Wisconsin Geological and Natural History Survey
Special Report 10

Wellhead-Protection Districts in Wisconsin: An Analysis and Test Applications

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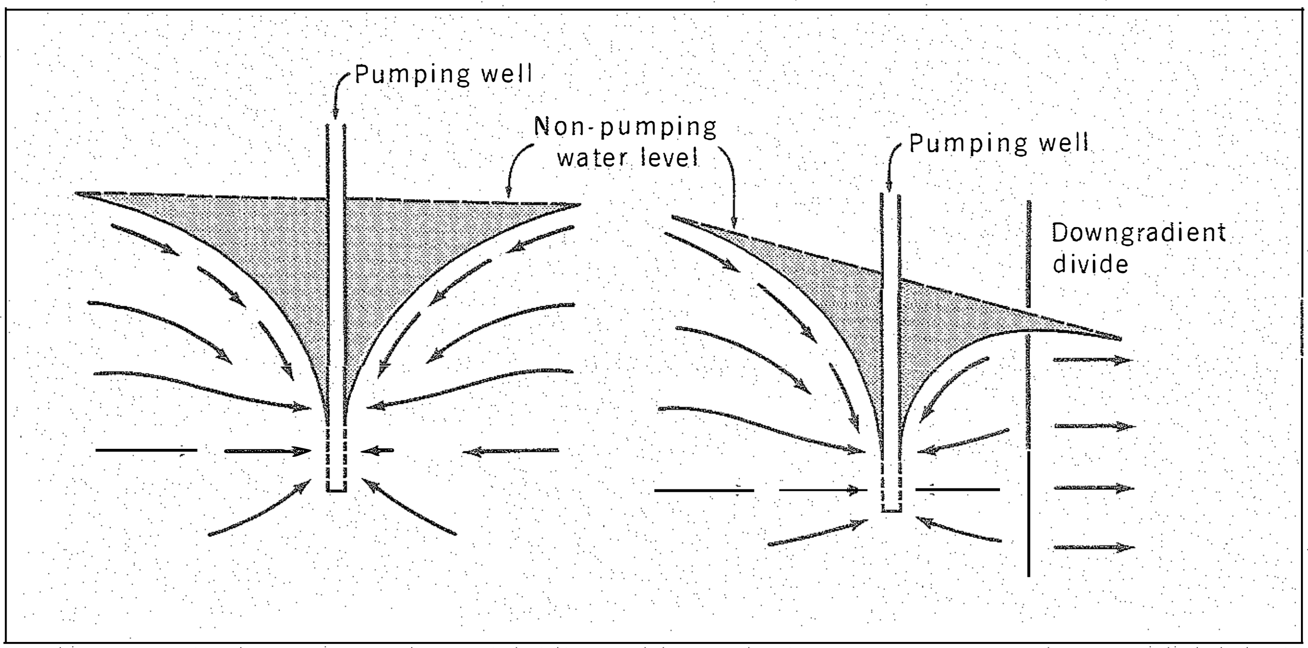

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Published by and available from
Wisconsin Geological and Natural History Survey
3817 Mineral Point Road, Madison, Wisconsin 53705

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1988

ISSN: 0512-0659

PREFACE

This report is published as part of the continuing cooperative efforts of the Wisconsin Geological and Natural History Survey and the Wisconsin Department of Natural Resources in providing information to local governments to assist their efforts in groundwater protection. The well-protection approach is a useful addition to state and local governmental management tools. Although the Wellhead-protection Program provided for in the 1986 amendments to the Federal Safe Drinking Water Act has not been funded by Congress, the well-protection district approach is likely to be useful to communities in Wisconsin and elsewhere that are looking for additional management tools to achieve their groundwater-protection objectives.

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ABSTRACT

Establishing well-protection districts has been widely practiced in Europe and elsewhere for many years. This approach appears likely to become an important component of groundwater-protection activities in the United States. In this report methods for delineating well-protection districts are reviewed and their applicability in representative Wisconsin hydrogeologic settings is assessed. The authors examine critical institutional factors, including local governmental authority and capacity, that must be related to hydrogeologic considerations when establishing well-protection programs. Examples illustrating the delineation of well-protection districts for selected Wisconsin cases are presented.

ACKNOWLEDGMENTS

The authors appreciate the review and comments on an early draft of this report by the following individuals: Mary Anderson, Kenneth Bradbury, Carey Carpenter, Keros Cartwright, R.D. Cotter, William Fetter, Ron Hoffer, Kevin Kessler, William Lontz, Thomas Osborne, Byron Shaw, Steven Skavronek, David Stephenson, John Tinker, and Alexander Zaporozec. We thank the following reviewers for their detailed reviews and constructive suggestions regarding the final manuscript:

Kenneth Bradbury, Wisconsin Geological and Natural History Survey;
Ronald Hoffer and associated staff, U.S. Environmental Protection Agency, Office of Ground Water Protection;
Thomas Osborne, Central Wisconsin Groundwater Clearinghouse, University of Wisconsin-Stevens Point;
Alexander Zaporozec, Wisconsin Geological and Natural History Survey.

Special thanks are due Jeanne Christie, Wisconsin Department of Natural Resources, Bureau of Water Resources Management, who served as project liaison and coordinated reviews of the final draft report by DNR staff, including: Robert Krill, Robert Baumeister, Kevin Kessler, Michael Smoller, Marcia Penner, and Patti Hanz. Patricia Cantrell's typing and administrative efforts were of enormous help in completing this report. Patricia Robinson's editorial assistance with the final manuscript is also appreciated.

We also gratefully acknowledge the Joyce Foundation for partial funding of this study, as well as the financial support of the Wisconsin Department of Natural Resources under Contract NRG91702.

CHAPTER I

INTRODUCTION AND PURPOSE

Groundwater is one of Wisconsin's most valuable natural resources. Our major aquifers produce six hundred million gallons of groundwater daily, of which half is used for residential and industrial use. Underground sources provide drinking water for more than 90 percent of the state's communities -- about half of our population. For years, clean, safe groundwater supplies have been taken for granted. Now we have come to recognize that groundwater in Wisconsin is threatened from many and varied pollution sources, and reports of contaminated wells are increasingly common. Although our groundwater resources are generally of high quality, we now perceive the need to plan and take steps to ensure safe drinking water supplies in the future.

Human activities, facilities, and land uses can ultimately lead to groundwater quality problems. Accordingly, land-use management, including regulation, may be used to protect the quality of drinking water supplies. For years, well-protection districts have been used to protect groundwater in Europe (Matthess and others, 1985; Milde and others, 1983; U.S. EPA, 1987b; Van Waegeningh, 1985a; 1985b), and this approach appears likely to become an important component of groundwater protection strategies in the United States very soon.

The basic idea of a well-protection district is to restrict potentially polluting activities near wells and well fields and within recharge or "catchment" areas of aquifers supplying water to these wells. Generally, activities are more restricted close to the well and less so farther away. This is based on 1) the concept that pollution tends to attenuate over time and distance and 2) the farther away from the well pollutants are detected, the more time there is to take emergency or remedial action to protect the well.

The well-protection approach is a useful addition to state and local government groundwater-management tools because it focuses attention on a critical part of the groundwater resource. Its application will be spurred on by the 1986 amendments to the Federal Safe Drinking Water Act, which provide for a program of federal cost-sharing to help the states establish well-protection districts (U.S. EPA, 1987a). The approach is not a panacea, however: it is more applicable to some hydrogeologic settings than others, as we will show later in this report. Furthermore, it is likely to be used -- at least initially -- to protect only community and municipal water supplies, rather than extensive shallow aquifers serving a dispersed rural population dependent upon private wells (although the approach can conceptually be expanded to such situations). Finally, to apply the well-protection approach in a scientifically sound manner requires that aquifers be mapped and groundwater flow systems delineated. For the most part, hydrogeologic information is not available statewide at this level of detail, although substantial basic data are available locally.

This report distinguishes between wellhead-protection (WHP) *areas*, which are delineated hydrogeologically, and wellhead-protection *districts*, which are established for management purposes. Although WHP districts should be based on WHP areas, in most cases they will not be congruent for reasons discussed later. The purpose of this publication is

1) to serve as a guide to appropriate and practical hydrogeologic methods for delineating WHP areas pertinent to the establishment of WHP districts in Wisconsin (chapter II);
2) to apply and assess these methods for delineating WHP areas in representative Wisconsin hydrogeologic settings (chapter III);
3) to review institutional issues relevant to the establishment of WHP districts in Wisconsin (chapter IV); and
4) to illustrate WHP district delineation for selected Wisconsin cases (chapter V).

This report is intended to assist technical personnel at the local governmental level -- public-works engineers, soil-conservation technicians, planning and zoning staff, consultants -- in the technical task of delineating possible WHP areas. In some cases, highly specialized hydrogeologic investigations may be needed, and we suspect that many communities will hire consultants to help. Thus, we hope that this report also will serve as a guide for local units of government in hiring consultants and defining the necessary scope of work. Finally, this report, along with other recent publications (for example, Born and others, 1987) should facilitate and augment a State of Wisconsin's proposal for a wellhead-protection program development grant from the U.S. Environmental Protection Agency.

CHAPTER II

HYDROGEOLOGIC ASPECTS OF EMPLOYING THE WELLHEAD-PROTECTION APPROACH: A REVIEW OF METHODS

Introduction

The establishment of WHP district boundaries is seldom based solely upon hydrogeologic factors. Legal, political, and economic factors will, in most cases, be equally or even more important. Our purpose here is to describe the hydrogeologic methods for delineating areas for consideration in establishing WHP districts.

Basic Hydrogeologic Concepts and Terminology

Hydrogeology is the study of the origin, occurrence, distribution, and movement of water beneath the earth's surface (Heath,1983). Hydrogeology places an emphasis on the geologic aspects because an understanding of groundwater and the effects of human actions on it is fundamentally tied to a knowledge of the "container" within which the groundwater is found. The geologic "containers" for groundwater are diverse, and groundwater flow systems vary accordingly. However, all groundwater flow systems operate on the same basic principles.

All groundwater flow systems contain areas of replenishment (recharge areas) and exit (discharge areas) (fig. II-1). In local flow systems, it may take only weeks or months for water to move from the recharge area to a discharge area or well. In regional flow systems the water must travel much farther, and it may take years to go from recharge to discharge.

Although groundwater can and does move through any type of geologic materials, the term *aquifer* refers specifically to saturated bedrock or unconsolidated deposits that can transmit economically important quantities of water to wells. An aquifer characteristically transmits water more easily than the surrounding geological units, and is said to have a higher *hydraulic conductivity* (K). Aquifers are divided into two broad categories, confined and unconfined. A *confined aquifer* is overlain by a confining unit of lower hydraulic conductivity, while an *unconfined aquifer* has the water table as its upper boundary. As a result, confined aquifers occur at depth, and unconfined aquifers occur near the ground surface (Freeze and Cherry,1979).

A *potentiometric surface* is the level to which water will rise in a well. The potentiometric surface thus represents the total head at a given depth within a confined aquifer, and like the water table for an unconfined aquifer, is used to determine the direction of groundwater flow. The *hydraulic gradient* (I) is the slope of the potentiometric surface or water table in a given direction. Groundwater moves downgradient in the direction of the maximum hydraulic gradient. Thus, those areas from which groundwater will

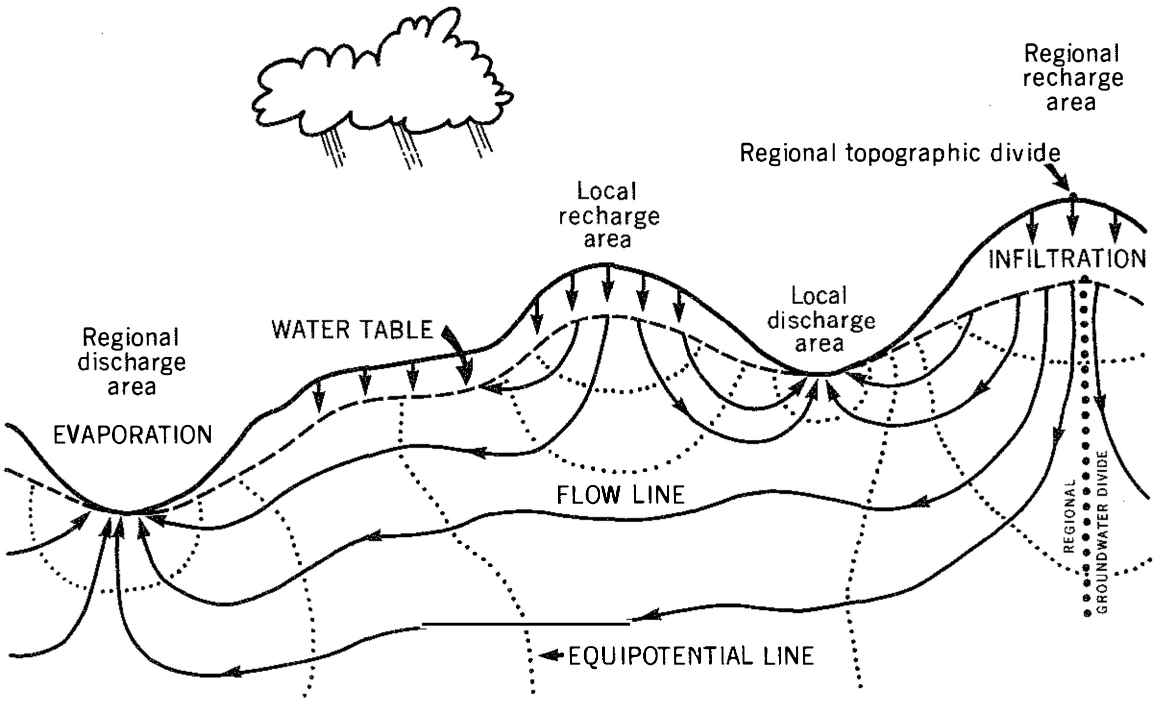


Figure II-1. Idealized groundwater flow system.

naturally move toward a well field are known as *upgradient areas. Flowlines* are idealized lines drawn to represent the paths followed by particles of water within a groundwater flow system. In recharge areas, flowlines indicate a downward motion of water into the aquifer, whereas in discharge areas, they show an upward motion of water leaving the aquifer. Generally, between areas of recharge and discharge, flow is horizontal. Pore spaces and/or fractures within the bedrock and unconsolidated materials provide the passageways through which groundwater moves.

Aquifer Characteristics and the Wellhead-protection Concept

The most important aquifer characteristic to consider in applying the WHP concept is its degree of confinement. Although aquifers are often labeled either confined or unconfined, they actually fall along a continuum of aquifer types between these two extremes. The confining units that overlie confined aquifers are never completely impermeable, and some aquifers receive significant recharge from leakage through overlying confining units. These are referred to as *semiconfined* or *leaky aquifers.* The degree of leakage may vary spatially due to the presence of fractures and stratigraphic variability. As with any other saturated medium, the flow of water through confining units is determined by their hydraulic conductivity and the hydraulic gradient of the confining bed as expressed in Darcy's law:

$$Q = KIA$$

where

- Q = the rate of discharge
- K = hydraulic conductivity
- I = hydraulic gradient
- A = cross-sectional area perpendicular to the flow direction.

The WHP concept is most appropriate when dealing with unconfined aquifers. They often have characteristics that make them susceptible to contamination from the surface: they are close to the land surface, they are mainly composed of permeable materials such as sand and gravel, and they receive moderate to high amounts of recharge during most years (Pacenka and others, 1984). In addition, the localized nature of groundwater flow in these shallow, unconfined systems simplifies the delineation and defense of WHP districts based on hydrogeologic factors. Municipal wells located in both outwash deposits and alluvial sand-and-gravel deposits are common in Wisconsin.

The usefulness of the WHP concept for semiconfined aquifers is directly related to the amount of water that is recharging the aquifer due to leakage through the overlying units. Semiconfined conditions are common in Wisconsin where irregular deposits of low permeability, such as glacial till, overlie the highly productive sandstone aquifer. In many of these cases, methods described in this report will be applicable on a limited basis.

The WHP concept is difficult to implement and defend where a well obtains water from a confined aquifer. In confined aquifers, some of the water that reaches a well may have traveled long distances over hundreds of years in a regional flow system, with recharge from the immediate area limited to places where the confining unit is thin or fractured. In addition, the movement of water from the surface to a confined aquifer depends not only on the thickness and permeability of the overlying deposits, but also on the vertical hydraulic gradient. If the head in the water-table aquifer is greater than in the lower aquifer, water (and possibly contaminants) will move into the lower aquifer. If, on the other hand, there are upward gradients, the chance of contamination from above is minimized. Therefore, a comparison of the water table with the potentiometric surface should be made wherever possible. Unfortunately, data of this sort will generally not be available. Therefore, hydrogeologic methods for delineation of WHP areas as described in this report are not particularly useful in confined situations. Such situations are common at the eastern edge of Wisconsin, along Lake Michigan, where the aquifer is covered by a thick confining layer of shale.

Fractured rock aquifers, such as the Silurian dolomite along the eastern edge of the state and the Precambrian crystalline rocks in northern Wisconsin, are beyond the scope of this report. Because the rock matrix itself is relatively impermeable in these cases, most of the groundwater flow takes place within the fractures that are present. A thorough knowledge of fracture patterns is needed to predict groundwater flow directions. This type of information will generally not be available.

As a result of the complex nature of recharge and groundwater movement in confined aquifers and fractured bedrock, more sophisticated techniques (such as numerical modeling and tracer studies) may be needed to determine appropriate, hydrogeologically based areas for inclusion in a WHP program.

Methods for Delineating the Hydrogeologic Areas for Wellhead-Protection Districts in Wisconsin

Introduction

Numerous delineation methodologies based on hydrogeologic criteria have been applied by the various water resource programs in the United States and Western Europe that have implemented the WHP approach to protect groundwater. The interested reader is referred to summary articles by Crystal (1983), Milde and others (1983), and the U.S. EPA (1987b). The methods discussed in this report are not intended to illustrate the entire spectrum of possible methods, but rather to focus on those methods most applicable in Wisconsin. In this section, we will describe and illustrate the hydrogeologic bases for potential WHP districts.

The Safe Drinking Water Act Amendments of 1986 defined a WHP area (fig. II-2) to be "the surface or subsurface area surrounding a water well or wellfield, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or wellfield" (U.S. EPA, 1987b). Accordingly, a protection area based on the entire contribution area to the well would be the theoretical goal of a WHP district program. The entire contribution area, which is usually determined using geologic/hydrogeologic mapping techniques, consists of the area immediately around the well plus the upgradient part of the aquifer inside which flowlines move toward the well (figs. II-2 and II-3). In many cases, this area will be too large to effectively manage. Economic, political, and legal issues will often require that WHP districts be based on smaller subareas within the total contribution area. These subareas can be hydrogeologically based on a cone of depression, travel time distances, or a water budget approach.

In some cases, it may be necessary or desirable to base WHP districts on separating distances that are applied uniformly around the well without consideration of the local groundwater flow patterns. The radius that is used to delineate these circular protection areas may relate to hydrogeologic factors, such as calculated travel time distances, or non-hydrogeologic factors, such as prior regulatory experience.

This report discusses six general types of hydrogeologic methods:

a) geologic/hydrogeologic mapping;
b) analytical flow models;
c) fixed separating distances;
d) calculated separating distances;
e) water budget approach; and
f) numerical flow/transport models (table II-1).

Geologic/Hydrogeologic Mapping

Geologic/hydrologic mapping is primarily useful to delineate an entire groundwater basin and the contribution area for a well. As with a surface-water drainage basin, the size and shape of a groundwater basin is determined by flow divides. In shallow aquifers, the groundwater basins are often congruent with the overlying surface drainage basins. Even where surface water and groundwater flow are not aligned, information about the surface drainage may be used to determine areas which send overland runoff into WHP districts.

The geologic mapping approach is most useful in dealing with unconfined aquifers where the size and shape of the basin can be fairly easily determined. The Rib Mountain case is a good example of this type of analysis. The approach is less useful with confined and semiconfined aquifers because much of the water moves in regional flow paths and may have traveled several miles. This makes the delineation of the contribution area for the water being pumped at a given well very difficult to determine. Even where the groundwater basin can be

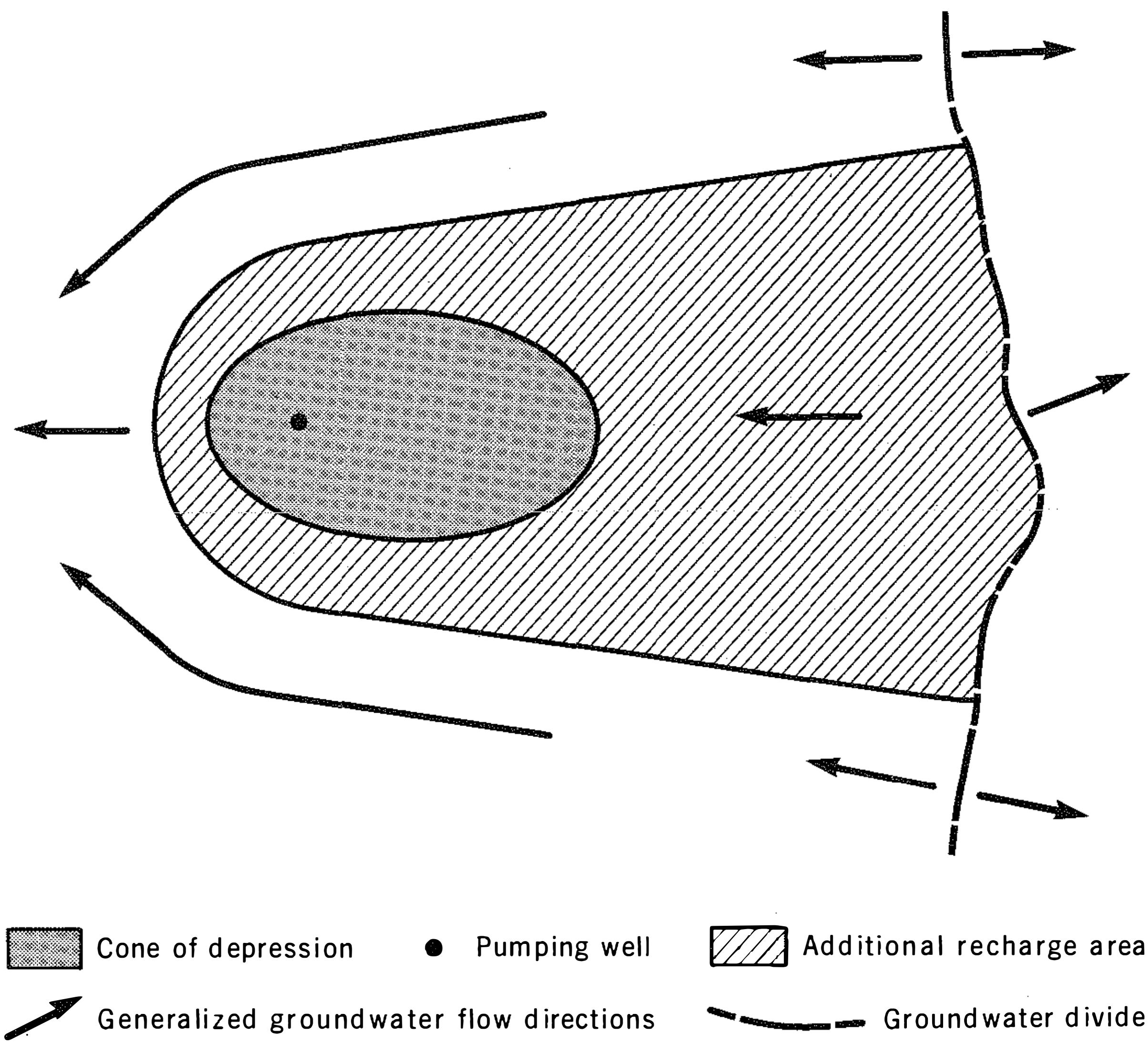


Figure II-2. Terminology for wellhead-protection area delineation.

