More than 80 per-

cent of all ground-water samples from the Silurian and Devonian bedrock aquifer system are chemically dominated by calcium, magnesium and sulfate (Ca-Mg-SO_4) ions. Whereas, the remaining bedrock well samples, less than 20 percent of the total, are characterized as calcium-magnesium-bicarbonate (Ca-Mg-HCO_3) waters (appendix 16). The bicarbonate domi-

NATIONAL DRINKING-WATER STANDARDS

National Drinking Water Regulations and Health Advisories (U. S. Environmental Protection Agency, 1993) list concentration limits of specified inorganic and organic chemicals in order to control amounts of contaminants in drinking water. Primary regulations list maximum contaminant levels (MCLs) for inorganic constituents considered toxic to humans above certain concentrations. These standards are health-related and legally enforceable. Secondary maximum contaminant

levels (SMCLs) cover constituents that may adversely affect the aesthetic quality of drinking water. The SMCLs are intended to be guidelines rather than enforceable standards. Although these regulations apply only to drinking water at the tap for public supply, they may be used to assess water quality for privately-owned wells. The table below lists selected inorganic constituents of drinking water covered by the regulations, the significance of each constituent, and their respective MCL or SMCL. Fluoride and nitrate are the only constituents listed which are covered by the primary regulations.

Constituent	Secondary Maximum Contaminant Level (SMCL) (ppm)	Maximum Contaminant Level (MCL) (ppm)	Remarks
Total Dissolved (TDS)	500	*	Levels above SMCL can give water a disagreeable taste. Levels above 1000 Solids mg/L may cause corrosion of well screens, pumps, and casings.
Iron	0.3	*	More than 0.3 ppm can cause staining of clothes and plumbing fixtures, encrustation of well screens, and plugging of pipes. Excessive quantities can stimulate growth of iron bacteria.
Manganese	0.05	*	Amounts greater than 0.05 ppm can stain laundry and plumbing fixtures, and may form a dark brown or black precipitate that can clog filters.
Chloride	250	*	Large amounts in conjunction with high sodium concentrations can impart a salty taste to water. Amounts above 1000 ppm may be physiologically unsafe. High concentrations also increase the corrosiveness of water.
Fluoride	2.0	4.0	Concentration of approximately 1.0 ppm help prevent tooth decay. Amounts above recommended limits increase the severity and occurrence of mottling (discoloration of the teeth). Amounts above 4 ppm can cause adverse skeletal effects (bone sclerosis).
Nitrate**	*	10	Concentrations above 20 ppm impart a bitter taste to drinking water. Concentrations greater than 10 ppm may have a toxic effect (methemoglobinemia) on young infants.
Sulfate	250	*	Large amounts of sulfate in combination with other ions (especially sodium and magnesium) can impart odors and a bitter taste to water. Amounts above 600 ppm can have a laxative effect. Sulfate in combination with calcium in water forms hard scale in steam boilers.
Sodium	NL	NL	Sodium salts may cause foaming in steam boilers. High concentrations may render water unfit for irrigation. High levels of sodium in water have been associated with cardiovascular problems. A sodium level of less than 20 ppm has been recommended for high risk groups (people who have high blood pressure, people genetically predisposed to high blood pressure, and pregnant women).
Calcium	NL	NL	Calcium and magnesium combine with bicarbonate, carbonate, sulfate and silica to form heat-retarding, pipe-clogging scales in steam boilers. For further information on calcium and magnesium, see hardness.
Magnesium	NL	NL	
Hardness	NL	NL	Principally caused by concentration of calcium and magnesium. Hard water consumes excessive amounts of soap and detergents and forms an insoluble scum or scale.
pH	-	-	USEPA recommends pH range between 6.5 and 8.5 for drinking water.

NL No Limit Recommended.

* No MCL or SMCL established by USEPA.

** Nitrate concentrations expressed as equivalent amounts of elemental nitrogen (N). (Adapted from U.S. Environmental Protection Agency, 1993)

Note: 1 part per million (ppm) = 1 mg/L.

nated ground-water samples from the Silurian and Devonian bedrock aquifer system generally originate from wells in northern Allen County. No samples that can be classified as bicarbonate-dominated were recovered from bedrock wells in Adams County or southeastern Allen County.

Both calcium-magnesium-bicarbonate dominated and calcium-magnesium-sulfate dominated ground-water samples are identified in the Hessen Cassel Aquifer system (appendix 16). The distribution of these hydrochemical facies in the Hessen Cassel Aquifer system is also similar to the bedrock aquifer system. Sulfate dominated ground-water samples from the Hessen Cassel Aquifer system were retrieved from wells in Adams County and eastern Allen County. Carbonate dominated ground-water samples from the Hessen Cassel Aquifer system originated from wells in central Allen County.

Differences in hydrochemical facies within and between aquifer systems may indicate differences in the processes influencing ground-water quality. Variations in the mineral content of aquifer systems is probably a significant control on the geochemistry of ground water. For example, the calcium-magnesium-bicarbonate waters in some wells probably result from the dissolution of carbonate minerals. Calcium-magnesium-sulfate dominated ground waters in the Maumee River basin probably result from the dissolution of gypsum, pyrite, or other sulfur-containing minerals. Ground-water flow from areas of recharge to areas of discharge and the subsequent mixing of chemically-distinct ground waters may also influence the geochemical classification of ground waters in the Maumee River basin.

Assessment of ground-water quality

Alkalinity and pH

The alkalinity of a solution may be defined as the capacity of its solutes to react with and neutralize acid. The alkalinity in most natural waters is primarily due to the presence of dissolved carbon species, particularly bicarbonate and carbonate. Other constituents that may contribute minor amounts of alkalinity to water include silicate, hydroxide, borates and certain organic compounds (Hem, 1985). In this report, alkalinity is expressed as an equivalent concentration of dissolved calcite (CaCO_3). At present, no

suggested limits have been established for alkalinity levels in drinking water. However, some alkalinity may be desirable in ground water because the carbonate ions moderate or prevent changes in pH.

Median alkalinity levels vary among samples from different aquifer systems in the Maumee River basin (figure 56). In general, higher alkalinity levels are observed in the unconsolidated aquifer systems in the northern portion of the basin (Kendallville Aquifer system and New Haven Aquifer system) relative to the other aquifer systems (figure 56 and appendix 15).

The pH, or hydrogen ion activity, is expressed on a logarithmic scale and represents the negative base-10 log of the hydrogen ion concentration. Waters are considered acidic when the pH is less than 7.0 and basic when the pH exceeds 7.0. Water with a pH value equal to 7.0 is termed neutral and is not considered either acidic or basic. The pH of most ground waters generally ranges between 5.0 and 8.0 (Davis and DeWiest, 1970).

The USEPA recommends a pH range between 6.5 and 8.5 in waters used for public supply. Over 95 percent of the ground-water samples used for this study are within this range. However, four Adams County water samples taken from three bedrock wells and one well in the Teays Valley and Tributary Aquifer system have reported pH levels below 6.5. However, a pH meter calibration error is suspected because the four samples were taken in sequence on the same day, and other chemical parameters reported for the wells appear to be normal. A sample taken from a Devonian bedrock well in Allen County has an abnormally high reported pH value, but also has numerous other chemical constituents that have suspect values reported. The source of the probable error in the Allen County analyses is not known.

The types of dissolved constituents in ground water can influence pH levels. Dissolved carbon dioxide (CO_2), which forms carbonic acid in water, is an important control on the pH of natural waters (Hem, 1985). The pH of ground water can also be lowered by organic acids from decaying vegetation, or the dissolution of sulfide minerals (Davis and DeWiest, 1970).

Hardness, calcium and magnesium

“Hardness” is a term relating to the concentrations of certain metallic ions in water, particularly magnesium and calcium, and is usually expressed as an

