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# Handbook

# Ground Water and Wellhead Protection

U S Environmental Protection Agency

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# *Disclaimer*

# *Acknowledgments*

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## Contents

## *Contents (continued)*

## *Contents (continued)*

## *Contents (continued)*

## Contents (continued)

## *Contents (continued)*

## Contents (continued)

# Figures

## *Figures (continued)*

## Figures (continued)

# *Tables*

## Tables (continued)

# Introduction

This handbook is divided into two parts (I) Wellhead Protection Area (WHPA) Delineation, and (II) Implementation of Wellhead Protection Areas Figure I-1 shows how Part I is organized Chapter 1 provides a general introduction to fundamentals of contaminant hydrogeology, followed by Chapters 2 (Potentiometric Maps) and 3 (Measurements and Estimation of Aquifer Parameters for Flow Equations) which cover essential hydrogeologic concepts for WHPA delineation The last three chapters in Part I cover specific WHPA delineation methods simple geometric and analytical methods (Chapter 4), hydrogeologic mapping (Chapter 5) and computer modeling (Chapter 6).

Figure I-2 shows how Part II is organized Chapter 7 provides an overview of the major steps in developing a wellhead protection program Chapters 8 (Contaminant Identification and Risk Assessment) and 9 (Wellhead Protection Area Management) contain numerous tables, checklists and worksheets for the steps that follow delineation of wellhead protection areas (Part I) Chapter 10 includes six case studies that illustrate delineation methods and implementation approaches for a variety of hydrogeologic settings

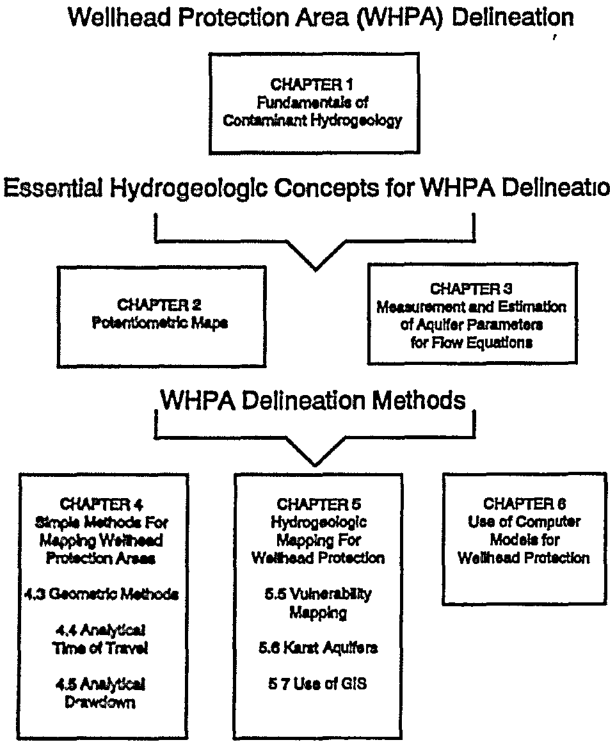


**Figure I-1. Guide to Part I of this publication**

## WHO SHOULD USE THIS HANDBOOK

Anyone responsible for delineating the boundaries of a wellhead protection area, identifying and evaluating potential contaminants, and identifying wellhead management options will find the handbook useful

### Users Without Specialized Training in Hydrogeology

Most of this handbook does not require specialized training in hydrogeology Basic math skills, including high school-level algebra, is required for understanding

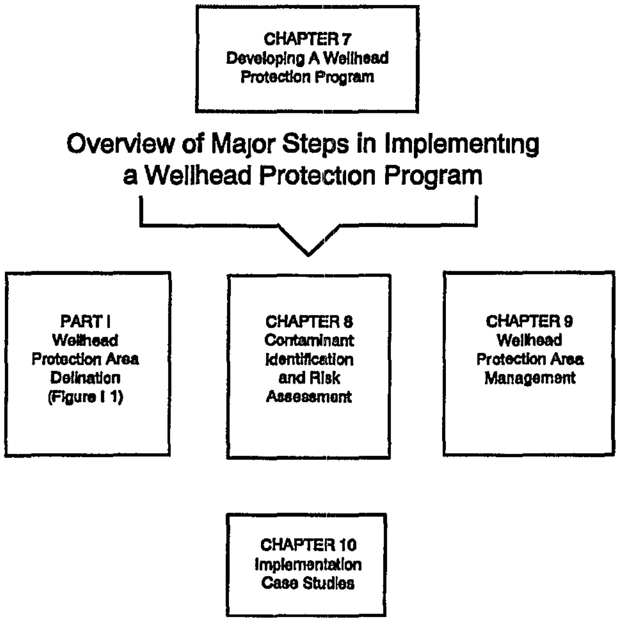


**Figure I-2 Guide to Part II of this publication**

and using the equations in the handbook Chapter 1 (Fundamentals of Contaminant Hydrogeology), Section 2 1 (Fundamental Hydrogeologic Concepts) and Section 3 1 (Hydrogeologic Parameters of Interest) provide the necessary background in hydrogeology for interpreting and using potentiometric maps (Chapter 2), estimating important aquifer parameters (Chapter 3), and using simple methods for mapping wellhead protection areas (Chapter 4)

Methods described in Chapters 5 (Hydrogeologic Mapping for Wellhead Protection) and 6 (Use of Computer Models for Wellhead Protection) generally require some special training in hydrogeology and should be used with great caution, if at all, by anyone without this training

## Users With Training in Hydrogeology

Users who have some training in hydrogeology but who are less familiar with hydrochemistry may find that Chapter 1 gives a useful introduction to chemical aspects of ground water contamination and transport Sections 4.1 (Criteria for Delineation of Wellhead Protection Areas) and 4 2 (Overview of Wellhead Protection Delineation Methods) are required reading for understanding the WHPA delineation process The purpose of Chapters 5 (Hydrogeologic Mapping for Wellhead Protection) and 6 (Use of Computer Models for Wellhead Protection) is to provide a comprehensive identification of available methods and some guidance on selection of methods A detailed discussion of specific methods is beyond the scope of this handbook, but major references containing more detailed information are cited in the text or identified at the end of each chapter in reference index tables

## RELATIONSHIP TO STATE GUIDANCE DOCUMENTS

In the United States, methods for protection of ground water and wellhead areas are in a creative period of development both in the technical and policy arenas There is no single "best" approach for all hydrogeologic or socio-political settings

During the preparation of this handbook, all state ground water and wellhead protection programs were contacted with a request for copies of any forms, worksheets, and guidance documents that had been developed as of late 1992 for wellhead protection Most states responded with materials that were very helpful for the development of this document This handbook represents a catalog and synthesis of guidance documents developed by U S EPA and approaches developed at the state level However, procedures established by state wellhead protection programs should be the primary guide in establishing wellhead protection areas Departures from state-established procedures based on information in this handbook should first be approved by the appropriate state authority

## HOW TO OBTAIN OTHER DOCUMENTS CITED IN THIS HANDBOOK

This handbook contains numerous references in which additional or more detailed information can be obtained about a topic Most chapters have a table just before the reference section which provides an index of references by topic Wherever possible, NTIS acquisition numbers or other sources of government documents are provided (National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161, 800/624-8301) EPA documents available from other sources are indicated by the following abbreviations

CERI U S EPA, Center for Environmental Research Information (CERI), 26 W Martin Luther King Drive, Cincinnati, OH 45268, 513/569-7562

EPCRA Emergency Planning and Community Right-To-Know Act (EPCRA) Information Hotline 800/535-0202

ODW U S EPA, Office of Drinking Water (WH-550), 401 M Street, SW, Washington, DC 20460, Safe Drinking Water Hotline 800/426-4791

RIC RCRA Information Center, Office of Solid Waste (OS-305), 401 M Street, SW, Washington, DC 20460, RCRA/Superfund Hotline 800/424-9346

# Chapter 1

# Fundamentals of Contaminant Hydrogeology

This chapter provides a brief review of fundamental concepts in contaminant hydrogeology Most methods for delineation of wellhead protection areas (WHPAs) use physical principles of ground water flow (Chapters 2 through 5) The purpose of wellhead protection, however, is to prevent or mitigate ground water contamination This requires an understanding of (1) how ground water becomes contaminated (Section 1 1), (2) basic processes that affect the transport of contaminants in ground water (Section 1 2), and (3) how the interaction of physical and chemical processes determine the shape of contaminant plumes (Section 1 3) Section 1 4 discusses how contaminant plume behavior is affected by geologic material properties, pH and Eh, leachate composition, and source characteristics

## 1.1 General Mechanisms of Ground Water Contamination

Contaminant releases to ground water can occur by design, by accident, or through neglect Most ground water contamination incidents involve substances released at or only slightly below the land surface Consequently, most contaminant releases affect shallow ground water initially Certain activities, however, such as oil and gas exploration, deep-well waste injection, and pumping of ground water underlain by saltwater, initially tend to affect deeper ground water

Ground water contamination can occur by infiltration, recharge from surface water, direct migration, and interaquifer exchange The first and second mechanisms primarily affect surface aquifers, the third and fourth may affect either surface or deep aquifers

### *1.1.1 Infiltration*

Infiltration is probably the most common ground water contamination mechanism A portion of the water that falls to the earth as precipitation slowly infiltrates the soil through pore spaces in the soil matrix As the water moves downward under the influence of gravity, it dissolves materials with which it comes into contact Water percolating downward through a contaminated zone can dissolve contaminants, forming leachate that may contain inorganic and organic constituents The leachate will continue to migrate downward under the influence of gravity until it reaches the saturated zone In the saturated zone, contaminants in the leachate will spread horizontally in the direction of ground water flow, and vertically due to gravity (Figure 1-1) This process can occur beneath any surface or near-surface contaminant source exposed to the weather and the effects of infiltrating water

### *1.1.2 Recharge From Surface Water*

Normally, ground water moves toward or "discharges" to surface water bodies However, movement of contaminants from surface water to ground water can occur in losing streams (where normal elevation of the water table lies below the stream channel) and during flooding Flood stages may cause a temporary reversal in the hydraulic gradient, with a flow of contaminants into bank storage, or contaminant entry through improperly cased wells (Figure 1-2a) Schwarzenbach et al (1983) documented movement of organic contaminants in river water into glacial sand and gravel aquifers in the Aare and Glatt valleys in Switzerland Contaminated surface water can enter an aquifer if the ground water level adjacent to a surface water body is lowered by pumping (Figure 1-2b)

### *1.1.3 Direct Migration*

Contaminants can migrate directly into ground water from below-ground sources (e g , storage tanks, pipelines) that lie within the saturated zone Much greater concentrations of contaminants may occur from these sources because of the continually saturated conditions Storage sites and landfills excavated to a depth near the water table may also permit direct contact of contaminants with ground water In addition, contaminants can enter the ground water system from the surface by vertical leakage through the seals around well casings, through wells abandoned without proper procedures, or as a result of contaminant disposal through deteriorated or improperly constructed wells

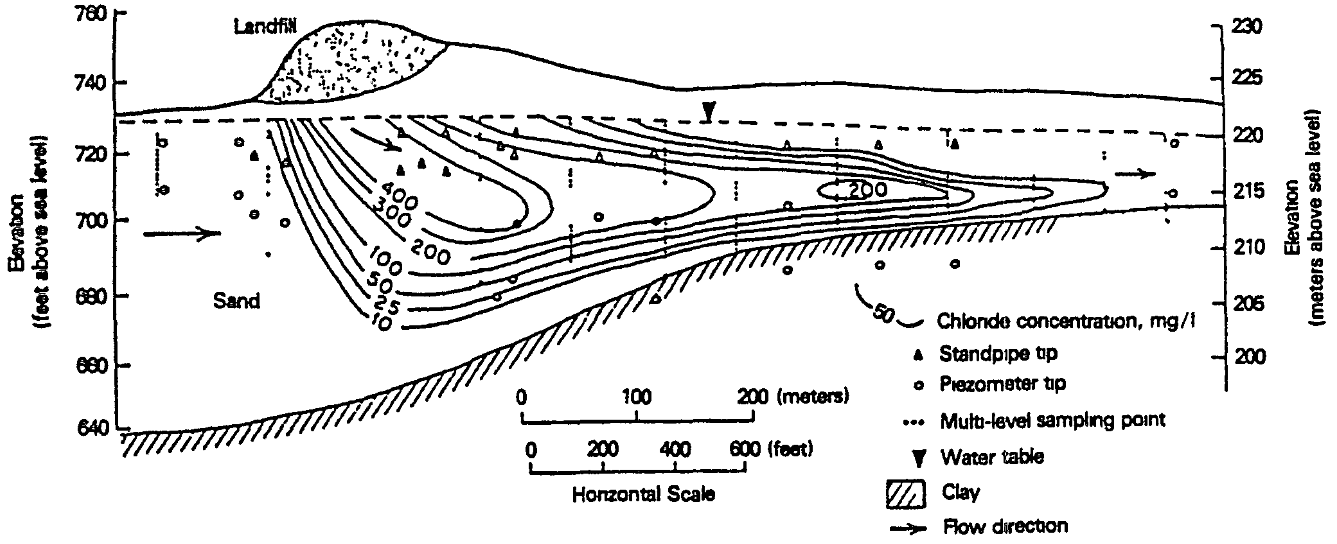


**Figure 1-1.** Plume of leachate migrating from a sanitary landfill on a sandy aquifer using contours of chloride concentration (from Freeze and Cherry, 1979)

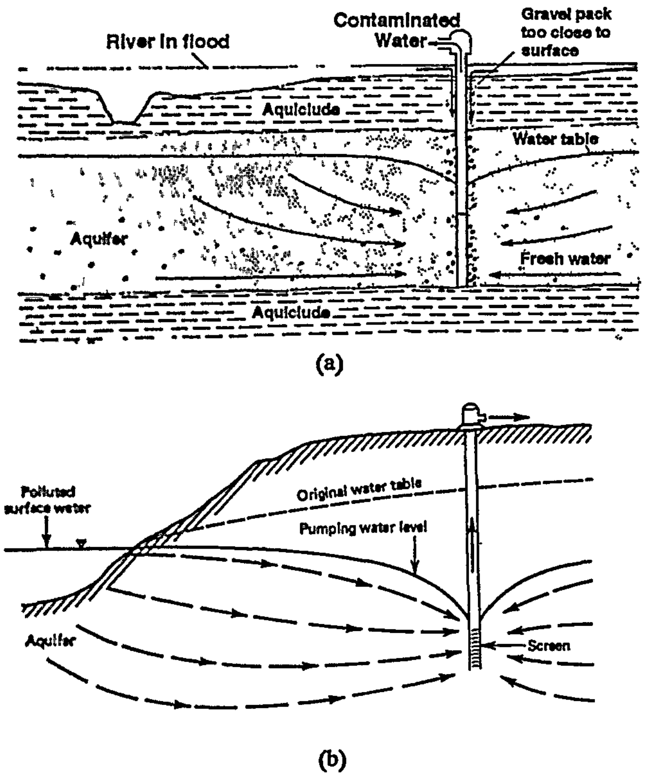


**Figure 1-2.** Ground water contamination from surface water recharge (a) contaminated floodwater entering an improperly cased well (from Deutsch, 1963), (b) contaminated water induced to flow from surface water to ground water by pumping (from Deutsch, 1965).

### *1.1.4 Interaquifer Exchange*

Contaminated ground water can mix with uncontaminated ground water through a process known as interaquifer exchange, in which one water-bearing unit communicates hydraulically with another This occurs most commonly in bedrock aquifers where a well penetrates more than one water-bearing formation to increase its yield Each water-bearing unit has its own head potential, some potentials being greater than others When the well is not being pumped, water moves from the formations with the greatest potential to formations of lesser potential If the formation with the greater potential contains contaminated or poorer quality water, it may degrade the quality of water in another formation

In a process similar to direct migration, old and improperly abandoned wells with deteriorated casings or seals may contribute to interaquifer exchange Vertical movement may be induced by pumping, or may occur under natural gradients For example, Figure 1-3 depicts an improperly abandoned well with a corroded casing that formerly tapped only a lower uncontaminated aquifer The corroded casing allows water from an overlying contaminated zone to communicate directly with the lower aquifer The pumping of a nearby well tapping the lower aquifer creates a downward gradient between the two water-bearing zones As pumping continues, contaminated water migrates through the lower aquifer to the pumping well Downward migration of the contaminant may also occur through the aquitard (confining layer) that separates the upper and lower aquifers The rate of contaminant movement through an aquitard, however, is often much slower than the rate of movement through the direct connection of an abandoned well

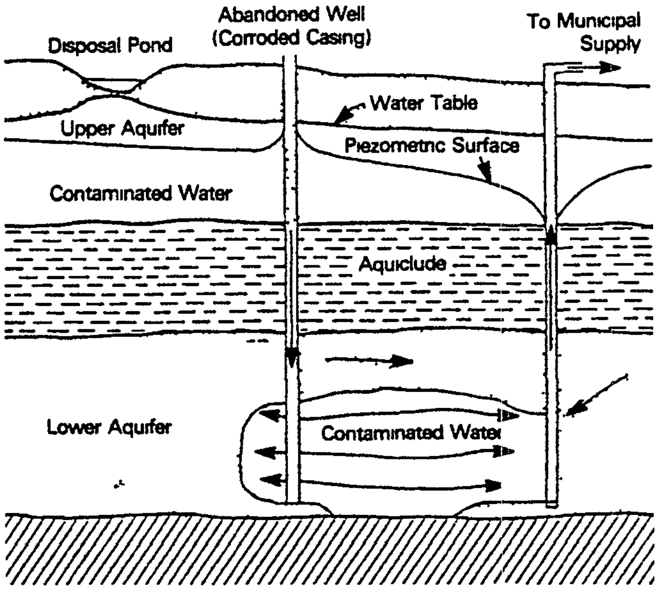


**Figure 1-3** Vertical movement of contaminants along an old, abandoned, or improperly constructed well (adapted by Miller, 1980, from Deutsch, 1961)

## 1.2 Contaminant Transport Processes

The extent to which a contaminant moves in ground water depends on its behavior in relation to various processes that encourage transport (Sections 1.2.1 through 1.2.4) and other processes that serve to retard movement (Section 1.3). The shape and speed of contaminant plumes are determined by these processes and by factors relating to the aquifer materials and characteristics of the contaminants (Section 1.4). EPA's Seminar Publication on Transport and Fate of Contaminants in the Subsurface (U.S. EPA, 1989) and Part II (Physical and Chemical Processes in the Subsurface) of EPA's Seminar Publication on Site Characterization for Subsurface Remediation (U.S. EPA, 1991) provide more detailed treatment of contaminant transport and retardation processes.

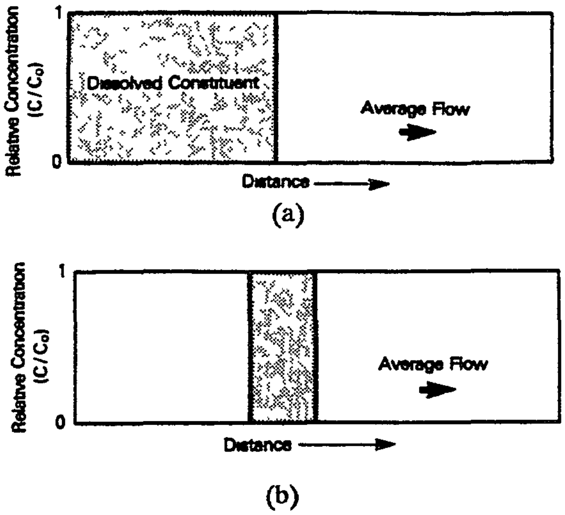
In broad terms, three processes govern the extent to which chemical constituents migrate in ground water: (1) advection, movement caused by the flow of ground water, (2) dispersion, movement caused by the irregular mixing of waters during advection, and (3) retardation, principally chemical mechanisms that occur during advection.

### *1.2.1 Advection*

Ground water in its natural state is constantly in motion, although in most cases it is moving very slowly, typically at a rate of inches or feet per day. Ground water flow, or advection, is calculated using Darcy's Law (Section 3.1.3) and is governed by the hydraulic principles discussed in Chapter 2. Time-of-travel calculations based on advective flow may *underestimate* the rate of migration of dissolved constituents, such as chlorides and nitrates, that experience minimal retardation by aquifer solids due to hydrodynamic dispersion (Section 1.2.2). On the other hand, time-of-travel estimates tend to *overestimate* the rate of migration for contaminants subject to retardation processes.

Figure 1-4a shows the relative concentration of a dissolved constituent emanating from a constant source of contamination versus distance along the flow path. Figure 1-4b shows a similar plot for a discontinuous contaminant source that produced a single slug of dissolved contaminant. Considering advective flow only, no diminution of concentration appears as a straight line moving at the rate of ground water flow.

Several mechanisms influence the spread of a contaminant in the flow field. Dispersion and density/viscosity differences may accelerate contaminant movement, while various retardation processes slow the rate of movement compared to that predicted by simple advective transport.



(a)

(b)

**Figure 1-4** Movement of a concentration front by advection only: (a) continuous source, (b) slug

### *1.2.2 Hydrodynamic Dispersion*

Hydrodynamic dispersion is the net effect of a variety of microscopic, macroscopic, and regional conditions that influence the spread of a solute concentration front through an aquifer (Mills et al., 1985, Schwartz, 1977). Quantifying dispersion may be important in fate assessment, because contaminants can move more rapidly through an aquifer by this process than by simple plug flow (i.e., uniform movement of water through an aquifer with a vertical front). In other words, physical conditions (such as the presence of more permeable zones where water can move more quickly) and chemical processes (such as the movement by molecular diffusion of dissolved species at greater velocities than the water) result in more rapid contaminant movement than would be predicted by ground water equations for physical flow, which assume average values for permeability

Dispersion on the *microscopic* scale is caused by (1) external forces acting on the ground water fluid, (2) variations in pore geometry, (3) molecular diffusion along concentration gradients, and (4) variations in fluid properties such as density and viscosity Dispersion at this scale, also called *mechanical dispersion,* is generally less accurate than estimated advective flow, and for this reason is often ignored Lehr (1988) warns against efforts to quantify dispersion at this scale

Dispersion on the *macroscopic* scale is caused by variations in hydraulic conductivity and porosity, which create irregularities in the seepage velocity and consequent additional mixing of the solute Over large distances, regional variations in hydrogeologic units can affect the amount of dispersion that occurs Macroscopic dispersion may result in substantially faster travel times of contaminants than predicted by equations for mechanical dispersion Therefore, it should be the focus of efforts to characterize dispersion (Wheatcraft, 1989) Anderson (1984) reviews various approaches to quantifying dispersion.

Dispersion can occur both in the direction of flow and transverse (perpendicular) to it Figure 1-5a depicts dispersion caused by microscopic changes in flow direction due to pore space orientation Macroscopic features, such as lenses of higher conductivity, are shown in Figures 1-5b and 1-5c Solution channeling and fracturing are other macroscopic features that may contribute to contaminant dispersion (Figure 1-6) Wells must be carefully placed when monitoring in complicated geologic systems such as those shown in Figures 1-5 (b and c) and 1-6 Figure 1-7a shows the effect of dispersion as a plot of relative constituent concentration versus distance along a flow path In the figure, the front of the dissolved constituent distribution is no longer straight, but instead appears "smeared " Some of the dissolved constituent actually moves ahead of what would have been predicted if only advection were considered Figure 1-7b gives an aerial view of dispersion of a contaminant plume from a continuous source

In a similar manner, the concentration of a slug of material introduced to a flow field appears as shown in Figure 1-8a, with the peak concentration declining over time and distance In such a situation, the total mass of dissolved constituent remains the same, however, it occupies a larger volume, effectively reducing the concentration found at any distance along the flow path An aerial view of intermittent sources affected by dispersion is shown in Figure 1-8b

Dispersion dilutes the concentration of a contaminant, thus reducing peak concentrations encountered in the ground water system Dilution alone may be sufficient to place a contaminated aquifer outside the area of regulatory concern

### *1.2.3 Density/Viscosity Differences (NAPLs)*

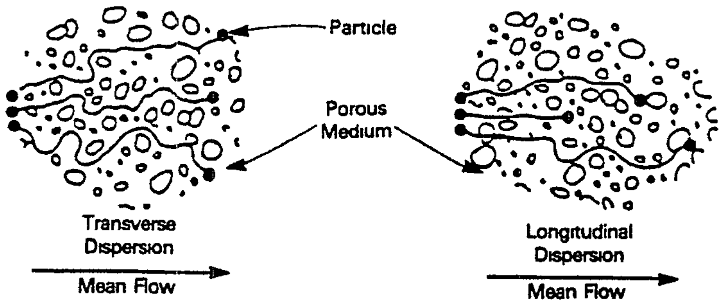
Contaminants having a density lower than ground water tend to concentrate in the upper portions of an aquifer, while those having a higher density concentrate in the lower portions The viscosity (tendency to resist internal flow) of specific contaminants affects their rate of migration from different portions of the aquifer Contaminants with these properties may be nonaqueous phase liquids (NAPLs), or ground water with different salinities (fresh and salt water) Figure 1-9 shows the effects of density on migration of NAPLs In the figure, the denser NAPL actually flows in the opposite direction of ground water flow, due to the negative slope of the confining bed Density variations in ground water in deep boreholes may result in significant errors in estimating flow directions (Oberlander, 1989) Density differences are also important in modeling interactions between fresh- and seawater (Frind, 1982)

Palmer and Johnson (1989) review the physical processes controlling the transport of NAPLs in the subsurface, Schwille (1988) and Tyler et al (1987) provide more comprehensive treatments of this topic The characterization and modeling of multi- and immiscible-phase flow (water-NAPLs, water-air, air-volatilized organic compounds) is the subject of much current research

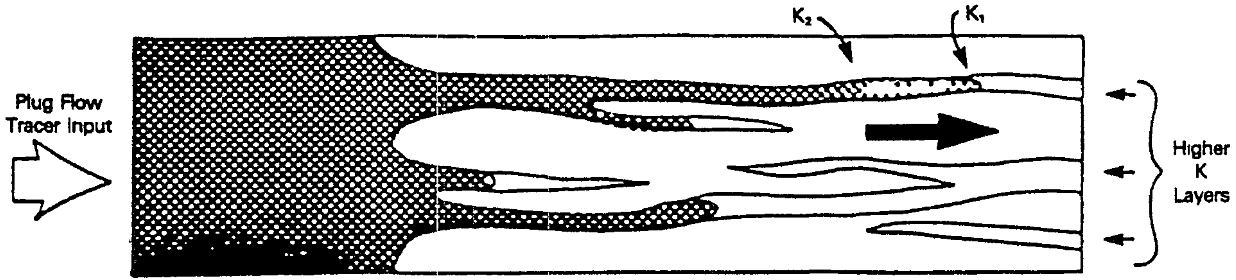
The viscosity of water decreases as temperature increases Sniegocki (1963) found that viscosity differences resulting from surface water at 66°F injected into ground water at 43°F reduced the specific capacity (gallons per minute per foot of drawdown) of an artificial recharge well in the Grand Prairie Region of Arkansas by 30 percent Kaufman and McKenzie (1975) observed that the apparent hydraulic conductivity of an injection zone in the Floridan aquifer receiving hot organic wastes increased about 2 5 times because of temperature differences alone

### *1.2.4 Facilitated Transport*

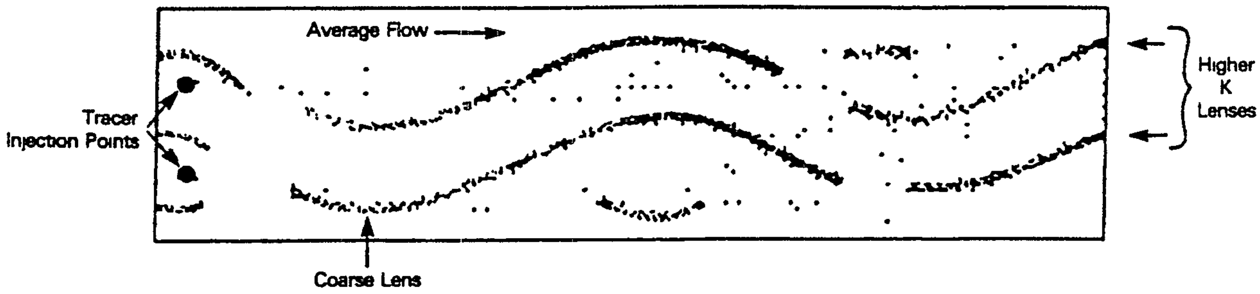
Facilitated transport, in which the mobility of a contaminant is increased relative to "expected" retardation by adsorption to subsurface solids, is a relatively new area of study in the field of contaminant transport Processes such as chelation (the formation of complex ions with organic ligands) have long been known to increase the mobility of metal ions More recently, attention has been focused on increased mobility of organic compounds by (1) *cosolvation* (increased solubility of hydrophobic organic contaminants when water-miscible organic sol-



A Microscopic scale of a granular medium



B Macroscopic illustration of fingering caused by layered beds and lenses



C Spreading caused by irregular lenses

**Figure 1-5** **Advance of a contaminant influenced by hydrodynamic dispersion (adapted from Freeze and Cherry, 1979, and Skibitz and Robinson, 1963)**

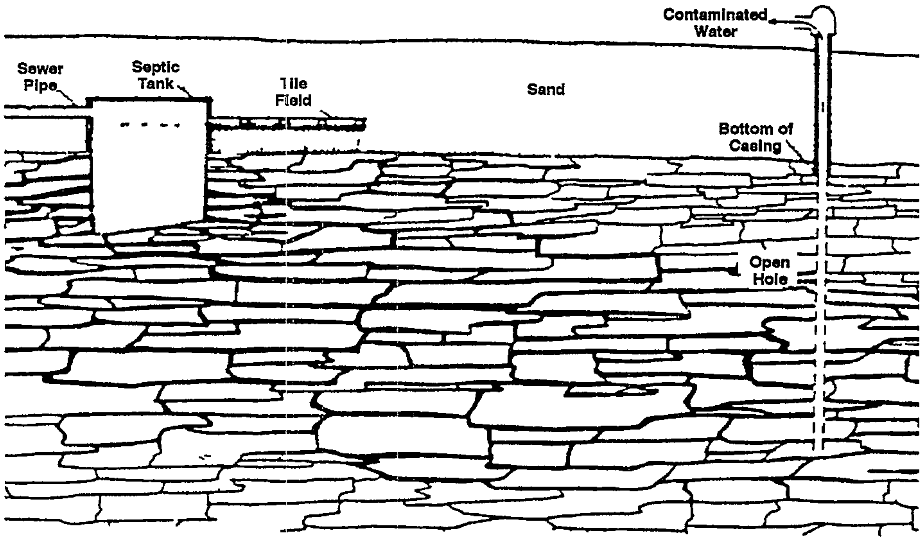


**Figure 1-6** **Movement of contaminants from a septic tank through secondary openings in limestone or dolomite (from Deutsch, 1963)**

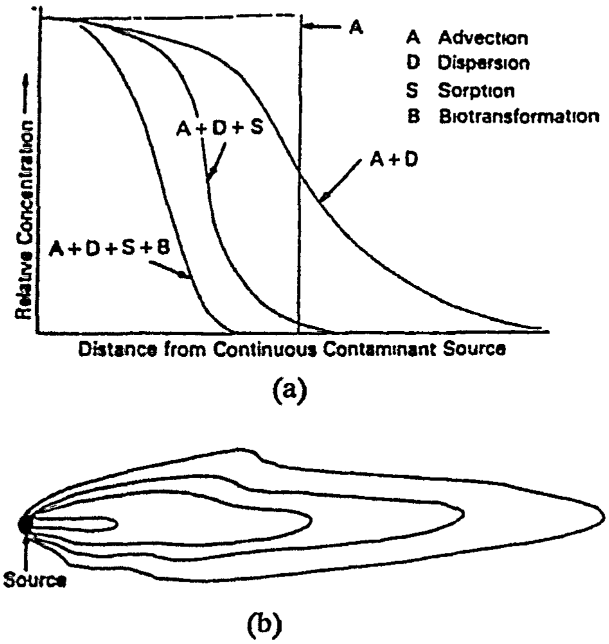


**Figure 1-7.** **Effect of dispersion and retardation on movement of a concentration front from a continuous source (a) relative concentrations compared to advection only, (b) development of a contamination plume from a continuous point source**

vents, such as ethanol, methanol, and acetone, are present in ground water), and (2) attachment to colloidal particles that are often mobile in the unsaturated and saturated zones of the subsurface (Huling, 1989) Staples and Geiselman (1988) and Woodburn et al (1986) describe methods for factoring cosolvation effects into estimates of retardation on subsurface solids

## 1.3 Contaminant Retardation Processes

In ground water contaminant transport, a number of chemical and physical mechanisms retard or slow the movement of constituents in ground water The three general mechanisms of retardation are (1) filtration, (2) partitioning, and (3) transformation or degradation

Figures 1-7a and 1-8c illustrate the movement of a concentration front by advection only (A), advection plus dispersion (A+D), and with the addition of sorption, a partitioning process (A+D+S) The greatest retardation, however, results from the combined effects of advection, dispersion, sorption, and biotransformation (A+D+S+B) The amount of retardation resulting from sorption and other partition processes and from biotransformation depends on physical and chemical properties of the aquifer and chemical properties of the contaminant

### *1.3.1 Filtration*

Filtration is the entrapment of solid particles and large dissolved molecules in the pore spaces of the soil and aquifer media Figure 1-10 shows three major mechanisms of filtration surface filtration, straining, and physical-chemical interactions *Surface filtration* results when particles are larger than the pore spaces and form a cake on the surface, at which the pore size becomes too small Caking may also result from biological activity, as in the clogging mat that develops in septic tank

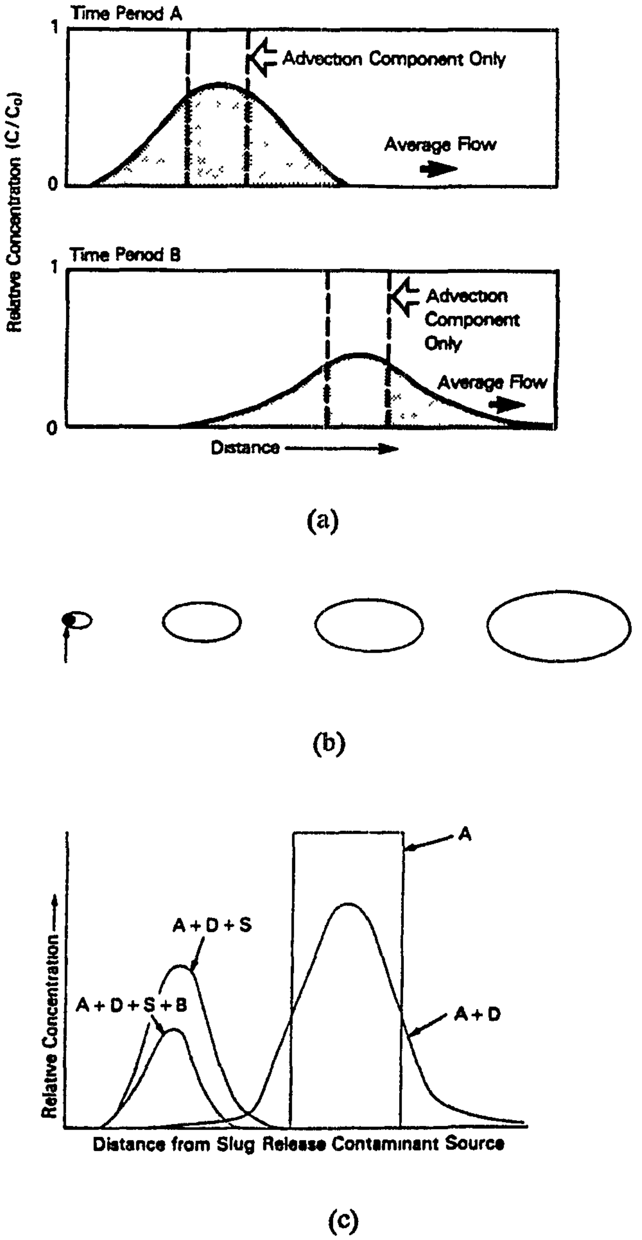


**Figure 1-8** **Effect of dispersion and retardation on movement of a dissolved constituent slug (a) relative concentrations of a one-time slug compared to advection only as it moves from time period A to B, (b) travel on a contaminant slug from a point intermittent source, (c) influence of sorption and biodegradation on concentrations downgradient at a given point in time**