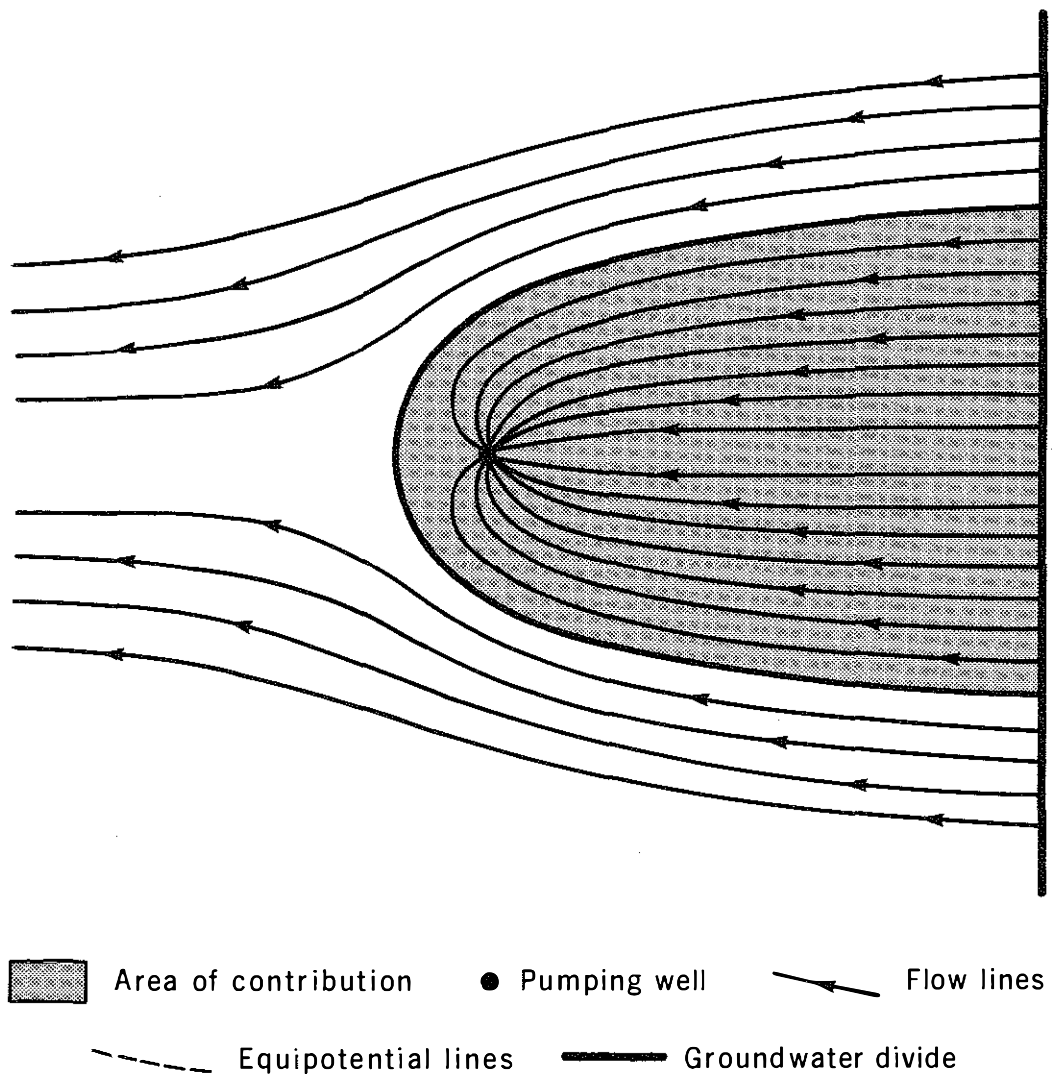


Figure II-3. Flow pattern in a simple groundwater flow system. In this system, a pumping well is superimposed on a uniformly sloping hydraulic head pattern. (Flow is from right to left.) The flow reflects the slope of the water table, starting at the right edge of the diagram and following the local gradient. All flow lines inside the heavy line enter into the well. The area of contribution to the well consists of all flow paths that reach the well. Adapted from Pacenka and others, 1984.

determined, it is likely to be so large that it may be of little value in delineating an area upon which to base a WHP boundary. Therefore, mapping is a technique that is most appropriate for use in unconfined cases.

In addition to defining a well's contribution area, geologic and hydrogeologic mapping can also be used to identify heterogeneities within surficial materials and the aquifer. These heterogeneities may indicate variations in recharge within the total recharge or contributing area. They may also point to land areas of differing vulnerability to groundwater pollution as determined by assessment of the pollution attenuation capacity of the soils and subsurface materials (see Born and others, 1987).

Many sources of information are available to aid in mapping. Topographic maps, surficial and bedrock geologic maps, and a potentiometric surface map can be used to determine the contribution area supplying water to the well in question. Valuable information concerning the groundwater basin of interest can sometimes be found in U.S. Geological Survey (USGS) water-supply papers and other published reports. A good first step in locating published reports dealing with a given area is to consult the Wisconsin Geological and Natural History Survey (WGNHS) List of Publications, which provides a good summary of available publications of state and federal agencies. It contains both a subject and a location index to help locate materials of interest. For example, the USGS hydrologic atlas series (covering the entire state) includes potentiometric surface maps that can be used to find the hydraulic gradient and the direction of groundwater movement. Additional reports should be consulted whenever possible. WGNHS and USGS reports dealing with groundwater are available for about one-third of the state.

Mapping is a method that can readily be understood by the general public and can lend a high degree of accuracy and defensibility to the designation of a WHP district. It is fairly easy to apply where

Table II-1. Wellhead-protection areas (and separating distances) delineated by six hydrogeologic methods.

	Area of interest				
	Total contribution area	Subareas within the total contribution area		Contribution area not defined	
Method	Groundwater basin/ recharge area	Cone of depression	Distance based on travel time	Distance based on travel time	Distance based on non-hydro-geologic factors
Geologic/ hydrogeologic mapping	X				
Analytical flow models		X			
Calculated separating distances			X	X	
Fixed separating distances			X	X	X
Water-budget approach				X	
Numerical flow models			X	X	

previous studies have already at least partially determined the groundwater basin. If the groundwater basin has not been predetermined, however, the amount of field work necessary will, in all but the simplest situations, make this approach impractical for general use in delineating WHP areas. When mapping is used to determine the total contribution area for a well, other methods are usually needed to subdivide the WHP area. The use of mapping in conjunction with other methods is discussed in detail later in this report.

Analytical Flow Models

Analytical flow methods use equations to define groundwater flow. Such models are particularly useful for determining the response of aquifers to withdrawals from wells. As water is removed from a well, the water level is lowered in the vicinity of the well with the greatest drawdown occurring at the well. This lowering in water level near the well causes water to move toward the well from all directions at an increasing rate as it reaches the well. This area is called the cone of depression of the well (see fig. II-2). The size and shape of the cone of depression depends on the rate at which water is being pumped from the well and the location of aquifer boundaries (Driscoll, 1986; Heath, 1983), as well as on properties of the aquifer itself. The most important of these are the capacity of the aquifer to transmit water (transmissivity); the ability of the aquifer to release water from storage (storage coefficient); and the thickness and horizontal extent of the aquifer.

Because water and pollutants that move with the water, that is, by advection, within the cone of depression, flow toward the well, the radius of the cone of depression, can be an appropriate boundary for a WHP district. The surface projection of the cone of depression will be circular or oval depending on whether the regional water table (or potentiometric surface) is flat (fig. II-4a) or sloping (fig. II-4b). Because water tables generally have very low slopes in Wisconsin, the effect of the slope on the shape of the cone will generally be fairly small. This fact and the generalizations used in deriving cones of depression justify the use of a circular approximation.

An aquifer test can be performed to determine both the transmissivity (T), which is defined as the hydraulic conductivity (K) times the thickness of the aquifer, and the storage coefficient (S) of the aquifer. Such a test is generally done by pumping a well at a known rate for a period ranging from hours to several days and measuring the decline in water level (drawdown) in wells located at different distances from the pumped well (Heath, 1983). The test data can then be analyzed using the Theis equation. Although in a strict sense the Theis equation applies only when certain assumptions are met, it will provide sufficiently accurate results for our purposes in a variety of different hydrogeologic situations. The Theis equation can be solved either manually (appendix 2) or by using computerized computations (Walton, 1984). For our purpose, the Theis equation (Freeze and Cherry, 1979; Heath, 1983) can be expressed as

$$s = \frac{Q}{4\pi T} W(u)$$

where

s = selected amount of drawdown
Q = pumping rate of well
T = transmissivity of the aquifer
W(u) = the well function of u

where

$$u = \frac{r^2S}{4Tt}$$

and

r = distance from the pumping well to the point where the drawdown in the cone of depression equals the selected drawdown (s)
S = storage coefficient of the aquifer
t = selected duration of pumping

Although the mathematics involved in applying the Theis equation is relatively simple, care must be taken to use consistent units.

Values for transmissivity (T), pumping rate of the well (Q), and storage coefficient (S) can be obtained from a variety of sources. In

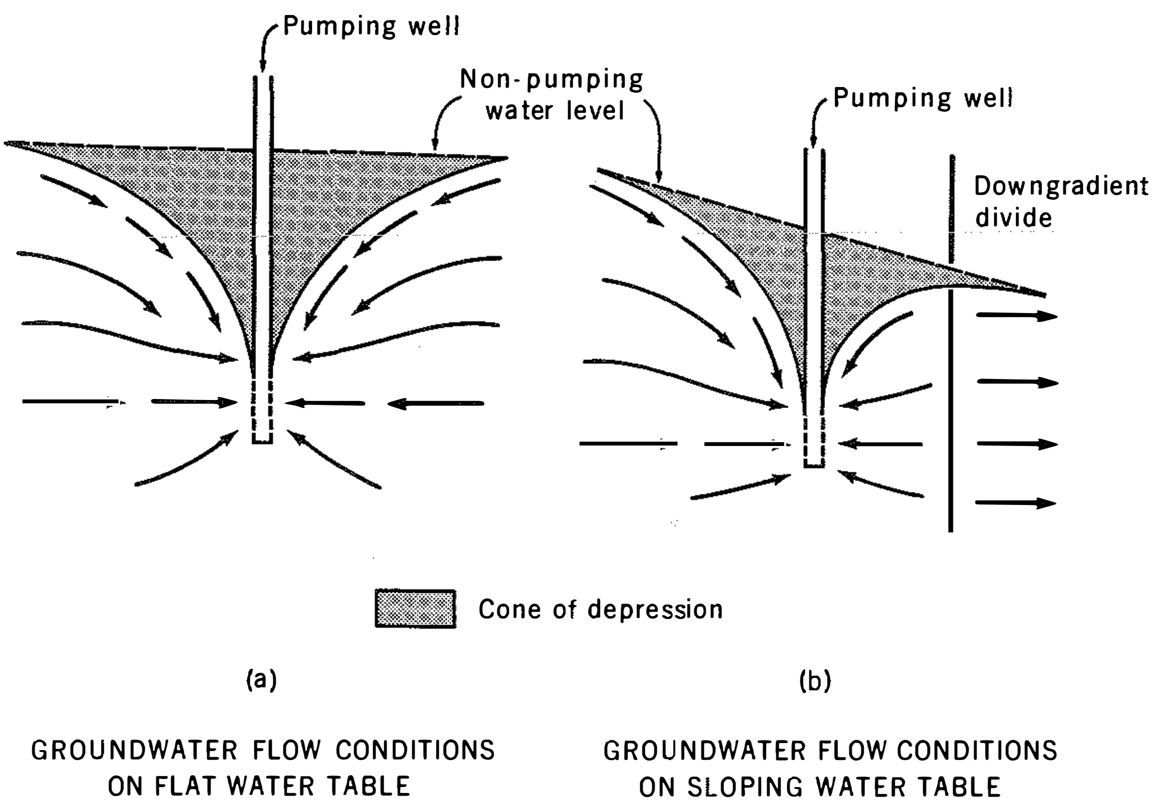


Figure II-4. Cross-section diagrams showing the effect of a flat and a sloping water table on a cone of depression.

addition to published reports, well logs for municipal wells are on file at both the DNR and WGNHS. Well logs provide information concerning the location, well depth, well radius, formations drilled, aquifer being utilized, and specific capacity. The specific capacity of a well is determined by pumping the well at a known rate and then dividing this rate by the distance the water has dropped in the well (drawdown). The specific capacity can then be used to estimate the hydraulic conductivity of the zone supplying water to the well. Because the construction of the well itself affects the values of hydraulic conductivity that are obtained from specific capacity data, hydraulic conductivity values obtained in this way may be somewhat less accurate than where other methods, such as aquifer pumping tests, are used. They should be checked against published values for the aquifer wherever possible. For our purposes, the use of specific capacity data to estimate hydraulic conductivity (K) and transmissivity (T) is reasonable. This method is described in detail in appendix 1. Municipalities are required to keep records of the pumping rate of the well (Q), and this information is also on file at the DNR. The storage coefficient (S), if not available in published reports, can be estimated based on aquifer type (Heath, 1983).

The Theis equation is then solved for the radius (r) of the cone of depression. Because recharge to the aquifer is not considered in the Theis equation, as the time of pumping of the well increases, the radius of the cone and the drawdown within the cone will continue to expand indefinitely. Therefore, a decision must be made as to the duration of pumping (t) and the drawdown (s) to use in determining an appropriate cone of depression. Previous WHP studies have used durations ranging from one day to hundreds of days, and drawdowns ranging from 5 ft to 0.01 ft. For this study, we used the guidelines that are commonly given for conducting an aquifer test, that is, a duration of one day for semiconfined and confined aquifers and a duration of three days for unconfined aquifers (Driscoll, 1986; Kruseman and DeRidder, 1979). The difference is because cones of depression expand much more rapidly in confined aquifers than they do in unconfined aquifers. To illustrate the effect that the selected drawdown value has on the size of the cone of depression, cones for a variety of drawdowns are presented in the Whiting and Seymour examples (appendices 2 and 3). Because recharge to an unconfined aquifer by infiltration is more direct and rapid than in a semiconfined aquifer, the selection of different levels of drawdown for different types of aquifers may be appropriate. Accordingly, we have used drawdowns of 1 ft in a semiconfined aquifer and 0.1 ft in an unconfined aquifer in this report.

Numerous values could also be chosen for an appropriate pumping rate, including average daily rate, maximum daily rate, and the maximum pump capacity rate. Because the maximum daily pumping rate is often two or three times the average daily pumping rate, using the average daily pumping rate would significantly underestimate the size of the cone that exists during periods of maximum pumpage. Therefore, the maximum daily pumping rate is a safer, more conservative choice, and it is used in this report. The maximum pump capacity rate was rejected because existing maximum pumping capacity for a given municipal well will not be used for an extended period. In fact, the DNR recommends a community begin working on an additional well when usage regularly exceeds 50 percent of the maximum pump capacity (L. Boushon, Wisconsin

Department of Natural Resources, Bureau of Water Supply, personal communication).

Although originally developed for use with confined aquifers, the Theis equation can be applied with some modifications to both unconfined and semiconfined aquifers. The cones of depression in unconfined and semiconfined aquifers will be smaller for a given pumping rate than in a confined aquifer with the same transmissivity, so using the basic Theis equation will generally ensure a conservative approach and provide reasonable results for our purposes.

The data required to create analytical flow models are available from previously described sources, so it should be possible to calculate the cone of depression for most municipal wells. As is true for the other hydrogeologic methods, using the cone of depression to define a WHP district is most applicable in an unconfined aquifer because the movement of water and pollutants to a semiconfined or confined aquifer is much less predictable. It is, nevertheless, important to protect the area immediately around the well even in these situations, making use of the cone of depression to define a WHP district a useful approach even in semiconfined cases. Because the appropriateness and defensibility of a WHP district determined this way depend on the values used in determining the cone of depression, some knowledge of hydrogeology and well hydraulics is required to use analytical methods effectively to delineate potential WHP districts.

Analytical methods to determine the cone of depression of the pumping well can be readily combined with both time-of-travel (TOT) distances and/or delineation of the area of contribution to the well. Either of the latter methods could be used to establish a WHP district without an analysis of groundwater flow within the aquifer, but it is much better to include flow analysis whenever possible so that upgradient areas supplying water to the cone of depression can be included in the WHP program in some way.

Calculated Separating Distances

Calculated separating distances is a method that uses the properties of the aquifer to determine a WHP area that is specific to a given well. The basis of this method is to determine the rate and direction that groundwater is moving through the aquifer. With this information, the distance groundwater will travel toward a well in a specified period of time can be determined. These time-of-travel (TOT) distances can be used to delineate intermediate areas for protection that are smaller than the total contribution area.

The most useful type of TOT distance is based on the average linear velocity of the groundwater ($\bar{v}$) and the assumption that contaminants in the groundwater move at the same rate as the groundwater (advective flow).

The groundwater velocity equation can be derived from Darcy's law and the velocity equation of hydraulics:

$$\bar{v} = \frac{KI}{n}$$

where $\bar{v}$ is the average linear velocity of the groundwater. The hydraulic conductivity (K) is the aquifer capacity to transmit water. The hydraulic gradient (I) is the driving force that causes the water to move and determines the rate of groundwater movement. The water moves from areas with higher total head toward those with lower total head. The hydraulic gradient can be determined by dividing the change in total head between two points by the distance between these two points. Therefore, when the gradient is known, flow directions can be approximated. Finally, the effective porosity (n) is the ratio of the volume of openings (voids) to the total volume of rock or soil, expressed as a percentage. The hydraulic conductivity (K) and the hydraulic gradient (I) can be determined as mentioned previously. Porosity (n) can be obtained from existing reports or can be estimated based on composition of the aquifer. Tables giving average porosity values can be found in most hydrogeology textbooks. With these parameters, the average linear velocity can be determined and then used to determine TOT distances.

In using this method, it is important to remember the assumptions and uncertainties involved, which limit precision. In general, a travel-time approach assumes that contaminants in the groundwater will move at the same velocity as the groundwater. This is not true for many contaminants, such as gasoline. In reality, the movement of contaminants in groundwater is also affected by other processes. For example, dispersion and diffusion cause contaminants to move faster and arrive at a point before the time calculated (Anderson, 1984). On the other hand, chemical and biological processes such as sorption and biodegradation tend to slow or retard the movement of contaminants (Freeze and Cherry, 1979). The dispersion and retardation of contaminants in groundwater systems are poorly understood, and they are difficult to quantify even when studied in great detail. As a result, the use of TOT-distance calculations based on the average linear velocity of the groundwater remains the most feasible approach for a generalized statewide WHP program that deals with many different aquifers and a large number of potential contaminants. However, these uncertainties, combined with natural fluctuations in flow and the uncertainty in the estimates of other aquifer characteristics, mean that travel-time calculations are approximations of what exists in the field. In some cases, calculating a probable range of TOT distances using various parameter values may be useful.

The choice of appropriate time periods for calculating TOT distances is generally made on one of two bases: The time required for contaminants to decay or attenuate in the aquifer or the time required to respond to contamination of a water-supply aquifer. As an example of the first basis, Dade County, Florida (Camp, Dresser, and McKee, Inc., 1983; Crystal, 1983) has based WHP zones on 10-, 30-, and 100-day travel times, related to how long bacterial pathogens, inorganic chemical contaminants, and viruses persist in groundwater. Several European nations have also used this approach (Milde and others, 1983); for example, West Germany and the Netherlands have established WHP zones based on 50- and 60-day TOT distances, respectively. The variability of both the contaminants and the aquifer attenuation capacity means considerable judgment must be exercised in selecting the appropriate travel times upon which WHP districts can be based. On the second basis, the choice of a given travel time is intended to provide time either to clean up the contaminated aquifer or to develop a new water supply. These remedial actions may take years to accomplish, and therefore, require the delineation of correspondingly large TOT distances.

TOT distances may be applied in several ways. First of all, where the total contribution area is known, TOT distances can be used to delineate smaller, intermediate subareas within the well recharge area. An example of this approach is presented in the Whiting case later in this report. Where the contribution area to the well is not known, a given TOT distance can be used as a radius to delineate a circular protection zone around a well. Because such a zone could in some cases include a considerable area in which the groundwater is *not* moving toward the well, TOT distances are best used in conjunction with geologic/hydrogeologic mapping techniques. Generally, in cases where TOT distances are based on average linear velocity (v) calculations, the direction of groundwater flow will also be known, so that TOT distances can be determined only in the upgradient direction.

Although the calculated separating distance method using travel times is fairly easy to understand, it does require some knowledge of basic hydrogeologic principles to apply. In particular, it requires using judgment to estimate some of the necessary parameters and evaluate results. With the exception of the fixed separating distance method, it is the easiest method to apply, but the accuracy, of course, depends on the accuracy of the input parameters.

Because this type of calculation can be done using only a well log, a USGS hydrologic atlas for the area, and an estimate of porosity, the method could theoretically be applied to any municipal well in the state. However, time lines determined by this approach apply only to the movement of water within the aquifer itself. Where recharge rates are low or thick deposits overlie the aquifer, the time it takes water to get from the surface into the aquifer may be much greater than the time it takes water to move through the aquifer to the well. As a result, calculations of this type are of little value in delineating WHP districts for wells in semiconfined or confined aquifers.

Fixed Separating Distances

Fixed separating distances are used to delineate a circular area of a specific size for use as a WHP district. The size can be based on either generalized hydrogeologic considerations or non-hydrogeologic guidelines.

Hydrogeologic measures such as the calculated cone of depression or TOT distance of a specific well could be used to select a fixed separating distance. This distance would then be applied uniformly to all wells in the area, or even the entire state, without further consideration of local conditions. For example, a separating distance could be calculated for each major aquifer in Wisconsin, and all municipal wells within the aquifer would then have the same size WHP districts. Because local variability in conditions and the rate at which water is being pumped from the specific well are not considered, this method will be less defensible hydrogeologically than the other methods discussed in this report.

Fixed separating distances can also be based on non-hydrogeologic factors. For example, municipal wells in Wisconsin are required by Wis. Admin. Code sec. NR 111.31 (4) (a) to have minimum lot sizes of 100 ft by 100 ft. The aim of this requirement is to restrict activities and sources of pollution in the immediate vicinity of the well, and the code also states that these dimensions may be modified on a case-by-case basis if it is demonstrated that they are inadequate to protect water quality. The site is, therefore, serving as a *de facto* WHP district.

Because WHP districts based on fixed separating distances would be the same for all wells on a regional or statewide basis, the time and cost to implement this type of approach would be less than for the more sophisticated methods. Set standards could be applied on a local level without the need for hydrogeologic consultation. However, because the choice of separating distances is based at least as much on political and economic considerations as on hydrogeologic factors, the fixed separating distance method will not be discussed further here or in the applications section (chapter III) of this report.

Water-Budget Approach

A supplemental method to estimate subareas within the total contribution area is the water-budget approach. This method assumes a direct relationship between the volume of water pumped from a well/well field and the land area needed to recharge that amount of water to the aquifer. This area is usually more or less elliptical, encompassing the well field and extending upgradient. This method may be useful when dealing with extensive unconfined aquifers.

