OhioEPA

OHIO WELLHEAD
PROTECTION PROGRAM'S

WELLHEAD PROTECTION AREA DELINEATION GUIDANCE

OHIO ENVIRONMENTAL PROTECTION AGENCY

DIVISION OF DRINKING AND GROUND WATERS
122 SOUTH FRONT STREET
COLUMBUS, OHIO

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FOREWORD

The Safe Drinking Water Act Amendments of 1986 mandate that each state develop a wellhead protection program to protect public water supplies that use a ground water source. Guidelines were prepared by the United States Environmental Protection Agency, recognizing that each state would develop and tailor a program to suit its own needs.

The Governor of Ohio designated the Ohio Environmental Protection Agency as the lead agency for carrying out the mandates outlined in the Safe Drinking Water Act. Ohio's Wellhead Protection Program was approved by the United States Environmental Protection Agency in May, 1992.

This document has been developed to assist public water supply owner/operators and/or their consultants in delineating wellhead protection areas in accordance with the requirements outlined in Ohio's Wellhead Protection Program.

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CHAPTER 1

INTRODUCTION TO WELLHEAD PROTECTION AREA DELINEATION

INTRODUCTION

Ohio EPA's mission is to protect human health and the environment through responsible regulation supported by sound science, effective management, and comprehensive environmental education. Wellhead protection (WHP) planning involves all of these components. The objective of WHP is to protect the health of the people using ground water for their public drinking water by providing a focus zone around public wells or wellfields to prevent, detect, and remediate ground water contamination. This objective is met through seven activities required by Ohio's Wellhead Protection Program:

- Delineating a WHP area using the method most appropriate to the type, setting, and resources of the public water system;

- Completing a pollution source inventory that identifies all past, present and proposed land use activities in or around the WHP area that may pose a potential threat to the well or wellfield;

- Implementing a management strategy that establishes policies and procedures to prevent contamination from all potential sources of ground water contamination identified in the pollution source inventory for all existing and future water supply wells;

- Assessing the need for ground water monitoring, and if needed, implementing a monitoring plan based upon the inventory that will provide an early warning of impending contamination;

- Completing a contingency plan that ensures timely and appropriate response to emergencies, and also identifies short-term and long-term alternative water sources in the event of ground water contamination;

- Implementing a public involvement/education program that informs people living and working in and around the WHP area of WHP planning efforts and provides an opportunity to be involved in the planning process; and

- Evaluating the need for new wells, and if necessary, investigating potential sites for future well development and taking steps to secure and protect that area from potential contamination.

The first element on this list–delineating a WHP area–is the subject of this guidance document. More details concerning the other elements of WHP planning are provided in the *Ohio Wellhead Protection Program* document (Ohio EPA, 1992).

DELINEATING A WHP AREA

Delineating a WHP area is a critical component of WHP planning, and provides the basis for the other aspects of a WHP plan. Through delineation, the community determines where the water supplying their wellfield is coming from. This provides the area of focus for identifying potential threats to their wellfield and implementing protection activities to reduce or eliminate those threats. In addition, the information collected for delineation can be used to determine how susceptible the aquifer supplying the wellfield is to contamination. This information will, in part, determine how restrictive the land-use controls on the WHP area should be. Information collected during delineation also may be used to design a ground water monitoring system (if one is implemented) and may even indicate the adequacy of the existing wellfield to meet future water demands.

It is important to commit the resources necessary to obtain an accurate WHP area delineation. If the WHP area is not delineated correctly (e.g., if it is too small or is oriented in the wrong direction) the wrong area could be protected and contaminants could eventually enter the public water supply from unprotected areas. Conversely, various productive uses of land may be restricted unnecessarily in areas not contributing water to the public well or wellfield. An accurately delineated WHP area will be neither underprotective nor overprotective.

ORGANIZING OF GUIDANCE DOCUMENT

The purpose of this document is to assist purveyors of public water supplies in delineating an accurate and acceptable WHP area by: defining the various methods which can be used; outlining the major factors to consider when selecting and applying the most appropriate method; and, presenting requirements for submitting a WHP area delineation to Ohio EPA for review. Detailed information on how to delineate a WHP area using the more complex methods is beyond the scope of this guidance; however, several other documents are referenced to assist in specific applications.

The document is organized into five chapters and five supporting appendices. A complete list of references may be found following Chapter 5. Chapter 1 (Introduction) addresses the criteria for delineating a WHP area and the basic concepts and terminology required to understand the specifics of properly delineating a Wellhead Protection Area. Chapter 2 (Factors to Consider in Selecting and Applying a Delineation Method) explains the factors to consider in selecting an appropriate method. Hydrogeologic, planning, and resource considerations are discussed in this chapter. Chapter 3 (Wellhead Protection Area Delineation Methods) discusses the various delineation methods approved for Ohio's WHP Program and summarizes each method's advantages and disadvantages. Geologic settings that are most appropriate for each method are listed. Chapter 4 (Applications and Common Problems) describes specific technical considerations. Chapter 5 (Presentation of Results) contains guidance on how the information should be presented and discusses Ohio EPA's review procedure. Appendix 1 lists recommended references for additional reading. Appendix 2 is a glossary of terms used throughout the document (indicated within the text by bold-faced type). Appendix 3 includes sources of information for hydrogeologic investigations and lists the name, address, and phone numbers of organizations that may be contacted for assistance. Appendix 4 contains useful information on conversion factors. Appendix 5 includes typical values of soil and rock hydraulic properties.

More information and technical assistance is available from the Central Office and District Offices of the Ohio EPA, Division of Drinking and Ground Waters, Ground Water Program (Figure 1).

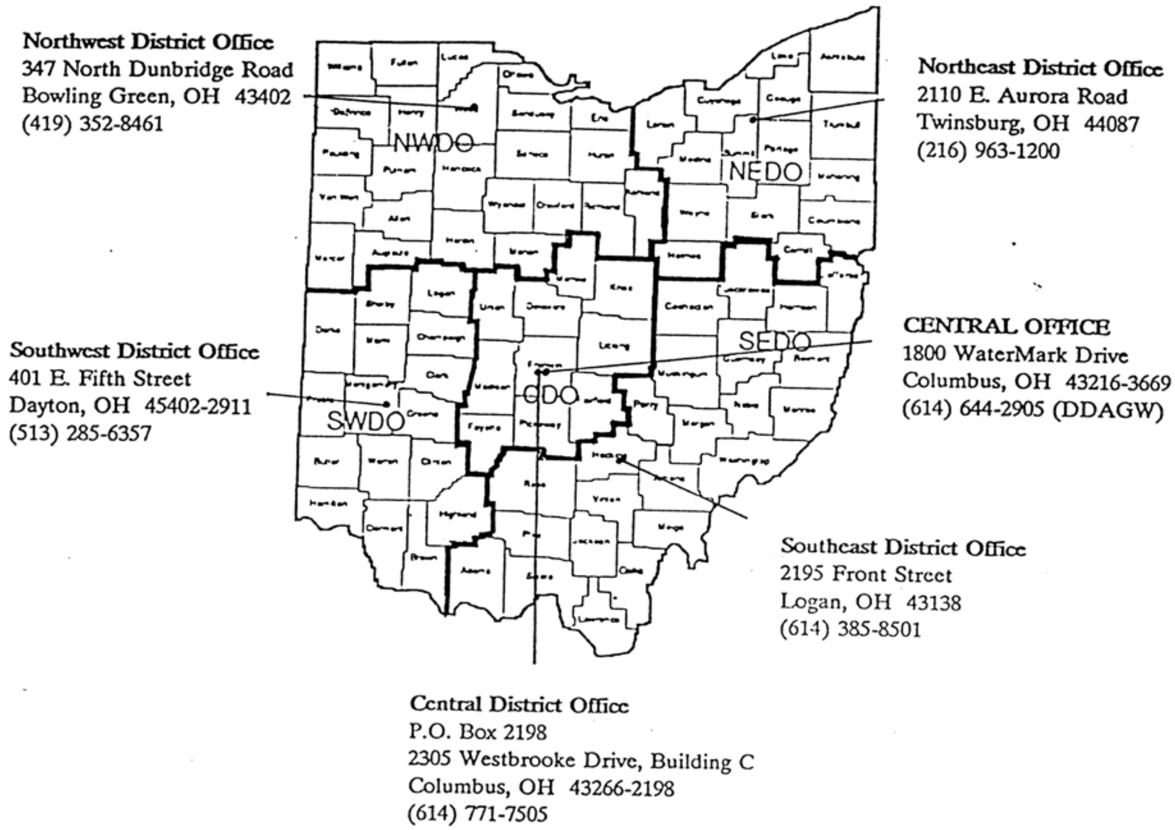


Figure 1. Ohio EPA's District Boundaries and Office Locations

GETTING STARTED

For those communities initiating wellhead protection planning, the Ohio EPA recommends the following steps to get started.

1. **Identify the threats to the wellfield.** Although the WHP area has not been defined yet, it is possible to identify the potential threats to the wellfield within the general vicinity–for example, within a radius of two miles from the wellfield. Many public water supply operators can identify most of the major threats to the wellfield without ever leaving their offices. Walking or driving around the area is another effective way of obtaining this information. Make a list of the various activities around the wellfield and explain why they present a threat. Make a simple map showing their relation to the wellfield(s).

2. **Evaluate the benefits of implementing wellhead protection.** Some questions that may help clarify the issues are listed below:

   - Based on the survey discussed above, how great is the potential for ground water contamination? What are the threats to the wellfield?

- If the current water supply becomes contaminated, what other economical alternatives are available? (Is a good surface water source available, and could the community afford the costs of developing a new source or providing for the additional treatment required for surface water sources?) If not, could the community afford to remediate or contain a serious ground water contaminant plume? Could the water system connect to another public water system?

3. **Evaluate the expected barriers to wellhead protection.** Some typical barriers include:

    - Cost. Wellhead protection may involve substantial initial and ongoing costs. The delineation effort can involve a considerable one-time expenditure.

    - Lack of resources. Small communities may initially lack the necessary expertise, equipment, and funding to conduct an adequate wellhead protection program.

    - Multi-jurisdictional disputes. A delineated WHP area frequently extends to several governmental units. Since wellhead protection involves decisions concerning land use, the affected jurisdictions may have strong feelings about whether and how wellhead protection is implemented. Cooperation among these entities is critical to the overall success of the WHP Program.

4. **Compare the costs and benefits.** The costs of preventing contamination and protecting the wellfield are almost always less than remediating contamination or finding an alternate source of water.

5. **Sell the program.** Armed with a preliminary potential pollution source inventory (including a map on which the sources are marked), and a written evaluation of the costs and benefits, discuss the idea with people, such as the city utilities director, the city manager, the mayor, members of city council, county commissioners, etc. Begin building a coalition of support within the community. Ohio EPA can assist in an introductory meeting to present information on WHP planning.

6. **Establish a working team.** Once a community has committed to wellhead protection, it will need to establish a Wellhead Protection Planning Committee. Members of the committee should consist of key local officials, including the water supplier, elected officials from all potential political jurisdictions, and staff from local health departments, planning organizations, the county Soil Conservation Service, the Solid Waste District, the Local Emergency Planning Commission, etc. This planning committee will be responsible for defining roles and responsibilities, resolving multi-jurisdictional disputes, developing the program, and organizing teams to conduct specific tasks.

    It also may be advisable to organize a Wellhead Protection Advisory Council composed of representatives of potentially affected businesses, residents, and landowners. This is one means of providing a forum for public participation, which is crucial to the acceptance of, and compliance with, the wellhead protection plan.

7. **Initiate planning effort.** Establish goals and objectives of WHP planning. Collect available information. Select appropriate delineation criteria and method. Begin a more detailed pollution source inventory (Ohio EPA, 1994). Begin evaluation and selection of management options.

    A community should not wait until it has a final WHP area delineated before initiating other components of WHP planning. This could cause unnecessary delays in getting a plan in place.

BASICS OF GROUND WATER OCCURRENCE AND GROUND WATER FLOW

Ground water is part of the hydrologic cycle–the continuous movement of water between the earth and the atmosphere through evaporation and precipitation, infiltration and runoff. As rain falls to the earth, some water runs off the land to rivers, lakes, and streams. Some water infiltrates the ground surface and moves downward through open spaces in rock and soil formations until it reaches the water table, which is the level below which the soil or rock is saturated with water. Water found in the saturated layer is called ground water.

Layers of soil or rock that provide significant amounts of ground water are called aquifers. In Ohio, the most productive aquifers tend to be units of sand and gravel located in major river valleys (river valley aquifers) or highly fractured units of limestone or sandstone (Figure 2). In some areas a layer of clay or other relatively impermeable materials (a confining layer) overlies the aquifer, causing the ground water in the aquifer to be under pressure. Consequently, when a well is drilled into the aquifer, ground water will rise within the casing to an elevation higher than the top of the aquifer (and sometimes as high as the ground surface, resulting in a "flowing well"). In such cases, the aquifer is described as a confined aquifer. Where such pressurized conditions do not exist, the aquifer is described as unconfined. Confining and unconfining conditions may exist in different parts of the same aquifer. Also, some aquifers may be confined during certain seasons and unconfined during others.

The surface defined by the elevation of water levels in wells is called the potentiometric surface. In a confined aquifer, this surface represents the elevations of pressurized water in wells, not the elevation at which ground water is encountered in the aquifer. However, in an unconfined aquifer, the potentiometric surface is identical to the water table, as it represents the elevation at which ground water is first encountered *in the aquifer*. The slope of the potentiometric surface determines the direction in which ground water will flow, and the steepness of the slope will partially determine how quickly the ground water will move. (For simplicity, the term "water table" will be used throughout this document to refer to a potentiometric surface, although this term is technically correct only when referring to an unconfined aquifer.) Maps of the potentiometric surface are called potentiometric maps.

Areas where precipitation and other surface water enters the ground water regime are called recharge areas. For example, a sandy surface layer may allow a great deal of precipitation to infiltrate quickly down to the water table. Also, surface water sometimes enters the ground through river and lake beds. Upon entering the subsurface, ground water flows very slowly toward discharge areas, where it leaves the subsurface and once again becomes surface water. Although various kinds of pressure fields affect the direction of ground water flow, it is driven primarily by gravity. In other words, ground water generally flows from higher elevations to discharge points at lower elevations. Typical discharge areas are rivers, lakes, springs ... and, of course, wells.

Zone of Influence

When ground water is pumped from a well, a lowering of the water table in the vicinity of the well can be measured within seconds, as a cone of depression forms around the pumping well (Figure 3). As pumping continues, the cone deepens and widens, until a state of equilibrium is reached. Within the WHP Program, the area affected by a pumping well is called the zone of influence. This area exhibits a measurable lowering of water levels due to pumping. In a water table that is perfectly flat, the zone of influence will be circular in plan view. However, natural water tables are never perfectly flat; they usually slope toward the nearest discharge area. This inclination of the (pre-pumping) water table or potentiometric surface is called the hydraulic gradient. As a result of the natural gradient, the zone of influence is more oval than circular in plan view (Figure 3).

Figure 2. Ohio's Aquifers: A Legacy of Ancient Seas and Glacial Meltwaters

Ohio's major aquifers can be categorized as two basic types:

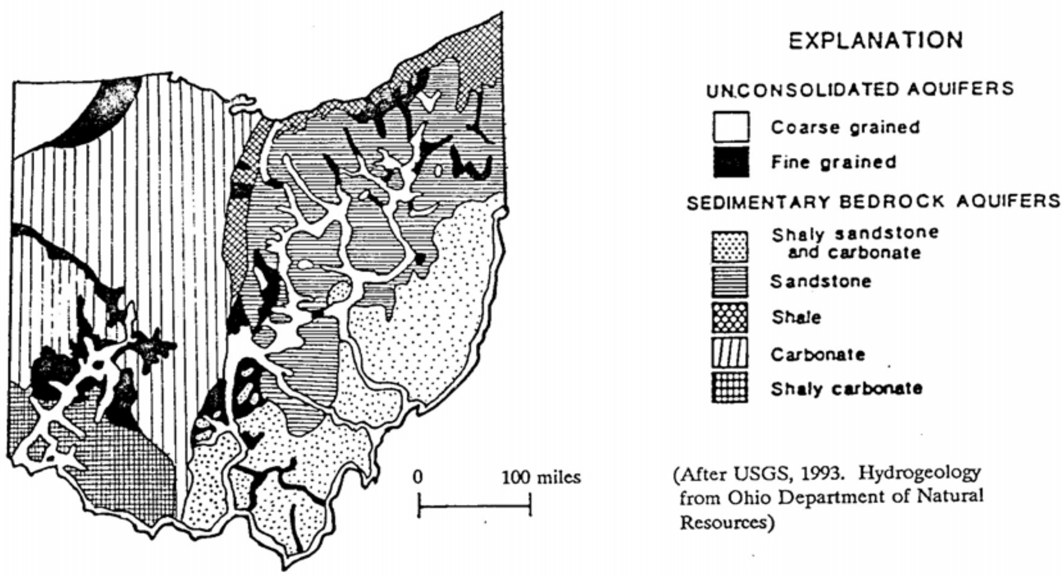
- bedrock aquifers (typically sandstone or limestone), which provide water via fracture networks; and
- unconsolidated deposit aquifers (typically sand and gravel), which lie within Ohio's former and present river valleys.

Bedrock Aquifers. As shown on the simplified map of Ohio's aquifers, a very thick and extensive aquifer of limestone and dolomite underlies much of northwestern Ohio. In northeastern Ohio, one of the most extensive and prolific aquifers is the Sharon Sandstone/Conglomerate. In southeastern Ohio, various interlayered units of sandstone, shale, limestone, and coal comprise the area's low-yielding bedrock aquifers. Similarly, in southwestern Ohio, bedrock aquifers are low-yielding, relatively thin beds of ancient limestone mixed with shale.

These bedrock units originated from sediments (dissolved carbonate, sea shells, sand, and silt) deposited in the bottom of the shallow areas and marshes that covered Ohio from 300-500 million years ago, during the Paleozoic Era.

Many of the bedrock aquifers are confined. Ground water enters the aquifers (recharges) in areas where the bedrock aquifer is exposed to the surface due to erosion of the overlying sediments, and where the aquifer is exposed to the atmosphere through excavations such as quarries or through poorly sealed abandoned wells.

Sand and Gravel Aquifers. Most of Ohio's most prolific aquifers consist of sand and gravel deposited in former and present river valleys by meltwaters from the great continental glaciers that advanced and retreated across Ohio during the Pleistocene Epoch (approximately 2 million to 10,000 years ago). These aquifers are recharged from above by precipitation, by ground water entering from fractures in surrounding bedrock valley walls, and sometimes by the rivers running through the valleys. Although sand-and-gravel aquifers may be protected somewhat by a thing overlying layer of clay-rich soil, they typically are unconfined and are relatively vulnerable to ground water contamination.



(After USGS, 1993. Hydrogeology from Ohio Department of Natural Resources)

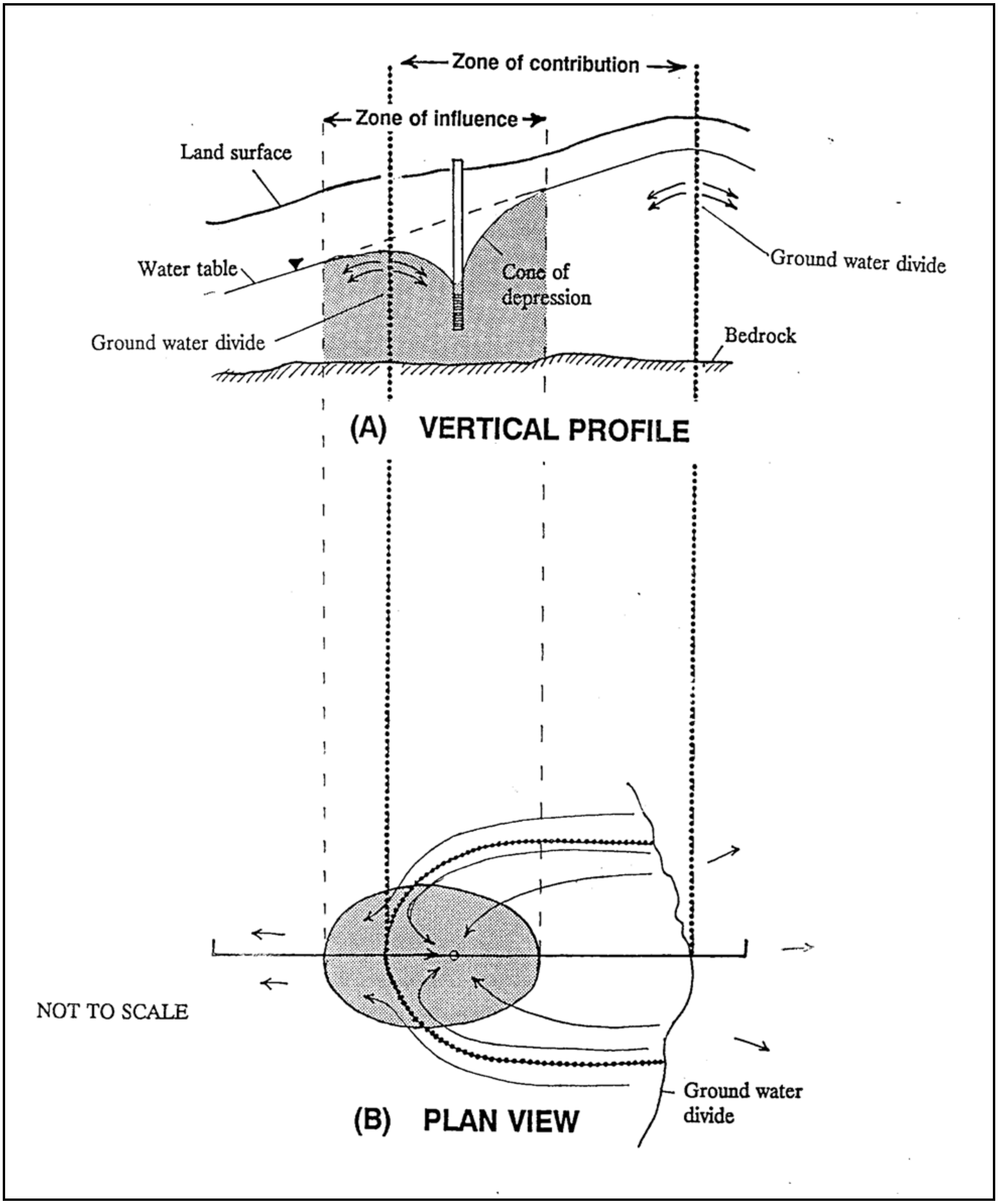


Figure 3. The Difference Between Zone of Influence and Zone of Contribution

Zone of Contribution

The area surrounding a pumping well that encompasses all areas and features that supply ground water to the well is called the zone of contribution. *The zone of contribution of a well is different from the zone of influence.* The zone of contribution includes all areas that contribute water to a well, while the zone of influence only includes the area within which water levels are lowered by pumping. While the zone of influence usually is smaller than the zone of contribution, it may not lie entirely within the zone of contribution. For example, if regional flow velocities are high, flow along the outermost and downgradient portions of the zone of influence may be carried *beyond* the well; this flow lies within the well's zone of influence but not its zone of contribution (Figure 3).

It is important to remember that the zones of influence and zones of contribution are three-dimensional, volumetric entities. In cross-section they will extend from the water table (or top of the aquifer, in a tightly confined aquifer) to the elevation of the bottom of the well's screened interval. If the well does not extend to the bottom of the aquifer, portions of the aquifer below the screened interval will also contribute flow to the well (Figure 4).

BASIC CONCEPTS AND TERMINOLOGY

Any discussion of WHP area delineation techniques requires an understanding of terminology that has a specific meaning for the wellhead protection program. The following pages outline some of the key terms used throughout the rest of the document.

DELINEATION CRITERIA

All WHP area delineation methods are based on one or several criteria that describe the physical processes of ground water flow and contaminant transport. Two basic delineation criteria are recommended for use in Ohio.

- Time-of-travel - the time period for ground water to flow through an aquifer and reach the well or wellfield; and

- Flow boundaries - Physical and hydrogeologic features that control ground water flow to the well or wellfield, such as ground water divides and impermeable bedrock valley walls.

Time-of-Travel

A WHP area based on time-of-travel is the area surrounding a well or wellfield that contributes ground water flow to the well(s) *within a specified period of time* (Figure 5A). Under Ohio's WHP Program, suppliers must delineate WHP areas based on a five-year time-of-travel. In other words, if drops of ground water located at the well could backtrack to where they were located five years ago, these locations would mark the five-year time-of-travel boundary of the WHP area. Several delineation methods use standard ground water flow equations to identify this boundary, as discussed in Chapter 3.

The five-year time-of-travel criterion fulfills Ohio's WHP Program objectives by allowing a supplier time to respond to ground water contamination reaching the WHP area. Theoretically, if a spill occurs just outside the controlled zone and results in ground water contamination, a supplier still has five years to try to control or remove the plume, put in a treatment system, or develop an alternate supply before the contaminants reach the pumping well(s). The five-year time-of-travel area also provides a manageable area on which suppliers can focus their pollution prevention activities.

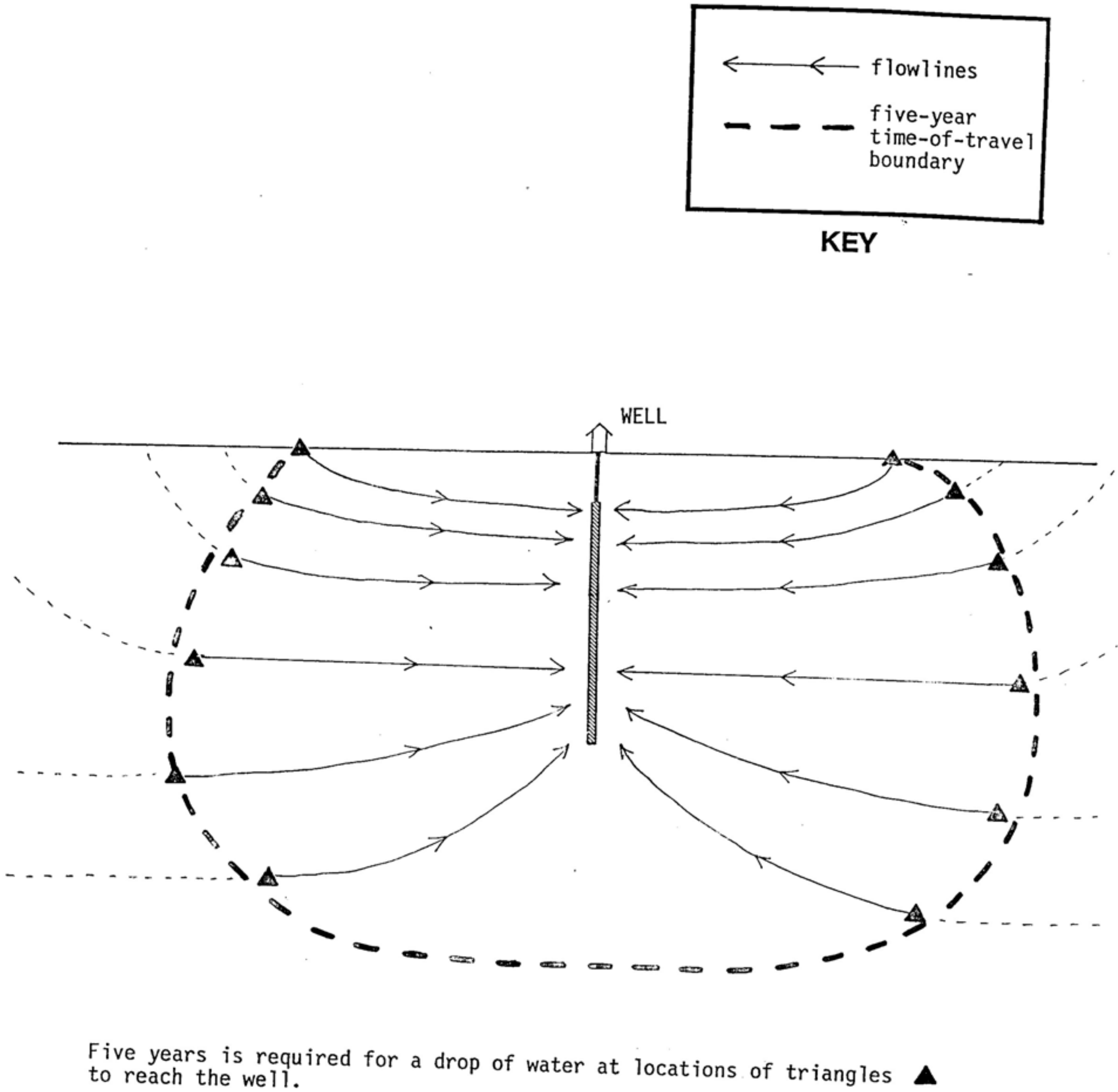
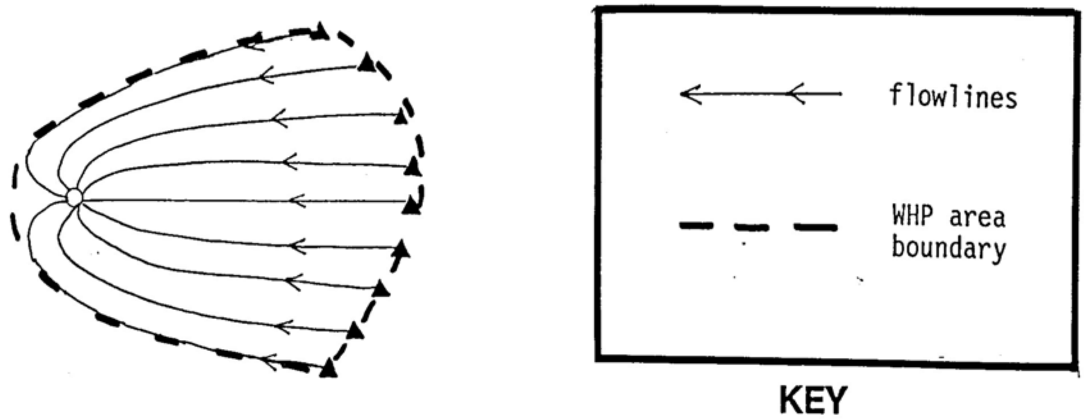
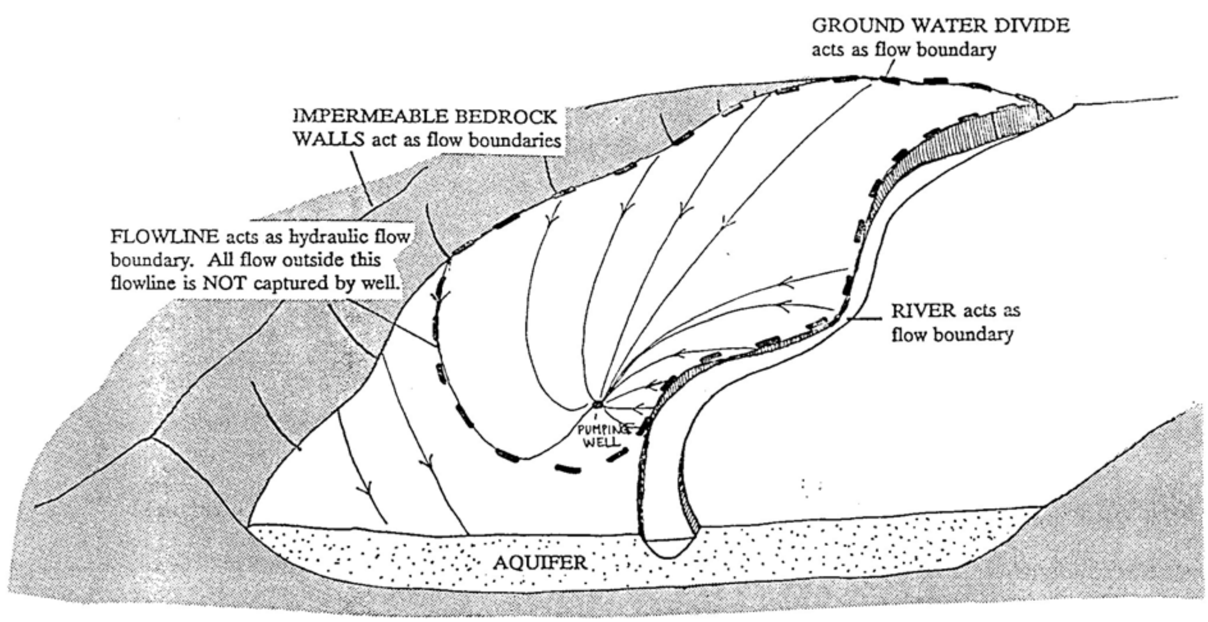


Figure 4. Cross-Sectional View of a Capture Zone



A. Time-of-Travel based WHP Area.
(Five years is required for a drop of water at locations of triangles ▲ to reach the well.)