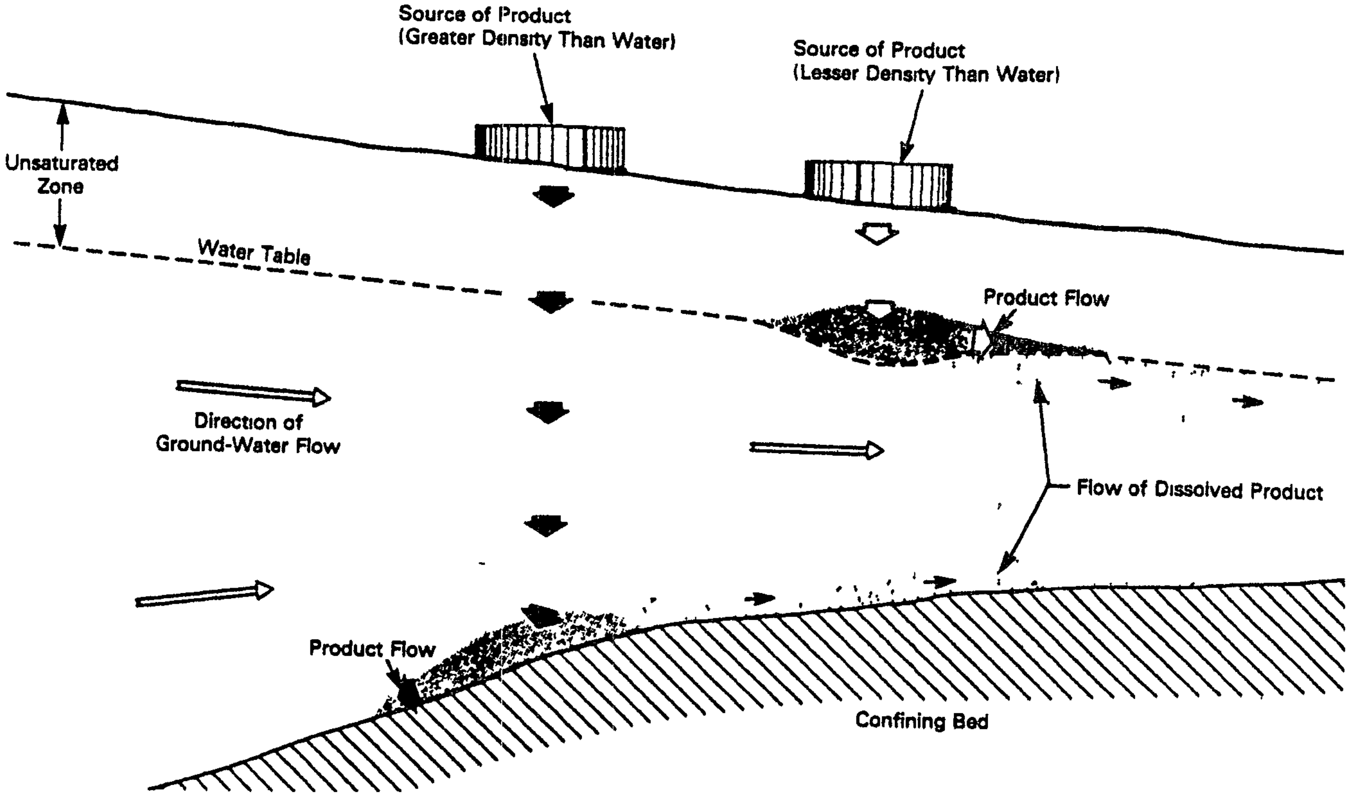


**Figure 1-9** **Effects of density on migration of contaminants (from Miller, 1985)**

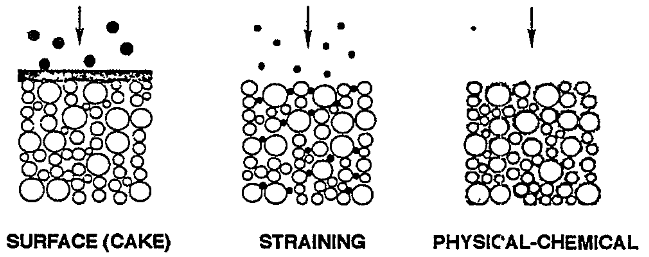


**Figure 1-10** **The three filtration mechanisms that limit particle migration through porous media (from McDowell-Boyer et al , 1986)**

absorption trenches *Straining* happens when the particles are about the same size as the pore spaces In this process, particles move through pores until they become lodged at the entrance to a pore that is too small Filtration resulting from *physical-chemical interactions* with solid surfaces is discussed under partitioning process in the next section

Filtration limits flow by clogging pore spaces and reducing the hydraulic conductivity of the material Most dissolved species are retarded by partitioning or transformation, but if the molecular size of a chemical reaction product exceeds the pore size of the soil or aquifer, mechanical filtration occurs Flocculation of colloidal material resulting from the precipitation of iron and manganese oxides, as well as clogging resulting from microbial activity, may hinder the movement of dissolved constituents Gas bubble formation may also eventually clog pore spaces, resulting in a filtering effect For example, a 10 percent increase in the air content of media voids can cause a 15 percent decrease in effective porosity, a 35 percent decrease in permeability, and about a 50 percent reduction in dispersion (Orlob and Radhakrishna, 1958)

Filtration may also result in residual contamination that is highly resistant to both mobilization by desorption into air and water and microbial degradation For example, the soil fumigant 1,2-dibromomethane, which is readily biodegraded under aerobic conditions, has been found in agricultural soils up to 19 years after its last known application, due to entrapment in soil micropores (Steinberg et al , 1987)

### *1.3.2 Partitioning*

Retardation of dissolved contaminants in an aquifer can result from two major processes that change the form, but not necessarily the toxicity, of the contaminant (1) sorption, including both ion exchange and physical adsorption, and (2) precipitation

*Ion exchange* involves the replacement of a cation attached to a negatively charged site on a mineral surface by another cation The mineralogy and cation exchange capacity of an aquifer gives a general indication of its effectiveness in retarding cationic contaminants As long as the ionic contaminant has a greater affinity for the solid surface than for existing adsorbed ions, retardation will occur Once the exchangeable sites are filled, the contaminant will travel unretarded (see A+D+S curve in Figures 1-7a and 1-8c) Precise predictions of retardation by ion exchange are not possible because of interactions among multiple ions Furthermore, changes in environmental conditions such as pH and Eh (Section 1 4 2) or ground water solution composition may remobilize contaminants formerly bound to geologic materials

In fact, the release of ions by exchange processes may aggravate a contamination problem Hughes et al (1971) documented increases in water hardness as a result of the displacement of calcium and magnesium ions from geologic materials by sodium or potassium in landfill leachate Rovers et al (1976) observed release of aluminum to solution from soil contaminated by industrial waste

Most organic contaminants are nonionic and, consequently, partitioning to aquifer solids usually occurs by *physical adsorption* processes such as Van der Waals and hydrophobic bonding

The *adsorption isotherm* is a measure of changes in the amount of a substance adsorbed at different concentrations at a constant temperature It is the simplest and most widely used method for predicting physical adsorption. Empirical constants can be calculated from adsorption isotherms, and these constants then can be used to predict the amount of adsorption at concentrations other than those measured This method assumes, however, that temperature and other environmental conditions are the same as those under which the isotherms were measured originally

*Precipitation* reactions, in which geochemical reactions in the aquifer result in a contaminant moving from a dissolved form to an insoluble form, may be an important retardation process for inorganic contaminants As with adsorption, precipitation reactions are reversible, so it is possible for a contaminant to remobilize if environmental conditions change in the aquifer Precipitation-dissolution reactions are largely determined by acid-base equilibria and redox conditions (Section 1.4 2). Geochemical distribution-of-species and reaction progress codes (Chapter 6) may help identify important inorganic precipitation reactions

### 1.3.3 Transformation

All processes that transform a contaminant retard transport in that the original contaminant is no longer present Unless the contaminant's reaction products are nontoxic inorganic elements, however, contamination may still persist Complexation reactions involving heavy metals may even increase toxicity and mobility Some organic contaminants may be transformed by *hydrolysis* in ground water, but they often produce intermediate organic compounds of varying toxicity Microbiological activity is probably the most important means by which contaminants are transformed in the subsurface

## 1.4 Contaminant Plume Behavior

The physical mechanisms of advection and dispersion, as well as a variety of chemical and microbial reactions, interact to influence the movement of contaminants in ground water The degree to which these mechanisms influence contaminant movement depends on a number of factors, including geologic material properties, pH and Eh, leachate composition, and source characteristics

### 1.4.1 Geologic Material Properties

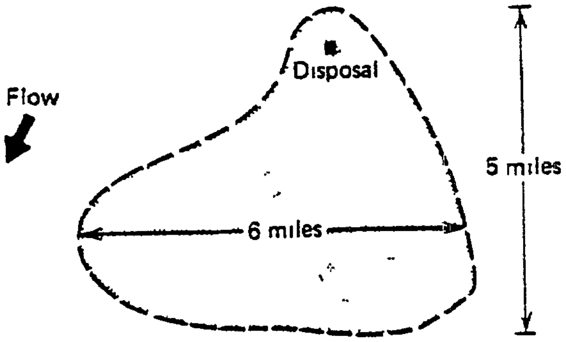
The rate of ground water movement is largely dependent on the type of geologic material through which it is moving More rapid movement can be expected through coarse-textured materials such as sand or gravel than through fine-textured materials such as silt and clay The physical and chemical composition of the geologic material is equally important Fine-textured materials with a high clay content favor retardation through ion exchange and physical adsorption Figure 1-11 illustrates the influence of differing geology on the shape of contaminant plumes

### 1.4.2 pH (Hydrogen Ion Activity) and Eh (Redox Potential)

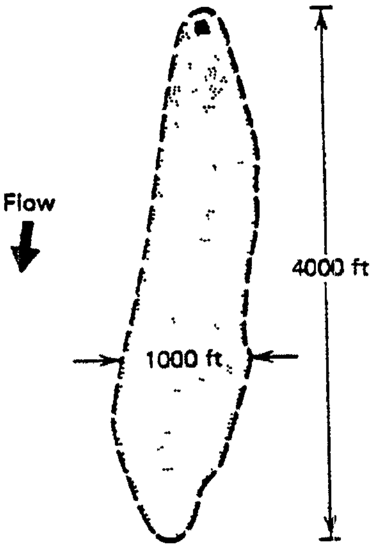
The pH and Eh of the geologic materials and the waste stream strongly influence contaminant mobility The pH affects the speciation of many dissolved chemical constituents, which in turn determines solubility and reactivity Ion exchange and hydrolysis reactions are also particularly sensitive to pH Eh influences many precipitation and dissolution reactions, particularly those involving iron and manganese, and determines in large measure the type of biodegradation that occurs

### 1.4.3 Leachate Composition

The influence of all other factors on contaminant migration ultimately depends on the composition of the leachate or contaminants entering the ground water system Similar contaminants may behave differently in the same environment due to the influence of other constituents in a complex leachate Solubility (which affects the mobile concentration), density, chemical structure, and many other properties can affect net contaminant migration For example, Figure 1-12 illustrates the appearance of two chemicals, benzene and chloride, in a monitoring well Even though both contami-



*(a)* Chloride plume, Inel, Idaho
Aquifer basalt
Time 16 years



*(b)* Chromium plume, Long Island
Aquifer sand and gravel
Time 13 years

**Figure 1-11** Effect of differences in geology on shapes of contaminant plumes (from Miller, 1985)

nants may have entered the ground water system at the same time and in the same concentration, their detection in the monitoring well reveals significantly different migration rates Chloride has migrated essentially unaffected, while benzene has been retarded significantly Table 1-2 identifies references with additional information on contaminant chemical behavior in soil and ground water

Sources releasing a variety of contaminants create complex plumes composed of different constituents at downgradient positions An idealized plume configuration composed of five different contaminants (A-E) moving at different rates through the ground water system is shown in Figure 1-13 Consequently, the onset of contamination at a supply well may mark the first of a set of

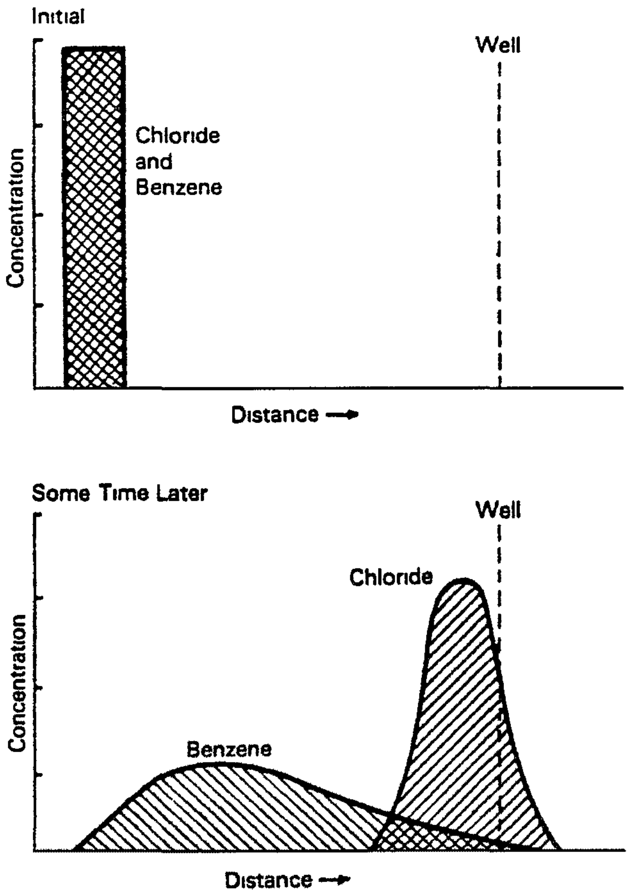


**Figure 1-12** Benzene and chloride appearance in a monitoring well (from Geraghty and Miller, 1985)

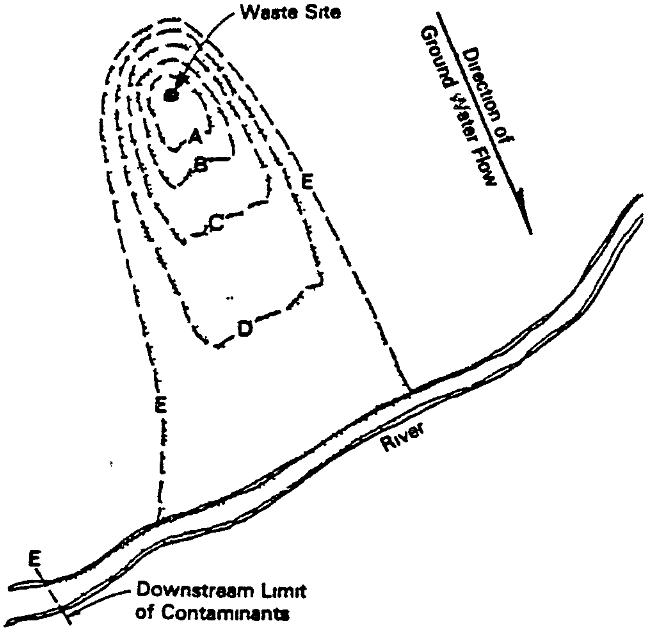


**Figure 1-13** Constant release but variable constituent source (from LeGrand, 1965)

overlapping plumes of different compounds advancing at different rates These plumes may affect the well in sequence for decades, even if the original contaminant source is removed (Mackay et al , 1985)

The effect of contaminant density on contaminant transport in ground water systems is presented in Figure 1-9 Substances with densities lower than water may "float" on the surface of the saturated zone Similarly, substances with densities higher than that of water can sink through the saturated zone until they encounter an impermeable layer In the situation shown in Figure 1-9, the surface of an underlying impermeable layer slopes opposite to the direction of ground water flow in the overlying formation Dense contaminant movement follows the slope of the impermeable boundary, while some dissolved product moves with the ground water

### 1.4.4 Source Characteristics

Source characteristics include the source mechanism (i.e., infiltration, direct migration, interaquifer exchange, ground water/surface water interaction), the type of source (particularly point or nonpoint origination), and temporal features Source mechanisms were discussed in Section 1.1. Source types are covered in more detail in Chapter 7. Temporal characteristics include the manner in which a contaminant is released over time and the time elapsed since the contaminant's release

Figure 1-14 presents the effects caused by changes in the rate of waste discharge on plume size and shape *Plume enlargement* results from an increase in the rate of waste discharge to the ground water system Similar effects can be produced if the retardation capacity of the geologic materials is exceeded, or if the water table rises closer to the source, causing an increase in dissolved constituent concentration Decreases in waste discharge, lowering of the water table, retardation through sorption, and reductions in ground water flow rate can *diminish* the size of the plume *Stable* plume configurations suggest that the rate of waste discharge is at a steady state with respect to retardation and transformation processes A plume will *shrink* in size when contaminants are no longer released to the ground water system and a mechanism to reduce contaminant concentrations is present Unfortunately, many contaminants, particularly complex chlorinated hydrocarbons and heavy metals, may persist in ground water for extremely long time periods without appreciable transformation Lastly, an intermittent or seasonal source can produce a *series* of plumes that are separated by the advection of ground water during periods of no contaminant discharge

### 1.4.5 Interactions of Various Factors on Contaminant Plumes

The various factors discussed above can result in widely varying sizes and shapes of contaminant plumes Figure 1-15 shows 18 different types of contaminated zones Table 1-1 explains the relative importance of dilution, degradation, and sorption in each plume and lists examples of the types of contaminants typically involved

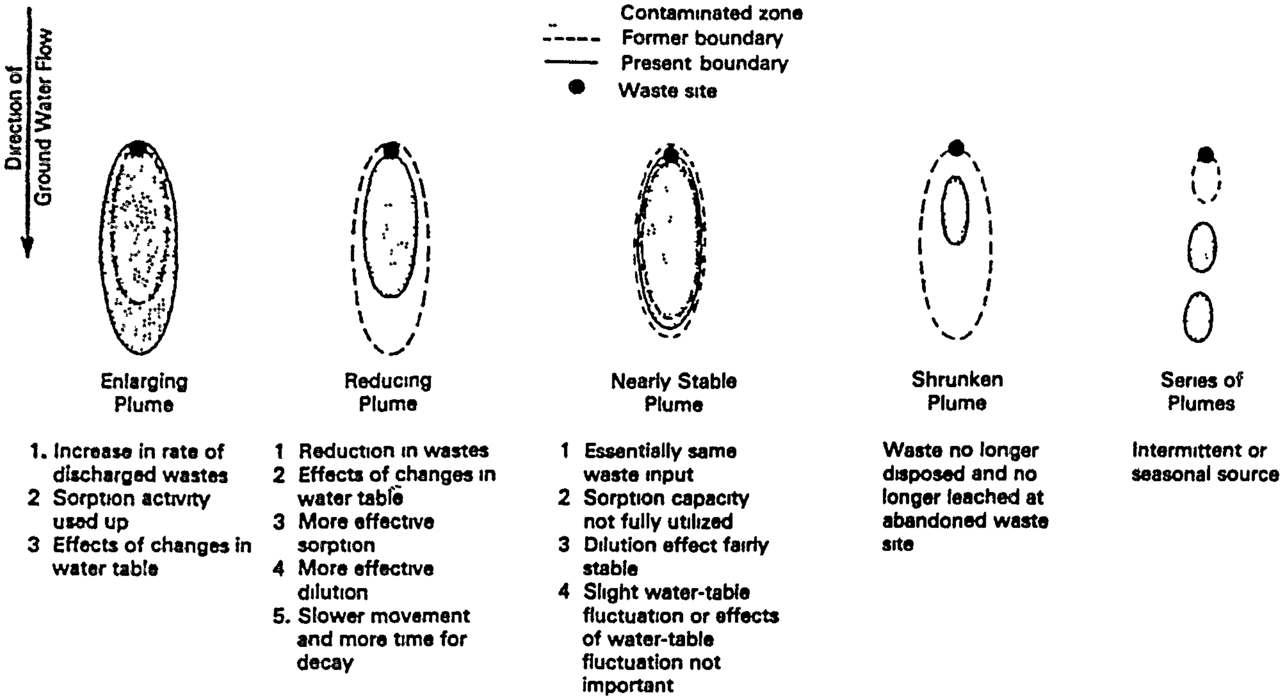


Figure 1-14. Changes in plumes, and factors causing the changes (modified from U S EPA, 1977, and LeGrand, 1965)

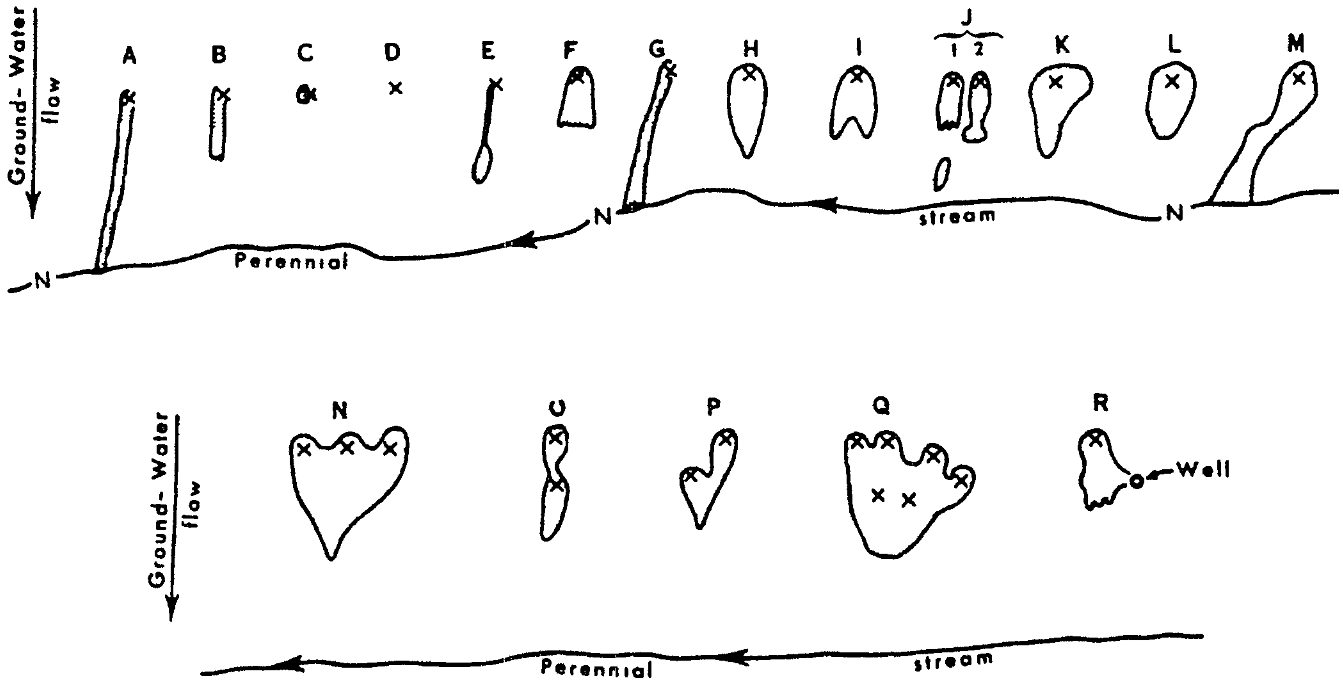


Figure 1-15 Various types of contaminated plumes in the upper part of the zone of saturation, X marks the core of contamination beneath a waste site, and Z marks the point downstream at which some zones terminate See Table 1-1 for interpretations (from LeGrand, 1965)

Table 1-1 Explanation of Contaminant Plumes Shown in Figure 1-15 (adapted from LeGrand, 1965)

| | Contaminant Plume Governed by | | | | | | |
|---|---|---|---|---|---|---|---|
| Site | Dilution | Decay | Sorption | Liquid Waste Recharge Forming Water-Table Mound | Composite Waste Sites | Examples of Type of Contaminant | Remarks |
| A | Not appreciable in ground, some in stream | No | No | No | No | Chlorides, nitrates | |
| B | Not appreciable | Either decay or sorption or both | | No | No | — | |
| C | Improbable | Perhaps | Perhaps | No | No | Sewage, radioactive wastes | Probably small waste release or good attenuation in zone of aeration |
| D | No plume formed (see remarks) | Either decay or sorption or both | | No | No | Sewage, radioactive wastes | Contaminant is completely attenuated in zone of aeration and does not reach zone of saturation |
| E | Slight near waste site, some at greater distance | Possibly | Possibly | No | No | — | Lack of dispersion near waste site typical of linear openings in rock, contaminated water downgradient disperses into different type of material |
| F | Yes, suggestive of nearly homogeneous porous materials | Improbable | Improbable | No | No | Chlorides, nitrates | |
| G | Not appreciable in ground, some near and in stream | Not appreciable | Not appreciable | No | No | Chlorides, nitrates | Irregularities in permeability cause deviation in plume |

**Table 1-1 Explanation of Contaminant Plumes Shown in Figure 1-15 (adapted from LeGrand, 1965) (Continued)**

| Site | Contaminant Plume Governed by | | | Liquid Waste Recharge Forming Water-Table Mound | Composite Waste Sites | Examples of Type of Contaminant | Remarks |
|---|---|---|---|---|---|---|---|
| | Dilution | Decay | Sorption | | | | |
| H | Yes, suggestive of nearly homogeneous porous material | Probably either decay or sorption or both | | No | No | Sewage, radioactive wastes | |
| I | Yes | Perhaps | Perhaps | No | No | — | Downgradient split in plume may be due to dense impermeable rock or great increase in sorptive materials |
| J | Slight | Not appreciable | Probably not appreciable | No | No | Chlorides, nitrates | Downgradient plume is due to shunting of contaminant to land surface at tail of upper plume and reinfiltration of contaminant |
| K | Yes, suggestive of nearly homogeneous porous materials | Either decay or sorption or both | | Yes, forming a water-table mound | No | Sewage, radioactive wastes | Irregularies in plume caused by changes in permeability and/or sorption |
| L | Yes, suggestive of nearly homogeneous materials | Either decay or sorption or both | | Yes, forming a water-table mound | No | Sewage, radioactive wastes | |
| M | Some in ground and stream | Not appreciable | Not appreciable | Yes, forming a water-table mound | — | Chlorides, nitrates | Deviation in plume due to impermeable zone |
| N | Yes | Either decay or sorption or both | | Yes, forming a water-table mound | No | Sewage, radioactive wastes | Contaminated water from three waste sites at right angles to ground water flow, merging to form a composite plume |
| O | Yes | Either decay or sorption or both | | No | Yes | Sewage, radioactive wastes | Contaminated water from two waste sites parallel to ground water flow, forming a compostive plume |
| P | Some | Either decay or sorption or both | | No | Yes | Sewage, radioactive wastes | Contaminated water from two waste sites at an angle with ground water flow, forming a composite plume |
| Q | Some | Either decay or sorption or both | | No | Yes | Sewage, radioactive wastes | Large composite plume formed by several waste sites |
| R | Yes | Either decay or sorption or both | | No | No | Sewage, radioactive wastes | Pumping well draws plume toward it, contaminated water is greatly diluted at well |

## 1.5 Guide to Major References on Contaminant Chemical Characteristics and Behavior in the Subsurface

As discussed in Chapter 8 (Section 8 1), the number of potential ground water contaminants is far too large to provide any detailed discussion of the chemical characteristics of specific contaminants Table 1-2 provides an index to major references containing more detailed information about specific chemical processes and chemical characteristics and behavior of contaminants in the subsurface Generally, only texts, edited volumes, and conference proceedings are indexed in Table 1-2, but some important review papers published in scientific journals are also included The references include (1) general chemical references, (2) compilations of degradation and other chemical constants for collections of chemicals, (3) references on ground water and vadose zone/soil chemistry, (4) references on trace elements and heavy metals, (5) references on toxic and other organic chemicals, and (6) references on microbial ecology and biodegradation

**Table 1-2 Index to Major References on Contaminant Chemical Characteristics and Behavior in the Subsurface**

| Topic | References |
|---|---|
| General Chemical References | ACS (annual), Budavari (1989), Dean (1992), Howard and Neal (1992), Lewis (1992a), Lide (1993), Perry and Chiltin (1973), Verschaueren (1983), *Hazardous Chemicals* ACGIH (1992), Armour (1991), Government Institutes (annual), Keith (1993), Lewis (1990, 1991, 1992b, 1993), NIOSH (1990), Occupational Safety Health Services (1990), Patnaik (1992), Shafer (1993), Shineldecker (1992), U S Coast Guard (1985), U S DOT (1990), U S EPA (1985, 1992a), *Agrochemicals* Fisher (1991), James and Kidd (1992), Kidd and James (1991), Montgomery (1993), Walker and Keith (1992) |
| Chemical Fate Data | Callahan et al (1979), Gherini et al (1988, 1989), Howard (1989, 1990a, 1990b, 1992, 1993), Howard et al (1991), Kollig et al (1991), Lyman et al (1990, 1992), Mabey et al (1982), Montgomery (1991), Montgomery and Welkom (1989), Ney (1990), Rai and Zachara (1984), U S EPA (1990), *Sorption/Partition Coefficients* Ellington et al (1991), Leo et al (1971), Sabli (1988), *Henry's Law Constants* Yaws et al (1991), *Hydrolysis Rate Constants* Ellington et al (1991) |
| Natural Baseline Chemistry | See Table 7-4 |
| Chemical/Contaminant Hydrogeology | *Texts* Devinny et al (1990), Domencio and Schwartz (1991), Fetter (1992), Matthess (1982), Mazor (1990), Palmer (1992), Tinsley (1979), *Papers* Back and Baedecker (1989), Back and Freeze (1983), Mackay et al (1985), *Subsurface Transport Processes* Gelhar et al (1985), Guarmaccia et al (1992-multiphase), Güven et al (1992a, 1992b), Knox et al (1993), Luckner and Schestakow (1991), U S EPA (1992b) |
| Vadose Zone/Soil Chemistry | Environmental Science and Engineering (1985), Yaron et al (1984), *Inorganic Chemicals* Bar-Yosef et al (1989), *Toxic Organic Chemicals* Dragun (1988), Gerstl et al (1989), Goring and Hamaker (1972), TNO/BMFT (1985, 1989) |
| Contaminant Sources | See Table 8-6 |
| Trace Elements/Heavy Metals | Bowen (1966), Hem (1964), National Research Council Canada (1976, 1978a, 1978b, 1979a, 1979b, 1981, 1982), Purves (1978), Thibodeaux (1979), Thornton (1983), Shaw (1989), *Soil* Alloway (1991), Aubert and Pinta (1978), Copenhaver and Wilkinson (1979a), Dotson (1991), Fuller (1977), Gibb and Cartwright (1987), Jacob (1989-selenium), Kabata-Pendias and Pendias (1984), Kotaby-Amacher and Gambrell (1988), Lisk (1972), McBride (1989), Page (1974), Rai and Zachara (1988), Zachara et al (1992), *Ground-Water* Allen et al (1990, 1993), Forstner and Wittman (1979), Kramer and Duinker (1984), Moore and Ramamoorthy (1984a), Rai and Zachara (1986), Singer (1973) |
| Toxic and Other Organic Chemicals | Lyman et al (1992), NAS (1972), Thibodeaux (1979), *Soil* Meikle (1972), Morril et al (1982), Nelson et al (1983), Overcash (1981), Sawhney and Brown (1989), *Ground Water* Borchardt et al (1977), Faust and Hunter (1971), Gerstl et al (1989), Moore and Ramamoorthy (1984b), *Halogenated Aliphatic Hydrocarbons* Britton (1984), Moore and Ramamoorthy (1984b), *Monocyclic Aromatic Hydrocarbons and Halides* Chapman (1972), Gibson and Subramian (1984), Moore and Ramamoorthy (1984b), Reinike (1984), *Phalate Esters* Ribbons (1984), Pierce et al (1980), *Polycyclic Aromatic Hydrocarbons* Moore and Ramamoorthy (1984b), Safe (1984), *Pesticides* Cheng (1990), Copenhaver and Wilkinson (1979b), Crosby (1973), Guenzi (1974), Hamaker (1972), Hamker and Thompson (1972), Haque and Freek (1975), Kearney and Kaufman (1972), Moore and Ramamoorthy (1984b), NAS (1972), Ou et al (1980), Rao and Davidson (1980), Somasundarum and Coats (1991), *Explosives* Environmental Science and Engineering (1985) |
| Biodegradation/ Contaminant Microbiology | Borchardt et al (1977), Gibson (1984), Kobayashi and Rittman (1982), Mitchell (1971), Rogers (1986), Scow (1982), Zehnder (1988), *Soil* Huang and Schnitzer (1986), Nelson et al (1983), Ramsey et al (1972), *Ground Water* Bitton and Gerba (1984), Bouwer and McCarty (1984), Ghiorse and Wilson (1988), Maki et al (1980), Tabak et al (1981), Wilson and McNabb (1983) |

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* See Introduction for information on how to obtain documents

# *Chapter 2*
# *Potentiometric Maps*

A water table or potentiometric map is one of the most basic and useful tools available for delineation of wellhead protection areas (WHPAs) This chapter covers basic concepts required for compilation and interpretation of ground water maps, and provides examples of common errors that result when these concepts or the characteristics of the site are not understood Chapter 5 discusses the actual process of hydrogeologic mapping for wellhead protection

## 2.1 Fundamental Hydrogeologic Concepts

### *2.1.1 Hydraulic Head and Gradients*

The water level in a well, usually expressed as feet above sea level, is the total head (ht), which consists of elevation head (z) and pressure head (hp)

$$ht = z + hp \qquad (2\text{-}1)$$

In an unconfined aquifer, pressure head (hp) equals zero at the water table surface because it marks the transition from negative pressure head in the vadose zone to a pressure head that may be either negative or positive in the saturated zone Serious inaccuracies in defining ground water flow paths may result from measuring water levels in monitoring wells without considering the pressure potential component