As is shown in the Whiting example (chapter III), where the upgradient extent of the aquifer is very large, the water-budget approach may serve to focus a WHP program on a smaller, more manageable area. However, because of the assumptions upon which a water-budget analysis is based, this approach should be used with caution. First of all, it is assumed that the volume of water pumped from a well in a year is equal to an annual rate of recharge times the recharge area. This implies that all recharge within that area will move through the aquifer and eventually be pumped at the well in question. In reality, some of this water will be pumped from other wells in the area or be discharged to surface water bodies. As a result, this approach will always underestimate the size of the area contributing water to the well. Furthermore, the recharge rate is often poorly known but is generally assumed to be uniform over the land surface. Several studies have shown that even with relatively uniform surficial and subsurface conditions, rates of recharge will vary spatially over the land surface (Faustini, 1985; Stoertz, 1985). This will, of course, affect both the size and shape of the recharge area. In short, all the limitations of this supplemental approach must be considered when employing it.

Numerical Models

Numerical methods can be used to solve mathematical models that simulate groundwater flow and contaminant transport. Numerical models use computers to solve series of equations in an effort to make predictions concerning groundwater head or the concentration of a contaminant. The simulated movement of groundwater and/or contaminants can then be used to delineate areas for use as WHP districts. Because field conditions are too complicated and/or poorly understood to simulate exactly, models are always simplifications of the actual field situation. The reliability of a particular groundwater model depends on how well it approximates the field situation (Wang and Anderson, 1982), but models always require some field calibration to be useful.

Numerical models can deal with complex situations. Presently, many computer models applicable to a variety of hydrogeologic environments exist. In addition to predicting groundwater flow and contaminant transport, models can also be used to delineate areas and rates of recharge and to simulate the effects of stresses, such as a pumping well's cone of depression. For example, McLeod (1975a), used a computer program to model groundwater flow in the sandstone aquifer underlying Dane County. Vales for the physical properties of the aquifer system were based on aquifer-test data. The model was verified by comparing measured 1970 drawdowns against those computed by the model. The model was then used to predict future drawdown in the aquifer. Figure II-5 illustrates the computed 1990 cone of depression. This predicted cone of depression can provide a hydrogeologic basis for delineating a WHP district that is anticipatory.

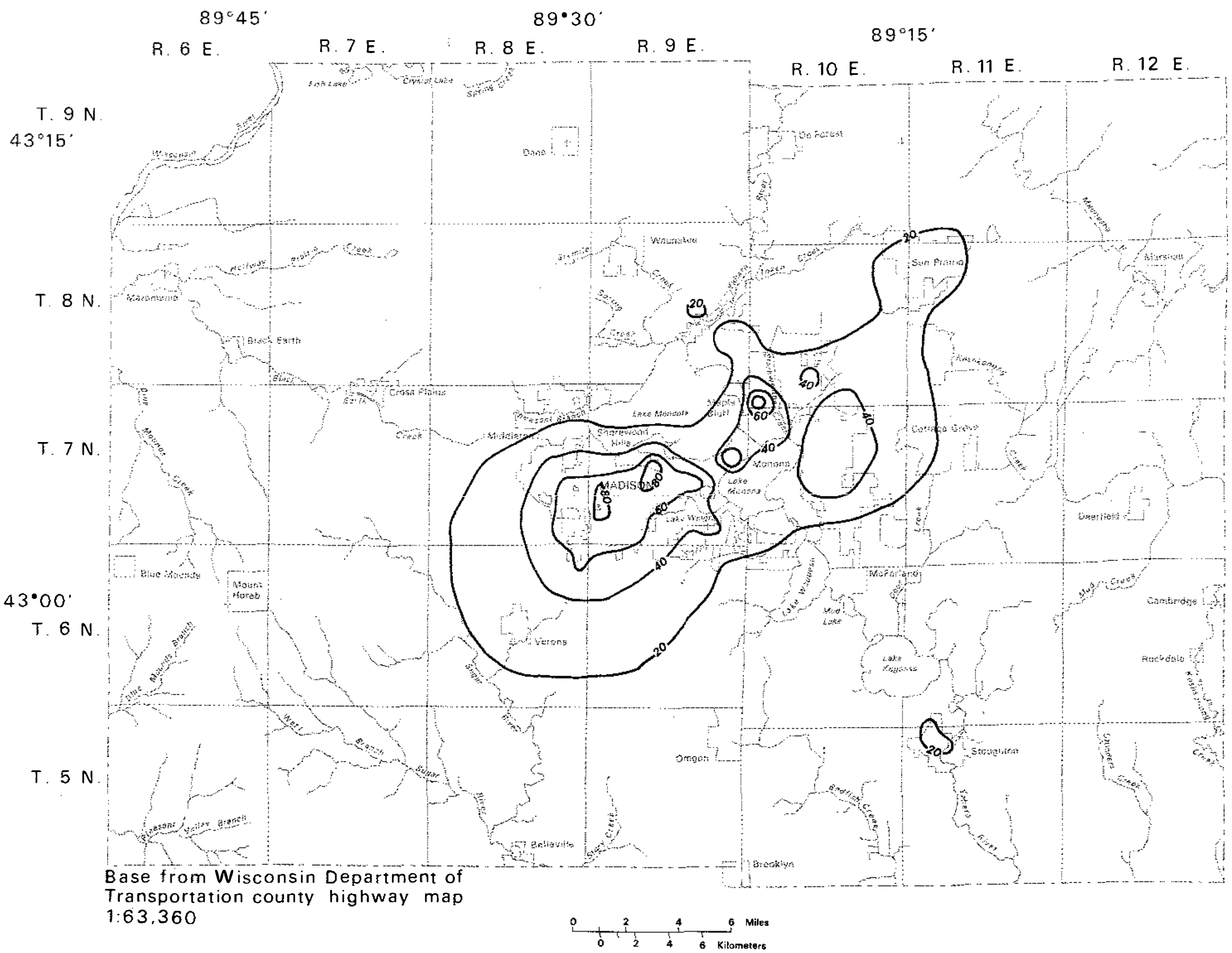


Figure II-5. Computed drawdowns in the Dane County sandstone aquifer by 1990 (from McLeod, 1975a).

Numerical models, however, pose numerous problems. First, as noted earlier, a significant amount of field data is required to design and check the performance of the model. Sufficiently detailed data are not available for most areas in the state. As a result, the use of computer models to delineate WHP areas would be both time consuming and costly because of the field studies needed to obtain adequate input data and the complexity of the modeling process. In addition, this type of model can only be applied by specially trained personnel.

Therefore, the use of computer models to delineate areas for a WHP program would be limited to cases where the required accuracy warrants the most sophisticated and costly tools. This would generally involve water supply for large municipalities, and particularly those that have already exhibited some indication of water-quality problems. Because computer models can provide insights into aquifer conditions, in some cases useful results may be obtained relatively inexpensively by using student researchers and comparatively limited data.

Results from previously modeled areas should, of course, be used wherever possible. Areas already modeled include northeastern Wisconsin (Emmons, 1987), southeastern Wisconsin (Young, 1976), Brown County (Krohelski, 1986), and Dane County (McLeod, 1975a; 1975b).

Summary

One or more of the methods for delineating WHP areas that have been described in this section will generally be applicable to municipal wells in unconfined and semiconfined aquifers in Wisconsin. The choice of which method or methods to use in a particular case will depend on a number of factors, including hydrogeologic conditions, availability and quality of data, and the time and cost allocated to program implementation. Although the exact method should be chosen on a case-by-case basis, several generalizations can be made.

First of all, the most important hydrogeologic factor to consider when selecting a method is the degree of confinement of the aquifer. All of the methods described, and the WHP district concept in general, are most applicable in unconfined situations. Because numerical modeling is not economically practicable on a statewide basis, the best approach in semiconfined cases would be to use analytical methods to determine a cone of depression, which then would serve as a basis for defining a WHP district. For unconfined cases a combination of several methods is likely to be most suitable.

Table II-1 summarizes the methods that we have discussed. At one extreme, the fixed separating distance method is the quickest and easiest to apply, but it is also the least hydrogeologically based and least defensible. Numerical models, on the other hand, can be highly detailed and accurate, but they are very time consuming and expensive to apply. As a result, while the use of one of these two methods may be the best approach in some circumstances, the use of one or several of the other methods will generally be more suitable for delineating areas for use as WHP districts in Wisconsin. The use of geologic/hydrogeologic mapping, analytical flow models, calculated separating distances, and/or a water-budget analysis add increased accuracy and defensibility to WHP districts. They are relatively quick and easy to apply, and should be used where possible. As noted at the outset of this report, these hydrogeologically based methods for delineating WHP districts will not be applicable to confined aquifer situations.

CHAPTER III

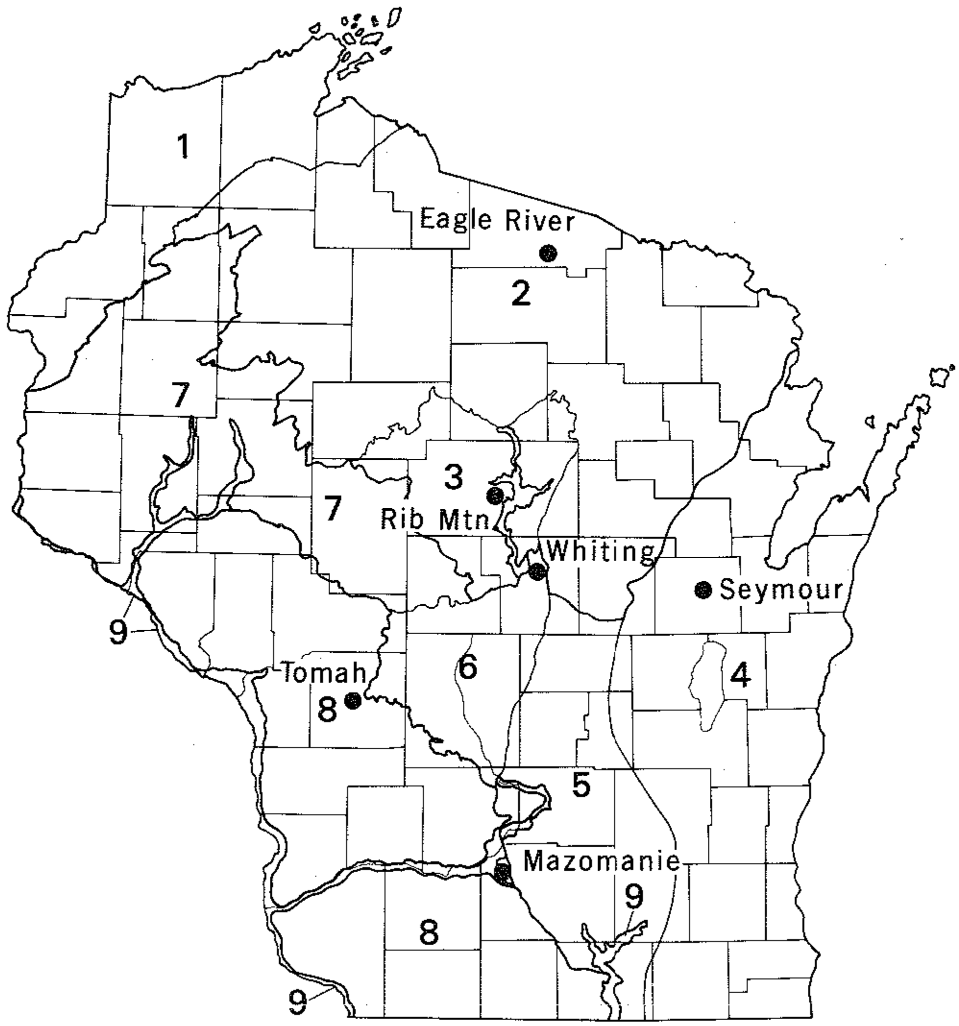
APPLYING THE HYDROGEOLOGIC METHODS TO REPRESENTATIVE GROUNDWATER ENVIRONMENTS IN WISCONSIN

Introduction and Rationale for Case Selection

The major aquifers of Wisconsin are the unconsolidated sand-and-gravel deposits, the eastern Silurian dolomite, and the upper and lower sandstone aquifers. Locally, shale and Precambrian crystalline rocks serve as minor aquifers where other productive units are absent or yield poor quality water. In selecting case examples to demonstrate the delineation of hydrogeologically based areas for protecting wells, we have chosen cases that are representative of both the sand-and-gravel aquifer and the sandstone aquifer, the principal sources of municipal water supplies throughout the state. Also, because the well-protection district concept is not particularly applicable to deep confined groundwater systems or fractured-rock aquifers, we have not included examples from the important deep confined and Silurian dolomite aquifers of southeastern Wisconsin. Other protection approaches are more appropriate in these cases (Feinstein, 1986; Young, 1976).

The cases that are illustrated in this report are representative of much of Wisconsin's groundwater resource. The examples are intended to facilitate the transfer of methods for use in areas of similar hydrogeology. Wisconsin has been divided into nine major groundwater units or hydrogeologic provinces (Zaporozec and Cotter, 1985). Groundwater occurrence within each district is somewhat uniform, and therefore, the districts provide a basis for the transfer of hydrogeologic knowledge within these units (fig. III-1). Our choice of cases was also influenced by trying to pick "typical" communities (with existing or potential groundwater quality problems) where we could illustrate a variety of approaches in which the availability of data, complexity of the problem, degree of sophistication of the analysis, and the level of funding differed. The locations of the case examples in this report are shown on figure III-1. The methods for delineating hydrogeologically based areas for WHP districts in each of these six cases are summarized in table III-1.

Whiting is a village located in the Central Sand Plain. The village shut down its municipal wells in July 1979 due to nitrate concentrations in excess of the drinking water standards. The nitrate contamination is believed to be from nonpoint agricultural sources upgradient of the well field, including irrigated liquid wastes, nitrate fertilizers, and animal feedlots. Whiting now receives its water from the city of Stevens Point. A network of wells and comparatively detailed hydrogeologic data allow us to use Whiting to demonstrate a variety of options for well-protection area delineation.



SUPERIOR UPLANDS
1. Lake Superior District
2. Northern Drift—Precambrian District
3. Central Precambrian District

GLACIATED PALEOZOIC
4. Eastern Drift—Paleozoic District
5. South Central Drift—Paleozoic District
6. Central Sand Plain District
7. West Central Drift—Paleozoic District

UNGLACIATED PALEOZOIC
8. Southwestern Paleozoic District

ALLUVIAL VALLEYS
9. Alluvial Valleys District

Figure III-1. Hydrogeologic provinces and districts in Wisconsin and the location of the six case examples (adapted from Zaporozec and Cotter, 1985).

Table III-1. Summary of the methods for delineating hydrogeologic areas for wellhead-protection districts for municipal wells in six Wisconsin case examples.

Case examples	Geologic/hydrogeologic mapping	Analytical models (cone of depression)	Calculated separating distances	Fixed separating distances	Water-budget approach	Numerical models	COMMENTS
Whiting	X	X	X		X		- Unconfined, sand-and-gravel aquifer - Analysis based on extensive hydrogeologic data; illustration of detailed calculations - Use of full array of hydrogeologic methods - Example of the effects of varying assumptions on the size of the cone of depression
Seymour	X	X					- Semiconfined, sandstone aquifer - Analysis based on substantial hydrogeologic data
Rib Mountain	X	X					- Unconfined sand-and-gravel aquifer, very small groundwater basin - First Wisconsin community to adopt a WHP ordinance
Eagle River		X	X				- Unconfined sand-and-gravel aquifer - Analysis based on minimal hydrogeologic data - Typical hydrogeologic conditions for much of northern Wisconsin
Tomah		X					- Unconfined, sandstone aquifer - Analysis based on mineral hydrogeologic data - Delineation of a single, potential WHP area based on the coalesced zone of depression of multiple municipal wells
Mazomanie		X					- Two municipal wells: one in unconfined, sand-and-gravel aquifer; and one in semiconfined, sandstone aquifer - Delineation of several distinct areas as potential WHP areas.

In the city of Seymour hydrocarbons have recently been detected in several private wells near the southern border. This has raised concerns about potential contamination of the city water supply. The Seymour example illustrates some of the limitations of applying the WHP concept where the aquifer is semiconfined.

The town of Rib Mountain recently drilled three high-capacity wells in constructing a new central water supply system. Several neighboring communities have detected volatile organic compounds and other groundwater contaminants in their water supplies, and Rib Mountain's well field is particularly susceptible to pollution. Rib Mountain has led the way in the state with the adoption of a well-protection ordinance to protect its drinking water.

The city of Eagle River was selected because its shallow, unconfined aquifer overlying crystalline bedrock is typical of much of northern Wisconsin. It also serves as an example of the delineation of hydrogeologic areas for potential WHP districts based on limited data.

In Tomah the sandstone aquifer is very near the surface, and is highly susceptible to pollution. Two of the city's four wells have yielded water samples that are contaminated with benzene. The Tomah example serves to illustrate a delineation based on the combined cone of depression of multiple municipal wells.

Finally, the village of Mazomanie illustrates a situation where both unconfined and semiconfined aquifers are being used to meet municipal water needs. It also serves to illustrate a case in which a single community may need multiple WRP districts.

Village of Whiting

Throughout large areas of the state, unconfined glacial deposits serve as important aquifers for domestic and municipal wells. The village of Whiting is a case in point, drawing large volumes of water from a shallow unconfined aquifer in the Central Sand Plain. The central sands is a glacial outwash plain consisting primarily of very well sorted deposits of sand and gravel that cover portions of 10 counties. At Whiting, approximately 100 ft of outwash deposits overlie the bedrock. These deposits extend 5 miles to the east to a glacial end moraine, where a change in topography and elevation occurs. The glacial deposits change from relatively uniform outwash sands to unsorted and less permeable sandy till. The end moraine trends north-south and acts as the ground and surface water divide. West of the divide, water moves through a continuous unconfined aquifer within the outwash deposits toward the Whiting well field (fig. III-2), and ultimately discharges to the Wisconsin River, located approximately 1 mile west of the well field. The outwash deposits are highly permeable, and where thick enough, comprise the most prolific aquifers in the state.

Recharge to the aquifer occurs when soil moisture deficiencies are overcome and water is transmitted through the soil -- primarily in the spring when rain and melting snow plus low evaporation rates allow rapid infiltration of water through the permeable sands. An additional source of water that is important from a water quality standpoint is irrigation return flow. Precipitation in the area averages 31 inches annually. Although rates of recharge vary spatially over the ground surface, due to geologic heterogeneities,

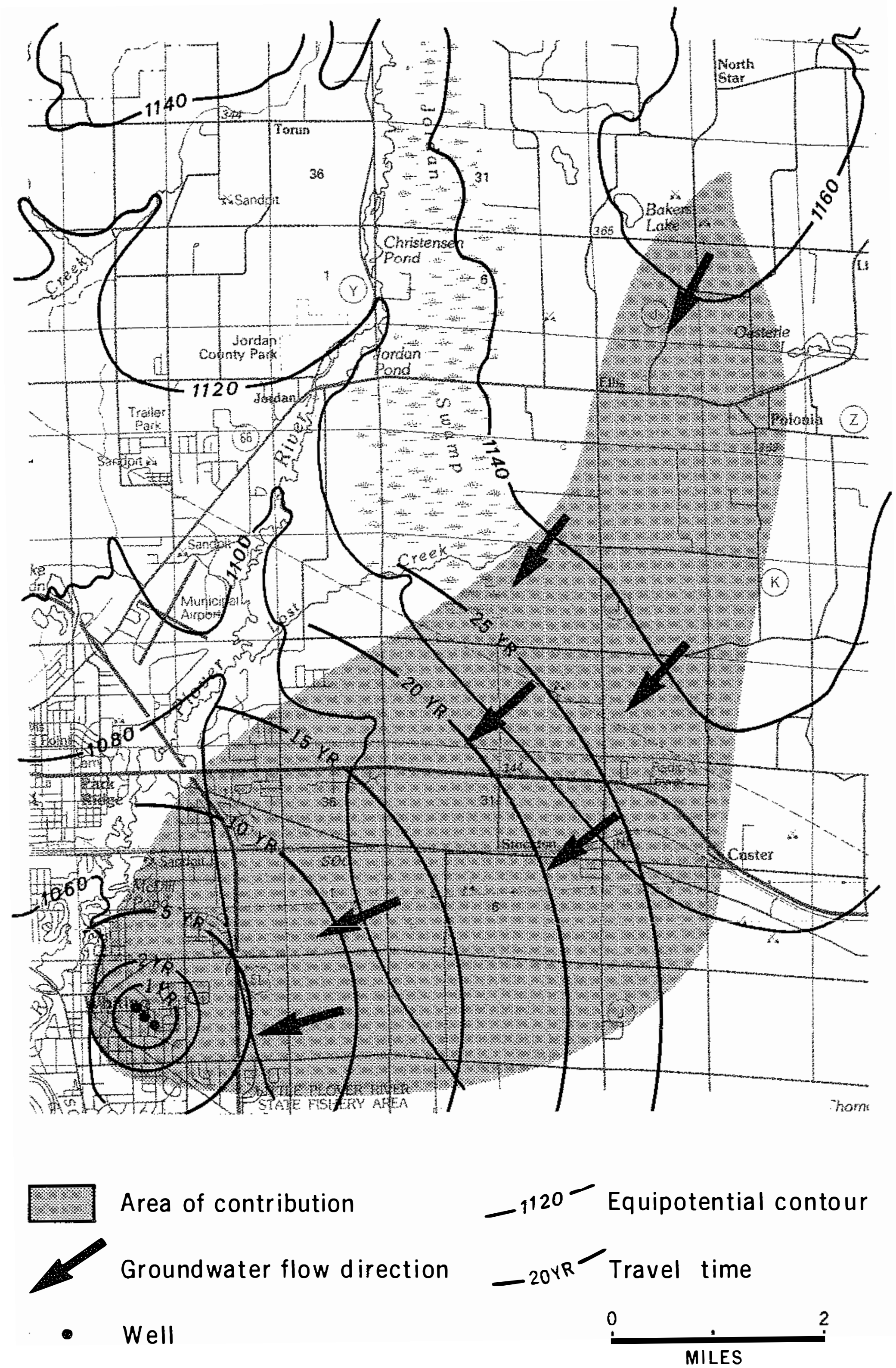


Figure III-2. Water-table map for the Whiting area showing the total contribution area to the Whiting well field, the direction of groundwater flow, and travel-time lines.

an average of approximately 8 inches of this precipitation infiltrates to recharge the aquifer (Stoertz, 1985).

Although the village of Whiting is not currently using its well field for municipal water supply, it was selected for demonstration because of its hydrogeology, representative data base, and coincidentally, its status as an excellent example of the effects of surface contaminants on water quality within a shallow, unconfined aquifer. This case study provides a detailed presentation of the process of delineating WHP areas using geologic mapping, TOT distance, water budget, and an analytical calculation of the cone of depression.

The first step in hydrogeologic mapping is to gather all available information from previous studies. In addition to well logs and the USGS Hydrologic Atlas (Olcott, 1968), several other published reports are also available. Besides general information on the geology and hydrology of Portage County, Holt (1965) provides information concerning the location of groundwater divides, the hydraulic conductivity (K), the hydraulic gradient (I), and the direction of groundwater movement. A water-table elevation map is also found in WGNHS Miscellaneous Paper 81-1 (Lippelt and Hennings, 1981).

From this information the groundwater basin for the Whiting area is determined. Its approximate boundaries (fig. III-2) include the end moraine to the east, the Plover River to the north and west, and the Little Plover River to the south. Because of Whiting's location near the mouth of the groundwater basin, water recharging the aquifer throughout much of the basin may eventually reach the well field. Although this total area of contribution to the well should be considered for a WHP district from a hydrogeologic viewpoint, its large size may make this impractical for Whiting. Therefore, the delineation of hydrogeologically based subareas for consideration as WHP districts is necessary.