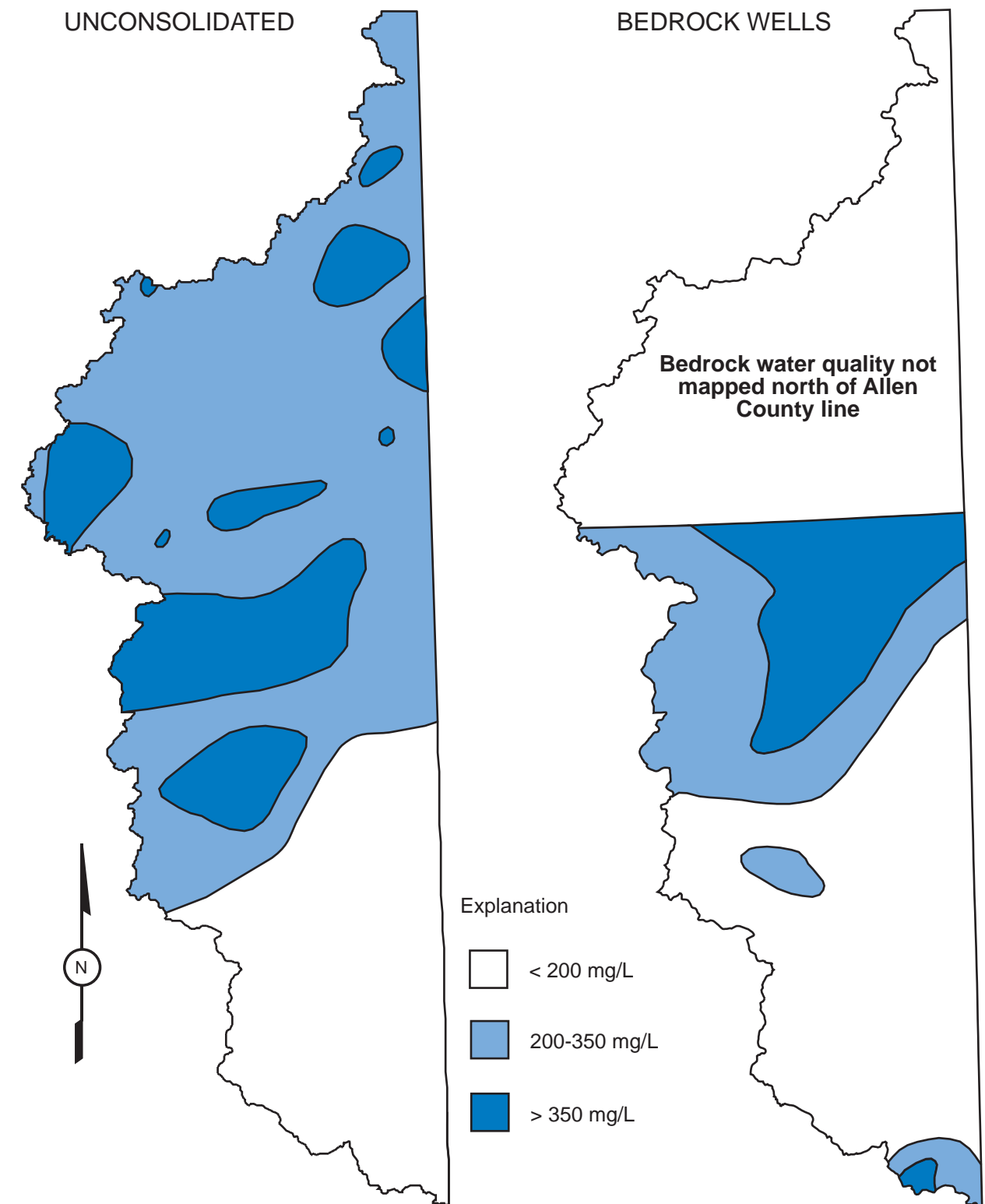


Figure 56. Generalized areal distribution for **Alkalinity** as CaCO_3

equivalent concentration of dissolved calcite (CaCO_3). In hard water, the metallic ions of concern may react with soap to produce an insoluble residue. These metallic ions may also react with negatively-charged ions to produce a solid precipitate when hard water is heated (Freeze and Cherry, 1979). Hard waters can thus consume excessive quantities of soap, and cause damaging scale in water heaters, boilers, pipes and turbines. Many of the problems associated with hard water, however, can be mitigated by using water-softening equipment.

Durfor and Becker (1964) developed the following classification for water hardness that is useful for discussion purposes: soft water, 0 to 60 mg/L (as CaCO_3); moderately hard water, 61 to 120 mg/L; hard water, 121 to 180 mg/L; and very hard water, over 180 mg/L. A hardness level of about 100 mg/L or less is generally not a problem in waters used for ordinary domestic purposes (Hem, 1985). Lower hardness levels, however, may be required for waters used for other purposes. For example, Freeze and Cherry (1979) suggest that waters with hardness levels above 60-80 mg/L may cause excessive scale formation in boilers.

Ground waters in the Maumee River basin can be generally characterized as very hard in the Durfor and Becker hardness classification system. The measured hardness level is below 180 mg/L (as CaCO_3) in only one ground-water sample. The lowest median hardness value is observed in samples from the Kendallville Aquifer system. Median hardness levels exceed 500 mg/L in samples from all other aquifer systems under consideration (appendix 15).

Figure 57 displays the spatial distribution of ground-water hardness levels in the Maumee River basin. In general, ground-water hardness levels are higher in the southern portion of the Maumee River basin relative to the northern portion of the basin. Because similar spatial trends are observed in sulfate concentrations (figure 59), it is likely that gypsum ($\text{CaSO}_4 \cdot 2\{\text{H}_2\text{O}\}$) dissolution may influence ground-water hardness in some areas of the basin.

Box plots of calcium and magnesium concentrations in ground water are presented in appendix 15. Because calcium and magnesium are the major constituents responsible for hardness in water, the highest levels of these ions generally occur in ground waters with high hardness levels. At the time of this publication, no enforceable or suggested standards have been established for calcium or magnesium.

Chloride, sodium and potassium

Chloride in ground water may originate from various sources, including the dissolution of halite and related minerals, marine water entrapped in sediments, and anthropogenic sources. Although chloride is often an important dissolved constituent in ground water, none of the samples from the aquifer systems in the Maumee River basin are classified as chloride dominated (appendix 15). Median chloride levels are less than 10 mg/L in samples from all of the aquifer systems under consideration. No chloride concentrations above 250 mg/L, the SMCL for this ion, are detected in any of the samples.

Some of the highest chloride concentrations in basin ground waters are observed in wells sampled from bedrock wells in or near urban areas. This may indicate that anthropogenic processes locally affect chloride concentrations in ground water. Some anthropogenic factors commonly cited as influences on chloride levels in water include road salting during the winter (Hem, 1985; 1993), improper disposal of oil-field brines, contamination from sewage, and contamination from various types of industrial wastes (Hem, 1993).

The dissolution of table salt or halite (NaCl) is sometimes cited as a source of both sodium and chloride in ground waters. A qualitative technique to determine if halite dissolution is an influence on ground-water chemistry is to plot sodium concentrations relative to chloride concentrations. Because sodium and chloride ions enter solution in equal quantity during the dissolution of halite, an approximately linear relationship may be observed between these ions (Hem, 1985). If the concentrations are plotted in milliequivalents per liter, this linear relationship should be described by a line with a slope equal to one.

No clearly-defined linear relationship between concentrations of chloride and sodium is apparent in the ground-water samples under consideration (figure 58). This suggests that the concentrations of sodium and chloride in ground waters of the Maumee River basin are influenced by other factors in addition to the dissolution of halite. Figure 58 and the box plots in appendix 15 indicate that sodium concentrations exceed chloride concentrations in many of the samples under consideration, suggesting that additional sources of sodium may be present. For example, calcium and magnesium in solution can be replaced by sodium on the surface of certain clays by *ion*

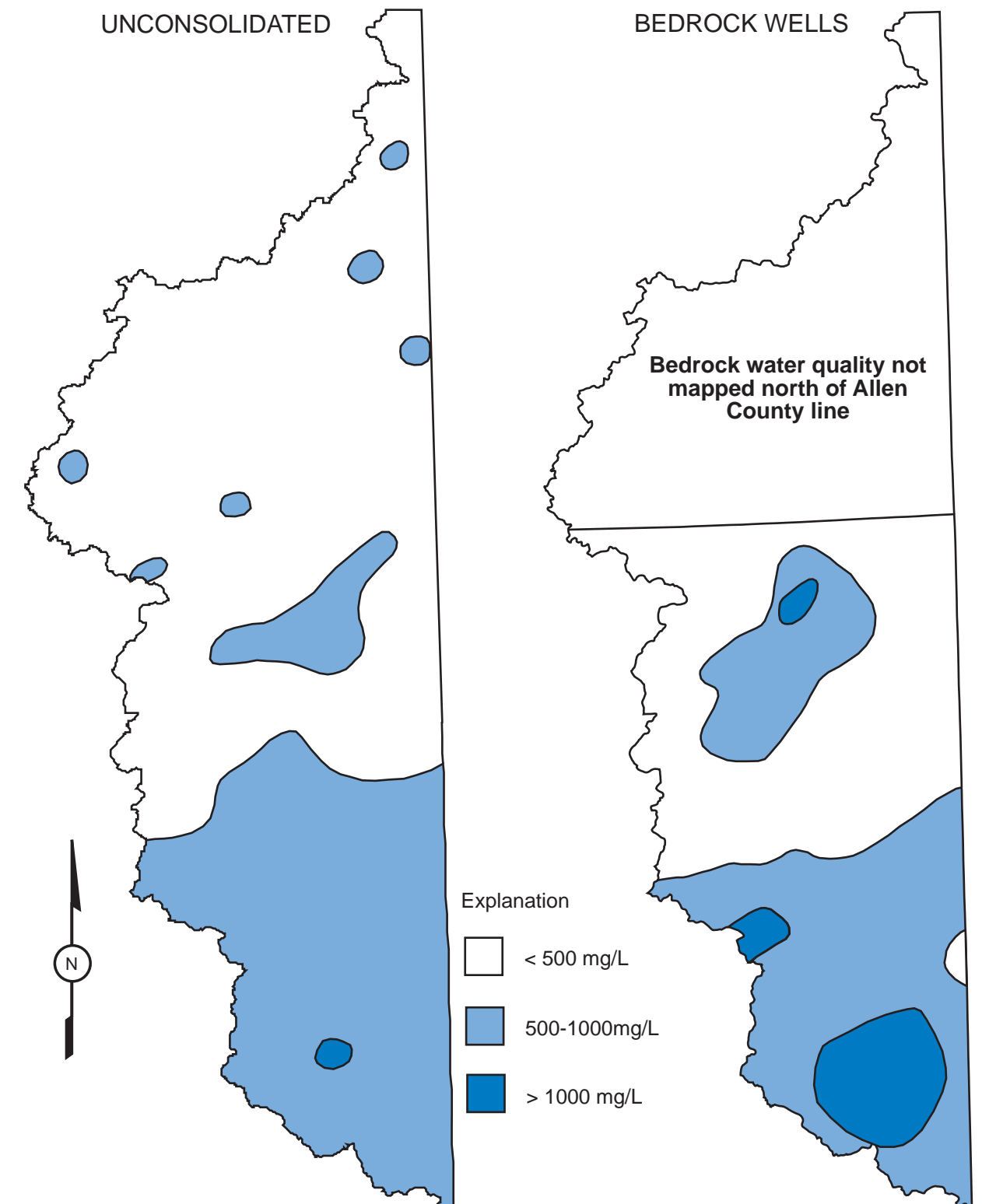


Figure 57. Generalized areal distribution for **Hardness** as CaCO_3

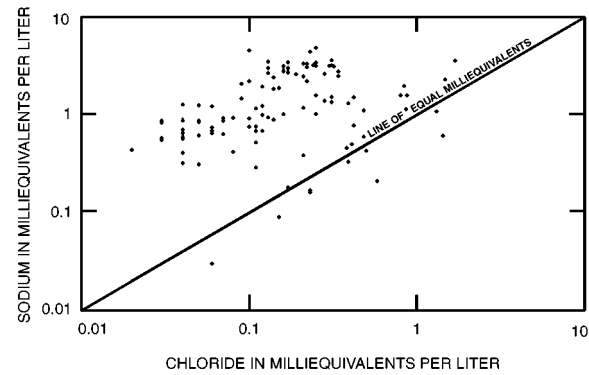


Figure 58. Sodium vs chloride in ground-water samples from the Maumee River basin

exchange. Another possible source of sodium in ground water is the dissolution of silicate minerals in glacial deposits.