B. Flow Boundary-based WHP Area.

Figure 5. WHP Areas Based on Delineation Criteria

Public water suppliers also should delineate an inner management zone with a one-year time-of-travel. Due to the proximity to the well(s) (i.e. shorter travel time and therefore shorter response time), this zone may require more stringent management controls than the five-year time-of-travel area. In some instances, a supplier also may choose to have an additional management zone beyond the five-year time-of-travel area (e.g., 10 or more years). This is especially useful where the aquifer is extremely susceptible to contamination from surface or near surface activities.

Flow Boundaries

Physical and hydraulic boundaries of an aquifer or ground water flow system can be used effectively to delineate a WHP area. Typical physical boundaries are impermeable bedrock valley walls surrounding a valley-fill aquifer. Typical hydraulic boundaries are regional or local ground water flow divides, or significant water bodies such as rivers and lakes. Delineating a WHP area based on this criterion involves identifying–at least roughly–the location or such boundaries. In this case, the delineated area will represent the entire area surrounding a well or wellfield that has the potential of contributing water to the wellfield, based on current pumping rates and ground water flow directions (Figure 5B).

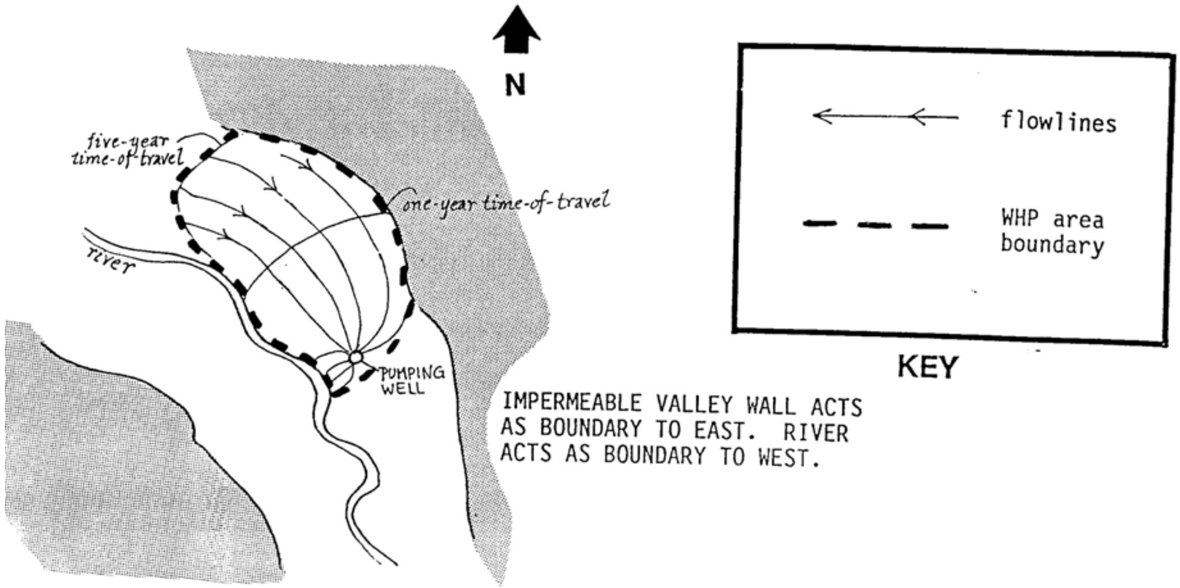
The flow boundary criterion fulfills Ohio's WHP Program objectives by identifying all areas that need to be protected to avoid contaminating the public drinking water source. The delineation method used to identify flow boundaries is called hydrogeologic mapping. Delineation of WHP areas using this method is discussed in more detail in Chapter 3 ("Flow Boundary Based Delineation Methods").

Combined Criteria

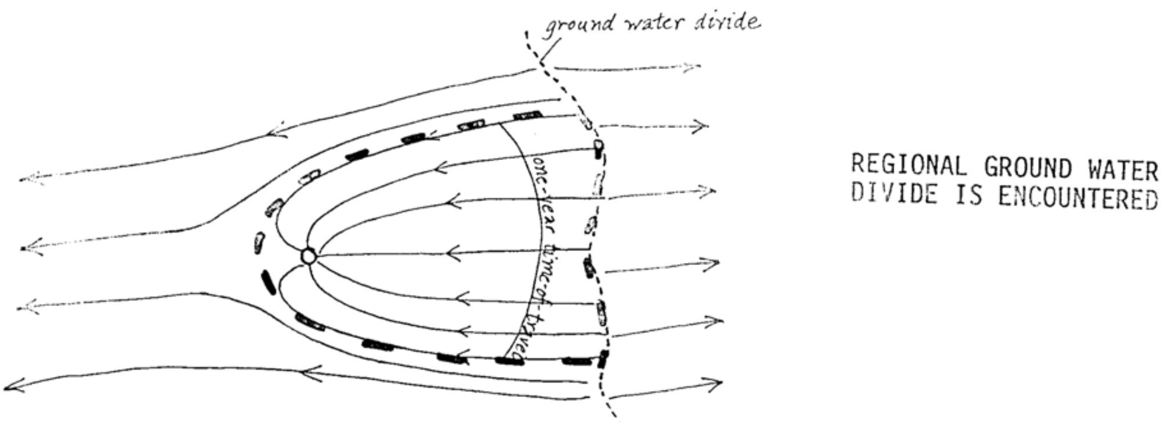
The Ohio WHP Program also accepts delineation of WHP areas based on a combination of the criteria listed above. In many cases, a five-year time-of-travel area will intercept some kind of natural flow boundary, which will then act as a limit of the WHP area in that direction (Figures 6A and 6B).

Under Ohio's WHP Program, a WHP area includes that portion of a well or wellfield's zone of contribution out to the five-year time-of-travel, unless a ground water flow divide is encountered first.

RULE OF THUMB: ***Under Ohio's WHP Program a WHP area includes that portion of a well or wellfield's zone of contribution out to the five-year time-of-travel, unless a ground water flow divide is encountered first.***



A. Combined Delineation Criteria: Flow Boundaries (Impermeable Valley Wall and River) with Time-of-Travel



B. Combined Delineation Criteria: Flow-Boundary (Regional Ground Water Divide) with Time-of-Travel

Figure 6. WHP Areas Based on Combined Delineation Criteria

CHAPTER 2

FACTORS TO CONSIDER IN SELECTING AND APPLYING A DELINEATION METHOD

INTRODUCTION

The objective of delineating a WHP area is to define the land surface expression of those areas contributing water to a public well or wellfield. In Ohio this area is usually defined as the zone of contribution out to the five-year time-of-travel boundary or some hydrogeologic boundary. Once it is defined, a community can focus efforts to protect the source of their drinking water in this area.

Several methods are available for delineating WHP areas, relying either on the use of ground water flow equations or on hydrogeologic mapping. The methods range from simple and inexpensive to complex and costly. Selecting the most appropriate WHP area delineation method requires the delineator to consider not only the hydrogeologic setting, but a number of other factors that are discussed below as "planning considerations". In general, the supplier's goal will be to balance the need for accuracy against the available resources. Selecting a delineation method should be justified in terms of the items listed under Hydrogeologic Considerations, Planning Considerations, and Resource Considerations. This justification should be clearly documented so that a reviewer can understand the supplier's logic and reasons for selecting the particular method.

HYDROGEOLOGIC CONSIDERATIONS

A WHP area delineation should be based on as much site-specific hydrogeologic information as possible. This information is obtained by researching relevant hydrogeologic information available in the public domain and through various site-specific hydrogeologic investigation techniques, such as test borings, pumping tests, and water level measurements. A list of various public sources of hydrogeologic information is presented in Appendix 3. The kind of information to be collected, and its significance to selecting a WHP area delineation method, is discussed in the following paragraphs.

Aquifer Material

Aquifer properties are largely determined by the materials that constitute the aquifer. In Ohio, unconsolidated aquifers–principally composed of sand and gravel–are typically found in river valleys (see Figure 2, page 1-6). These aquifers yield water to wells via the pore spaces between the individual grains. If the sediments are primarily coarse-grained and well-sorted, the pore spaces will be large. In this case, ground water yields will be greater, hydraulic conductivity will be high, and the zone of contribution should be relatively symmetrical in shape. Most porous flow equations are suited to this kind of aquifer. Conversely, significant amounts of fine-grained materials such as clay may inhibit ground water yields and channel ground water flow in unexpected directions, so that the capture zone may be irregular in shape and greatly extended.

Bedrock aquifers typically provide most water via fracture networks. The amount of water yielded by pumping depends on the size, density, and "interconnectedness" of the fractures. If the fracture network is very dense and interconnected, porous flow equations may describe ground water flow adequately.

Most fracture networks have a dominant orientation. For example, fractures in the limestone found in portions of Northwest Ohio tend to be oriented dominantly in the northeast-southwest direction, with minor fracturing in the northwest-southeast direction (Bair and others, 1990). In such a setting, it may be necessary to elongate the WHP area in the direction of the dominant fractures. Therefore, before selecting a delineation method, the investigator should obtain as much information as possible about the fracture network, and should evaluate whether the aquifer can be modeled as a porous flow medium. (This issue is discussed in more detail in Chapter 3, pages 3-22 to 3-28). If not, then flow-boundary mapping may be the most suitable delineation technique.

Aquifer Vulnerability

By assessing the aquifer's vulnerability to contamination, an investigator further defines the need for accuracy of the delineation. An aquifer that is judged to be "vulnerable" warrants a more accurate delineation. If the community is unable to provide for the desired degree of accuracy, the WHP area should be expanded beyond the boundaries delineated, to provide for more protection.

Additionally, a vulnerability assessment aids a community in choosing the most appropriate management options. A highly vulnerable aquifer probably will require careful land-use controls over the entire acreage delineated. On the other hand, a relatively invulnerable aquifer may require only land-use controls and/or monitoring around breaches in the confining layer that exist within the delineated WHP area (such as around wells, quarries, isolated outcrops, etc.).

Indicators of aquifer vulnerability include:

- high surface soil permeability (typical of very sandy soils)
- flat terrain (resulting in more infiltration, less run-off)
- shallow depth to ground water
- coarse-grained or highly fractured geologic material overlying the aquifer
- the presence of "young" water in the wellfield, as determined by isotopic dating or geochemical indicators.

Aquifer Confinement

It is important to know whether the aquifer is confined, unconfined, or semi-confined for a number of reasons. First of all, unconfined, semi-confined, and highly confined aquifers have different vulnerabilities to ground water contamination. An unconfined aquifer is the most vulnerable, because there is no confining layer above it to slow the infiltration of surface-contaminated water. Highly confined aquifers are the least vulnerable, because they are isolated by the confining layer.

Secondly, most computer models for ground water flow and capture zone modeling require that the user specify whether the aquifer is confined or unconfined. The more sophisticated models may include a separate routine for semi-confined conditions. Designating the confining conditions incorrectly could result in over- or underprotecting the aquifer.

Whether the aquifer is confined, unconfined, or semi-confined also must be known to obtain values for aquifer parameters that may be required for delineation (e.g., hydraulic conductivity and storativity or specific storage). It would be inaccurate, for example, to use a confined aquifer method of analysis (such as the Theis Method) to derive a value of conductivity for a very leaky aquifer. Therefore, an investigator must determine whether the aquifer is confined or otherwise before selecting a method for obtaining conductivity or storativity values from pumping test data.

One simple method of determining whether an aquifer is confined is to compare the depth to ground water with the depth to the top of the aquifer. If the water level in a well is higher than the top of the aquifer, then the aquifer is considered to be at least partially confined. A trained investigator also can make this determination by inspection of the curve produced when pumping test data are plotted on graph paper. Other methods are discussed in the U.S. EPA guidance document entitled *Wellhead Protection Strategies for Confined-Aquifer Settings* (1991a), and in Ohio EPA's *Technical Guidance Manual for Hydrogeologic Investigations and Ground Water Monitoring Program* (1993).

Flow Boundaries

Ground water flow boundaries may affect the size and orientation fo a capture zone significantly, and many of the most widely-used computer flow models require knowledge of their location and orientation. The major types of flow boundaries are discussed below.

Recharge boundaries are those areas (usually rivers and lakes) that provide so much water to a pumping well, they act as a natural boundary to the pumping well's capture zone. In humid regions like Ohio, a river most commonly acts as a discharge area, where ground water flows OUT of the ground. However, as the cone of depression created by a pumping well extends out to the river and the ground water level drops below the river stage, surface water may begin to infiltrate, percolating through the sediments to the pumping well. The river is then transformed from a discharge area to a recharge area.

In Ohio, many major pumping centers are located adjacent to a stream to take advantage of induced infiltration*. In such cases, the capture zone may be relatively small, because the river provides an almost inexhaustible source of water and cone of depression does not become steep enough to pull in water from greater distances.

Barrier boundaries are impermeable areas that restrict ground water flow to a certain area. For example, extensive, continuous layers of clay within a sand-and-gravel river valley aquifer can act as barrier boundaries. The most typical barrier boundaries encountered in Ohio, however, are relatively impermeable bedrock valley walls enclosing river valley aquifers, as shown in Figure 6A [Chapter 1, page 1-12].

Because boundaries can have a major impact on capture zone size and orientation, the choice of a delineation method may be influenced by how well the various methods model boundaries. Delineation methods based on simple equations do not account for flow boundaries. Simple computer models may be able to account for simple, linear boundaries located along the perimeter of the field of interest. The investigator needs to be aware, however, that two-dimensional models assume that recharge boundaries are fully-penetrating, meaning that they penetrate or occur below the bottom of the aquifer. In reality, most rivers are not fully-penetrating. A more detailed discussion of this conceptual problem is provided in Chapter 4, pages 4-11 to 4-13.

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*Note that from the perspective of wellhead protection, this location also poses certain disadvantages because the stream itself becomes a potential pollutant source–one that is not amenable to the standard land-use controls that are associated with the wellhead protection program.

Of all the delineation methods listed, numerical computer models and some analytic-element models can be used to model the effects of a river with the greatest accuracy.

Ground water flow divides are local or regional ridges in the ground water surface, where ground water flows in different or opposite directions. Flow divides are similar to the ridgeline of a roof: water on either side of the divide tends to flow downslope away from the divide. Because the water table tends to mimic the ground surface above it, ground water flow divides often are located beneath local areas of high topography. However, the location of a flow divide is not fixed; it tends to shift in accordance with variations in recharge (due to variations in surface water infiltration) and discharge rates (due to variations in pumping levels, or locations of other pumping centers). As illustrated in Figure 7, the initiation of a new pumping center may cause a nearby ground water divide to shift away from the pumping center, reflecting drawdown of water levels caused by the pumping.

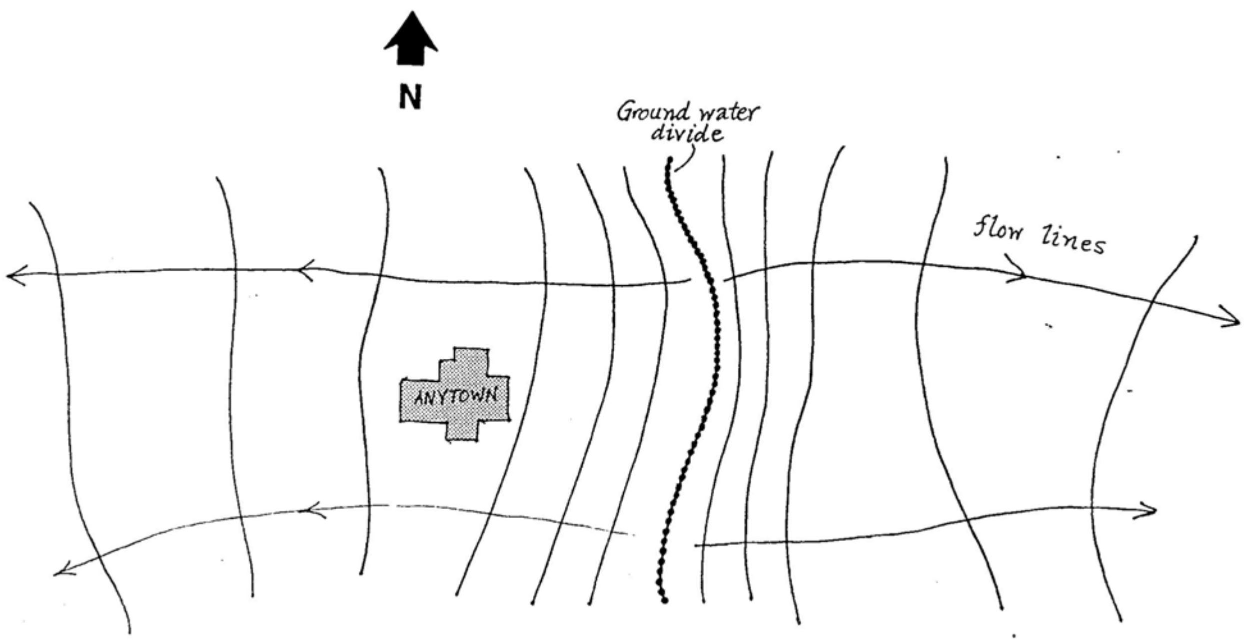
Another typical scenario is illustrated in Figure 8, where the cones of depression created by a number of nearby industrial pumping centers create ground water boundaries that limit the zone of contribution for a public supply wellfield. If one or more of the local pumping centers reduce or cease pumping, the flow boundaries may shift and allow the public supply wellfield's zone of contribution to expand. As a result, additional potential pollution sources may be included within the public wellfield's capture zone. In such cases, Ohio EPA may recommend modeling all potential combinations of pumping scenarios, and having plans in place to address any potential changes in flow divide locations.

Hydraulic Properties

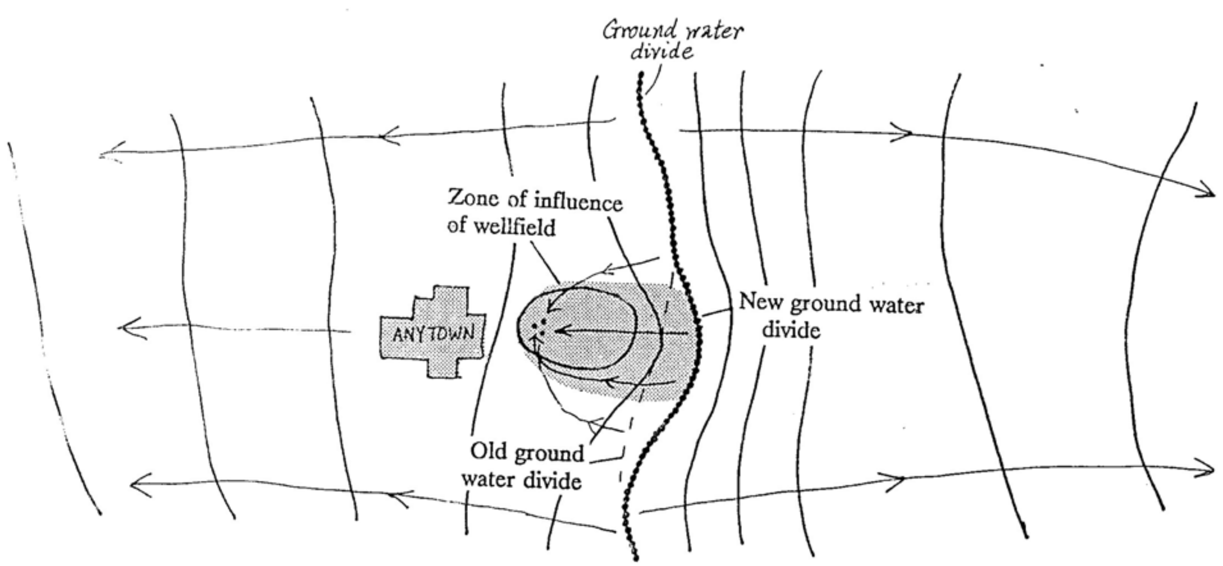
The size of a well's capture zone is affected by values of such aquifer parameters as transmissivity, horizontal and vertical hydraulic conductivity, storage coefficient and porosity (see Glossary, Appendix 2, for definitions). Because these properties are intrinsic to the aquifer material, they are fixed in space and do not vary significantly over time. In fact, the hydraulic conductivity value is one of the most important–and most problematic–determinants of flow velocity. As indicated in Table 1 below, the hydraulic conductivity value can range over twelve orders of magnitude. In other words, the hydraulic conductivity of a unit of clean gravel may be a *trillion times* greater than that of a tight clay unit. Within a typical unconsolidated aquifer, hydraulic conductivity values commonly vary up to three or more orders of magnitude. For example, if flow in a relatively clay-rich portion of the aquifer is one-tenth of a foot per day, flow in a sandier portion may be ten or more feet per day, based solely on hydraulic conductivity differences.

The choice of a delineation method may be partly determined by the ability to obtain values for various hydraulic properties. All delineation methods except the volumetric equation method require a value for the horizontal hydraulic conductivity of the aquifer. Some computer models, such as MODFLOW, may require values for vertical hydraulic conductivity as well.

Also, correct application of a selected method will be determined in part by the quantity and quality of values obtained for hydraulic properties. Some methods of obtaining these values are better than others. For example, site-specific values for hydraulic conductivity can be obtained from laboratory permeameter tests, slug tests, and pumping tests. Values derived from pumping tests are considered the most reliable, yet even these tests commonly yield a range of conductivity values that vary by a factor of 10 or 100. In these cases, it may be advisable to model the capture zone using a range of values that includes the maximum and minimum values.



A. 1955 potentiometric map completed for Anytown vicinity.



B. 1995 potentiometric map completed for Anytown vicinity

Figure 7. Alteration of a Local Flow Divide by Installation of a Wellfield (for hypothetical town - "Anytown")

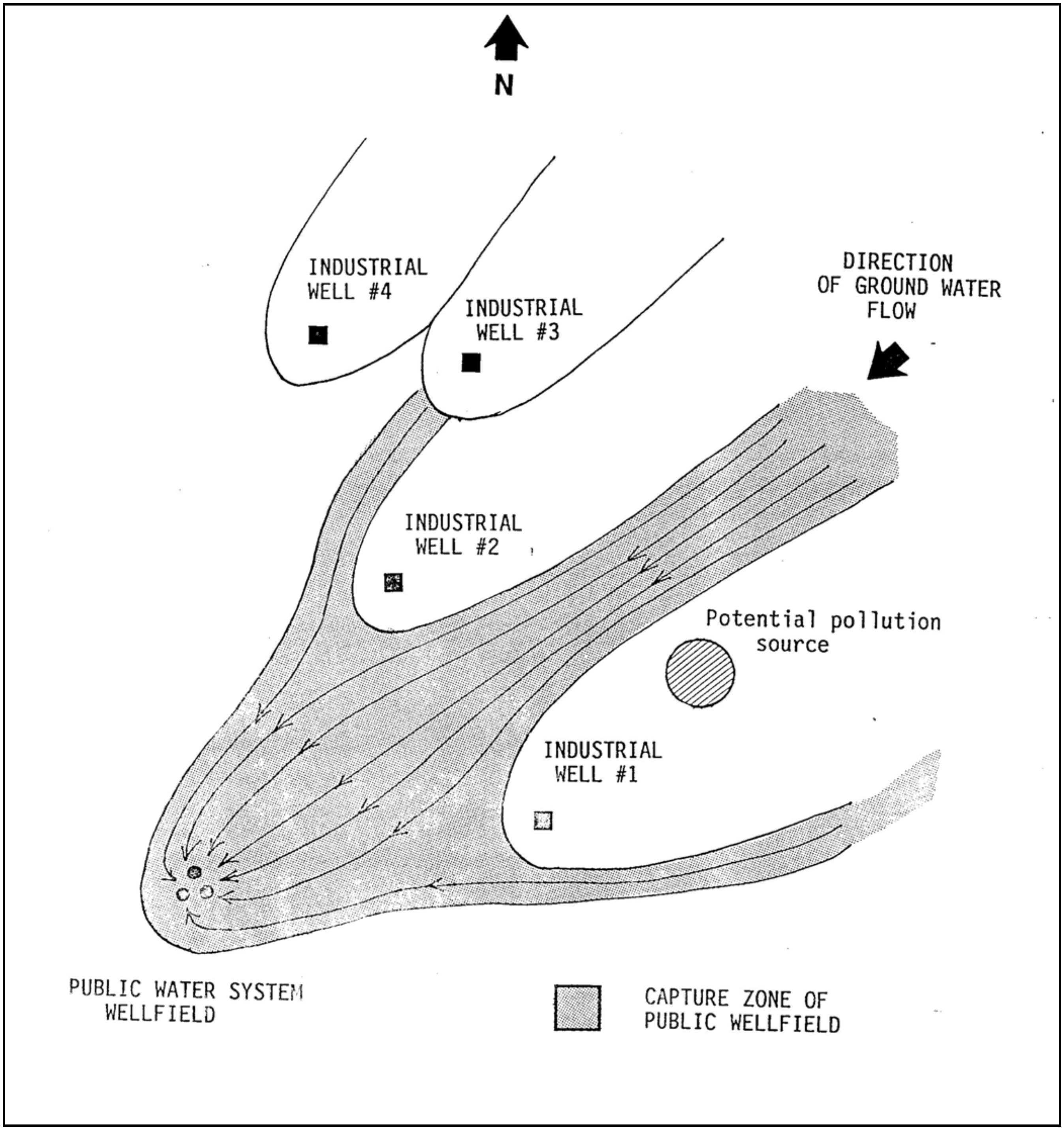
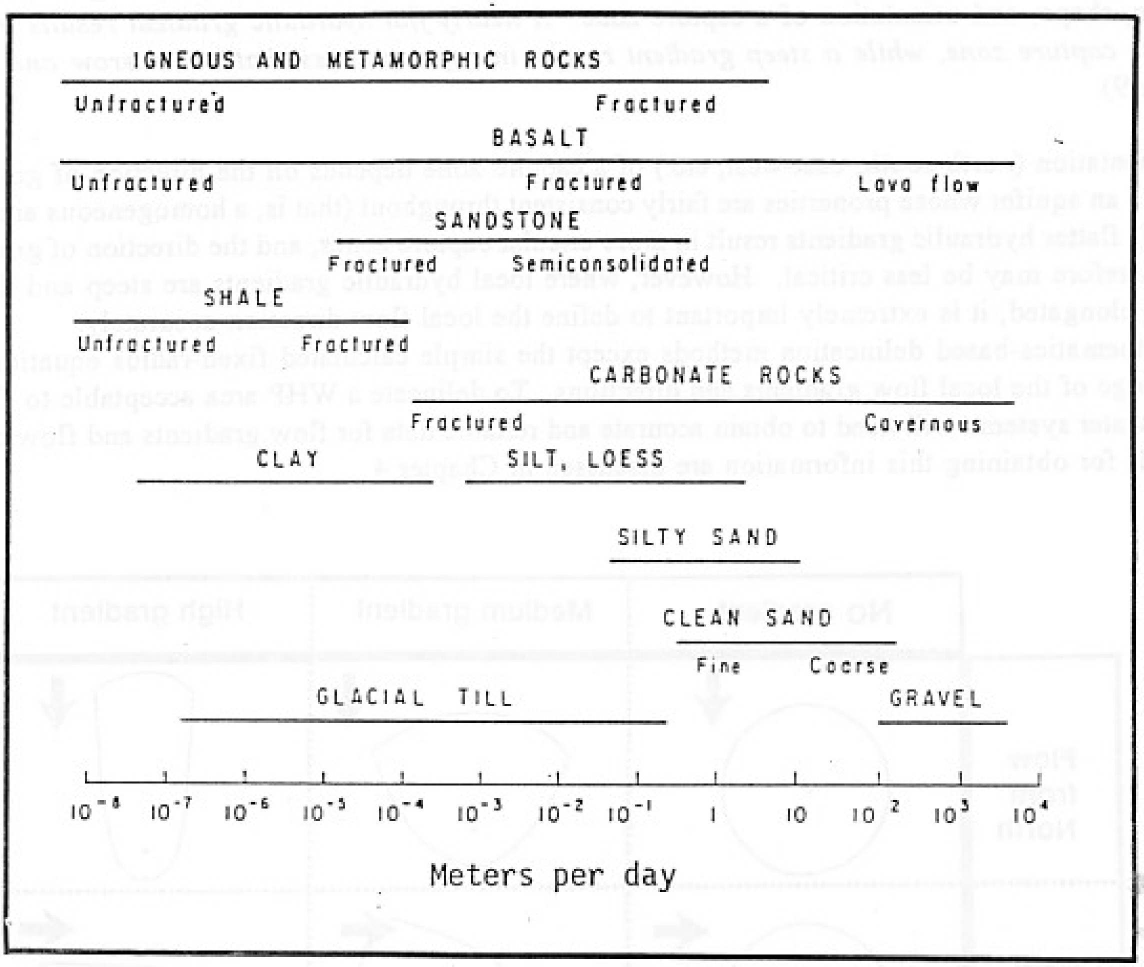


Figure 8. Effect of Multiple Pumping Centers on the Shape of a Public Wellfield's Capture Zone

Table 1. The Range of Hydraulic Conductivity Values
(after Heath, 1984)



Pumping tests commonly are conducted upon installation of new public water supply wells. Values of hydraulic conductivity, transmissivity, and storage derived from these tests may be on file at the public water supplier's office and at the district and central offices of the Ohio EPA (Division of Drinking and Ground Waters' Drinking Water Program).