To do the necessary TOT calculations, information concerning aquifer characteristics must be gathered. Holt (1965) reports a transmissivity of 18,700 sq ft/day, a value which is in reasonable agreement with the transmissivity values calculated using specific capacity data from the well logs. Included in appendix 2 are the results of transmissivity calculations from both hand and computerized calculations. These ranged from 14,400 sq ft/day to 23,000 sq ft/day. Where possible, values for aquifer properties based on aquifer tests should be used; therefore, the hydraulic conductivity of the aquifer can be calculated as follows:

$$K = \frac{T}{b} = \frac{18{,}700 \text{ sq ft/day}}{80 \text{ ft}} = 234 \text{ ft/day}$$

where

K = hydraulic conductivity
T = transmissivity
b = saturated thickness of the aquifer

We now solve for the average linear velocity ($\bar{v}$) of groundwater at Whiting using a version of Darcy's Law:

$$\bar{v} = \frac{KI}{n} = \frac{(234 \text{ ft/day})\ (0.0025)}{0.20} = 2.9 \text{ ft/day} = 1{,}070 \text{ ft/year}$$

where

$\bar{v}$ = average linear velocity of groundwater flow
I = hydraulic gradient (determined from water-table map)
n = effective porosity assumed to be 20 percent.

Therefore, the average rate of groundwater flow within the recharge area toward the Whiting well field is 1,070 ft per year (0.20 miles per year).

Using the water-table map from Holt (1965), an average hydraulic gradient for the basin was determined. This average hydraulic gradient was used to determine a series of travel-time distances, each corresponding to the distance water within the aquifer will move within a specified time period (fig. III-2). Although the movement of contaminants in groundwater is controlled by a number of factors in addition to the rate of groundwater flow, the average linear velocity is the best approximation available and will be used here.

The age of the water being pumped at the Whiting well field has been estimated using radiometric dating techniques (Blanchard and Bradbury, 1986). These analyses, based on the half-life of tritium, suggest that at least some of the water produced by the well was between 13 and 30 years old. This is consistent with the results of the TOT calculations, and implies that water recharging the aquifer miles upgradient is eventually flowing to and being captured by the well field. Therefore, to effectively protect groundwater, a WHP district for Whiting must consider land use and management practices several miles upgradient.

The water-budget approach is another method by which subareas within the total contribution area may be determined. It is useful in cases such as Whiting, where the total contribution area is too large to use as a WHP district. As discussed previously, the water-budget approach implies that under steady-state conditions, a direct relationship exists between the volume of water pumped at the well and the land area needed to recharge that amount of water to the aquifer.

The Whiting well field is currently producing a total of 134,000,000 cubic ft of water annually for use by the Consolidated Paper Company. Using an estimated average rate of recharge equal to 8 inches (0.67 ft) per year (Stoertz, 1985), the total land area needed to recharge a volume of water equal to the volume being withdrawn by pumping is calculated to be

$$\text{total recharge area} = \frac{\text{volume pumped per year}}{\text{depth of recharge per year}}$$

$$= \frac{134{,}000{,}000 \text{ cu ft/year}}{0.67 \text{ ft/yr}}$$

$$= 200{,}000{,}000 \text{ sq ft,}$$
or approximately 7 sq mi.

The first step in locating this 7-square-mile area of contribution to the Whiting well field is to construct flowlines at approximately right angles to the equipotential lines (lines of equal head) found on the water-table map. The flowlines should extend all the way to the groundwater divide (fig. III-3), approximately 7 miles. The next step is to locate the lateral boundaries of this recharge area relative to the central flowline. For this case the lateral boundaries are established approximately 0.5 miles from the central flowline to achieve the total recharge area of roughly 7 square miles. Remember that a water-budget analysis will always underestimate the size of the recharge area. Factors such as seasonal variation in precipitation and flow patterns, variations in pumping rates, and discharge to streams or other wells result in fluctuations in the lateral boundaries of the recharge area.

In addition to the travel-time and water-budget methods just described, calculation of the cone of depression around the Whiting well field can also be used to delineate subareas of the total contribution area. (Examples of both hand calculations and computer output using the Theis equation are included in appendix 2.) Because we are dealing with an unconfined aquifer, the cone of depression analysis is based on a 3-day pumping test. The water being pumped at the Whiting well comes from three wells that are in a line approximately 1,100 ft long (fig. III-4). Pumping from the site is continuous with individual wells pumping in alternating 8-hour intervals. In this case, computer analysis showed that cones of depression, based on a model in which all pumping occurred at the center well, were very similar to the cones of depression generated by a more detailed approach using the actual pumping schedule. Results presented here are based on this model in which all pumping occurs at the center well.

The size of the cone will vary markedly with the drawdown selected to represent the outer limit of the cone. To illustrate this point, three different cones of depression are presented for Whiting. The selected drawdowns were 0.1 ft, 0.5 ft, and 1.0 ft. The corresponding radii of the cones of depression were 1,422 ft, 948 ft, and 711 ft, respectively (fig. III-4). Because all water within the cone of depression moves toward the pumping well, the area of the cone is an important area to be considered in establishing a WHP district.

A final composite showing the results of travel-time calculations, geologic mapping, and water-budget analysis, and the cone of depression (based on 0.1 ft of drawdown) is presented in figure III-3.

City of Seymour

The next example, the city of Seymour, is located in northeastern Outagamie County, about 10 miles west of Green Bay. The city water supply is pumped from a deep, semiconfined sandstone aquifer by two municipal wells. Unlike Whiting, where the highly permeable aquifer extends to the land surface, in Seymour the aquifer is overlain by several hundred feet of unconsolidated deposits and bedrock (fig. III-5). These unconsolidated units are generally less permeable than the lower sandstone aquifer, and as a result, they tend to restrict the movement of water from the surface to the aquifer.

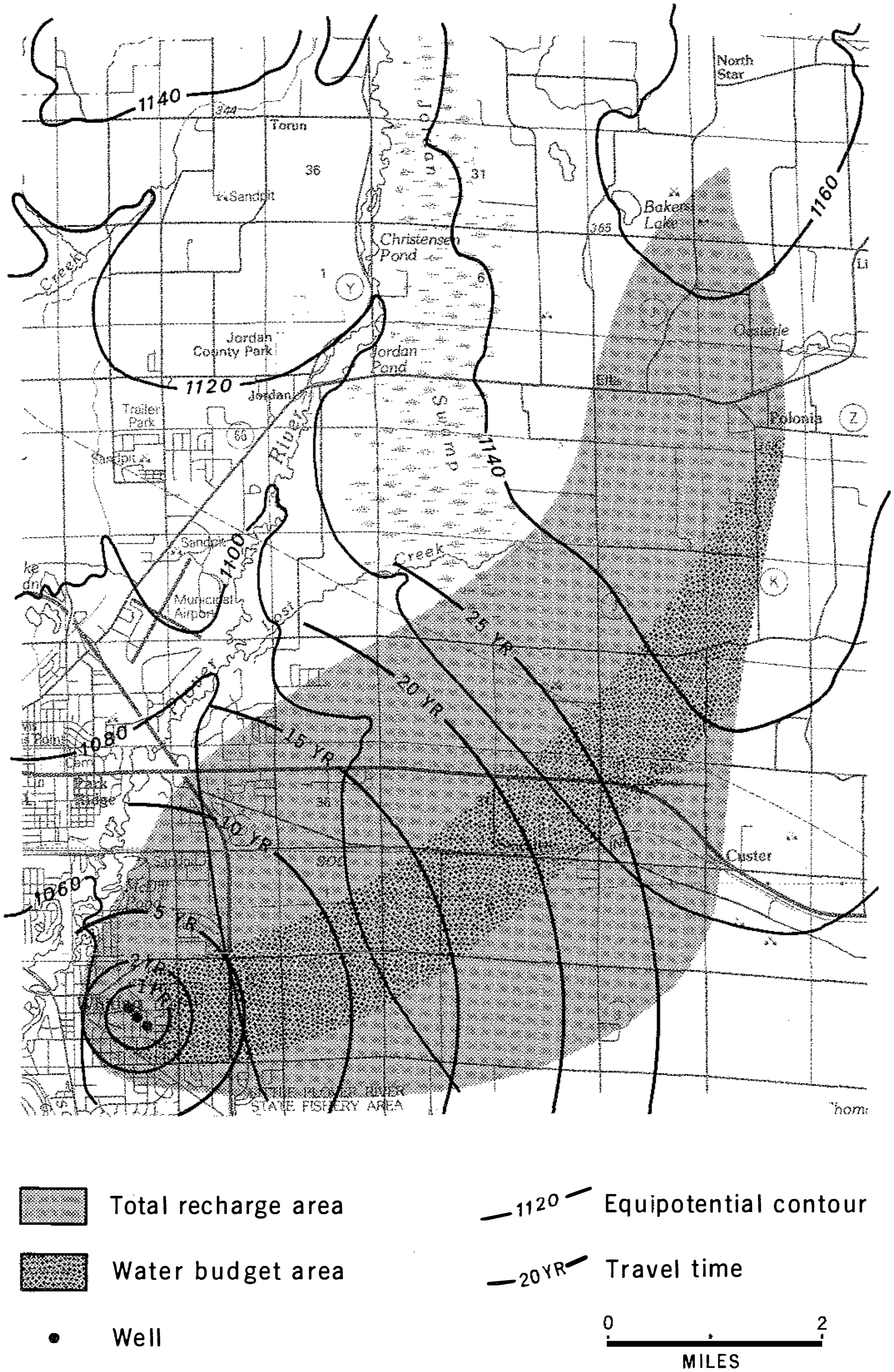


Figure III-3. Comparison of the areas calculated for the Whiting well field based on total contribution area, travel time, water budget, and cones of depression (adapted from Holt, 1965).

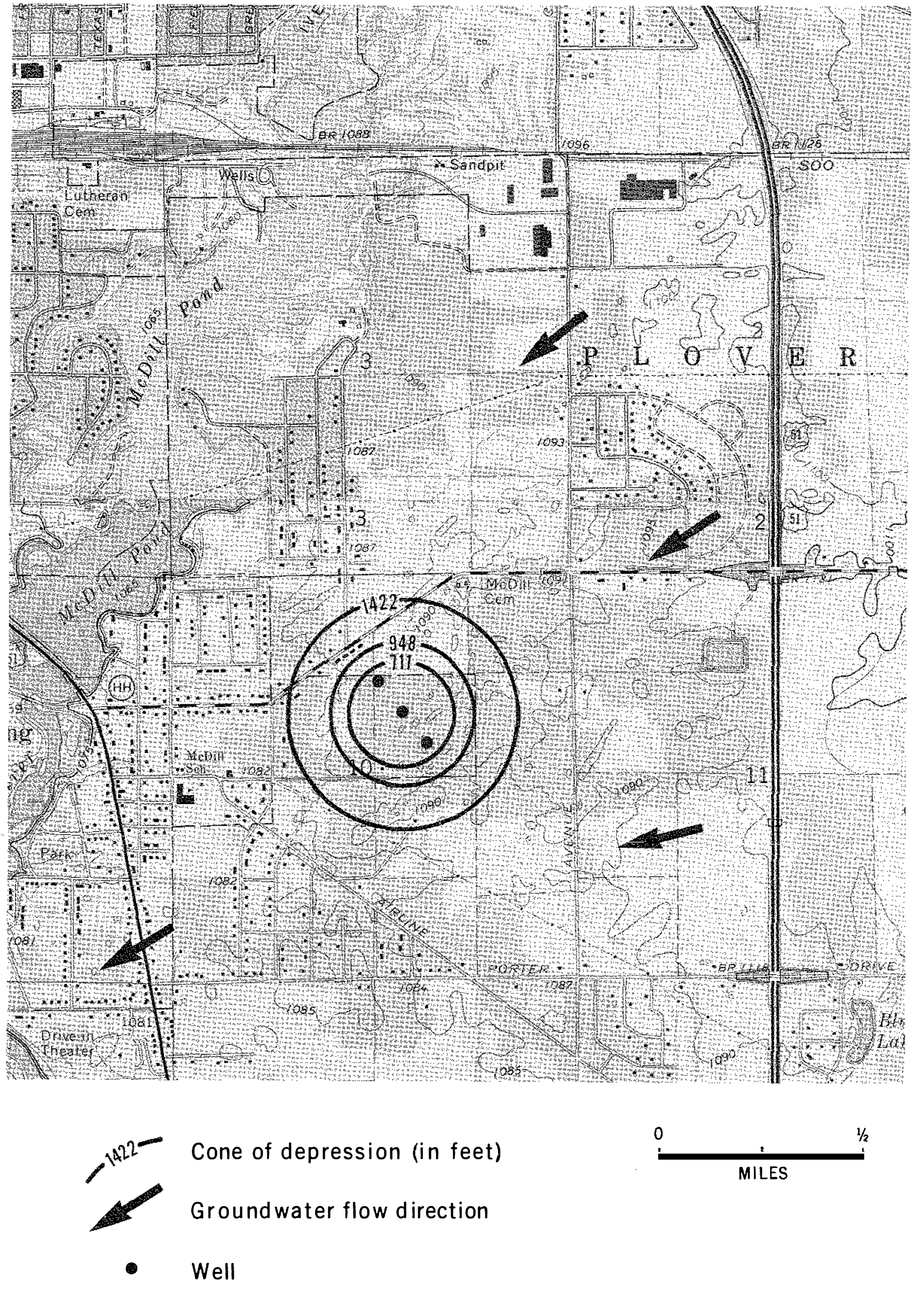


Figure III-4. Cones of depression for the Whiting well field.

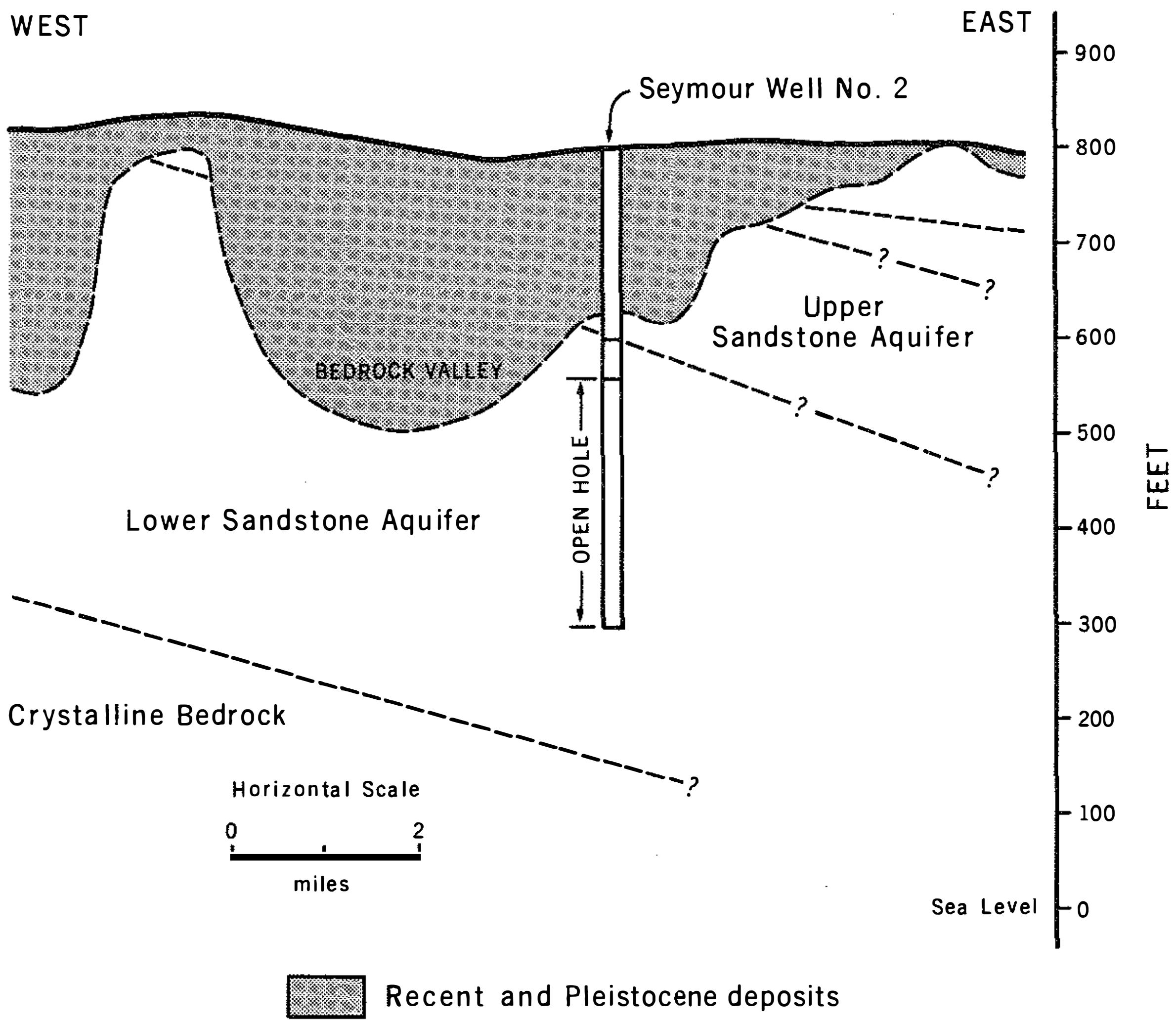


Figure III-5. West-east geologic cross section through Seymour municipal well number 2 (adapted from Le Roux, 1957).

The WHP concept is more difficult to apply in the case of semiconfined aquifers. The delineation of a recharge area or groundwater basin in a semiconfined situation like Seymour is difficult for several reasons. First of all, the movement of groundwater in the lower sandstone aquifer is controlled by regional flow patterns in which the water may move many miles from its point of recharge to its eventual discharge. In addition, the movement of water in surface drainage patterns and of groundwater in shallow flow systems in the overlying units may not coincide with the regional flow patterns. Finally, recharge occurs due to the slow leakage of water from the saturated overlying deposits to the lower sandstone aquifer. Because the deposits can be highly variable both horizontally and vertically, the infiltration of water will be greatest where the overlying deposits are thin, fractured, or have greater vertical permeabilities. As a result, recharge rates may vary greatly over relatively short distances (LeRoux, 1957).

We feel that the best approach in semiconfined situations such as at Seymour is to use the calculated cone of depression, supplemented by the area of contribution as determined from the potentiometric surface map (fig. III-6), as the basis for defining a WHP district. The TOT distance approach deals only with the time it takes water to move through the aquifer. Because it takes water many years to move vertically down through the unsaturated zone and enter the groundwater flow system, TOT distance calculations were not used.

Figure III-6 shows the movement of groundwater flow toward Seymour from the north. The movement of groundwater is influenced by the large bedrock valley filled with unconsolidated materials near Seymour (figs. III-5 and III-6). Water moves into the valley and then continues westward (LeRoux, 1957). Therefore, water recharging the aquifer north of Seymour may eventually be pumped by the city wells. Much of the water that is pumped from the city wells may have entered the aquifer at distant recharge areas outside the cone of depression. However, the large size and uncertain shape of the upgradient recharge areas for a semiconfined aquifer make the use of the entire recharge area as a WHP district impractical for Seymour.

To determine the cone of depression, information concerning the aquifer and the rate of pumping at the Seymour municipal wells was collected. Well logs were used to determine the nature and extent of the aquifer, and transmissivity was calculated from specific capacity data (appendix 3). A USGS report (LeRoux, 1957) provided information on transmissivity, hydraulic conductivity, storage coefficient, and the direction and rate of groundwater movement. Information on pumpage rates at these wells was obtained from DNR records.

Using the maximum daily pumping rate, the Theis equation was used to determine the cone of depression. For comparison purposes, figure III-6 shows the 1.0-ft, 0.5-ft, and 0.1-ft drawdown radii (5,150 ft, 6,500 ft, and 9,500 ft respectively). For reasons given in the methods section of this report, a 1.0-ft drawdown is appropriate to determine the cone of depression in semiconfined cases.

Although it is not possible to quantify the amount of water leaking into the aquifer from the overlying deposits without a detailed and costly study, water does converge on the wells from all directions within the cone of depression. Therefore, we can assume that any contaminant infiltrating the soil within this area could make its way to Seymour's wells. Although the 150 ft of glacial and lake deposits that overlie the sandstone aquifer in the area will, on average, provide a certain degree of protection of the groundwater against contamination, these deposits vary greatly in their ability to transmit water. The deposits are made up of many interbedded units with differing hydraulic properties and thickness. Glacial till units generally have low hydraulic conductivities and would, therefore, limit the movement of contaminants. However, geologic discontinuities (till joints and/or permeable seams of sand and silt), which would allow rapid migration of contaminants (Gordon and Huebner, 1984), are common. Therefore, at a minimum, the area within the cone of depression should be protected against undesirable uses.

In conclusion, although the use of the WHP concept is less applicable in a semiconfined situation like Seymour, the identification of key hydrogeologic area(s) can be useful for municipal well protection. Because hydraulic breaks in the overlying

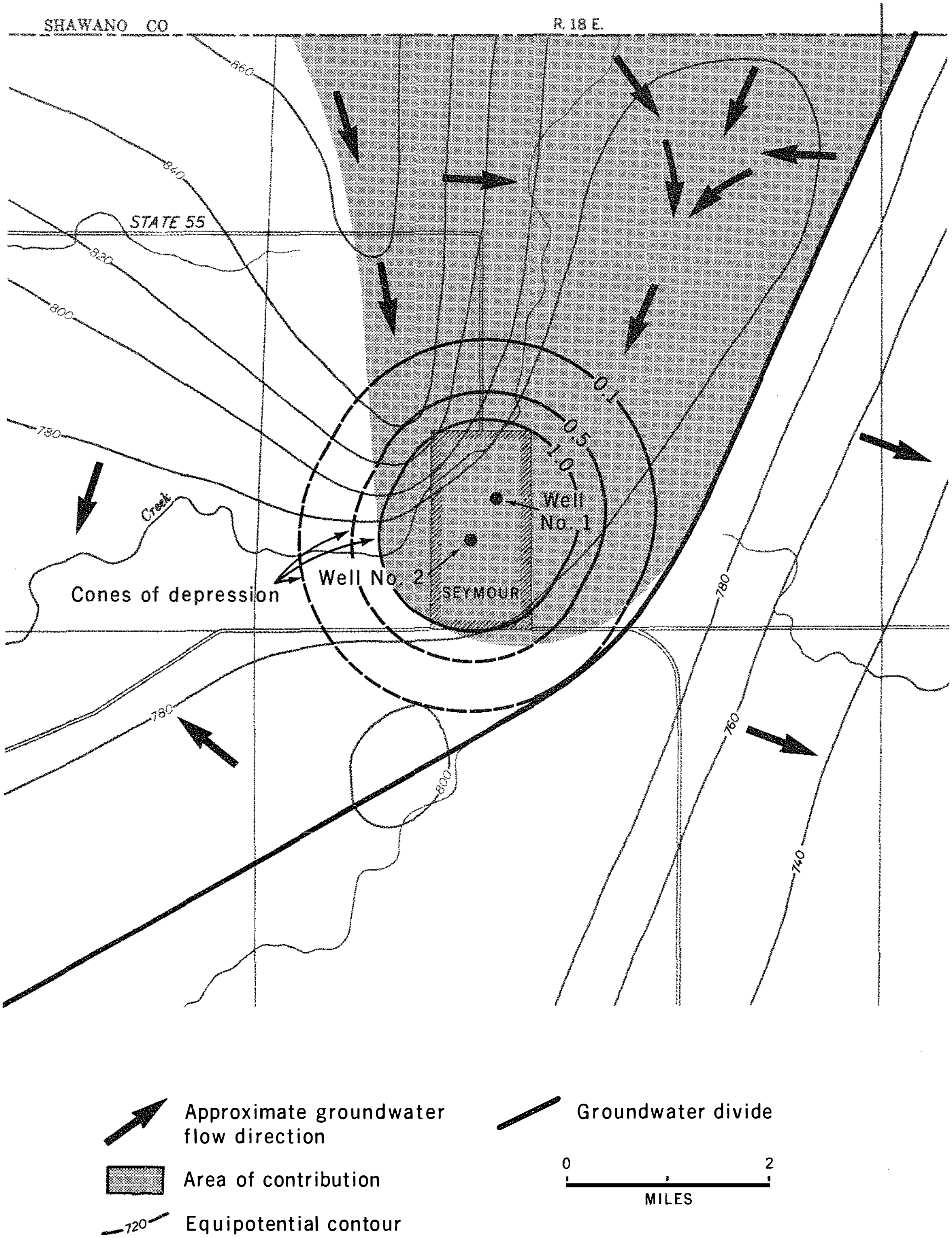


Figure III-6. Potentiometric surface map of the Seymour area showing the contribution area to the municipal wells and the cone of depression for 1.0-ft drawdown (0.5- and 0.1-ft drawdown cones are shown for comparative purposes). Adapted from Le Roux, 1957.

protective deposits within the cone of depression may become pathways for the rapid movement of contaminants to the drinking water, careful enforcement of well-protection and abandonment codes becomes very important.