Box plots of potassium concentrations in ground-water samples from the aquifer systems under consideration are displayed in appendix 15. In many natural waters, the concentration of potassium is commonly less than one-tenth the concentration of sodium (Davis and DeWiest, 1970). Almost 90 percent of the samples used for this report have potassium concentrations that are less than one-tenth the concentration of sodium.

Sulfate and sulfide

Sulfate (SO_4), an anion formed by oxidation of the element sulfur, is commonly observed in ground waters. The established secondary maximum contaminant levels for sulfate is 250 mg/L. Ground-water samples with sulfate concentrations above this level were collected from each of the aquifer systems under consideration. However, the relative proportion of samples with a sulfate concentration that exceeds the SMCL varies considerably among the aquifer systems. Sulfate concentrations above the SMCL are observed in approximately 6.5 percent of all ground-water samples from the Kendallville Aquifer system. In contrast, sulfate concentrations above the SMCL are measured in every sample from the Teays Valley and Tributary Aquifer system. Sulfate concentrations above the SMCL occur in more than 50 percent of ground-water samples from all other aquifer systems analyzed in this report (appendix 15).

Concentration ranges of sulfate in ground water are mapped in figure 59. Ground-water sulfate levels above the SMCL are generally observed in the southern portion of the Maumee River basin, particularly in Adams County and areas of Allen County. Lower sulfate levels, however, are generally observed in ground waters north of the Allen/DeKalb County line. Over 90 percent of the ground-water samples from the Kendallville Aquifer system in DeKalb, Noble and Steuben Counties contain sulfate levels less than 100 mg/L; and no samples contain sulfate levels above the SMCL of 250 mg/L.

The concentration of sulfate in ground waters may be influenced by various geochemical processes, sources, and time. One important source is the dissolution or weathering of sulfur-containing minerals. Two possible mineral sources of sulfate have been identified in the aquifers of the Maumee River basin. The first includes evaporite minerals, such as gypsum and anhydrite (CaSO_4). Evaporite minerals are known to occur in both Devonian and, to a lesser extent, Silurian bedrock. Fragments of evaporite-bearing rocks may also have been incorporated into some unconsolidated units during glacial advances. The second possible mineral source of sulfate is pyrite (FeS_2), a mineral present in the Antrim Shale and also in Silurian dolomite as highly localized nodules. The oxidation of pyrite can release iron and sulfate into solution. Pyrite oxidation may be a source of sulfur in shallow, unconsolidated aquifers containing fragments of the Antrim Shale (Fleming, 1994).

Under *reducing*, low-oxygen conditions, sulfide (S^{2-}) may be the dominant species of sulfur in ground water. One of the most important influences on the levels of sulfide in ground water are the metabolic processes of certain types of anaerobic bacteria. These bacteria use sulfate reduction in their metabolism of organic matter, which produces sulfide ions as a by-product (Freeze and Cherry, 1979; Hem, 1985).

A sulfide compound that is commonly considered undesirable in ground water is hydrogen sulfide (H_2S) gas. In sufficient quantities, hydrogen sulfide gas can give water an unpleasant odor, similar to that of rotten eggs. At present, there is no established SMCL for hydrogen sulfide in drinking water. Hem (1985) notes that most people can detect a few tenths of a milligram per liter of hydrogen sulfide in solution, and Freeze and Cherry (1979) state that concentrations greater than about 1 mg/L may render water unfit for drinking. Hydrogen sulfide is also corrosive to metals and,

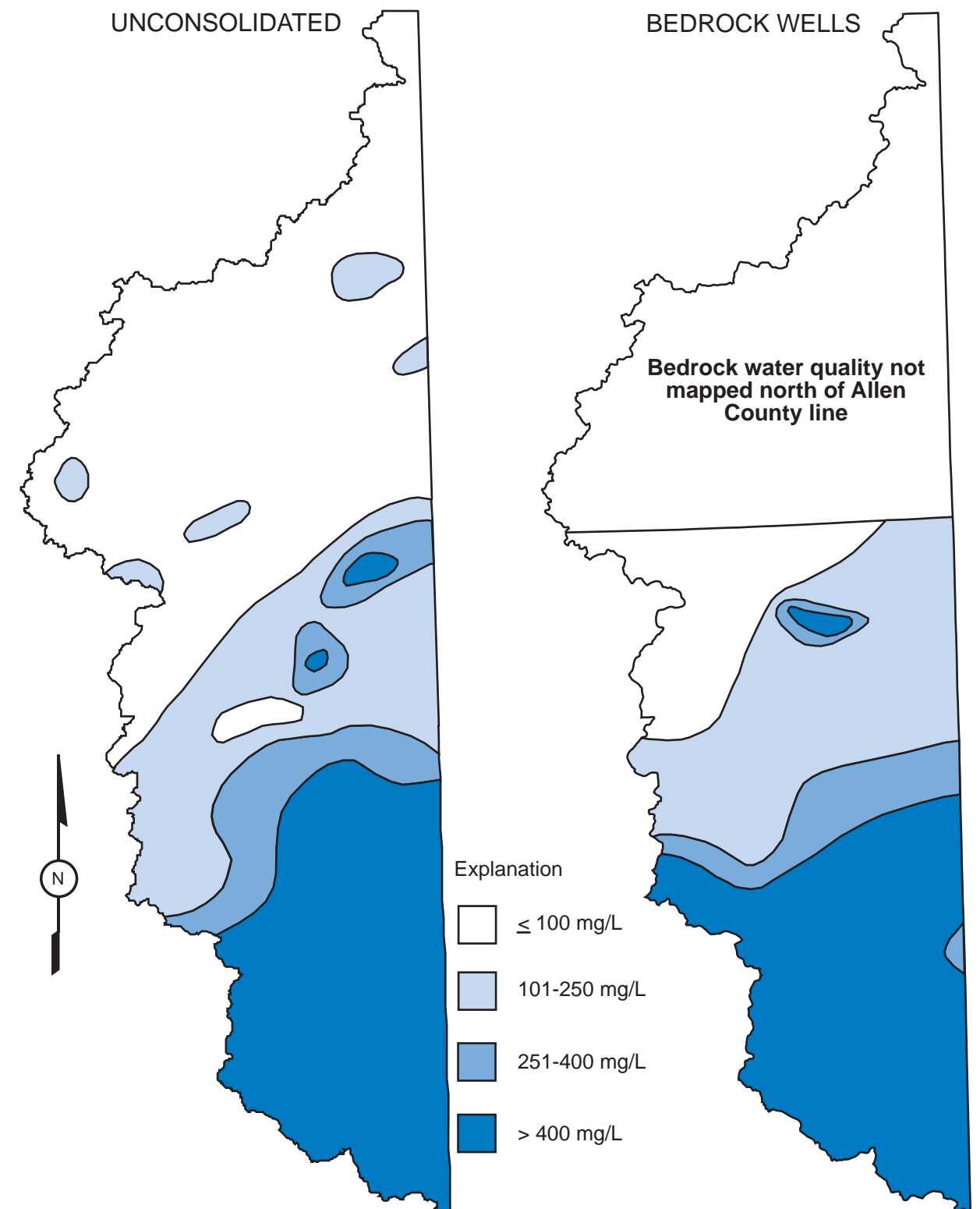


Figure 59. Generalized areal distribution for Sulfate

if oxidation to sulfuric acid occurs, concrete pipes. Possible results of hydrogen sulfide-induced corrosion include damage to plumbing, and the introduction of metals into water supplies (GeoTrans Inc., 1983).

Available data on the occurrence of hydrogen sulfide in the ground waters of the Maumee River basin are qualitative. Well drillers may note the occurrence of “sulfur water” or “sulfur odor” on well records. This observation usually indicates the presence of noticeable levels of hydrogen sulfide gas in the well water. The occurrence of hydrogen sulfide is recorded on a few well records from Adams, Allen and Wells Counties. Scattered incidences of hydrogen sulfide in wells are also noted in Adams County by Watkins and Ward (1962) and in central Allen County by Bleuer and Moore (1978). Most of the recorded instances of detectable hydrogen sulfide levels examined for this report occurred in wells completed in the Silurian and Devonian bedrock aquifer system.

Iron and Manganese

Iron concentrations commonly exceed the SMCL of 0.3 mg/L in water samples from the unconsolidated and the bedrock aquifer systems (figure 60). Calculated median iron concentrations range between approximately 1.6 mg/L and 2.0 mg/L in samples from the aquifer systems. Iron levels equal to or below the SMCL are observed in less than 6 percent of all samples analyzed for this constituent.

Water samples with iron levels below the SMCL are observed in samples from 7 wells completed in the Silurian and Devonian bedrock aquifer system and 2 wells completed in the Kendallville Aquifer system. All of the bedrock ground-water samples with iron levels below the SMCL originate from wells completed in Devonian carbonates in central Allen County. The low iron concentrations in these samples may reflect the precipitation of iron minerals by iron-reducing bacteria (Hem, 1985).

Because iron is the second most abundant metallic element in the Earth’s outer crust (Hem, 1985), iron in ground water may originate from a variety of mineral sources. In the Maumee River basin, the mineral pyrite (FeS_2) is present in the Antrim Shale. Because Antrim Shale fragments are abundant in many unconsolidated deposits, pyrite oxidation may contribute iron to the unconsolidated aquifer systems. The presence of high iron concentrations in ground waters with

low sulfate levels may reflect siderite (FeCO_3) dissolution or the reduction of sulfate created by pyrite oxidation (Hem, 1985). The concentration of iron in ground water can also be influenced by oxidation-reduction potentials, organic matter content, and the metabolic activity of bacteria.

Although the geochemistry of manganese is similar to that of iron, the manganese concentration in unpoluted waters is typically less than half the iron concentration (Davis and DeWiest, 1970). Manganese has a low SMCL (0.05 mg/L) relative to many other common constituents in ground water because even small quantities of manganese can cause objectionable taste and the deposition of black oxides. Because the detection limit for manganese in the DOW-IGS samples is twice the value of the SMCL, the number of times the SMCL is exceeded in this data set cannot be quantified. However, ground-water samples with manganese concentrations equal to or above the detection limit are observed in all of the aquifer systems excluding the Teays Valley and Tributary Aquifer system (appendix 15).