In a ground water *recharge zone*, the pressure head *decreases* with increasing depth (i e , hp in equation 2-1 is negative), in a *discharge* zone, the pressure head *increases* with depth This is illustrated in Figure 2-1 In the figure, the water level in well b is lower than the water table surface This is because the well is cased to a depth where it is actually measuring the pressure potential of the water table at well c Conversely, wells d and e in the discharge area are measuring the pressure potential of the water table upslope from the actual discharge area Wells d and e will flow like artesian wells even though there is no confining layer

Typically, wells are not installed at different depths in the same location to allow determination of whether the area is in a recharge or discharge zone Topography is a simple indicator, with discharge in topographically low areas and recharge in topographically high areas Plotting of depth-to-water table versus well depth for a number of wells in an area can also serve as an indicator of whether ground water is recharging or discharging Figure 2-2 defines the areas of such a plot where the scatter of points would be expected to fall in recharge areas and discharge areas

The hydraulic gradient (I or i) is measured as the change in water level per unit of distance along the direction of maximum head decrease It is determined by measuring the water level in several wells that measure the true unconfined water table or the same confined aquifer The hydraulic gradient is the driving force that causes ground water to move in the direction of decreasing total head, and is generally expressed in consistent units such as feet per foot For example, if the difference in water level in two wells 1,000 feet apart is 8 feet, the gradient is 8/1,000 or 0 008 The direction of ground water movement and the hydraulic gradient can be determined with information from three wells (Section 2 2 1)

### *2.1.2 Unconfined and Confined Aquifers*

Aquifers are broadly classified as *unconfined*, where the top of the saturated zone is at atmospheric pressure, and *confined*, where a slowly permeable geologic layer prevents upward flow when the hydraulic head is above the level of the confining layer, causing pressure head at the top of the aquifer to exceed atmospheric pressure Confining layers are also called *aquitards* Confined aquifers are classified as either *semiconfined (leaky)* or *highly confined*, depending on how permeable the confining layer is Aquifer classification is especially important in selecting methods for interpreting pump test data and serves as an indicator of the vulnerability to ground water contamination

In humid and semiarid regions, in particular, the water table in an unconfined aquifer generally conforms to the surface topography, although it usually has greater depth under hills than under valleys (Figure 2-1) The hydraulic gradient (Section 2 1 1) slopes away from divides and topographically high areas toward adjacent

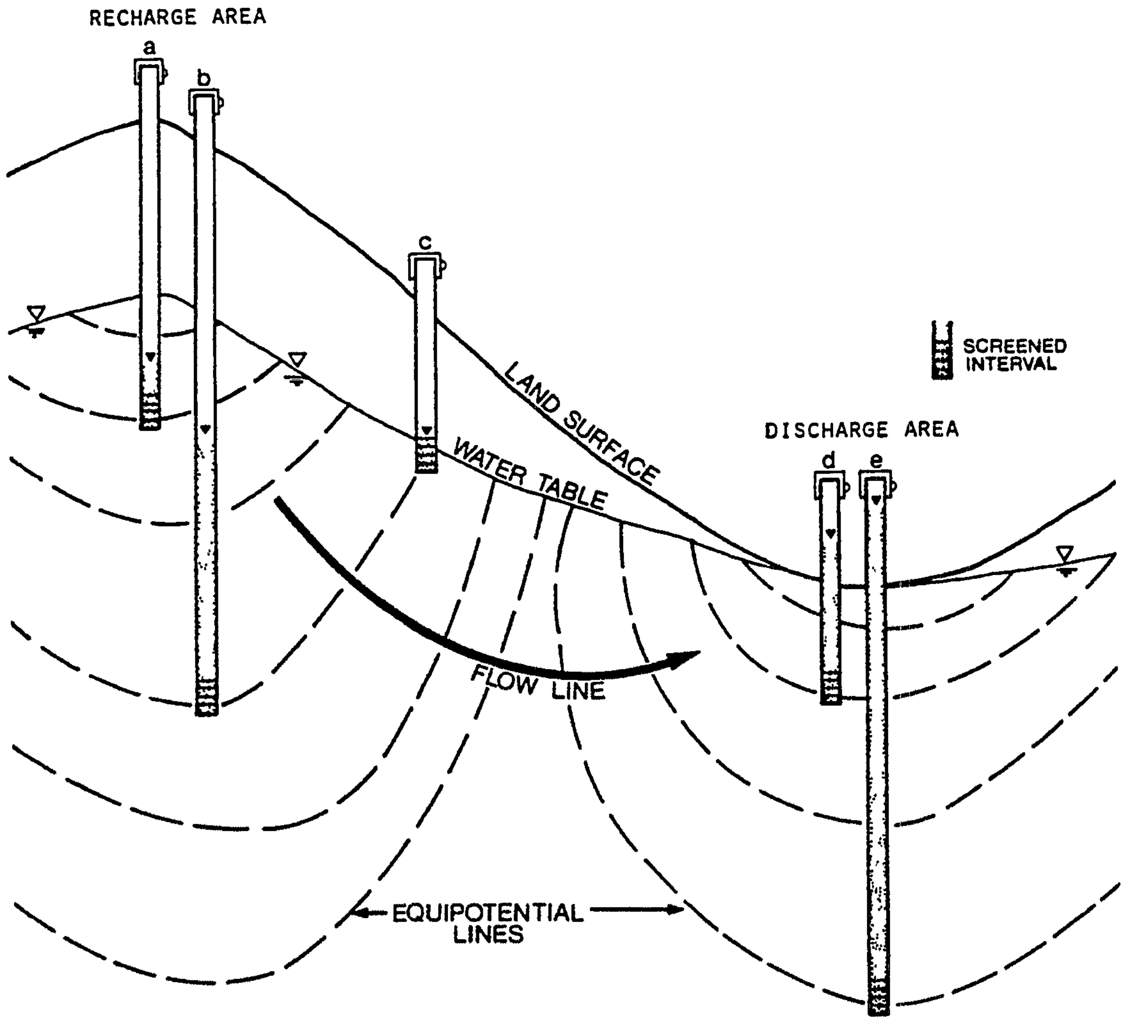


**Figure 2-1.** **Cross-sectional diagram showing the water level as measured by piezometers located at various depths The water level in piezometer c is the same as well b since it lies along the same equipotential line (from Mills et al , 1985).**

low areas, such as streams and rivers The high areas serve as ground water recharge areas, while the low areas are ground water discharge zones In general, the water table lies at depths ranging from 0 to about 20 feet in humid and semiarid regions, but often lies hundreds to thousands of feet deep in some desert environments Generally, surface streams and waterbodies such as swamps, ponds, lakes, and flooded excavations (abandoned gravel pits, highway borrow pits, etc ) can be considered surface expressions of the water table

Unconfined water tables may be either *perched* or *regional* Perched water tables rest on impermeable strata, below which unsaturated flow occurs (see Figure 2-3, upper right corner) In regional aquifers, all water moves by saturated flow until it reaches a point of surface discharge (Figure 2-3, Aquifer C) Aquifers A and B in Figure 2-3 exhibit characteristics of both perched and regional water tables Most of their water is part of the regional water, although it may travel part-way by unsaturated flow before reaching Aquifer C Some water, however, reaches the surface as springs, a common situation with perched aquifers

### 2.1.3 Heterogeneity and Anisotropy

Aquifers in which the hydraulic conductivity or other properties are nearly uniform are called *homogeneous,* those in which properties are variable are *heterogeneous* or nonhomogeneous If hydraulic conductivity at a given point in an aquifer differs in the vertical or horizontal directions, it is *anisotropic* If hydraulic conductivity is uniform in all directions, which is rare, the aquifer is *isotropic* Figure 2-4a illustrates four possible combinations of these characteristics The distinctions between these terms may not seem obvious at first, but a careful examination of this figure should provide a clearer understanding

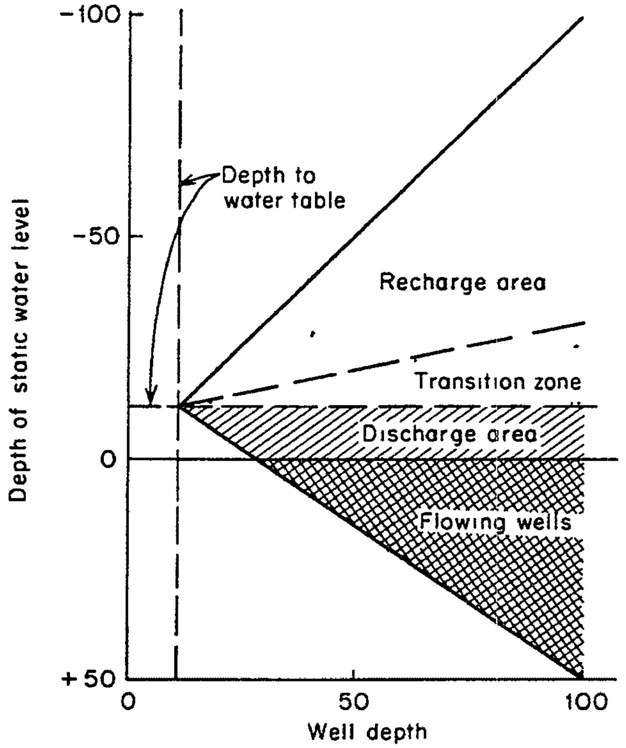


**Figure 2-2** Generalized plot of well depth versus depth to static water level (from Freeze and Cherry, 1979)

Figure 2-4b illustrates three different types of aquifer heterogeneity Because both unconsolidated and consolidated sedimentary strata are typically deposited in horizontal units (example B in the figure), hydraulic conductivity is generally greater horizontally than vertically by at least an order of magnitude The third example (C in the figure) is most likely to occur as a result of faulting or other tectonic activity Failure to consider heterogeneity and anisotropy can lead to significant underestimation of time of travel of contaminants and incorrect delineation of the direction of ground water flow

Aquifer heterogeneity is usually characterized by identifying vertical and lateral changes in the texture and other physical characteristics of soil, other unconsolidated material, and rock from borehole logs (Section 5 4 2) Anisotropy is usually characterized by aquifer tests (Section 3 3 5)

### *2.1.4 Porous Media Versus Fracture/Conduit Flow*

Ground water flows in the interconnected pore spaces between solid particles in an aquifer Most ground water flow equations assume that the water is flowing through material where the pore sizes are small enough that water flows without turbulence This is generally true in aquifers where *primary porosity* has not been altered by geologic or soil-forming processes that create secondary openings, often called *secondary porosity* Secondary openings are classified as fractures, which develop as a result of deformation and stress release by geologic processes, and as solution openings, which are formed from the enlargement of fractures by dissolution of soluble minerals such as carbonate in limestone (Figure 2-5)

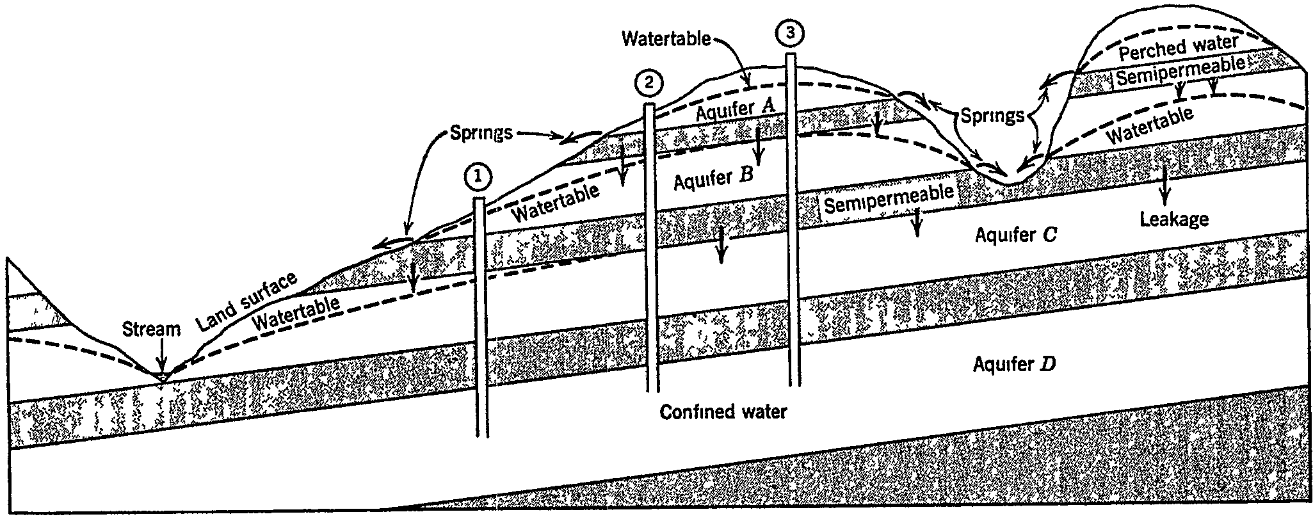


**Figure 2-3** Confined, unconfined, and perched water in a simple stratigraphic section of sandstone and shale (from Davis and DeWiest, 1966)

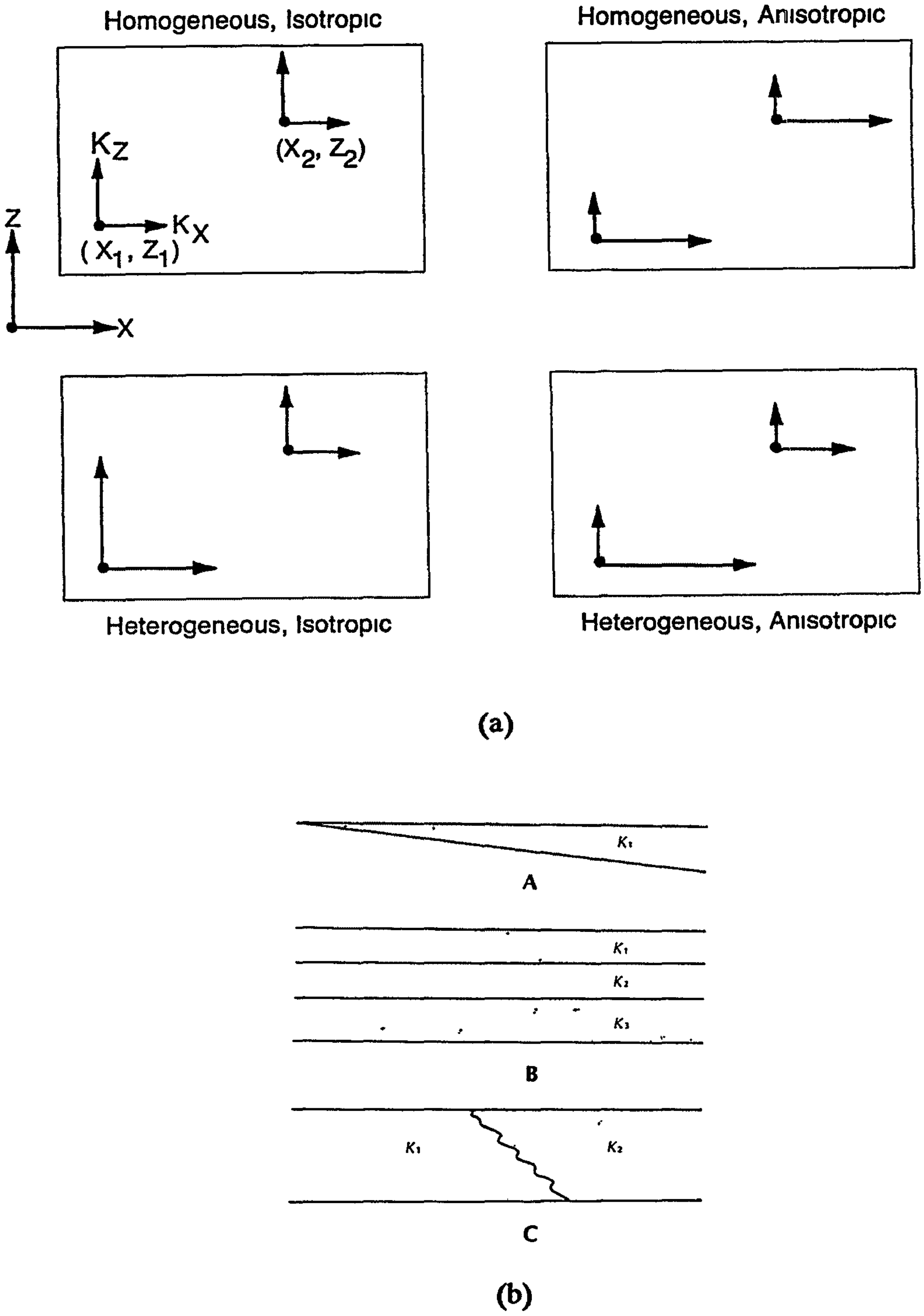


**Figure 2-4** Heterogeneity and anisotropy (a) four possible combinations (from Freeze and Cherry, 1979), (b) three types of aquifer heterogeneity—(A) varying thickness, (B) layers with differing hydraulic conductivity, and (C) lateral changes in hydraulic conductivity (from Fetter, 1980)

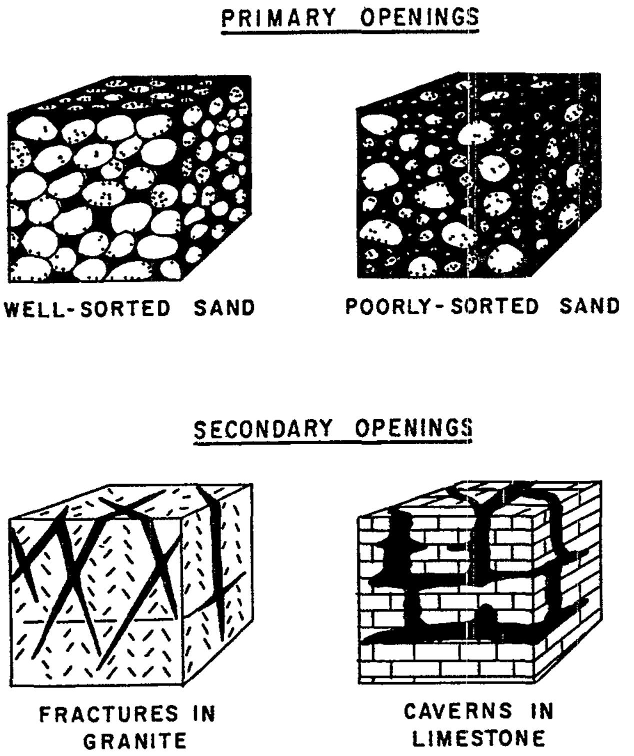


**Figure 2-5** **Examples of primary and secondary porosity (from Heath, 1983)**

Flow in fractures is most significant in crystalline rocks (granites, various metamorphic rocks) because primary porosity of these rocks is very low Many consolidated sedimentary aquifers are fractured to varying degrees Aquifers where fracture flow is significant tend to be anisotropic Ground water flow directions in these aquifers may depart significantly from the directions indicated by potentiometric surface maps Analysis of pump test data in fractured rocks requires special care because most analytical solutions assume porous-media flow Fractures are typically narrow enough to prevent turbulent flow, however, making adaptation of ground water flow equations possible Fracture flow is a major contributor to macro-scale hydrodynamic dispersion, causing contaminants to move much more quickly in an aquifer than would be predicted by flow calculations based on primary porosity

Flow in cavernous limestones and dolomites is called *conduit* flow The subsurface channels can be large and continuous enough that the system is more like a series of interconnected pipes than a porous material As with crystalline rocks, primary porosity of limestones tends to be very low, so that most ground water flow is concentrated in fractures and solution channels Aquifers where conduit flow dominates are called *karst* aquifers Unlike fracture-rock aquifers, however, ground water flow in karst aquifers is often rapid enough that Darcy's Law (Section 3 1 3) is not valid The irregular shape of solution channels in these aquifers makes the use of conventional methods for analyzing pump test data and modeling ground water flow essentially useless Figure 2-6 illustrates the wide fluctuation in ground water levels that can occur in a karst aquifer Table B-2 in Appendix B identifies major references where more information can be obtained about karst geomorphology and hydrology

### *2.1.5 Ground Water Fluctuations*

Ground water levels fluctuate throughout the year in response to natural changes in recharge and discharge (or storage), changes in pressure, and artificial stresses Fluctuations brought about by changes in pressure are limited to confined aquifers Most of these changes are short-term and are caused by loading, such as by a passing train compressing the aquifer, or by an increase in discharge from an overlying stream Others are related to changes in barometric pressure, tides, and earthquakes Languth and Treskatis (1989) describe an unusual situation where a pumping test in a semiconfined aquifer system temporarily increased water levels in observation wells tapping the overlying confining bed instead of resulting in the usual immediate lowering None of these fluctuations reflect a change in the volume of water in storage Table 2-1 summarizes 13 mechanisms that lead to fluctuations in ground water levels

Water level fluctuations in confined aquifers can be characterized by the *barometric efficiency,* the ratio of change in head to change in atmospheric pressure This ratio usually falls in the range of 0 20 to 0 75 (Freeze and Cherry, 1979) The possibility of using barometric efficiency to estimate the storage properties of confined aquifers was first suggested by Jacob (1940) Use of barometric efficiency to estimate a range of aquifer properties, including storage coefficient, transmissivity, and bulk elastic properties, has been reported in a number of relatively recent papers (see Table 2-2)

Fluctuations that involve changes in storage are generally more long lived Most ground water recharge takes place during the spring and causes the water level to rise Following this period of a month or two, the water level declines in response to natural discharge, largely to streams Although the major period of recharge occurs in the spring, minor events can happen any time it rains A number of human activities cause long-term fluctuations in ground water levels Ground water pumpage reduces ground water levels, activities such as agricultural irrigation, artificial recharge, leakages from ponds, lagoons and landfills tend to cause localized increases in ground water levels Deep well injection into confined aquifers causes elevation in the potentiometric surface

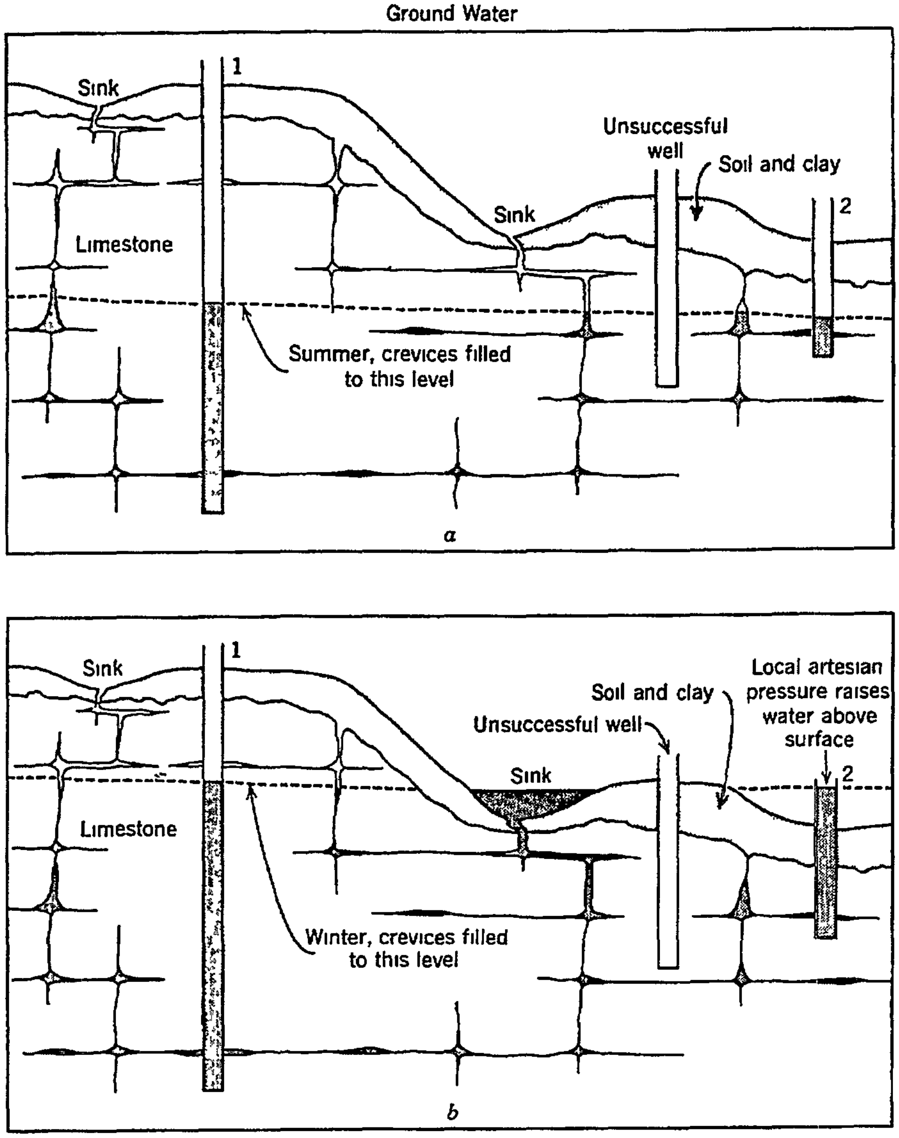


**Figure 2-6. Diagram of karst aquifer showing seasonal artesian conditions (from Walker, 1956)**

Evapotranspiration effects on a surficial or shallow aquifer are both seasonal and daily Plants, serving as minute pumps, remove water from the capillary fringe or even from beneath the water table during hours of daylight in the growing season This results in a diurnal fluctuation in the water table and stream flow

Table 2-3 summarizes typical natural conditions affecting ground water fluctuations in response to (1) freezing, (2) moisture regime, (3) surface drainage and degree of slope, and (4) thickness of the zone of aeration All these factors need to be considered in compiling data on water levels in wells when preparing potentiometric surface maps Table 2-2 provides an index to references that provide more detailed information on mechanisms that cause water level fluctuations

### *2.1.6 Ground Water Divides and Other Aquifer Boundaries*

In surface hydrology, a drainage divide forms the boundary between two watersheds Ground water drainage basins are similar to surface watersheds, except that they are defined by contour of equal hydraulic head (equipotential lines) rather than topographic contours In unconfined, homogenous, isotropic aquifers, these contours generally follow the surface topography, albeit with a more subdued gradient (see Figure 2-1) However, topography is only one of many factors that influence the location of ground water divides and the flow of water within a basin Defining a well's *zone of contribution* (Section 4 1 4) is a major focus of the wellhead protection process Consequently, an understanding of the *boundary conditions* in an aquifer is essential, both in

**Table 2-1 Summary of Mechanisms That Lead to Fluctuations in Ground Water Levels**

| | Unconfined | Confined | Natural | Man-Induced | Short-lived | Diurnal | Seasonal | Long-term | Climatic Influence |
|---|---|---|---|---|---|---|---|---|---|
| Ground water recharge | x | | x | | | | x | | x |
| Air entrapment during recharge | x | | x | | x | | | | x |
| Evapotranspiration | x | | x | | | x | | | x |
| Stream bank storage effects | x | | x | | | | x | | x |
| Tidal effects near ocean | x | x | x | | | x | | | |
| Atmospheric pressure effects | x | x | x | | | x | | | x |
| Confined aquifer external loading | | x | | x | x | | | | |
| Earthquakes | | x | x | | x | | | | |
| Ground water pumpage | x | x | | x | | | | x | |
| Deep-well injection | | x | | x | | | | x | |
| Artificial recharge/leakage | x | | | x | | | | x | |
| Agriculture irrigation/drainage | x | | | x | | | | x | x |
| Geotechnical drainage | x | | | x | | | | x | |

Source Adapted from Freeze and Cherry (1979)

**Table 2-2 Index to References on Water Level Data Interpretation and Flow Net Analysis**

| Topic | References |
|---|---|
| *Potentiometric Maps* | |
| Water Level Fluctuations | Andreason and Brookhart (1963—reverse fluctuations), Freeze and Cherry (1979), Kohout (1960—effects of salt water), Languth and Treskatis (1989), Moench (1971), Rockaway (1970), Sayko et al (1990), Walton (1963), Weiss-Jennemann (1991—offsite effects), Winograd (1970), *Barometric Effects* Peck (1960), Todd (1980), Turk (1975), Weeks (1979) |
| Data Interpretation | Blanchard and Bradbury (1987), Chapus (1988), Crouch (1986), Davis and DeWiest (1966), Fetter (1981), Henning (1990), Hoeksma et al (1989), Rockaway (1970), Saines (1981), Stallman (1956), Struckmeier et al (1986) |
| Confined Aquifer Barometric Efficiency | *Determination* Clark (1967), Davis and Rasmussen (1993), *Aquifer Transmissivity/Storage Coefficient* Evans et al (1991), Furbish (1991), Jacob (1940), Ritzi et al (1991), Rojstaczer (1988), *Aquifer Bulk Elastic Properties* Domenico (1983), Evans et al (1991), Rojstaczer and Agnew (1989) |
| *Flow Net Analysis* | |
| General | Nelson (1960, 1961), Scott (1992) |
| Case Studies | Hollet (1985), Hunt and Wilson (1974), Rice and Gorelick (1985) |

hydrogeologic mapping (Chapter 5) and the use of models (Chapter 6) for delineating WHPAs

As noted above, a ground water divide is one of the most important boundaries for delineating a well's zone of contribution Figure 2-3 illustrates several ground water divides Infiltrating water entering the aquifer flows to a discharge point determined by where the water enters the aquifer (which side of the divide) Note that the topographic divide for Aquifer A does not quite coincide with the ground water divide due to the dip of the sediments

Figure 2-7 illustrates more than 40 boundary conditions that may define the edges of a ground water drainage area These boundary conditions are classified as (1) *barrier boundaries*, created by geologic or other materials of contrasting (lower) permeability compared to the aquifer, (2) *permeable recharge* boundaries, and (3) *permeable discharge* boundaries Figure 2-7 further classifies boundary conditions according to whether they represent head conditions or flow conditions It also shows the number of dimensions required to represent the condition (1) points (one-dimensional), (2) lines (two-dimensional), and (3) areas (three-dimensional) These distinctions become important when analytical and numerical ground water models are selected and used (Chapter 6)

**Table 2-3 Factors and Natural Conditions Affecting Natural Ground Water Fluctuations**

| Factor/Zone | Ground Water Conditions and General Characteristics of Water Level Fluctuations |
|---|---|
| *Soil Freezing* | |
| 1 Permafrost areas | Two summer water level rises |
| 2. Uniform freezing in the soil zone at the land surface | Marked water level rise in the spring, followed by water level recession until autumn A second smaller water level rise in autumn, followed by gradual decline until spring |
| 3 Sporadic freezing of the zone of aeration | Water level rises mainly in the winter |
| 4 Complete absence of soil freezing | Water level rises during rainy season |
| *Soil Moisture Regime* | |
| 1. Region of high moisture | The amount of precipitation is higher than evapotranspiration Water levels affected rapidly by small rains and small temperature variations Small amplitude of water fluctuations |
| 2 Region of moderate moisture | As water table is at greater depth than in zone 1, amplitudes of water level fluctuations are more distinct and greater than in zones 1 and 3 |
| 3. Region of small moisture | Evapotranspiration is a dominant factor in water level fluctuations |
| *Surface Drainage and Degree of Slope* | |
| 1 Well developed drainage (generally mountainous topography) | High runoff and low infiltration to ground water Water level fluctuation amplitude may be high |
| 2 Moderately developed drainage (generally uplands) | Moderate runoff and infiltration to ground water Water level fluctuation amplitudes are lower than in zone 1 but higher than in zone 3 |
| 3 Poorly developed drainage (generally plains and valley bottoms) | Low runoff and high infiltration to groundwater Water table at shallow depth High evapotranspiration |
| *Thickness of Zone of Aeration* (d) | |
| 1. *d* is less than 0 5 m | Water level fluctuations of small amplitude Evapotranspiration from the water table prevails over spring discharge |
| 2. *d* is between 0 5 and 4 m thick. | Water level fluctuations of larger amplitude than in zone 1 Spring discharge prevails over evapotranspiration |
| 3 *d* is greater than 4 m | Water level fluctuations of small amplitude and evapotranspiration might be of limited importance |

Source Adapted from Brown et al (1983)

### 2.1.7 Gaining and Losing Streams

From a hydrogeologic point of view, there are three major stream types—ephemeral, intermittent, and perennial. Stream type is determined by the relation between the water table and the stream channel Consequently, observation of the character of water flow in a stream provides useful information about ground water in the area

An *ephemeral* stream owes its entire flow to surface runoff. It may have no well-defined channel and the water table consistently remains below the bottom of the channel (Figure 2-8, A-A') Water leaks through the channel into the ground, recharging the underlying strata

*Intermittent* streams flow only part of the year, generally from spring to midsummer, as well as during wet periods During dry weather, these streams flow only because ground water discharges into them when the water table rises above the base of the channel (Figure 2-8, B-B'). Eventually, sufficient ground water discharges throughout the basin to lower the water table below the channel, which then becomes dry This reflects a decrease in the quantity of ground water in storage During late summer or fall, a wet period may temporarily raise the water table enough for ground water to discharge into the stream Thus, during part of the year the floodplain materials are full to overflowing, causing the discharge to increase in a downstream direction At other times, water will leak into the ground, reducing the discharge

*Perennial streams* flow year-round Typically, the water table is always above the stream bottom Hence, ground water is discharged to the surface and streamflow increases downstream (Figure 2-8, C-C') A stream in which the discharge increases downstream is called a *gaining stream* A stream in which the discharge decreases downstream due to leakage is called a *losing stream* In a losing stream, the water table is below the bottom of the stream, but the amount discharged from the stream to the subsurface is not enough to eliminate surface flow during dry periods During wet periods,