When site-specific values for hydraulic properties are not available, the investigator should use values typical of the aquifer(s) in that locality. Typical local values of transmissivity and hydraulic conductivity may be obtained from regional water surveys that are on file, referenced by county, at the Ohio Department of Natural Resources' Division of Water (See Appendix 3).

When nothing else is available, the investigator may be obliged to use hydraulic parameter values typical of specific geologic materials, as listed in ground water textbooks. Porosity values, for example, usually are based on literature values. Typical literature values for hydraulic conductivity, transmissivity, specific yield, and porosity are provided in Appendix 5.

Local Flow Gradients and Flow Directions

Modeling studies indicate that local flow gradients and directions may have the most significant effect on the size, shape, and orientation of a capture zone. *A nearly flat hydraulic gradient results in a nearly circular capture zone, while a steep gradient results in capture zones that are narrow and elongated* (Figure 9).

The orientation (north-south; east-west, etc.) of a capture zone depends on the direction of ground water flow. In an aquifer whose properties are fairly consistent throughout (that is, a homogeneous and isotropic aquifer), flatter hydraulic gradients result in more circular capture zones, and the direction of ground water flow therefore may be less critical. However, where local hydraulic gradients are steep and the capture zone is elongated, it is extremely important to define the local flow direction accurately.

All mathematics-based delineation methods except the simple calculated fixed-radius equations require knowledge of the local flow gradients and directions. To delineate a WHP area acceptable to Ohio EPA, public water systems will need to obtain accurate and reliable data for flow gradients and flow directions. Methods for obtaining this information are discussed in Chapter 4.

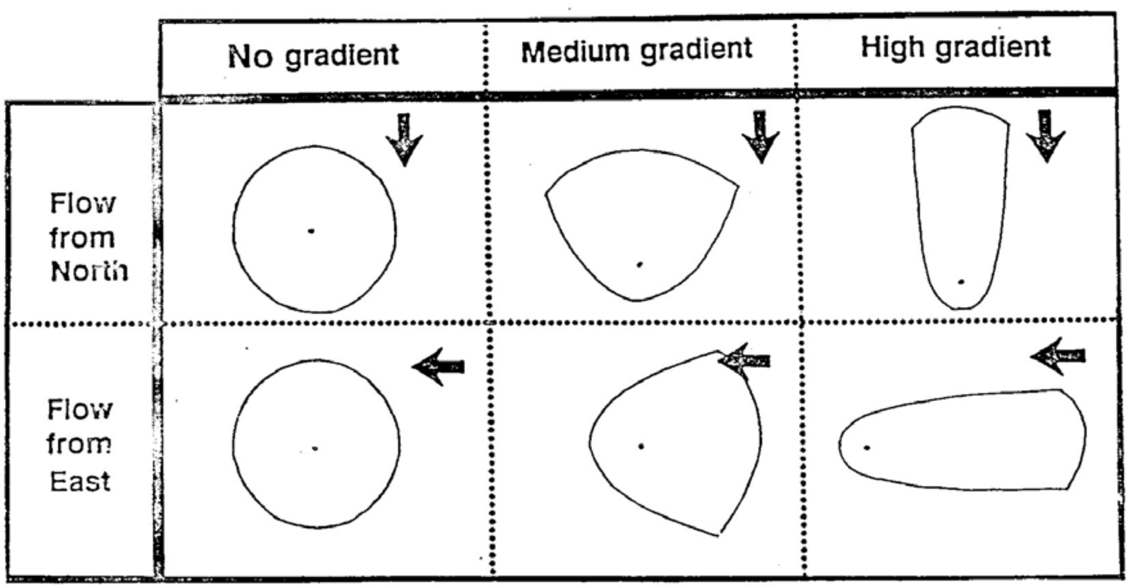


Figure 9. Effects of Local Flow Gradient and Direction of Ground Water Flow on Shape and Orientation of Capture Zone

SUMMARY

Table 2 summarizes the above discussion of hydrogeologic considerations into seven questions. The investigator should try to answer these questions as completely as possible. If these questions cannot be answered adequately based on the information derived from public sources, then additional information will need to be obtained through field studies.

Table 2. Summary of Hydrogeologic Considerations

QUESTION	RELEVANCE TO WHP AREA DELINEATION AND METHOD SELECTION
What is the AQUIFER MATERIAL? More specifically, is the aquifer material nearly HOMOGENEOUS or is it HETEROGENEOUS? Is it likely to behave as a porous medium? Will ground water flow in this aquifer conform to POROUS flow equations?	All Ohio-approved WHP area delineation methods–except flow mapping–are based on porous-flow equations. If ground water flow in the aquifer does not conform to porous-flow theory (due to heterogeneity, anisotropy, etc.), flow mapping may be most acceptable method.
Is the aquifer CONFINED, UNCONFINED or SEMI-CONFINED? How VULNERABLE is the aquifer to ground water contamination?	A more vulnerable (unconfined) aquifer warrants a more accurate delineation. Confining conditions also must be known to correctly obtain values for aquifer properties from pumping test data.
Do any FLOW BOUNDARIES exist within the area of interest?	Flow boundaries significantly affect capture zone size and orientation. Choice of a delineation method may be partially based on how well the method models boundary effects. Simple equation delineation methods cannot account for boundaries; simple two-dimensional computer models may account for simplified, fully-penetrating boundaries. Numerical and analytic-element models provide the greatest accuracy in reproducing a boundary's location and effect on water levels.
What are the HYDRAULIC PROPERTIES of the aquifer?	These must be known to apply all but the simplest delineation techniques.
What are the local FLOW DIRECTIONS in the aquifer volume of interest? How steep is the local ground water FLOW GRADIENT?	These have a significant effect on size, shape, and orientation of capture zone. Must be known to apply any delineation method more sophisticated than a calculated fixed radius equation.

Field studies also may be required if the community ultimately decides to use a sophisticated delineation method. Table 3 lists the various delineation techniques approved by Ohio EPA for WHP delineation, and indicates which parameters must be evaluated for each technique. Detailed methods for acquiring these kinds of information are discussed in numerous texts and technical guidance documents, including Ohio EPA's *Technical Guidance Document for Hydrogeologic Investigations and Ground Water Monitoring* (Ohio EPA, 1993).

Table 3. Hydrogeologic Information Required for Various Delineation Techniques

Information Type	Input Value or Information Required to Delineate WHP Area Using:					Used as Background to Develop the Conceptual Model	Required to Determine Appropriateness of Most Methods	Primary Sources of Information (See Appendix 3 for addresses and phone numbers)
	Calculated Fixed Radius / Volumetric Equation	Uniform Flow Equation	Semi-Analytical Computer Models	Numerical Computer Models	Hyrdro-Geologic Mapping			
Local and Regional Hydrogeologic Setting						X	X	ODNR well logs, ODNR ground water resource maps, regional ground water bulletins published by USGS and ODNR.
Aquifer Composition					X	X	X	ODNR well logs, ODNR ground water resource maps, ODNR regional water surveys; site-specific soil borings.
Saturated Thickness of Aquifer and Thickness of Confining Units						X	X	ODNR well logs; ODNR ground water resource maps; ODNR regional water surveys; site-specific soil borings; geophysical methods.
Presence of Recharge or Barrier Boundaries			X*	X		X	X	Obvious recharge boundaries (streams, lakes) displayed on various maps. Locations of flow divides may be estimated from topographic high areas on topographic maps. Pumping tests may provide useful information. Geophysical techniques may locate barrier boundaries and permeable zones in bedrock aquifers.
Confined or Unconfined Conditions			X*			X	X	Site-specific water level data; ODNR well logs; ODNR regional surveys
Local Flow Direction(s)		X	X	X		X	X	Derived from potentiometric maps.
Local Flow Gradient		X	X*			X	X	Derived from potentiometric maps.
Horizontal Hydraulic Conductivity (K_H)		X	X	X		X		From most accurate to least accurate: pumping tests, slug tests, laboratory permeameter tests, ODNR regional water surveys, and literature.
Vertical Hydraulic Conductivity (K_Y)				X		X		Pumping test data.
Porosity	X		X*			X		Can be obtained from bulk density testing and other methods listed in Javandel, 1984; however, usually based on literature values.
Pumping Rate of Wells(s) (Q)	X	X	X	X		X		PWS should have this information.

Table 3. (continued)

Information Type	Input Value or Information Required to Delineate WHP Area Using:					Used as Background to Develop the Conceptual Model	Required to Determine Appropriateness of Most Methods	Primary Sources of Information (See Appendix 3 for addresses and phone numbers)
	Calculated Fixed Radius / Volumetric Equation	Uniform Flow Equation	Semi-Analytical Computer Models	Numerical Computer Models	Hyrdro-Geologic Mapping			
Water Levels in Surrounding Wells			X*	X	X	X		Field measurements of water levels. Also, ODNR well logs are often used; see discussion starting on page 4-2.
Recharge Rate			X*	X		X		May be listed in ODNR regional ground water bulletins. Often based on a percentage of average annual rainfall for the area.
Well Configuration (distance from other wells and hydrogeologic boundaries)			X*	X		X	X	PWS should know distances between wells in the wellfield. Distances from wells to hydrogeologic boundaries may be estimated from appropriate maps or derived from pumping test data.
Storage Coefficient			X*	X		X		Pumping test data.

X = Required
X* = Required for most models

Current and Anticipated Size of System

The type of system (community, transient, non-transient) and its size need to be considered when selecting the appropriate delineation method. The more people served by the system, the greater the population at risk if the delineated area is significantly inaccurate. The large water provider also will pump more wells at higher rates, resulting in a larger capture zone around the wellfield than the smaller water system. Thus, the odds of the larger system encountering geologic barriers and including more potential pollution sources are higher than they are for a small system. For all these reasons, *a larger system may need to select a more sophisticated delineation method than a smaller system*, basing the selection on more site-specific information, to ensure a satisfactory degree of accuracy.

A wellhead protection area should be delineated in accordance with the predicted maximum average monthly pumping rate of the water supply system, as projected for the next five to 20 years. A recommended method for obtaining the "maximum average monthly pumping rate" is presented in Chapter 4.

RULE OF THUMB: ***WHP areas should be delineated in accordance with the predicted maximum average monthly pumping rate of the water system over the next five to twenty years. (See sample calculation in Chapter 4, Figure 24).***

Wellhead protection planning should not be limited to the existing wellfield(s). A rapidly growing community may exhaust the capacity of the current wellfield(s) and be obliged to develop another one. Thus, the community's WHP planning may need to be expanded to protect a more distant area that possibly has not yet been secured for future use.

WHP Goals and Management Stategies

It is very important to consider the overall WHP goals and anticipated management strategies when selecting a delineation method. Communities should explore the most feasible management options available even before delineating the wellfield, as this may aid in the choice of a delineation method. For example, if voluntary educational management strategies are the most practical for a locality, then inexpensive, less accurate delineation methods that require less defensibility may be in order. Conversely, *the more complex, restrictive, controversial and/or costly the goals and strategies, the more accurate the delineation method needs to be.* Those systems considering zoning restrictions, land purchases, purchasing development rights, or large ground water monitoring systems will desire a highly accurate delineation to avoid restricting a greater area than necessary. **While the costs of a more accurate delineation may be high, applying management options to the wrong area, or an area much larger than necessary, could be much more expensive in the long run.**

Defensibility

The public water system may opt to use a more advanced delineation method if it is anticipated that the accuracy of the delineated area will be challenged. This may be the case where the WHP area extends into other political jurisdictions, or when potential pollution sources may be located near the edge of a delineated area. Also, where land uses on the delineated WHP area are highly restricted, the supplier may encounter resistance and legal challenges from entities protesting the restrictions.

Similar Cases or Nearby WHP Area

The operators of a public water supply system should investigate whether a comparable system has already delineated a WHP area and how they selected a delineation method. If a community with similar hydrogeology and planning considerations has already selected a method, then its experience could be helpful, as it may provide useful information otherwise not available or expensive to acquire. It could also help the supplier avoid problems previously encountered by another community.

The supplier also is advised to investigate whether nearby communities with wellfields pumping from the same aquifer are attempting to delineate a WHP area. *Cooperating with adjacent water suppliers in selecting the delineation method allows for sharing of information and costs.* This could give all communities involved access to information otherwise too expensive for them to acquire individually, and allows them to share the cost in acquiring this new information. Such cost-sharing may enable them to use a more sophisticated delineation method.

Information concerning WHP planning in neighboring communities may be obtained by calling the public water suppliers in the communities of interest. The Ohio EPA's Central Office (Division of Drinking and Ground Waters) also maintains information on those systems that have contacted the Agency regarding their WHP planning. However, some communities may have initiated WHP planning without contacting the Ohio EPA; therefore, the list likely is incomplete.

Preliminary Assessment of Potential Pollution Sources

Suppliers will need to consider the number, type, and location (proximity to wellfield) of existing potential pollution sources. A more accurate delineation will be desirable where:

- numerous pollution sources (or actual ground water contaminant plumes) exist;
- pollution sources include highly toxic materials; and
- pollution sources are located close to the edge of the delineated area.

Wellfield Geometry

The operator will need to consider the spatial relationship between the existing wells and also factor in any wells planned for the future. This is important as some delineation methods will account for pumping well interferences, but other methods will not. For example, simple equations used to calculate a fixed radius or a steady-state capture zone do not consider the effects of multiple wells.

Nearby Pumping Centers

Nearby pumping centers can distort the shape of the WHP area by acting as a barrier to ground water flow. Such pumping centers may include industrial wells, other public water supply wells, agricultural wells and even a high density of residential wells. It is important to know where these pumping centers are located in relation to the wellfield and to use a method that can handle multiple wells if they appear close enough to influence the WHP area.

Information concerning the location of other pumping centers can be obtained by contacting the Water Withdrawal Facility Registration Program, at the Ohio Department of Natural Resources' Division of Water (see Appendix 2). This program registers all facilities capable of producing over 100,000 gallons per day, and requires an annual reporting of withdrawal.

Quality of Data

It is important that the supplier know the accuracy and precision of the data collected, and compare it to the required accuracy of the WHP area. Some methods of collecting hydrogeologic information are more accurate than others. Where data of questionable accuracy must be used, the supplier may consider evaluating the effect on the delineated capture zone by determining the possible range of values for the questionable parameter(s), and delineating the capture zone with the highest and lowest values of those parameters. Computer programs such as MONTEC (part of U.S. EPA's WHPA code) are available for this purpose.

Ability to Collect Additional Data

After collecting all the available information, the need to conduct field studies to acquire additional information can be assessed. For example, the investigator may find that no information is available to enable an estimate to be made of the wellfield's hydraulic conductivity. However, because multiple potential pollutant sources exist in the vicinity (or for a variety of other reasons), the investigator believes there is a substantial need to delineate the wellfield fairly accurately. The investigator then must consider which techniques for determining hydraulic conductivity are appropriate for the wellfield in question.

A related consideration is the ability to collect additional data. An investigator may be constrained by lack of funds or lack of access to the necessary expertise. On another level, constraints may be imposed by the presence of physical obstructions. For example, an investigator may wish to collect soil samples from an area that is overlain by pavement or extensive construction, such that it is inconvenient or nearly impossible to bring a drill rig onto the site. Finally, further collection of data may be hindered by public health reasons. For example, an investigator may wish to conduct a pumping test to verify the presence of a suspected barrier boundary; however, an area of known contamination overlies the aquifer and there is concern that a pumping test may draw this contamination down into the aquifer. The investigator then may need to consider alternate methods of data collection to determine the presence of the barrier boundary.

Table 4 summarizes the above discussion into eight questions. The investigator should try to answer these questions as completely as possible before choosing a delineation method.

Table 4. Summary of Planning Considerations

QUESTION	RELEVANCE TO WHP AREA DELINEATION
How large is the water supply system? How large will it be in the future?	Greater water withdrawals result in larger capture zones. WHP areas should be delineated in accordance with the maximum anticipated average pumping rate for the next five to twenty years.
What kind of management strategies are anticipated? Will they be restrictive, controversial, costly, or complex?	Communities that enforce more "difficult" strategies require greater delineation accuracy, to avoid restricting a greater area than necessary.
Is the delineation likely to be challenged in court?	If so, the community may opt to use a more sophisticated delineation method.
Have other communities with similar circumstances done WHP area delineation? How did they proceed and what were their results? Are other communities in the area, attempting to delineate a WHP area?	This information may help produce a better delineation at less cost, and may help avoid problems.
Where are the potential pollution sources? What kinds of contaminants are involved, and how mobile and toxic are they?	The presence of numerous and/or highly toxic pollution sources warrants a more accurate delineation.
How many wells are used–currently and in the future? How are they located relative to each other and to nearby pumping centers?	Some delineation methods account for well interferences, while others do not.
How accurate are the available data?	If accurate data are not available, it may be necessary to collect additional data or else base the WHP area delineation on figures that produce the largest area that can result from the range of data.
Is it possible to collect additional data?	If not, the community may need to use a simpler delineation method.

RESOURCE CONSIDERATIONS

For many public water systems, the selection of a delineation method may be limited by available resources, including monetary resources, equipment, and technical expertise. Since lack of equipment or technical expertise may be addressed by purchasing the services of a consulting firm or similar entity, the ability to conduct a delineation using the most desirable method ultimately may depend on the supplier's budget.

Equipment

The water supplier should inventory all available equipment that may be necessary to use the desired delineation method. If computer modeling is desired, necessary equipment will include computers, printers, plotters, software, etc. If water levels in wells need to be measured, water level gauges and surveying equipment may be required. Surveying equipment may be available at the County Engineer's Office. Also, local universities or colleges may be able to provide technical equipment needed for the delineation.

Technical Expertise

A community's WHP committee may include members with the kind of expertise needed to delineate a WHP area. For example, individuals with training and expertise in civil and agricultural engineering, geology, hydrogeology, and other fields may be qualified. However, since all delineations are based on hydrogeologic characterization of the aquifer, it is important that the individual's background includes some level of training in hydrogeology.

When local expertise is insufficient, the public water system (or WHP committee, if one has been organized) may decide to obtain outside professional assistance with WHP area delineation. A list of consulting firms can be obtained from the local Yellow Pages directory, under the heading "Environmental and Ecological Services". In a small community, it may be necessary to obtain the directory of the nearest large city. Also, many larger firms advertise in such industry-related journals as *Ground Water* and *Ground Water Monitoring Review.*

The choice of a consulting firm should be based on a careful evaluation of the experience and expertise of the firm's staff, as indicated in its proposal. Some environmental firms with limited experience in hydrogeologic investigation may offer their services at a very competitive rate; however, the quality of the hydrogeologic investigation may be questionable. The committee should question any bidding firm about the number of kinds of hydrogeologic investigations the firm has completed and–if possible–contact some of that firm's previous clients to obtain an evaluation of the services performed. Specifically, the committee should question the bidding firm about any expertise it may have in delineating wellhead protection areas, and find out how much of the firm's experience is based locally. Since the program is relatively new, few firms have acquired experience with WHP area delineation; however, any bidding firm should at least demonstrate a familiarity with WHP program concepts.

The supplier should be aware that assistance with WHP area delineation may be obtained by contacting Areawide Planning Organizations. Also, assistance may be obtained by contacting the Departments of Geology, Natural Resources, or Civil/Agricultural Engineering at nearby universities. Graduate students and their advisors may be eager to locate potential research sites, and may be able to conduct site investigations using university equipment, incurring minimal cost to the supplier.

Some potential drawbacks of using graduate students to delineate a WHP area are that the study typically will take longer, and the student may not complete the thesis work. In some cases, students have finished a thesis and then moved to another part of the country, leaving behind incomplete documentation and unanswered questions. Also, some universities are more familiar with the WHP Program than others. In any case, the qualifications and experience of the student and the student's advisor should be checked the same as with a consultant. Liability coverage and insurance issues also should be reviewed.

Table 5 below summarizes the above discussion into three questions. The answers to these questions may largely determine the initial level of effort that will be invested in delineation. It may be necessary for a public water supplier to complete a preliminary delineation based on a less expensive method to initiate the WHP effort, and then work on raising funds for a more accurate delineation. The Ohio EPA's Central Office, Division of Drinking and Ground Waters, can provide information concerning potential sources for WHP funding.

Table 5. Summary of Resource Considerations

QUESTION	RELEVANCE TO WHP AREA
Equipment: Are computers available for delineation modeling? Is surveying equipment available to survey wells?	A delineation based on computer models will require computers and supporting equipment. If the delineation method requires site-specific measurements of water levels, water level gauges and surveying equipment will be needed.
Expertise: Is there a pool of technical expertise within the community sufficient to conduct all aspects of a delineation effort?	More sophisticated delineation methods may require the assistance of qualified ground water professionals, from consulting firms, universities, or planning agencies.
Budget: What level of sophistication can the public water system currently afford? Can additional funds be obtained?	Sophisticated delineation methods are more expensive.

MAKING THE DECISION

Based on a complete understanding of planning and site-specific hydrogeologic considerations, the supplier should be ready to select a WHP area delineation method that will best balance the level of accuracy required with the available resources. Unfortunately, there is no "cookbook" approach that can be recommended for making this decision. However, certain factors stand out:

The ability to locate (or construct) a credible potentiometric map. Without a potentiometric map to determine local ground water flow direction, there is no point in using a WHP area delineation technique more sophisticated than a calculated fixed radius method. As discussed in Chapter 3, this method produces a circular WHP area which, for most systems, will be highly inaccurate.

The applicability of porous flow models to the aquifer. If the aquifer does not behave as a porous medium, the delineation methods based on equations probably will be inaccurate. In this case, hydrogeologic mapping may be more appropriate.

Numerical modeling. Because of its expense, numerical modeling should be selected primarily when a high degree of accuracy is required, and the site is too complex to be modeled accurately with a less sophisticated method.

Budget. No matter how complex the hydrogeology or how high the need for accuracy, the budget will limit the level of effort that can be spent on WHP area delineation. It may be advisable to do a rough delineation based on a simpler, less expensive method, and initiate efforts to obtain funding for a more precise delineation in the future. The Ohio EPA can assist in determining the amount of additional detail necessary, based on its review of the rough delineation report.

Generally, for a supplier whose wellfield hydrogeology is not unduly complicated, and whose planning considerations do not dictate a need for the utmost accuracy, the Ohio EPA recommends the use of one of the more advanced semi-analytical computer models to delineate a time-of-travel based WHP area. Although semi-analytical models require simplifying assumptions about aquifer properties and dimensions, research in Ohio has shown they can provide a high level of precision in delineating time-of-travel boundaries. Since most semi-analytical models can simulate the effects of certain arrays of hydraulic boundary conditions, the selection should consider the ability of a given model to simulate the array of boundary conditions present at the site. Finally, semi-analytical models can be adjusted to accommodate changing hydraulic conditions such as increased water usage or variations in recharge conditions, which makes them useful for predicting a variety of potential scenarios.

CHAPTER 3

WELLHEAD PROTECTION AREA DELINEATION METHODS

INTRODUCTION

Several methods are available for delineating WHP areas, relying either on the use of ground water flow equations or on hydrogeologic mapping. The methods range from simple and inexpensive to complex and costly. Depending on the method's complexity, the level of expertise needed to use a method correctly also varies. The methods based on simple equations may be applied by anyone with a working knowledge of basic algebra. Such a person also may be able to use some of the simpler computer models used for WHP area delineation, particularly if he or she is comfortable with computers and has some knowledge of hydrogeology. However, use of the hydrogeologic mapping and numerical computer models will require the assistance of a ground water professional.

This chapter describes those methods which may be used to meet the requirements of Ohio's WHP Program. It discusses the major advantages and disadvantages of using each method and then outlines in what settings each method may be most applicable and acceptable to Ohio EPA.

TRAVEL TIME-BASED DELINEATION METHODS

CALCULATED FIXED RADIUS METHODS

Calculated fixed radius methods are easy techniques for delineating a WHP area. They also are inexpensive and require little technical expertise. However, they are the least accurate method, can result in overprotecting or underprotecting the actual zone of contribution, and are not recommended. In most cases, they will not be accepted by Ohio EPA for delineating a final WHP area. These methods involve calculating the radius of a circle to be drawn around a well. The radius of the circle corresponds to the length of a one-year or five-year time-of-travel, and may be calculated by using the volumetric equation or the Darcy equation, as explained below.

Volumetric Equation

The volumetric equation requires three input values: volume of water pumped, porosity of the aquifer material, and the length of the open interval or well screen. By likening the pumping well's zone of contribution to a cylinder of aquifer materials surrounding a well, the zone of contribution can be described as follows:

$$\underset{\text{(volume pumped)}}{Qt} = \underset{\text{(volume of cylinder)}}{n(\pi)Hr^2}$$

where Q = maximum anticipated pumping rate of well (in units of volume per unit time, e.g. $feet^3$/year)
t = time (in years. For a five-year time-of-travel calculation, use 5)
H = open interval or length of well screen (feet)
n = aquifer porosity (unitless)
π = 3.1416 (unitless)

This equation then can be arranged to solve for the radius (r) of the cylinder, which is equivalent to the radius of a circular five-year time-of-travel area:

$$r = \sqrt{\frac{QT}{\pi nH}}$$

Figure 10 explains how to use this method, and provides an example using values that are reasonable for a sand-and-gravel buried valley aquifer in Ohio.

Darcy Equation

The Darcy equation is used to calculate the velocity of ground water flow through the aquifer. It requires three input values: hydraulic conductivity of the aquifer material, the hydraulic gradient (i.e., slope) of the ground water table or potentiometric surface, and the effective porosity of the aquifer material. The Darcy equation is written as follows:

$$v = \frac{K\ i}{n_e}$$

where v = velocity of ground water flow (in units of length per time, e.g., feet/second; meters/second, etc.)