Town of Rib Mountain

River valley (alluvial) aquifers composed of sand-and-gravel deposits are located beneath the floodplains of Wisconsin rivers. Where they are thick, these sand-and-gravel deposits are often prolific aquifers. These geologic formations are common along major river systems in the state, including the Chippewa, Rock, Mississippi, and Wisconsin rivers. The town of Rib Mountain, in Marathon County near Wausau, is located in this type of hydrogeologic setting. The town of Rib Mountain lies between the west bank of the Wisconsin River and two large bedrock bluffs, Rib Mountain and Mosinee Hill. Together, the bluffs and the river act as flow boundaries enclosing a relatively small (2.1 sq mi), well-defined surface and groundwater drainage basin. The basin's high relief and strong topographic boundaries channel flow down from the bluffs and into alluvial sand-and-gravel deposits, before discharging into the Wisconsin River. These highly permeable alluvial deposits are confined to the lowlands and are thickest (at least 100 ft) near the Wisconsin River (fig. III-7). Crystalline bedrock underlies the sand and gravel in the lowlands and is at or near the surface at higher elevations. This bedrock is relatively impermeable and is not an adequate source of water for municipal wells. The limited extent of the alluvial deposits, as well as their geographical location at the end of a small drainage basin, make the delineation of the recharge area for wells within these deposits by geologic mapping straightforward.

Because the highly permeable deposits that make up this unconfined aquifer extend to near the surface, the aquifer is recharged directly by precipitation and by surface and groundwater flow discharging into the alluvial deposits from higher elevations. Rib Mountain wells are located about 500 ft from the Wisconsin River, at the bottom of the basin. As a result, these wells intercept flow originally derived from points throughout the entire basin (fig. III-8). Therefore, contaminants that enter the ground anywhere within the basin have the potential of being captured by the town wells. The thin soil cover, a very permeable aquifer, and the location of town upgradient from the well field, make Rib Mountain wells very susceptible to contamination.

For purposes of protecting the town water supply, an ordinance was adopted regulating activities within a WHP district, delineated on the basis of several hydrogeologic methods. Using pump test results and specific capacity information for the three new wells, the hydraulic properties of the aquifer were determined. Using these parameters and the current maximum daily pumping rates, the Theis equation was used to determine a cone of depression. The high transmissivity of the aquifer resulted in a broad, flat cone of depression with the 0.1-ft drawdown radius being approximately 1,100 ft. As a result, the cone of depression covers almost the entire mouth of the basin (fig. III-8). When natural variations in flow paths from seasonal changes and climatic conditions are considered,

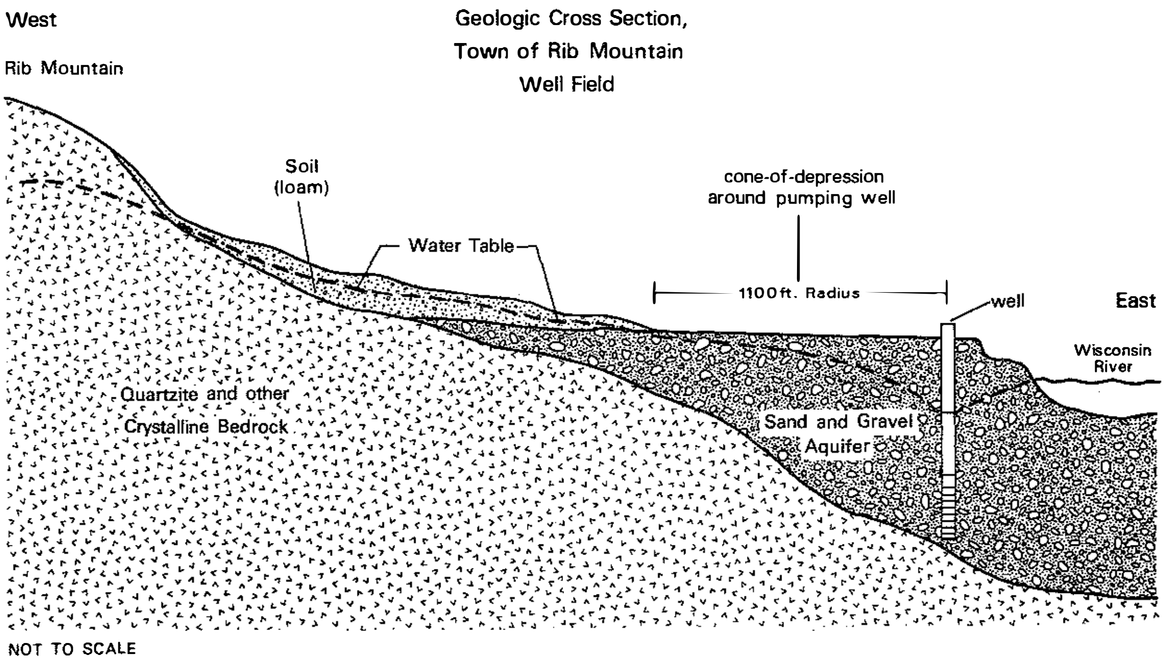


Figure III-7. Geologic cross section of the Rib Mountain groundwater basin (adapted from Hennings and others, 1985).

it becomes clear that the entire basin contributes to the town water supply. It should be noted that despite the Wisconsin River's being close to the well field, water-quality testing suggests that river water is not entering the municipal wells.

The size and shape of the basin were determined using the standard technique of delineating the topographic drainage basin (fig. III-8), and assuming that the surface-water and groundwater basins and divides were largely congruent. This is a reasonable assumption for a small basin, with significant topography and a shallow, unconfined aquifer. Next, the extent of the sand-and-gravel aquifer was mapped within the basin. Surficial geologic maps, well logs, and to some extent soil surveys were used for this purpose. Because these alluvial deposits have a much higher hydraulic conductivity (K) than the other deposits in the basin, contaminants entering the alluvial deposits will move to the municipal well field very rapidly. Therefore, in this case, geologic mapping techniques were used to delineate the most vulnerable area -- the alluvial deposits -- within the total area of contribution (fig. III-8).

City of Eagle River

The city of Eagle River is located in northern Wisconsin in Vilas County. It is in the upper Wisconsin River basin, and the area is characterized by an irregular glacial landscape consisting primarily of pitted outwash plains. The basin in general has a poorly developed drainage network and numerous lakes (Oakes and Cotter,

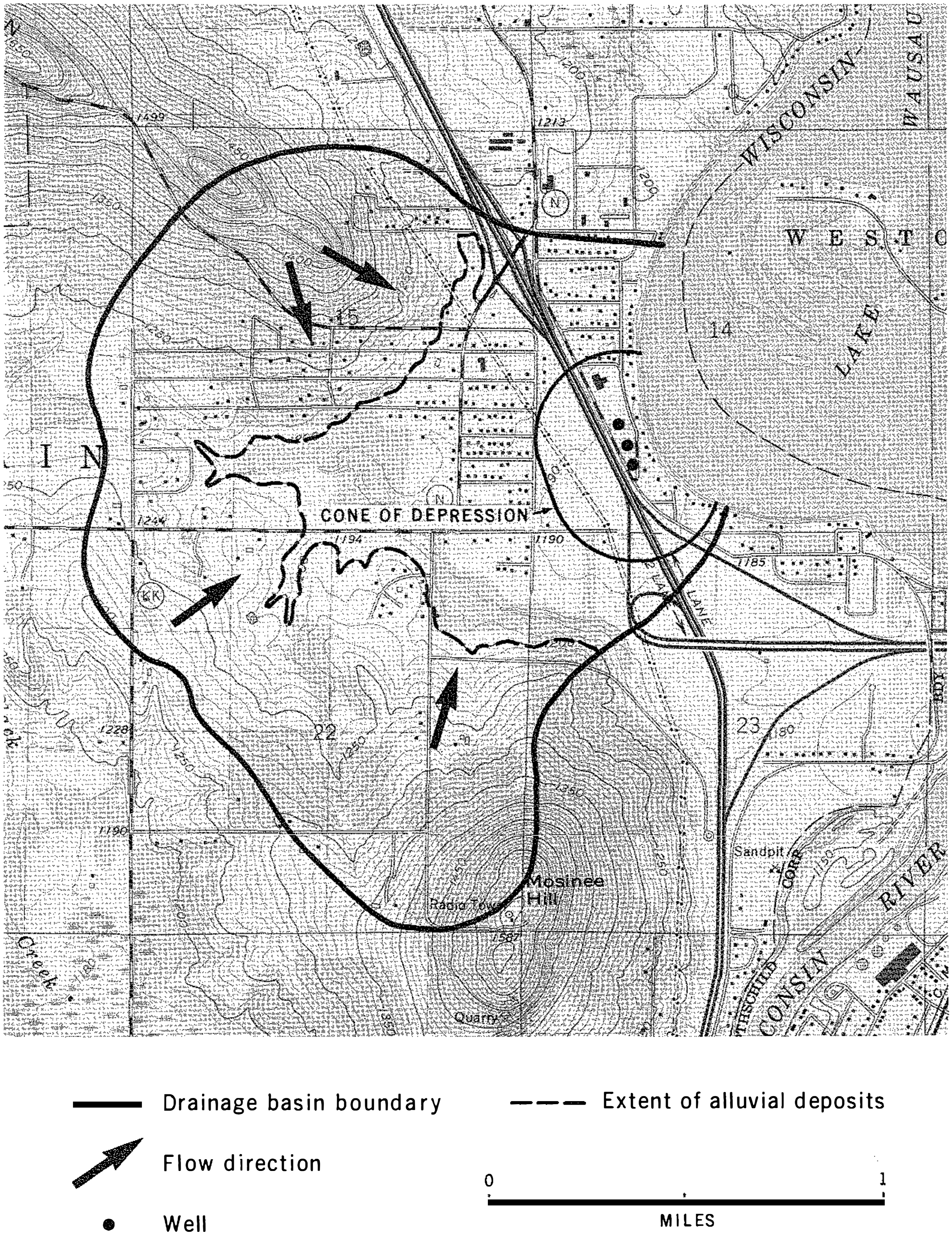


Figure III-8. The town of Rib Mountain's drainage basin showing flow directions and cone of depression of the well field (adapted from Hennings and others, 1985).

1975). Pleistocene deposits overlie Precambrian crystalline bedrock throughout the basin, which in this area yields only small quantities of water from weathered and fractured zones. As a result, the sand-and-gravel aquifer, which includes Pleistocene deposits and recent river sediments, is the only significant source of groundwater in the basin (Zaporozec and Cotter, 1985). Although only limited hydrogeologic data are available for this area, it was possible to delineate WHP areas using a USGS Hydrologic Atlas (Oakes and Cotter, 1975), one available well log (for well number 3), and pumpage records submitted to the DNR by the city of Eagle River.

Eagle River has three municipal wells completed in the sand-and-gravel aquifer. Well number 1 is currently on standby, and wells number 2 and number 3 are alternately pumped to meet local water demand (Syftestad, 1985). The deposits making up the aquifer in the vicinity of Eagle River are generally 100-150 ft thick; they are typically stratified outwash consisting of sand and gravel with some patches of ground moraine containing sandy clay (Oakes and Cotter, 1975). The depth to water in well number 3 is approximately 20 ft. This well is 130 ft deep and has been cased to a depth of 98 ft. As a result, it draws water from the lower, more productive portion of the aquifer. The surface materials are quite permeable and allow good local recharge. The general direction of groundwater flow in the vicinity of the municipal wells is toward Eagle River.

Because of the poorly developed drainage system and the relatively flat topography in this area, we did not delineate the groundwater basin, that is, the total area of contribution to the well. Instead, we focused on delineating a potential WHP district based on the cone of depression and travel-time distances.

To determine the cone of depression, calculated values were used for hydraulic conductivity (K) and transmissivity (T) based on the specific capacity of well number 3 (the only well with a well log). These values were 66 ft/day and 8,000 sq ft/day, respectively. The cone of depression was then calculated using the maximum daily pumpage rate (Q) of 389 gpm, an estimated storage coefficient (S) of 0.15, and a duration time of 3 days. The cone of depression based on a 0.1-ft drawdown had a radius of 920 ft. Figure II-9 shows the location of the Eagle River municipal wells and their cones of depression. For both wells, the cones of depression reach the river, and the movement of water from the river into the aquifer is likely.

To determine TOT distances, the average linear velocity (v) of the groundwater was calculated using the following parameters: a hydraulic conductivity (K) of 66 ft/day, a hydraulic gradient (I) based on the water-table map (Oakes and Cotter, 1975) of 0.001, and a porosity estimated to be 0.20. This gives an average linear velocity (v) of 0.33 ft/day or 120 ft/year. Selected TOT distances based on this velocity are shown in figure III-9.

In conclusion, it appears that, even in cases where there are limited hydrogeologic data, the delineation of potential WHP districts based on hydrogeologic factors will generally be possible. Because hydrogeologic information is limited for much of Wisconsin, a simple analysis of the type done here may be adequate and appropriate for many municipal wells; refinement of areal delineations could occur at a later time.

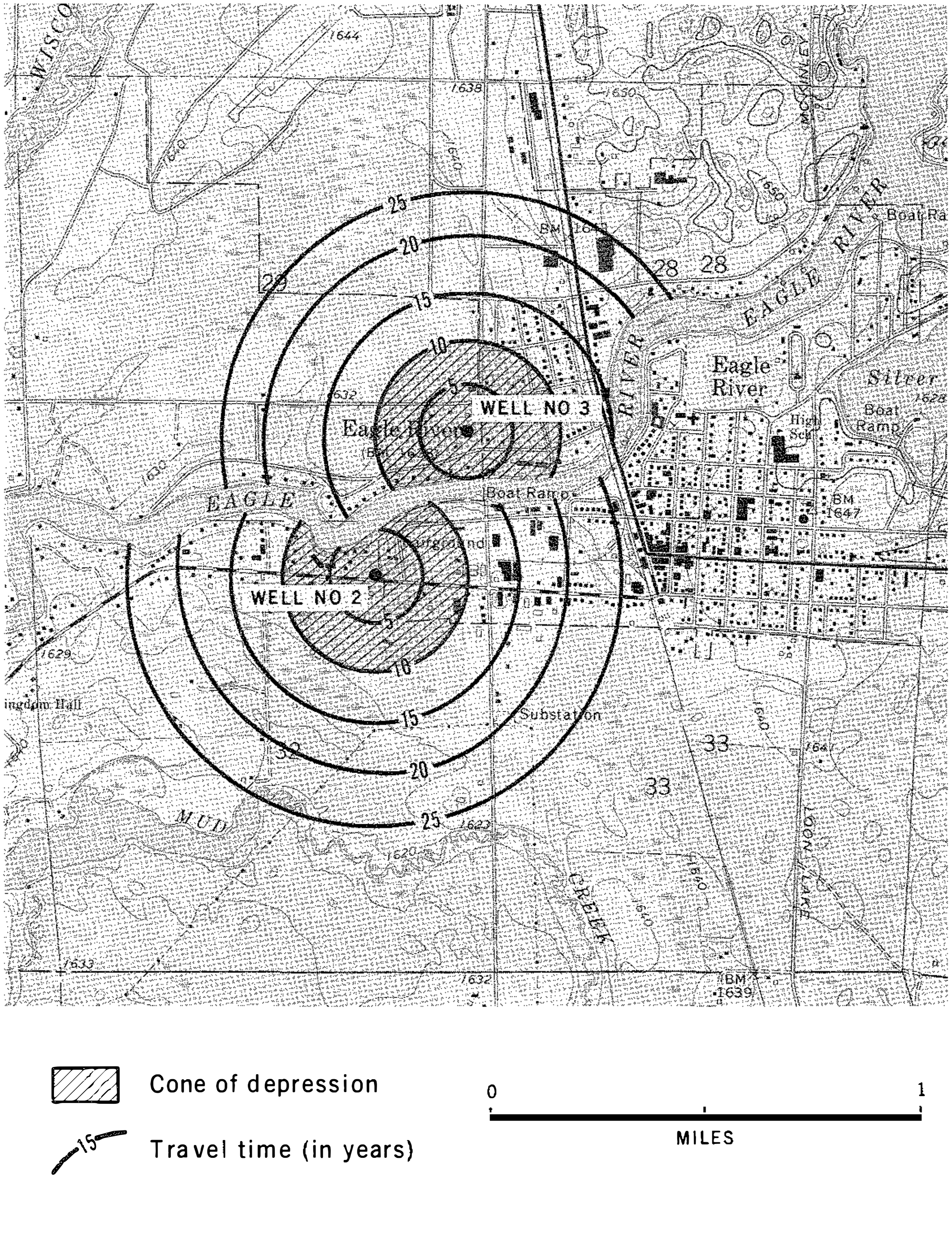


Figure III-9. Travel-time lines and cones of depression for the city of Eagle River's well numbers 2 and 3.

City of Tomah

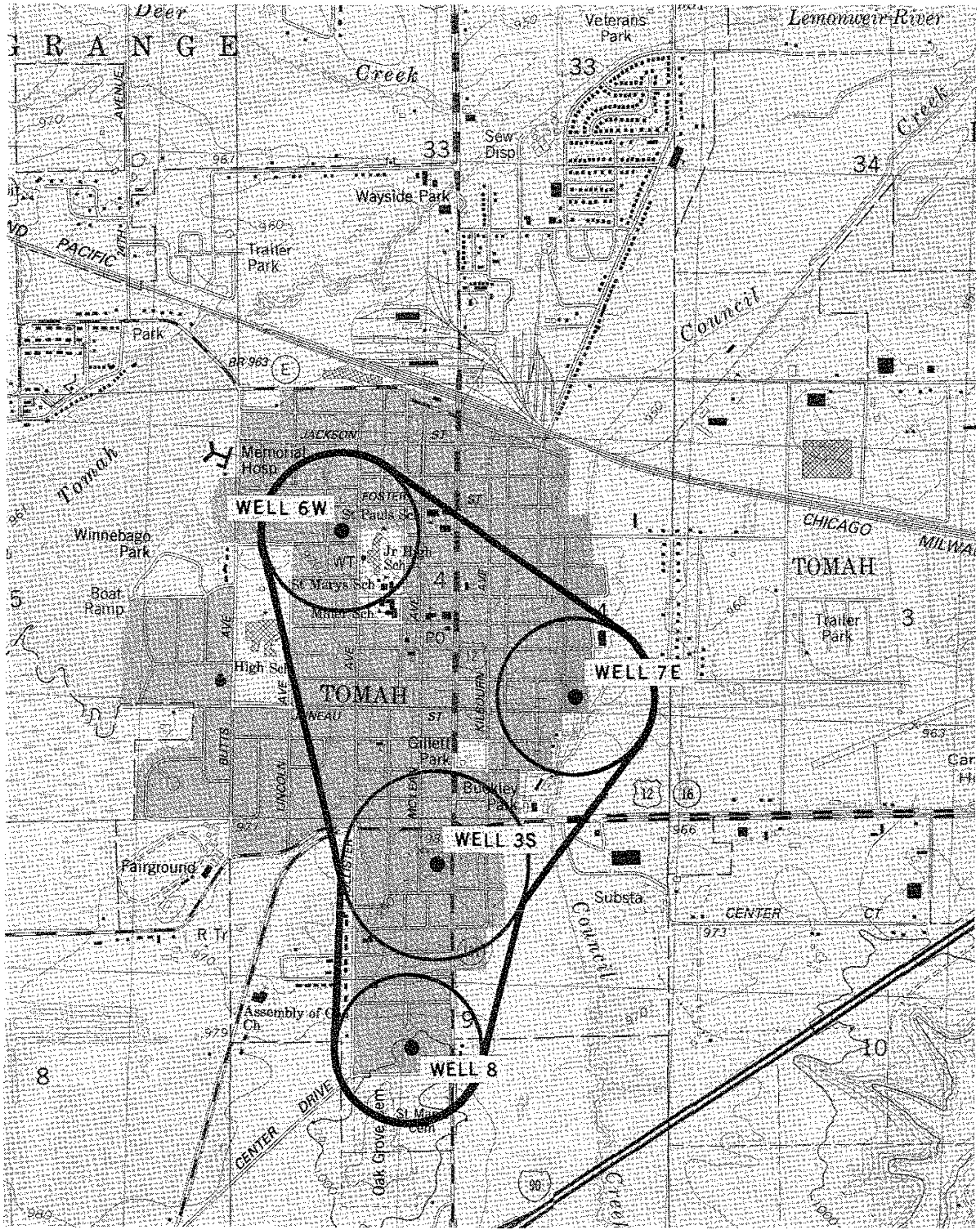
The city of Tomah is located in west-central Wisconsin in Monroe County and is within the Wisconsin River drainage basin. In an effort to meet a growing demand for water, Tomah has recently drilled a new well, which, like its other three municipal wells, is completed in the lower sandstone aquifer. In addition to increasing water demands, Tomah is also faced with water-quality problems. Because of the thin soils that overlie the aquifer and the shallow depth to the water table, the groundwater is highly vulnerable to contamination. At present, two of the municipal wells and numerous private wells have been affected by gasoline contamination. Although Tomah appears to be clearly in need of a WHP program to prevent further contamination of groundwater in the area, the extent of the current problems may require a detailed hydrogeologic study of the area and perhaps a remedial action program to remove contaminants that are already in the groundwater system.

Tomah is located on what was once the shoreline of glacial Lake Wisconsin. As a result, the unconsolidated deposits that overlie the sandstone aquifer in this area are mostly fine sand. Well logs for the four municipal wells (wells 3S, 6W, 7E, and 8) indicate that these deposits are only 10-20 ft thick and that the water table is within 5-25 ft of the surface. In addition to its relatively high permeability, the sandy soil has little capacity to attenuate contaminants that may be transported downward by water that is recharging the aquifer. Downward vertical gradients induced by the pumping may have helped move the organic contaminants, in this case benzene, deep within the sandstone aquifer.

At the present time, water from wells 3S and 7E (figure III-10) have benzene levels of 8.5 parts per billion (ppb) and 1.6 ppb, respectively. Because 8.5 ppb exceeds the drinking water standard for benzene of 5 ppb, well 3S is pumped only at night to the surface reservoir and not directly to the supply system. Although water in the supply system has had detectable levels of benzene on several occasions, levels have never exceeded the standard (P. Swailes, Wisconsin Department of Natural Resources, West Central District Water Supply, personal communication). Well 6W has not had detectable benzene levels and a new well (number 8) was put in service in May 1987 (fig. III-10).

Tomah is also the location of three proposed Superfund sites. As a result, this area will probably be the scene of detailed hydrogeologic investigations in the future. The analysis done in this report is based on very limited hydrogeologic data and may be viewed as a preliminary attempt to delineate areas for potential WHP districts until new studies can be completed.