Manganese in Maumee River basin ground water originates from the weathering of rock fragments in the unconsolidated deposits and oxidation/dissolution of the underlying bedrock. The Antrim Shale probably contains a relatively higher manganese content than the Silurian-Devonian carbonates. However, limestones and dolomites may also be a minor source of manganese, because small amounts of manganese commonly substitute for calcium in the mineral structure of carbonate rocks (Hem, 1985). Oxides of manganese can also accumulate in bog environments or as coatings on stream sediments (Hem, 1985). Therefore, it is possible that high manganese levels may occur in ground waters from wetland environments or buried stream channels.

Fluoride

Many compounds of fluoride can be characterized as only slightly soluble in water. Concentrations of fluoride in most natural waters generally range between 0.1 mg/L and 10 mg/L (Davis and DeWiest, 1970). Hem (1985) noted that fluoride levels generally do not exceed 1 mg/L in most natural waters with TDS levels below 1000 mg/L. The beneficial and potentially detrimental health effects of fluoride in drinking water are outlined in the sidebar titled

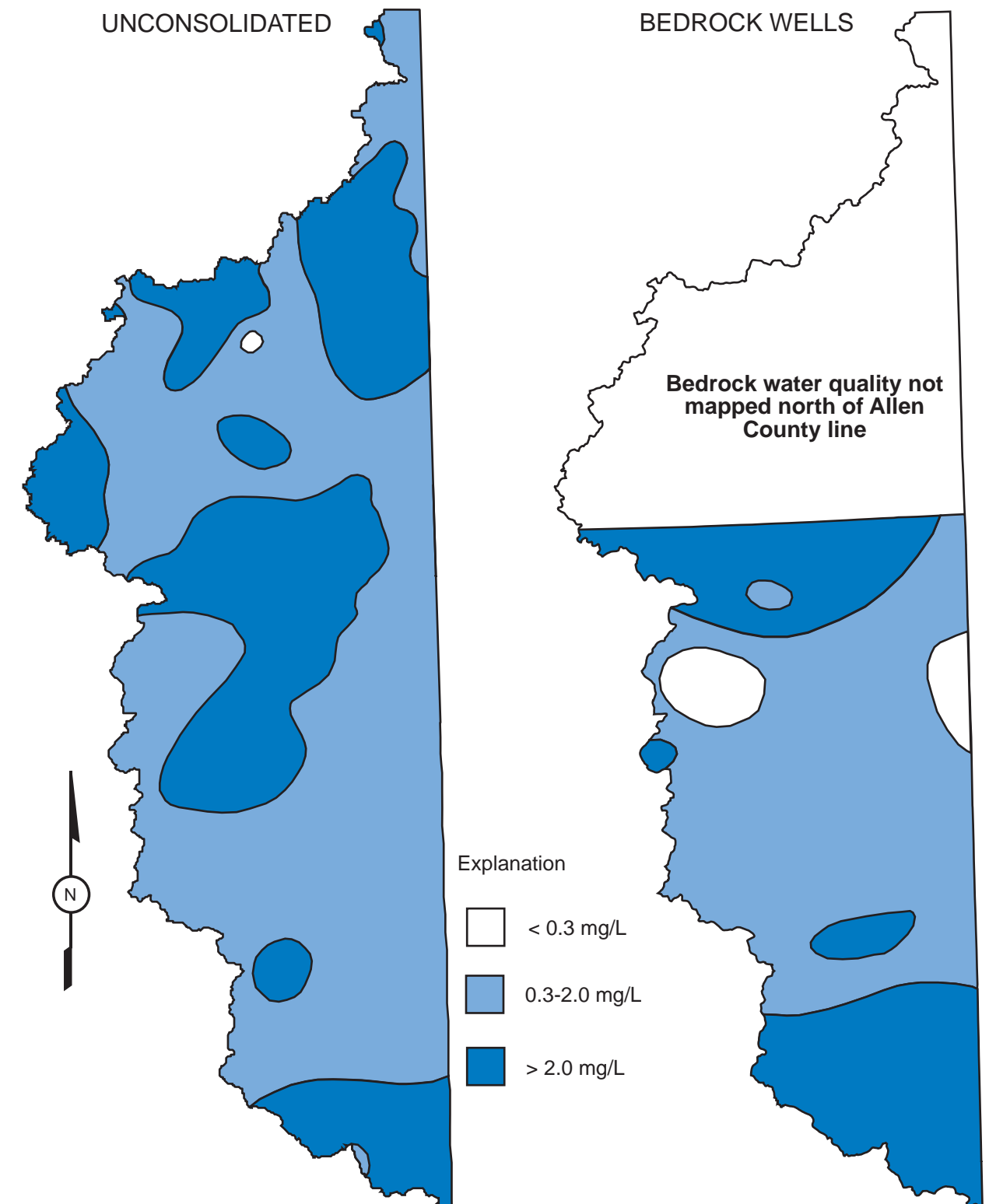


Figure 60. Generalized areal distribution for Iron

National Drinking-Water Standards.

Box plots of fluoride concentrations in ground water samples from the aquifer systems under consideration are displayed in appendix 15. None of the well samples analyzed for fluoride contained levels above the 4.0 mg/L MCL. Concentrations equal to or above the SMCL for fluoride (2.0 mg/L) are detected in 4 samples from the bedrock aquifer system, and 1 sample from the Hessen Cassel Aquifer system. All 5 of these wells are located in southern Adams County near the towns of Decatur and Berne (figure 61).

Fluoride-containing minerals such as fluorite, apatite and fluorapatite commonly occur in clastic sediments (Hem, 1985). The weathering of these minerals may thus contribute fluoride to ground waters in sand and gravel units. The mineral fluorite may also occur in limestones or dolomites. Fluoride may also substitute for hydroxide (OH⁻) in some minerals because the charge and ionic radius of these two ions are similar (Manahan, 1975; Hem, 1985).

Nitrate

Nitrate (NO₃⁻) is the most frequently detected drinking-water contaminant in the State (Indiana Department of Environmental Management, [1990]) as well as the most common form of nitrogen in ground waters (Freeze and Cherry, 1979). Madison and Brunett (1984) developed a concentration criteria to qualitatively determine if nitrate levels (as an equivalent amount of nitrogen) in ground water may be influenced by anthropogenic sources. Using these criteria, nitrate levels of less than 0.2 mg/L are considered to represent natural or background levels. Concentrations ranging from 0.21 to 3.0 mg/L are considered transitional, and may or may not represent human influences. Concentrations between 3.1 and 10 mg/L may represent elevated concentrations due to human activities.

High concentrations of nitrate are undesirable in drinking waters because of possible health effects. In particular, excessive nitrate levels can cause *methemoglobinemia* primarily in infants. The maximum contaminant level, MCL, for nitrate (measured as N) is 10 mg/L.

Ranges of nitrate levels in ground-water samples from the Maumee River basin are plotted in figure 62. Because the detection limit for the DOW-IGS samples is 1.0 mg/L, the occurrence of “background” levels as

defined by Madison and Brunett (1984) cannot be quantified. However, figure 62 indicates that most of the samples contain nitrate concentrations below the level interpreted by Madison and Brunett (1984) to indicate possible human influences.

The only sample with a nitrate level equal to the MCL was recovered from a well in central Allen County (figure 62). Ground-water samples from two nearby wells also contain elevated (above 3.1 mg/L) nitrate levels. In southern Adams County, a nitrate concentration of 6.7 mg/L is observed in one sample obtained from a bedrock well. The nitrate level in a sample from a nearby unconsolidated well, however, is below the 1.0 mg/L detection limit. Overall, the distribution of nitrate concentrations in ground waters of the Maumee River basin appears to indicate that levels generally do not exceed 1.0 mg/L. High concentrations of nitrate, which may suggest human influences, appear to occur in isolated wells or limited areas.

In 1987, the Indiana Farm Bureau, in cooperation with various county and local agencies, began the Indiana Private Well Testing Program. The purpose of this program is to assess ground-water quality in rural areas, and to develop a statewide database containing chemical analysis of well samples. By the end of 1993 samples from over 9000 wells, distributed over 68 counties, had been collected and analyzed as a part of the program (Wallrabenstein and others, 1994). Most of the ground-water samples collected during this study were analyzed for inorganic nitrogen and some specific pesticides. The results of the pesticide sampling are presented in the section entitled **Pesticides in Maumee River basin ground waters.**

The techniques used to analyze the samples collected for the Farm Bureau study actually measured the combined concentrations of nitrate and nitrite (nitrate+nitrite). However, the researchers noted that nitrite concentrations were generally low. Thus the nitrate+nitrite concentrations were approximately equal to the concentrations of nitrate in the sample (Wallrabenstein and others, 1994). The MCL for nitrate+nitrite (as equivalent elemental nitrogen) is 10 mg/L.

Ground-water samples analyzed for nitrate+nitrite were collected for the Farm Bureau study from wells in the following counties which lie partially in the Maumee River basin: Adams (136 samples); Allen (278 samples); Steuben (64 samples) and Wells (42 samples). Some samples from each county under con-