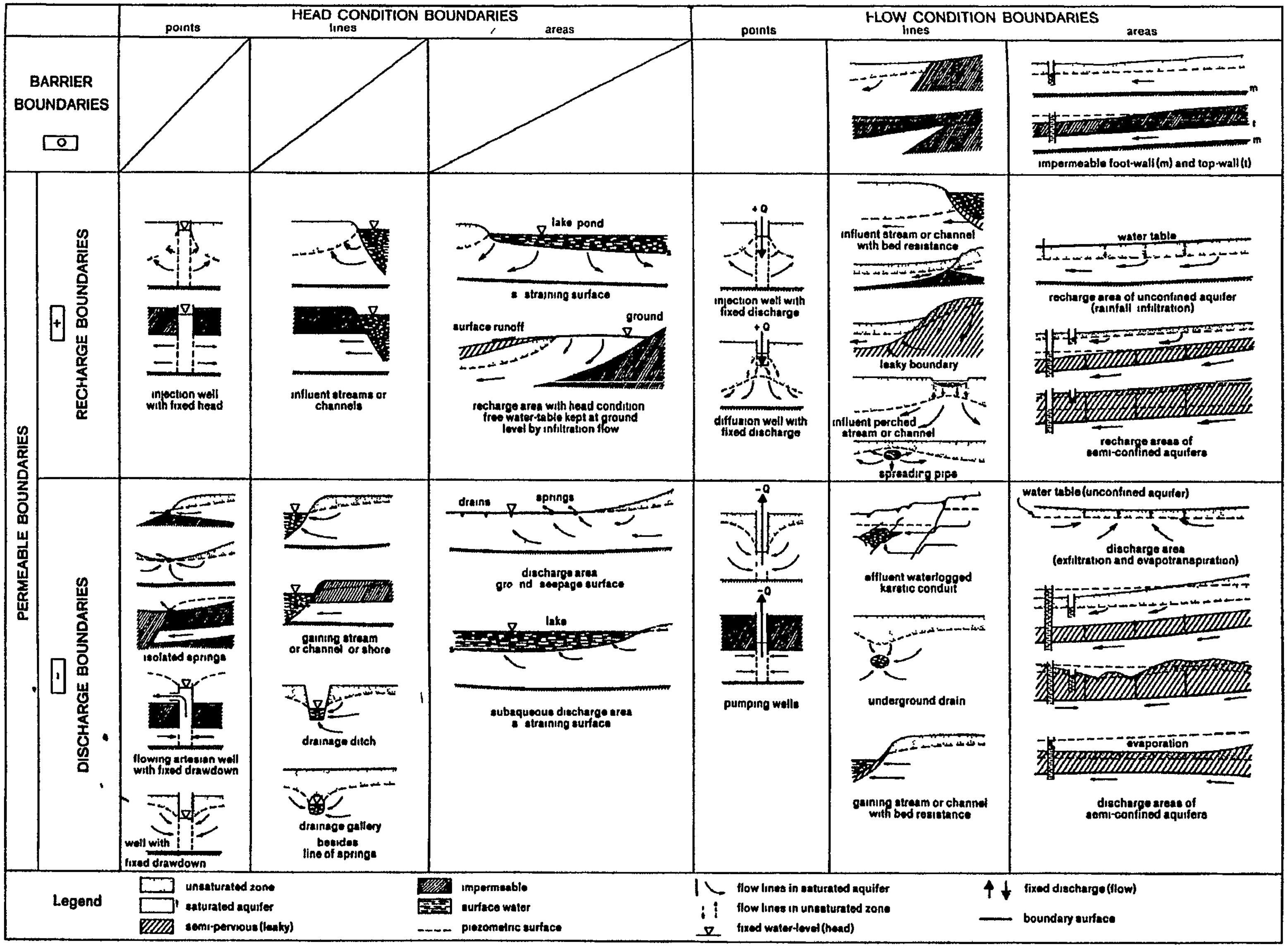


Figure 2-7 Types of aquifer boundary conditions (from Struckmeier et al , 1986, after Castany and Margat, 1977)

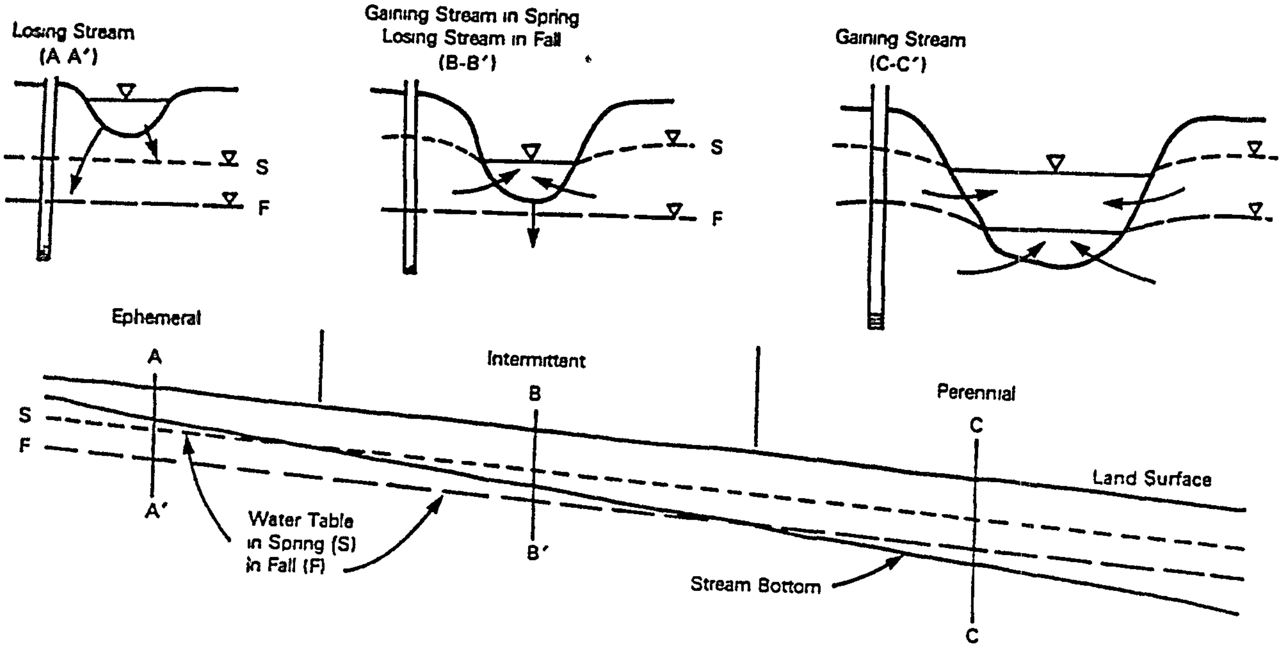


**Figure 2-8 Relationship between water table and stream type (from U S EPA, 1990)**

surface flow in perennial streams comes from a mixture of surface runoff and ground water inflow During dry periods, the flow of perennial streams comes primarily from ground water discharge and is called the *base flow*

## 2.2 Preparing and Using Potentiometric Maps

### 2.2.1 Plotting Equipotential Contours

The hydraulic gradient can be graphically shown by plotting either unconfined water table levels or pressure potentials (if the pressure head of a confined aquifer is high enough to raise the total head above the ground surface) on a map A *water table* map usually refers to the hydraulic gradient of an unconfined aquifer, and a *piezometric* (pressure) surface map usually refers to the pressure potentials of confined aquifers Either type of map is called a *potentiometric* map In practice, the terms "water table," "potentiometric," and "piezometric" are often used interchangeably Struckmeier et al (1986) provide a good review of other types of hydrogeological maps and graphical representation of ground water systems.

The contours on a potentiometric map are called *equipotential* lines, indicating that the water has the "potential" to rise to that elevation In the case of a confined aquifer, however, it cannot reach that elevation unless the confining unit is perforated by a well Potentiometric surface maps are essential to any ground water investigation, because they indicate the direction in which ground water is moving, and provide an estimate of the gradient, which controls ground water velocity As discussed in Section 2 3 2, interpretations of flow directions in aquifers must take into account anisotropy and heterogeneity

Potentiometric maps provide some information on aquifer homogeneity, provided that well data points are close enough to allow reasonably accurate contouring A map of a uniform, homogeneous aquifer will have equally spaced equipotential lines and no dramatic changes in hydraulic gradient, because ground water is moving at about the same speed at all points in the aquifer Irregularly spaced contours and differing hydraulic gradients in different areas of the aquifer indicate lateral changes in aquifer properties

Preparing a potentiometric map involves plotting water level measurements on a base map and then drawing contours In isotropic, porous-media aquifers, the direction of ground water flow is perpendicular to the ground water contour lines The next section on flow nets describes in more detail how contour maps can be used to infer the direction of ground water flow A minimum of three points is required to determine the general direction of ground water flow Figure 2-9 shows a manual graphical depiction of ground water contours, drawn based on water elevations in three wells The difference in elevation between each well was calculated and divided into the distance between the wells This distance was scaled on each line as tick marks that represent a change in elevation of one-tenth of a foot The lines connecting the points of equal elevation (27 0 and 27 5 feet in Figure 2-9) are potentiometric contours Ground

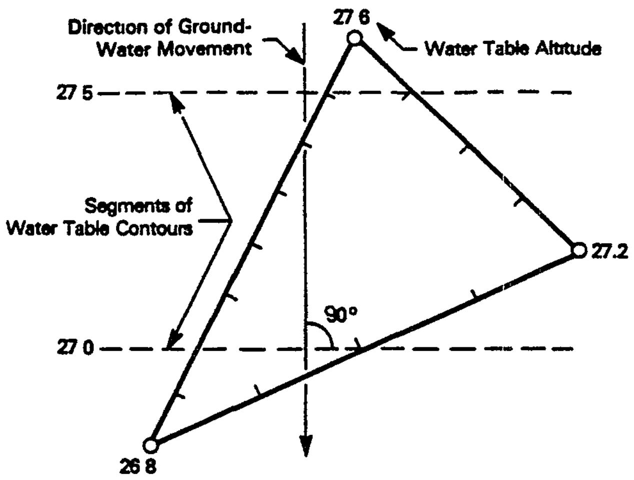


Figure 2-9 The generalized direction of ground water movement can be determined by means of the water level in three wells of similar depth (from Heath and Trainer, 1981)

water flow direction is on the path line perpendicular to the contours

Figure 2-10 illustrates a slightly different approach to determining the direction of ground water flow from three well points Steps in this solution involve

1 Identifying the well that has the intermediate water level

2 Calculating the position between the well having the highest head and the well having the lowest head at which the head is the same as that in the intermediate well

3 Drawing a straight line between the intermediate well and the point identified in step 2 This line represents a segment of the water level contour along which the total head is the same as that in the intermediate well

4 Drawing a line perpendicular to the water level contour and through the well with the lowest (or highest) head This indicates the direction of ground water movement in an isotropic aquifer

5 Dividing the difference between the head of the well and that of the contour by the distance between the well and the contour This gives the hydraulic gradient

A large number of well measurements is needed to develop an accurate potentiometric surface map Geostatistical methods allow the estimation of water table elevations in unsampled locations where the water table is approximately parallel to the ground surface (Hoeksma et al , 1989)

The most important consideration in preparing a potentiometric map is that the water level measurements should describe a single flow system in an aquifer Section 2 3 1 describes in detail some common pitfalls in preparing potentiometric maps Worksheet 2-1 provides a form for compiling well information used to de-

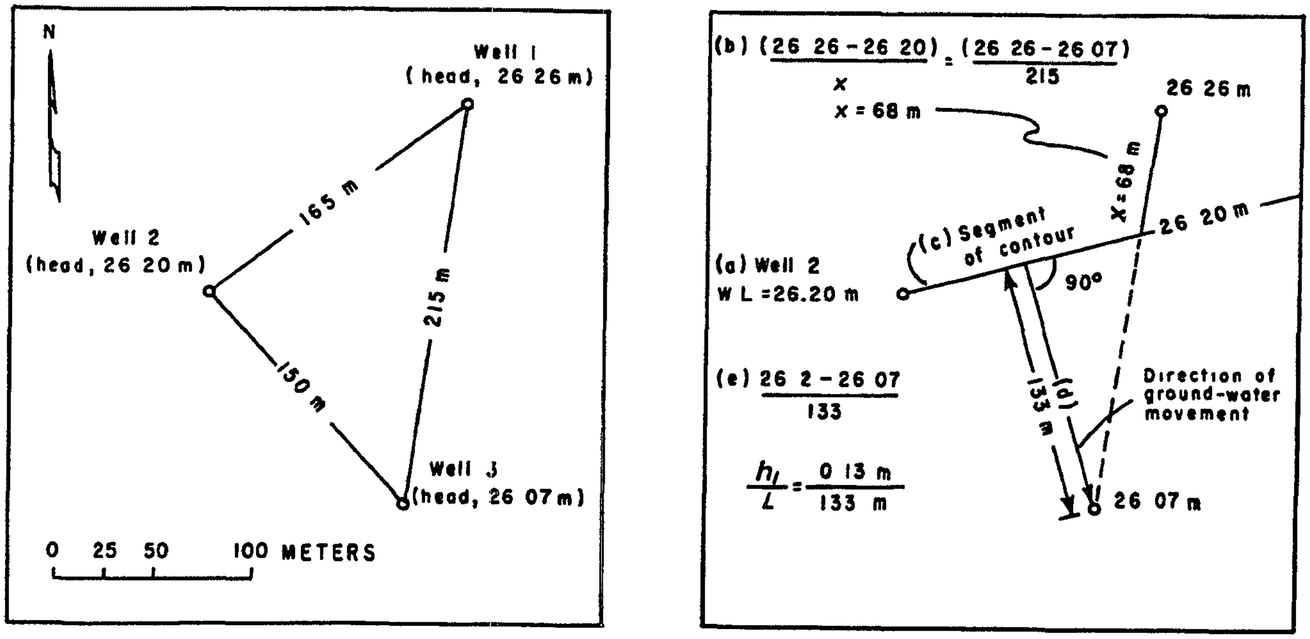


Figure 2-10 Alternative procedure for determination of equipotential contour and direction of ground water flow in homogeneous, isotropic aquifer (from Heath, 1983)

## Worksheet 2-1. Water Well Data

**Well Data (Attach drillers log):**

Location: Screen Interval Depth ________

Water level data

Date ______ ______ ______ ______ ______ ______ ______ ______ ______ ______ ______

Level (ft ) ______ ______ ______ ______ ______ ______ ______ ______ ______ ______ ______

**Pumping Characteristics:**

Current non-pumping water level (feet below ground surface) _____
Current pumping rate (gpm) ____
Typical pumping duration (hours/day) ____
Current pumping water level (feet below ground surface) ____
Typical nonpumping duration (hours/day) ____
Estimated annual pumpage (pumping rate x hours/day x 365 x 60) = __________
Specific capacity (pumping rate/(non-pumping water level minus pumping water level) = _____ gpm/ft drawdown*
Estimated transmissivity (specific capacity x 2000) = ____________ gpd/ft*
Estimated hydraulic conductivity (transmissivity/aquifer thickness) = ________ gpd/$ft^2$*

**Aquifer Material:**

Unconsolidated Sediments
- ___ Gravel
- ___ Coarse sand
- ___ Medium to fine sand
- ___ Silt
- ___ Clay, till

Consolidated Sediments
- ___ Limestone, Dolomite
- ___ Coarse, medium sandstone
- ___ Fine sandstone
- ___ Shale, siltstone

Volcanic rocks
- ___ Basalt
- ___ Acid volcanic rocks

Crystalline Rocks
- ___ Granite/gabbro
- ___ Metamorphic

| | **Porosity (%)** | Ksat** (________) | **Specific Yield (%)** |
|---|---|---|---|
| Low | ________ | __________ | _______ |
| Average | ________ | __________ | _______ |
| High | ________ | __________ | _______ |
| Sources | | | |
| Table(s) | ________ | __________ | _______ |
| Figure(s) | ________ | __________ | _______ |

**Aquifer Classification:**

| *Unconfined* | *Confined* | *Number of Aquifers* |
|---|---|---|
| ___ Perched | ___ Semiconfined | ___ One |
| ___ Regional | ___ Highly confined | ___ Two |
| | | ___ > Two (# _____) |

## Worksheet 2-1 (Continued)

### Aquifer Boundaries

*Recharge Boundaries*
___ Interfluv
___ Losing stream
___ Lake, pond
___ Sinkholes (karst)
___ Injection well

___ Ground Water Divide

*Discharge Boundaries*
___ Artesian/pumping well
___ Gaining stream
___ Drainage ditch
___ Tile drains
___ Springs
___ Lakes, ponds
___ Semiconfined aquifer leakage

### Expected water level fluctuations (see Table 2-2)

*Moisture regime*
___ High moisture (H)***
___ Moderate moisture (M)
___ Low moisture (L)

___ Well developed/steep (H)***
___ Moderate/upland (M)
___ Poor/flat, bottoms (L)

*Zone of Aeration (d)*
___ d  m (H)***
___ d = 0 5 to 4 m (M)
___ d 4 m (L)

*Diurnal/Intermittent Fluctuations*
___ Evapotranspiration
___ Tidal effects near ocean
___ Atmospheric pressure effects

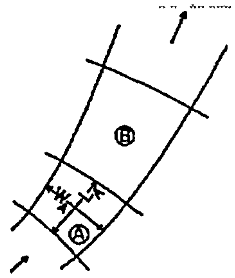
*Seasonal Fluctuations*
___ Ground water recharge area
___ Stream bank storage effects

*Long-Term Fluctuations*
___ Ground water pumpage
___ Deep-well injection
___ Artificial recharge
___ Pond, lagoon, landfill leakage
___ Agricultural irrigation
___ Agricultural drainage
___ Geotechnical drainage (open pit mines)

* See Section 3 2 3 for additional discussion of this simple well test for estimating hydraulic conductivity
** Saturated hydraulic conductivity (specify units)
*** Rating for expected degree of fluctuation  H = high, M = moderate, L = low

velop an potentiometric map This information may prove helpful in evaluating individual well elevations that appear to be anomalous This worksheet also includes (1) a section for recording information on pumping characteristics of the well, which can be used to estimate transmissivity and hydraulic conductivity from specific capacity (Section 3 2 3), (2) a section for recording estimated aquifer properties (porosity, saturated conductivity, and specific yield) from the aquifer matrix type (Section 3 2 2), (3) a section on aquifer classification and boundaries for guidance in the selection of simple analytical methods (Section 4 4 and 4 5) or computer models (Section 6 4) for delineation of WHPAs, and (4) a section for recording information characterizing the expected degree of water level fluctuation in a well

### Sidebar 2-1. Distribution of Transmissivity From Flow Nets



Horizontal flow within a segment in a flow net can be calculated as (refer to figure above):

$$q_A = T_A \Delta H_A W_A / L_A$$

where

$q_A$ = flow in segment A ($m^3$/day)
$T_A$ = transmissivity in segment A ($m^2$/day)
$W_A$ = average width of segment
$L_A$ = average length of segment
$\Delta H_A$ = drop on ground water level across segment

The flow in the next segment B is similarly calculated as:

$$q_B = T_B \Delta H_B W_B / L_B$$

Assuming that there is no flow added between segments by recharge (or that recharge is insignificant), $q_A = q_B$, allowing combination of the two above equations and solving to $T_B$ as follows

$$T_B = T_A(L_B W_A \Delta H_A / L_A W_B \Delta H_B)$$

which allows calculation of $T_B$ from $T_A$.

Measurement or estimation of transmissivity for one segment (Section 3.2) allows calculation of variations in T upgradient and downgradient. If variations in aquifer thickness are known, or can be estimated, for different segments, variations in hydraulic conductivity can also be calculated as follows:

$$K = T/b$$

where

K = hydraulic conductivity (m/day)
b = aquifer thickness (m)

### 2.2.2 *Flow Nets*

A potentiometric surface map can be developed into a flow net by constructing flow lines that intersect the equipotential lines or contour lines at right angles Flow lines are imaginary paths that trace the flow of water particles through the aquifer Although there are an infinite number of both equipotential and flow lines, the former are constructed with uniform differences in elevation between them, while the latter are constructed so that they form, in combination with equipotential lines, a series of squares A flow net carefully prepared in conjunction with Darcy's Law allows estimation of the quantity of water flowing through an area, and of the variability of transmissivity and hydraulic conductivity (Sidebar 2-1) Figure 2-11 illustrates plan and cross-section views of flow nets drawn for a gaining stream (2-11[1]&[2]) and a losing stream (2-11[3]&[4]) Plan view flow nets are a valuable tool in delineating the zone of contribution to a well Table 2-3 identifies references that provide additional information on flow net analysis and case studies that use this method

A standard flow net assumes that the aquifer is isotropic When an aquifer is anisotropic, commonly the case in unconsolidated and sedimentary aquifers, the actual direction of ground water flow will not be perpendicular to the equipotential contours Instead, the direction of flow will deviate from the perpendicular at an angle that depends on the ratio of the horizontal to the vertical hydraulic conductivity[1] Figure 2-12 illustrates how anisotropy in a fractured rock aquifer alters the direction of ground water flow compared to that expected in an isotropic aquifer

---

[1] The discussion here assumes that the aquifer is anisotropic in only two directions, with the horizontal conductivity greater than the vertical conductivity This situation is typical of horizontally layered sediments (Fetter, 1981) Anisotropy in three directions is possible, but not amenable to simple graphical solutions for determining flow direction Section 3 3 5 discusses methods for determining anisotropy in three dimensions

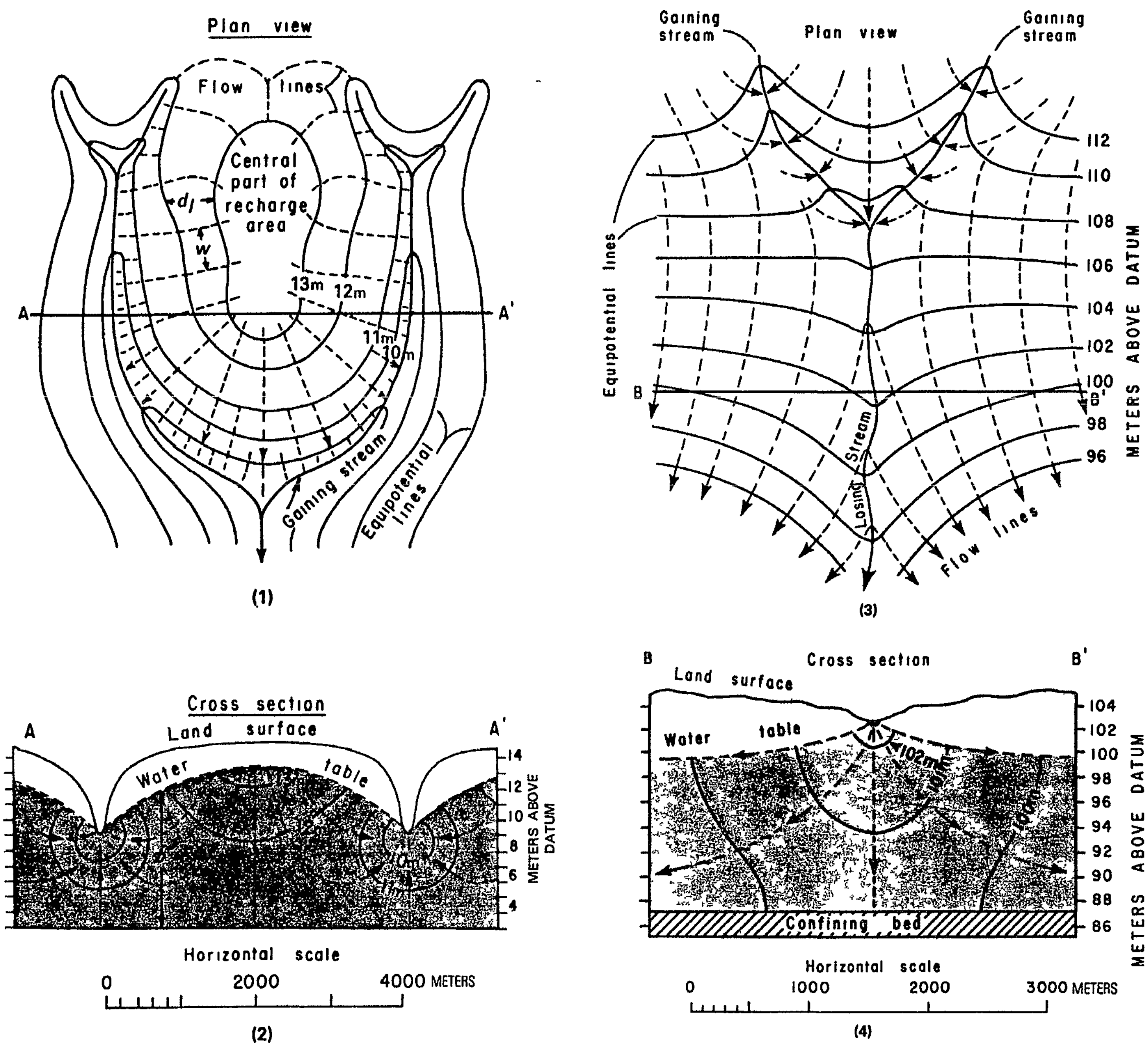


**Figure 2-11** Flow nets for gaining and losing streams (from Heath, 1983)

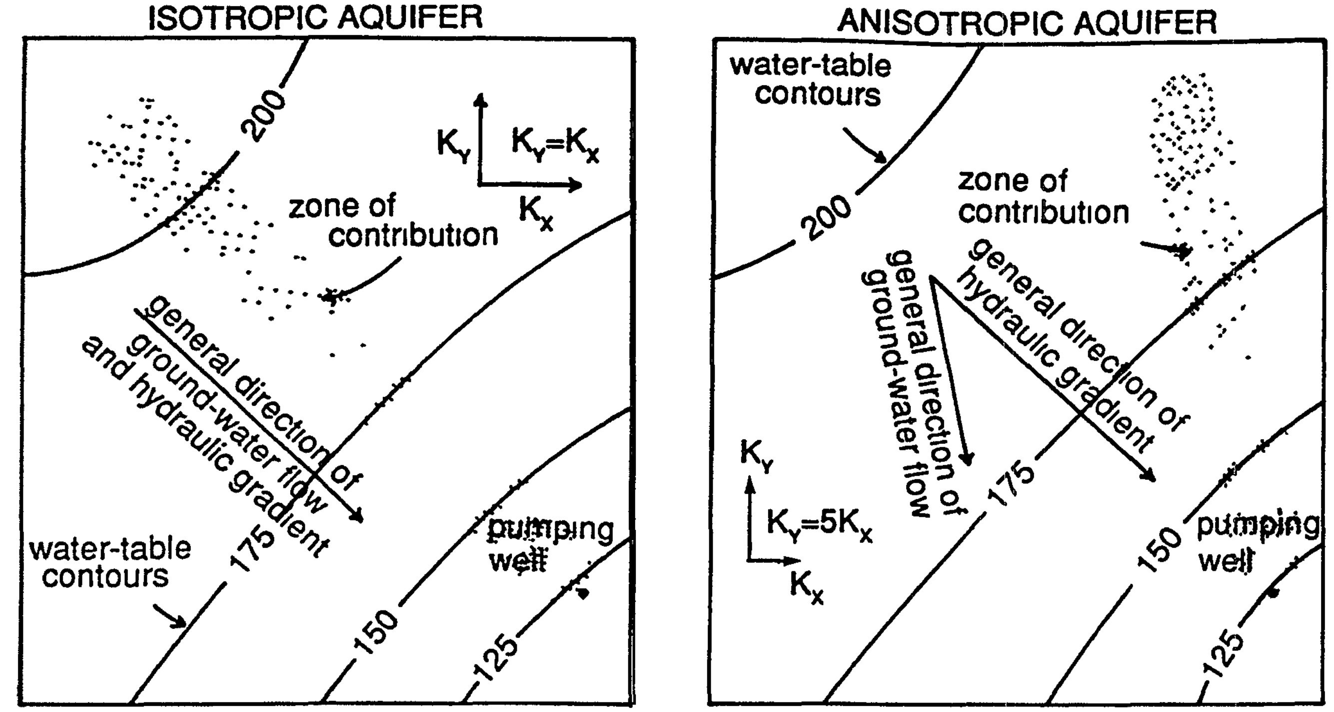


**Figure 2-12.** Effect of fracture anisotropy on the orientation of the zone of contribution to a pumping well (from Bradbury et al , 1991).

Several methods are available for determining the direction of flow lines where the degree of anisotropy is known Figure 2-13 illustrates a procedure for transforming a vertical anisotropic flow net to an isotropic section For potentiometric surface maps, Llakapoulos (1965) developed a graphical technique for determining this deviation This technique uses a "permeability tensor ellipse," which has semi-axes equal to the inverse square root of the principal permeability values Figure 2-14 illustrates the five-step sequence for using this method Fetter (1981) provides some additional guidance on using this technique Section 3 3 5 provides some guidance on how to determine directional components of hydraulic conductivity in an aquifer

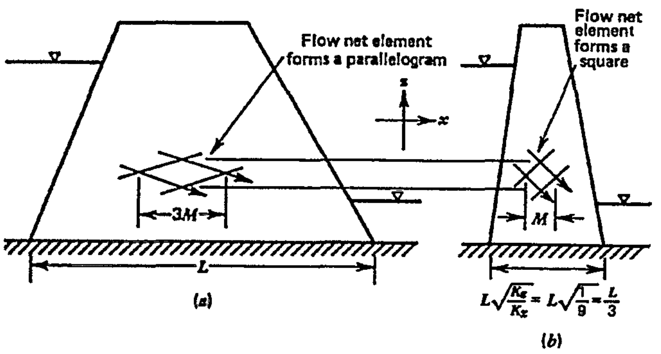
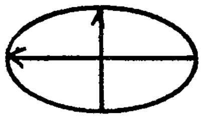


**Figure 2-13.** Illustration of slow net analysis for anisotropic hydraulic conductivity in an earth dam (a) true anisotropic section with $K_x = 9K_z$, (b) transformed isotropic section with $K_x = K_z$ (from Todd, 1980)

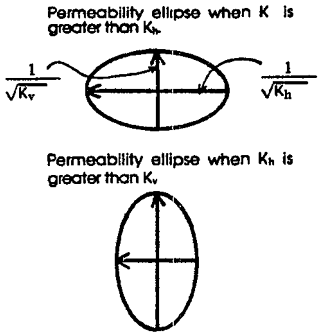
Figure 2-15a shows the effect of increasing anisotropy on the direction of ground water flow using permeability ellipses for $k_h/k_v$ ratios up to 9 6 Note that when the ratio is one (isotropic), a circle results, so that the flow direction is perpendicular to the equipotential line When the ratio is around 10 to 1 (not uncommon in sedimentary formations), the flow line diverges almost 45 degrees from the "expected" direction when the axis of the equipotential line is at a 45 degree angle to the axis of maximum permeability Flow direction in an anisotropic aquifer can be perpendicular to an equipotential line if the axis of greater permeability in a permeability ellipse and the equipotential line are parallel Figure 2-15b illustrates the effect of changes in the angle of the equipotential line with the axis of greater permeability

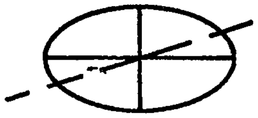
## 2.3 Common Errors in Preparation and Interpretation of Potentiometric Maps

Developing a potentiometric map is not as straightforward as preparing a topographic map An accurate potentiometric map requires enough well observations to develop water table contours that do not miss important features of the flow system Considerable interpretation and judgment may be required in developing contours when well data points do not seem to fit into a coherent pattern For example, if water level data from

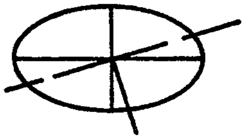


1 Construct a permeability ellipse

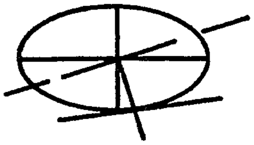




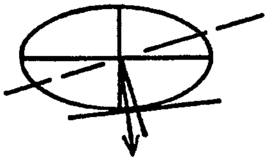
2 Draw the equipotential line as it is oriented to the permeability axes



3 Draw the hydraulic gradient vector perpendicular to the equipotential line



4 Draw a tangent to the ellipse at the point where the hydraulic gradient vector intersects the ellipse



5 Draw the flowline so that it passes through the origin of the ellipse and is perpendicular to the tangent

**Figure 2-14** **Steps in the determination of ground water flow direction in an anisotropic aquifer (from Fetter, 1981)**

wells are drawn from multiple sources, measurements in nearby wells may have been taken at different times of the year and may not be directly comparable On the other hand, if all the data have been collected so as to minimize effects of short-term or seasonal fluctuations, examination of individual well characteristics may yield explanations for anomalous data points For example, a single well data point that is far out of line with nearby wells may be tapping a different aquifer If an anomalous well data point cannot be readily explained as being unrepresentative for any reason, then further field investigation may be required to determine whether any localized hydrogeologic conditions are causing the anomaly

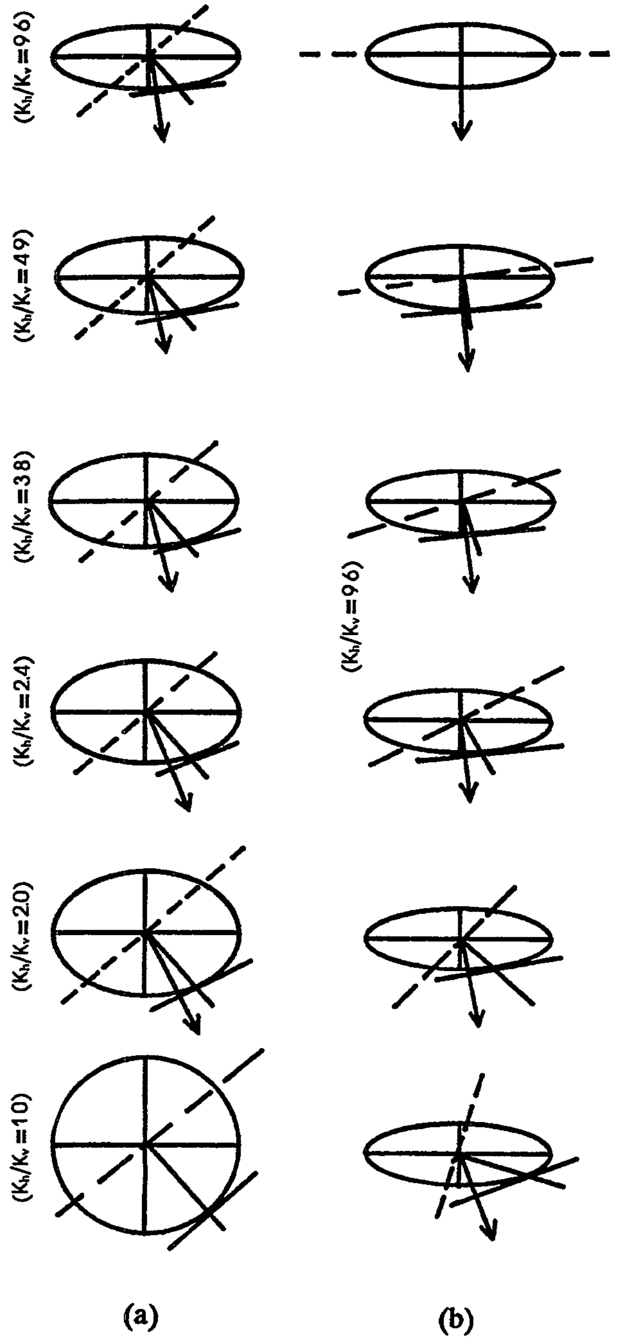
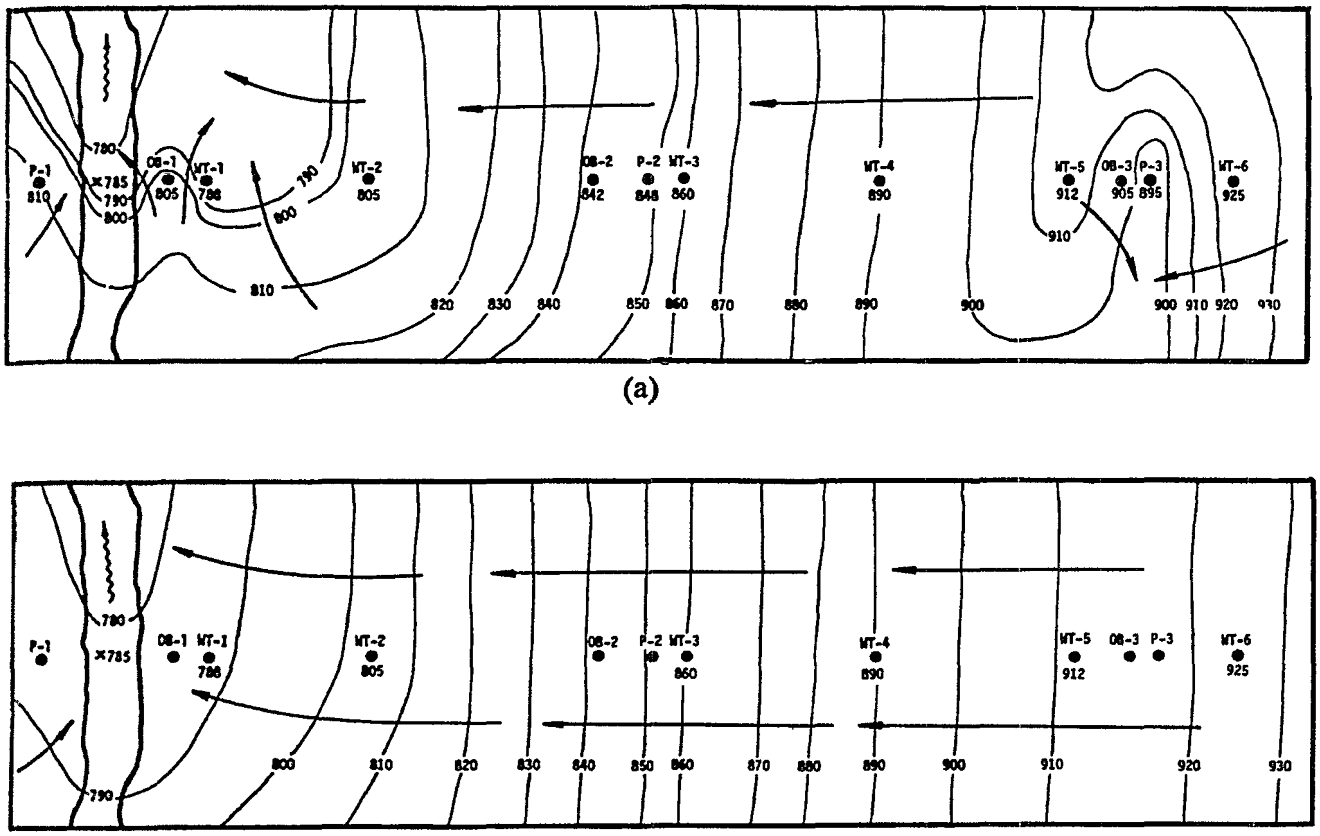