To determine potential WHP districts for Tomah, we first gathered all the available data, which in this case consists of well logs for the four municipal wells, USGS Hydrologic Investigation Atlas HA-367 (Devaul and Green, 1971), and a water-table elevation map (Lippelt and Hennings, 1981). These indicated that local flow in the area is from local topographic highs to nearby streams, lakes, and wetlands. Deep regional flow is toward the Wisconsin River to the east. Figure III-11 shows the area of contribution to Tomah's municipal wells. The area of contribution upgradient of the city of Tomah is primarily rural and undeveloped lands, and is not a likely source of the present groundwater contaminants. Therefore, the delineation of smaller areas in the immediate vicinity of Tomah for consideration as WHP districts is warranted.



Approximate boundary
of combined cones of depression

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Figure III-10. Location and cones of depression for the city of Tomah's municipal wells.

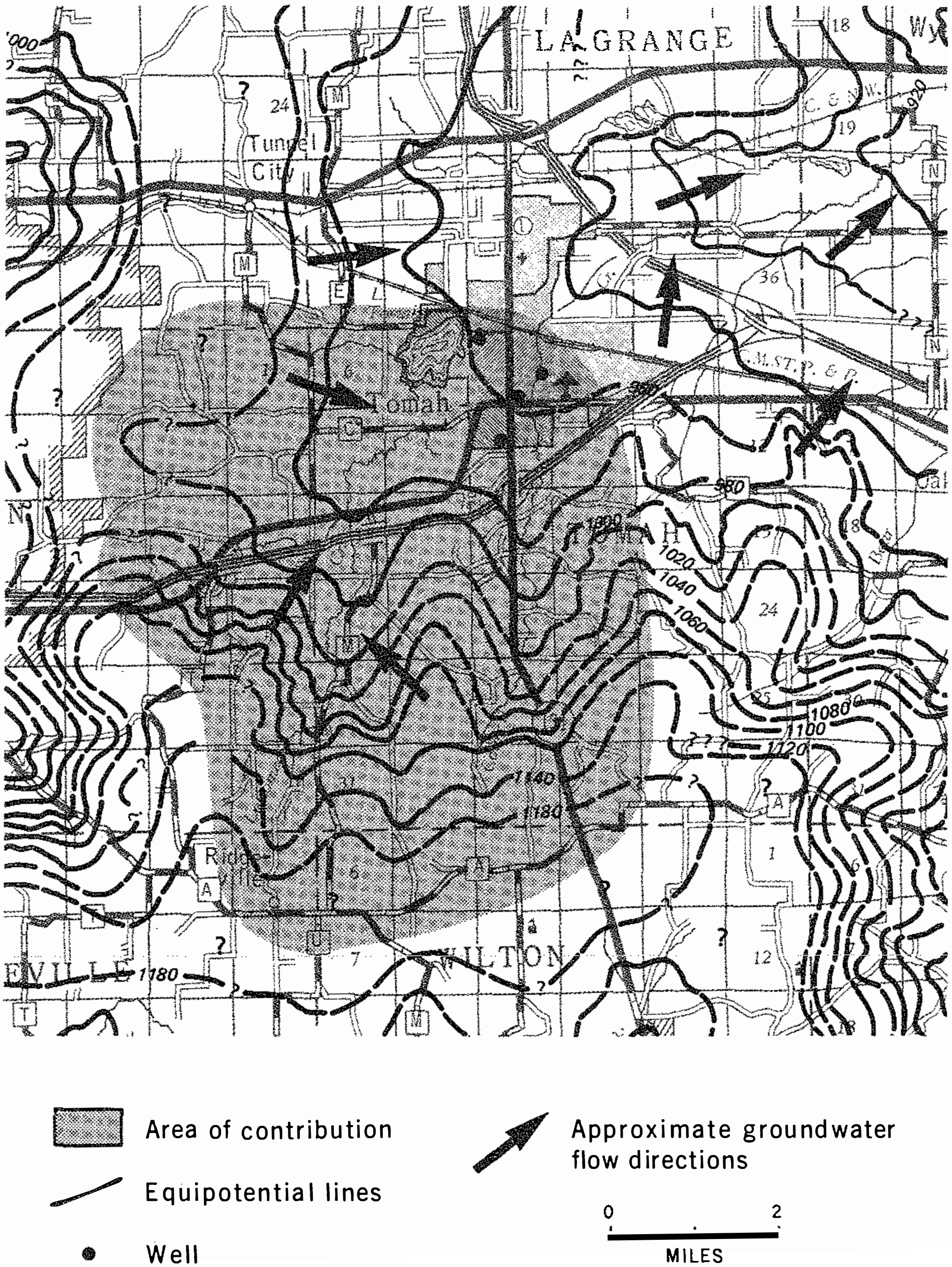

Figure III-11. Water-table elevation map showing the area of contribution to municipal wells at Tomah (adapted from Lippelt and Hennings, 1981).

The relatively flat topography, plus subtle local changes in the configuration of the water table due to the existence of multiple pumping wells, makes the determination of a flow direction and a hydraulic gradient in the vicinity of Tomah impossible without a more detailed hydrogeologic study. Therefore, we did not calculate TOT distances in this case, but focused on defining a subarea within the total area of contribution based on the cones of depression of the wells.

Because all four of the wells are used to supply water for the municipal water system, a cone of depression was calculated for each one. A value for transmissivity (T) based on the specific capacity was determined for each well, and a pumping rate (Q) for each was based on the maximum daily pumping rate. (Because well number 8 had just been put into service, no information on pumpage was available. Its cone of depression was calculated by arbitrarily using the same pumping rate as well number 3S.) The storage coefficient of the unconfined, sandstone aquifer was estimated to be 0.06 (Heath, 1983). Because the sandstone aquifer is in this case unconfined, the drawdown (s) and the duration of pumping (t) were chosen to be 0.1 ft and 3 days, respectively. The radii of the cones of depression for the four wells ranged from 900 to 1,200 ft (fig. III-10).

Although these cones of depression, which were based on a 0.1-ft drawdown, do not overlap, the cones of depression for lesser drawdowns will. In cases like this -- in which pumping wells are relatively close together -- pumping in one well may cause a drawdown in the others. As a result, the drawdown at any point is equal to the sum of the drawdowns caused by all the wells (Heath, 1983). A pumping test on recently completed well number 8 resulted in significant drawdown in well 3S, indicating that this type of well interference is occurring in Tomah (P. Swailes, Wisconsin Department of Natural Resources, West Central District Water Supply, personal communication). Consequently, there may be a coalescing of individual cones into one large area in which the water table has been lowered (fig. III-10). In addition, water pumped by private wells located in Tomah will lead to further depression of the water table. Therefore, the use of a coalesced cone of depression as the hydrogeologic basis for a WHP district may be the most practical approach for Tomah.

In conclusion, the City of Tomah is an example of a Wisconsin community where a WHP plan is essential. Because contamination of the aquifer has already occurred, protective measures cannot by themselves totally ameliorate Tomah's water quality problems. Remedial actions designed to eliminate sources of contamination and to reduce the level of contaminants already in the aquifer will be needed. However, the establishment of a WHP program would be an important step to prevent future contamination of the aquifer.

Village of Mazomanie

The village of Mazomanie is located in northwestern Dane County at the junction of the Black Earth Creek and Wisconsin River basins. The principal aquifers of Dane County and southwestern Wisconsin are the lower (Cambrian) sandstone aquifer and local sand-and-gravel aquifers (Cline, 1965). Mazomanie is an interesting example because it has municipal wells that take water from each of these aquifers.

The Black Earth Creek basin is hilly with steep-sided valleys cut into the upland. This well defined topographic relief controls the local groundwater flow systems (Cline, 1963). In addition, the high topographic relief tends to increase the depth of the local flow systems (Zaporozec and Cotter, 1985). Regional groundwater flow is toward the Wisconsin River. Figure III-12 shows the location of Mazomanie's municipal wells and the approximate direction of groundwater flow. Most water being pumped at Mazomanie will have moved toward the wells from upgradient areas as indicated by figure III-12.

Mazomanie well number 2 extends to a depth of 640 ft into the lower sandstone aquifer. The well log indicates that the top of the aquifer lies only 26 ft below the surface, as does the water table. The presence of shale layers within the sandstone is a partial barrier to the vertical circulation of water (Cline, 1965). Because the well is screened in zones above and below the shale layers, water is being pumped from both unconfined and semiconfined parts of the aquifer. Although this type of situation is most appropriately analyzed using a numerical model such as the one developed by McLeod (1975), the use of the Theis equation to calculate the radius of the cone of depression will provide a conservative estimate that is sufficiently accurate to provide the hydrogeologic basis for delineating a WHP district.

To determine the cone of depression, we used a storage coefficient (S) and transmissivity (T) of 0.0002 and 4,000 sq ft/day, respectively (McLeod, 1975). This transmissivity value was in good agreement with the transmissivity of 4,800 sq ft/day that was based on the specific capacity of the well. At present, well number 2 is on standby, and Mazomanie water needs are being met exclusively by well number 3. Because well number 2 will be used whenever well number 3 is incapable of meeting demand, the delineation of a potential WHP district around well number 2 is necessary even though it has not been used in the past year. As a result, the cone of depression for well number 2 was based on the maximum daily pumping rate of well number 3. The cone of depression based on a duration (t) of 1-day and a 1.0-ft drawdown (s) was found to be 2,800 ft (fig. III-12).

Mazomanie well number 3 extends to a depth of 120 ft into the highly permeable, sand-and-gravel deposits. Beneath local valleys, these deposits are estimated to have a maximum thickness of about 150 ft, and they are an important local aquifer. Because of the high permeability of the aquifer and the surficial deposits, well number 3 is potentially very susceptible to contamination. Its location west of Mazomanie makes agricultural activities in the vicinity and upgradient of the well the major sources of potential contamination. Because of the high transmissivity (T) and storage coefficient (S) of this aquifer (37,000 sq ft/day and 0.20, respectively), the radius of the 3-day cone of depression for well number 3 was only 500 ft at the current maximum daily pumping rate (fig. III-12).

This case illustrates a situation in which the location of community wells may result in the delineation of multiple distinct areas based on hydrogeologic factors for consideration as WHP districts. Further, we suggest the importance of applying the WHP

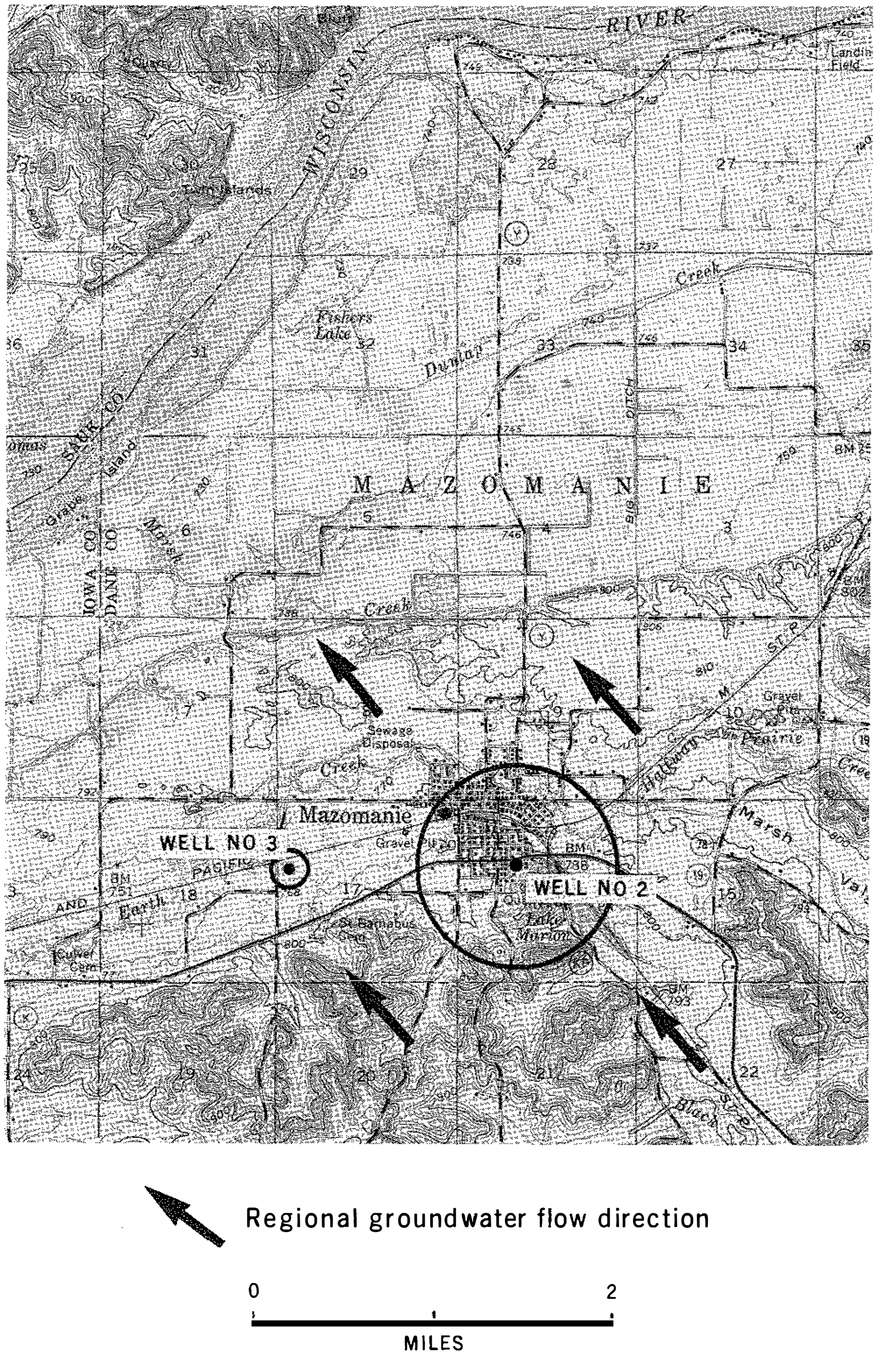

Figure III-12. Groundwater flow and cones of depression around village of Mazomanie's municipal well numbers 2 and 3.

concept to existing wells not currently being used, but which may be needed to meet future demand. A community may also want to use hydrogeologic methods to delineate potential WHP districts near parcels of land that are being considered for future development as municipal well sites. Because there is no quick or easy means for removing contaminants once they have reached the aquifer, long-term planning is essential to assure the availability of high-quality water in the future.

CHAPTER IV

INSTITUTIONAL AND NON-HYDROGEOLOGIC CONSIDERATIONS IN APPLYING THE WELLHEAD-PROTECTION DISTRICT CONCEPT

Introduction

Ideally, the area within a WHP district would include all of the groundwater flow system that contributes to the well or well field, and hydrogeologic analysis would serve as the basis for the areal delineation of the WHP district. As shown in Chapter III, data and analytical limitations preclude exact definition of hydrogeologically based areas for WHP management, and substantial professional judgment is incorporated in the analytical methods. Barring extensive hydrogeologic investigations, estimated hydrogeologic boundaries of WHP areas are particularly "shaky" for deep confined aquifers and for fractured and soluble bedrock aquifers. Therefore, while hydrogeologic factors are important in defining areas to be embraced by the WHP district concept, other non-hydrogeologic concerns can influence -- and in some cases determine -- the ultimate configuration of a WHP district.

Wisconsin's *De Facto* WHP Program

The delineation of WHP districts for groundwater management does not take place in a vacuum. The state of Wisconsin has a number of regulatory and other management programs intended to control potential polluting activities and sources of pollution (see Born and others, 1987; and Lohr, in preparation). WHP efforts should be considered in the context of this array of existing groundwater management programs. These state siting and separating distance criteria represent a *de facto* WHP management program.

The siting of new municipal wells, for example, is regulated by the Public Water Supply Section of the Bureau of Water Supply, DNR, under Wis. Admin. Code Ch. NR 111 (Requirements for the Operation and Design of Community Water Systems). The authority to promulgate and enforce these rules is contained in Wis. Stat. Chs. 144 and 162.

Municipal well locations are approved on a case-by-case basis depending upon geological and topographic conditions and possible sources of contamination. A well-site survey containing this information must be submitted to the DNR for each municipal water system. This survey, generally conducted by the DNR district engineer, considers distance to sanitary hazards, physical features such as topography and drainage, and geologic information. The DNR encourages municipalities to submit four or five alternative site surveys for review (no fee is charged). By getting early input from the DNR, a municipality can avoid wasting time and/or money on a site that will not meet the current criteria.

General requirements found in Wis. Admin. Code sec. NR 111.31(4) provide that a municipal well shall be constructed at the center of a lot with minimum dimensions of 100 ft by 100 ft and constructed so that the pumphouse floor is 2 or more feet above the regional flood elevation. Existing wells are inspected by DNR personnel annually, and water-quality sampling of municipal water supplies is conducted in accordance with Wis. Admin. Code Ch. NR 109. Other than these general requirements, the municipal well code contains no set locational requirements.

In contrast, Wis. Admin. Code Ch. NR 112, which applies primarily to private wells, prescribes a series of minimum separating distances between wells and sources of contamination (Wis. Admin. Code sec. NR 112.07(2)). These require that a private well be located at least 50 ft from a wastewater disposal unit or sanitary sewer, 100 ft from a bulk subsurface storage tank for petroleum products, and 250 ft from a wastewater storage lagoon. Minor separation distances such as 8 ft to a basement floor drain, 10 ft to a clear-water waste drain, and 15 ft to a sewer-connected foundation drain are also included. The greatest separating distance called for is 1,200 ft between a well and the nearest edge of an existing or proposed sanitary landfill disposal site.

Although the private well code regulates the location of a well in relation to contamination source, other chapters of the administrative code regulate the location of various sources of contamination in relationship to a well. For example, Wis. Admin. Code Ch. NR 180 requires that a sanitary landfill must be at least 1,200 ft from a public or private well, thus keeping this source of contamination from "coming to the well." Similarly, Wis. Admin. Code Ch. NR 110 requires that wastewater storage lagoons must be a minimum of 1,000 ft from a municipal supply well, and that sanitary sewers must be at least 200 ft from a municipal well. The latter criterion is often the most difficult to meet in practice, and lesser distances are allowed under a variance (L. Boushon, Wisconsin Department of Natural Resources, Bureau of Water Supply, personal communication).

The minimum separating distances specified in the administrative code for private wells and in codes regulating various pollution sources and activities are considered by DNR when it makes its case-by-case decisions on siting municipal wells. Figure IV-1 illustrates some commonly used criteria.

A recently enacted addition to the Wis. Admin. Code Ch. NR 145 enables DNR to delegate to counties the authority to administer the private well code (Wis. Admin. Code Ch. NR 112). By choosing to administer the private well code (under DNR supervision), counties will increase their power to regulate and protect groundwater. County administration of the private well code has been recommended in both the Dane and Marathon County groundwater-protection plans.

In summary, the state's present approach to protecting the water quality of municipal water supply wells is largely through case-by-case site approval and monitoring of water quality. It is premised on maintaining minimum separating distances between the well and potential pollution sources and regulating the various pollution sources to prevent contamination of the groundwater. Although this is similar, in some ways, to the WHP concept described here, there are several major differences. In the present program, separation distances are based neither on local hydrogeologic conditions nor on the municipality's rate of water use. Not all potential pollution sources are regulated with respect to existing municipal wells.

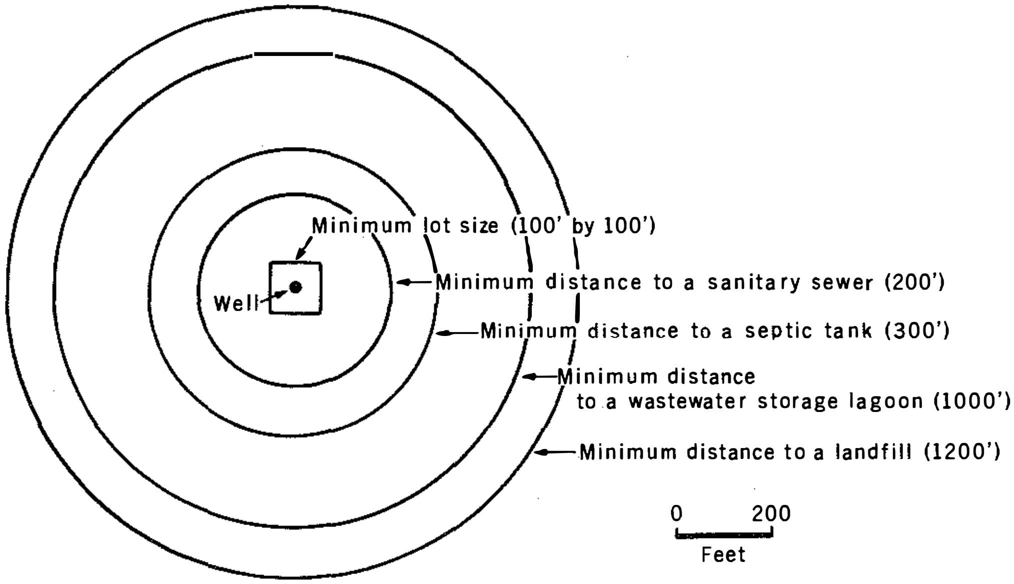

Figure IV-1. Separating distance criteria for a municipal well under current regulatory practices in Wisconsin.

Planned wells proposed to be developed some time in the future are not covered. Finally, the present *de facto* program relies exclusively on state authorities to administer it.

The WHP concept would include a review of the existing regulations including separating distances, which could be done in conjunction with the review of Wis. Admin. Code Ch. NR 111, expected to take place in approximately 18 months (R. Krill, Wisconsin Department of Natural Resources Bureau of Water Supply, personal communication). At that time a decision could be made whether to include minimum separating distances in the public well code as in the private well code. Any specified distances would result from a coordinated review of minimum separating distances between wells and pollution sources regulated by DNR and other state agencies, ensuring that gaps in regulatory coverage would be filled. The distances specified could vary depending on hydrogeologic conditions. Finally, the role of local government in supplementing state regulations would be spelled out.

Non-Hydrogeologic Factors of Concern

Previous discussion looked at the concept of WHP and the hydrogeologic basis for determining the groundwater basin, the cone of depression, and intermediate areas. Here the focus shifts from delineation of hydrogeologically derived WHP areas to the establishment of WHP districts within which a variety of water-quality management measures will be applied. Although the WHP district(s) is based upon the WHP area(s), a number of non-hydrogeologic factors are of concern as well.

The first and most obvious of these is the need to delineate the district boundaries so that they can be easily located in the field.

This means "squaring up" the boundaries of the WHP area using a large-scale topographic map or aerial photo so that the district follows boundaries that can be easily located on the ground (roads, water bodies, fence lines, and similar features). The next consideration is to determine appropriate locations within the district for the various management activities, that is, monitoring, inventorying of potential pollution sources, prohibiting various uses, and regulating other uses according to performance standards or design criteria. Where feasible, a time/distance delineation is helpful. For example, if a 25-year TOT line has been established, it may define the minimum area within which inventorying of pollution sources would take place. Monitoring of any major sources of pollution that can be identified should be undertaken regardless of their location within the groundwater basin. An additional network of monitoring stations at, for example, the 5-year and 2-year intervals could provide early warning before pollution from unidentified sources reaches a well. The expense of such a monitoring network could be reduced by using existing private wells.