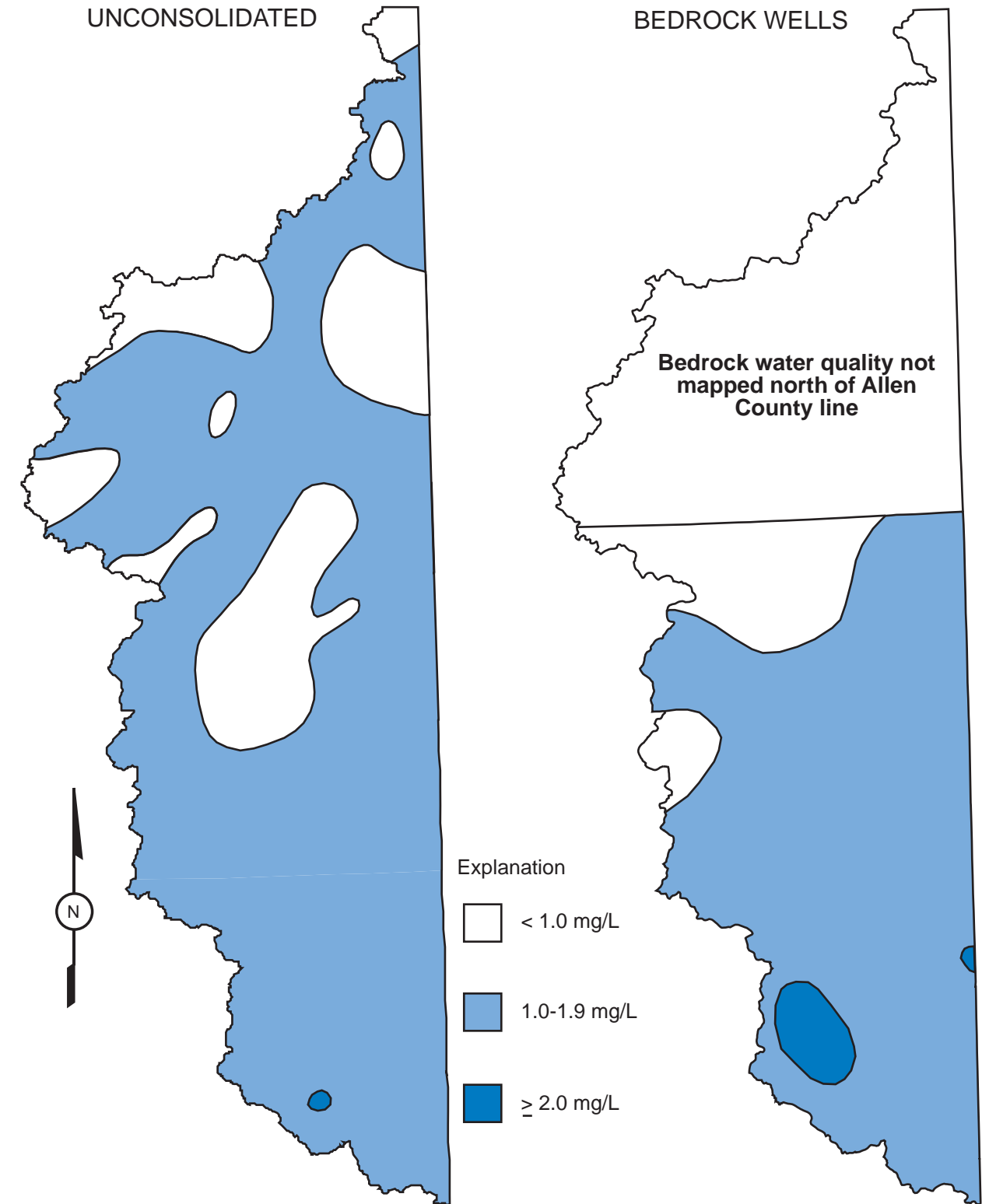


Figure 61. Generalized areal distribution for **Fluoride**

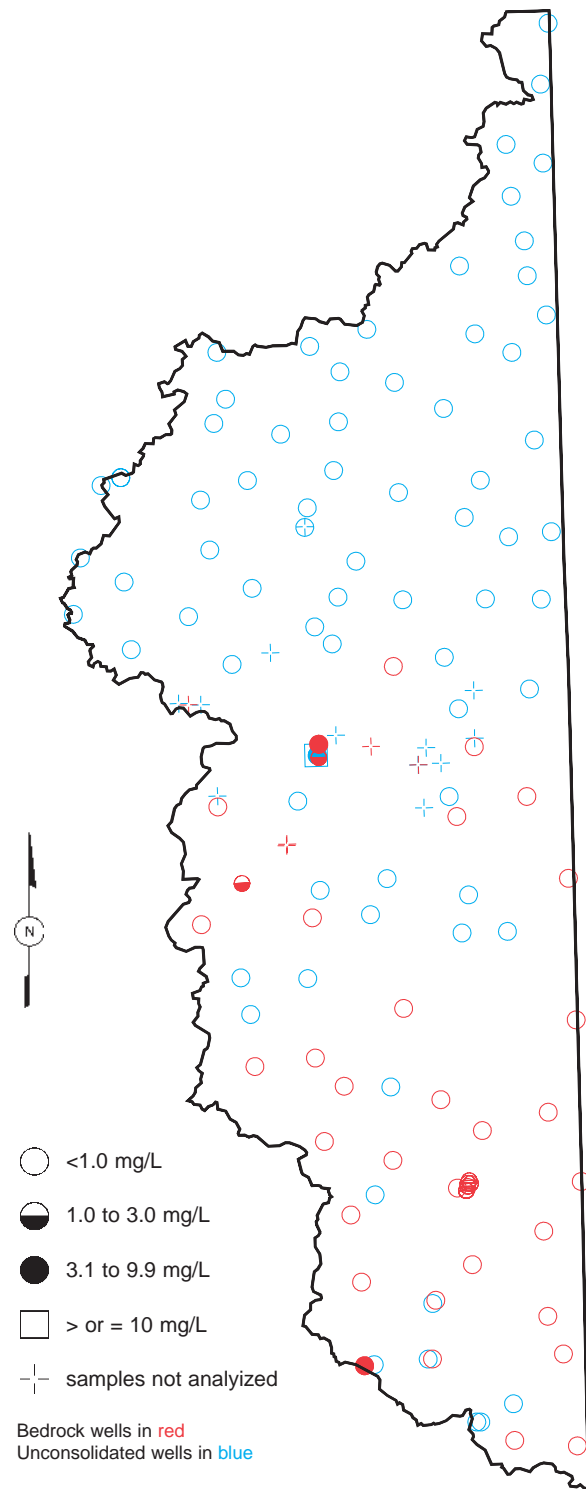


Figure 62. Distribution of Nitrate-nitrogen concentrations for wells sampled in bedrock and unconsolidated deposits

sideration contained nitrate+nitrite levels over the reporting limit (0.3 mg/L). The most detections were observed in Steuben County, where detectable levels of nitrate+nitrite were found in over 26 percent of all samples. Nitrate+nitrite levels above the reporting limit were found in fewer than 10 percent of all samples collected from wells in Adams, Allen, and Wells Counties.

Nitrate+nitrite concentrations above the MCL were observed in samples from 6 wells located in Steuben County. All 6 of these samples were collected from wells in the western half of the county, and do not appear to be located within the Maumee River basin. The exact locations of these wells, however, cannot be determined. Data on the owners and exact locations of the wells sampled for the Farm Bureau study were not provided in the report.

A variety of anthropogenic activities can contribute nitrate to ground waters, and may increase nitrate concentrations above the MCL. Because nitrate is an important plant nutrient, nitrate fertilizers are often added to cultivated soils. Under certain conditions, however, these fertilizers may enter the ground water through normal infiltration or through a poorly-constructed water well. Nitrate is commonly present in domestic wastewater, and high levels of this constituent are often associated with septic systems. Animal manure can also be a source of nitrate in ground-water systems, and high nitrate levels are sometimes detected in ground waters down gradient from barnyards or feedlots. Because many sources of nitrate are associated with agriculture, rural areas may be especially susceptible to nitrate pollution of ground water. To help farmers and other rural-area residents assess and minimize the risk of ground-water contamination by nitrate and other agricultural chemicals, the American Farm Bureau Federation has developed a water quality self-help checklist specifically for agricultural operations (American Farm Bureau Federation, 1987).

Strontium

Ground waters in the Maumee River basin may be characterized as containing high concentrations of strontium relative to ground water in other regions. For example, Skougstad and Horr (1963) analyzed 175 ground-water samples from throughout the United States and noted that 60 percent contained less

than 0.2 mg/L of strontium. Of the 95 ground-water samples analyzed for strontium in this report, however, about 85 percent contained strontium concentrations above 1.0 mg/L. Davis and DeWiest (1970) report that concentrations of strontium in most ground waters generally range between 0.01 and 1.0 mg/L. In contrast, median strontium concentrations in samples from the unconsolidated and bedrock aquifer systems are 4.4 mg/L and 9.7 mg/L, respectively.

The lowest median strontium concentration is observed in the ground-water samples from the Kendallville Aquifer system. Median strontium concentrations in samples from the Hessen Cassel Aquifer system and the New Haven Aquifer system are almost 3 times the median in the Kendallville Aquifer system (appendices 14 and 15). In the unconsolidated aquifer systems, strontium concentrations are generally higher in ground waters south of the Maumee River compared with ground waters north of the river (figure 63). However, elevated concentrations of strontium are apparent in some areas of DeKalb County. Ground waters in the unconsolidated deposits of Adams County may also contain high strontium concentrations. Although only 5 strontium measurements in ground-water samples from wells completed in unconsolidated deposits are available for Adams County, the lowest of these concentrations exceeds 80 percent of all samples from wells in the unconsolidated deposits.

The median strontium concentration in ground waters from the Silurian and Devonian bedrock aquifer system is similar to the median concentrations in samples from the Hessen Cassel Aquifer system and the New Haven Aquifer system (appendix 15). Foley and others (1973) identified high concentrations of strontium in ground water from bedrock aquifers in southern Allen County. Analysis of the available data from the Silurian and Devonian bedrock aquifer system indicates that strontium concentrations are generally higher in bedrock waters from Adams County and southern Allen County than in northern Allen County (figure 63).

At the time of this report, no enforceable drinking-water standards have been established for strontium. However, the non-enforceable lifetime *health advisory* for strontium is set at 17.0 mg/L. Only one sample from a well completed in the Kendallville Aquifer system in Steuben County contained a strontium concentration in excess of the health advisory (see appendix 14).

Sources of strontium in ground waters are generally the trace amounts of strontium present in rocks. The strontium-bearing minerals celestite (SrSO_4) and strontianite (SrCO_3) may be disseminated in limestone and dolomite. In their study of strontium in Allen County ground waters, Foley and others (1973) suggest that Silurian rocks of several different lithologies may be the source of high strontium and sulfate concentrations in southeastern Allen County.

Because strontium and calcium are chemically similar, strontium atoms may also be absorbed on clay particles by ion exchange (Skougstad and Horr, 1963). Ion-exchange processes may, thus reduce strontium concentrations in ground waters found in clay-rich sediments.

Zinc and copper

Generally, significant dissolved quantities of the metal zinc occur only in low pH or high-temperature ground waters (Davis and DeWiest, 1970). Concentrations of zinc in ground-water samples from the Maumee River basin are plotted in figure 64. Of the 110 ground-water samples analyzed for zinc, 75 (approximately 68.2 percent) contain levels below 0.05 mg/L. None of the samples analyzed contain zinc in concentrations above the 5 mg/L SMCL established for this constituent (appendix 14).

Samples collected by the DOW-IGS during the 1988 survey of ground-water quality in the Maumee River basin were analyzed to determine levels of copper in solution. However, none of the samples contain copper levels exceeding the 0.05 mg/L detection limit (appendix 14).