**Figure 2-15** **Effect of anisotropy on the direction of flow (a) changes in ratio of horizontal to vertical conductivity, (b) change in angle of equipotential line with axis of greater permeability (from Fetter, 1981)**

The rest of this chapter identifies common errors in contouring water level data and in interpreting the direction of ground water flow using a potentiometric map Filling out Worksheet 2-1 for each well in the area of hydrogeologic interest may help identify problematic wells that should not be used for contouring The information may also be useful in developing hydrogeologic interpretations of the resulting potentiometric map



(a)

(b)

**Figure 2-16.** **Effect of well level measurements in recharge and discharge areas (a) Incorrect contours using well measurements that do not reflect water table surface, (b) correct contours after elimination of nonrepresentative well level measurements (from Saines, 1981)**

### 2.3.1 Contouring Errors

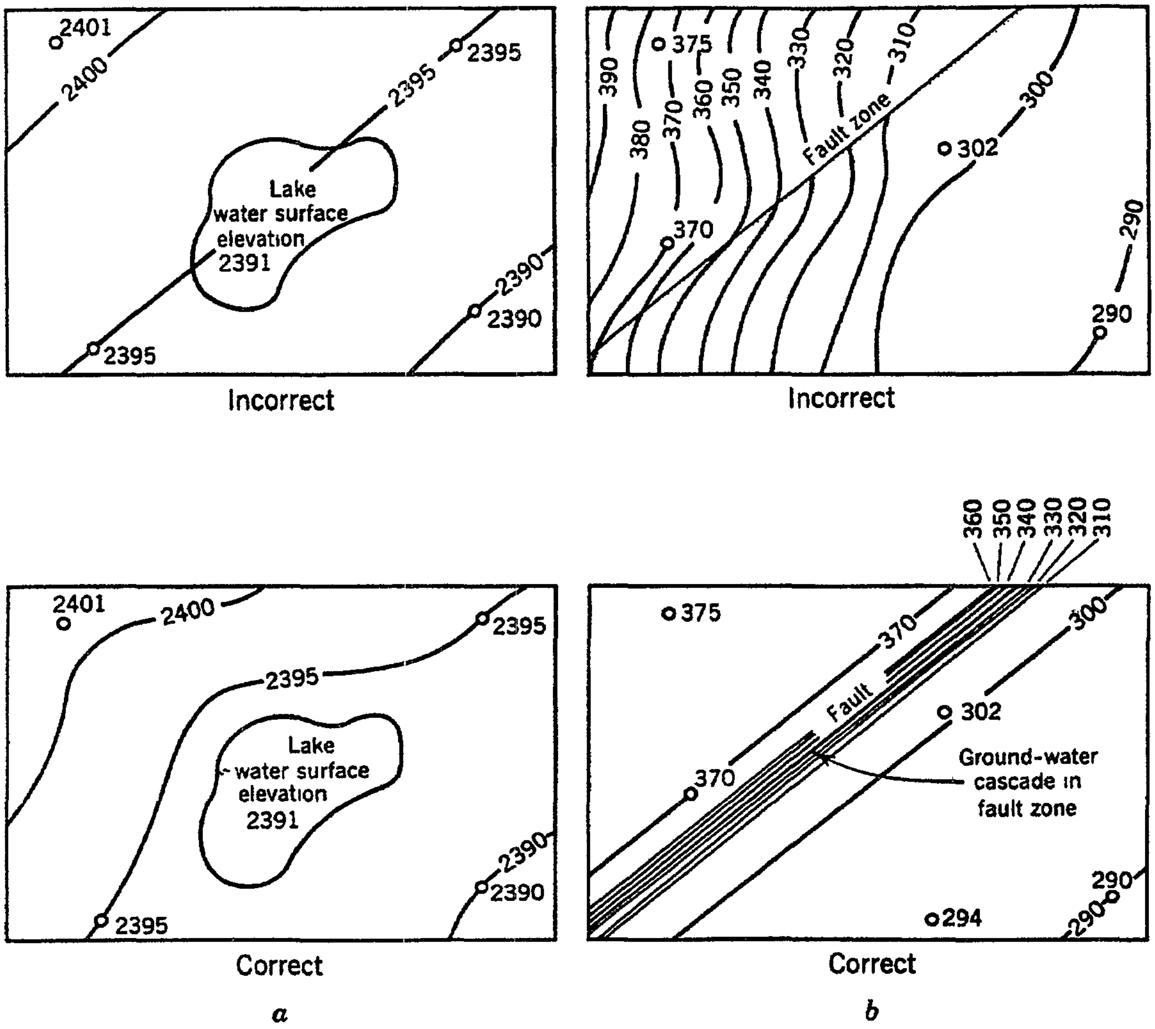
The starting point for a potentiometric map is a base map. The base map identifies well locations and water level elevations in the well and other surface hydrologic features, such as streams, rivers, and water bodies Drawing equipotential contours requires some skill and judgment Errors in contouring fall into two general categories· (1) failure to exclude data points that are not representative; and (2) failure to take into account subsurface features that change the distribution of potentiometric head as a result of aquifer heterogeneity or boundary conditions. The following are six situations in which contouring errors might occur

1. *Failure to exclude well measurements from wells cased below the water table surface in recharge and discharge areas* For example, only well c in Figure 2-1 gives an accurate reading of the water table surface Figure 2-16a illustrates distortions in contouring that result from this effect, and Figure 2-16b shows the correct interpretation

2 *Failure to adjust contour lines in areas of topographic depressions occupied by lakes* Figure 2-17a illustrates the incorrect and correct interpretations in this situation

3 *Failure to recognize locally steep gradients caused by fault zones* Figure 2-17b illustrates how conventional contouring methods erroneously portray the ground water flow systems on the two sides of a fault

4 *Failure to consider localized mounding or depression of the potentiometric surface from anthropogenic recharge or pumping* Pumping wells create a cone of depression around the well (Section 4 4 2) with steepened hydraulic gradients Agricultural irrigation, artificial recharge using municipally treated wastewater, and artificial ponds and lagoons usually cause a mounding of water tables When the source of recharge is confined to a relatively small area, a localized mound develops with elevations increasing toward the center, rather than decreasing as in a pumped well Area-wide recharge will reduce hydrau-



Incorrect

Incorrect

Correct

Correct

a

b

**Figure 2-17** **Common errors in contouring water table maps (a) topographic depression occupied by lakes and (b) fault zones (from Davis and DeWiest, 1966)**

lic gradients compared to natural aquifer conditions These features are especially significant when they are located near a ground water divide, because small shifts in the location of a divide may have a major impact on the direction in which contaminants flow

5 *Failure to consider seasonal and other short-term fluctuations in well levels* If an aquifer experiences seasonal high and low water tables, well measurements are not comparable unless they are taken at the same time of year Other factors, such as dramatic changes in atmospheric pressure and precipitation events, might reduce the comparability of well measurements even if the measurements are taken at the same time of year

6 *Use of measurements from wells tapping multiple aquifers* Wells in which the screened interval includes multiple aquifers generally yield inaccurate water level or piezometric measurements, because the measured head reflects the interaction between heads of the intersected aquifers Figure 2-18 illustrates how the failure to differentiate measurements from wells completed in two aquifers, combined with a well that connects the two, results in a apparent depression in the potentiometric surface

### 2.3.2 Errors in Interpretation of Flow Direction

As noted earlier, ground water flow is perpendicular to contours on a potentiometric map if the aquifer is isotropic Failure to account for anisotropy and heterogeneities in an aquifer, however, can result in significant errors in the interpretation of ground water flow direction Following are three situations in which flow direction will

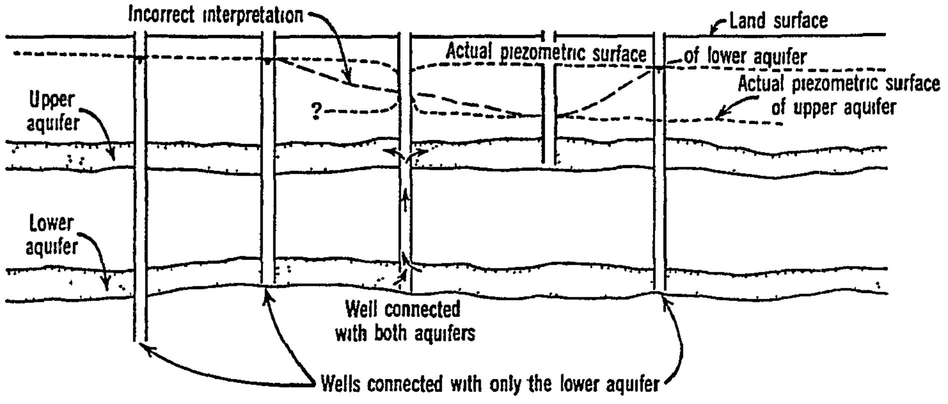


**Figure 2-18. Error in mapping potentiometric surface due to mixing of two confined aquifers with different pressures (from Davis and DeWiest, 1966)**

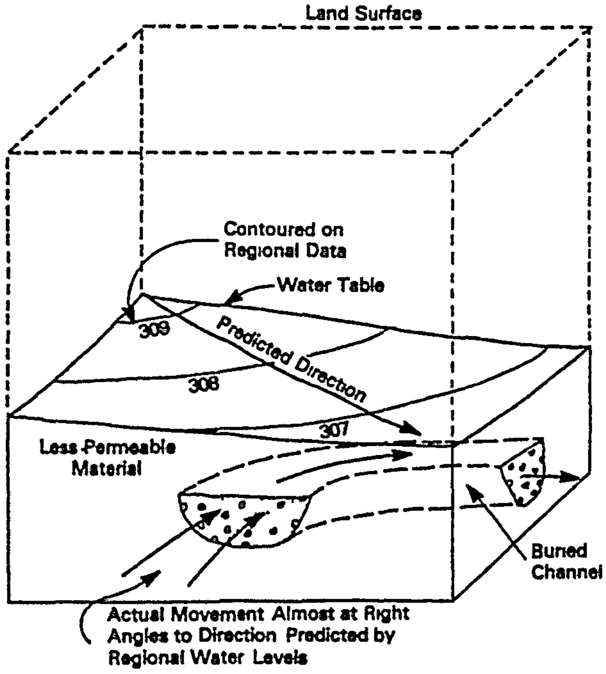


**Figure 2-19. Divergence from predicted direction of ground water resulting from aquifer heterogeneity (from Davis et al, 1985)**

differ from that indicated by conventional flow net construction using an accurate potentiometric map

1. *Homogeneous, anisotropic aquifers* Figure 2-12 illustrates how flow direction can diverge from flow in an isotropic aquifer. Section 2 2 2 discusses how to determine the direction of flow in this situation

2. *Heterogenous aquifers with contrasting hydraulic conductivity* Figure 2-19 illustrates an example of divergence of flow from the direction predicted by ground water contours as a result of a buried channel of higher permeability oriented across the direction of the potentiometric surface This kind of divergence is difficult to predict accurately Careful examination of well logs for the areal distribution of materials with contrasting hydraulic conductivity and the use of tracer tests may help modify flow direction interpretations when this situation occurs

3. *Backwater effects in discharge areas* Short-term reverses in the direction of ground water occur when streams or rivers are at high stage (Figure 2-20) These effects can extend for hundreds of feet from the stream edge Wells that may be subject to bank storage can be identified by monitoring changes in water levels in response to stream flood events

### 2.3 3 *Reverse Flow of Contaminants*

Several situations can cause contaminants to flow in a different direction from that indicated by flow net construction using a potentiometric map Dissolved contaminants follow the direction of ground water flow Attention should be paid, however, to the possibility of localized flow patterns that run against the general direction of ground water flow (mounding of ground water caused by ponds and lagoons and backwater effects in discharge areas) Dense leachates and non-aqueous phase liquids (NAPLs), on the other hand, can flow in an entirely different direction from that of ground water flow if the slope of the geologic material forming the base of the aquifer does not follow the potentiometric surface Figure 1-9 illustrates a dense NAPL flowing in the opposite direction of ground water flow as a result of geologic controls

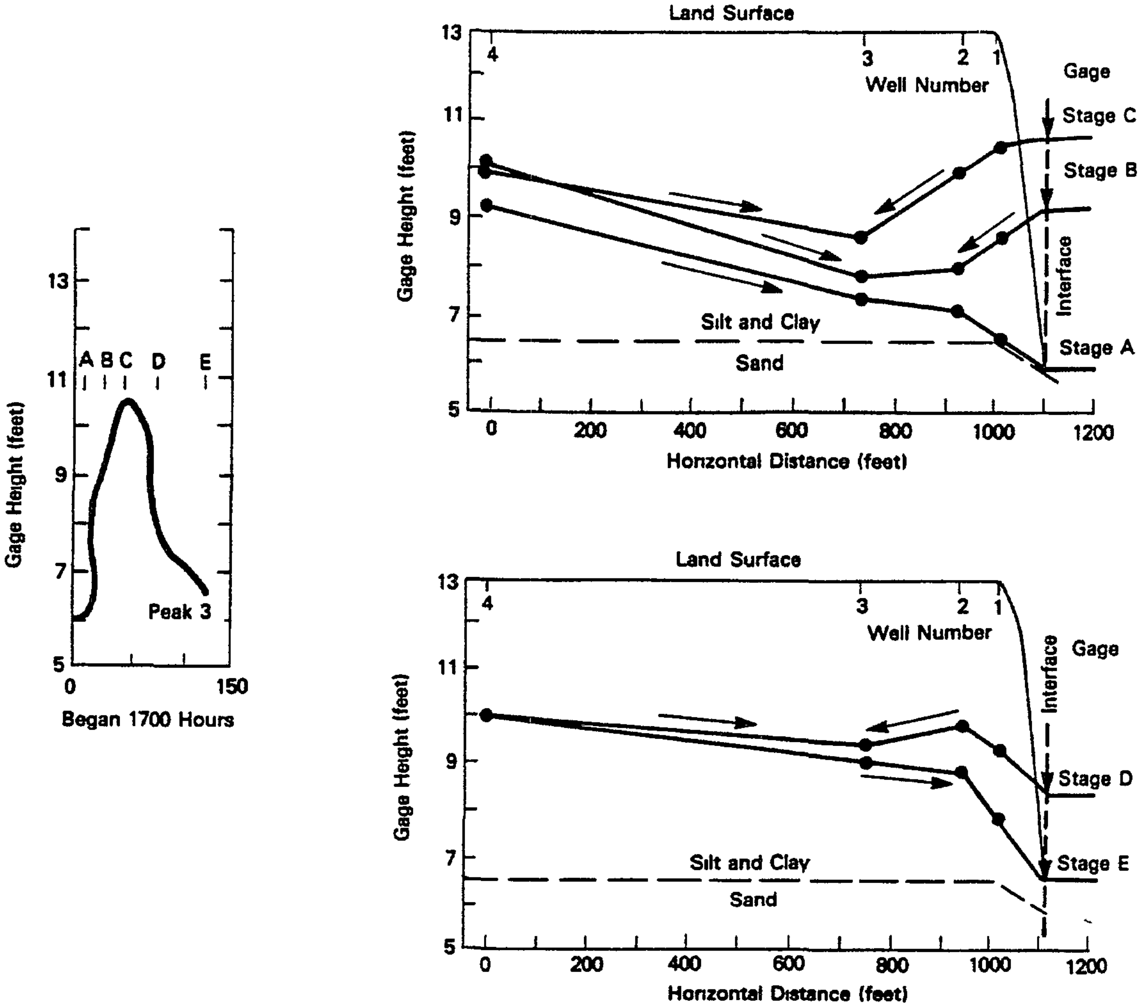


**Figure 2-20** Movement of water into and out of bank storage along a stream in Indiana (from Daniels et al , 1970)

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* See Introduction for information on how to obtain documents

# Chapter 3

# Measurement and Estimation of Aquifer Parameters for Flow Equations

All methods for delineation of wellhead protection areas (WHPAs) require measurement or estimation of aquifer properties or parameters that affect ground water flow Specific delineation methods are discussed in more detail in the next three chapters This chapter discusses major aquifer parameters and how they are measured or estimated Table 3-1 identifies parameters used in equations for methods covered in Chapter 4 and methods for measuring or estimating each parameter

## 3.1 Hydrogeologic Parameters of Interest

Measurement or quantification of parameters, such as pumping rate, hydraulic gradient, saturated thickness, and well specifications listed in Table 3-1, is relatively straightforward Other parameters such as transmissivity, travel time, and velocity are readily calculated once values for the parameters from which they are derived are known This chapter focuses on three critical aquifer parameters that require relatively sophisticated field or laboratory procedures for accurate measurement (1) porosity, (2) specific yield (or storativity for confined aquifers), and (3) hydraulic conductivity (including anisotropy) Another important aquifer characteristic, *heterogeneity,* involves delineation of spatial variations in these properties Heterogeneity is discussed further in Chapter 5 (Hydrogeologic Mapping)

### 3.1.1 Aquifer Storage Properties: Porosity and Specific Yield/Storativity

*Porosity,* expressed as a percentage or decimal fraction, is the ratio between the openings in the rock and the total rock volume It defines the amount of water a saturated rock volume can contain If a unit volume of saturated rock drains by gravity, not all of the water it contains will be released The volume drained is the *specific yield,* a percentage, and the volume retained is the *specific retention* Therefore, porosity is equal to

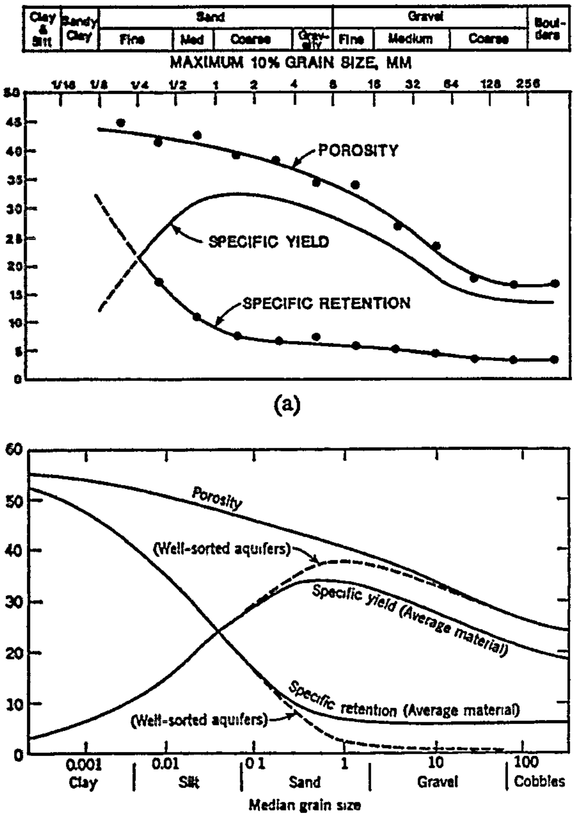
**Table 3-1 Aquifer and Other Parameters Required for Different WHPA Delineation Methods**

| Parameter | Symbol | WHPA Delineation Methods* | Measurement Methods |
|---|---|---|---|
| Pumping rate of well | Q | Cylinder method, analytical solutions for pump tests | Estimated or measured at wellhead |
| Aquifer porosity | n | Cylinder method, time of travel equations | Estimated from tables, measured from aquifer samples |
| Open interval or length of well screen | H | Cylinder method | Well log |
| Travel time | t | Calculated fixed radius, time of travel equations | Chosen or calculated for the specified distance |
| Hydraulic conductivity | K | Time of travel and drawdown equations | Estimated from tables, pumping test. |
| Saturated thickness | b | Some time of travel equations, most drawdown equations | Potentiometric and geologic logs |
| Hydraulic gradient | i | Time of travel equations, some drawdown equations | Potentiometric map |
| Velocity | v | Time of travel equations | Calcuated from other parameters, tracer tests |
| Specific yield or storativity | S | Some time of travel equations, most drawdown equations | Estimated from tables, pumping test. |
| Drawdown | s | Selected for drawdown equations | Chosen or calculated from pump test data |
| Transmissivity | T | Some time of travel equations, most drawdown equations | Hydraulic conductivity (K) times the aquifer thickness (b) |

* Cylinder method is discussed in Section 4 3 2, time of travel methods are covered in Section 4 4 and drawdown methods in Section 4 5

specific yield plus specific retention Knowing any two of these terms allows calculation of the third [1]

Figure 3-1 shows graphs of the relationship between porosity, specific yield and specific retention for unconsolidated materials with texture ranging from clay and silt to gravel. Porosity and specific yield of alluvial, unconsolidated aquifers can be estimated from these figures if particle size data are available Figure 3-1a requires knowing the grain size at which the cumulative total, beginning with the coarsest material, reaches 10 percent of the total sample Figure 3-1b is based on the median grain size Both of these particle size parameters can be determined from conventional particle-size distribution analysis Figure 3-2 can be used to estimate specific yield in unconsolidated materials if only the sand, silt, and clay percentages are known



(a)

(b)

**Figure 3-1.** **Porosity, specific yield, and specific retention (a) mean curves for South Coastal Basin in the Los Angeles area of California (adapted from Todd, 1959, by Devinny et al, 1990), (b) alluvium from large valleys (from Davis and DeWiest, 1966, using various sources)**

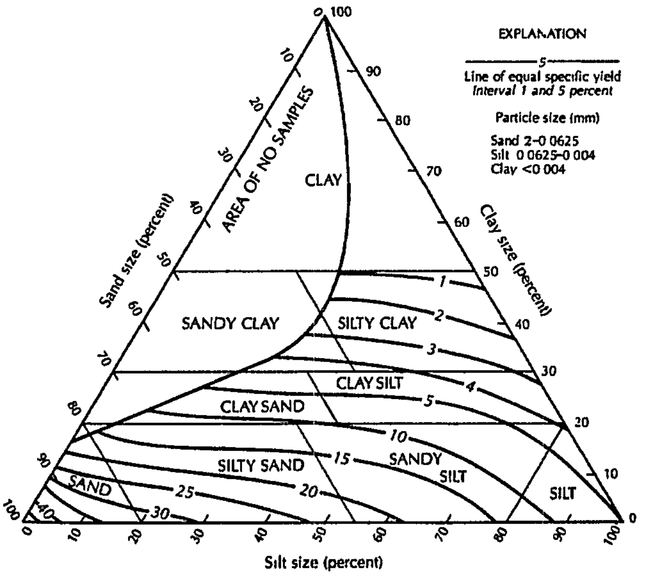


**Figure 3-2** **Textural classification triangle for unconsolidated materials showing the relation between particle size and specific yield (from Morris and Johnson, 1967)**

As discussed in Section 2 1 4, the presence of secondary porosity complicates ground water flow analysis, and the relative proportions in relation to total porosity must be measured or estimated where secondary porosity contributes significantly to ground water flow Table 3-2 identifies measured or "typical" values/ranges of porosity for a variety of aquifer materials The data from Heath (1983) and Brown et al (1983) provide some information about the relationship between primary and secondary porosity, which rarely exceeds 10 percent However, this percentage may account for most of the actual flow of ground water Figure 3-3 provides some additional information on the characteristics of secondary porosity in different types of rocks

Another important term is *storativity* (S), which describes the quantity of water that an aquifer will release from storage or take into storage per unit of its surface area per unit change in head In unconfined aquifers, the storativity is, for all practical purposes, equal to the *specific yield* Table 3-3 identifies measured or "typical" values/ranges of specific yield for a variety of aquifer materials The storativity of confined aquifers is substantially smaller, because the water released from storage when the head declines comes from the expansion of water and compression of the aquifer, both of which are very small For confined aquifers, storativity generally ranges between 0 005 and 0 00005, with leaky confined aquifers falling in the high end of this range [2] The small storativity of confined aquifers means that a large pressure change throughout a wide area is needed to obtain a sufficient supply from a well This is not the case with unconfined aquifers, because the water derived is not

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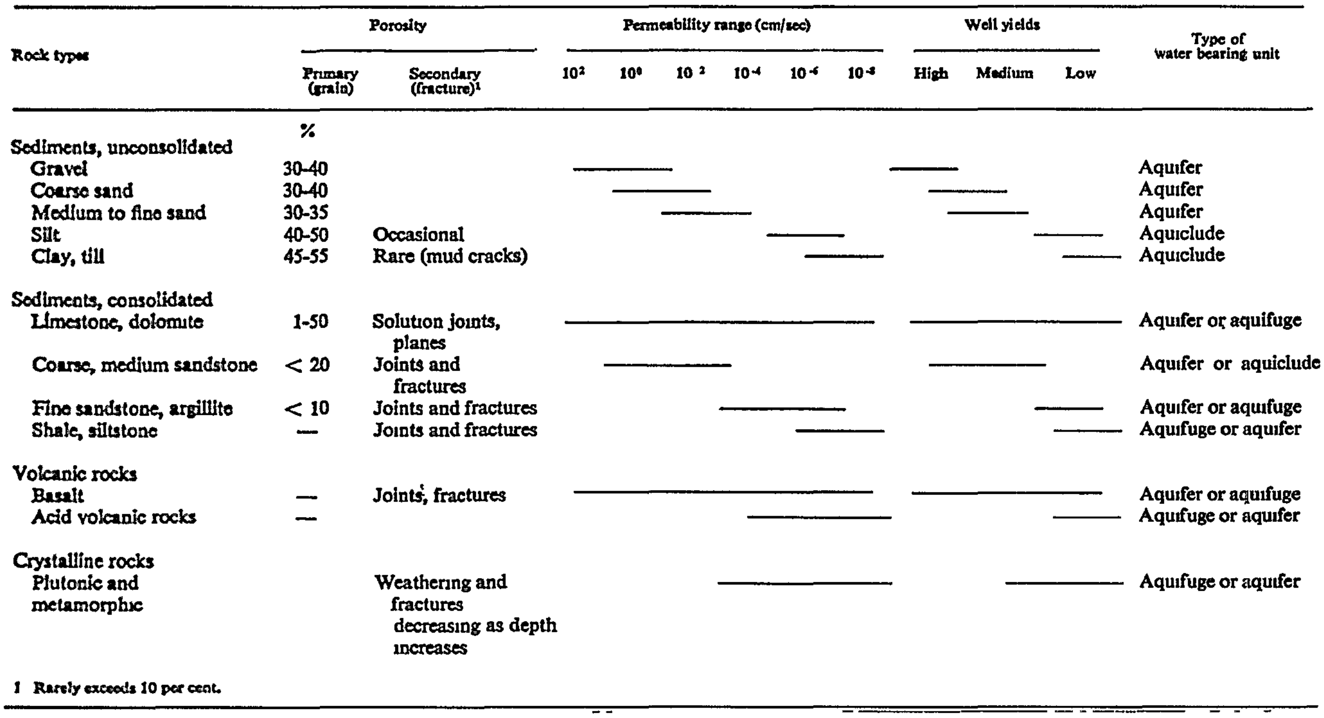
[1] This includes only interconnected pores through which water can flow. Isolated pores, whether air- or water-filled, can be considered part of the solid volume of a rock for purposes of ground water flow analysis

[2] 0 0001 to 0 00001 may also be cited in the literature as a typical range

**Table 3-2 Porosity (% of Volume) of Different Aquifer Materials**

| Soil/Rock Types | (1) P/S* | (2) P/S* | (3)*** | (4) | (5) | (6) | (7)**** |
|---|---|---|---|---|---|---|---|
| *Unconsolidated Sediments* | | | | | | | |
| Gravel | 20/- | 30-40/- | 23 7-44 1 | 25-40 | 25-40 | | |
| Coarse | | | | | | 20-35 | |
| Medium | | | | | | 20-35 | |
| Fine | | | | | | 20-40 | |
| Sand and gravel | | | | | | 20-35 | |
| Sand | 25/- | | 26 0-53 3 | 25-50 | 15-48 | | |
| Gravelly | | | | | | 20-35 | |
| Coarse | | 30-40/- | | | | 25-45 | |
| Medium | | | | | | 25-45 | |
| Medium to fine | | 30-35/- | | | | | |
| Fine | | | | | | 25-55 | |
| Dune sand | | | | | | 35-45 | |
| Silt | | 40-50/yes** | 33 9-61 1 | 35-50 | 35-50 | 35-60 | |
| Clay | 50/- | 45-55/yes** | 34 2-56 9 | 40-70 | 40-70 | 35-55 | |
| Sandy | | | | | | 30-60 | |
| Till | | 45-55/yes** | | | | 25-45 | |
| Unstratified drift | | | 22 1-40 6 | | | | |
| Stratified drift | | | 34 6-59 3 | | | | |
| Loess | | | 44 0-57 2 | | | 60-80 | |
| Peat | | | | | | 60-80 | |
| Soil | 55/- | | | | | | |
| Alluvium | | | | | | | 10-40(30) |
| Basin fill | | | | | | | 5-30(20) |
| Ogalla formation | | | | | | | 15-45(35) |
| *Consolidated Sediments* | | | | | | | |
| Limestone | 10/10 | 1-50/yes** | 6 6-55 7 | 0-20 | 0-20 | 5-55 | 1-20(4) |
| Karst | | | | 5-50 | 5-50 | | |
| Chalk | | | | | 5-40 | | |
| Dolomite | | 1-50/yes** | 19 1-32 7 | 0-20 | 0-20 | | |
| Sandstone | | | 13 7-49 3 | 5-30 | 5-40 | | 1-20(10) |
| Semiconsolidated | 10/1 | | | | | 1-50 | |
| Coarse, medium | | <20/yes** | | | | | |
| Fine, argillite | | <10/yes** | | | | | |
| Siltstone | | -/yes** | 21 2-41 0 | | | 20-40 | |
| Shale | | -/yes** | 1 4-9 7 | 0-10 | 0-10 | | |
| *Crystalline Rocks* | | | | | | | |
| Granite (unaltered) | -/0 1 | | | | 0-2 | | |
| Crystalline (fractured) | | | | 0-10 | | | |
| Crystalline (dense) | | | | 0-5 | | 0-5 | |
| Igneous/Metamorphic | | -/yes** | | | | | |
| Weathered | | | | | | 40-50 | |
| Unaltered gneiss | | | | | 0-2 | | |
| Quartzite | | | | | 0-1 | | |
| Slates/mica schists | | | | | 0-10 | | |
| *Volcanic Rocks* | | | | | | | |
| Basalt | 10/1 | -/yes** | | | | | |
| Fractured | | | | 5-50 | 5-50 | 5-50 | |
| Volcanic tuff | | | | | 30-40 | 10-40 | |
| Acid volcanic rocks | | - | | | | | |

* P = primary porosity, S = secondary porosity
** Rarely exceeds 10 percent
*** Compiled by Barton et al (1985)
**** Number in parentheses is typical value
Sources (1) Heath (1983), (2) Brown et al (1983), (3) Morris and Johnson (compiled by Barton et al, 1985), (4) Freeze and Cherry (1979), (5) Sevee (1991), (6) Devinny et al (1990), (7) Wilson (1981)



| Rock types | Porosity |  | Type of water bearing unit |
|---|---|---|---|
|  | Primary (grain) | Secondary (fracture)[1] |  |
|  | % |  |  |
| Sediments, unconsolidated |  |  |  |
| Gravel | 30-40 |  | Aquifer |
| Coarse sand | 30-40 |  | Aquifer |
| Medium to fine sand | 30-35 |  | Aquifer |
| Silt | 40-50 | Occasional | Aquiclude |
| Clay, till | 45-55 | Rare (mud cracks) | Aquiclude |
| Sediments, consolidated |  |  |  |
| Limestone, dolomite | 1-50 | Solution joints, planes | Aquifer or aquifuge |
| Coarse, medium sandstone | < 20 | Joints and fractures | Aquifer or aquiclude |
| Fine sandstone, argillite | < 10 | Joints and fractures | Aquifer or aquifuge |
| Shale, siltstone | — | Joints and fractures | Aquifuge or aquifer |
| Volcanic rocks |  |  |  |
| Basalt | — | Joints, fractures | Aquifer or aquifuge |
| Acid volcanic rocks | — |  | Aquifuge or aquifer |
| Crystalline rocks |  |  |  |
| Plutonic and metamorphic |  | Weathering and fractures decreasing as depth increases | Aquifuge or aquifer |

[1] Rarely exceeds 10 per cent.