Regulation of land uses within the cone of depression is important because within this area pollutants move directly to the well. The size of the cone of depression should be compared with minimum separating distances specified for various state-regulated uses, such as 1,200 ft between a well and a landfill. Both the cone of depression and the minimum separating distances should be evaluated in terms of time and distance for pollutant travel. As will be seen in Chapter V, there may be considerable variation from one hydrogeologic setting to another depending upon the velocity of groundwater flow. Since a minimum separating distance from a given use to a well in effect excludes that use, zoning provisions could prohibit contaminating uses within that area. Note, however, that the minimum separating distances for different contamination sources vary (see fig. IV-1), and that not all potential sources are regulated in terms of well separation.

Outside the area where various potentially contaminating uses are prohibited by local regulation lies an area where they could be zoned as conditional uses (special exceptions) if they met performance standards or design criteria. The preventive action limits (PALS) in Wis. Stat. Ch. 160 are a form of performance standards that can be applied to all potentially polluting land uses. Some uses could be permitted if they incorporated appropriate design criteria, such as spill containment facilities, or operational features such as a contingency spill plan and emergency spill training for employees.

The 100 ft x 100 ft area around the well that the municipality is required to own by Wis. Admin. Code Ch. NR 111 is the innermost zone of protection. This area could be made larger where appropriate, for example, when siting a new well in conjunction with a park, recreation area, or other non-contaminating land use. Purchase of easements, to limit the right to use the land for a potentially contaminating use may be a way to control additional areas where the municipality does not wish to purchase the land in fee simple.

The control techniques discussed so far apply primarily to new land uses proposed to be located within the various management districts. In many situations, however, wells will be located in developed areas with already existing uses. Here the primary control mechanism would be regulations setting requirements for reporting, storage, handling, and disposal of contaminating substances rather than regulating their appropriate location as a land use under zoning. Cities and villages probably have this power under their home-rule power, and counties have this power under their authority to adopt sanitary regulations. However, legislative clarification would be desirable. An extensive discussion of local and state powers is contained in *Groundwater Quality Regulations: Existing Governmental Authority and Recommended Roles* (Yanggen and Amrhein, in preparation).

Up to this point, we have dealt with management districts that will be established and controlled by the municipality whose well is to be protected. Typically, however, as revealed in Chapter III, the WHP area will extend beyond the municipal boundaries. In these cases, the municipality has three basic options:

1) use its extraterritorial land-use control powers;
2) rely on state regulation to protect groundwater quality; and
3) work out cooperative mechanisms with other local governments.

These options should undergo detailed legal analysis because it is important to have substantial congruence between the WHP area and governmental authority to initiate appropriate management measures.

Other largely non-hydrogeologic factors will affect the manner in which Wisconsin employs the WHP district concept. The 1986 Federal State Drinking Water Act Amendments and the U.S. EPA Guidance (U.S. EPA, 1987a) make it clear that the WHP district program should apply to proposed public water-supply wells as well as existing ones. Judgements about the size of a proposed WHP management district must consider protecting future sources of water supply from sources of contamination. However, at present in Wisconsin, outside major urban areas, there is little formalized water-supply planning that systematically assesses future needs and anticipates the location of new wells. For communities with growing populations and demands, greater attention to groundwater protection in local land-use planning and more liberal delineation of WHP districts may be advisable.

Applying the WHP program in established metropolitan areas may be complex and cumbersome. These built-up areas already have an established set of land uses and practices. Some state controls of potential sources of contamination are in place, but others may be needed. Such urbanized areas are typically served by multiple wells. Where there are coalescing cones of depression (or a general drawdown of pressure regionally for confined and semiconfined systems), the contributory area of the groundwater basin may be extensive (see fig. II-5).

General Overview of Local Governmental Authority

A brief overview of Wisconsin local governmental authority and capacity to undertake protective actions for groundwater is important to understanding the local governmental role in a WHP program.

Regulation of potential sources of contamination within WHP districts is the primary management method that will be relied on by local government. The regulatory authority of each type of local government (that is, city, village, town, or county) in regard to each potential pollution source and each regulatory control mechanism must be addressed in terms of the following questions:

1) Is local government authorized to regulate, or has state government preempted local authority, and is preemption partial or complete?
2) Does the particular type of local unit have broad home-rule powers (that is, city and village) allowing it to regulate in the absence of a statute indicating it may not, or is it a type of government (town or county) that must find a statutory basis authorizing it to regulate?
3) Do the statutes authorize a particular type of local government to regulate a specific contamination source, and is the local government in question empowered to adopt the necessary type of ordinance?

In some cases the law gives the state sole authority to adopt certain types of regulations, such as the right to set groundwater quality standards. In other cases the law mandates state regulation, for example, for bulk storage of fertilizers, pesticides, and road salt, but does not indicate whether these responsibilities may be shared with local government. The statutes do sometimes clearly define local authority vis-a-vis the state and specify which type of local unit may exercise a given power. For example, cities, villages, and towns (but not counties) may assist in administering the groundwater-protection provisions of the Flammable and Combustible Liquid Code (Wis. Admin. Code Ch. DILHR 10); however, counties (but not cities, villages or towns) may administer the state Private Well Code (Wis. Admin. Code Ch. NR 112). All local units, cities, villages, towns, and counties, are authorized to use zoning to protect groundwater quality.

If a WHP district is located entirely within the municipal (city or village) limits, the question of who has regulatory primacy on the local level is relatively unimportant. Many WHP districts, however, will extend outside the corporate boundaries, and then the authority of a municipal unit to adopt extraterritorial controls or the power of a town or county to regulate potential pollution sources within the extraterritorial portion of the WHP district becomes a critical question.

Added protection from pollution sources in WHP districts can be accomplished by authorizing state agencies to control unregulated substances and by authorizing some local units to adopt regulations they are not presently empowered to enact. Important examples are state control of the storage of those unregulated hazardous substances such as certain solvents, thinners, and caustic acids that are only subject to state control if they become a waste through a production process or are spilled. An example of needed local authorization is for counties to regulate hazardous substances in a way to complement state control. Whether a particular authorization should apply throughout an entire regulatory jurisdiction or only within WHP districts is an issue that may have to be decided on a source-by-source basis. If broad jurisdictional authority is selected, priority can be given to regulation within WHP districts. Legal analysis of the respective state and local programs involving pesticides, underground storage tanks, municipal well protection, and hazardous substances has been done (Yanggen and Amrhein, in preparation), but this should be refined in the context of analyzing the legal and institutional issues in developing a WHP program.

CHAPTER V

APPLYING THE WELLHEAD-PROTECTION DISTRICT CONCEPT

Introduction

The first WHP district in Wisconsin was established in the town of Rib Mountain by zoning ordinance. As noted earlier, several counties and municipalities throughout the country have adopted zoning or other land-use regulations to protect present and potential water supplies. In Wisconsin, as a result of the 1984 groundwater legislation, groundwater protection is one specified statutory purpose of local zoning. By limiting polluting uses and practices on land areas contributing groundwater to a well(s), protection of groundwater quality can be fostered. The area to be protected may be subdivided into several management zones, depending on local hydrogeologic conditions, the nature and geographic dimensions of existing and potential groundwater problems, and local political and economic considerations. The delineation of appropriate and workable management zones involves a substantial degree of judgment. In most cases, the final district configuration will be a compromise between political and administrative factors and hydrogeologic ones. The European experience has given rise to a "rule" for the size of protection districts that should dictate the final boundaries: AS LARGE AS NECESSARY, AS SMALL AS POSSIBLE.

This chapter illustrates the delineation of WHP districts, including subzones, using two of the hydrogeologic cases described in chapter III. Our focus is on the straightforward on-the-ground definition of WHP management districts using recognizable features such as roads, railroad lines, jurisdictional boundaries, property lines, and the like. The adjustment of estimated hydrogeologic boundaries to fit cultural and political features is a mechanical, slightly arbitrary process. The specific nature of potential threats to groundwater quality, based on source inventories and assessments, as well as on the nature of alternative management tools, provides the basis for selecting among alternative management district configurations. We present two illustrations: Rib Mountain, where local decision-makers have already established a WHP district; and Whiting, where an array of possible WHP district configurations is presented.

Rib Mountain Example

Using the hydrogeologic analysis described earlier, the town of Rib Mountain adopted land-use regulations covering essentially the entire recharge basin to protect its groundwater supplies. The town's ordinance defines two zones within the well-protection area (fig. V-1a). These zones, delineated along readily identifiable street and property lines, approximate both the sand-and-gravel aquifer (Zone A) and the outer boundaries of the basin (Zone B). Because of hydraulic characteristics and proximity to the wells, greater restrictions are placed on lands overlying the sand-and-gravel aquifer than on higher areas of the watershed. In Zone A industrial and commercial uses are prohibited. In Zone B they are allowed as conditional uses if they meet requirements designed to protect groundwater. Figure V-1b shows an alternative means of delineating protection zones based on 2-year TOT distances. Given the small dimensions of the groundwater basin and the short travel times involved, the Rib Mountain case clearly illustrates the importance of regulating the storage and handling of existing sources of potential contamination, in addition to controlling new land uses.

Because the wells are close to the Wisconsin River, some water will flow from the river toward the wells if the pumping cone of depression intersects the river water level. Wells closer to the river with much higher pumping rates, such as in Wausau, appear to have had their water quality impaired by this induced recharge from the Wisconsin River. Water-quality tests at Rib Mountain indicate that river water is not reaching the municipal wells (L. Boushon, Wisconsin Department of Natural Resources, Bureau of Water Supply, personal communication). Because it is impossible for the town of Rib Mountain to control the quality of the water in the Wisconsin River, the river is not part of the WHP area. Scheduling pumping operations to minimize the size and depth of the cone of depression and practicing water conservation are the best approaches to keep induced river water from adversely affecting town wells.

Whiting Example

The Whiting example in chapter III delineated several areas based on hydrogeologic analysis for possible WHP district designation. Figure V-2 shows a potential WHP district, defined using readily identifiable features, that circumscribes the entire contributory portion of the groundwater basin (fig.V-2a). It also shows possible management subzones based on the cone of depression (fig.V-2b) and time of travel (fig. V-2c). The management zone based on the cone of depression could also be outlined using a separating distance equivalent to the radius of the cone of depression.

We have illustrated TOT-determined zones for 2 years and fifteen years. Selection of a TOT threshold has an enormous effect on the areal extent of the management subzone, especially in permeable aquifers such as at Whiting, where groundwater velocities are high. Unfortunately, there is no absolute guide to selecting an appropriate TOT and associated management zone or district. EPA believes that thresholds shorter than 5 to 10 years may be inadequate in most hydrogeologic settings; the agency recommends that where it is "feasible and implementable" states seriously consider more protective thresholds in the 15- to 25-year range (U.S. EPA, 1987a).

Our selection of two years for illustrative purposes is based on the notion that a two-year warning of imminent contamination problems would be the minimum needed to deploy a remedial action or intervention strategy. A higher threshold, based on prior state experience with contingency actions, may be desirable. In any event, the effectiveness of employing such a zone would depend on the establishment of a monitoring system reflective of the desired intervention period goal. The 15-year threshold represents the lower

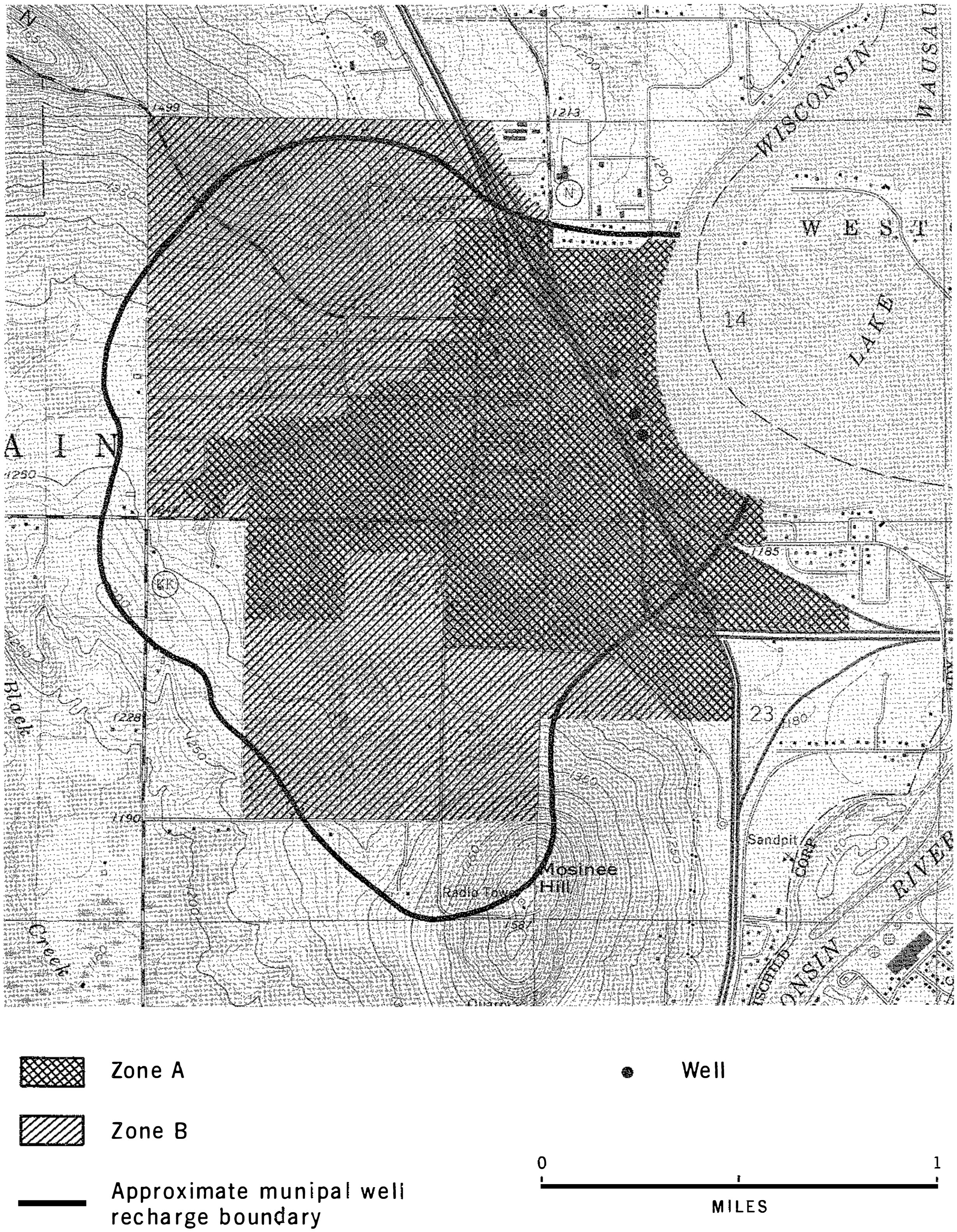

Figure IV-1. Separating distance criteria for a municipal well under current regulatory practices in Wisconsin.

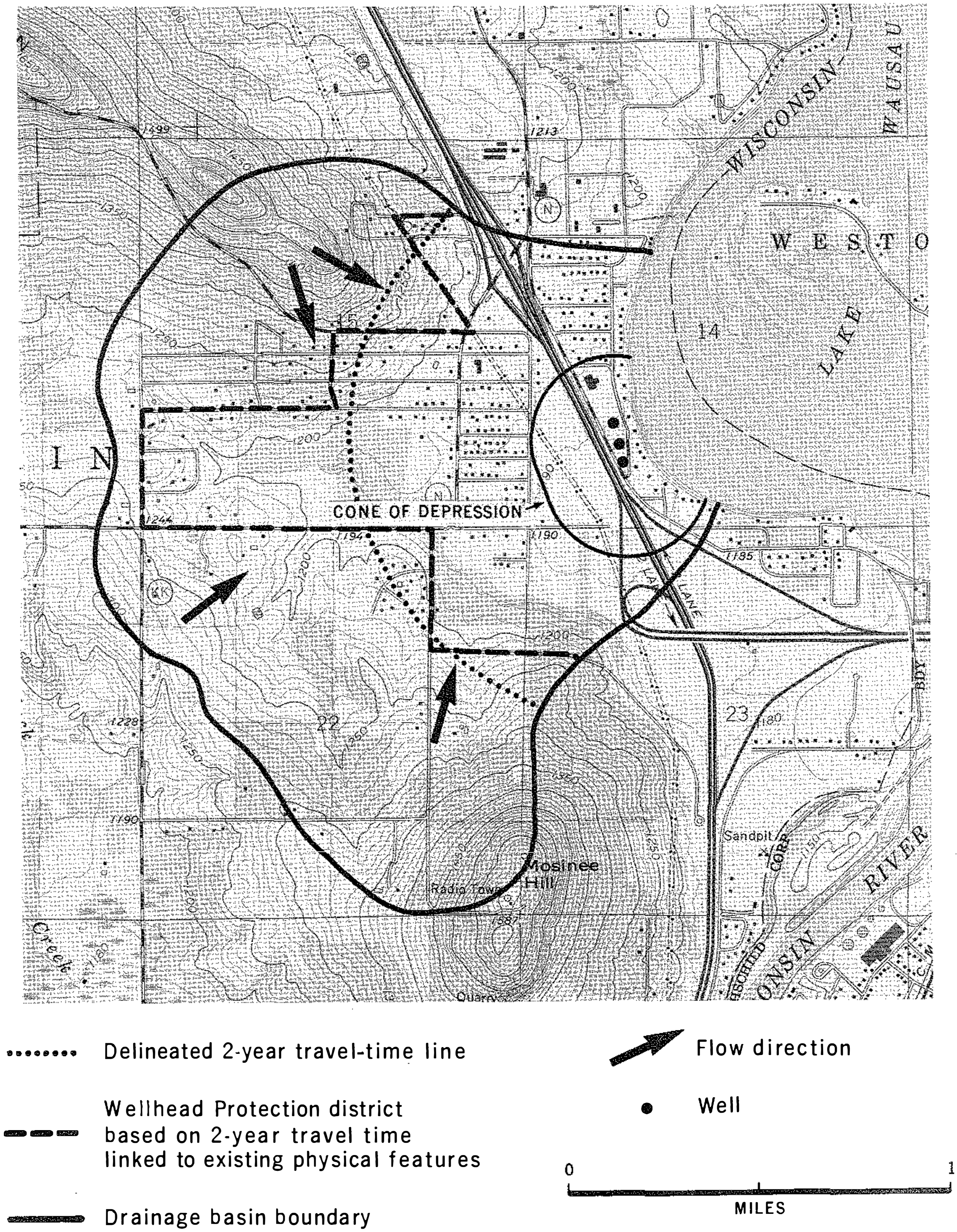

Figure V-1b. Example of a wellhead-protection district based on the 2-year travel-time line linked to existing physical features at the town of Rib Mountain.

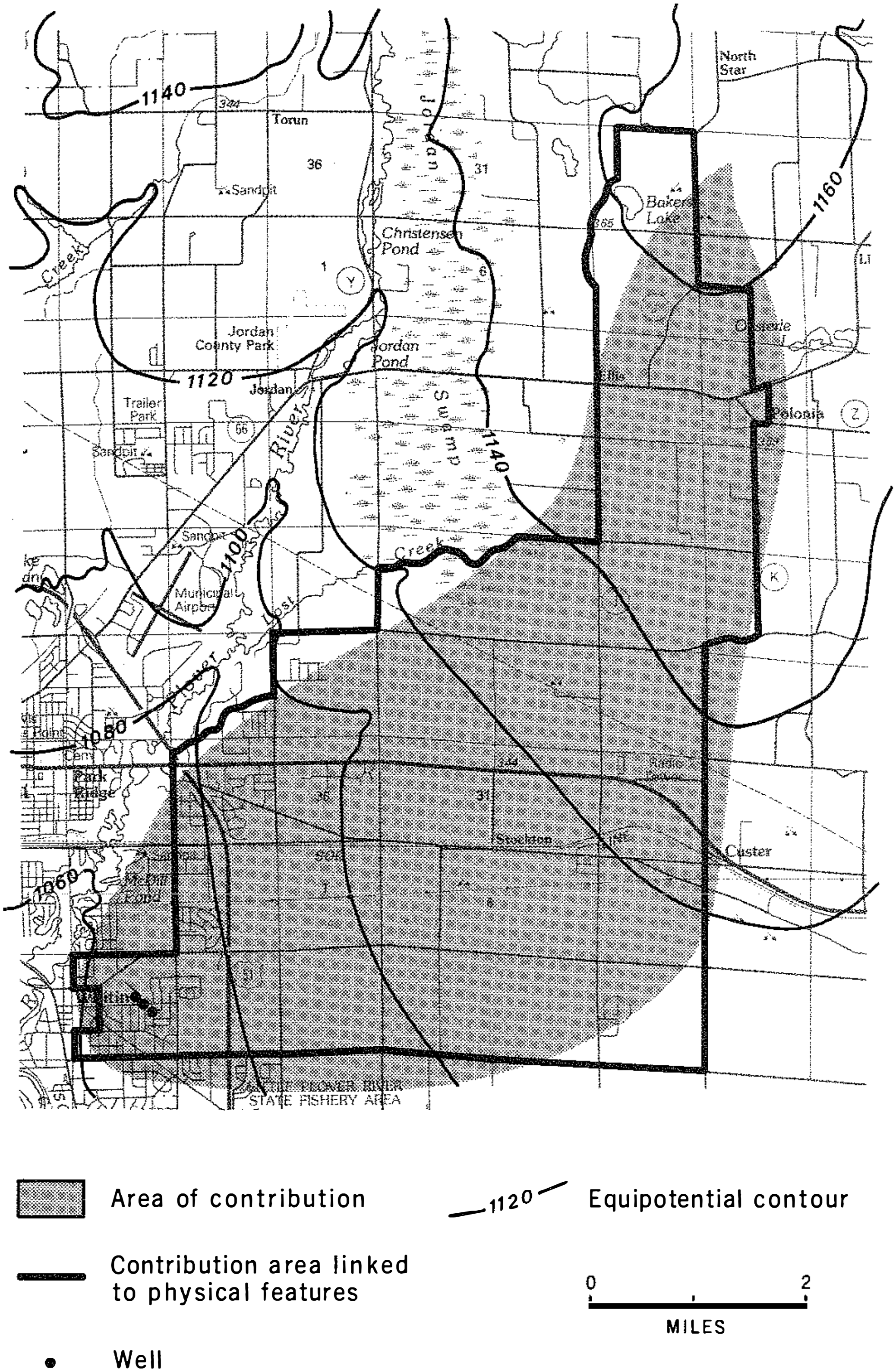

Figure V-2a. Example of a wellhead-protection district based on the total area of contribution to the Whiting well field.