Lead

Naturally-occurring minerals that contain lead are widely dispersed, but have low solubility in most natural ground water. The coprecipitation of lead with manganese oxide and the adsorption of lead on organic and inorganic sediment surfaces help to maintain low lead concentration levels in ground water (Hem, 1992). Much of the lead present in tap water may come from anthropogenic sources, particularly lead solder used in older plumbing systems. Because natural concentrations of lead are normally low and because there are so many uncertainties involved in

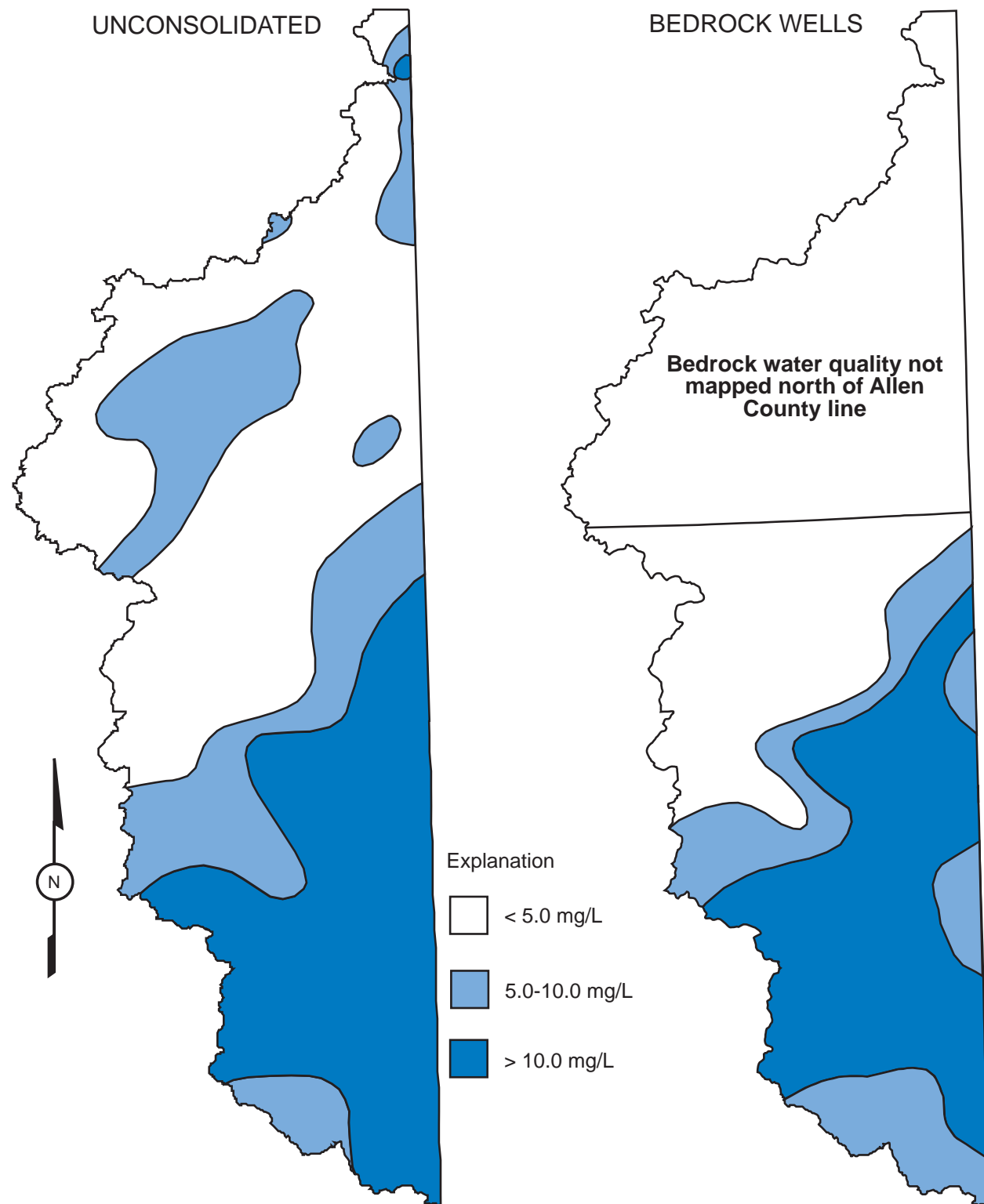


Figure 63. Generalized areal distribution for **Strontium**

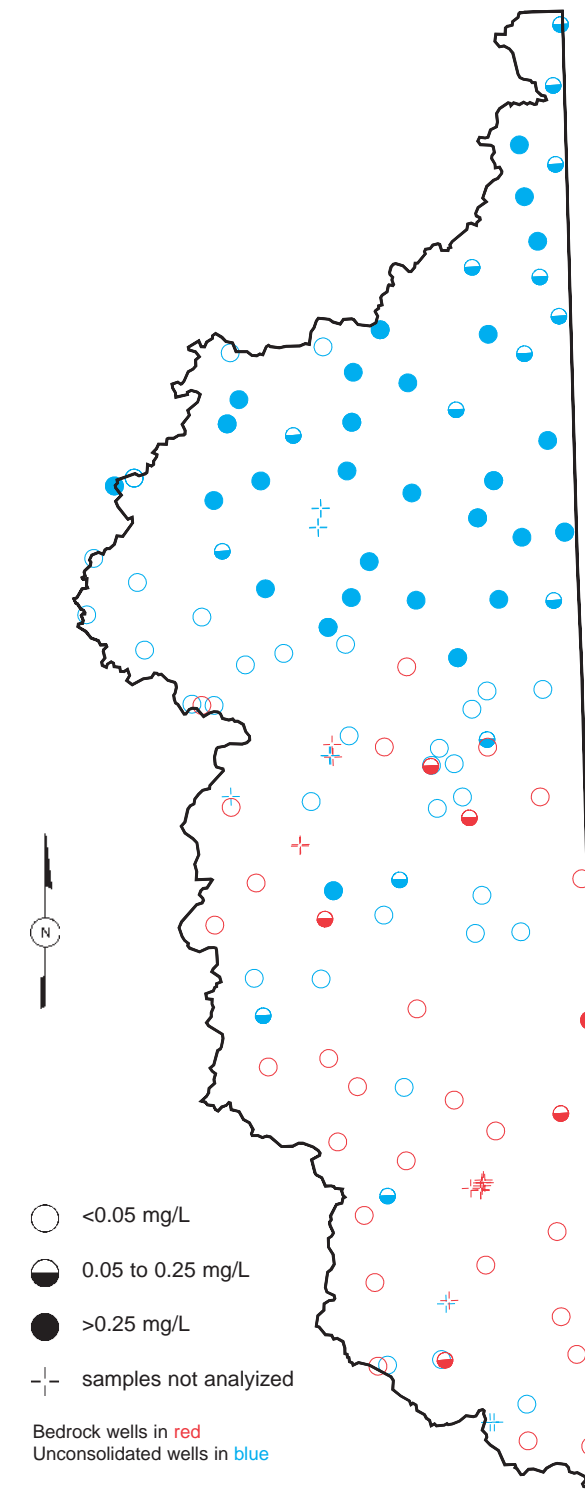


Figure 64. Distribution of **Zinc** concentrations for wells sampled in bedrock and unconsolidated deposits

collecting and analyzing samples, lead was not analyzed in this study.

Total dissolved solids

Total dissolved solids (TDS) are a measure of the total amount of dissolved minerals in water. Essentially, TDS represent the sum of concentrations of all dissolved constituents in a water sample. In general, if a ground-water sample has a high TDS level, high concentrations of major constituents will also be present in that sample. The secondary maximum contaminant level for TDS is established at 500 mg/L. Drever (1988), however, defines fresh water (water sufficiently dilute to be *potable*) as water containing TDS of less than 1000 mg/L.

Many samples collected from wells in the Maumee River basin contain TDS levels that exceed the SMCL. The lowest median TDS level is observed in samples from the Kendallville Aquifer system (figure 65). Nevertheless, TDS levels above the SMCL are observed in approximately 25 percent of all samples from the Kendallville Aquifer system. Of the unconsolidated aquifer systems under consideration, ground-water TDS levels are especially high in the Teays Valley and Tributary Aquifer system. Although only three measurements of ground-water TDS are available from this aquifer system, all three measurements exceed 1000 mg/L.

The median TDS level in ground-water samples from the Silurian and Devonian bedrock aquifer system exceeds the median level in samples from the three largest unconsolidated aquifer systems in the basin (the Kendallville, Hessen Cassel and New Haven Aquifer systems). Herring (1969) also calculated a higher median TDS level in ground waters from bedrock aquifers relative to sand and gravel aquifers in the Maumee River basin. TDS levels in ground water are especially high in the bedrock aquifer systems of Adams County, exceeding 1000 mg/L in most samples. The high TDS levels in the Silurian and Devonian bedrock aquifer system could reflect long residence times in the bedrock system, and/or dissolution of evaporite minerals.