Figure 3-3. Porosity, permeability, and well yields of major rock types (from Brown et al , 1983)

related to expansion and compression, but instead comes from gravity drainage and dewatering of the aquifer

### 3.1.2 *Water-Transmitting Properties: Hydraulic Conductivity and Transmissivity*

The terms *permeability* (P) and *hydraulic conductivity* (K) are often used interchangeably to refer to the ease with which water moves through soil or an aquifer under saturated conditions Hydrogeologists draw a distinction between *intrinsic permeability* (k—a property of the porous medium alone that is independent of the nature of the liquid or potential field) and *hydraulic conductivity* (K—a function of both the medium and the fluid flowing through it) A precise definition of hydraulic conductivity is:

> The quantity of water that will flow through a unit cross-sectional area of a porous material per unit of time under a hydraulic gradient of 1 0 (measured at right angles to the direction of flow) at a specified temperature (Nielsen, 1991)

The terms hydraulic conductivity and permeability in this handbook refer to saturated hydraulic conductivity unless otherwise specified Soil permeability rates are typically reported in units of inches/hour based on percolation tests Hydraulic conductivity may be reported in a variety of units µm/second, cm/second, m/second, ft/day, and gpd/ft$^2$ (gallons per day per square foot) Currently, centimeters per second is probably the most commonly used unit Hydraulic conductivity values range widely from one rock type to another and even within the same rock Table 3-4 shows measured ranges of hydraulic conductivity for various unconsolidated and consolidated sediments and typical values for unconsolidated materials for which the unified soil classification is known

Figures 3-3 to 3-6 show ranges of hydraulic conductivity and permeability from a number of different sources Note also that Figures 3-4 and 3-5 provide nomographs for approximate conversions between different units of intrinsic permeability (k) and hydraulic conductivity (K) Figure 3-7 can be used to estimate hydraulic conductivity of unconsolidated materials based on general classification (Figure 3-7a) from particle-size distribution curves of alluvial sands (Figure 3-7b)[3] and from median grain size of stratified drift aquifers (Figure 3-7c)

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[3] To use the nomograph 3-7(b)(ii), on the right-hand side of Figure 3-7b, the particle-size distribution curve 3-7(b)(i) must be plotted using $\rho$ units, where $\rho = -\log_2 d$, d being the grain size diameter in mm The *inclusive standard deviation* must also be calculated as follows

$\sigma_I = (d_{16} - d_{84})/4 + (d_5 - d_{95})/6$ 6

where the subscripts for d (in $\rho$ units) represent the cumulative percentage finer than that diameter

Figure 3-7(b) provides an illustrative example Median grain size $d_{50}$ is first determined from the particle-size curve, 3-7(b)(i) (2 0 in the example) The inclusive standard deviation (calculated from the data used to plot the curve) in the example (0 8) has been interpolated between the curves in the nomograph on the right, 3-7(b)(ii), yielding an approximate K of 0 7 cm/min

**Table 3-3 Specific Yield (%) for Different Aquifer Materials**

| Soil/Rock Types | (1) | (2) Mean | (2) Range | (3) | (4) | (5) |
|---|---|---|---|---|---|---|
| *Unconsolidated Sediments* | | | | | | |
| Gravel | 19 | | | 15-30 | | |
| Coarse | | 21 | 13-25 | | 10-25 | |
| Medium | | 24 | 17-44 | | 15-25 | |
| Fine | | 18 | 13-28 | | 15-35 | |
| Sand and gravel | | | | 15-25 | 15-30 | |
| Sand | 22 | | | 10-30 | | |
| Gravelly | | | | | 20-35 | |
| Coarse | | 30 | 18-43 | | 20-35 | |
| Medium | | 32 | 16-46 | | 15-30 | |
| Fine | | 33 | 1-46 | | 10-30 | |
| Dune sand | | 38 | 32-47 | | 30-40 | |
| Silt | | 20 | 1-39 | | 1-30 | |
| Loess | | 18 | 14-22 | | 30-50 | |
| Clay | 2 | 6 | 1-18 | 1-10 | 1-20 | |
| Sandy | | | | | 1-30 | |
| Till | | | | | 5-20 | |
| Peat | | | | | 30-50 | |
| Soil | 40 | | | | | |
| Alluvium | | | | | | 1-25(15) |
| Basin fill | | | | | | 1-30 (15) |
| Ogalla formation | | | | | | 1-30(20) |
| *Consolidated Sediments* | | | | | | |
| Limestone/Carbonate | 18 | 14 | 0-36 | 0 5-5 | 1-24 | 1-5(2) |
| Sandstone | | | | 5-15 | | |
| Semiconsolidated | 6 | | | | 1-48 | 0 1-5(1) |
| Medium | | 27 | 12-41 | | | |
| Fine | | 21 | 2-40 | | | |
| Siltstone | | 12 | 1-33 | | 1-35 | |
| Shale | | | | 0 5-5 | | |
| *Volcanic Rocks* | | | | | | |
| Basalt | 8 | | | | | |
| Fractured | | | | | 1-30 | |
| Tuff | | 21 | 2-47 | | 2-35 | |
| *Crystalline Rocks* | | | | | | |
| Granite | 0 09 | | | | | |
| Schist | | 26 | 22-33 | | | |
| Crystalline (dense) | | | | | 0-2 | |
| Igneous/Metamorphic | | | | | | |
| Weathered | | | | | 20-30 | |

Sources (1) Heath (1983), (2) Morris and Johnson (1967), as complied by McWhorter and Sunada (1977), (3) Sevee (1991), (4) Devinny et al (1990), (5) Wilson (1981)

A large number of empirical equations have been developed to estimate hydraulic conductivity based on texture (particle size distribution) of unconsolidated materials Alyamani and Sen (1993), Bedinger (1961), Cosby et al (1984), Hazen (1893), Hendry and Paterson (1982), Horn (1971), Krumbein and Monk (1942), Puckett et al (1985), Uma et al (1989), Vukovic and Soro (1992), Wiebenga et al (1970) Figure 3-7d illustrates a particle size distribution plot and five of these empirical equations Such equations can be a useful supplement to other measurements or estimates of hydraulic conductivity, but should be used with care Bradbury and Muldoon (1990) found that application of the five equations to unlithified glacial and fluvial materials provided estimates of hydraulic conductivity that spanned three or four orders of magnitude for any given lithostratigraphic unit Each method is most applicable for the type of unconsolidated material used to derive it and should not be extended to other types of material without field tests to verify the results

Figure 3-8 shows the range of measured permeabilities of glacial tills in various locations McKay et al (1993)

## Table 3-4 Representative Values for Hydraulic Conductivity of Unconsolidated and Consolidated Sediments

| Rock/Soil Type | | Hydraulic Conductivity (cm/s) |
|---|---|---|
| *Unconsolidated Matenals** | | |
| Gravel (repacked) | | 3 1 to 3 4x10$^{2}$ |
| Sand | | 9 0x10$^{-2}$ to 4 7x10$^{-6}$ |
| Silt | | 7 1x10$^{-3}$ to 9 4x10$^{-9}$ |
| Clay | | 1 4x10$^{-6}$ to 1 4x10$^{-9}$ |
| Unstratified drift | | 1 0x10$^{-2}$ to 3 8x10$^{-9}$ |
| Stratified drift | | 6 6x10$^{1}$ to 4 7x10$^{5}$ |
| Loess | | 1 8x10$^{-4}$ to 4 7x10$^{-6}$ |
| *Sedimentary Rocks** | | |
| Sandstone | | 1 0x10$^{-2}$ to 3 7x10$^{7}$ |
| Siltstone | | 1 4x10$^{-6}$ to 9 4x10$^{10}$ |
| Shale | | - |
| Limestone | | 2 6x10$^{2}$ to 1 0x10$^{-8}$ |
| Dolomite | | 3 3x10$^{-6}$ to 3 8x10$^{-9}$ |
| *Unified Soil Classification*** | | |
| GW | Well graded gravels, gravel-sand mixtures, little or no fines | 10$^{-2}$ |
| GP | Poorly graded gravels, gravel-sand mixtures, little or no fines | 10$^{-2}$ |
| GM | Silty gravels, gravel-sand-silt mixtures | 10$^{-3}$ to 10$^{-6}$ |
| GC | Clayey gravels, gravel-sand-clay mixtures | 10$^{-6}$ to 10$^{-8}$ |
| SW | Well graded sands, gravelly sand, little or no fines | 10$^{-3}$ |
| SP | Poorly graded sands, gravelly sands, little or no fines | 10$^{-3}$ |
| SM | Silty sands, sand-silt mixtures | 10$^{-3}$ to 10$^{-6}$ |
| SC | Clayey sands, sand-clay mixtures | 10$^{-6}$ to 10$^{-8}$ |
| ML | Inorganic silts and fine sands, silty or clayey fine sands or clayey silts with slight plasticity | 10$^{-3}$ to 10$^{-6}$ |
| CL | Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays | 10$^{-6}$ to 10$^{-8}$ |
| OL | Organic silts and organic silty clays of low plasticity | 10$^{-4}$ to 10$^{-6}$ |
| MH | Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts | 10$^{-4}$ to 10$^{-6}$ |
| CH | Inorganic clays of high plasticity, fat clays | 10$^{-6}$ to 10$^{-8}$ |
| OH | Organic clays of medium to high plasticity, organic silts | 10$^{-6}$ to 10$^{-8}$ |
| Pt | Peat and other highly organic soils | Not classified |

* Compiled from Morris and Johnson (1967) by Barton et al (1985)
** Compiled by Brown et al (1991) from SCS (1990)

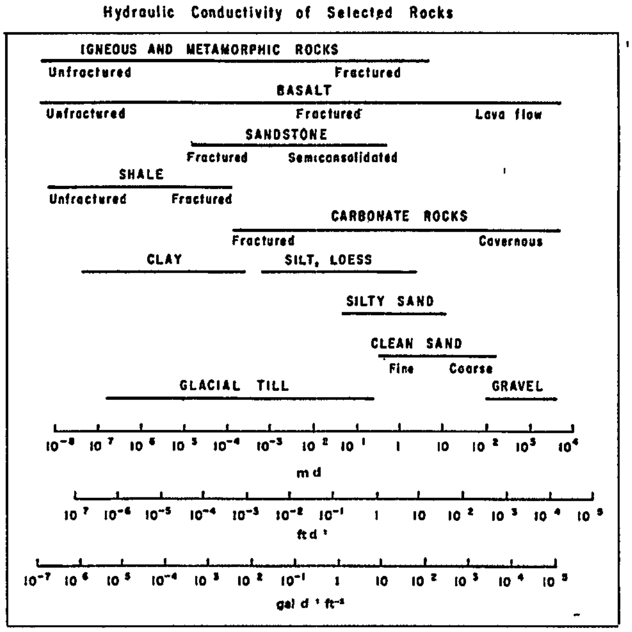

**Figure 3-4** Hydraulic conductivity of selected rocks (from Heath, 1983)

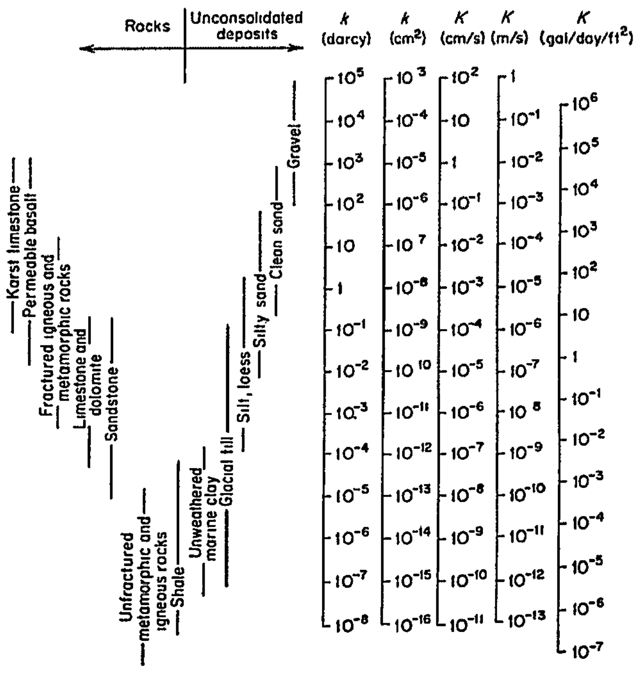

**Figure 3-5** Range of values of hydraulic conductivity (from Freeze and Cherry, 1979)

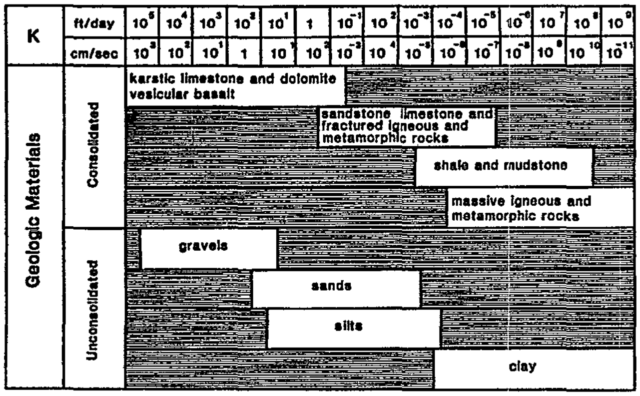

**Figure 3-6** Representative ranges of saturated hydraulic-conductivity values for geologic materials (adapted from Freeze and Cherry, 1979, by Thompson et al , 1989)

found that field measurements of hydraulic conductivity in glacial till were generally two to three orders of magnitude higher than laboratory measurements on cores This study also found that field values measured in conventional augered piezometers were typically one to two orders of magnitude lower than those measured in piezometers designed to reduce smearing

If the porosity and texture of a consolidated sandstone aquifer is known, Figure 3-9 allows estimation of permeability in millidarcys (see Figure 3-5 for nomograph to convert darcys to hydraulic conductivity values) Section 3 3 describes the use of these tables for estimating hydraulic conductivity from geologic data

*Transmissivity* (T), a term derived from hydraulic conductivity, describes the capacity of an aquifer to transmit water Transmissivity is equal to the product of the aquifer's saturated thickness (b) and the hydraulic conduc-

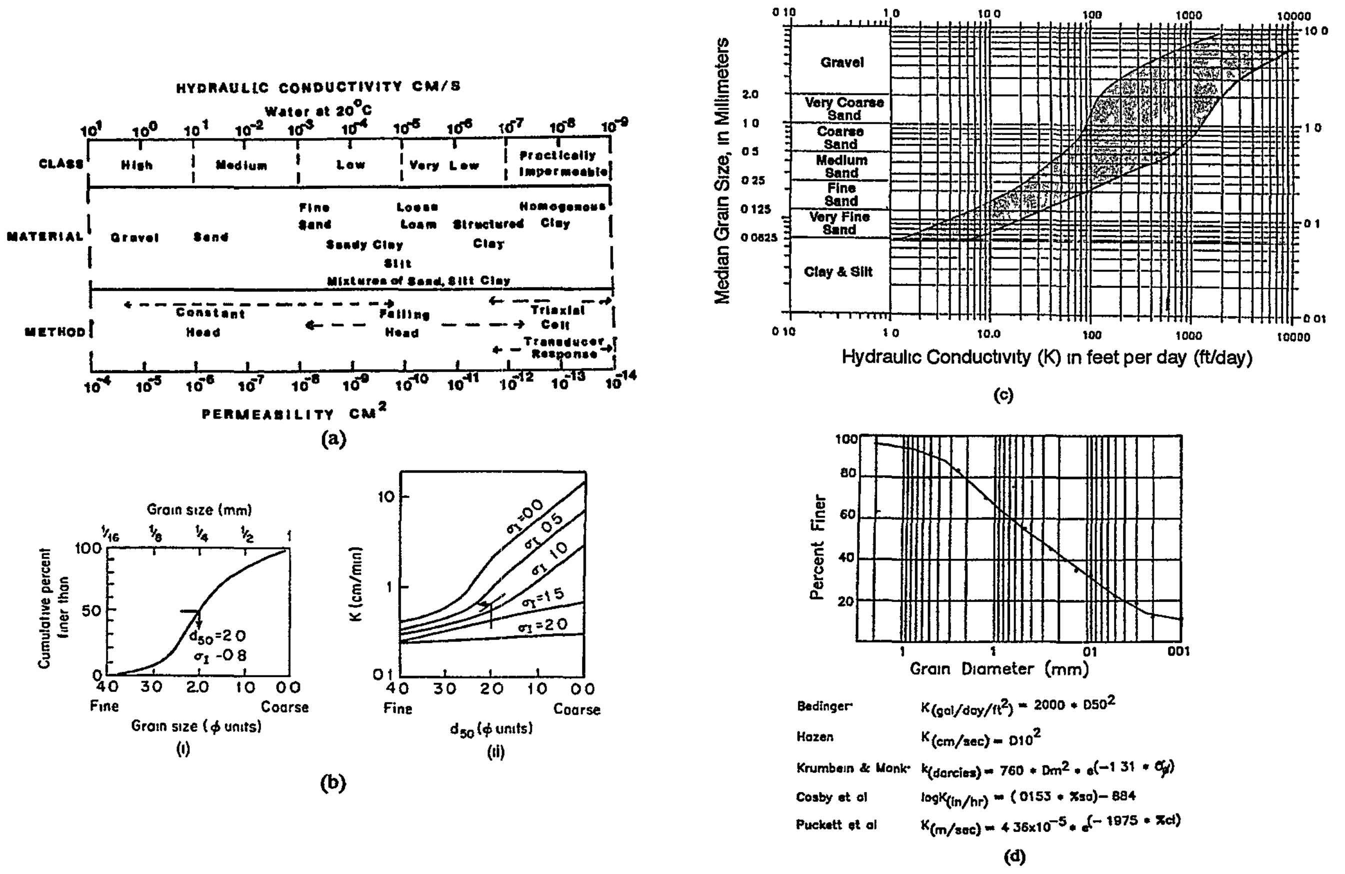

**Figure 3-7** Saturated hydraulic conductivity of unconsolidated materials (a) various materials (from Klute and Dirksen, 1986), (b) determination from grain-size gradation curves for sands (Freeze and Cherry, 1979, after Masch and Denny, 1966), (c) relationship between grain size and hydraulic conductivity in stratified drift aquifers (Connecticut Department of Environmental Protection, 1991, (d) sample particle-size distribution curve and five empirical equations used to estimate hydraulic conductivity of unconsolidated materials D50 = median diameter, in millimeters, D10 = diameter, in millimeters, at which 10% of the sample is finer, Dm = mean diameter, in millimeters, $\sigma_\phi$ = phi standard deviation, %sa = percentage of the sample coarser than 0 05 mm, %cl = percentage of the total sample finer than 0 002 mm (Bradbury and Muldoon, 1990)

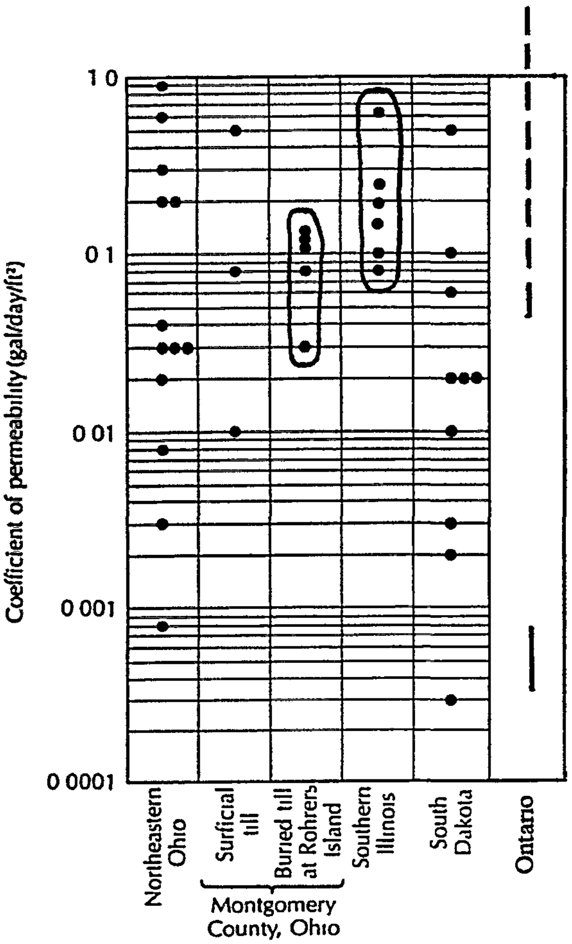

**Figure 3-8.** Range of permeability of glacial tills • = laboratory measurements (Norris, 1963), circled clusters of dots based on pumping tests (Norris, 1963), Ontario data from McKay et al (1993) with solid line indicating range of laboratory measurements and dashed line indicating the range of mean values using four different types of piezometer construction for field measurements

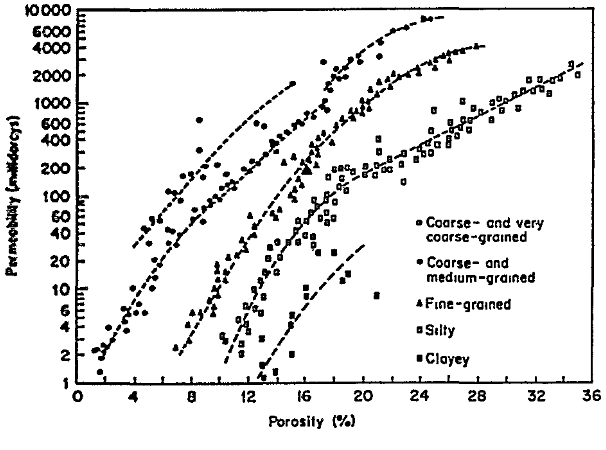

**Figure 3-9.** Relationship between porosity and permeability for sandstone in various grain-size categories (Freeze and Cherry, 1979, after Chilingar, 1963)

tivity (K) It is commonly measured in units of gpd/ft of aquifer thickness

$$T = Kb \qquad (3\text{-}1)$$

Krásny (1993) has recently described a standard classification scheme for transmissivity of local and regional aquifers based on magnitude and variation

### *3.1.3 Darcy's Law*

Darcy's Law, expressed in many different forms, allows calculation of the quantity of water flowing through a defined area of an aquifer, provided that the hydraulic conductivity and the hydraulic gradient are known One means of expressing Darcy's Law is

$$Q = KiA \qquad (3\text{-}2)$$

where

$Q$ = quantity of flow per unit of time, in gpd
$K$ = hydraulic conductivity, in gpd/ft$^2$
$i$ = hydraulic gradient, in ft/ft
$A$ = cross-sectional area through which the flow occurs, in ft$^2$

Darcy's Law assumes that flow is *laminar*, which means that the water will follow distinct flow lines rather than mix with other flow lines Most ground water flow in porous media is laminar The equation does not work for *turbulent* flow, as in the case of the unusually high velocity that might be found in fractures or solution openings or adjacent to some pumping wells

Figure 3-10 shows an example of the use of Darcy's Law In this case, a sand aquifer about 30 feet thick lies within the flood plain of a river about 1 mile wide The aquifer is covered by a confining unit of glacial till, the bottom of which is about 45 feet below the land surface

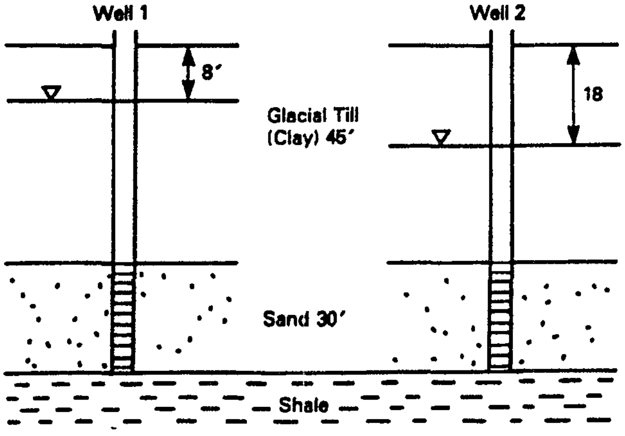

**Figure 3-10** Using Darcy's Law to estimate underflow in an aquifer

The difference in water level in two wells 1 mile apart is 10 feet, and the hydraulic conductivity of the sand is 500 $\text{gpd/ft}^2$ Therefore, the quantity of underflow moving through the cross-section in Figure 3-10 is

$$Q = KiA = 500 \text{ gpd/ft}^2 \times (10 \text{ ft}/5280 \text{ ft}) \times (5280 \times 30) = 150,000 \text{ gpd}$$

Ground water moves through both aquifers and confining units Because hydraulic conductivity commonly differs between aquifers and confining units by several orders of magnitude, the head loss per unit of distance in an aquifer is far less than in a confining unit Consequently, lateral flow in confining units is small compared to that in aquifers, but vertical leakage through them can be significant Because of the large differences in hydraulic conductivity, flow lines in aquifers tend to parallel the boundaries, but in confining units they are much less dense (Figure 3-11) The flow lines are refracted at the boundaries to produce the shortest flow path in the confining unit, with the angles of refraction proportional to the differences in hydraulic conductivity

## 3.2 Estimation of Aquifer Parameters

The critical aquifer parameters of porosity, specific yield, and hydraulic conductivity are typically not measured for most water wells Therefore, the initial stages of the wellhead protection delineation process often require estimation for one or more of these parameters Estimation requires some knowledge of the geologic character of the aquifer and data on the ranges or typical values that have been measured in similar settings elsewhere When used cautiously, such estimates can increase the effectiveness and reduce the cost of any required field measurements and additional data collection

### 3.2.1 Estimation From Soil Survey Data

When aquifers are in unconsolidated deposits and the water table is relatively near the surface, soil surveys published by the Soil Conservation Service (SCS) of the U S Department of Agriculture are an excellent source of information about the character of subsurface materials and soil hydrologic properties A two-page soil series description sheet and a two-page soil survey interpretation sheet are available for every established soil series in the United States Table 3-5 summarizes the information that is available from these records The table highlights in bold-face type the information that may be useful for geologic and hydrogeologic interpretations

SCS soils surveys typically do not provide any detailed information deeper than 5 feet below the ground sur-

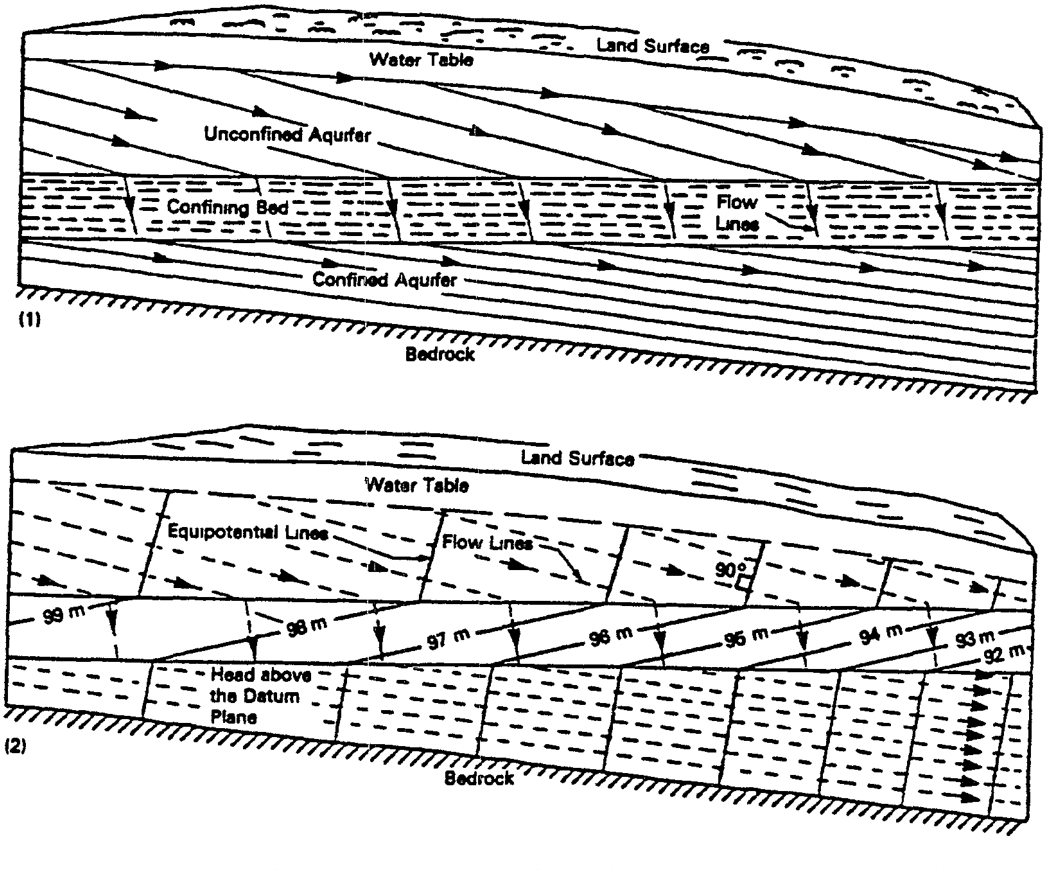

**Figure 3-11** Ground water flow and equipotential lines as a function of different hydraulic conductivity (from Heath, 1983)

**Table 3-5. Types of Data Available on SCS Soil Series Description and Interpretation Sheets**

*Soil Series Description Sheet*
- Taxonomic class
- Typical soil profile description
- **Range of characteristics**
- **Geographic setting**
- **Geographically associated soils**
- **Drainage and permeability**
- Use and vegetation
- Distribution and extent
- Location and year series was established
- Remarks
- Availability of additional data

*Soil Survey Interpretations Sheet**
- Estimated soil properties (major horizons)
  - **Texture class** (USDA, Unified, and AASHTO)
  - **Particle size distribution**
  - Liquid limit
  - Plasticity index
    - Moist bulk density (g/cm$^3$)
  - **Permeability (in/hr)**
  - **Available water capacity (in/in)**
  - Soil reaction (pH)
  - Salinity (mmhos/cm)
  - Sodium absorbtion ratio
  - Cation exchange capacity (Me/100g)
  - Calcium carbonate (%)
  - Gypsum (%)
  - Organic matter (%)
  - Shrink-swell potential
  - Corrosivity (steel and concrete)
  - Erosion factors (K,T)
  - Wind erodability group
  - **Flooding (frequency, duration, months)**
  - **High water table (depth, kind, months)**
  - **Cemented pan (depth, hardness)**
  - **Bedrock (depth, hardness)**
  - Subsidence (initial, total)
  - **Hydrologic group**
  - Potential frost action
- Use/Suitability ratings
  - Sanitary facilities
  - Source material
  - Community development
  - Water management
  - Recreation
  - Crop/pasture capability and predicted yields
  - Woodland suitability
  - Windbreaks (recommended species for planting)
  - Wildlife habitat suitability
  - Potential native plant community (rangeland or forest)

Note Boldface entries are particularly useful for evaluating contaminant transport
* Units indicated are those used by SCS

face, but they do provide a general indication of the type of deeper geologic materials In the absence of, or in combination with, other geologic data about the area of interest, this information provides a basis for estimating porosity, specific yield, and hydraulic conductivity, as discussed in the next section

If a published SCS soil survey is available for a site of interest, the information in Table 3-5 will be contained in the report, but scattered in different locations It is probably useful to obtain the single soil series descriptions and interpretations (usually available from the SCS State Office as a four-page handout) as a convenient consolidated reference for the soil series of interest This sheet should be checked against data in the published soil survey, however, since the soil survey often will have additional data specific to the county in question

### *3.2.2 Estimation From Aquifer Matrix Type*

Porosity, specific yield, and hydraulic conductivity fall within reasonably well-defined ranges for most aquifer materials, although some rocks, such as basalt, encompass the entire natural range of hydraulic conductivity (see Figure 3-3) The following tables and figures provide information compiled from a variety of sources

*Porosity* Table 3-2 and Figure 3-1
*Specific Yield* Table 3-3 and Figures 3-1 and 3-2
*Hydraulic Conductivity* Table 3-4, Figures 3-2 through 3-9

Sources may differ somewhat in the ranges given for a specific aquifer material These differences probably exist because of slight differences in the way the material has been defined, or because different sets of data measurements were examined Worksheet 2-1 (water well data) provides space for compiling information on aquifer characteristics Below are some guidelines for estimating porosity, specific yield and hydraulic conductivity for a specific WHPA

1 Define the nature of the aquifer material as thoroughly as possible, using available well logs, soil surveys, geologic maps, and hydrogeologic maps

2 On the well data worksheet, enter values (or ranges) for porosity, specific yield, and hydraulic conductivity from all sources in the tables and figures identified above that provide data on similar or related aquifer materials

3 If the sources provide different ranges for the same material, review the tables and/or figures again to see if any subtle distinctions in the way the materials are described might make one more appropriate for the aquifer in question

4 Select a range of values that seems reasonable based on the information available, and enter the range in the well data worksheet For aquifer materi-

als with a wide possible range, the range should be narrowed based on the presence or absence of characteristics that tend to increase or decrease the parameter in question (Table 3-6)

**Table 3-6 Aquifer Characteristics Affecting Porosity, Specific Yield, and Hydraulic Conductivity**

| Parameter | Tendency To Increase | Tendency To Decrease |
|---|---|---|
| Porosity | Well sorted (same size) | Poorly sorted |
| | Rounded particles | Irregular-shaped particles |
| | Stratified | Unstratified |
| | Small particle size | Large particle size |
| | Unconsolidated | Cemented/lithified |
| | High secondary porosity | Low secondary porosity |
| Specific Yield | Sand particle size | Gravel, silt, clay |
| | High secondary porosity | Low secondary porosity |
| Hydraulic Conductivity | Gravel, sand | Clay |
| | Well sorted (same size) | Poorly sorted |
| | Stratified | Unstratified |
| | Unconsolidated | Cemented/lithified |
| | High secondary porosity | Low secondary porosity |

Table 3-6 identifies factors that tend to increase or decrease porosity, specific yield, and hydraulic conductivity Interactions between factors may mitigate or offset a given tendency Many of the same factors tend to increase and decrease all three factors, but there are some interesting differences Porosity tends to decrease as particle size increases, whereas the reverse is true for hydraulic conductivity This is because clays have a high porosity, but the size of pores is so small that water moves very slowly Specific yield, on the other hand, is typically highest in sandy materials and generally decreases with larger and smaller particle sizes This is because as particle size increases to gravels, the pore space available to store water decreases, and as particle size decreases, water drains less readily from the smaller pores

### *3.2.3 A Simple Well Test for Estimating Hydraulic Conductivity*

The next section describes more complex well tests for measuring aquifer parameters, but a rough estimate of hydraulic conductivity is possible if three easily measured parameters are known (1) the *static* water level prior to any pumping, (2) the normal well pumping rate, and (3) the level to which water drops after pumping starts and stays when inflow into the well equals the pumping rate *Drawdown* is the difference between the static level and the level to which the water drops during pumping The discharge rate of the well divided by the drawdown is the *specific capacity,* not to be confused with specific yield (Section 3 1 1) The specific capacity indicates how much water the well will produce per foot of drawdown It can be calculated by the following equation

$$\text{Specific capacity} = Q/wd \qquad (3\text{-}3)$$

where

Q = discharge rate, in gpm

wd = well drawdown, in ft (elevation of static water surface - elevation when pumped)

If a well produces 100 gpm and the drawdown is 8 feet, the well will produce 12 5 gpm for each foot of available drawdown Multiplying specific capacity by 2,000 gives a crude estimate of transmissivity (T = 2,000 x specific capacity), which in turn can be used to estimate hydraulic conductivity by rearranging equation 3-1

$$K = T/b = 2{,}000 \times \text{specific capacity}/b \qquad (3\text{-}4)$$

Transmissivity estimates based on specific capacity measurements, however, are commonly low because of well construction details (e g , screen length is less than the thickness of the aquifer) Worksheet 2-1 contains space for recording information for calculating the specific capacity of a well

## 3.3 Field Measurement of Aquifer Parameters

Detailed discussion of field methods for measuring aquifer parameters is beyond the scope of this handbook, but this section provides a general discussion of major field methods Table 3-7 provides summary information on more than 30 specific aquifer test techniques[4] These are broadly grouped into (1) shallow water table tests, (2) well tests, (3) tracer tests, and (4) other techniques Each group is discussed briefly below