K = hydraulic conductivity (in units of length per time, consistent with those used for velocity)

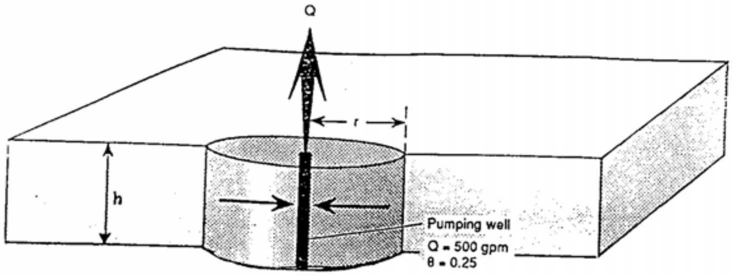
i = slope of the water table (unitless)

n_e = effective porosity (unitless)

Once a value for velocity is obtained, it can be multiplied by the appropriate number of years to obtain a value for time-of-travel distance. For example, to calculate the five-year time-of-travel distance from the well, velocity (in units of length per year) should be multiplied by five years. Figure 11 explains how to use this method, and provides an example using values that are reasonable for a sand-and-gravel buried valley aquifer in Ohio.

Advantages: Calculated fixed radius methods are easy to apply. None of the input parameters in the volumetric equation require field investigation. Information concerning pumping rates and the length of screen(s) should be on file at the public water supplier's office, and aquifer porosity can be based on literature values for various types of geologic materials (see Appendix 5). Values used in the Darcy equation also can be obtained from the literature if site-specific values are not available. Methods used to obtain field values for hydraulic conductivity are listed in Table 3 (Chapter 2, pages 2-10 to 2-11) and a standard technique for calculating the slope of the water table is presented in Chapter 4. Effective porosity usually is estimated from literature values.

Disadvantages: Calculated fixed radius methods may be inaccurate, since the equations do not account for many factors that influence ground water flow. For example, the circular area delineated would be accurate only for a perfectly flat "natural" water table, which is virtually never encountered in nature. In this respect, the WHP area delineated will exceed the actual zone of contribution in the area downgradient of the wellfield, but will be underestimated in the area upgradient of the wellfield (Figure 12). Also, this method incorrectly assumes a steady velocity of flow toward the well; in reality the flow velocity of a water particle *increases* as it nears the pumping well. This factor could result in a radius that is too small.



SUPPLIER MUST KNOW:

Maximum expected pumping rate of well (Q)

Open interval or length of well screen (H)

Aquifer porosity (n)

$$r = \sqrt{\frac{Qt}{n\pi H}}$$

EXAMPLE:

Q = 500 gpm = 35,128,993 ft^3/year
n = 0.25
H = 50 feet
t = travel time to well (5 years)

$$r = \sqrt{\frac{(35,129,000\ ft^3/yr)(5\ yr)}{(0.25)(3.14)(50\ ft)}}$$

$$= \sqrt{4475031.8\ ft^2}$$

$$= 2,115\ ft$$

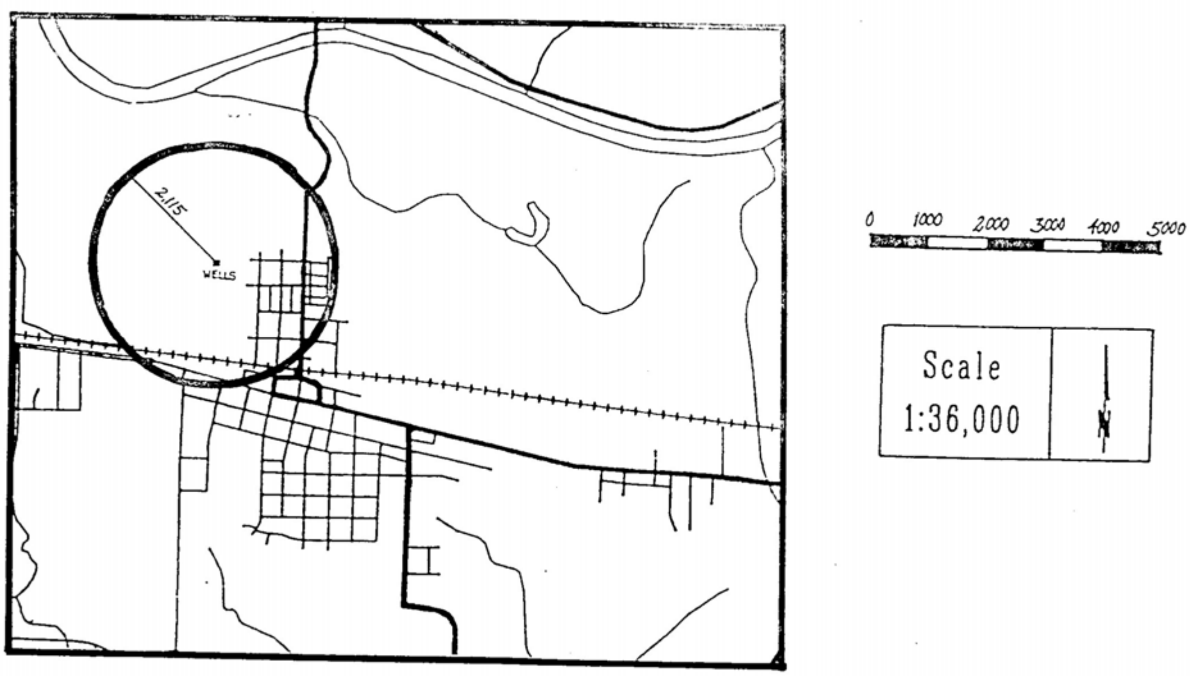
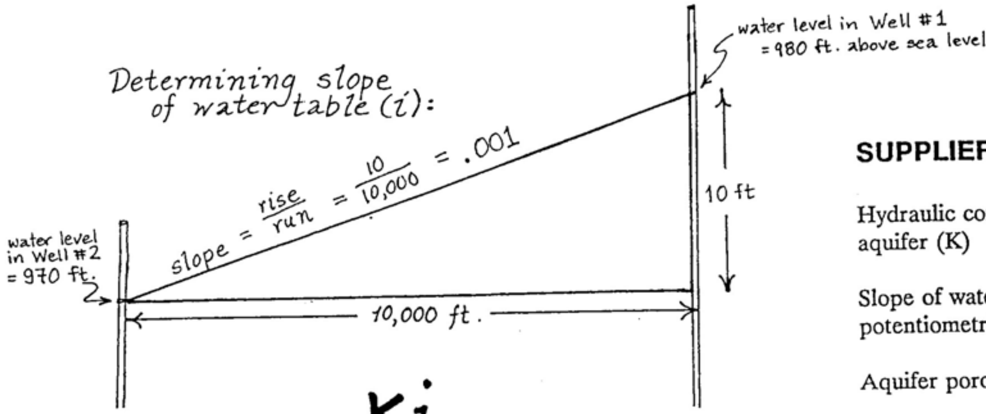


Figure 10. WHP Area Delineation Using the Volumetric Equation



SUPPLIER MUST KNOW:

Hydraulic conductivity of aquifer (K)

Slope of water table or potentiometric surface (i)

Aquifer porosity (n)

$$v = \frac{Ki}{n}$$

EXAMPLE:

K = 350 ft/day
i = .001
n = 0.25

$$v = \frac{(350 \text{ ft/day})(.001)}{.25}$$

$$= 1.4 \text{ ft/day} \times 365 \text{ days/yr}$$

$$= 511 \text{ ft/yr} \times 5 \text{ yrs}$$

$$= 2{,}555 \text{ ft in } 5 \text{ years}$$

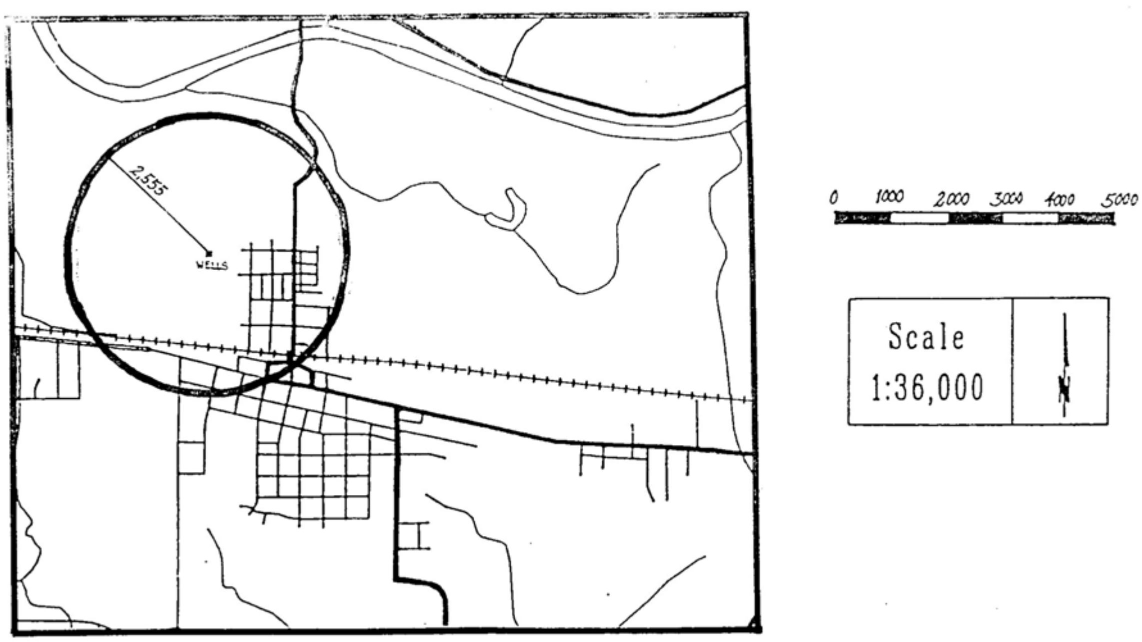


Figure 11. WHP Area Delineation Using the Darcy Flow Equation

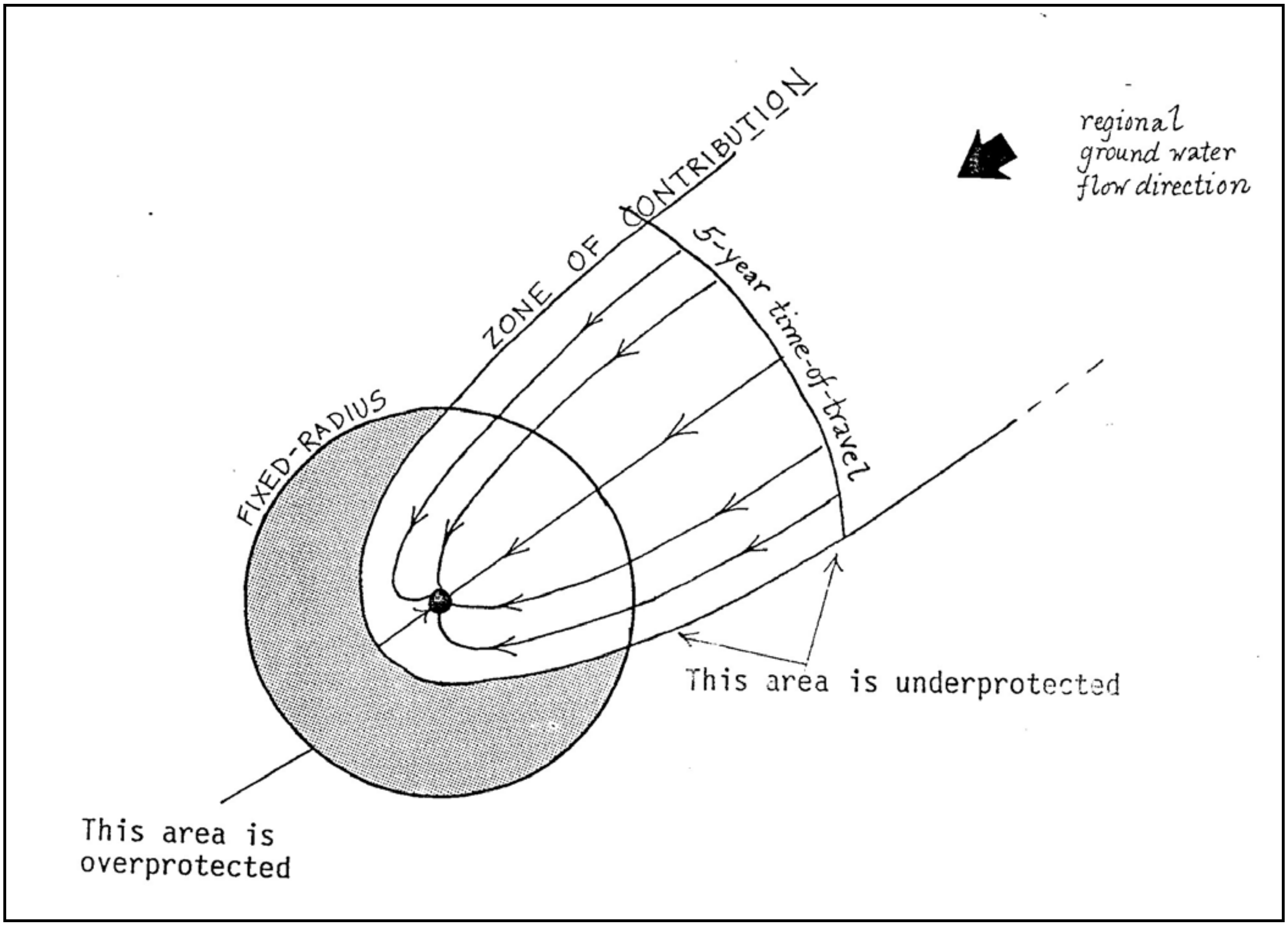


Figure 12. Types of Inaccuracies in WHP Areas Based on Fixed-Radius Methods

This method assumes a homogeneous, isotropic aquifer without any significant hydrogeologic boundaries–which rarely occurs in nature. The effects on capture zone size of leakage and recharge are ignored. Steady-state conditions–including a constant pumping rate–are assumed.

The volumetric equation will overestimate the size of a WHP area when the wellfield contains partially penetrating wells, which are wells screened or open only to a portion of the aquifer thickness. In such cases, the well will draw some water from below or above the screened portion of the aquifer (see Figure 4, pages 1-9). As a result, less water will be drawn from the sides, thereby decreasing the WHP area. Because the volumetric equation does not account for the water drawn from the unscreened aquifer volume, it tends to overestimate the WHP area where partially penetrating wells are involved.

Applications: Calculated fixed radius methods usually are not acceptable to Ohio EPA for delineating a *final* WHP area. They may be used in some very simple hydrogeologic settings–that is, settings characterized by relatively uniform values of hydraulic conductivity across the wellfield and adjacent area, the absence of hydraulic boundaries, and very low "regional" flow gradients. Such conditions sometimes are encountered in thick, areally extensive confined aquifers that are distant from any significant recharge or discharge boundaries.

These methods may be suitable to define a preliminary area to provide a focus for other WHP work while completing a more precise delineation. For example, a community may use a fixed-radius equation to calculate a five-year time-of-travel WHP area, and use that area to start conducting a pollution source inventory. Meanwhile it would continue to delineate a more refined WHP area using more complex methods. This often will help prevent delays in getting a WHP plan completed. Strong justifications would have to be presented to use the calculated fixed radius method for more than a preliminary delineation.

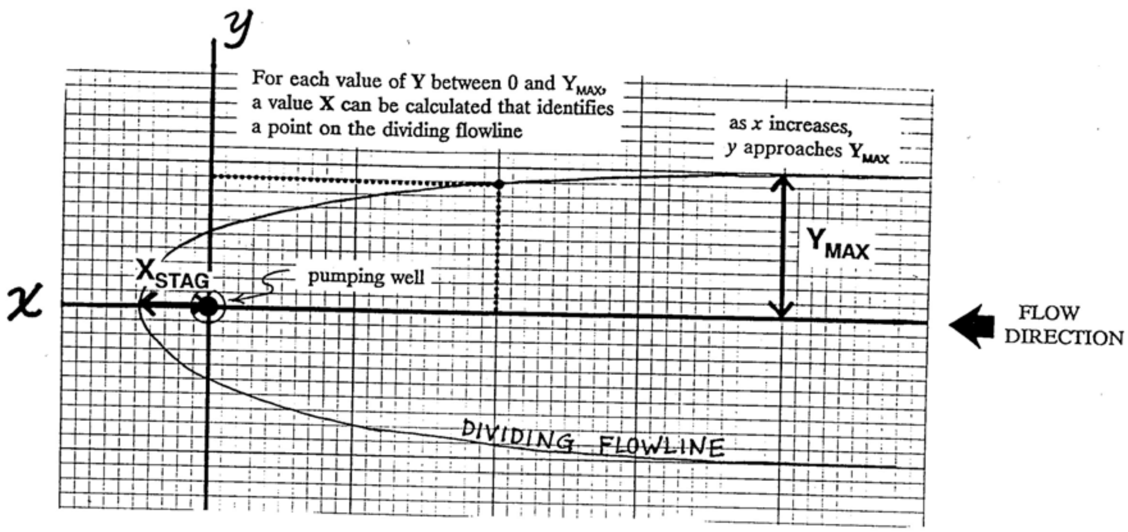
THE UNIFORM FLOW EQUATIONS

The uniform flow equations define the zone of contribution to a pumping well in a sloping water table. The equations require four input values: pumping rate of the well; hydraulic conductivity of the aquifer; saturated thickness of the aquifer; and regional hydraulic gradient. (See Table 3, pages 2-10 to 2-11, and Appendix 3 for potential sources of this kind of information.)

The uniform flow equations are more accurate than the fixed radius methods because they account for a "natural" slope to the regional water table, while the fixed radius methods assume a flat water table. Instead of the circular area defined by fixed radius methods, the WHP area defined using a uniform flow equation is shaped like a parabola that opens in the upgradient direction. (It should be noted, however, that since this technique delineates an open-ended parabola, another technique must be used to establish the five-year time-of-travel boundary of the open (upgradient) end.)

Two delineation methods based on the uniform flow equation are presented here: one for a confined aquifer under steady-state conditions (Todd, 1980) and another for an unconfined aquifer under steady-state conditions (Grubb, 1993). Both techniques involve a general equation and two simple bounding solutions to the equation, as follows:

1. The general equation yields the location of the dividing flowline (X_{DIV}), which is the boundary of the capture zone (see Figure 13). In addition, there are two simple boundary solutions to this equation that yield the following parameters:



For confined aquifers:

$$X_{STAG} = \frac{Q}{2\pi Kbi}$$

$$Y_{MAX} = \frac{Q}{2Kbi}$$

$$X_{DIV} = -\frac{Y}{\tan\left[\frac{2\pi Kbi}{Q} y\right]}$$

For unconfined aquifers:

$$X_{STAG} = \frac{QL}{\pi K(h_2^2 - h_1^2)}$$

$$Y_{MAX} = \frac{QL}{K(h_2^2 - h_1^2)}$$

$$X_{DIV} = -\frac{Y}{\tan\left[\frac{\pi K(h_2^2 - h_1^2)}{QL} y\right]}$$

where:

Q	=	pumping rate of well (ft^3/day)
K	=	hydraulic conductivity (ft/day)
b	=	saturated thickness of aquifer (ft)
i	=	local hydraulic gradient (dimensionless)

X and Y are distances in *x* and *y* directions, as indicated above.

h_1 and h_2 are water levels (in feet ABOVE THE BASE OF THE AQUIFER) in two observation wells along the axis of ground water flow

tan(y) is in RADIANS

Figure 13. Parameters Obtained From Uniform-Flow Equations

2. X_{STAG}–the distance from the pumping well downstream to the stagnation point, i.e., the point that marks the downgradient end of the capture zone; and

3. Y_{MAX}–the half-width of the capture zone as x approaches infinity. The value for Y_{MAX} multiplied by 2 yields the maximum possible width of the capture zone.

As shown in Figure 13, the equations used to obtain X_{STAG}, Y_{MAX} and the dividing flowline differ according to whether the aquifer is confined or unconfined. To plot the shape of the capture zone, one should first obtain a value for Y_{MAX}, then substitute smaller values of Y into the equation for X_{DIV} to find the position of the capture zone boundary on an (x,y) grid. Finally, the position of the stagnation point can be obtained by using the equation for X_{STAG}. The confined aquifer delineation technique is illustrated in Figure 14 with a sample equation. Similarly, the unconfined aquifer delineation technique is illustrated in Figure 15. Both of these techniques are described in more detail on pages 502-505 of Fetter, 1994.

In the examples provided in Figure 14 and 15, the capture zones for the confined aquifer and the unconfined aquifer are virtually identical. Generally, the capture zone for an unconfined aquifer will be smaller than the capture zone for an equivalent confined aquifer (see Grubb, 1993).

Advantages: The uniform flow equation is easily understood and solved. The equation takes into account some important site-specific hydrogeologic parameters, namely, hydraulic conductivity, saturated thickness and hydraulic gradient. It eliminates much of the unaffected downgradient area that is enclosed by calculated radius delineations and incorporates more of the upgradient area, resulting in a more accurate WHP area. In contrast to the calculated fixed radius methods, the uniform flow equation can account for drawdown in the area closest to a pumping well (U.S. EPA, 1987).

Disadvantages: The uniform flow equation requires knowledge of site-specific hydrogeologic parameters that may be difficult and expensive to obtain–such as hydraulic conductivity and hydraulic gradient. In aquifers whose drawdowns represent 10 percent or more of the total saturated thickness, the method may not be appropriate due to dominance of vertical flow components (U.S. EPA, 1994). Finally, this method also assumes a planar water table, a steady-state flow field, no hydrogeologic boundaries, and perfect uniformity of the aquifer material–a set of conditions that is not commonly encountered in nature.

Applications: The uniform flow equation will only be accepted by Ohio EPA in limited situations. For example, it may be appropriate for some very simple hydrogeologic settings–those characterized by relatively uniform values of hydraulic conductivity across the wellfield, an absence of hydraulic boundaries, and an aquifer whose saturated thickness greatly exceeds the drawdown at the well. As discussed previously, these conditions sometimes are encountered in thick, areally extensive confined aquifers that are distant from any significant recharge or discharge boundaries and lack any other pumping centers. Also, the uniform flow equation may be used to define a preliminary area to provide a focus for other WHP work while proceeding with a more precise delineation.

Some of the analytical computer models presented next are very easy to use, require the same kinds of input data, and produce superior results. In most cases Ohio EPA will expect a community to use one of the more advanced analytical or other computer models discussed in the next section.

SAMPLE PROBLEM - CONFINED AQUIFER

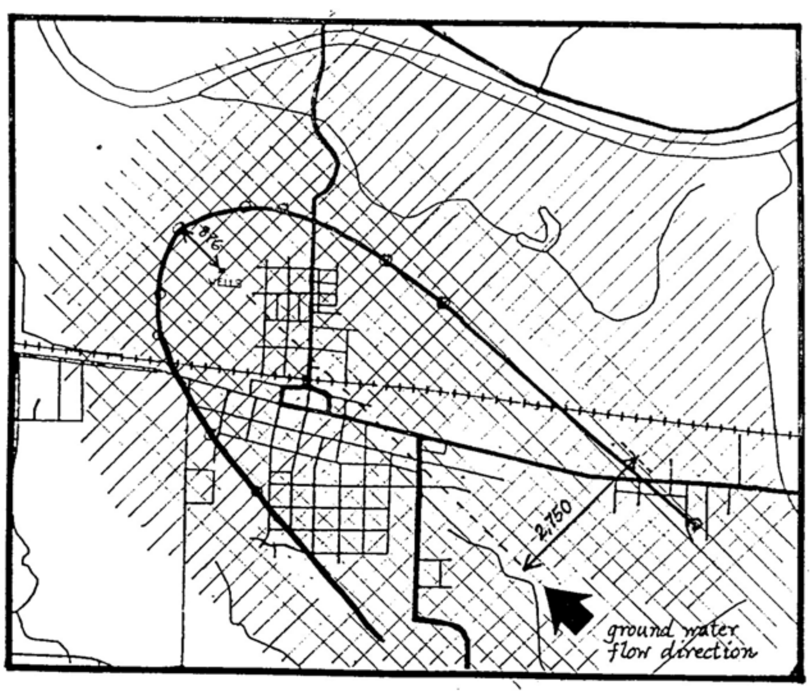
Q = 500 gpm = 96,244 ft^3/day
K = 350 ft/day
b = 50 ft
i = .001
tan(y) is in RADIANS

$$X_{STAG} = \frac{Q}{2\pi Kbi} = \frac{96{,}244\ ft^3/day}{2(3.14)(350\ ft/day)(50\ ft)(.001)} = 876\ ft$$

$$Y_{MAX} = \frac{\pm Q}{2Kbi} = \frac{96{,}244\ ft^3/day}{2(350\ ft/day)(50\ ft)(.001)} = 2{,}750\ ft$$

$$X_{DIV} = -\frac{Y}{\tan\left[\frac{2\pi Kbi}{Q}y\right]} = \frac{-Y}{\tan\left[\frac{2(3.14)(350)(50)(.001)}{96{,}244}Y\right]} = \frac{-Y}{\tan[.001143Y]}$$

x	y
-875.323	1
-813.528	400
-616.854	800
-456.639	1000
-243.095	1200
-7.75507	1370
420.669	1600
1733.273	2000
3020.935	2200
8474.392	2500
47301.68	2700



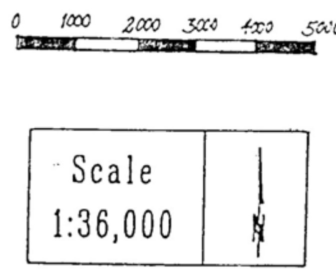


Figure 14. WHP Area Delineation Using Uniform Flow Equation for Confined Aquifer (Todd, 1980)

SAMPLE PROBLEM - UNCONFINED AQUIFER

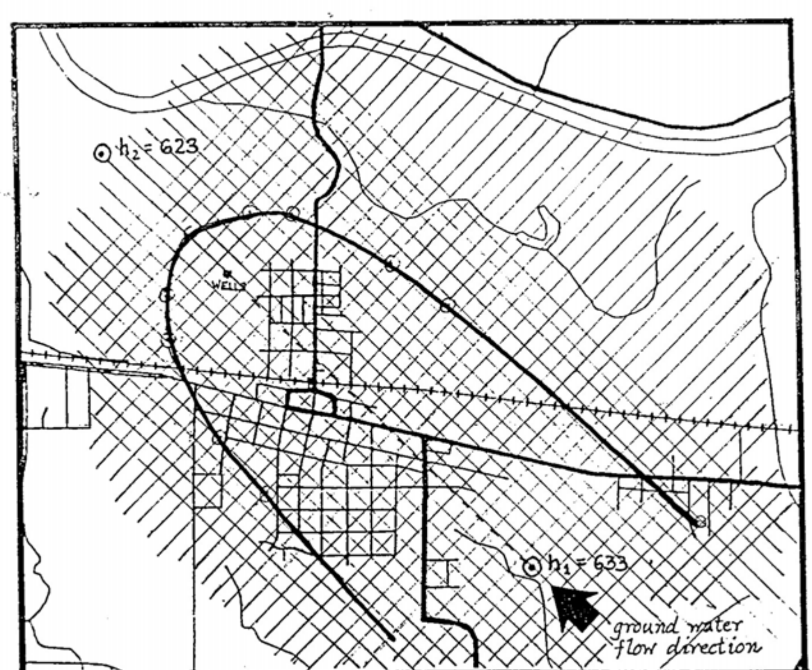
Q = 500 gpm = 96,244 ft^3/day
K = 350 ft/day
h_2 = 45 ft
h_1 = 55 ft
L = 10,000 ft
tan(y) is in RADIANS

$$X_{STAG} = \frac{QL}{\pi K(h_2^2 - h_1^2)} = \frac{(96{,}244\ ft^3/day)(10{,}000\ ft)}{(3.14)(350\ ft/day)(45^2 - 55^2)} = -875$$

$$Y_{MAX} = \frac{\pm QL}{K(h_2^2 - h_1^2)} = \frac{\pm(96{,}244\ ft^3/day)(10{,}000\ ft)}{(350\ ft/day)(45^2 - 55^2)} = 2{,}750$$

$$X_{DIV} = -\frac{Y}{\tan\left[\frac{\pi K(h_2^2 - h_1^2)}{QL}y\right]} = \frac{-Y}{\tan\left[\frac{(3.14)(350)(45^2-55^2)}{(96{,}244)(10{,}000)}Y\right]} = \frac{-Y}{\tan[.00114Y]}$$

x	y
-875.323	1
-875.171	20
-874.714	40
-873.952	60
-871.512	100
-860.038	200
-777.983	500
-456.639	1000
215.7536	1500
1733.273	2000
47301.68	2700



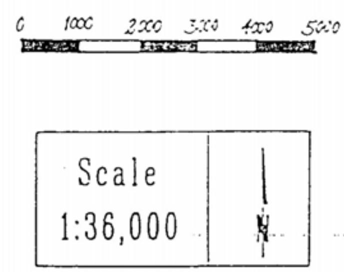


Figure 15. WHP Area Delineation Using Uniform Flow Equation for Unconfined Aquifer (Grubb, 1993)

WHP AREA DELINEATION BASED ON COMPUTER MODELS

A wide variety of computer models that simulate ground water flow can be used to delineate WHP areas. Typically these models solve various flow equations to derive values for the hydraulic head (elevation of the ground water inside a nonpumping well) at specified locations within the area of interest. Once these values are calculated or approximated, it is possible to complete a potentiometric map of the area of interest. A separate program often is used to calculate the shape of the five-year capture zone, based on flow velocities calculated by the flow model. The flow lines to the well(s) may be drawn on the computer screen and printed out.