Very high total dissolved solids concentrations are generally observed in deep bedrock formations. In Allen County for example, TDS levels in three brine samples collected from oil wells in the Trenton formation (Ordovician) range from 33,400 to 84,300

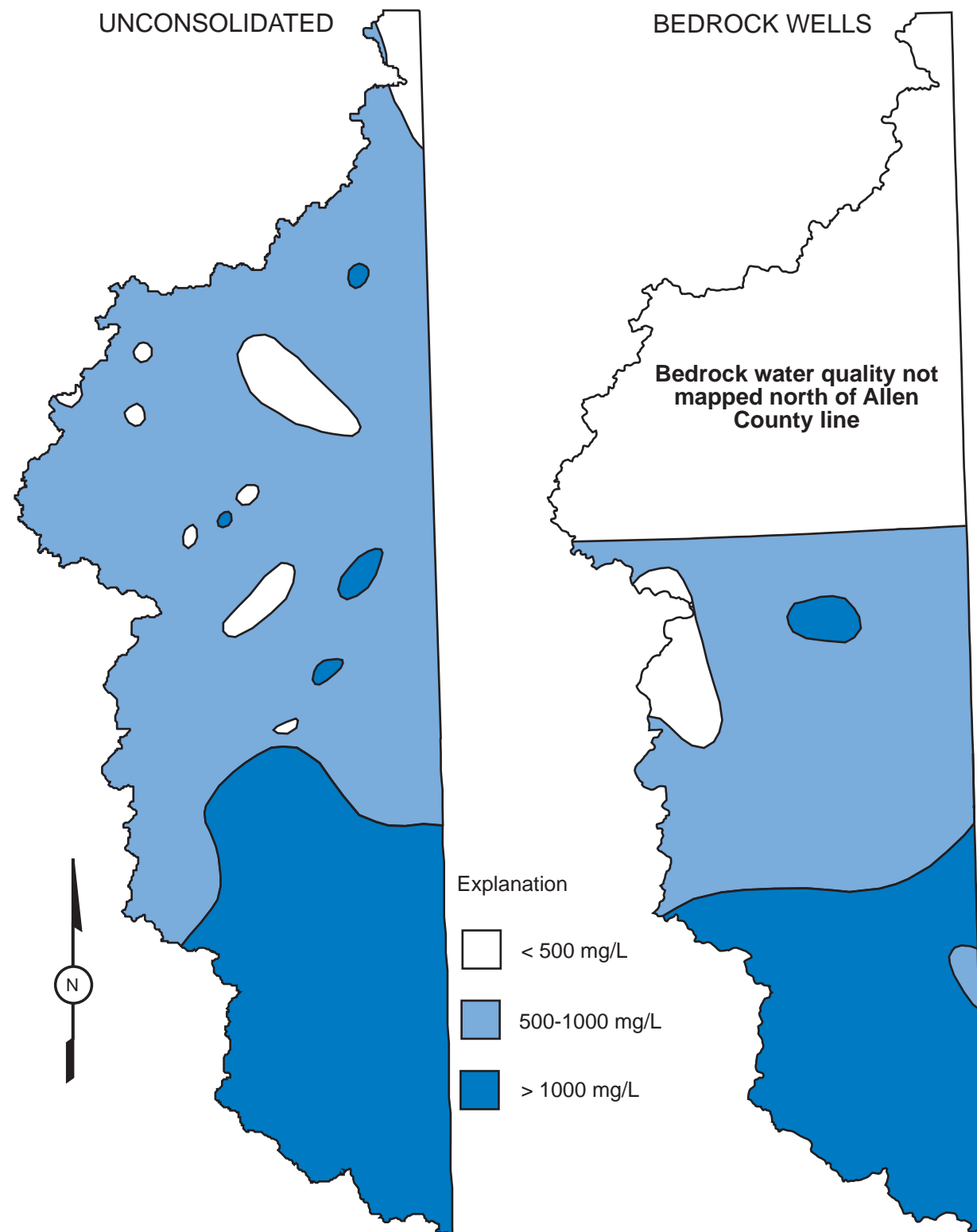


Figure 65. Generalized areal distribution for **Total Dissolved Solids**

mg/L (Keller, 1983). The high TDS level is a factor that prevents deep bedrock formations from being considered practical sources of potable ground water in the Maumee River basin.

Because of the wide range in solubilities of different minerals, one of the principal influences on TDS levels in ground water is the minerals that come into contact with the water. Water in contact with highly-soluble minerals, such as gypsum and halite, will probably contain higher TDS levels than water in contact with less soluble minerals. The residence time of ground water in an aquifer can also influence TDS, because ground water with long residence times can reach a state of chemical saturation with respect to dissolved solutes. Ion-exchange processes in clays can increase TDS because, in order to maintain electrical charge balance, two *monovalent* sodium or potassium ions must enter solution for each *divalent* ion absorbed. Total dissolved solids levels may also be influenced by ground-water pollution. Road salting, waste disposal, mining, landfills, and runoff from urban or agricultural areas are some human factors that may add dissolved constituents to ground water.

Pesticides

Because agriculture is an important form of land use in Indiana, pesticides are widely used in the state to control weeds and insects. In 1990 for example, a reported 28 million pounds of corn and soybean pesticides were used throughout the state (Risch, 1994). The widespread use of pesticides has created concerns about possible adverse affects that these chemicals may have on the environment. Among these concerns is the possibility that pesticides may contaminate ground-water supplies.

Through a cooperative effort, the U.S. Geological Survey and the Indiana Department of Environmental Management have developed a statewide computerized database containing analyses of pesticides in ground-water samples. This database contains the results of 725 ground-water samples collected during 6 statewide and 15 localized studies between December 1985 and April 1991. Sources of data consist of the U.S. Geological Survey, the Indiana Department of Environmental Management, the Indiana Department of Natural Resources, and the U.S. Environmental Protection Agency. A comprehensive summary of the pesticide database has been writ-

ten by Risch (1994).

The pesticide data base includes water sample analyses from 37 different wells in the Maumee River basin. Thirty-five of the 37 wells were sampled in 1988 as a part of a cooperative effort between the IDNR and IDEM. The other two wells include a public water-supply well in Adams County sampled by the USEPA and a bedrock well in Allen County sampled by the USGS in 1991.

The 35 wells are a subset of 95 wells sampled for inorganics by the DOW-IGS. The inorganic chemical analyses from only 34 of the 35 samples are included in appendices 13 and 14, because one of the water samples appears to have been treated in a water softener.

Of the 37 wells sampled in the basin for pesticides, 3 (8 percent) contained detectable levels of the herbicide *dicamba*. None of these samples, however, contained concentrations above the health advisory for dicamba (0.2 mg/L). All of the samples with detectable dicamba levels were collected from wells completed in the Kendallville Aquifer system. The depths of these wells ranged from 80 to 260 feet.

In January 1989, the IDEM resampled the wells that contained detectable levels of dicamba to verify the continued presence of any pesticides at levels above the analytical detection limit. None of the new samples contained detectable levels of dicamba or any other pesticide (Indiana Department of Environmental Management, [1990]).

A major focus of a recent private well-water testing program in Indiana (Wallrabenstein and others, 1994) is to collect information on the presence of triazine herbicide and alachlor in rural water supplies. In the Maumee River basin, data from this program are currently available for wells in Adams, Allen, Steuben and Wells Counties. The private testing program, which is sponsored by the Indiana Farm Bureau, Soil and Water Conservation Districts, County Health Departments, Resource Conservation and Development Districts, County Extension Offices, and other local entities, uses *immunoassay* analyses to screen for triazine herbicides and alachlor. Nitrate levels in rural water supplies are also examined, as discussed on the previous pages of this section under the heading of **Nitrate**.

The *triazine* immunoassay screen indicates the presence of one or more of the common triazine herbicides including atrazine (AAtrex), cyanazine (Bladex), and simazine (Princep), and some triazine

metabolites. The alachlor screen indicates the presence of alachlor (Lasso), metolachlor (Dual), metaxyl (Ridomil) or one of the related *acetanilide* herbicides. The alachlor screen may also react to various alachlor metabolites. The immunoassay procedures, thus do not indicate which specific pesticide(s) is (are) present, but will confirm the absence of triazine- or acetanilide-pesticides at concentrations above the method detection limit (MDL). In the assessment of data collected during the private-well screening program, the researchers used the term “triazine” to refer to triazine herbicides and their metabolites, and used the term “acetanilide” in reference to alachlor, metolachlor and related metabolites (Wallrabenstein and others, 1994).

The results of the triazine and alachlor screening were assessed in terms of two standards; the *detection limit* (DL) and the maximum contaminant level (MCL). The MCLs used for this study were those for atrazine (3.0 µg/L) and alachlor (2.0 µg/L). Samples were categorized into one of the following four groups: 1) no triazine or acetanilide detected; 2) concentrations above DL, but less than one-half MCL; 3) concentrations above one-half MCL up to the MCL; 4) concentrations above the MCL. The detection limits for triazine and acetanilide for this study are reported as 0.05 micrograms per liter (µg/L) or parts per billion (ppb) and 0.2 µg/L, respectively. Because of the ambiguity in the analysis, well owners whose samples contained levels of triazine in the range of 3.0 µg/L or acetanilide in the range of 2.0 µg/L were encouraged to have another sample analyzed with gas chromatographic methods (Wallrabenstein and others, 1994).

None of the samples from wells in Adams, Allen, Steuben or Wells Counties contained triazine concentrations above 3.0 µg/L. Levels of triazine above the detection limit, but less than 1.5 µg/L, were observed in 3 out of 275 samples from Allen County. Detectable levels of triazine below 1.5 µg/L were also observed in 1 of the 137 samples from Adams County, 1 of the 24 samples from Steuben County, and 1 of the 42 samples from Wells County.

Acetanilide concentrations ranging from 0.2 µg/L to less than 1.0 µg/L were detected in two samples from wells in Allen County, 1 sample from a well in Steuben County, and 1 sample from Wells County. Higher concentrations (1.0 µg/L to 2.0 µg/L) were also detected in a sample from a well in Allen County and in a single ground-water sample from Steuben County. None of the samples from wells in Adams

County contained detectable levels of acetanilide. Concentrations of acetanilide were below 2.0 µg/L in all of the ground-water samples from the wells analyzed in this study.

Throughout the state, over 90 percent of the water samples analyzed for the Indiana Farm Bureau pesticide study contained no detectable amounts of triazine or acetanilide. The MCL for triazine was exceeded in only 0.1 percent of all samples. Approximately 1.6 percent of all samples contained acetanilide levels above 2.0 µg/L, however, the majority of acetanilide detects were believed to be caused by a soil metabolite of alachlor (Wallrabenstein and others, 1994). In general, triazine and acetanilide were most frequently detected in shallow (less than 50 feet deep) wells. Furthermore, samples collected from dug or driven wells contained a higher percentage of detects than samples collected from drilled wells. The occurrence of detectable concentrations of triazine and acetanilide in ground water suggests that shallow, poorly-constructed wells may be especially susceptible to pesticide contamination.

Previous ground-water sampling studies

Some of the earliest descriptions of ground-water quality in areas of the Maumee River basin were prepared by the Indiana Department of Conservation (now called the Indiana Department of Natural Resources). The Indiana Department of Conservation developed basic data reports on the ground-water resources for Noble and Adams Counties. These reports contain brief descriptions of the levels of major constituents in well samples from these counties.

Stallman and Klaer (1950) prepared the report on ground-water resources in Noble County for the Indiana Department of Conservation. This report includes a description of ground-water quality from several municipal well systems, including the town of Avilla within the basin and the town of Kendallville near the basin boundary. Ground water from these wells was generally characterized as being very hard, and contained iron concentrations sufficient to stain plumbing fixtures. Total dissolved solids concentrations exceeded the current SMCL in most of the samples examined.