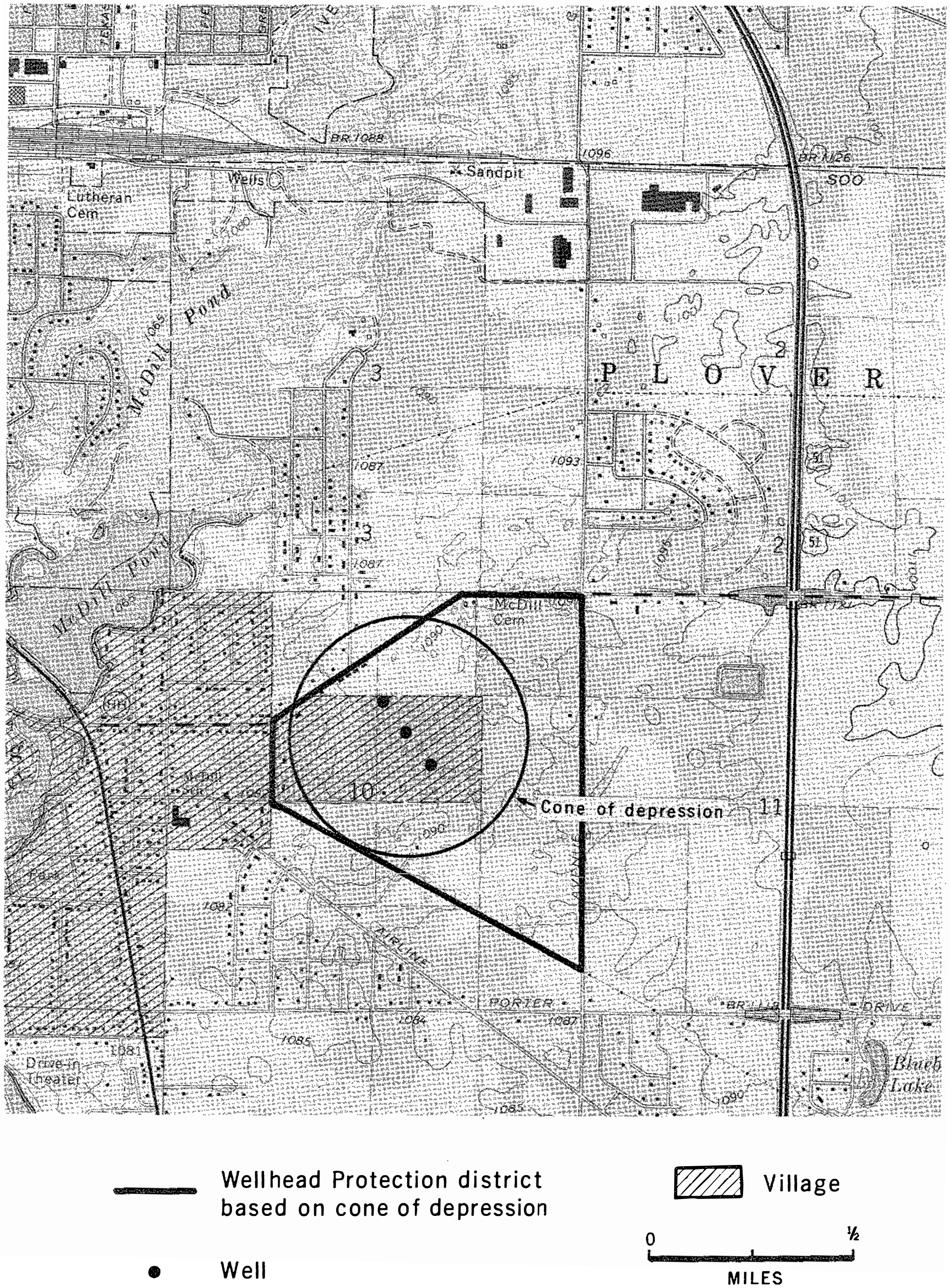

Figure V-2b. Example of a wellhead-protection district based on the cone of depression linked to existing physical features in the Whiting area.

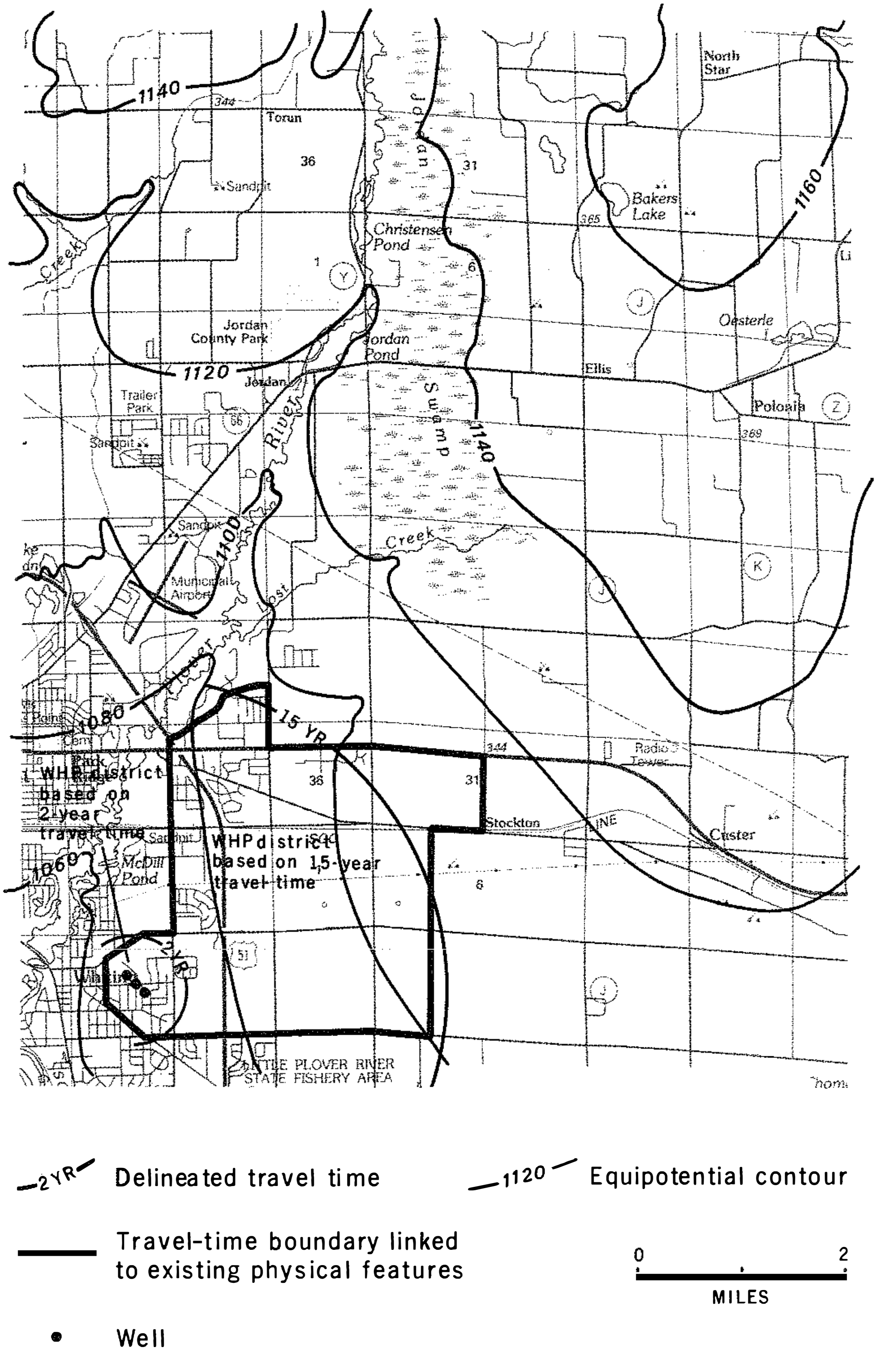

Figure V-2c. Map of the Whiting area showing wellhead-protection areas based on the 2- and 15-year travel-time lines and the wellhead-protection districts as related to existing physical boundaries.

end of EPA recommendations, but the reader should note that in the prior Rib Mountain example, this lower threshold is not possible because of the small size of the groundwater basin (fig. V-1b).

Discussion

Given hydrogeologically based areas, WHP districts can be readily delineated. However, the selection of district boundaries involves more than hydrogeologic factors. It must reflect program objectives, management options, and the assessment of potential pollution sources that might affect the well(s). The areal extent of a WHP district selected for monitoring and education efforts might be quite different than that selected for restricting land uses and activities. In the Whiting case, it might be possible to delineate a WHP district embracing the whole contributory part of the groundwater basin to establish a monitoring or voluntary well-testing program. The same district boundaries might also be acceptable for a limited regulatory program, for example, required agricultural chemical management practices, such as use limitations. However, it is improbable that so large an area, involving several units of government, could serve to successfully implement a management program severely limiting or excluding a wide variety of land uses and activities. In short, no simple prescription is possible; careful judgment will be required in choosing a WHP district that is smaller than the total contributory groundwater basin.

The case examples in this report also reveal the pitfalls of using a single fixed regulatory separating distance regardless of hydrogeologic conditions. Table V-1 shows that the distances associated with a particular TOT threshold can vary considerably from area to area. WHP plans based on TOT thresholds often assume a generalized time for various pollutants to attenuate and an estimated time necessary for intervention once pollution is discovered. Note that the present minimum regulatory separating distance of 1,200 ft (for landfills) represents 10 years of travel at Eagle River but less than 1 year at Rib Mountain. If WHP districts are chosen based on TOT factors, existing separating distance requirements may need to be reexamined.

Departing from uniform, hydrogeologically independent regulatory requirements can, of course, complicate the regulatory process. It makes it necessary to examine the specific requirements for each WHP district rather than being able to rely on a known uniform figure. It also may make it difficult to tell by casual visual inspection whether a proper minimum separating distance has been maintained. On the local level, however, determining varying minimum dimensional standards and other regulatory requirements on the basis of a map is an integral part of local zoning. To the extent that state minimum separating distances apply only in the absence of locally adopted and state-approved WHP controls, it will be possible to mesh local regulatory efforts with state regulatory requirements.

Table V-1. Range in travel-time distances of case examples.

Example	Travel-time distances (in ft)			
	2-Year	5-Year	15-Year	25-Year
Whiting	2,100	5,250	15,750	26,250
Rib Mountain	3,980	N/A	N/A	N/A
Eagle River	240	600	1,800	3,000

CHAPTER VI

CONCLUSIONS AND SELECTED STATE WELLHEAD-PROTECTION PROGRAM DESIGN RECOMMENDATIONS

In this report we have demonstrated the application of various methods for delineating WHP areas based on hydrogeology and their use in establishing possible protection districts for management purposes. Our cases have been selected from the significant hydrogeologic environments and aquifers in Wisconsin where the WHP district concept can be most appropriately and effectively employed. We have attempted to refine the WHP concept described by U.S. EPA (1987a; 1987b) and to clarify certain aspects relevant to making it operational.

In particular, we have drawn a distinction between WHP *areas* based on hydrogeologic analysis and the subsequent delineation of WHP *districts*. These districts are defined for management purposes and incorporate all or part of the hydrogeologically based areas. Although we firmly believe that any sound WHP program must have a solid hydrogeologic basis, we find a tendency in the U.S. EPA Guidance documents (U.S. EPA, 1987a) and elsewhere to treat the scientific delineation of areas contributing groundwater to wells as the definitive and objective process and product. We have tried to show that many assumptions, judgments, and limitations are associated with practical WHP area delineation. Viable and valid hydrogeologic boundaries can be established, but they are imperfect.

Our major conclusions and selected recommendations follow.

1. WHP programs must have a sound hydrogeologic underpinning.

WHP districts need to be closely related to hydrogeologic factors to the maximum practical extent. Given the limitations of analytical methods and data noted here, the relatively simplified methods described in this report will produce an adequate hydrogeologic basis for defining WHP districts. Even if the total groundwater basin cannot be identified, subareas based on the cone of depression and time-of-travel (TOT) distances will be useful for conducting various management activities (monitoring, inventorying, regulation, education). The ability to explain clearly the procedures and bases for WHP boundaries will facilitate their acceptance and improve the chances for success.

On the basis of experience gained in preparing this report, we believe that an experienced technician with ready access to the data and supplemental scientific expertise can complete a hydrogeologically based delineation of a WHP area in approximately 2-10 hours per location.

2. In delineating WHP districts, WHP areas must be modified to reflect pertinent non-hydrogeologic considerations.

We have shown how hydrogeologically defined areas can be adjusted to consider physical and cultural features and political and administrative boundaries to establish "on-the-ground" recognizable borders for a WHP district. Determining the boundaries and size of the district (and hence what property is within the district and subject to management actions) is perhaps one of the most potentially controversial components of any program. From a hydrogeologic viewpoint, the entire portion of the groundwater basin contributing to the well(s) should be circumscribed by a management district. This ideal must be modified in many "real-world" situations, either because the resulting district is too large to be manageable in practice, or because smaller management zones can be defined where specific management tools can be tailored to effectively address particular problems.

3. **WHP programs must be considered in the context of existing state and federal programs.**

We have suggested that a WHP program must be considered institutionally in the context of existing state and federal regulatory standards and guidelines. *De facto* partial WHP programs already exist in Wisconsin based on separating distances and siting guidelines relative to wells and to potential sources of pollution. WHP areas delineated on a hydrogeologic basis should be compared to the separating distances now embedded in various agency regulatory programs. These separating distances should themselves be reviewed for internal consistency and for adequacy of protection in terms of areal extent and coverage of pollution sources.

4. **Successful WHP programs will depend greatly on state-local collaboration.**

We have provided a preliminary assessment of what local governments in Wisconsin can actually do with a WHP district program. However, there are limitations on local governmental jurisdiction, authority and capacity; a successful WHP program will require substantial interaction between state and local government. Consultation will ensure that actions taken at each governmental level to protect groundwater quality are complementary and compatible. Detailed information on the local role in groundwater protection and management is available in Born and others (1987), Yanggen and Amrhein (in preparation), and Yanggen and Webendorfer (in preparation).

5. **By setting priorities, Wisconsin can avoid a misapplication of the WHP approach while targeting its efforts to those areas where the approach is most applicable and useful.**

A. We recommend that primary attention be given to delineation of WHP areas in those parts of the state where unconfined and semiconfined aquifers are the sources of drinking-water supplies. These are the areas where the WHP concept is most appropriate and applicable.

B. For those areas of the state where aquifers are largely confined (especially the populous eastern and southeastern regions), the WHP approach is of limited use. Other methods for protecting the drinking-water supply in these areas should be given equal priority in the overall state drinking-water protection program. A resource assessment should be conducted in these parts of the state as part of the state WHP program. Goals of this assessment should include a careful review of the degree of hydrogeologic confinement of primary aquifers and an inventory and assessment of "breaks" in confinement (improperly abandoned wells, poorly cased wells, geologic conditions limiting aquifer confinement). Such an assessment might be conducted in cooperation with the Southeastern Wisconsin Regional Planning Commission.

C. We further recommend that program priority be given to municipal drinking-water supplies, with non-municipal systems addressed at a later time. This staging of activities would appear to be consistent with the U.S. EPA's broad interpretation of the Amendments to the Safe Drinking Water Act of 1986 that would allow phasing or sequential development of components of the state program.

6. Development of the state WHP program should be carried out at the state level, with close collaboration and involvement of concerned local and regional entities.

During this study, it became apparent that there are substantial economies of scale in centralizing, rather than dispersing, the technical analytical work that must underpin a WHP program. Information and document availability, access to specialized scientific counsel, and more efficient use of personnel favor such an administrative arrangement. Centralization of this activity would also favor consistency in analytical procedures and better coordination with related state units. Technical analysts could be housed within either the Department of Natural Resources or the Wisconsin Geological and Natural History Survey. Close cooperation with regional units (such as regional planning commissions with the requisite technical expertise, DNR districts, and the Central Wisconsin Groundwater Center) and local governments is essential to foster working relationships with those units; those entities may have major roles to play in some aspects of a WHP program, such as conducting source inventories. Their involvement could also facilitate coordination of WHP program efforts with other related water-quality planning and management activities at the local and regional levels.

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APPENDIX 1

Estimating Hydraulic Conductivity of an Aquifer from Specific Capacity Data

Specific capacity, which is defined as the pumping rate (Q) of a well divided by the drawdown (s) in the well, is widely available from well-construction reports and can provide useful estimates of hydraulic conductivity (K). According to Bradbury and Rothschild (1985), these estimates are "quick, easy, and inexpensive, and when used in conjunction with limited pumping test data, may be the best method for mapping aquifer characteristics over large areas." These authors developed a simple computer program to determine hydraulic conductivity from specific capacity and applied it to approximately 500 wells in two different areas in Wisconsin. The results showed good agreement with values calculated using full-scale pumping tests. This program is available for IBM personal computer from the Groundwater Modeling Center at Indianapolis.

Hand calculation can also be done using a modified version of the Theis equation (Heath, 1983):

$$T = \frac{W(u)}{4\pi} \times \frac{Q}{s} \times \frac{1 \text{ cu ft}}{7.48 \text{ gal}} \times \frac{1{,}440 \text{ min}}{1 \text{ day}}$$

where

T = transmissivity of the well, in sq ft/day
Q = pumping rate of well, in gpm
s = drawdown in the well, in ft
W(u) = the well function of u

where

$$u = \frac{r^2 S}{4Tt}$$

and

r = radius of the well, in ft
S = storage coefficient of the aquifer
t = duration of pumping, in days.
T = estimated transmissivity value, in sq ft/day.

The well function is then obtained from a well-function table based on the calculated value of u. Well-function tables are available in most hydrogeology textbooks.

Heath (1983) concludes that transmissivity estimated by this method applies only to the part of the well open to the aquifer. To apply this value to the entire aquifer, the transmissivity must be divided by the open length of the well and then multiplied by the thickness of the aquifer. Because this method assumes steady-state conditions and a homogeneous aquifer, it will be less accurate than the technique that is incorporated in the computerized solution developed by Bradbury and Rothschild (1985).

Calculations using this method are presented in detail for an unconfined aquifer case (Whiting) and a semiconfined case (Seymour). Hydraulic conductivity values based on specific capacity and aquifer pumping tests are compared and are found to be in reasonable agreement for both of these cases. Because transmissivity (T) and hydraulic conductivity (K) values are not available for many parts of Wisconsin, the use of values based on specific capacity will be necessary in many cases.

APPENDIX 2

CHECKING ACCURACY OF TRANSMISSIVITY VALUES BASED ON SPECIFIC CAPACITY DATA: WHITING, WISCONSIN

A variety of sources of information concerning the aquifer characteristics at Whiting are available. Values for transmissivity (T) and hydraulic conductivity (K) are reported by Holt (1965) to be 18,700 sq ft/day and 234 ft/day, respectively. To check the accuracy of transmissivity values based on specific capacity data, transmissivities for the aquifer in the vicinity of Whiting were determined using both the hand-calculation and the computerized methods described in appendix 1.

The information necessary to do the calculation is taken from the well log for Consolidated Paper Company well number 2 (which is the center well at the Whiting well field). A modified version of the Theis equation is used (Heath, 1983):

$$T = \frac{W(u)}{4\pi} \times \frac{Q}{s} \times \frac{1 \text{ cu ft}}{7.48 \text{ gal}} \times \frac{1{,}440 \text{ min}}{1 \text{ day}}$$

where

T = transmissivity of the well, in sq ft/day
Q = pumping rate of well (578 gpm)
s = drawdown in the well (18 ft)
W(u) = the well function of u

where

$$u = \frac{r^2S}{4Tt}$$

and

r = radius of the well (0.33 ft)
S = storage coefficient of the aquifer (0.20)
t = duration of pumping (1 day)
T = estimated transmissivity value (100,000 sq ft/day)

The first step is to solve for u. Based on the above values, u is found to 5.4×10^{-8}. Using this value for u and a well function table, such as the one in Heath (1983) page 35, the value for W(u) is determined to be 16.1. Therefore,

$$T = \frac{16.1}{4\pi} \times \frac{578 \text{ gpm}}{18 \text{ ft}} \times \frac{1 \text{ cu ft}}{7.48 \text{ gal}} \times \frac{1{,}440 \text{ min}}{\text{day}} = 7{,}920 \text{ sq ft/day}$$

This transmissivity value applies only to the part of the well open to the aquifer. To find the value for the full aquifer thickness, we must multiply by the saturated thickness of the aquifer (88.5 ft) and then divide by the length of the screened interval of the well (30 ft). This gives a transmissivity value of 23,000 sq ft/day. Similar calculations for the other two Consolidated Paper Company wells at Whiting gave values 15,800 sq ft/day and 14,400 sq ft/day. The computerized solution (Bradbury and Rothschild, 1985) gave an average value of about 14,400 sq ft/day. These values all show good agreement with the transmissivity value of 18,700 sq ft/day based on an aquifer test (Holt, 1965).

Hydraulic conductivity can now be determined for CPC well number 2 as follows:

$$K = \frac{23{,}000 \text{ sq ft/day}}{88.5 \text{ ft (saturated thickness of aquifer)}} = 260 \text{ ft/day}$$

This also shows close agreement with the value given by Holt (1965) of 234 ft/day.

The following version of the Theis equation was modified to correct the inconsistent units, and was used to calculate the cone of depression:

$$s = \frac{Q}{4\pi} \frac{W(u)}{T} \times \frac{1 \text{ cu ft}}{7.48 \text{ gal}} \times \frac{1{,}440 \text{ min}}{1 \text{ day}}$$

where

T = transmissivity at the well (18,000 sq ft/day)
Q = pumping rate of well (1,900 gpm)
s = selected amount of drawdown in well (0.1 ft)
$W(u)$ = the well function of u

where

$$u = \frac{r^2S}{4Tt}$$

and

r = distance from the pumping well to the point

where

the drawdown in the cone of depression equals the selected drawdown (s)

S = storage coefficient of the aquifer (0.20)

t = selected duration of pumping (3 days)

The first step is to solve for W(u). Based on the above values, W(u) is found to be 0.06. Using a well function table, u is found to be approximately 1.8. Now the second equation can be solved for the radius (r).

$$r = \left(\frac{(1.8 \times 4 \times 18{,}000 \text{ sq ft/day} \times 3 \text{ days})}{0.2}\right)^{1/2} = 1{,}400 \text{ ft}$$

Similar calculations for the cone of depression based on 0.5 ft and 1.0 ft of drawdown had radii of approximately 950 ft and 700 ft, respectively.

The cone of depression can also be calculated using a computerized version of the Theis solution. One such program is presented in Walton (1984). Results using the computerized solution in the Whiting case were very similar to the hand-calculated results.

APPENDIX 3

CHECKING ACCURACY OF TRANSMISSIVITY VALUES BASED ON SPECIFIC CAPACITY DATA: SEYMOUR, WISCONSIN

In addition to determining the transmissivity (T) of the aquifer at Seymour on the basis of the specific-capacity data found on the well logs, a value may be based on an aquifer test, as is given in LeRoux (1957). As we did for Whiting, we will go through the calculations here to illustrate the method of calculating transmissivity (T) based on a specific capacity test as described in appendix 1, and also to check the validity of this method for a semiconfined aquifer.

The modified version of Theis equation is used (Heath, 1983):

$$T = \frac{W(u)}{4\pi} \times \frac{Q}{s} \times \frac{1 \text{ cu ft}}{7.48 \text{ gal}} \times \frac{1{,}440 \text{ min}}{1 \text{ day}}$$

where

T = transmissivity of the well, in sq ft/day
Q/s = specific capacity of the well (8.43 gpm/ft)
W(u) = the well function of u

where

$$u = \frac{r^2S}{4Tt}$$

and

r = radius of the well (0.5 ft)
S = storage coefficient of the aquifer (0.0002)
t = duration of pumping (2 days)
T = estimated transmissivity value (2,400 sq ft/day)

These values are based on the specific capacity data contained in the well log for Seymour well number 2 and the aquifer test (LeRoux, 1957). Solving for u, we get a value of 2.6×10^{-9}. Then using the well function table (Heath, 1983), the value of W(u) is found to be 21.4. Therefore,

$$T = \frac{21.4}{4\pi} \times \frac{8.43 \text{ gpm}}{\text{ft}} \times \frac{1 \text{ cu ft}}{7.48 \text{ gal}} \times \frac{1{,}440 \text{ min}}{\text{day}} = 2{,}764 \text{ sq ft/day}$$

This transmissivity value applies only to the part of the well open to the aquifer. To find the value for the full aquifer thickness, we multiply by the saturated thickness of the aquifer (305 ft) and divide by the length of the open interval of the well (230 ft). This gives a transmissivity value of 3,665 sq ft/day. The computerized solution for transmissivity based on specific capacity (Bradbury and

Rothschild, 1985) gave a value of 2,880 sq ft/day. Again these values show reasonable agreement with the transmissivity value of 2,448 sq ft/day based on the aquifer test of Seymour well number 2 (LeRoux, 1957).

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WISCONSIN
DEPT. OF NATURAL RESOURCES

ISSN 0512-0659