Traditionally, ground water professionals have identified two categories of computer models for flow modeling–"analytical models" and "numerical models". This categorization was based on the mathematical technique used by the models to solve the ground water flow equations. In recent years, however, many hybrid models have come into use that incorporate both analytical and numerical techniques. These models are referred to as "semi-analytical computer models".

Analytical techniques solve ground water flow equations through simple, calculus-based mathematics, generating an exact mathematical solution for the unknown variable. (The "unknown variable" typically is the hydraulic head at a given location.) The ability to generate such a solution depends on simplifying the ground water equation, by assuming the aquifer is homogeneous and isotropic, and that flow is strictly one-or two-dimensional. Because of these limiting assumptions, the accuracy of an analytical solution may be questionable when applied to ground water flow through a heterogeneous aquifer with complicated boundary conditions. Some analytical and semi-analytical models that are popularly used for WHP area delineation include U.S. EPA's WHPA codes (described below) and CAPZONE (Bair and others, 1991).

Numerical techniques are approximating techniques that change the basic ground water flow equation to a form that can be quickly solved by a computer. (The flow equation may be defined at hundreds of locations in the aquifer, which are called "nodes".) The set of transformed equations generated at each node then can be solved using a combination of matrix and iterative solution techniques, to obtain values for hydraulic heads at each note. Numerical techniques are extremely versatile. They can be used for modeling layered aquifers, partially penetrating wells and boundaries, and many other common scenarios that cannot be addressed by analytical computer models. Although a number of numerical techniques exist, in the United States only finite-difference and finite-element techniques have been widely used for ground water modeling (Anderson and Woessner, 1992). Currently, the numerical flow model used most commonly in Ohio for WHP area delineation is MODFLOW (McDonald and Harbaugh, 1987), coupled with MODPATH (Pollock, 1989).

The analytic element technique (Strack, 1989) is used in a number of ground water flow models that recently have come into popular use. This technique applies analytical solutions to various "elements" in an aquifer, such as streams, lakes, wells, and areas of recharge. For example, rivers are modeled by mathematical functions called line-sinks, while other mathematical functions are used to simulate uniform flow through the aquifer and uniform recharge. The individual analytic solutions are then superposed to obtain a solution (of hydraulic head) for any location in the aquifer. One attractive feature of this technique is its lack of a fixed grid; this allows the user to extend the model any distance to incorporate regional features without sacrificing accuracy in the area of interest. As a result, an analytic element model can solve for the head at any location in the field of interest–not just at the nodes. However, the method's applicability is limited to steady-state, two-dimensional ground water flow problems. Some analytic element models that have been used for WHP area delineation include TWODAN (Fitts, 1994), QuickFlow™ (Rumbaugh, 1991), and GFLOW (Kelson and Haitjema, 1994).

Gridding the Flow Domain

All ground water flow computer models require that the aquifer be described by a grid such that points on the aquifer can be referred to in terms of (x,y) coordinates on the grid. The simplest analytical and semi-analytical models may only be able to designate wells and some simple, linear boundaries on this grid. However, numerical models can define the boundaries of many hydrogeologic features, and assign appropriate equations to operate within those boundaries. This ability to "divide up the area of interest" is called "discretizing", and is one of the greatest advantages of the numerical models, providing for greater modeling flexibility and greater potential accuracy of the solutions. In addition, many numerical models can be used to model the aquifer in three dimensions, allowing for more accurate analysis of flow in a complex, layered aquifer.

Calibration

Calibration of a flow model refers to demonstration that the model is capable of producing field-measured heads and flows within an acceptable range of error (Anderson and Woessner, 1992). Calibration is accomplished by finding a set of parameters, stresses, and boundary conditions that result in a model simulation with heads (and/or flows) that match those actually measured at the site. Because hydraulic conductivity values can range so widely, are usually not known precisely, and have a significant effect on simulated hydraulic heads, modelers frequently begin calibration by adjusting values of hydraulic conductivity across the site until the model reproduces field-measured values of head at specific wells. These field-measured head values are referred to as "calibration targets". Upon calibrating the model to steady-state conditions, a "stress" on the aquifer should be simulated, such as pumping. Then the aquifer itself should be identically stressed and water levels in the target wells should be measured, so that a comparison can be made between actual and simulated values.

Calibration is a key component of the modeling process. The amount of faith that anyone can place in a model's results and predictions is directly related to whether or not the model is calibrated, and how well it can be calibrated to a given set of field conditions. Some models–including the WHPA codes–are not designed to allow for detailed calibration of hydraulic heads or other parameters. It may be difficult to "demonstrate" that these models are accurate. For this reason, the results of these models are considered inherently less reliable than those of a model that can be calibrated to numerous calibration targets (assuming quality of input data is the same).

It should be remembered, however, that a well calibrated model is not necessarily proof that the model is an exact replica of the ground water flow regime. There are many possible "solutions" to a given set of head/flow values. Also, a model that is perfectly calibrated to very few calibration targets (or to numerous targets clustered in a few locations) is less reliable than a model that is acceptably calibrated to numerous targets that are uniformly distributed across the site.

Capture Zone Delineation

Capture zone computer models can be used to delineate a wellfield's zone of contribution and to generate time-of-travel zones. The models accomplish this by instructing a hypothetical "particle"–such as a ground water molecule–to move from a specified point for a specified period of time. The particle moves in accordance with the computed velocity of the ground water flow at any given point along the flow path. The program then "traces" the movement of that particle across the grid.

Most capture zone models are designed to forward track and reverse track. "Forward tracking" refers to tracking water particles in the direction of ground water flow, and may be used to determine whether particles at a given location on the grid will be captured by the well. "Reverse tracking" refers to tracking water particles in the direction opposite of flow. By positioning a number of particles around the well and reverse tracking, the outline of the capture zone can be traced on the computer screen. If the model is instructed to reverse track for five years, the outline of the five-year time-of-travel area will be traced.

To delineate capture zones, the most widely-used numerical ground water flow models often can be coupled with separate capture-zone programs. For example, MODFLOW may be coupled with MODPATH to generate a capture zone. However, a number of stand-alone capture zone models are available. For example, in the late 1980's the U.S. EPA developed a computer model to assist state and local technical staff with the task of WHP area delineation. The result is called WHPA (Blandford and Huyakorn, 1991), and consists of four independent computational modules called MWCAP, RESSQC, MONTEC and GPTRAC. The last module has an analytical and a numerical option. These semi-analytical modules are two-dimensional and assume a homogeneous, isotropic aquifer, and horizontal, steady-state flow. They are capable of modeling multiple pumping and injection wells, as well as simple linear barrier and recharge boundaries. Additionally, the numerical option of GPTRAC can account for more complicated boundary conditions as well as aquifer heterogeneities and anisotropies. The kinds of information required to simulate a flow system using WHPA are typical of many analytical and semi-analytical models (Table 6).

The WHPA modules are menu-driven and are very user-friendly. Capture zones drawn by the program are displayed directly on the computer screen (Figure 16).

More recently, U.S. EPA also has developed an analytic element computer modeling package called WhAEM (Kramer and others, 1994), which is capable of modeling capture zones for wellhead protection. This model consists of two components: a user-friendly preprocessor (GAEP), and the flow model (CZAEM). While WhAEM also is two-dimensional and is subject to the same simplifying assumptions that limit the WHPA codes, it is more sophisticated that WHPA in that it can:

- model an area of constant recharge;
- model aquifers that are confined in some areas and unconfined in others; and
- model internal linear boundaries. (WHPA only models linear boundaries on the perimeter of the area of interest)

Additional guidance on selecting a computer model is provided in the U.S. EPA document entitled *Model Assessment for Delineating Wellhead Protection Areas* (U.S. EPA, 1988). This document also contains a very detailed - although somewhat dated - description of 64 ground water flow/contaminant transport models.

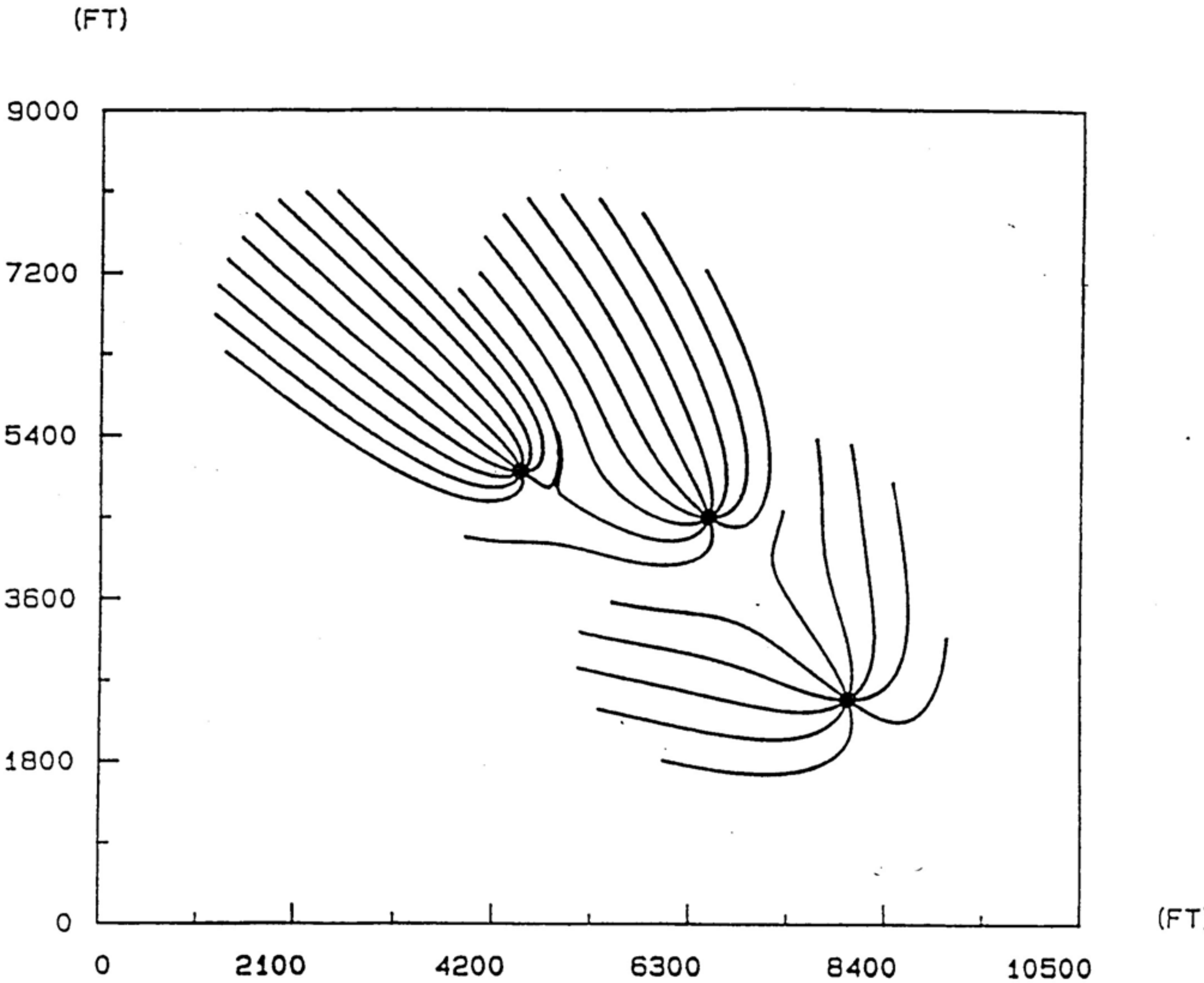
For more current information concerning available ground water flow models and capture zone models, the reader should contact such organizations as the United States Geological Survey, the International Ground Water Modeling Center, and the National Ground Water Association. Copies of WhAEM and WHPA can be obtained at no charge from U.S. EPA's Kerr Laboratories in Ada, Oklahoma. (See Appendix 3 for addresses and phone numbers of these organizations.) Also, information on the latest models may be found in industry journals such as *Ground Water* (National Ground Water Association, Westerville, Ohio).

Table 6. Required Input for WHPA Model Computation Modules

(Source: U.S. EPA, 1994)

			GPTRAC	
Requird Input	**RESSQC**	**MWCAP**	**Semi-analytical**	**Numerical**
Units used	■	■	■	■
Aquifer type*			■	
Study area limits	■	■	■	■
Maximum step length	■	■	■	
No. of pumping wells	■	■	■	■
No. of recharge wells	■		■	■
Well locations	■	■	■	■
Pumping/injection rates	■	■	■	■
Aquifer transmissivity	■	■	■	■
Aquifer porosity	■	■	■	■
Aquifer thickness	■	■	■	■
Angle of ambient flow	■	■	■	
Ambient hydraulic gradient	■	■	■	
Areal recharge rate			■	
Confining layer hydraulic conductivity			■	
Confining layer thickness			■	
Boundary condition type		■	■	
Perpendicular distance from well to boundary		■		
Orientation of boundary		■	■	
Capture zone type		■		
No. of pathlines used to delineate capture zones	■	■	■	■
Simulation time	■		■	■
Capture zone time	■	■	■	■
Rectangular grid parameters				■
No. of forward/reverse pathlines	■		■	■
Starting coordinates for forward/reverse pathlines	■		■	■
Nodal head values				■
No. of heterogeneous aquifer zones				■
Heterogeneous aquifer properties				■

*Confined, unconfined or leaky-confined.



Simulation Options	Aquifer Properties	Well #1	Well#2	Well #3
Units = ft and days	T = 3,750	X = 8,000	6,500	4,500
Step Length = 25	b = 25	Y = 2,500	4,500	5,000
Simulation time = 1,825	θ = 0.22	Q = 30,000	30,000	25,000
No. Capture Zone times = 0	i = 0.0019	No. Pathlines = 10	10	10
	α = -45°	Plotting Interval = 1	1	1

Figure 16. Five-Year Capture Zones Delineated Using a Semi-Analytical Computer Model (Source: U.S. EPA, 1994)

Advantages: Computer models used for delineation of capture zones are the most sophisticated and potentially accurate method of delineating a WHP area. They can incorporate much more site-specific information than any other delineation method. For example, most analytical and semi-analytical models can incorporate various types of confining conditions, the effects of linear boundaries, multiple wells, variable pumping rates, various aquifer thicknesses, and areal recharge rates. In addition, numerical models can model three-dimensional flow, variable contribution to the system by multiple aquifer layers, and spatial variation of hydrogeologic parameters across the field of interest, both horizontally and vertically. This allows for a realistic treatment of layered aquifers and complex flow conditions. When correctly developed and applied, such models may provide a high degree of accuracy.

In addition, computer models can be used to model hypothetical scenarios. If, for example, a community wishes to determine how the wellfield's capture zone might be altered by a change in pumping rates, or the addition of a well, or a drought, most computer models can be adjusted to provide such information.

Disadvantages: Computer models require much more site-specific information than other delineation methods. Numerical models, especially, may require vast amounts of information, and the validity of the model depends largely on the quantity and quality of the data. Most of the analytical and semi-analytical models available are based on simplifying assumptions, such as a homogeneous, isotropic aquifer, horizontal steady-state flow, and fully-penetrating wells and boundaries. These assumptions may lead to inaccurate delineations, especially in more complicated geologic settings. In addition, the "user-friendliness" of some computer models can give an unqualified person a false sense of security, enabling him or her to generate results that look reasonable but may not be scientifically valid.

Numerical models have their own disadvantages. Finite-difference models typically provide less accurate solutions for hydraulic heads around wells than models using analytical solutions. The degree of error is directly related to the size of the grid spacing. This problem may have a significant effect on the accuracy of capture zone delineations because the velocity of ground water flow is governed in part by the hydraulic gradient, which is based on the change in head. Other disadvantages are related to costs: the more sophisticated computer models require an array of computer equipment, and staff who have specialized training in both computer modeling and hydrogeology. As a result, the use of sophisticated models may be prohibitively expensive.

Applications: Simple computer models may be suitable for sites with fairly uncomplicated geology. For example, analytical and semi-analytical models that make the standard simplifying assumptions may be sufficiently accurate for thick, extensive single-layer aquifers characterized by a relatively uniform geologic material (such as sand or sand-and-gravel), and simple, nearly-linear boundaries. These models may be less accurate when applied to sites that are located in regional recharge or discharge areas, due to vertical flow gradients that violate the assumptions of the governing ground water flow equations. Also, partially penetrating wells and partially penetrating flow boundaries (such as rivers, or shallow ground water divides) may compromise the accuracy of the simulation. Such complications should be analyzed carefully. If the analyst concludes that they may exert a significant effect on the flow system, it may be wise to consider either numerical modeling or extending the boundaries beyond the delineated area, to provide for a more conservative WHP area. In general, the analyst must examine the limitations of the proposed model very carefully, and decide whether the model can be applied to the site.

Theoretically speaking, numerical models are applicable to any site, because they are the most versatile models available. In practice, however, many communities may be unable to collect the amount of data required to make optimal use of such models. Also, the use of a numerical model to simulate a simple system may be simply “overkill”. While Ohio EPA rarely would require a community to use a numerical model to delineate a WHP area, numerical modeling might be recommended for various scenarios. Among the more common applicable scenarios are the following:

- The aquifer is extremely heterogeneous and anisotropic. A typical example might be a valley fill aquifer composed of sand units interspersed with abundant silt and clay units.

- The aquifer contains irregular boundaries that cannot be modeled as linear, external boundaries. Examples might include meandering rivers or creeks, outcrops of impermeable bedrock within a valley-fill aquifer, or extensive lenses of clay within the aquifer that channel the flow along certain paths.

- The aquifer contains boundaries that are not fully penetrating, and it is critical that the effects of the boundary be accurately modeled. For example, if a number of significant pollution sources exist on the far side of a river, it may be important to determine whether ground water from that area could be flowing beneath the river to the wellfield.

- The wellfield is supplied by multiple aquifers that are interconnected. For example, in many communities the wells are screened through valley fill, and are open to flow through an underlying bedrock unit that is hydraulically in connection with the overlying aquifer.

- Ground water flows to the wellfield preferentially from several different directions. (Simple analytical flow models can only accommodate a single flow direction. While a WHP area may be delineated by running the model for several different flow directions and connecting the five-year time-of-travel boundaries, this area probably will be much larger than necessary. This is because each simulation assumes that ALL water discharged by the well is coming from the one direction used in the simulation.)

- Ground water flows to the wellfield along an nonlinear path. Figure 17 illustrates how a numerical model simulates a capture zone for flow along curved flowpaths more accurately than an analytical model.

As discussed previously in Chapter 2, the choice of a model also will be influenced by the number and type of potential pollution sources involved, the size of the population affected, and the kinds of management strategies that the community is prepared to implement.

FLOW BOUNDARY-BASED DELINEATION METHODS

DELINEATIONS BASED ON HYDROGEOLOGIC MAPPING

In many hydrogeologic settings, flow boundaries can be identified from various kinds of maps, and these boundaries may be used to delineate the zone of contribution to the well. For example, topographic maps can be used to locate large rivers or other water bodies that, if deep enough, may act as boundaries to a capture zone. Because the water table in an unconfined aquifer tends to mimic the topographic surface, an investigator also may roughly locate regional drainage basin divides from the surface “highs” shown on topographic maps. Regional potentiometric maps, if available, may be used to locate major flow divides more reliably. In addition, since flow generally is perpendicular to the potentiometric lines in an isotropic aquifer, flowlines toward the pumping well may be sketched, this providing a rough outline of the likely zone of contribution (Figure 18).

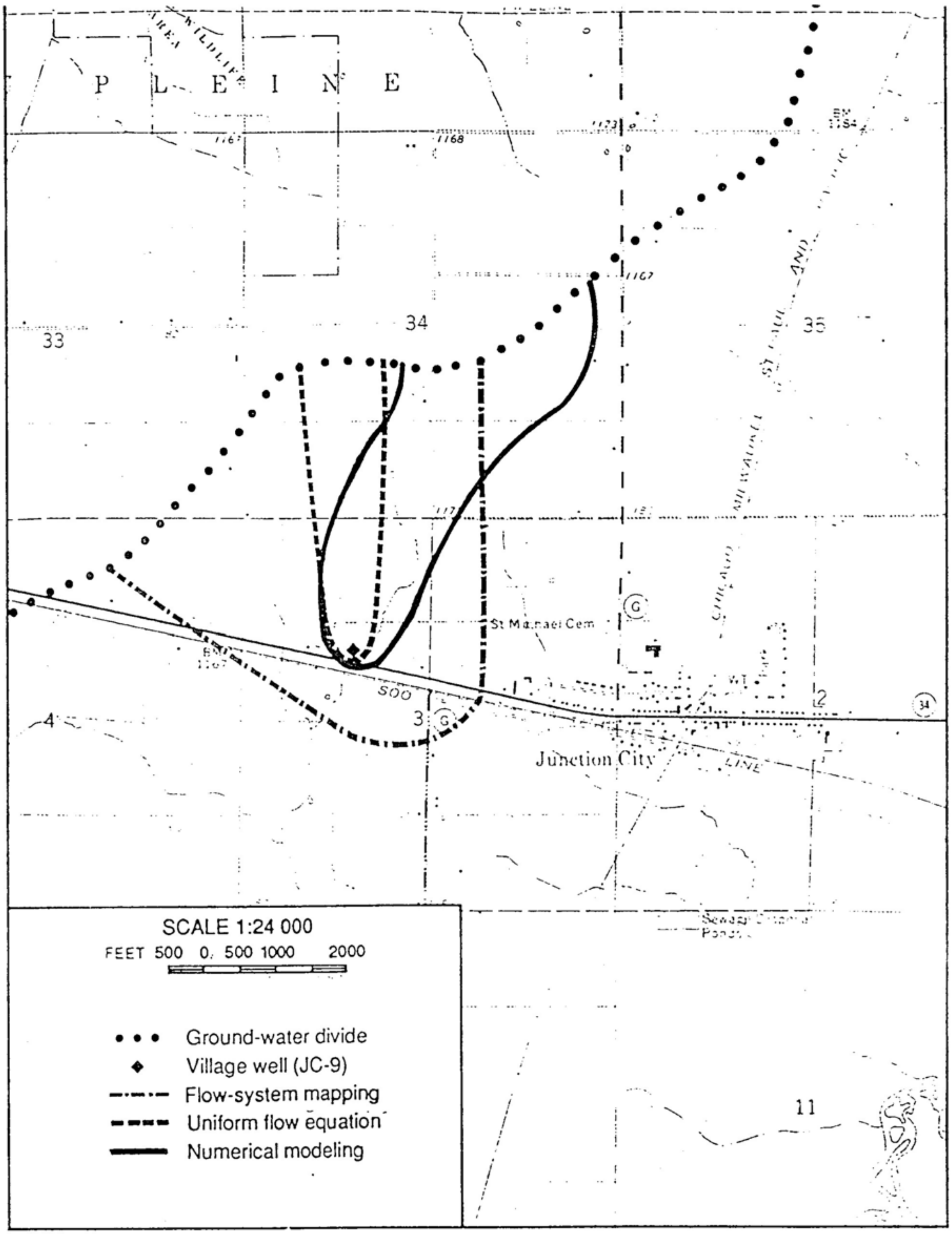
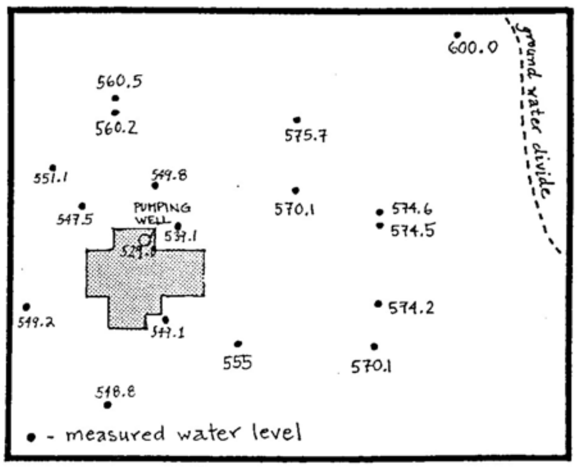
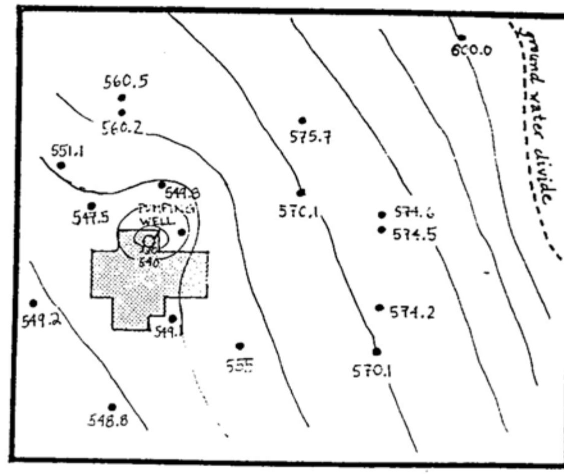


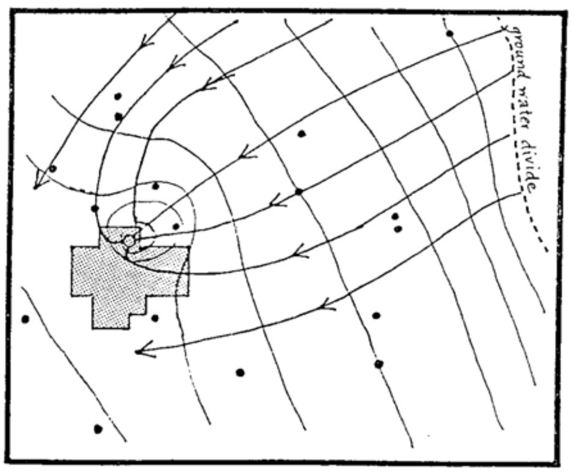
Figure 17. A Comparative Analysis: Delineations of Zone of Contribution Using the Uniform Flow Equation, Flow-Boundary Mapping, and Numerical Modeling.
(Source: U.S. EPA, 1991b)



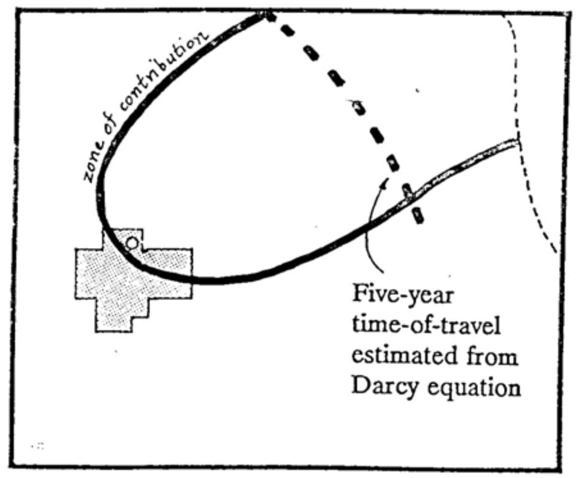
Identify usable wells. Measure water levels in wells.



Construct potentiometric map.



Starting from the pumping well and proceeding toward the ground water divide, construct flow lines perpendicular to the potentiometric isolines.



Delineate the WHP area

Figure 18. Delineating a Zone of Contribution from a Potentiometric Map

Because ground water divides are dynamic boundaries, care must be taken when identifying them from potentiometric maps. The investigator must try to determine whether the current pumping situation is identical to the situation existing when the map was constructed. For example, if the potentiometric map was constructed in 1955 and a community installed a wellfield within the mapped area in 1965, the wellfield has probably created a depression in the potentiometric surface that will not be reflected in the map. This depression may have altered the location of the ground water divide, as shown in Figure 7, page 2-5.

Various types of geologic maps can be used to identify physical boundaries, such as surface geological maps, top-of-rock maps, and ground water resource maps. For example, bedrock valley walls surrounding a river valley aquifer can be identified from surface geological maps. If the bedrock is composed of a relatively impermeable material (such as shale) that is not highly fractured, the bedrock walls may be considered to act as boundaries to the capture zone. Generally, they will tend to channel the capture zone more directly upvalley.

Where such maps are unavailable or are too regional to be useful, surface geophysical methods may be used to determine depth to bedrock. These methods involve generating waves of energy at or above the ground surface that are reflected or absorbed variously by different earth materials. Sensors at the surface detect reflected waves and computers are used to calculate the distance to the reflecting material based on the time between generation and detection of the wave. Surface geophysical methods include ground-penetrating radar and electrical, electromagnetic, seismic, and gravity methods. Zohdy and others (1974) provide a review of these methods applied to ground water studies.

Yet another technique that has been used for WHP area delineation is tracer tests. These test involve injecting a"tracer"–such as chloride, tritium, dyes, etc.–into the ground water, and monitoring the arrival of the injected substance at locations downgradient from the injection point, using monitoring wells equipped with appropriate sensors. A carefully planned and executed tracer test may yield detailed information about ground water flow paths and flow velocities. In fact, it may be the most accurate way to determine flowpaths in bedrock that contains large fractures and void spaces (such as portions of the Columbus limestone beneath Seneca County). However, tracer tests generally are not recommended by Ohio EPA because injecting any substance into the ground water carries a degree of risk. This is especially true where the ground water is being pumped to supply a community's drinking water. Any community considering the use of a tracer test must first contact Ohio EPA's Underground Injection Control Unit, which is located at Ohio EPA's Central Office, Division of Drinking and Ground Waters.