### *3.3.1 Shallow Water Table Tests*

All the techniques in Table 3-7 for shallow water table measure hydraulic conductivity The auger hole method is the most widely used This method involves boring an open hole below the water table, removing water, and measuring the water level at intervals until water reaches the original level Other methods may be more appropriate for different site conditions This type of test is generally not suitable for purposes of WHPA delineation, because it requires a water table near the surface and measures only hydraulic conductivity of the upper part of the aquifer An exception may be in areas where potential contamination from agricultural chemicals in the wellhead area is a concern Because the tests are

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[4] The section and table references in Table 3-7 refer to sections and tables in the EPA guide from which the table is taken (U S EPA, 1993) containing additional information about the technique This guide is available from EPA's Center for Environmental Research Information

**Table 3-7. Summary Information on Aquifer Test Methods**

| Technique | Confined/ Unconfined | Porous/ Fractured | Aquifer Properties Measured | Chapter Section[a] | Table[a] |
|---|---|---|---|---|---|
| *Shallow Water Table* | | | | | |
| Auger Hole | Unconfined | Porous | K (horizontal)* | 4 2 1 | 4-5, 7-2 |
| Pit Bailing | Unconfined | Porous** | K (undefined) | 4 2 1 | 4-5 |
| Pumped Borehole | Unconfined | Porous | K (undefined) | 4 2 1 | 4-5 |
| Piezometer | Unconfined | Porous | K (undefined) | 4 2 2 | 4-5, 7-2 |
| Tube | Unconfined | Porous** | K (vertical) | 4 2 2 | 4-5 |
| Well Point | Unconfined | Porous | K (undefined) | 4 2 2 | 4-5 |
| Two-Hole | Unconfined | Porous | K (undefined) | 4 2 3 | 4-5 |
| Four-Hole | Unconfined | Porous | K (undefined) | 4 2 3 | 4-5, 7-2 |
| Multiple-Hole | Unconfined | Porous | K (undefined) | 4 2 3 | 4-5 |
| Drainage Outflow | Unconfined | Porous | K (undefined) | 4 2 3 | 4-5 |
| *Well Tests* | | | | | |
| Slug (Injection/Withdrawal) | Both | Porous | K, H, T | 4 3 1 | 4-5 |
| Slug (Displacement) | Both | Porous | K, H, T | 4 3 1 | 4-5 |
| Single-Well Pump | Both | Porous | K, S, T | 4 3 2 | 4-5 |
| Multiple-Well Pump | Both | Porous | A, K, S, T | 4 3 2 | 4-5 |
| Single Packer | Both | Both | K, H, T | 4 3 3 | 4-5 |
| Two-Packer*** | Both | Both | K, H, T | 4 3 3 | 4-5 |
| *Tracers* | | | | | |
| Ions | Both | Both | D, F, V | 4 4 1 | 4-3 |
| Dyes | Unconfined | Both | D, F, V | 4 4 2 | 4-3, 4-6 |
| Gases | Unconfined | Both | D, F, R, V | 4 4 3 | 4-3 |
| Stable Isotopes | Both | Both | D, F, R, V | 4 4 4 | 4-3, 4-6 |
| Radioactive Isotopes | Both | Both | D, F, R, V, T**** | 4 4 5 | 4-3, 4-6 |
| Water Temperature | Unconfined | Both | D, F, V | 4 4 6 | 4-3 |
| Particulates/Microorganisms | Unconfined | Both | D, F, V | 4 4 7 | 4-3, 4-6 |
| *Other Techniques* | | | | | |
| Water Balance | Unconfined | Both | R | 4 5 1 | 4-5 |
| Moisture Profile | Unconfined | Porous | S | 4 5 2 | |
| Shallow Geothermal | Unconfined | Porous | F, R | 1 6 2 | |
| Fluid Conductivity Log | Both | Both | F | 3 1 3 | |
| Neutron Activation | Both | Both | F, H, V | 3 3 5 | |
| Differential Temperature Log | Both | Both | F | 3 5 2 | |
| Flow Meters | Both | Both | F, H, V | 3 5 3-3 5 5 | |
| Single-Well Tracer Methods | Both | Both | F, H, V | 3 5 6 | |
| Other Borehole Methods | Both | Both | H | Section 3 | |
| Piezometric Map | Both | Both | F, H | 4 1 | |

[a] Chapter section and tables covering topic in U S EPA (1993)
Boldface = most commonly used methods
A = anisotropy; D = dispersivity; F = flow direction, H = heterogeneity, K = hydraulic conductivity, R = recharge/age, S = specific storage/yield, T = Transmissivity; V = Velocity

* Directional ratings are qualitative in nature Different references may give different ratings depending on site conditions and criteria used to define directionality For example, U S EPA (1981) and Hendrickx (1990) note that this method often measures primarily horizontal conductivity, whereas Bouma (1983) indicates that the direction is undefined (see Figure 7-2)

** Can be used in rocky soils, other methods generally require fine-grained soils

*** Can be used to measure saturated hydraulic conductivity both above and below the water table in open holes in consolidated rock

**** Actual uses are much more restricted due to health concerns relatively fast and inexpensive, they may be useful for measuring variations in hydraulic conductivity in the wellhead area with a shallow water table

### 3.3.2 Well Tests

Well tests are the most common and versatile methods for directly measuring aquifer parameters They fall into three main categories (1) single-well slug tests, (2) pumping tests (single and multi-well), and (3) packer tests (single- and two-packer) *Slug* tests involve measuring the rate at which water in a well returns to its initial level after (1) a sudden injection or withdrawal of a known volume of water from a well, or (2) instantaneous displacement by a float, weight, or change in pressure *Pumping* tests involve removing water from a well over a period of time from days to possibly weeks and measuring the changes in water levels in the pumping well (single-well test) and adjacent monitoring wells (multiple-well test) *Packer* tests are used to measure hydraulic conductivity in isolated sections of a borehole by monitoring the time-pressure response of the aquifer section when water is injected The data from well tests are plotted and matched against curves calculated using analytical solutions to ground water flow appropriate for the well construction and aquifer characteristics (Section 4 5)

As Table 3-7 indicates, all well tests measure hydraulic conductivity, but the types of other aquifer parameters that can be obtained from these tests vary Slug and packer tests provide information on relatively small portions of an aquifer, but are relatively easy to conduct and consequently are well-suited for characterizing aquifer heterogeneity Pumping tests are more complex and difficult to carry out, but provide information on a larger portion of the aquifer Pumping tests are the only well test method that provides information on the aquifer storage properties of an entire aquifer

A key element of aquifer testing is the selection of an appropriate analytical solution, or type curve developed from an analytical solution, to analyze the test data Characteristics of the aquifer should not violate the assumptions used in developing the analytical solution Checklist 4-1 should be used to identify key aquifer characteristics that affect aquifer test results ASTM (1991) provides guidance on the selection of aquifer well test methods Figure 3-12 provides a decision tree for the selection of methods covered in that guide Table 3-8 provides an index of references that give analytical solutions to aquifer test data according to pump test conditions and type of test This table includes quite a few references not cited in ASTM (1991) and is most likely to be useful when aquifer conditions depart significantly from assumptions in the most commonly used analytical methods (Sections 4 4 and 4 5) Well test methods are best suited for porous media, and most methods tend to give misleading results where fracture or conduit flow is an important component of ground water flow Section 5 4 2 discusses how the response of an aquifer to pumping can be used to evaluate whetner fracture flow is a significant component of flow in an aquifer

### 3.3.3 Tracer Tests

Ground water tracers are primarily used to identify the source, direction, and velocity of ground water flow and the dispersion of contaminants Depending on the type of test and the hydrogeologic conditions, other parameters, such as hydraulic conductivity, porosity, chemical distribution coefficients, source of recharge, and age of ground water can also be measured Any detectable substance that can be injected into the subsurface and travel in the vadose or saturated zone can serve as a tracer Table 3-9 identifies more than 60 substances that have been reported or suggested as tracers in ground water studies Any contaminant that is detected in ground water functions as a tracer, provided that the original source is known

Table 3-9 groups tracers into seven major categories and provides some summary information on uses of these groups of tracers for aquifer characterization The categories are (1) ions and other water soluble compounds, (2) dyes, (3) gases, (4) stable isotopes, (5) radioactive isotopes, (6) water temperature, and (7) particulates (including spores, bacteria, and viruses) Dyes and ions are probably the most commonly used tracers at contaminated sites Dye tracer tests are especially valuable for characterizing fracture flow and flow in karst limestone systems, where conventional well tests may yield misleading results and ground water flow directions tend to be unpredictable Tritium, released into the atmosphere during nuclear bomb testing in the 1950s, serves as a useful tracer to identify ground water that has been recharged in the last 30 years or so

### 3.3.4 Other Techniques

Table 3-7 identifies ten miscellaneous techniques for aquifer characterization Piezometric maps were covered in detail in the previous chapter Numerous procedures have been developed for hydrologic analysis based on the *water balance* or *budget* for an area A simple water balance equation is as follows (Dunne and Leopold, 1978)

$$\Delta GWS = P - I - AET - OF - \Delta SM - GWR \qquad (3\text{-}5)$$

where

$\Delta GWS$ = change in ground water storage

$P$ = precipitation

$I$ = interception

AET = actual evapotranspiration
OF = overland flow
ΔSM = change in soil moisture
GWR = ground water outflow

Many variants are possible The usual procedure is to formulate the equation with the parameter of interest on the left-hand side and the other components that define the hydrologic system of an area or aquifer of interest on the right-hand side Dunne and Leopold (1978) and Brown et al (1983) are good sources for further information on the water balance approach

The most useful application of the water balance approach in relation to wellhead protection is for estimation of recharge in the zone of contribution of a well The Thornthwaite Water Balance method is commonly used for this purpose (Thornthwaite and Mather, 1955 and 1957) In an unconfined aquifer, changes in soil moisture profiles in response to changes in the water table provide an alternative to pumping tests for measurement of *specific yield*

The barometric efficiency of confined aquifers, a measure of the response of a confined aquifer to changes in atmospheric pressure, is being increasingly used to estimate aquifer storage properties and transmissivity (Section 2 1 5 and Table 2-3) Table 3-7 also identifies some of the more commonly used borehole geophysical logging methods for measuring aquifer parameters These methods are used primarily for characterizing aquifer heterogeneity vertically within a single borehole and laterally between boreholes Chapter 5 (Hydrogeologic Mapping) describes this process further

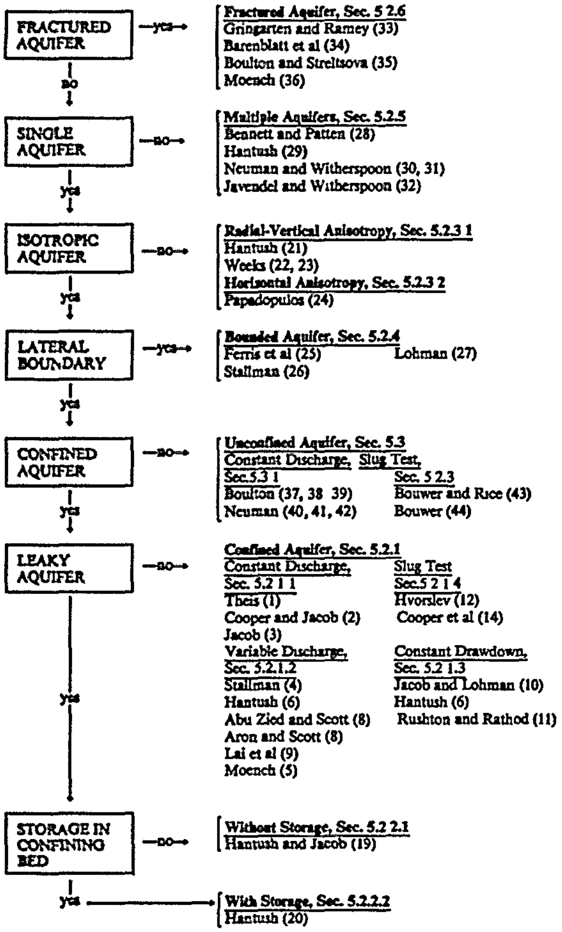

**Figure 3-12.** Decision tree for selection of aquifer test methods (ASTM, 1991)

**Table 3-8 Index to References on Analytical Solutions for Pumping Test Data**

| Pump Test Conditions | References |
|---|---|
| *Confined* | |
| Non-leaky, fully penetrating wells | *Constant Discharge* Theis (19935), Cooper and Jacob (1946), Jacob (1950), *Variable Discharge* Abu-Zied and Scott (9163), Aron and Scott (1965), Hantush (1964), Lai et al (1973), Moench (1971), Stallman (1962), *Constant Drawdown* Hantush (1964), Jacob and Lohman (1952), Rushton and Rathod (1980), *Unclassified* Boulton and Streltsova (1977a,b)*, Brutsaert and Corapcioglu (1976), Moench and Prickett (1972), Papadopulos (1967) |
| Non-leaky, partially penetrating wells | Hantush (1964) |
| Leaky, fully penetrating wells | *No Storage in Confining Bed* Hantush and Jacob (1955), *Storage in Confining Bed* Hantush (1960), *Multiple Aquifers* Hantush (1967), Neuman and Witherspoon (1972), *Unclassified* Corapcioglu (1976), Hantush (1956, 1959, 1964*), Jacob (1946), Lai and Su (1974) |
| *Unconfined* | |
| Fully penetrating wells | *Constant Discharge* Boulton (1954a, 1954b, 1963), Neuman (1972, 1973), *Unclassified* Boulton and Streltsova (1978)*, Cooper and Jacob (1946), Jacob (1963), Neuman (1975)*, Prickett (1965) |
| Partially penetrating wells | Hantush (1962), Boulton and Streltsova (1976)*, Streltsova (1974*, 1976*) |
| *Multiple Aquifers* | Aral (1990a, 1990b), Bennet and Patton (1962), Hantush (1967), Javendal and Witherspoon (1969), Neuman and Witherspoon (1969-confined, 1972-leaky) |
| *Lateral Boundary* | Ferris et al (1962), Lohman (1972), Stallman (1963) |

* Analytical solutions for anisotropic aquifer conditions See also Table 3-10

Source Categories in first column taken from Driscoll (1986), subcategories in the second column taken from ASTM (1991) Unclassified references are identified in Driscoll (1986), but not ASTM (1991)

**Table 3-9 List of Major Ground Water Tracers**

| | INJECTED TRACERS | | |
|---|---|---|---|
| **Natural Tracers** | **Radioactive** | **Activable** | **Inactive** |
| *Stable Isotopes* | | | *Ionized Substances* |
| Deuterium ($^2H$) | Tritum | Bromine-35 | $Na^+$ Cl |
| Oxygen-18 | Sodium-24 | Indium-39 | $K^+$ Cl |
| Carbon-12 | Chromium-51 | Manganese-25 | $Li^+$ Cl |
| Carbon-13 | Cobalt-58 | Lanthanum-57 | $Na^+$ I |
| Nitrogen-14 | Cobalt-60 | Dysprosium-68 | $K^+$ $Br^-$ |
| Nitrogen-15 | Gold-198 | | |
| Strontium-88 | Iodine 131 | | *Drift Material* |
| Sulfur-32 | Phosphorus-32 | | |
| Sulfur-34 | | | Lycopodium spores |
| Sulfur-36 | | | Bacteria |
| | | | Viruses |
| *Radioactive Isotopes* | | | Fungi |
| | | | Sawdust |
| Tritium ($^3H$) | | | |
| Carbon-14 | | | *Fluorescent Dyes* |
| Silicon-32 | | | |
| Chlorine-36 | | | Optical brighteners |
| Argon-37 | | | Tinopal 5Bm6x(FDA 22) |
| Argon-39 | | | Direct Yellow 96 |
| Krypton-81 | | | Fluorescein |
| Krypton-85 | | | Acid Yellow 7 |
| Bromine-32 | | | Rhodamine WT |
| Radon-222 | | | Eosin (Acid Red 87) |
| | | | Amidorhodamine 6 (Acid Red 50) |
| *Gases* | | | |
| | | | *Physical Characteristics* |
| Fluorocarbons | | | |
| | | | Water Temperature |
| | | | Flood pulse |
| | | | *Gases* |
| | | | Helium |
| | | | Argon |
| | | | Neon |
| | | | Krypton |
| | | | Xenon |

Source U S EPA (1993)

### 3.3.5 Measurement of Anisotropy

Measurement of anisotropy requires determination of the direction of maximum and minimum hydraulic conductivity In a homogenous, horizontally layered aquifer, the direction of minimum conductivity is usually assumed to be in the vertical direction, and the maximum in the horizontal direction (Section 2 2 2) Fetter (1981) suggests collecting undisturbed cores for measurement of vertical hydraulic conductivity in the laboratory and using slug tests, which primarily measure horizontal conductivity, in the test hole This procedure also requires installation of at least three wells to determine accurately the orientation of equipotential lines

A number of other methods have been developed for estimating anisotropy in layered aquifers using pumping tests Most require a minimum of two or three observation wells, in addition to a pumping well, to measure the degree of departure from a circular cone of depression that occurs in an isotropic aquifer In fractured rock aquifers, anisotropy can occur in three directions with no principle axis aligned in a vertical or horizontal direction In this situation, various approaches have been developed for measuring anisotropy using packer tests in multiple holes The *dipole flow test,* recently described by Kabala (1993), is a single hole, multi-level packer test that measures distribution of horizontal and vertical hydraulic conductivity and the specific storativity when applied to different bounded intervals

Table 3-10 provides an index to references where more detailed information on specific methods for measuring anisotropy can be obtained Figure 5-3 in Chapter 5 illustrates pumping test responses that serve as qualitative indicators of anisotropy

## 3.4 Laboratory Measurements of Aquifer Parameters

Laboratory measurements of the properties of aquifer materials require the collection of undisturbed soil cores using thin-wall samplers for unconsolidated materials or rotating core samplers for rock Porosity can be calculated if the dry bulk density of a known volume of soil or rock and the average particle density are known (Danielson and Sutherland) Various laboratory methods are available for measuring saturated hydraulic conductivity of soil cores Alemi et al (1986), ASTM (1968, 1990), Cleveland et al (1992), Klute and Dirksen (1986)

A disadvantage of measuring aquifer properties from core samples is that they sample a very small portion of the aquifer. Consequently, values for hydraulic conductivity tend to be low compared to values measured in the field, which include the effects of secondary porosity and aquifer heterogeneities (Bradbury and Muldoon, 1990, Bryant and Bodocsi, 1987) On the other hand, laboratory measurement of multiple samples can provide valuable information on the vertical and lateral variability of aquifer properties This information is especially important for constructing grids for three-dimensional aquifer modeling (Chapter 6)

## 3.5 References*

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**Table 3-10 Index to References on Characterizing Hydraulic Properties of Anisotropic and Fractured Rock Aquifers**

| Topic | References |
|---|---|
| *Anisotropy* | |
| General | Bear and Dagan (1965), Fetter (1981), Freeze (1975), Liakopoulos (1965), Maasland (1957a, 1957b), Marcus (1962), Scheidegger (1954) |
| Pump Test Methods* | *Cited by ASTM* Hantush (1961), Papadopoulos (1965), Neuman (1975), Weeks (1964, 1969), *Other Citations* Boulton and Streltsova (1976), Butler and Liu (1993), Dagan (1967), Hantush (1966a, 1966b), Hantush and Thomas (1966), Hsieh and Neuman (1985), Mansur and Dietrich (1965), Neuman et al (1984), Norris and Fidler (1966), Way and McKee (1982) |
| Other Methods | *Laboratory Methods* Banton (1993), Rocha and Franciss (1977), *Other Field* Loo et al (1984-surface tiltmeter survey), Maasland (1955-auger hole method) |
| *Fractured Rock* | |
| General | Duguid and Lee (1977), Gal (1982), Gerke and van Genuchten (1993), Long and Billaux (1987), Long et al (1982), Nelson (1985), Schmelling and Ross (1989), Snow (1969), Tsang and Tsang (1987) |
| Pump Test Methods | *Cited by ASTM* Barenblatt et al (1960), Boulton and Streltsova (1977b), Gringarten and Ramey (1974), Moench (1984), *Other Citations* Boulton and Streltsova (1977a, 1978), Elkins and Skov (1960), Gal (1982), Gringarten (1982), Gringarten and Witherspoon (1972), Hsieh and Neuman (1985), Hsieh et al (1983, 1985), Jenkins and Prentice (1982), Lewis (1974), McConnell (1993), Ramey (1975), Sauveplane (1984), Smith and Vaughn (1985) |
| Other Methods | Barker and Black (1983-slug tests), Bianchi and Snow (1968-fracture orientation), Huntley et al (1992-specific capacity), Kerfoot (1992—thermal flowmeter, dye tracers), Moore (1992-hydrograph analysis), Ritzie and Andolesk (1992-azimuthal resistivity), Tsang (1992), Witherspoon et al (1987-seismic), Young and Waldrop (1990-EM borehole flowmeter) |

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Bianchi, L and D Snow 1968 Permeability of Crystalline Rock Interpreted from Measured Orientations and Apertures of Fractures Ann Arid Zone 8(2) 231-245

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* See Introduction for information on how to obtain documents

# Chapter 4
# Simple Methods for Mapping Wellhead Protection Areas

This chapter describes a number of simple methods for mapping wellhead protection areas (WHPAs) These range from the very simple arbitrary fixed radius method (Section 4 3 1), which requires only a map and a compass for inscribing a circle of the defined radius around a well, to analytical methods that can be solved graphically or with a hand calculator A microcomputer with a spreadsheet program, although not required, can greatly facilitate the use of these methods (Section 6 4 1)

Most of the methods covered in this chapter represent adaptations of basic ground water flow equations and equations developed to analyze data collected from pumping tests using one or more criteria for WHPAs (Section 4 1) Section 4 2 briefly examines some basic ground water flow equations, and the remaining sections describe fixed-radius and simplified shape methods (Section 4 3) and simple analytical methods for wellhead delineation (Sections 4 4 and 4 5)

## 4.1 Criteria for Delineation of Wellhead Protection Areas

U S EPA (1987) defined five criteria that may be used singly or in combination to define the area around a well in which contamination could represent a threat to drinking water drawn from the well (1) distance, (2) drawdown, (3) time of travel, (4) flow boundaries, and (5) assimilative capacity These are described briefly below Section 4 2 2 examines interactions between areas defined by thresholds established under different criteria

### *4.1.1 Distance*

The distance criterion uses a fixed radius or other dimension from a well to delineate a WHPA As discussed in Section 4 3 1, this criterion usually is based on some kind of analysis involving the application of other criteria to generalized hydrogeologic settings The approach is simple and very inexpensive It is only suitable as a preliminary step, because the criterion considers ground water flow or contaminant processes only indirectly Since the zone of contribution (Section 4 1 4) rarely is circular, a fixed radius that provides adequate protection will almost always include areas for which protective actions are not required Distance is also the *end-product* of the application of other delineation criteria

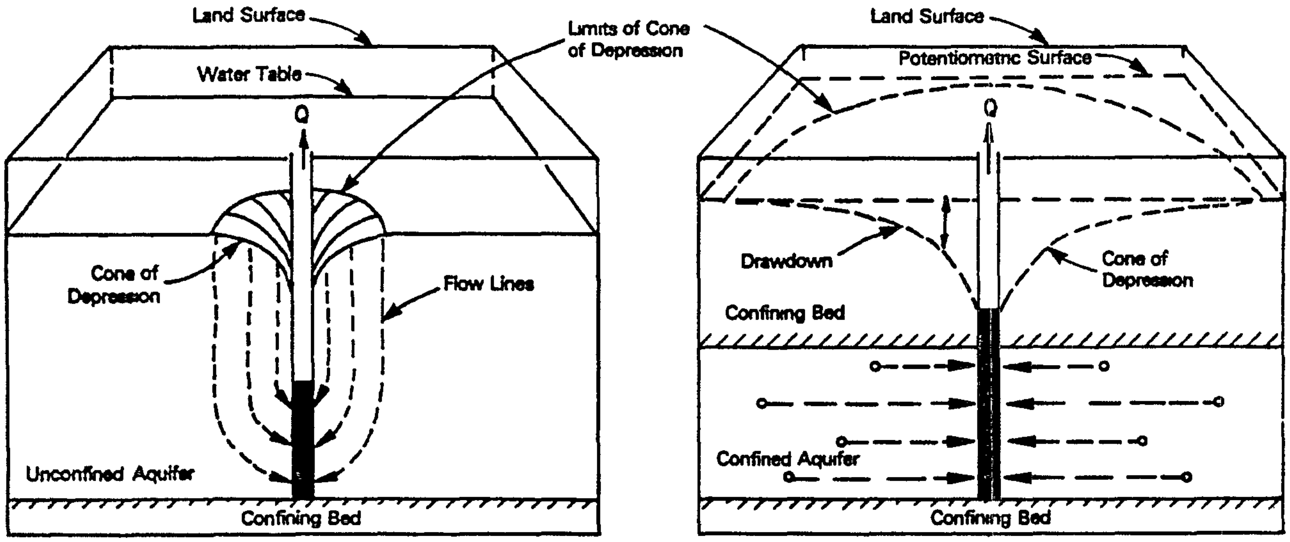
### *4.1.2 Drawdown*

Drawdown occurs when water is removed from an aquifer by pumping The water level declines in the vicinity of the well, creating a gradient that drives water toward the discharge point The gradient becomes steeper closer to the well, because the flow is converging from all directions and the area through which the water flows gets smaller This results in a *cone of depression* around the well (Figure 4-1) The cone of depression around a well tapping an unconfined aquifer is relatively small compared to that around a well in a confined system The former may be a few tens to a few hundred feet in diameter, while the latter may extend outward for miles

The *zone of influence* (ZOI) is the distance from the well where changes in the ground water surface can be measured or inferred as a result of pumping (Figure 4-2) In a homogenous, porous aquifer, the ZOI will be circular In heterogenous porous and fractures aquifers, the ZOI typically has an elliptical or irregular shape Ground water velocities increase within the cone of depression of a well, causing contaminants to flow more rapidly toward the well The drawdown criterion accurately defines areas requiring protection over the aquifer downgradient from the well, but generally does *not* include the zone of contribution upgradient based on flow boundaries (Figure 4-2 and Section 4 1 4)

### *4.1.3 Time of Travel (TOT)*

The time of travel criterion requires delineation of *isochrones* (contours of equal time) on a map that indicate how long water or a contaminant will take to reach a well from a point within the zone of contribution (Section 4 1 4) The WHPA falls in the portion of the zone of contribution that is downgradient from the selected isochronia (say 50 years time of travel) This area is called the *zone of transport* (ZOT) When the zone of contribution to a well is large (i e , ground water from the farthest parts may take hundreds or thousands of years to reach the well), the ZOT will define a smaller area than the



The cone of depression surrounding a pumping well in an unconfined aquifer is relatively small compared to that in a confined system

**Figure 4-1. Cones of depression in unconfined and confined aquifers (from Heath, 1983)**

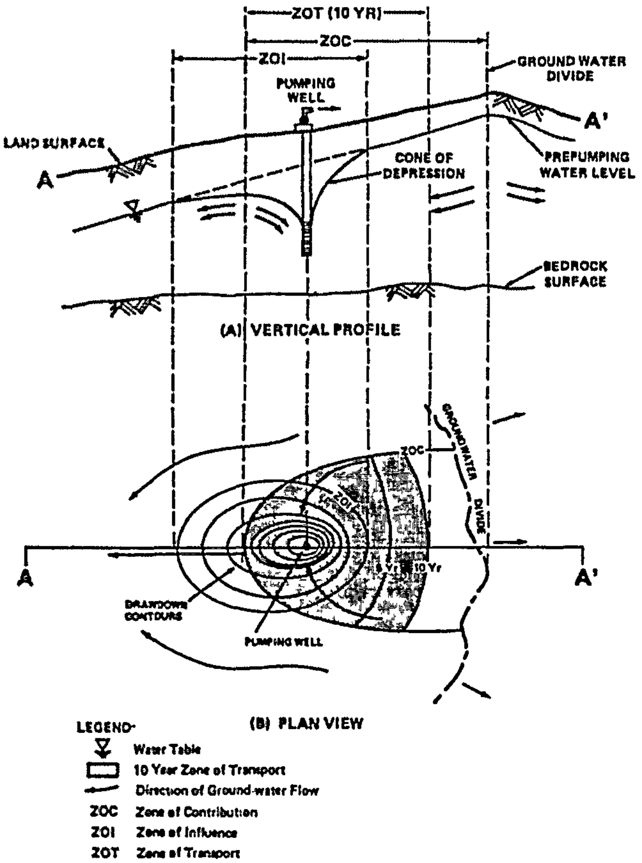


**Figure 4-2. Relationship between zone of influence (ZOI), zone of transport (ZOT), and zone of contribution (ZOC) in an unconfined porous-media aquifer with a sloping regional water table (from U S EPA, 1987)**

zone of contribution criterion (Figure 4-2) If the ZOC is small, the two will generally overlap

### 4.1.4 Flow Boundaries (Zone of Contribution)

The flow boundary criterion uses mapping of ground water divides and/or other physical and hydrologic features that control ground water flow to define the geographic area containing ground water that flows toward a pumping well (Figure 4-2) Designating this *zone of contribution* (ZOC) as the WHPA provides the maximum amount of protection, although there are special cases where the drawdown (zone of influence) and time of travel (zone of transport) criteria will coincide with the ZOC (Section 4 2 2)

### 4.1.5 Assimilative Capacity

The assimilative capacity criterion allows the reduction of a WHPA if contaminants are immobilized or attenuated while moving through the vadose zone of the aquifer so that concentrations are within acceptable limits by the time they reach a pumping well This may occur by processes of dilution, dispersion, sorption, chemical precipitation, and biological degradation (Section 1 2) A WHPA defined by this criterion would include the *zone of attenuation* (ZOA)

This criterion can be used in several ways Incorporation of an empirical *retardation factor* for a specific contaminant that represents the combined effects of attenuation processes in the aquifer into time of travel calculations would result in a shift of isochrones closer to the well A more complex application involves establishing an acceptable concentration of a contaminant at the well and using solute transport models to define the distance required to avoid exceeding the target concentration (Figure 4-3)

In practice, this is an unrealistic approach because of the difficulty of characterizing aquifer physical and chemical properties for transport modeling of multiple contaminants Where only one or two contaminants, such as nitrate loadings from septic tanks or pesticide loadings, are of primary concern, this approach may be very useful

## 4.2 Overview of Wellhead Protection Delineation Methods

### *4.2.1 Classification of Delineation Methods*

Because the process of wellhead delineation typically involves the use of more than one of the criteria discussed in the previous section, methods for wellhead delineation are not readily classified into distinctive categories This guide classifies WHPA delineation methods into four major groups of generally increasing complexity

1 *Geometric* methods that involve the use of a pre-determined fixed radius and aquifer geometry without any special consideration of the flow system, or the use of simplified shapes that have been pre-calculated for a range of pumping and aquifer conditions (Section 4 3)

2 *Simple analytical* methods that allow calculation of distances for wellhead protection using equations that can be solved using a hand calculator or microcomputer spreadsheet program These methods fall into two major groups, which are often used in combination time of travel calculations (Section 4 4) and drawdown calculations (Section 4 5)

3 *Hydrogeologic mapping,* which involves identification of the zone of contribution (as defined by flow boundaries) based on geomorphic, geologic, hydrologic, and hydrochemical characteristics of an aquifer This is often used in combination with simple analytical methods and is usually required when using more complex analytical and numerical computer flow and transport models Chapter 5 covers techniques for hydrogeologic mapping

4 *Computer modeling* methods, which involve the use of more complex analytical or numerical solutions to ground water flow and contaminant transport

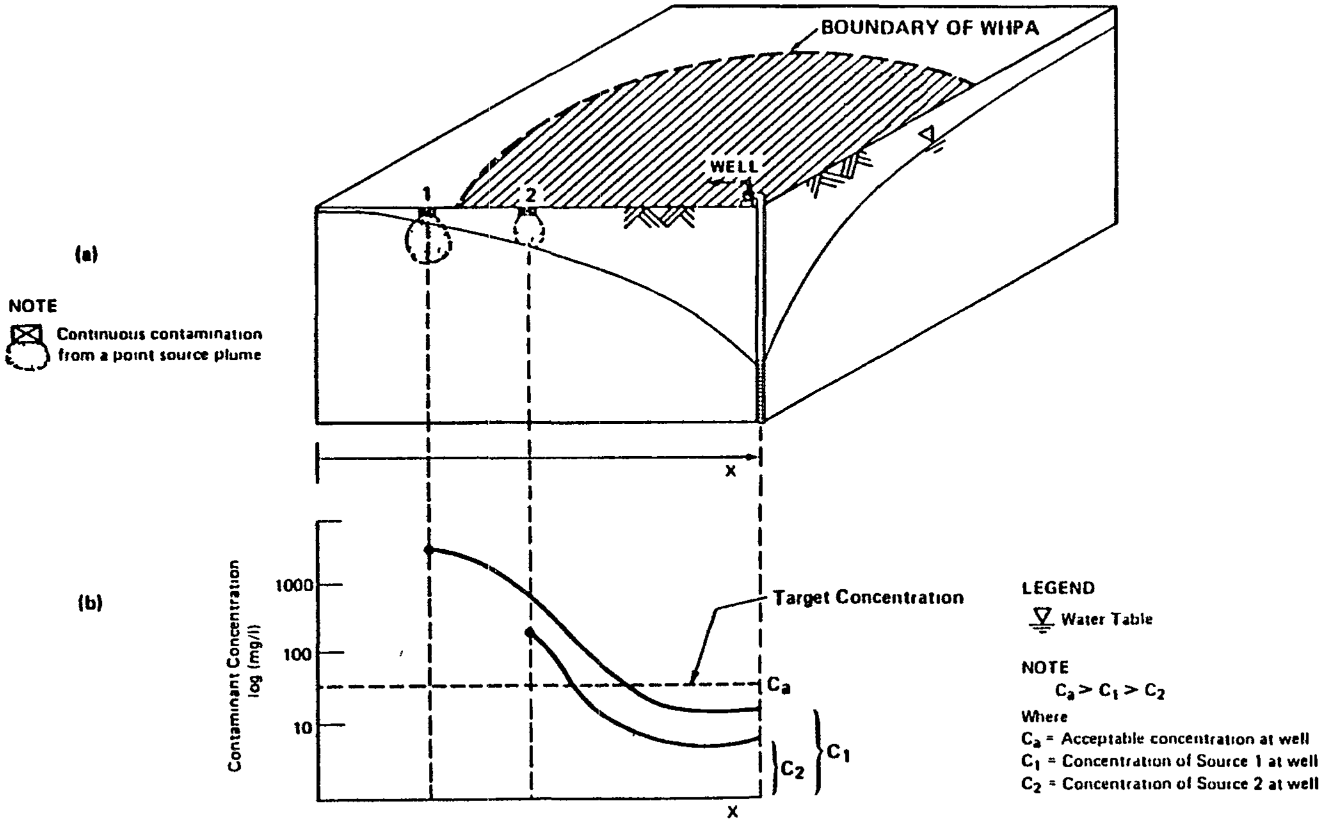


**Figure 4-3 Conceptual illustration of WHPA delineation based on zone of attenuation (from U S EPA, 1987)**

processes. These methods can be broadly grouped into simple and complex models, as discussed in Chapter 6