Watkins and Ward (1962) provided a description of ground-water quality in Adams County based on 33

ground-water samples collected in 1949 and 1950. The samples analyzed by Watkins and Ward were characterized as having hardness levels above 300 mg/L as CaCO₃ and TDS levels above 500 mg/L. Concentrations of both iron and sulfate varied by two orders of magnitude among the samples, but most samples contained iron and sulfate concentrations in excess of their respective SMCLs.

A report on the ground-water resources in the Maumee River basin by Herring (1969) documented variations in water quality within the basin. Fifty-one analyses of samples from private and public ground-water supplies were used to describe ground-water quality in the Maumee River basin. Higher levels of sulfate and hardness were observed in samples from wells in the bedrock aquifers of the southern part of the basin than in samples from wells in unconsolidated sediments. Ground-water samples from sands and gravels in the buried valleys of Adams County, however, were geochemically similar to ground waters in the bedrock aquifers (Herring, 1969).

Foley and others (1973) studied the influence of aquifer lithology and ground-water flow on the geochemistry of ground water in Allen County. A total of 14 samples from wells in glacial deposits were analyzed to describe the chemistry of ground water in unconsolidated aquifers. Ground waters from the glacial deposits were described as having high concentrations of iron, sulfate and strontium. The authors also delineated a general decrease in the ratio of calcium concentrations to magnesium concentrations from north to south. This decrease may be indicative of increasing dolomite content in the glacial deposits (Foley and others, 1973).

Thirty-one ground water samples from wells completed in bedrock were also analyzed by Foley and others (1973) as part of their geochemical study in Allen County. Ground waters from the bedrock aquifers generally contained lower iron concentrations, but higher levels of strontium and sulfate, than ground waters from glacial deposits. The highest concentrations of strontium, sulfate and TDS were observed in samples obtained from Silurian carbonates south of the Maumee River.

Ground-water contamination

A ground-water supply, that under natural conditions would be acceptable for a variety of uses, can be

adversely affected by contamination from human activities. Contamination, as defined by the Indiana Department of Environmental Management [1988a], occurs when levels of contaminants are in excess of public drinking-water standards, or health protection guidance levels promulgated by the USEPA.

Over the past 100 years industrial and agricultural practices that accompany development have created ample opportunity for ground-water contamination in the Maumee River basin. Numerous potential sources for ground-water contamination exist in the Maumee River basin, including sanitary landfills, sewage treatment plants, industrial facilities, agricultural operations, septic and underground storage tanks, and road-salt storage facilities.

Some cases of actual ground-water contamination have been identified in the basin. The Indiana Department of Environmental Management (IDEM), Ground Water Section maintains a database of Indiana sites having ‘confirmed’ ground-water contamination. To date, 13 sites have been confirmed in the Maumee River basin including 9 sites in Allen County, 3 in DeKalb County, and 1 in Adams County (IDEM, Ground-Water Section, unpublished data, 1996). One of these sites has been placed on the USEPA National Priorities List (NPL) of Superfund sites and has been undergoing remediation of soil and ground water. Another site of known ground-water contamination in the basin is a Defense Environmental Restoration Program (DERP) site. In addition to the ground-water contamination sites on the ‘confirmed’ list, there are several leaking underground storage tanks in the basin (Indiana Department of Environmental Management, 1995; IDEM, Office of Environmental Response, unpub. data, 1996).

Susceptibility of aquifers to surface contamination

Because contaminants can be transmitted to the ground-water system by infiltration from the surface, the susceptibility of an aquifer system to contamination from surface sources depends in part on the type of material that forms the surface layer above the aquifer. In general, sandy surficial sediments can easily transmit water from the surface, but provide negligible filtering of contaminants. Clay-rich surficial deposits, such as glacial till, generally have lower vertical hydraulic conductivity than sand and gravel deposits, thereby limiting the movement of contami-

nated water. However, the presence of fractures can locally decrease the effectiveness of a till to protect ground water. The differences in basic hydrologic properties of sands and clays make it possible to use surficial geology to estimate the potential for ground-water contamination.

The highly complex relationships of the various glacial deposits in the Maumee River basin preclude site-specific comments about susceptibility of the regional aquifer systems to contamination. However, a few gross generalizations can be made. Detailed mapping, including mapping for ground-water sensitivity to contamination, is available for Allen County (Fleming, 1994).

The Kendallville Aquifer system, consisting chiefly of intertill lenses of outwash sand and gravel, has low to moderate susceptibility to surface contamination. Clay-rich Erie Lobe tills, commonly ranging from about 10 to 100 feet in thickness, overlies much of the aquifer system and offer some protection to the underlying aquifers. However, in northeastern DeKalb County and many parts of Steuben County, Erie Lobe tills are absent and more permeable sediments in the form of ice-contact and mixed-drift deposits occur at the surface. Thus, the northern extent of the Kendallville Aquifer system has a significantly higher susceptibility to surface contamination than other parts of the system.

Along its northern extent, the Aboite Aquifer system is moderately susceptible to surface contamination. The aquifer system, comprised of outwash sand and gravel deposits that occur at various horizons, is overlain by clay-rich Erie Lobe tills in the north. In the south, however, the system is highly susceptible to surface contamination because there is little if any till present, and the thick outwash channel and fan deposits that comprise the water-bearing units in this area are poorly confined by heterogeneous surficial sediments.

In general, the Hessen Cassel Aquifer system has low susceptibility to surface contamination. Across large parts of the southern Maumee River basin, the seldom-used scattered intertill lenses of glacial outwash that comprise the aquifer system are overlain by about 20 to 40 feet of clayey basal Erie Lobe tills. The till cap contains a well-developed system of near-vertical fractures that extend to a depth of 20 to 25 feet (Fleming, 1994). However, the shallow fracture zone of the Erie Lobe tills does not significantly reduce the high degree of confinement of the aquifer system

because the few wells that reach productive zones of sand and gravel have depths ranging from 50 to 90 feet. In the northeastern part of the aquifer system, *glaciolacustrine* sediments of the Maumee Lacustrine Plain appear as a surficial veneer of laminated silt and clay, tills, debris flow deposits and interlayered sand and silt. In some areas of the lacustrine plain where surficial deposits are thin, the underlying sand and gravel aquifers are susceptible to surface contamination.

The New Haven Aquifer system has low to moderate susceptibility to surface contamination. The northern part of the nearly-continuous outwash plain deposit is moderately susceptible because it is overlain by an extensive blanket of fine sand. The remainder of the aquifer system, overlain by tills, debris flow deposits, and glaciolacustrine sediments, has low susceptibility to surface contamination.

The unconfined portions of the Cedarville and the Eel River-Cedar Creek Aquifer systems are highly susceptible to contamination from surface sources because the surficial valley train sediments of both aquifer systems are highly permeable. Although tills beneath the surficial valley train deposits may provide some protection to the confined portions of both aquifer systems, in many places surficial valley train deposits coalesce with the deeper outwash deposits. Hence, the overall susceptibility of the Cedarville and the Eel River-Cedar Creek Aquifer systems is considered high.

The Teays Valley and Tributary Aquifer system has a low susceptibility to surface contamination because outwash sediments within the bedrock valleys are generally overlain by dense tills of the Trafalgar Formation and clayey tills of the Lagro Formation. Although lenses of outwash sand and gravel may occur within the tills, the predominance of fine-grained sediments above the bedrock valleys limits the migration of contaminants from surface sources to the deep aquifers.

The susceptibility of bedrock aquifer systems to surface contamination is dependant on the nature of the overlying sediments, because the bedrock throughout the basin is overlain by unconsolidated deposits. Just as recharge for bedrock aquifers cannot exceed that of overlying unconsolidated deposits, susceptibility to surface contamination will not exceed that of overlying deposits. However, because the bedrock aquifer systems have complex fracturing systems, once a contaminant has been introduced into a

basin bedrock aquifer system, it will be difficult to track.

Regional estimates of aquifer susceptibility can differ considerably from local reality. Variations within geologic environments can cause variation in susceptibility to surface contamination. Also, man-made structures such as poorly-constructed water wells, unplugged or improperly-abandoned wells, and open excavations, can provide contaminant pathways which bypass the naturally-protective clays. In contrast, man-made structures can also provide ground-water protection that would not normally be furnished by the natural environment. For example, large containment structures can inhibit infiltration of both surface water and contaminants. Current regulations administered by the IDEM contain provisions for containment structures, thereby permitting many operations to occur that would otherwise provide an increased contamination risk to soils and the ground water. Other regulations administered by the IDNR regulate the proper construction of new wells and sealing (plugging) of abandoned wells, whether related to petroleum or water production.

Protection and management of ground-water resources

Major ground-water management and protection activities in Indiana are administered by the IDEM, IDNR, and the Indiana State Department of Health (ISDH). An expanded cooperative effort in the form of the Inter-Agency Ground-Water Task Force involves representatives of these three agencies as well as the State Chemist, State Fire Marshal, and

members of local government, labor, and the business, environmental and agricultural communities. The Task Force was first formed in 1986 to develop a state ground-water quality protection and management strategy, and is mandated by the 1989 Ground Water Protection Act (IC 13-18-17, previously 13-7-26) to coordinate the implementation of this strategy. The strategy is an agenda of state action to prevent, detect, and correct contamination and depletion of ground water in Indiana (Indiana Department of Environmental Management, 1988c). The 1989 act also requires the IDEM to maintain a registry of contamination sites, operate a clearinghouse for complaints and reports of ground-water pollution, and investigate incidents of contamination that affect private supply wells.

Developing a program plan for delineating and managing wellhead protection (WHP) areas for public water supplies is one priority action designated by the state ground-water strategy and draft implementation plan (Indiana Department of Environmental Management, 1988b). The federal Safe Drinking Water Act Amendments of 1986 established the program for protection of wellhead areas for public supply systems from contamination, but requires a state to complete a program plan in order to be eligible for federal financial assistance. The Indiana WHP program plan has been developed and is expected to become effective in 1997. The program plan establishes regulations which will become effective in phases based on the number of customers served by a public supply facility. This program is administered by the IDEM Office of Water Management, Drinking Water Branch, Ground Water Section.