With the exception of tracer tests, the techniques listed above cannot be used to delineate a time-related capture zone. However, used in conjunction with a time-of-travel-based technique, they may be used to delineate hybrid capture zones. For example, where a wellfield lies within a narrow river valley bounded on both sides by impermeable bedrock, it may be reasonable to delineate the bedrock valley walls as lateral WHP area boundaries, and use the Darcy equation to estimate the distance upgradient to the five-year time-of-travel limit. In this case, the community also may be advised to delineate "buffer zones" along the valley walls. Buffer zones are extensions of the WHP management area up the valley wall, beyond the boundaries of the aquifer (Figure 19). The objective is to avoid contamination of the valley aquifer by precipitation running down the slopes through unmanaged contaminant sources and infiltrating the aquifer below.

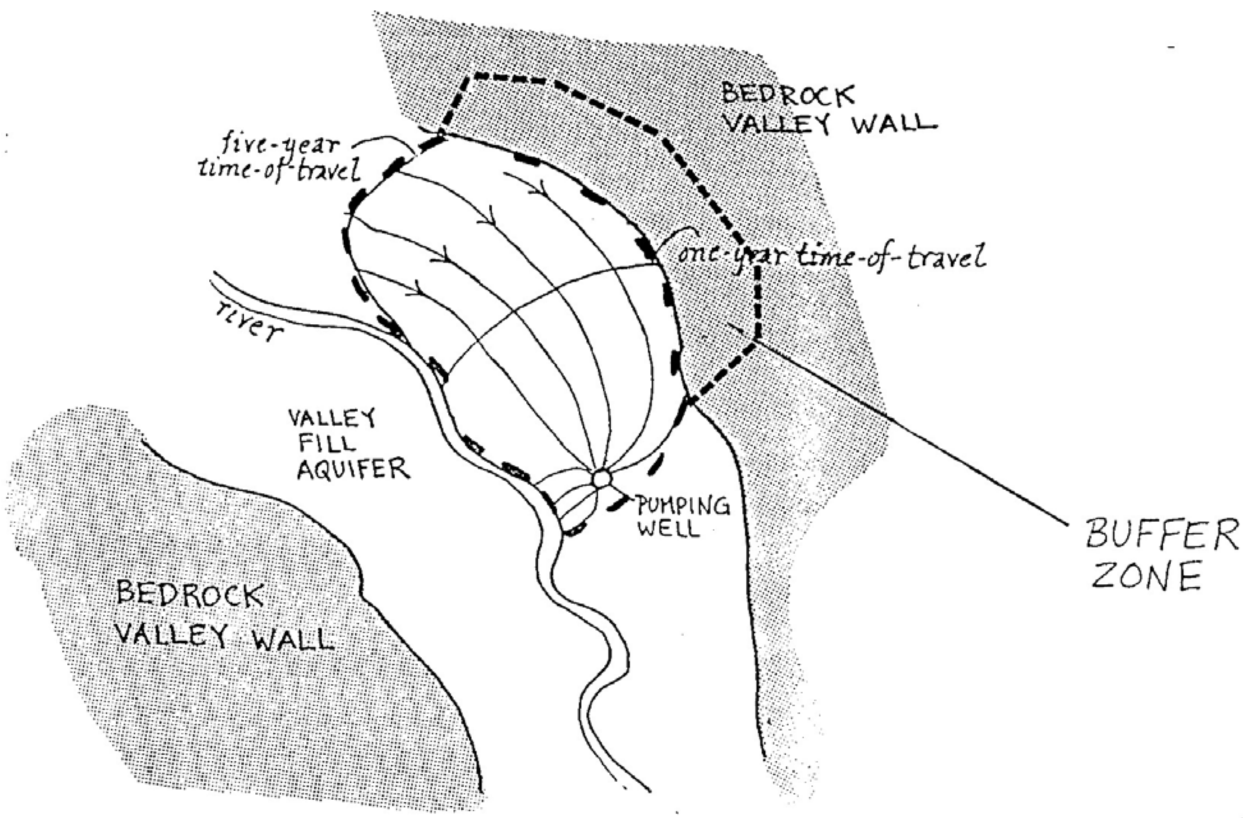


Figure 19. Designating "Buffer Zones"

Advantages: Because it must be based on site-specific information, this method can be highly credible. However, its accuracy depends largely on the accuracy and detail of the information used. Generally, hydrogeologic mapping tends to provide a conservative WHP area that is based on site-specific data rather than the idealized conditions assumed by ground water flow equations.

Disadvantages: The capture zone delineated by hydrogeologic mapping tends to be a steady-state capture zone that includes the entire zone of contribution. One- and five-year WHP areas cannot be delineated by this technique alone. Also, hydrogeologic mapping requires expertise in constructing and/or interpreting the various kinds of maps used. Where maps are not available, field data may need to be acquired and maps may need to be constructed, which will be costly. Applying geophysical methods and interpreting the results require expertise. Also, maps provide information primarily for the uppermost geologic layer. Information on deeper layers and deeper flow regimes may not be available on maps.

Applications: Hydrogeologic mapping may be applied and is acceptable in almost any setting. It is well suited to hydrogeologic settings dominated by near-surface flow boundaries, which are found in many glacial and alluvial aquifers with high flow velocities (U.S. EPA, 1991b). It may be especially useful for delineating zones of contribution in fractured bedrock, where porous flow models may not be applicable (see next section).

DELINEATIONS IN FRACTURE FLOW SETTINGS

The ground water flow and well hydraulics equations discussed earlier describe the movement of water through granular, porous materials, such as sand and gravel. These equations often will not accurately describe the movement of water through fractures. Flow through fractures can be much faster than through porous materials. For example, dye tracer tests performed on the weathered Columbus Limestone underlying Seneca County indicated flow rates of as much as 500 feet per day (Raab, 1994). By contrast, flow through a clean sand aquifer under typical hydraulic gradients rarely exceeds a few feet per day. Fracture flow differs from porous flow in a number of other ways, as summarized in Table 7.

While flow through fractured rocks can be described mathematically using other equations, it is difficult to make simplifying assumptions about the nature of the fracture network. Individual fractures tend to vary in length and width. Some fractures may be filled with precipitates, while others are open. Some areas may be more densely fractured than others. Some fractures may be interconnected, and therefore able to transport water, while others are not. A mathematical description of fracture flow thus requires extremely detailed information about the fracture network. As a result, direct application of such equations to WHP area delineation is difficult.

It should be noted that computer programs designed for modeling fracture flow do exist, but they are not widely available. Most of the existing programs are proprietary codes originally developed by oil exploration companies. These models tend to be extremely large in scale and setting them up requires intensive geologic research and a great deal of computer expertise. Few of these models are designed to simulate the movement of particles through a flow field. As a result, they are not suitable for a community wellhead protection program.

Clearly, delineating a WHP area for wells completed in fractured rock is problematic. However, credible delineations can be made based on two standard approaches, as described below.

Table 7. Differences Between Flow Through Porous Materials and Fractured Materials (Source: U.S. EPA, 1994)

Aquifer Characteristics	Porous Media	Fractured Media
Porosity	Mostly primary	Mostly secondary
Flow	Slow, laminar	Possibly fast and turbulent
Isotropy	More isotropic	Less isotropic
Homogeneity	More homogeneous	Less homogeneous
Flow Predictions	Darcy's law applies	Darcy's law may not apply

The Discrete Approach

Under the discrete approach, the individual fractures are characterized as much as possible. The width, length, wall roughness, orientation, and interconnectivity of fractures is measured or eliminated, using a variety of methods. For example, if there are bedrock outcrops, road-cuts or quarries nearby, investigators may be able to measure the width, density and orientation of the fractures directly. Where the bedrock is covered by a thin layer of sediment, aerial photographs may reveal primary feature patterns. Where such visual expressions are unavailable, information may be obtained from drilling rock cores. If carefully drilled, the cores may provide good visual expression of fractures. In addition, geophysical techniques may be used in the boreholes to locate horizontal fracture zones. Tsang (1987), Paillet and Hess (1987), and Hess (1988) provide reviews of fractured-aquifer analyses using a variety of borehole logging techniques. Also, the Ohio Department of Natural Resources' Division of Oil and Gas maintains several types of borehole geophysical logs for oil and gas wells.

The information obtained by the above methods is used to determine the main zones and direction(s) of ground water flow within the aquifer. The WHP area then may be delineated in accordance with the flow-boundary criterion by extending the area along the orientation(s) of flow upgradient from the well until a significant physical or hydraulic boundary is encountered. Physical boundaries in bedrock may include major faults–which are rare in Ohio's surficial geology–or abrupt changes in geologic material, such as localized sandstone aquifers that pinch out in less permeable shales. More typically, the boundary encountered will be a hydraulic boundary, such as a ground water divide. The "capture zone" thus delineated will encompass the entire zone of contribution to the well.

In extensive regional aquifers like the carbonate aquifer of northwest Ohio, the zone of contribution may extend for many miles, well beyond a community's corporate limits. In such cases it will be impractical for the community to try to manage the entire delineated area. The Ohio EPA recommends that the community focus on protecting at least the area within its jurisdictional limits, and share its findings with those communities lying within its extended zone of contribution. City and county health departments and county Soil Conservation Survey offices should also be made aware of the community's delineation.

The Continuum Approach

Under the continuum approach, it is assumed that the fractured medium approximates a porous medium at some working scale; therefore, all delineation methods based on porous flow equations are applicable. For example, a fracture one-quarter inch wide may dominate the flow in a three foot-squared block of rock. However, in an aquifer with an area of one square mile, a dense network of such fractures may in fact permit the movement of water in a manner very similar to the movement of water through pore spaces. Generally, the validity of the continuum approach is greater when:

- fracture density is increased;
- apertures are constant;
- fracture orientations are distributed rather than constant;
- the size of the WHP area is greater

As noted above, direct measurement of the above parameters is difficult. Other techniques have been developed that may be used to demonstrate whether or not fractured-rock aquifers behave as porous media, as discussed below.

1. **Pumping test responses.** IF a series of one-hour pumping tests is conducted at increasing discharge rates, a flow system dominated by discrete fractures will exhibit greatly increased drawdown with each increase in discharge (Figure 20-A). Also, any sharp irregularities in plots of drawdown versus time may indicate non-porous medium conditions (Figure 20-B).

2. **Water table surface configuration.** A potentiometric map that exibits a “stair-step” appearance may indicate a flow system dominated by fracture flow (Figure 20-C).

3. **Hydraulic conductivity distribution.** If the logarithms of hydraulic conductivity values (obtained from slug tests or specific-capacity tests) are plotted on graph paper, for porous flow the distribution of these numbers should form a bell-shaped curve. If the values appear to be distributed around two centers, fracture flow may be indicated (Figure 20-D).

4. **Variations in water chemistry.** Ground water moving through a porous material usually will have relatively uniform chemical composition through time and from place to place within the aquifer. The chemistry of ground water moving through a fractured medium may vary significantly through time and from place to place. It also tends to have low concentrations of total dissolved solids.

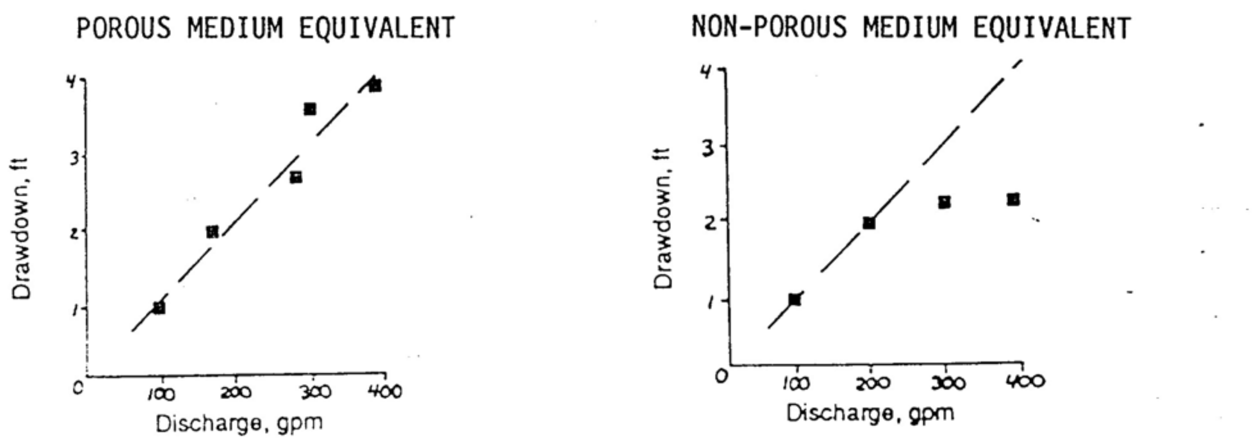
5. **Water level response to rainstorms.** Where the aquifer is close to the surface, rainstorms may cause sudden “spikes” in water levels of wells intercepting fracture-dominated flow. For example, in Seneca County’s Columbus Limestone, water levels have risen as much as sixty feet in a 24-hour period after a rainstorm (Raab, 1994). Water levels in wells intercepting porous flow will rise much more gradually.

6. **Ratio of fracture scale to problem scale.** Bedrock fractures should be numerous and closely spaced. U.S. EPA recommends that, as a rule of thumb, the minimum dimension of the WHP area should be at least 100 times the average fracture spacing. For example, if the average distance between major fractures is ten feet, the minimum dimension of the WHP area should be at least 1,000 feet.

RULE OF THUMB: ***To justify using porous-flow methods to delineate WHP areas in fractured bedrock aquifers, the minimum dimension of the WHP area should be at least 100 times the average fracture spacing.***

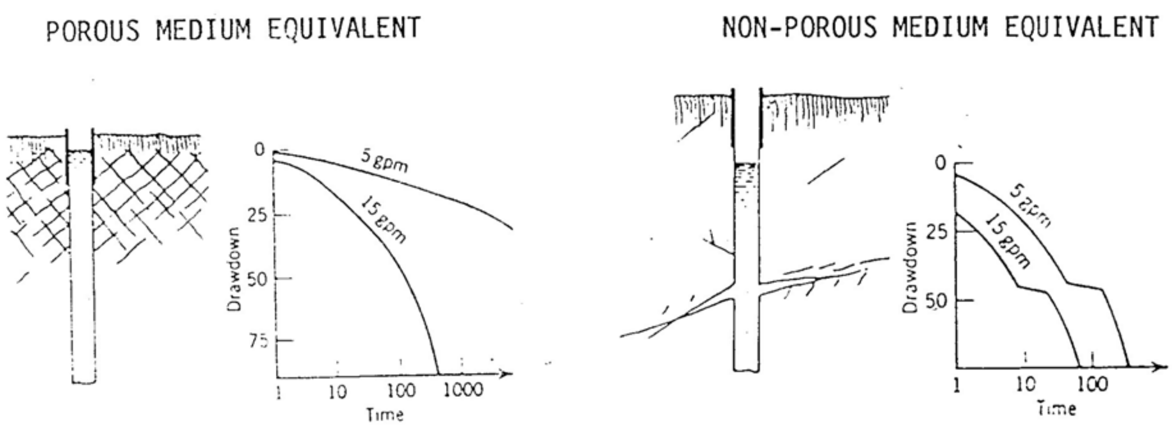
Most of the above “tests” are described in more detail in the 1991 U.S. EPA guidance entitled *Delineation of Wellhead Protection Areas in Fractured Rocks* (pages 16-18). This guidance is an excellent resource for anyone involved in delineating WHP areas for public water systems deriving ground water from fractured rock.

If it can be demonstrated that the fractures in the aquifer approximate a porous medium, then any of the WHP area delineation methods based on the time-of-travel criterion can be used. If such demonstrations cannot be provided, the community should consider extending its WHP boundaries beyond the boundary obtained using a time-of-travel method. This will help address the uncertainty concerning the delineation’s accuracy.



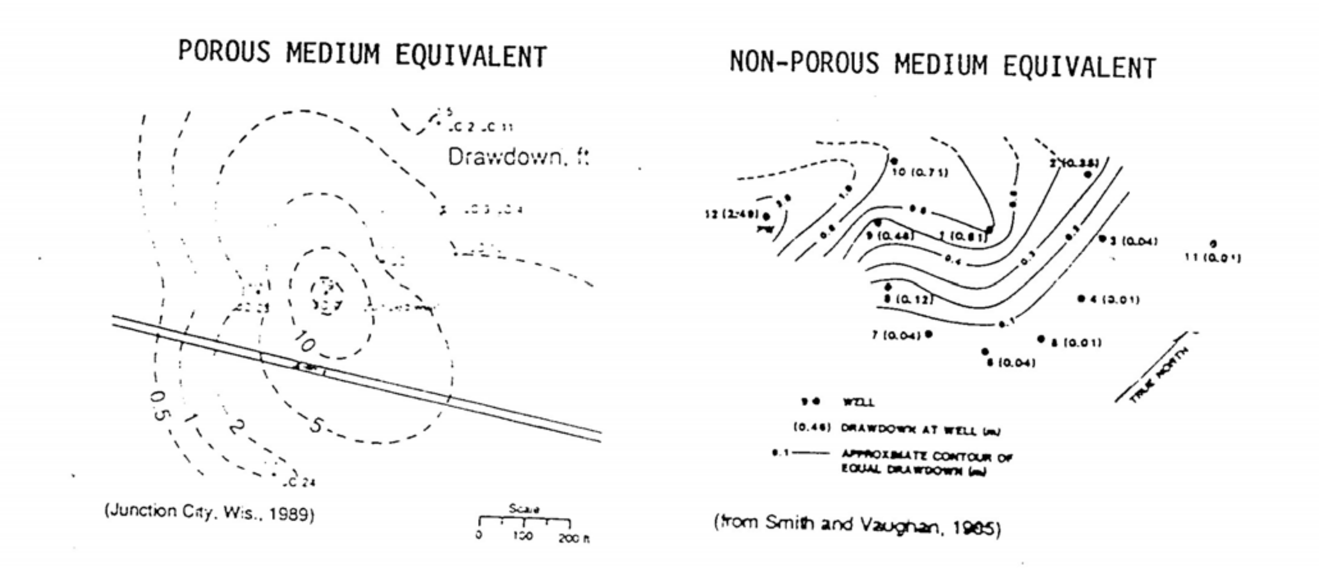
A. For a porous medium equivalent, plots of drawdown values versus discharge rates should form a straight line. (From U.S. EPA, 1991)

B. For a porous medium equivalent, plots of drawdown versus time should form smooth curves. (From

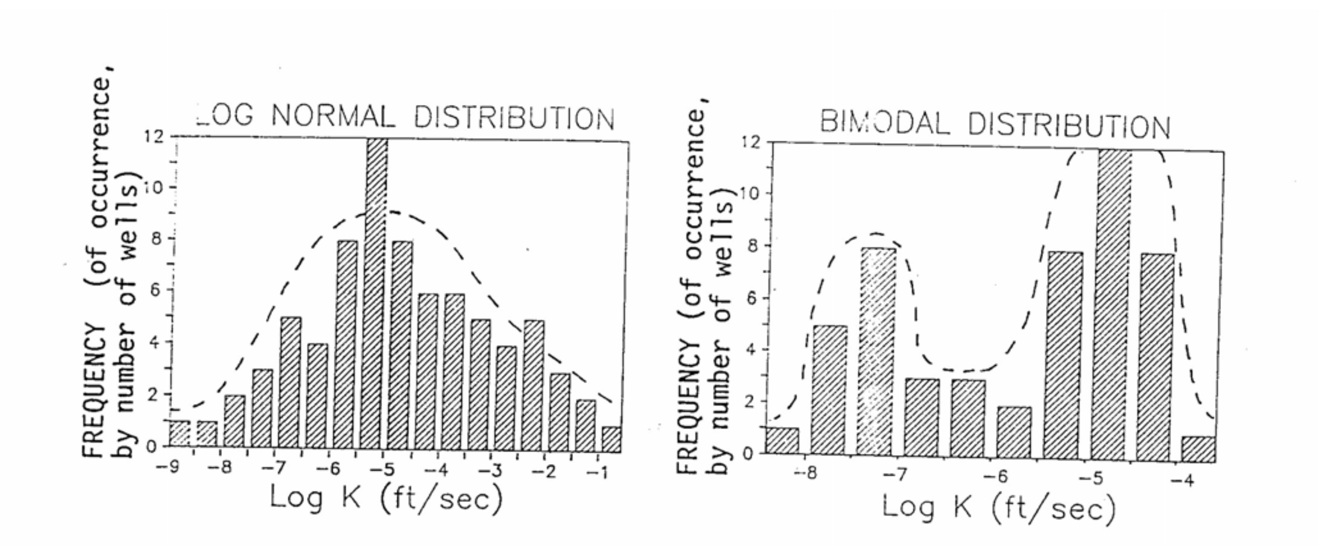


U.S. EPA, 1991)

Figure 20. Techniques for Demonstrating Whether a Fractured Medium Behaves As a Porous Medium



C. For a porous medium equivalent, potentiometric maps should display smooth curves.



D. For a porous medium equivalent, logarithms of hydraulic conductivity values are normally distributed (i.e., form bell-shaped curves on distribution plots)

Figure 20. (continued) Techniques for Demonstrating Whether a Fractured Medium Behaves As a Porous Medium

CHAPTER 4

APPLICATIONS AND COMMON PROBLEMS

INTRODUCTION

Once a delineation method has been selected, most effort will focus on obtaining, verifying and refining data required to apply the method. Upon completing the delineation, the resulting WHP area is drawn on a site map. Some problems or errors that occur frequently during data collection or data manipulation are identifed below.

INADEQUATE DETERMINATION OF FLOW DIRECTION

An accurate determination of flow direction is critical to an accurate WHP area delineation. Modeling studies have shown that the size and orientation of a capture zone are especially sensitive to variations in local flow direction and flow gradient. Even the most sophisticated WHP area delineation methods may produce inaccurate results if the direction of flow is not determined adequately. In the worst case, the delineated WHP area may extend in a direction that is completely wrong, such that it barely overlaps the ACTUAL zone of contribution. The costs of redesigning a WHP area study–or worse, of failing to protect the wellfield from contamination due to an erroneous delineation–can be extremely high. Remediation of contaminated wellfields has cost Ohio communities millions of dollars. For these reasons, Ohio EPA strongly recommends that public water suppliers make the effort necessary to ensure that flow direction determinations are accurate.

The average flow direction(s) can best be determined from a potentiometric map constructed from actual water level measurements. The Ohio EPA recommends that water level measurements be taken within a few days of each other to determine an accurate potentiometric surface. Gross errors in flow direction can be made when water levels are collected over an extended period of time. For example, if some measurements within a database were taken during spring (when water levels typically are high) and some measurements were taken during autumn (when water levels typically are low), then the apparent direction of flow will reflect when the points were sampled, and may not reveal the actual flow direction.

Similar inaccuracies may result if various measurements were taken over the course of many years, especially if the influences on the flow pattern have changed during that period of time. Although an excellent potentiometric map may exist for water levels measured twenty or more years ago, the influences on this flow pattern may have changed. Therefore, any potentiometric map used for delineation should be verified to reflect existing influences on the wellfield (i.e., pumping rates and locations, and any other points of recharge or discharge to the aquifer).

RULE OF THUMB: ***Flow directions should be based on water levels that have been measured within an acceptable period of time (no more than a few days) in wells that are appropriately installed and screened in the same aquifer.***

To enable Ohio EPA to evaluate the adequacy of the potentiometric map and flow direction, supporting documentation must be provided. This information should, at a minimum, include:

- The dates the wells were sampled;
- The depths of the wells;
- The locations of the wells (keyed to the potentiometric map);
- The elevation above mean sea level (msl) of the top and bottom of the screened (or open) interval of the wells, to the nearest tenth of a foot (0.1 foot);
- The elevation (msl) of the top of casing reference mark or other measuring point, to 0.1 foot; and
- The measured depth to water surface from the reference mark, to 0.1 foot.

Using Well Logs to Develop Potentiometric Maps

Unfortunately, site-specific potentiometric maps rarely are available from public sources. In such cases, investigators often attempt to construct potentiometric maps based on water levels recorded in ODNR well logs completed for local wells. When an adequate number of well logs are available, this method can usually produce a reasonable estimate of regional flow direction; however, it may not accurately represent flow direction and gradient in proximity to the wellfield. Combining water level information from logs completed at different times for different types and depths of wells may be unreliable for the following reasons:

a. Water levels vary with the season; typically they are higher during spring and lower during autumn. Some investigators attempt to address this problem by "averaging" water levels at each well over the seasonal range to construct an "average" potentiometric surface. However, this practice is not recommended by Ohio EPA. As noted above, a potentiometric map should be based on water levels measured within a few days of each other.

b. Water levels may fluctuate considerably in accordance with nearby pumping. If pumping in and around the wellfield has varied significantly over a long period of time (e.g., a decade), the water levels recorded in early logs may be significantly higher or lower than those in later logs. Also, some users may pump seasonally, such that seasonal differences will be artificially increased.

c. In complicated hydrogeologic settings, it can be difficult to ascertain from the logs whether the wells are completed in the same geologic unit. Different geologic units may have markedly different potentiometric surfaces.

d. Surface elevations are not surveyed accurately for the kinds of well installation recorded on most ODNR well logs. Sometimes the surface elevation is estimated from the well's location on a topographic map, but this technique can result in considerable error.

e. The accuracy of the water level measurement depends on the precision of the person making the measurement and the quality of the equipment used–variables which cannot be evaluated from the information on the well log.

f. When the water level is reported as a depth–as it typically is–it is important to know whether the depth is measured from ground surface or some other reference point. Such information rarely is included on the well logs.

It is possible for an experienced hydrogeologist to sort through larger well log databases and pick sets of wells that meet specific time, design and hydrogeologic criteria. Based on these sets, a relatively reliable "historic" potentiometric map can be constructed using a contour interval that is greater than the normal seasonal water level fluctuation.* This map, combined with water withdrawal facility registration data (see Appendix 3), can be used to target and prioritize where new data should be collected for an accurate, updated map. Items to consider when collecting data for an updated potentiometric map are discussed below.

Conducting water level measurements in existing wells. Where there is an adequate number of existing production wells, they may be used to determine flow direction. To use existing wells, the investigator will have to obtain permission from the well owners. These wells also will need to be surveyed to obtain accurate elevation measurements. Many communities have used the county or city Engineers Office or the Engineering Department in a nearby university to survey wells.

The investigator also will need to verify the total depth and the screened intervals of the wells, from their respective well logs or from owners' records. A potentiometric map must be based on water levels measured in wells that are completed in the same hydrogeologic unit, over approximately the same interval.

A number of different methods are available for measuring depth to water in a well. These vary from a simple chalked and weighted string to electronic recording devices. Which ever method is used, the investigator needs to accurately record the depth to water from some measuring point, normally the top of the well casing. This same point should be used to measure elevation of the well casing. Depth to water should be recorded as accurately as possible (preferably to the nearest 0.1 foot). When using existing wells, arrangements should be made with the well owner to not use the well for a period of at least 12 hours before measurement of water levels, to ensure that water levels have recovered to their normal static level.

Many investigators are reluctant to use existing wells because field measurement is labor-intensive and requires the cooperation of private well-owners–some of whom may be suspicious of the investigators' motives, and worried about possible effects on their wells. The supplier and consultant must consider the possibility of litigation by private well owners claiming water quality or well function problems caused by the investigators.

Installing monitoring wells or piezometers. Where there is not an adequate number of existing wells, the investigator may consider installing wells or piezometers. In many cases the investigator may choose to use a combination of existing wells and monitoring wells and/or piezometers to determine flow directions. Existing wells should be used as much as possible to reduce costs; however, it is often necessary to install additional wells or piezometers where there are large gaps.

If a decision is made to install piezometers, however, the following comments apply: Since flow directions near the wells are assumed to be nearly radial, the supplier should install piezometers in locations beyond the area exhibiting significant drawdown due to pumping. Also, since the zone of contribution will extend upgradient, it is more important to focus on local flow directions upgradient from the well.

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*Within most aquifers composed of unconsolidated materials, water levels fluctuate approximately 3 to 5 feet over the four seasons, with the highest levels in spring and the lowest in autumn. In large regional bedrock aquifers, such as the carbonate aquifer of northwest Ohio, fluctuations may be even smaller. However, in bedrock characterized by large fractures and void spaces, water levels may fluctuate as much as sixty feet directly after a precipitation event (Raab, 1994).

To obtain a flow direction, water levels from a minimum of three wells/piezometers must be obtained. At least one piezometer should be installed in an area that appears to be (1) upgradient from the wellfield (generally, a topographically higher area). These points all should be outside the area surrounding the well(s) that exhibit significant drawdown due to pumping. Also, if only three points are used, the piezometers should be spaced to form an equilateral triangle such that the area of interest is mostly enclosed by the area of the triangle (Figure 21).

RULE OF THUMB: ***Water level readings from a minimum of THREE points are required to determine flow direction in a given area. The points (i.e., piezometers) should be spaced to form the vertices of a roughly equilateral triangle whose area mostly encloses the area of study. The three piezometers must be completed in the same aquifer.***

The steps involved in doing a three-point problem to determine flow direction are explained in Figure 21.

It is important to recognize that the use of only three measuring points may be appropriate *only when the study area is relatively small and/or the potentiometric surface is expected to be nearly planar,* as is sometimes true of thick, extensive aquifers (such as the carbonate aquifer in northwest Ohio). If these conditions do not exist, additional measuring points must be used to ensure a reasonable degree of accuracy.

Expanding the WHP area to provide protection for any reasonable flow direction. If the above two options are not feasible, the investigator is advised to expand the WHP area to cover the broadest conceivable zone of contribution. In other words, if a given flow direction CANNOT be ruled out based on the available data, the WHP area must include the area affected by any flow from that direction, out to the five-year time-of-travel. For example, a wellfield located in a valley could draw water from both sides of the valley. In this case, a series of capture zones could be delineated and joined together to form a composite capture zone, as shown in Figure 22.

VARYING or MULTIPLE FLOW DIRECTIONS

The regional or local flow upgradient from the wellfield's zone of influence is not necessarily unidirectional. A single flow direction may be encountered in very extensive, thick, confined aquifers, such as the carbonate aquifer of northwest Ohio. However, it is common for ground water to flow toward the wellfield from a number of directions, especially when the wellfield is located in a valley (Figure 23). Also, in some areas flow directions vary with the seasons; for example, flow may be from the northeast during the winter and from the northwest during the summer. Although numerical computer models can account for multiple flow directions, most semi-analytical computer models cannot. For example, the WHPA codes all handle only one flow direction at a time, and the WHP areas delineated are based on the assumption that the wellfield's entire discharge is derived from the single specified flow direction. Such an assumption may result in inaccuracies. The five-year time-of-travel area will extend out too far in the specified flow direction, and will not extend out far enough in the other flow directions.

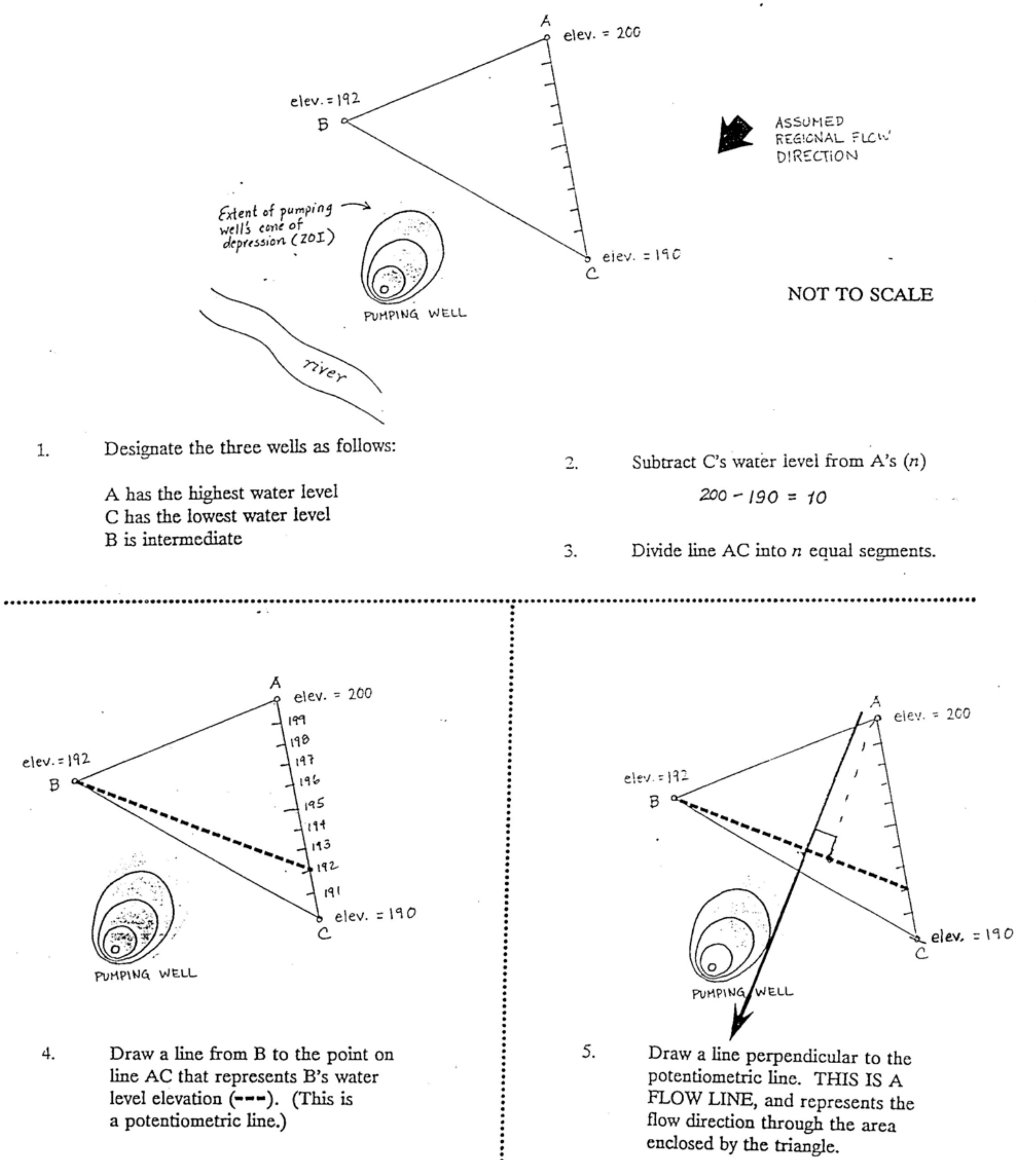


Figure 21. Determining the Direction of Local Ground Water Flow Using a "Three-Point Problem"

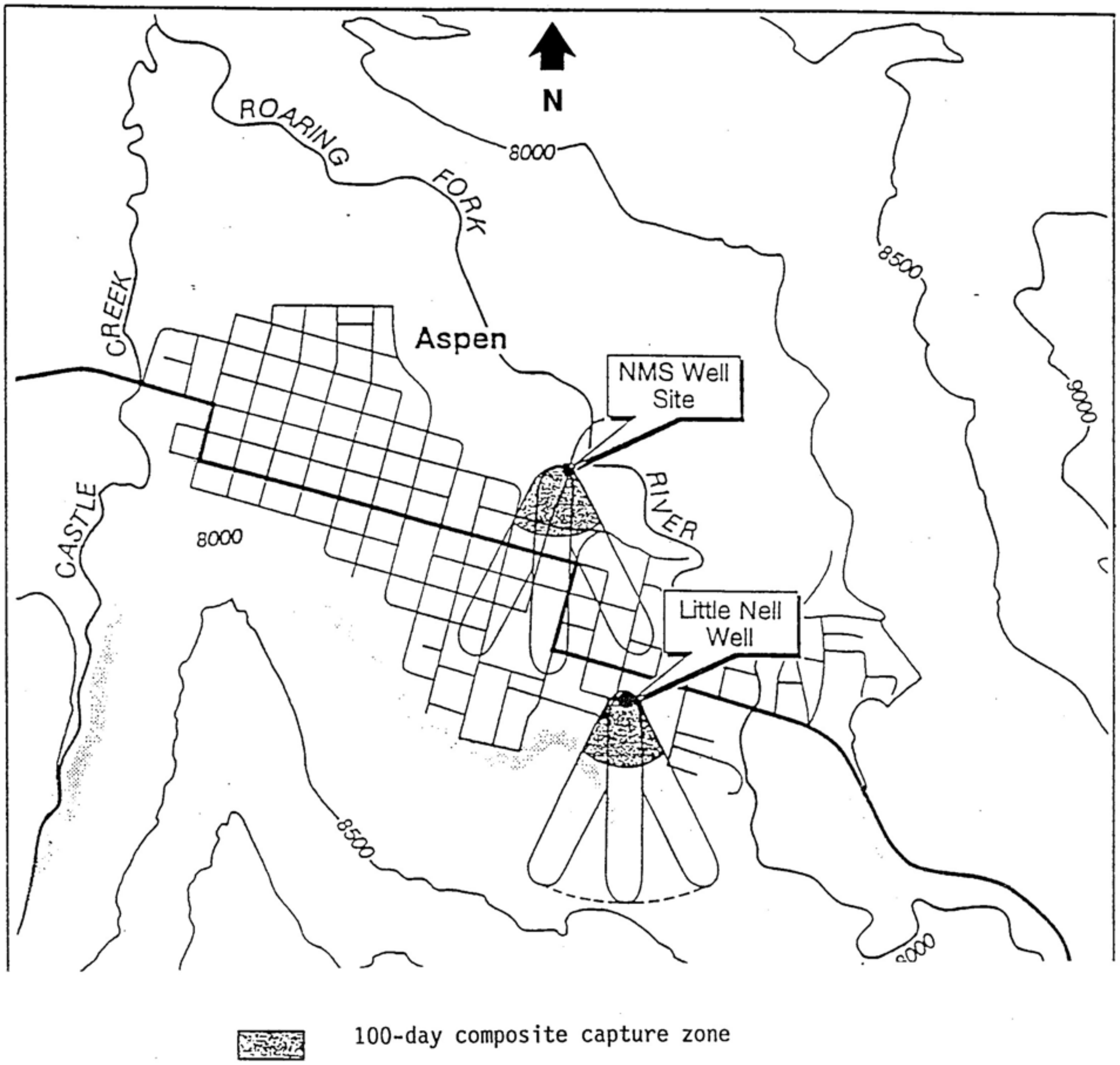


Figure 22. "Composite Capture Zones" Used to Delineate a WHP Area Where Flow May be From Multiple Directions
(Source: U.S. EPA, 1994)

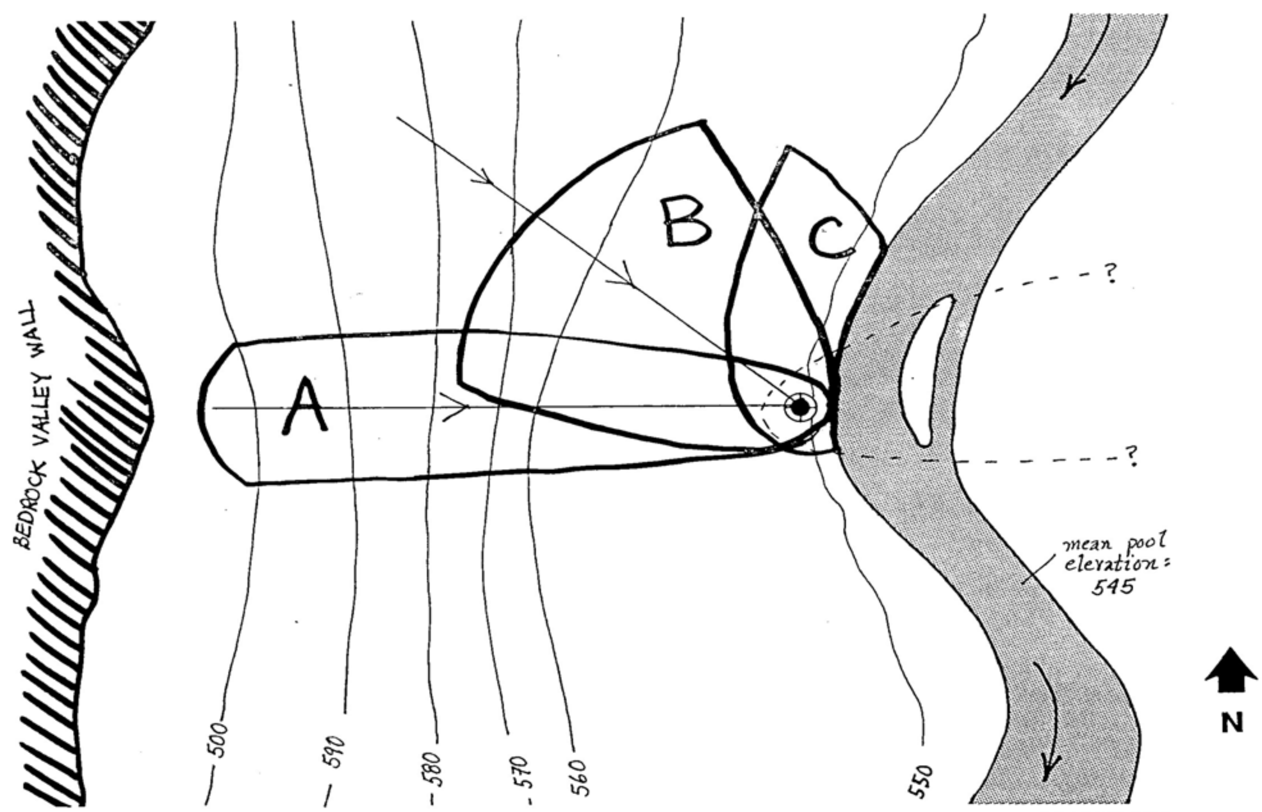
Figure 23. Delineating A Capture Zone In a River Valley: Which Capture Zone is Correct?

In this example, the direction of flow toward the pumping well is unknown. Because the topography slopes toward the river, capture zone A may be correct. Note that if the ground water gradient mimics the topographic slope, the gradient will be steeper here, and capture zone A should be relatively long and narrow (as drawn).

However, ground water flow in most river valleys also has a downvalley component. In this example, downvalley flow would be southerly. Therefore, capture zone B may be correct. Note that if the ground water gradient mimics the topographic slope, the gradient will be flatter here, and capture zone B should be shorter and wider (as drawn).

A third alternative: because the pumping well is located near the river, the well may be drawing most of its water from the river, especially if there is good hydraulic conductivity through the river bed. (This is not necessarily the case; many rivers contribute very little water to a ground water system because their channels are filled with fine-grained materials that do not transmit water easily.) If the river is supplying most of the water pumped by the well, then capture zone C may be correct. Note that it is much smaller than the other two capture zones.

Finally, if the river is not fully-penetrating (and few rivers are), the well may be capturing flow from beneath the stream. However, the direction(s) of flow from the east side of the river also are unknown.



Where a WHP area is delineated in such areas using methods that can only handle a single flow direction, Ohio EPA recommends delineating multiple capture zones. For example, if there is evidence that ground water flows toward the wellfield from three primary directions, three capture zones should be delineated. Unless the modeler has a technique for determining the relative contribution of flow from the various directions–and can document this technique convincingly–it will be necessary to input for each capture zone the value of discharge (Q) for the entire wellfield. This will result in a WHP are that is overextended in all directions, but is not likely to be underprotective in any direction. Clearly, an overprotective delineation is not ideal, but it may be the only assuredly adequate delineation possible with a model based on single flow direction.

INADEQUATE DETERMINATION OF REGIONAL FLOW GRADIENT

The magnitude of the regional flow gradient (i.e., the steepness of the regional water table slope) is another critical element of most WHP area delineations, as the size of a capture zone appears to be highly sensitive to changes in this parameter. Again, a potentiometric map based on water levels from the same aquifer is essential for determining regional flow gradient with any accuracy.

The magnitude of regional flow gradients can be calculated from potentiometric maps by completing the following steps:

a. An area just outside the zone of influence of the pumping well(s) but representative of regional topography is selected. (The extent of the zone of influence may be obtained from a distance-drawdown graph based on pumping test data, if available. Also, if the potentiometric map is detailed enough, the zone of influence may be roughly defined from the potentiometric map.) The area selection should consider the number of available wells near the wellfield.

b. The perpendicular distance between two contour lines traversing the selected area (x) is calculated from the map, based on the map scale.

c. The elevation represented by the lower contour line is subtracted from the higher contour line to obtain the vertical distance between two contour lines (y).

d. Y is then divided by x to obtain the magnitude of the ground water gradient.

A good site-specific potentiometric map often is not available. When a river runs near the wellfield, suppliers sometimes estimate the regional flow gradient by measuring the river stage at two points near the wellfield and dividing the difference in stage by the distance between the two points. However, the gradient measured is not the gradient of ground water moving toward the river, but of surface water moving directly downriver.

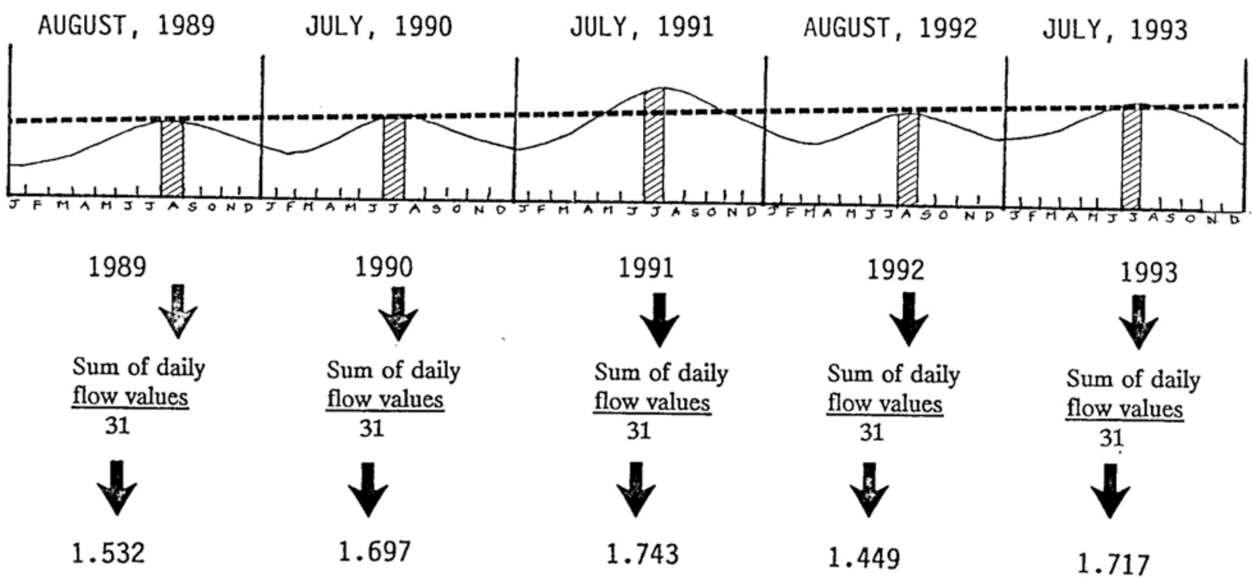
DETERMINING THE APPROPRIATE VALUE FOR “MAXIMUM PROJECTED PUMPING RATE”

All delineation methods require a value for the pumping rate, Q. This value should be based on historical average peak values, multiplied by a growth factor, as illustrated in Figure 24. The base value may be obtained by collecting average daily pumping rate data from the last five years (if available), identifying the month of average highest pumping rate within each of the five years, and using the average daily pumpage–averaged for all the days in that month. This will provide five numbers, which should be summed. The sum should be divided by 5 to obtain an average high-usage pumping rate for the five-year period. This is the base value. A sample calculation is provided in Figure 24.

Figure 24. Recommended Method for Calculating a Value for "Projected Maximum Pumping Rate"

In the following hypothetical example, the public water supplier has plotted average daily pumpage on graph paper to obtain a general curve. The curve indicates that 1991 may have been a drought year, as pumping was especially high that year. The curve also indicates that overall water demand has increased from 1989 to 1993. The rate of increase over the last five years can be obtained graphically by determining the slope of the dashed line. (This line ignores the higher values of 1991, the drought year.)

STEP 1. Identify the month in each of the last five years when the average pumping was highest. Calculate the average daily flow rate for each month by adding the daily flows and dividing by the number of days in the month.



The above hypothetical numbers represent AVERAGE DAILY FLOW IN THE HIGH-FLOW MONTH, in million gallons per day (mgd).

STEP 2. Add up the five numbers obtained above (the high-month average flow values) and divide this sum by 5. This is the "base number", which reflects pumpage over the previous five years.

STEP 3. Multiply the base number by a growth factor to account for future usage.

The base value then should be multiplied by a growth factor that estimates the average daily use in the month of highest use five to twenty years in the future. Many methods for calculating a growth factor are available; however, it is beyond the scope of this document to review them here. Most local and regional planning agencies can assist a community with calculations of future water usage. The method used by a community should be documented for reference, but Ohio EPA will not evaluate the method critically. Instead it will expect a community to reevaluate its delineation when use by an individual system increases pumpage by fifteen percent or more above **the discharge value (Q) used in the initial delineation**; or, new wells are constructed which are more than 500 feet from existing wells.

RULE OF THUMB: ***A WHP area delineation should be reevaluated when:***

1. ***quantity of water pumped (Q) increases by fifteen percent or more above the value used in the initial delineation; or***

2. ***new wells are constructed which are more than 500 feet from existing wells.***

WELLFIELDS WITH WELLS COMPLETED IN MULTIPLE AQUIFERS

Some wellfields contain wells completed in an upper aquifer and wells completed in a separate lower aquifer. When the two aquifers are separated by a confining layer that is relatively impermeable, it is possible for the two aquifers to have very different hydraulic characteristics. For example, in a river valley setting, flow directions in the upper aquifer may be toward a river located at the center of the aquifer, while ground water in the lower aquifer may flow in a single (presumably downvalley) direction. Hydraulic conductivities and other properties within the two aquifers also may differ markedly. Where this is the case, separate five-year time-of-travel areas will need to be calculated for each aquifer, and the WHP areas will need to be superimposed on a site map. The boundary of the final WHP area should enclose all areas separately calculated.

Less commonly, a wellfield may include a well that is screened in more than one aquifer. In this case, the modeler will again need to delineate separate WHP areas for all aquifers providing ground water to the well (assuming that the aquifers are not inter-connected and have different hydraulic properties). However, when assigning a value for discharge (Q), the modeler may wish to determine the relative contribution of flow to the well by different aquifers. With a numerical model such as MODFLOW, a rough estimation of relative contribution may be possible. In its discussion of the WELL package, the MODFLOW documentation presents a method based on obtaining a ratio between total transmissivity and the transmissivity of each aquifer (McDonald and Harbaugh, 1988). If the relative contribution of aquifers cannot be determined, the modeler will be obliged to delineate the WHP area for each aquifer based on the total discharge from the well.

EFFECT OF WELL DRAWDOWN ON DELINEATION VALIDITY

An easily overlooked qualification to using methods based on idealized flow assumptions is that these methods usually assume constant aquifer thickness. This assumption often is valid over relatively limited areas, especially for confined aquifers. In an unconfined aquifer, however, if the drawdown around the well(s) is significant, error is introduced. As a rule of thumb, it is valid to use equations and computer models that assume constant aquifer thickness where the drawdown in an unconfined aquifer represents ten percent or less of the aquifer's total saturated thickness (U.S. EPA, 1994). For example, if the total saturated thickness is 100 feet, drawdown due to pumping should not exceed ten feet.

RULE OF THUMB: ***Delineation methods that assume constant aquifer thickness may be applied to unconfined aquifers provided the drawdown represents ten percent or less of the aquifer's total saturated thickness.***

CONCEPTUAL ERRORS

Misconceptions or over-idealization of the hydrogeologic system may result in the selection of an inappropriate model, or the misuse of a model. Among the more common conceptual errors encountered in ground water modeling are the following:

1. **Inappropriate assumption of fully-penetrating boundaries.** Those involved in delineating a WHP area using an analytical computer model must understand that the model can only handle two dimensions; therefore, when recharge and barrier boundaries are designated, the model assumes that they are fully-penetrating. In other words, the boundary is assumed to be in contact with the entire saturated thickness of the aquifer. In reality, this often is not the case. Barrier boundaries sometimes are not fully-penetrating, as shown in Figure 25. The results of modeling a partially-penetrating barrier boundary as a fully-penetrating boundary is: *the modeled capture zone will exclude the area of contribution on the opposite side of the barrier boundary, and the WHP area based on this model will be less protective than it should be.*

   Recharge boundaries such as rivers and lakes typically are not fully-penetrating, as illustrated in Figure 25. The result of modeling a partially-penetrating recharge boundary as a fully-penetrating boundary is: *the modeled capture zone will be smaller than the actual capture zone*, because the model assumes unlimited contribution of flow to the well from the river and less flow from the land surrounding the well. As a result, *the WHP area based on this model will be less protective than it should be.*

   Also, when a river is modeled as a fully-penetrating boundary, the model assumes that there is no potential for the wells to capture contaminated flow that may be moving *underneath the river channel* toward the pumping wells. In fact, public wells in Ohio have been contaminated by toxic materials disposed of on the opposite side of the river (Figure 26).

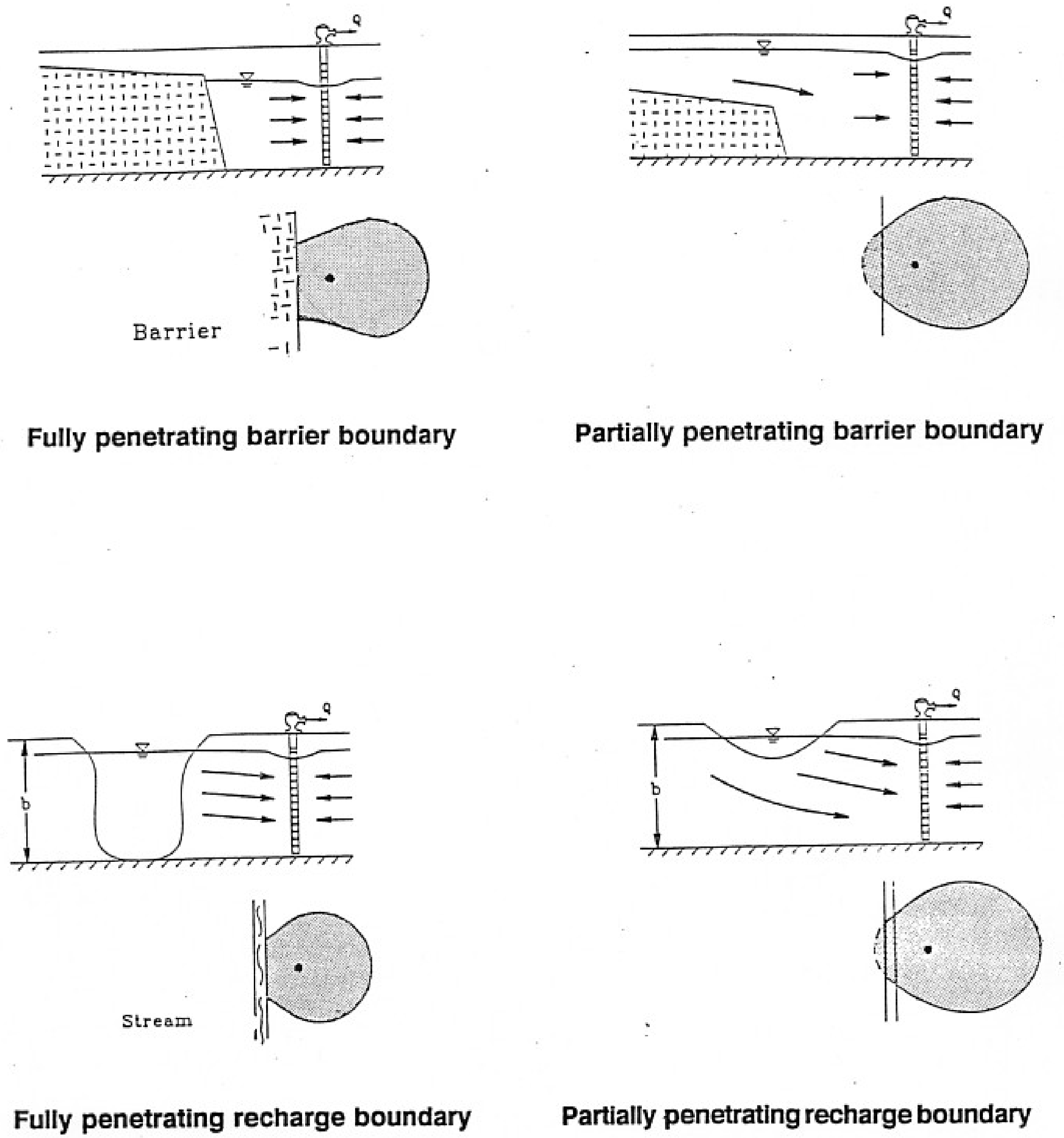


Figure 25. Fully Penetrating Boundaries Versus Partially Penetrating Boundaries: The Effect on Capture Zone Size and Shape (After Blandford and Huyakorn, 1991)

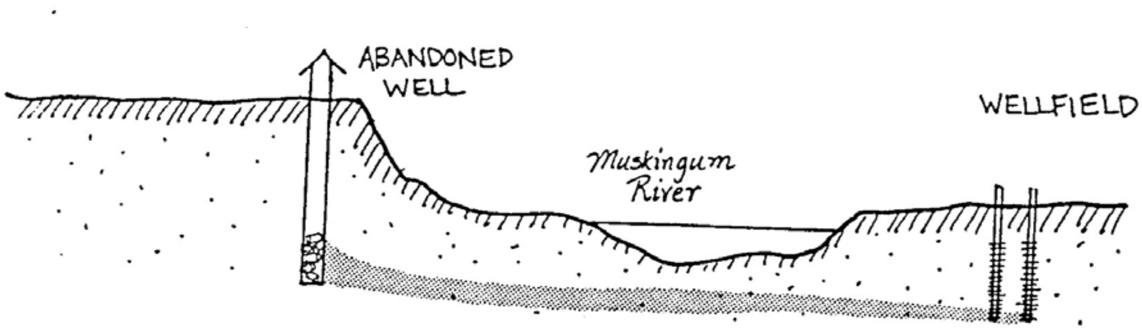
There are some circumstances, however, in which a recharge boundary that is not fully penetrating can behave approximately as a fully penetrating boundary:

1. When the recharge boundary is very deep in relation to the depth of the aquifer or the depth of the pumping wells; and

2. When the recharge boundary is very wide in relation to the wellfield.

An investigator using a two-dimensional flow model to model sites containing recharge boundaries should explain why this model is suitable for the site. Otherwise, provision should be made for a more protective WHP area than is indicated by the model.

Figure 26. Contaminated Flow Beneath A River: An Ohio Case Study



*In the early 1980s, trichloroethylene (TCE)–a carcinogenic chlorinated solvent–was detected in a public wellfield located along the Muskingum River. The source of the TCE remained a mystery until investigators searched the opposite bank of the river–where several hundred leaking drums of TCE were found in the bottom of an abandoned well. This site became one of Ohio's first Superfund sites. Over a decade since the discovery, containment wells are still pumping to keep the TCE plume away from the public wells, and the ground water pumped from these wells is being treated by air stripping.

2. **Inappropriate use of a porous flow model for a system that is predominantly heterogeneous.** While this kind of conceptual error may occur commonly, it is difficult to recognize without extensive field work. If the available logs indicate an extremely heterogeneous environment, the supplier should consider modeling the site using a numerical model based on additional field investigation. If additional field investigation is impractical, the supplier should consider expanding the size of the WHP area.

3. **Inappropriate designation of aquifer thickness.** Occasionally an investigator will designate the thickness of an entire geologic unit as the "saturated thickness", when in fact only a relatively thin portion of it–or several thin portions–is supplying water to the wells. As a result, the *modeled capture zone will be smaller than the actual capture zone, and the WHP area based on this model will not be protective enough*. It is important to remember that for confined aquifers the value for aquifer thickness should be the thickness of the saturated unit, not the difference between the **potentiometric surface** (i.e., the elevation of water in wells) and the bottom of the aquifer. Where the wells partially penetrate a confined aquifer, the value for thickness usually is taken to be the thickness of the aquifer that is penetrated by a well screen or open borehole. For unconfined aquifers the value for saturated thickness may vary significantly and should be based on actual measurements of water levels in wells.

DATA GAPS AND UNCERTAINTY OF INPUT PARAMETERS

Boundary properties, initial conditions, and values of hydraulic conductivity, recharge, or other parameters may be highly uncertain or may be unavailable. Inaccuracies in these parameters may result in incorrect model predictions, depending on the sensitivity of the model to a given (incorrect) parameter, and the magnitude of the error. Consequently, Ohio EPA recommends executing a series of models with an appropriate range of parameter values.

FAILURE TO ACCOUNT FOR THE FUTURE

A WHP area delineated for the potential pollution sources and pumping scenarios of today may not be appropriate for the circumstances in the future, especially if pumping centers are deactivated or new ones are developed.

DATA ERRORS

Errors may arise in the handling of the data. One common source of error in ground water resource work involves mixing the various systems of units used to describe the parameters, such as:

- discharge: gallons per minute (or per day); cubic feet per minute (or per day); cubic meters per minute (or per day);
- hydraulic conductivity: feet per second (or per minute, day or year); meters per second (or per minute, day or year); gallons per day per square foot; and
- transmissivity: feet squared per second; meters or centimeters squared per second; gallons per day per foot.

To help avoid errors related to misuse of units, a supplier should always include the units in each step of a calculation, and use dimensional analysis to determine that units cancel out correctly, so that the final answer is expressed in the correct units. Generally, any parameter of volume expressed as gallons or liters should be converted to feet cubed or meters cubed. (Conversion tables are provided in Appendix 4) Finally, a supplier should always have a second person carefully check all calculations before submitting the report for outside review.

RULE OF THUMB: ***Consistent units must be used in all calculations. To simplify calculations, any parameter of volume should be expressed as feet cubed or meters cubed.***

CHAPTER 5

PRESENTATION OF RESULTS

DOCUMENTATION OF THE EFFORT

Complete documentation of a WHP area delineation effort is extremely important. Good documentation will enable Ohio EPA to accurately evaluate the adequacy of the delineation. It also allows for peer review and enables other communities to adopt any techniques that are appropriate for their own wellfields. The following provides an outline of important components that should be incorporated into a report when presenting a WHP area delineation effort to the Ohio EPA.

Introduction

The introduction should describe the community's water needs (population served, current usage, and planned usage). Also, discussion should be provided of the considerations that motivated the community to develop a wellhead protection plan, and how the delineation effort is related to the overall plan. A map of the wellfield and its surroundings should be included, along with a narrative description of the wellfield. Any known plumes of ground water contamination should be described and indicated on the map.

Hydrogeologic Setting

A narrative with appropriate cross-sections and maps of the local and regional hydrogeologic system should be provided. Such a discussion typically includes regional and local topography, soil types, surface water features, regional and local geology (including stratigraphic identification and description of units), regional and local recharge and discharge areas, and ground water resources.

Conceptual Hydrogeologic Model

A discussion of the local ground water flow system should be provided. The direction of local flow and the known or estimated zone of influence of the wellfield should be described and indicated on a site map. The text should be supported by a site-specific potentiometric map.

Rationale for Delineation Method Choice

The reasons for the selection of a particular delineation method should be explained in terms of hydrogeologic, planning, and resource considerations, as discussed in Chapter 2.

Data Collection

Methods and techniques for collecting, analyzing, and interpreting data should be explained. Levels of confidence for parameters should be discussed, as well as any data gaps and any simplifying assumptions used. If aquifer tests (pumping tests, slug tests, etc.) were conducted, the supplier may summarize the results in the text of the report, but should include in the appendix the time-drawdown data, the type curves produced from the data, and equations used to analyze the data. All terms used in an equation should be defined. Units should be indicated consistently throughout the analysis.

Presentation of Input Data

All data used to delineate the zone of contribution, directly or indirectly, should be presented. Presentation methods include tables, cross-sections, and various maps, such as: hydrogeologic maps showing flow boundaries, topographic maps showing surface water features, potentiometric surface maps, bedrock configuration maps, saturated thickness maps, hydraulic conductivity maps, and storage coefficient maps.

All maps should be clear and readable, with scale markings. To provide sufficient detail, the scale of site maps should be not smaller than 1:24,000. On potentiometric maps, the location of wells providing water level measurements should be indicated clearly. Well logs for those wells should be included in an appendix to the Report, keyed to their locations on the map. The date of each water level reading used to construct the map should be included (preferably in a single table, provided either in the text or the appendix). The aquifer unit(s) and any confining unit(s) should be described in as much detail as possible.

Presentation of Computer Modeling Information

If computer models are used for the delineation of a WHP area, then "screen dumps" of the input data should be included in the documentation so that any reviewer with a copy of the model can reproduce the modeling effort exactly, to check for accuracy. (Again, such information could be included in an appendix to the report.) Also, within the text of the report additional items may need to be discussed, as applicable to the type of model used.

Model Calibration - Where the model requires matching measured and model-derived values at nodes (i.e., calibration), the specific goals and procedures of calibration should be presented and discussed. Results of the final calibrated model should be presented and analyzed, and departure from the calibration targets should be analyzed. The departure may be presented graphically as histograms or as superposed maps, wherein the potentiometric map achieved by the model is superposed over a potentiometric map based on actual water level measurements. The advantage of the map presentation is that the location(s) of greatest discrepancy can be identified. The effects of this departure on the model results should be discussed in the text. If available, the overall water and/or chemical balance of the model should be evaluated and presented.

Sensitivity Analysis - All model sensitivity analyses should be presented and interpreted. Input parameters that have the greatest impact on modeling results should be identified, and their effect(s) on the model should be described.

Additional History Matching - Goals and procedures of any additional history matching should be presented and discussed. Documentation of historical data or an applied stress for model comparison should be presented. Additional sensitivity analyses on these new comparisons should be made and documented.

Data Pre- and Post-Processing - All pre- and post-processing of model input and output data should be described and any computer codes utilized should be documented. The modeler(s) should describe the data manipulation process and why it was conducted.

Model Prediction - All predictive simulations should be described in detail, and the output from these scenarios should be presented and interpreted. The modeler(s) should present and discuss model water balance, highlighting such features as pumpage, recharge, leakage, etc. All predictions should be presented in the context of the fundamental assumptions of the model. Limitations of and confidence in model predictions should also be stated.

Delineation Results/Summary

The results of the delineation effort should be presented, including the limitations of the method and all assumptions. The degree of uncertainty–and any measures taken to address the uncertainty–should be discussed. The delineated one-year and five-year time-of-travel areas should be drawn on an unfolded original USGS 7.5 minute quadrangle map for the area, to enable Ohio EPA to enter the information into its Geographical Information System database.

OHIO EPA REVIEW PROCEDURE

Upon completion of the WHP Area Delineation Report, the supplier should send the report to the Division of Drinking and Ground Waters at the Ohio EPA's Central Office in Columbus, Ohio. The report will be reviewed for major conceptual or technical errors, and will be evaluated as "acceptable" or "unacceptable". The supplier should be aware, however, that the delineation of a WHP Area is only one component of the entire Wellhead Protection Plan, and Ohio EPA acceptance of one component does not constitute endorsement of the entire Plan. When the WHP Plan is submitted in its entirety, the supplier should have addressed adequately all Ohio EPA comments on the original delineation report. Only then can the Ohio EPA endorse a community's Wellhead Protection Plan as adequately addressing all components of Ohio's WHP Program.

REFERENCES CITED

Anderson, M.P. and Woessner, W.W. 1992. *Applied Groundwater Modeling: Simulation of Flow and Advective Transport.* Academic Press, Inc. New York, New York.

Bair, E.S., Springer, A.E. and Roadcap, G.S. 1991. CAPZONE: An Analytical Flow Model for Simulating Confined, Leaky Confined, or Unconfined Flow to Wells with Superposition of Regional Water Levels. The Ohio State University, Columbus, Ohio.

Bair, E.S., Springer, A.E. and Roadcap, G.S. 1990. The Effectiveness of Methods Used to Delineate Wellhead Protection Areas of Municipal Wells Based on Common Hydrogeologic Settings in Ohio. Report submitted to Ohio Environmental Protection Agency, Columbus, Ohio.

Blanford, N.T. and Huyakorn, P.S. 1991. WHPA: A Modular Semi-Analytical Model for the Delineation of Wellhead Protection Areas. U.S. EPA Office of Ground-Water Protection, Washington, D.C.

Fetter, C.W. 1994. *Applied Hydrogeology.* Third Edition. Macmillan College Publishing Company. New York, New York.

Fitts, C.R. 1994. TWODAN (Two-Dimensional Analytical Groundwater Flow Model) Manual. 79 Winnocks Neck Road, Scarborough, Maine.

Freeze, R. A. and Cherry, J. A. 1979. *Groundwater.* Prentice-Hall, Inc. Englewood Cliffs, New Jersey.

Grubb, S. 1993. "Analytical Model for Estimation of Steady-Sate Capture Zones of Pumping Wells in Confined and Unconfined Aquifers". *Ground Water.* Volume 31, Number 1. January-February 1993. National Ground Water Association. Dublin, Ohio.

Heath, R. C. 1984. Ground-Water Regions of the United States: U.S. Geological Survey Water-Supply Paper 2242. Denver, Colorado.

Hess, A.E. 1988. Characterizing Fracture Hydrology Using a Sensitive Borehole Flowmeter with a Wireline-Powered Packer. Proceedings of the International Conference on Fluid Flow in Fractured Rock. Atlanta, Georgia. May 15-18, 1988. p. 385-345.

Kelson, V. and Haitjema, H.M. 1994. GFLOW: Analytic Element Ground Water Flow Modeling Users Manual, Version 1.0. Haitjema Software LLC. Indianapolis, Indiana.

McDonald, M.G. and Harbaugh, A.W. 1988. A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. U.S. Geological Survey Open File Report 83-875 A1, Book 6. Washington, D.C.

Ohio EPA. 1992. Ohio Wellhead Protection Program. Ohio EPA. Columbus, Ohio.

Ohio EPA. 1993, DRAFT. Technical Guidance Manual for Hydrogeologic Investigations and Ground Water Monitoring Programs. Ohio EPA. Columbus, Ohio.

References Cited (continued)

Ohio EPA. 1994, Draft. Wellhead Protection Potential Pollution Source Inventory Guidance. Ohio EPA. Columbus, Ohio.

Paillet, F.L. and Hess, A.E. 1987. Geophysical Well Log Analysis of Fractured Granitic Rocks at Atikokan, Ontario, Canada. U.S. Geological Survey. Water Resources Investigation Report 87-4154. Denver, Colorado.

Pollock, D.W. 1989. Documentation of Computer Programs to Compute and Display Pathlines Using Results from the USGS MODFLOW. USGS Open File Report 89-381. Denver, Colorado.

Raab, J. 1994. Personal Communication.

Rumbaugh, J.O. 1991. QuickFlow: Analytical 2D Groundwater Flow Model. Geraghty & Miller, Inc. Modeling Group. 9-91.

Strack, O.D.L. 1989. *Groundwater Mechanics.* Prentice-Hall. Englewood Cliffs, New Jersey.

Todd, D.K. 1980. *Groundwater Hydrology*. John Wiley & Sons, Inc. New York, NY.

Tsang, C.F. 1987. A Borehole Fluid Conductivity Logging Method for the Determination of Fracture Inflow Parameters. Report LBL-32096, NCD-1. Lawrence Berkeley Laboratory. Earth Sciences Division.

U.S. EPA. 1994. Wellhead Protection Area Delineation Methods for Fractured-Aquifer Settings: A Training Workshop. Presented by American Institute of Hydrology. Pittsburgh, Pennsylvania. March 28-29, 1994.

U.S. EPA. 1991a. Wellhead Protection Strategies For Confined-Aquifer Settings. EPA 570/9-91-008. U.S. EPA Office of Water (WH-550G). Washington, D.C.

U.S. EPA. 1991b. Delineation of Wellhead Protection Areas in Fractured Rocks. EPA 570/9-91-009. U.S. EPA Office of Water (WH-550G). Washington, D.C.

U.S. EPA. 1988. Model Assessment for Delineating Wellhead Protection Areas. EPA 440/6-88-002. U.S. EPA Office of Ground-Water Protection (WH-550G). Washington, D.C.

U.S. EPA. 1987. Guidelines for Delineation of Wellhead Protection Areas. EPA 440/6-87-010. U.S. EPA Office of Ground-Water Protection. Washington, D.C.

U.S. Geological Survey. 1993. Current Water-Resources Activities in Ohio, 1993-94. U.S.G.S. Open File Report 93-458. Columbus, Ohio.

Zohdy, A.A.R., Eaton, G.P. and Mabey, D.R. 1974. Application of Surface Geophysics to Ground Water Investigations. Book 2, Chapter D1. Techniques of Ground Water Investigation of the U.S. Geological Survey.

Appendices

Appendix 1 A SHORT LIST OF RECOMMENDED REFERENCES

GENERAL HYDROGEOLOGY

Fetter, C. W. 1988. Applied Hydrogeology, second edition. Merrill Publishing Company. Columbus, Ohio.

Freeze, R. A. and Cherry, J. A. 1979. Groundwater. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Domenico, P. A. and Schwartz, F. W. 1990. Physical and Chemical Hydrogeology. John Wiley & Sons, Inc. New York, New York.

EFFECTS OF PUMPING ON GROUND WATER FLOW AND CAPTURE ZONES

Keely, J. F. And Tsang, C. F. 1983. Velocity Plots and Capture Zones of Pumping Centers for Ground-Water Investigations. Ground Water. Vol. 21, No. 6. November-December. Pages 701-714. National Ground Water Association, Dublin, Ohio.

Morrissey, D. J. 1987. Estimation of the Recharge Area Contributing Water to a Pumped Well in a Glacial-Drift, River-Valley Aquifer. U.S. Geological Survey Open-File Report 86-543, Denver, Colorado.

GROUND WATER COMPUTER MODELING

Anderson, M. P. and Woessner, W. W. 1992. Applied Groundwater Modeling: Simulation of Flow and Advective Transport. Academic Press, Inc. New York, New York.

Walton, W. C. 1989. Analytical Ground Water Modeling: Flow and Contaminant Migration. Lewis Publishers, Inc. Chelsea, Michigan.

Walton, W. C. 1989. Numerical Ground Water Modeling: Flow and Contaminant Migration. Lewis Publishers, Inc. Chelsea, Michigan.

AQUIFER TEST ANALYSIS

Dawson, K. J. and Istok, J. D. 1991. Aquifer Testing: Design and Analysis of Pumping and Slug Tests. Lewis Publishers, Inc. Chelsea, Michigan.

Kruseman, G. P. and deRidder, N. A. 1990. Analysis and Evaluation of Pumping Test Data, second edition. International Institute for Land Reclamation and Improvement (ILRI) Publication 47. Wageningen, The Netherlands.

Mercer, J. W. and Faust, C. R. 1981. Ground-Water Modeling. National Water Well Association. Dublin, Ohio.

Walton, W. C. 1987. Groundwater Pumping Tests: Design and Analysis. Lewis Publishers, Inc. Chelsea, Michigan.

Appendix 2 GLOSSARY

The purpose of this glossary is to provide a list of terms used in this document and commonly used by hydrogeologists, as well as some specific terms used in ground water contamination assessments and wellhead protection. The definitions provided in this glossary are not necessarily endorsed by the Ohio Environmental Protection Agency nor are they to be viewed as suggested language for regulatory purposes. This list of definitions is condensed from Bair and others, 1991, and U.S. EPA 1991a.

Advection. The process by which solutes are transported by the bulk motion of the flowing ground water.

Analytical model. A model that provides approximate or exact solutions to simplified mathematical forms of the differential equations for water movements and solute transport. Analytical models can generally be solved using calculators or computers.

Anisotropy. The condition of having different properties in different directions. The condition under which one or more of the hydraulic properties of an aquifer vary according to the direction of flow.

Aquifer. A formation, group of formations, or part of a formation that contains sufficient saturated permeable materials to yield sufficient, economical quantities of water to wells and springs.

Aquifer test. A test to determine hydrologic properties of an aquifer, involving the withdrawal of measured quantities of water from, or addition of water to, a well and the measurement of resulting changes in head in the aquifer both during and after the period of discharge or addition.

Barrier boundary. Rock or artificial material with a relatively low permeability that occurs (or is placed) below ground surface, where it impedes the movement of ground water and thus may cause a pronounced difference in the heads on opposite sides of the barrier.

Calibration. The process of matching measured values of water levels to model-simulated values, by varying the model's input values.

Cone of depression. A depression in the ground water table or potentiometric surface that has the shape of an inverted cone and develops around a well from which water is being withdrawn. Its trace (perimeter) on the land surface defines the zone of influence of a well. Also called *pumping cone* and *cone of drawdown*.

Confined aquifer. An aquifer overlain by a confining layer in which the potentiometric surface of the aquifer lies above the base of the confining layer.

Confining layer. A body of material of low hydraulic conductivity that overlies or underlies an aquifer.

Contaminant. An undesirable substance not normally present, or an unusually high concentration of a naturally occurring substance, in water, soil, or other environmental medium.

Contamination. The degradation of natural water quality as a result of man's activities.

Discharge areas. An area where ground water exits the subsurface, such as at streams, lakes, springs, and wells.

Dividing flowline. A line that defines the boundary between flow in different directions. In WHP, refers to the boundary of a capture zone wherein all flow inside the dividing flowline is captured by the pumping well, and all flow outside the dividing flowline continues down-gradient past the well, to another discharge area.

Drawdown. A lowering of the water table of an unconfined aquifer or the potentiometric surface of a confined aquifer caused by pumping of ground water from wells.

Flow line. The general path that a particle of water follows under laminar flow conditions. Line indicating the direction followed by ground water toward points of discharge. Flow lines generally are considered perpendicular to equipotential lines.

Flow path. The path a water molecule or solute follows in the subsurface.

Fracture. A general term for any break in a rock, which includes cracks, joints, and faults.

Ground water flow divide. Ridge in the water table, or potentiometric surface, from which ground water moves away at right angles in both directions.

Heterogeneity. Characteristic of a medium in which material properties vary from point to point.

Homogeneity. Characteristic of a medium in which material properties are identical throughout.

Hydraulic conductivity. A coefficient of proportionality describing the rate at which water can move through a permeable medium.

Hydraulic gradient. Slope of water table or potentiometric surface. More specifically, the difference in hydraulic head (h_1-h_2), divided by the distance (L) along the flowpath.

Hydraulic head. Height of the column of water at a given point in a ground water system above a datum plane such as mean sea level.

Hydrogeologic mapping. A WHP area delineation technique based on identifying flow boundaries from various kinds of maps.

Hydrogeologic unit. Any soil or rock unit or zone that because of its hydraulic properties has a distinct influence on the storage or movement of ground water.

Impermeable. Characteristic of geologic materials that limit their ability to transmit significant quantities of water under the head differences normally found in the subsurface environment.

Interference. The condition occurring when the area of influence of a water well comes into contact with or overlaps that of a neighboring well. At a given location, the total well interference is the sum of the drawdowns due to each individual well.

Isotropy. The condition in which the properties of interest (generally hydraulic properties of the aquifer) are the same in all directions.

Leakage. The vertical flow of ground water; commonly used in the context of vertical ground water flow through confining strata.

Monitoring well. A small diameter well (usually 2 inches or less) equipped with a short screen (10 feet or less) that is used to obtain water samples and measure water levels at a specific depth.

Numerical flow model. A mathematical model of a ground water flow system based on noncontinuous variables defined at discrete points associated with a grid. The governing flow equations are solved using numerical methods and matrix algebra.

Observation well. A well drilled in a selected location for the purpose of observing parameters such as water levels or water chemistry changes.

Partially penetrating well. A well whose intake (i.e., screen or open borehole) is less than the full thickness of the aquifer.

Porosity. The ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment.

Potentiometric surface. A surface that represents the level to which water will rise in tightly cased wells. If the head varies significantly with depth in the aquifer, then there may be more than one potentiometric surface. The water table is a particular potentiometric surface for an unconfined aquifer.

Potentiometric map. A map of potentiometric surface.

Pumping test. See “Aquifer test”.

Radial flow. The flow of water in an aquifer toward a well.

Recharge area. Area in which water reaches the ground water reservoir by surface infiltration. An area in which there is a downward component of hydraulic head in the aquifer.

Recharge boundary. A recharge area that acts as a hydraulic boundary. In WHP, refers to a lake, stream, or recharge area that acts as a boundary to a portion of the WHP area.

Secondary porosity. Porosity of a rock or sediment due to fractures or other structural openings and void spaces. This may exist in addition to primary porosity, which is due to the void spaces between individual grains of a sediment or granular rock.

GLOSSARY - Continued

Stagnation point. A place in a ground water flow field at which the ground water is not moving. The magnitude of vectors of hydraulic head at the point are equal but opposite in direction.

Storage coefficient. The volume of water released from or taken into storage per unit volume of a porous medium per unit change in head.

Storativity. The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. It is equal to the product of specific storage and aquifer thickness. In an unconfined aquifer, the storativity is equivalent to the specific yield.

Till. Unsorted and unstratified drift, generally unconsolidated, deposited directly by and underneath a glacier without subsequent reworking by water from the glacier, and consisting of a heterogeneous mixture of clay, sand, gravel, and boulders varying widely in size and shape.

Time-of-travel. The time required for a contaminant to move in the saturated zone from a specific point to a well.

Topographic maps. Maps representing the surface features of a region, including its relief (in feet above mean sea level), rivers, lakes, and man-made structures such as roads and buildings.

Tracer tests. Tests that involve injecting a relatively inert substance into ground water (usually via an injection well) and tracking the movement of the substance through the subsurface using various types of sensors.

Transmissivity. The rate at which water of a prevailing density and viscosity is transmitted though a unit width of an aquifer or confining bed under a unit hydraulic gradient. It is a function of properties of the liquid, the porous media, and the thickness of the porous media.

Unconfined aquifer. An aquifer over which there is no confining layer.

Wellfield. An area containing two or more wells supplying a public water supply system.

Wellhead. The physical structure, facility, or device at the land surface from or through which ground water flows or is pumped from subsurface, water-bearing formations.

Wellhead protection area. The surface and 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.

Zone of contribution. The area surrounding a pumping well that encompasses all areas and features that supply ground water to the well.

Zone of influence. The area surrounding a pumping well within which the water table or potentiometric surfaces have been changed due to ground water withdrawal.

Appendix 3 Sources of Information for Hydrogeologic Investigations

Type of Resource	Organized By	Available From
Well Log and Drilling Reports Ground Water Resource Maps Ground Water Resource Bulletins Pollution Potential Maps (DRASTIC maps)	County and Township Watershed County	Ohio Department of Natural Resources, Division of Water (614) 265-6740
Geologic Reports and Maps Topographic Maps Top-of-Bedrock Maps Drift Thickness Maps	County USGS 7.5 - minute quadrangle	Ohio Department of Natural Resources, Division of Geologic Survey (614) 265-6605
Ground Water Flow and Ground Water Chemistry Data Surface Water Flow and Surface Water Chemistry Data		U.S. Geologic Survey, Ohio Water Science Center, 6480 Doubletree Avenue, Columbus, OH 43229-1111 (614) 430-7700
Soil Survey Information Aerial Photography Services	County	Ohio Department of Natural Resources, Division of Soil and Water Conservation (614) 265-6610
Water Quality Reports for Public Water Systems	Name of Public Water System	Ohio Environmental Protection Agency, Division of Drinking and Ground Waters, Drinking Water Program (614) 644-2752
Surface Water Quality Reports		Division of Surface Water (614) 644-2856
Ground Water Quality Reports for Specific Sites (landfills, commercial sites, etc.)	County and Name of Site	Division of Drinking and Ground Waters, Ground Water Program (614) 644-2752
Computer Models (analytical and numerical for Analysis of Ground Water Flow, Delineation of Capture Zones	Model Name	International Ground Water Modeling Center, Colorado School of Mines, Golden, CO (303) 273-3103
(For a fee): Computer Searches of Relevant Databases, including U.S. EPA and U.S. Geological Survey Publications		National Ground Water Association, 601 Demsey Road, Westerville, OH 43081-8978 (800) 551-7379
Shipping of Federal Documents, including U.S. EPA and U.S. Geological Survey Publications		National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161 1-800-553-NTIS

Appendix 4 Conversion Factors

	A	B	C
	Multiply	By	To Obtain
Length	ft mile	3.048×10^{-1} 1.609	m km
Volume	ft^3 ft^3 ft^3 gallon (U.S.)	2.832×10^{-2} 7.481 2.832×10 3.785	m^3 gallons (U.S.) liters liters
Velocity	ft/s	3.048×10^{-1}	m/s
Discharge	ft^3/s U.S. gal/min gal/min	2.832×10^{-2} 6.309×10^{-5} 1440	m^3/s m^3/s gal/day
Hydraulic Conductivity (K)	ft/s U.S. gal/day/ft^2	3.048×10^{-1} 4.720×10^{-7}	m/s m/s
Transmissivity (T)	ft^2/s U.S. gal/day/ft	9.290×10^{-2} 1.438×10^{-7}	m^2/s m^2/s

Note: To obtain Column C units from Column A units, multiply A by B. To obtain Column A units from Column C units, divide C by B.

Appendix 5 Typical Values of Soil and Rock Hydraulic Properties

The following figures provide guidance for developing preliminary analytical flow models for a wellfield using best-estimate values of hydraulic properties. This information also can be used to verify that values measured in the field fall within the range of expected values. If not, the investigator should check the field data for systematic errors.

Transmissivity

(ft^2/day)	10^8	10^7	10^6	10^5	10^4	10^3	10^2	10^1	1	10^{-1}	10^{-2}
(ft^2/min)		10^4	10^3	10^2	10^1	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}
(gal/ft/day)		10^6	10^5	10^4	10^3	10^2	10^1	1	10^{-1}	10^{-2}	10^{-3}

Well Potential

Irrigation					Domestic			
UNLIKELY	VERY GOOD	GOOD	FAIR	POOR	GOOD	FAIR	POOR	INFEASIBLE

NOTES: Transmissivity (T) = Kb where,
K = Hydraulic conductivity
b = Saturated thickness of the aquifer

Hydraulic Conductivity

(ft/day)	10^5	10^4	10^3	10^2	10^1	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}
(ft/min)		10^1	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}
(gal/day/ft^2)		10^5	10^4	10^3	10^2	10^1	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}

RELATIVE HYDRAULIC CONDUCTIVITY

VERY HIGH	HIGH	MODERATE	LOW	VERY LOW

REPRESENTATIVE MATERIALS

Clean gravel	-	Clean sand and sand and gravel	-	Fine sand	-	Silt, clay and mixtures of sand, silt and clay	-	Massive clay
Vesicular and scoriaceous basalt and cavernous limestone and dolomite	-	Clean sandstone and fractured igneous and metamorphic rocks	-	Laminated sandstone shale, mudstone	-	Massive Igneous and metamorphic rocks		

(Source: Bair and others, 1991; U.S. Department of the Interior, 1981)

APPENDIX 5 - Continued

Storage Coefficient

In unconfined aquifer ("specific yield")	In confined aquifer ("storativity")
0.01 to 0.30 (i.e., 1 to 30 percent - see below	0.005 to 0.00005

MATERIAL	SPECIFIC YIELD (in percent)		
	Maximum	Average	Minimum
Clay	5	2	0
Silt	19	8	3
Sandy clay	12	7	3
Find sand	28	21	10
Medium sand	32	26	15
Coarse sand	35	27	20
Gravelly sand	35	25	20
Fine gravel	35	25	21
Medium gravel	26	23	13
Coarse gravel	26	22	12

(Source: Bair and others, 1991; Johnson, 1967)

Porosity

	Porosity (in percent)
Unconsolidated deposits	
Gravel	25-40
Sand	25-50
Silt	35-50
Clay	40-70
Rocks	
Fractured basalt	5-50
Karst limestone	5-50
Sandstone	5-30
Limestone, dolomite	0-20
Shale	0-10
Fractured crystalline rock	0-10
Dense crystalline rock	0-5

(Source: Freeze and Cherry, 1979)