This classification scheme is generally similar to that used in U S EPA (1987) with the following differences (1) the arbitrary fixed radius, volumetric flow equation, and simplified shapes methods are all placed in the geometric category, (2) calculated fixed radius is dropped as a category because the two examples given fall into separate categories (the volumetric equation is geometric, and the Vermont Department of Water Resources method is a simple analytical method using a drawdown criterion), (3) the numerical flow/transport models category includes more complex analytical models that require computer programs for solution

Table 4-1 summarizes the advantages and disadvantages and identifies the type of threshold criteria used for the three geometric methods and the three other

**Table 4-1 Comparison of Major Methods for Delineating Wellhead Protection Areas**

| Methods/Criteria | Advantages | Disadvantages |
|---|---|---|
| *Geometric Methods* | | |
| Arbitrary Fixed Radius (distance) | —Easily implemented<br>—Inexpensive<br>—Requires minimal technical expertise | —Low hydrogeologic precision<br>—Large threshold radius required to compensate for uncertainty will generally result in overprotection<br>—Highly vulnerable aquifers may be underprotected<br>—Highly susceptible to legal challenge |
| Cylinder Method (calculated fixed radius) | —Easy to use<br>—Relatively inexpensive<br>—Requires limited technical expertise<br>—Based on simple hydrogeologic principles<br>—Only aquifer parameter required is porosity<br>—Less susceptible to legal challenge | —Tends to overprotect downgradient and underprotect upgradient because does not account for ZOC<br>—Inaccurate in heterogeneous and anisotropic aquifers<br>—Not appropriate for sloping potentiometric surface or unconfined aquifer |
| Simplified Variable Shapes (TOT, flow boundaries) | —Easily implemented once shapes of standardized forms are calculated<br>—Limited field data required once standardized forms are developed (pumping rate, aquifer material type and direction of ground water flow)<br>—Relatively little technical expertise required for actual delineation<br>—Greater accuracy than calculated fixed radius for only modest added cost | —Relatively extensive data on aquifer parameters required to develop the standardized forms for a particular area<br>—Inaccurate in heterogenous and anisotropic aquifers |
| *Other Methods* | | |
| Simple Analytical Methods (TOT, drawdown, flow boundaries) | —More accurate than simplified variable shapes because based on site-specific parameters<br>—Technical expertise required, but equations are generally easily understood by most hydrogeologists and civil engineers<br>—Various equations have been developed, allowing selection of solution that fits local conditions<br>—Allows accurate characterization of drawdown in the area closest to a pumping well<br>—Cost of developing site-specific data can be high | —Relatively extensive data on aquifer parameters required for input to analytical equations<br>—Most analytical models do not take into account hydrologic boundaries, aquifer heterogeneities, and local recharge effects |
| Hydrogeologic Mapping (flow boundaries) | —Well suited for unconfined aquifers in unconsolidated formations and to highly anisotropic aquifers such as fracture bedrock and conduit-flow karst<br>—Necessary to define aquifer boundary conditions | —Less suitable for deep, confined aquifers<br>—Requires special expertise in geomorphic and geologic mapping and judgement in hydrogeologic interpretations<br>—Moderate to high manpower and data collection costs |
| Computer Semi-Analytical and Numerical Flow/Transport Models (TOT, drawdown, flow boundaries) | —Most accurate of all methods and can be used for most complex hydrogeologic settings, except where karst conduit flow dominates<br>—Allows assessment of natural and human-related affects on the ground water system for evaluating management options | —High degree of hydrogeologic and modeling expertise required<br>—Less suitable than analytical methods for assessing drawdowns close to pumping wells<br>—Extensive aquifer-specific data required<br>—Most expensive methods in terms of manpower and data collection/analysis costs |

major types of methods for delineating WHPAs (simple analytical methods, hydrogeologic mapping, and computer modeling) With the minor differences described above, this table follows the sequence of methods covered in U S EPA (1987) Other important general references on wellhead protection delineation methods include Everett (1992), Matthess et al (1985), and Southern Water Authority (1985) Important references focusing on special geologic settings for WHPA delineation include Kreitler and Senger (1991) for confined aquifers and Bradbury et al (1991) for fractured rock aquifers

Guidance documents for WHPA delineation have been developed by a number of states Most of these documents use or elaborate on methods outlined in U S EPA (1987) Baize and Gilkerson (1992—South Carolina), Connecticut Department of Environmental Protection (1991a, 1991b), Heath (1991—North Carolina, also used in Piedmont areas of South Carolina and Georgia), Illinois Environmental Protection Agency (1990), Maryland Department of the Environmental (1991), Muldoon and Payton (1993—Wisconsin), New Hampshire Department of Environmental Services (1991), Oregon Department of Environmental Quality (1991), Swanson (1992—Oregon), Vermont Agency of Environmental Conservation (1983), and Vermont Agency of Natural Resources (1990)

In addition, all state submittals to the U S Environmental Protection Agency for approval of wellhead protection programs contain a section describing WHPA delineation methods to be used in the state Often these documents contain state-specific criteria foi the application of geometric methods (see examples in Section 4 3)

### *4.2.2 Relationship of Protection Areas Based on Different Criteria*

Table 4-2 provides summary definitions of types of wellhead areas based on four of the five criteria for wellhead protection (1) zone of influence (ZOI), (2) zone of travel (ZOT), (3) zone of contribution (ZOC), and (4) zone of attenuation (ZOA) The first criterion, a fixed distance threshold, is based on a qualitative or semiquantitative application of one or more of these criteria Table 4-2 also defines the hydrogeologic or other conditions required for one zone to be less than, equal to, or greater than another zone, and provides an indication of how commonly the relationship occurs In general the following relationships occur ZOA < ZOI < ZOT < ZOC

**Table 4-2 Relationships of WHPAs Based on Zone of Influence, Time of Travel, Zone of Travel, Zone of Contribution, and Zone of Attenuation**

| Terms/ Relationship | Description |
|---|---|
| Zone of Influence | ZOI = area of drawdown or the cone of depression around a well created by pumping |
| Zone of Travel[a] | ZOT = area around a well defined by a time of travel (TOT) isochron and aquifer boundaries $ZOT_{max}$ = ZOT defined by $TOT_{min}$ isochron or the edge of the ZOC, whichever is closer to the well |
| Zone of Contribution | ZOC = portion of an aquifer in which all recharge and ground water flows toward a pumping well The boundaries of the ZOC are defined by ground water divides and other aquifer boundaries |
| Zone of Attenuation | ZOA = area around an aquifer capable of reducing concentrations of a contaminant entering the area at a specified maximum concentration level to less than a defined acceptable concentration at the well |
| ZOI < ZOT | When distance to $TOT_{min}$ isochron (i e $ZOT_{max}$ boundary edge) lies outside the cone of depression Most common situation for unconfined aquifers |
| ZOI = ZOT | When distance to $TOT_{min}$ isochron = distance to ZOI boundary edge |
| ZOI > ZOT | When $TOT_{min}$ isochron lies within cone of depression for a well Unlikely to occur in unconfined aquifers, may occur in confined aquifers with very large ZOI |
| ZOI < ZOC | When upgradient ground water divide lies outside cone of depression The case in most hydrogeologic settings |
| ZOI = ZOC | Rare May occur with flat water table, with high recharge from rainfall within ZOI Also possible when ZOI straddles a ground water divide |
| ZOI > ZOC | Cannot occur |
| ZOT < ZOC | When distance to $TOT_{min}$ isochron < distance to ZOC boundary The most common situation The difference between the two zone decreases as the TOT threshold criterion increases |
| ZOT = ZOC | When distance to $TOT_{min}$ isochron = distance to ZOC boundary |
| ZOT > ZOC | By definition, cannot occur However, in this situation TOT is less than $TOT_{min}$ indicating that the well is very vulnerable to contamination from sources within the ZOC |
| ZOA < ZOT | When assimilative capacity is > 0 |
| ZOA = ZOT | When contaminant is not attenuated by the aquifer |

[a] Defined by time of travel criterion TOT = time of travel for ground water or contaminants from a point in an aquifer to a pumping well $TOT_{min}$ = the minimum acceptable time of travel for purposes of wellhead delineation TOT isochron = a line from which TOT is the same at all points to a pumping well

## 4.3 Wellhead Delineation Using Geometric Methods

Site-specific use of geometric methods for wellhead delineation requires no mathematical calculations (arbitrary fixed radius and simplified variable shapes) or very simple volumetric calculations based on pumping rate and aquifer porosity (cylinder method) The arbitrary fixed radius and simplified variable shape methods, however, must be based on prior use of more sophisticated analysis of ground water flow in hydrogeologic settings similar to the site at which the geometric method is being used Figure 4-4 illustrates these three methods

### 4.3.1 Arbitrary Fixed Radius

The arbitrary fixed radius method (Figure 4-4a) requires only (1) a base map, (2) a defined distance criterion based on a generalized application of time of travel or drawdown criteria to aquifers with similar characteristics to the aquifer to be protected, and (3) a compass to draw a circle with a radius around the well(s) that equals the distance criterion The method does not explicitly account for site-specific conditions, except that some assessment of the applicability of the assumptions used in developing the distance criterion to the site is required Table 4-1 summarizes advantages and disadvantages of this method

Figures 4-5 through 4-7 illustrate applications of this method. Figure 4-5 illustrates two graphs used in Massachusetts to determine a protective radius based on pumping rate The Zone 1 protective radius is subject to the most stringent protection measures and is applied to all wells (Figure 4-5a) The radius for interim wellhead protection (Figure 4-5b) is used to delineate an outer protective Zone II until the result of more accurate WHPA delineation methods are available Figure 4-6 illustrates a graph for determining the radius of an outer management zone based on pumping rate for crystalline rock aquifers in Georgia Figure 4-7 illustrates a graph for determining an initial protective radius in stratified drift aquifers based on both pumping rate and transmissivity. Table 4-3 illustrates a slightly different format for this method The Theis method (Section 4 5 3) was used to calculate typical 2- and 5-year time of travel distances at different pumping rates for the five major aquifer types in Idaho. This table allows identification of an interim protective radius until more accurate wellhead delineation methods can be used

### 4.3.2 Cylinder Method (Calculated Fixed Radius)

The cylinder method uses a volumetric flow equation to calculate a fixed radius around a well through which water will flow at a specified travel time (Figure 4-4b) The radius, in effect, defines a circular time of travel isochrone around the well, which, extended through the aquifer, delimits a cylinder with a pore volume equal to the volume of water pumped during the specified period The basic equation is:

$$Qt = n\pi Hr^2 \qquad (4\text{-}1)$$

where:

$Q$ = pumping rate of well
$t$ = time of travel threshold
$n$ = aquifer porosity
$H$ = open interval or length of well screen
$r$ = radius of cylinder

Solving for the radius, r, yields the equation

$$r = \mathrm{Sqrt}(QT/\pi nH) \qquad (4\text{-}2)$$

This equation is most appropriate for a highly confined aquifer with no vertical leakage from the overlying confining bed The Florida Department of Environmental Regulation uses the volumetric equation and a 5-year time of travel criterion to define Zone II of a WHPA (U S EPA, 1987)

The volumetric flow equation is not appropriate for unconfined aquifers because the cone of depression creates an aquifer geometry that is not cylindrical and does not take recharge into account It also requires a negligible regional gradient (<0 0005 or 0 001) Steeper gradients will result in a zone of influence that is not circular (see Figure 4-2) Since all water is assumed to come from the aquifer, the volumetric flow equation results in overprotection of semiconfined aquifers, because it does not account for flow into the aquifer from vertical leakage through the confining bed

If the vertical flow of water can be quantified by analyzing pumping test data or using the variant of Darcy's Law covered in Section 4 5 4, leakage can be incorporated into the volumetric equation as follows

$$Q = Q_a + Q_l \qquad (4\text{-}3)$$

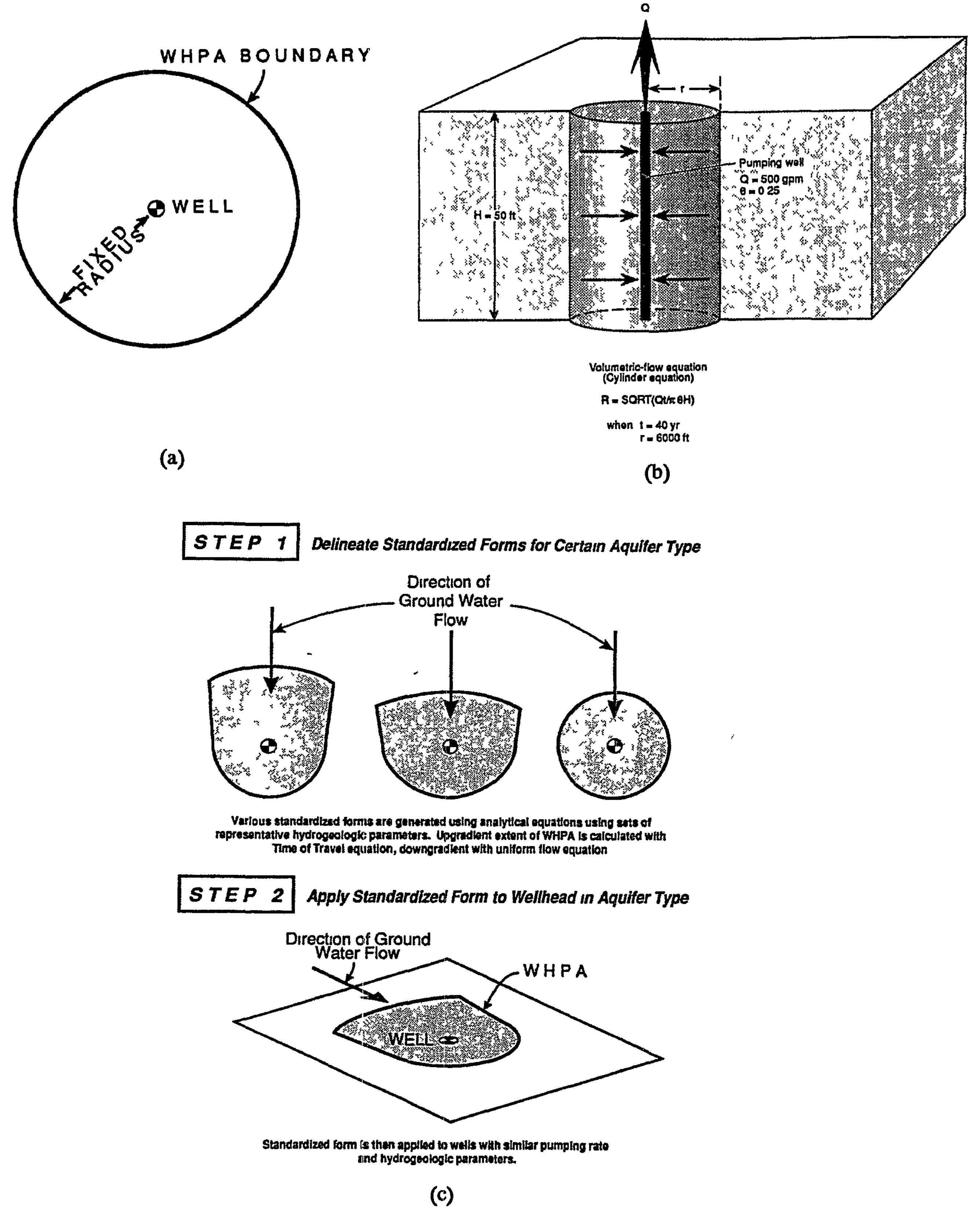
where

$Q_a$ = volume of water pumped from the aquifer
$Q_l$ = volume of water entering the aquifer through leakage

Since both of these values depend upon the radius, which is the unknown, a trial-and-error solution using a computer spreadsheet is probably the easiest way to determine the radius at which the $Q_a + Q_l$ equals the pumping rate

### 4.3.3 Simplified Variable Shapes

The simplified variable shapes approach is really based on a combination of analytical solutions using time of travel (Section 4 4) and drawdown equations (Section 4 5) Once the shapes are established, however, site-specific application of the method involves orienting and drawing the shapes on a base map without any mathematical calculations If aquifer characteristics (porosity, hydraulic conductivity) in an area are relatively uniform, representative or standardized shapes for different levels of pumping are established using drawdown and time of travel criteria If aquifer characteristics vary in the area in which the shapes are to be used, then different combinations of aquifer parameters and pumping rates



Volumetric-flow equation
(Cylinder equation)

R = SQRT(Qt/π θH)

when t = 40 yr
r = 6000 ft

Various standardized forms are generated using analytical equations using sets of representative hydrogeologic parameters. Upgradient extent of WHPA is calculated with Time of Travel equation, downgradient with uniform flow equation

Standardized form is then applied to wells with similar pumping rate and hydrogeologic parameters.

**Figure 4-4** WHPA delineation using geometric methods (a) fixed radius (U S EPA, 1991), (b) cylinder method, (c) simplified shapes (U S EPA, 1987)

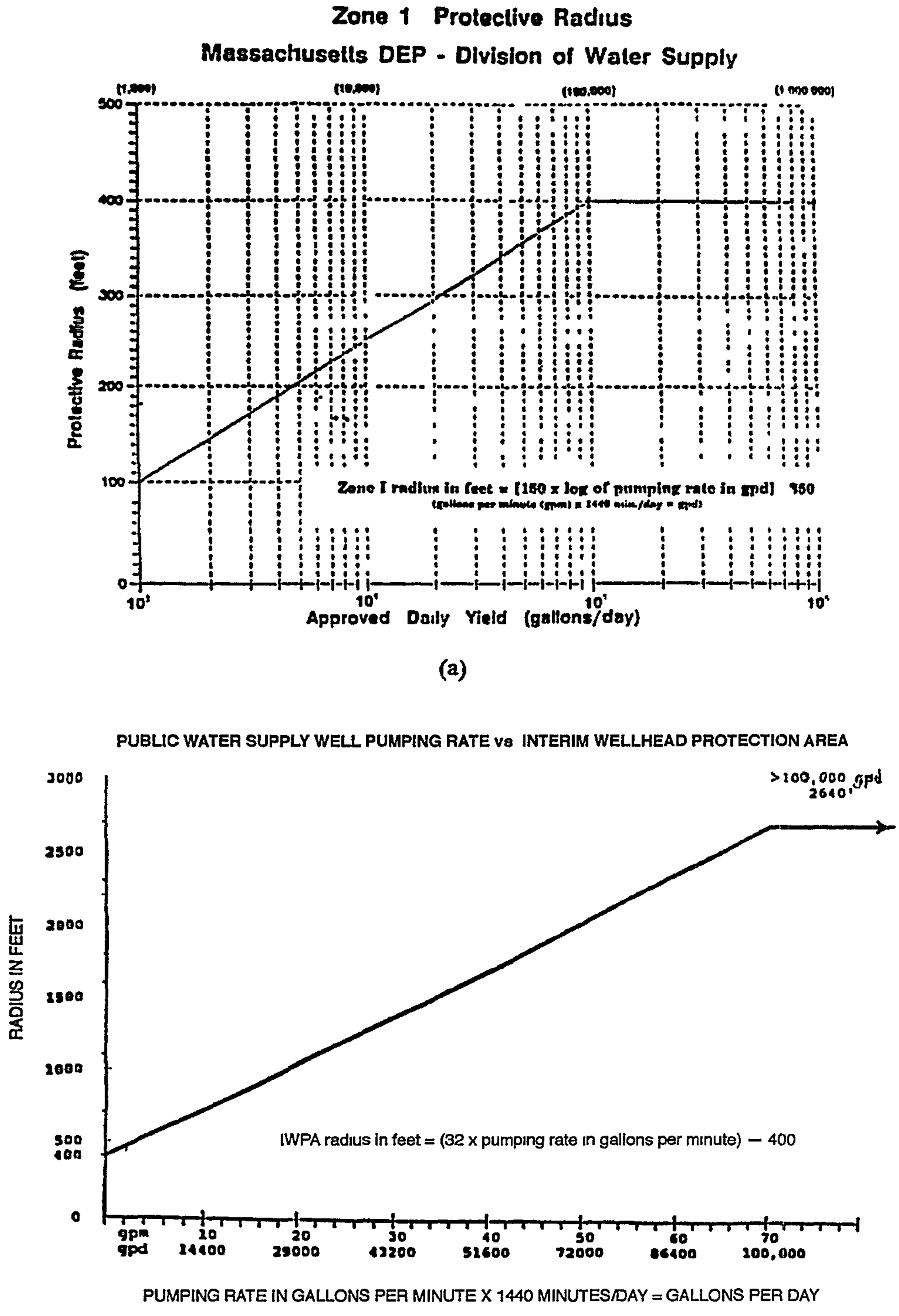


**Figure 4-5** Fixed radius for wellhead protection in Massachusetts based on pumping rate (a) Zone 1 protective radius, (b) protective radius for Zone II interim wellhead protection area (Pierce, 1992)

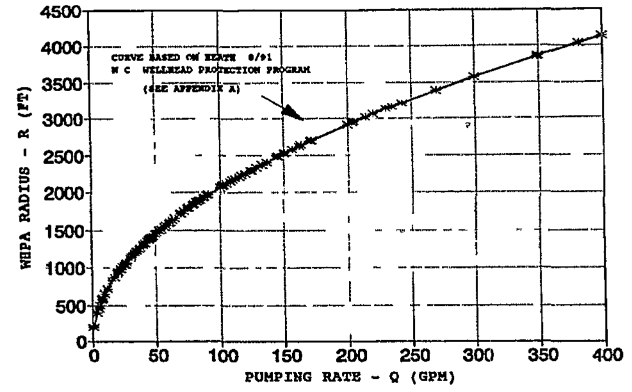


**Figure 4-6** Radius of outer management zone based on pumping rate for crystalline rock aquifers, Piedmont and Blue Ridge (Georgia Department of Natural Resources, 1992, based on Heath, 1991)

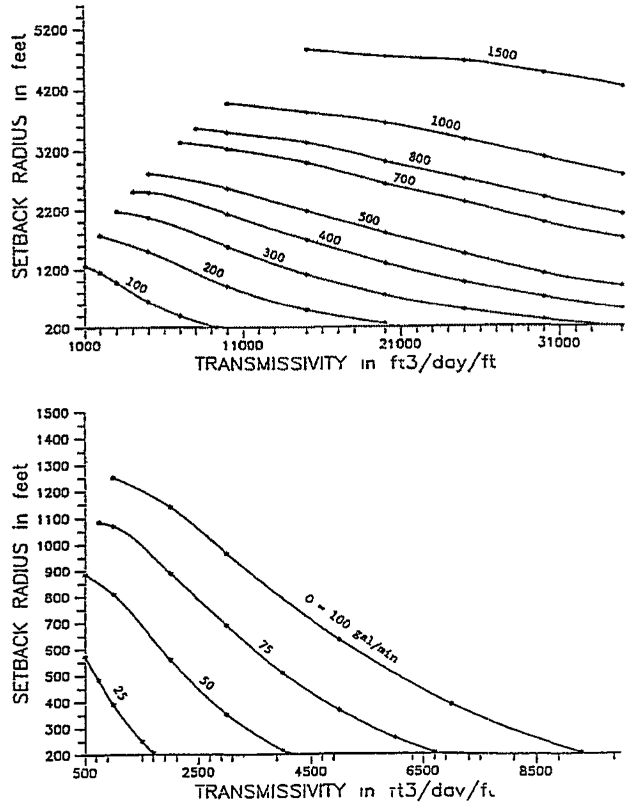


**Figure 4-7** Initial setback distance for level B mapping of stratified drift aquifers based on pumping rate and transmissivity (Connecticut Department of Environmental Protection, 1991b)

are tested to determine a large set of shapes Hundreds of calculations may be required to establish "typical" shapes for different aquifer characteristics and pumping rates

This method requires that the necessary preliminary work to define shapes has been completed Delineation of a WHPA then only requires (1) enough information about a well to determine which shape "fits," and (2) knowledge of the general direction of natural ground water flow to orient the shape if it has any asymmetry Figure 4-4c illustrates this process Table 4-1 identifies relative advantages and disadvantages of this method Figure 4-8 illustrates shapes used in New Jersey for delineation of interim WHPAs in the three major types of aquifers found in that state

## 4.4 WHPA Delineation Using Simple Analytical Methods: Time of Travel (TOT)

Dozens of analytical equations have been developed to solve ground water flow problems The reason for the large number is that different hydrogeologic settings and well configurations require modifications of basic ground water flow equations (Darcy's Law and the equation of continuity) to account for aquifer boundary conditions and other conditions, such as partial rather than full penetration of an aquifer by a well Any ground water flow equation can be reformulated to solve for distance at a specified travel time The important thing is to choose an equation with assumptions appropriate for the well and aquifer in question This is discussed further in Section 4 5

Many analytical equations describing ground water flow can be solved with a hand calculator or by using a microcomputer spreadsheet program (Section 6 4 1) This section focuses on time of travel equations that have been reported in the wellhead protection literature that do not require special programming ability or off-the-shelf software packages Section 6 4 2 discusses in more detail relatively easy-to-use computer software programs that allow more computationally complex analytical and semianalytical solutions to ground water flow problems without the extensive data and specialized knowledge required for numerical modeling with computers

The equations covered here do not consider hydrodynamic dispersion (Section 1 2 2) or contaminant retardation processes (Sections 1 3 and 4 1 5) In homogeneous aquifers with no secondary porosity, retardation processes for most contaminants tend to be more significant than dispersion In this situation, time of travel calculations will generally be overprotective Where contaminants are not subject to attenuation (for example, chlorides and nitrates) and where facilitated transport is occurring (Section 1 2 4), time of travel calculations should provide a reasonably accurate delineation of the area at risk

On the other hand, time of travel calculations for homogenous aquifers with significant secondary porosity and heterogeneous aquifers may significantly underprotect wellhead areas, because hydrodynamic

Table 4-3 Calculated Fixed Radii for Major Aquifers in Idaho (Idaho Wellhead Protection Work Group, 1992)

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| E. SNAKE RIVER PLAIN BASALTS | | | | | | | | | | |
| PUMP RATE | 50 GPM | 100 GPM | 500 GPM | 1000 GPM | 2000 GPM | 3000 GPM | 4000 GPM | 5000 GPM | 6000 GPM | 7000 GPM |
| 2 YEAR TOT | 1800' | 1600' | 2000' | 2300 | 2700' | 3100' | 3500' | 3900 | 4200' | 4600' |
| 5 YEAR TOT | 4400' | 4400' | 4700' | 5000' | 5600' | 6000' | 6500' | 6900' | 7300' | 7700' |
| COLUMBIA RIVER BASALTS | | | | | | | | | | |
| PUMP RATE | 50 GPM | 100 GPM | 500 GPM | 1000 GPM | 2000 GPM | 3000 GPM | 4000 GPM | 5000 GPM | 6000 GPM | 7000 GPM |
| 2 YEAR TOT | 300' | 400' | 900' | 1300' | 2200' | 2900' | 3700' | 4500' | 5300' | 6000' |
| 5 YEAR TOT | 400' | 600' | 1300' | 2000' | 2900' | 3700' | 4600' | 5400' | 6200' | 7000' |
| UNCONSOLIDATED ALLUVIUM | | | | | | | | | | |
| PUMP RATE | 50 GPM | 100 GPM | 500 GPM | 1000 GPM | 2000 GPM | 3000 GPM | 4000 GPM | 5000 GPM | 6000 GPM | 7000 GPM |
| 2 YEAR TOT | 6500' | 6600' | 7100' | 7700' | 8800' | 10000' | 11000 | 12000 | 13000' | 14000' |
| 5 YEAR TOT | 16000' | 16000' | 17000' | 18000' | 19000' | 20000' | 21000' | 22000' | 23000' | 24000' |
| MIXED VOLCANICS/SEDIMENTARY ROCKS – PRIMARILY SEDIMENTARY ROCKS | | | | | | | | | | |
| PUMP RATE | 50 GPM | 100 GPM | 500 GPM | 1000 GPM | 2000 GPM | 3000 GPM | 4000 GPM | 5000 GPM | 6000 GPM | 7000 GPM |
| 2 YEAR TOT | 200' | 200' | 400' | 600 | 900' | 1000' | 1300' | 1600' | 1800' | 2000' |
| 5 YEAR TOT | 300' | 400' | 700' | 1000' | 1300' | 1700 | 1900' | 2200 | 2500' | 2700' |
| MIXED VOLCANICS/SEDIMENTARY ROCKS – PRIMARILY VOLCANICS AND SEDIMENTARY ROCKS | | | | | | | | | | |
| PUMP RATE | 50 GPM | 100 GPM | 500 GPM | 1000 GPM | 2000 GPM | 3000 GPM | 4000 GPM | 5000 GPM | 6000 GPM | 7000 GPM |
| 2 YEAR TOT | 3200' | 3300' | 3400' | 3600 | 3900' | 4200 | 4500 | 4800 | 5000' | 5400' |
| 5 YEAR TOT | 8200' | 8200' | 8400' | 8600 | 9000 | 9300' | 9700 | 10000' | 10000' | 11000' |

GPM = Gallons per minute TOT = Time of Travel

dispersion tends to be more significant than retardation in such aquifers Hydrodynamic dispersion is significant in these aquifers for several reasons (1) highly permeable porous zones and fracture/conduit flow result in localized velocities that are significantly higher than the average ground water velocity, (2) retardation processes are reduced in permeable zones (gravels, sands, fractures, conduits) because permeable aquifer materials tend to be less geochemically reactive For example, the cation exchange capacity (CEC) of a sandy permeable zone in an aquifer will be significantly lower than the CEC of less permeable fine-grained sediments It is necessary to choose higher-than-measured hydraulic conductivity values or use values in the upper range of similar aquifer materials (Section 3 2 2) when the potential for hydrodynamic dispersion is high

### *4.4.1 TOT Using Darcy's Law and Flow Net*

The simplest equation for calculating time of travel is the form of Darcy's law that describes average linear velocity:

$$\bar{v} = Ki/n \qquad (4\text{-}4)$$

where:

$\bar{v}$ = average interstitial (linear) velocity
K = horizontal hydraulic conductivity
i = horizontal hydraulic gradient
n = porosity

This equation is most easily used when a potentiometric map of the aquifer is available for measuring hydraulic gradients For preliminary calculations, K and n can be estimated (Chapter 3) Once average velocity is known, the time of travel over a given distance can be easily calculated

$$t = d/\bar{v} = dn/Ki \qquad (4\text{-}5)$$

where
t = specified time of travel
d = distance

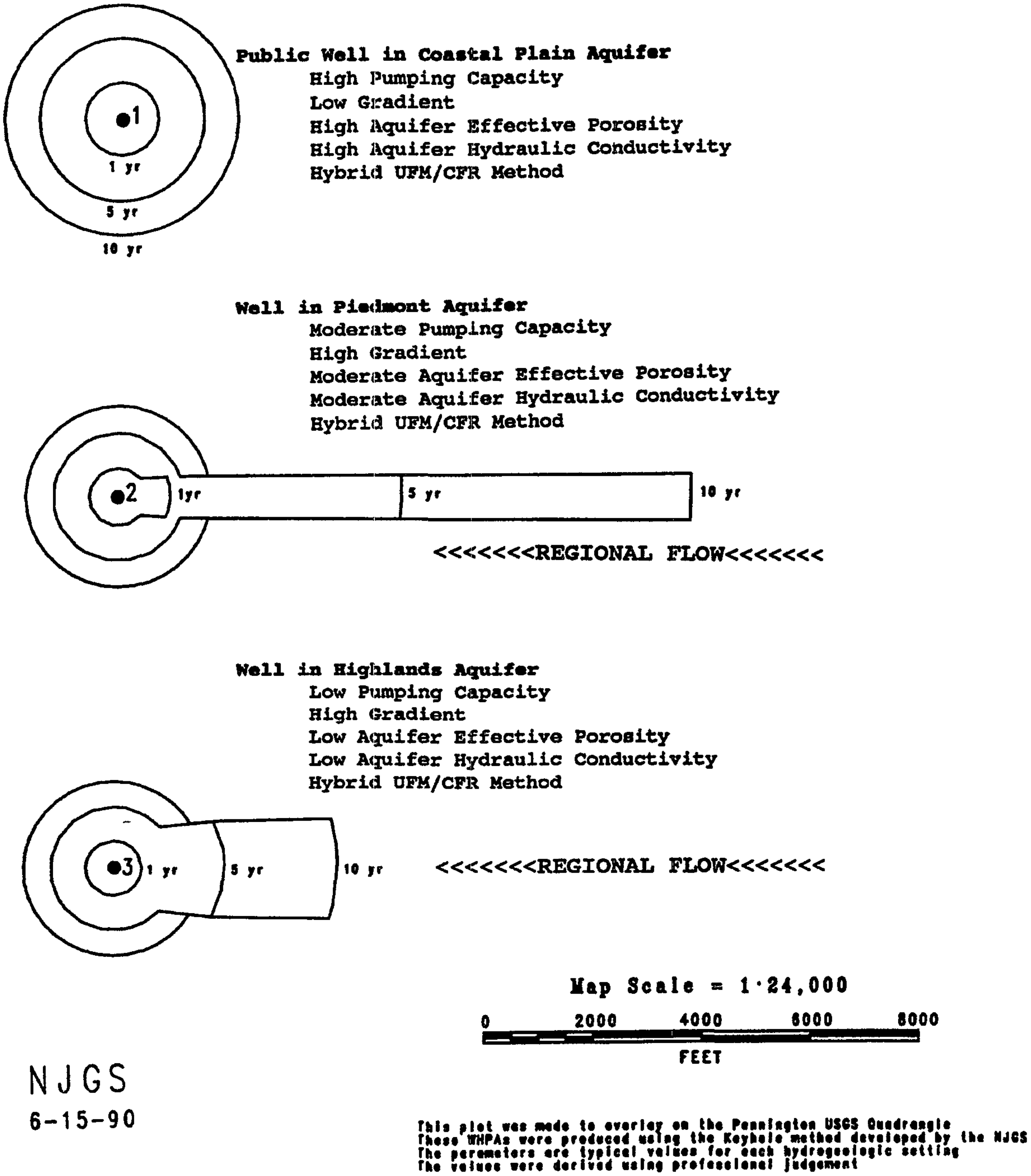
Or the distance to time of travel contours is calculated as follows

$$d = \bar{v}t = tKi/n \qquad (4\text{-}6)$$

where
d = the upgradient distance from the well to the TOT line
$\bar{v}$ = average linear velocity (Equation 4-4)
t = specified time of travel

Sidebar 4-1 illustrates use of these equations This equation is most applicable to the following situations

- To calculate time of travel in a highly confined aquifer with a nearly flat potentiometric surface (gradient of <0 0005 to 0 001)
- To calculate time of travel in an unconfined aquifer with a nearly flat water table and with drawdown that



**Public Well in Coastal Plain Aquifer**
- High Pumping Capacity
- Low Gradient
- High Aquifer Effective Porosity
- High Aquifer Hydraulic Conductivity
- Hybrid UFM/CFR Method

**Well in Piedmont Aquifer**
- Moderate Pumping Capacity
- High Gradient
- Moderate Aquifer Effective Porosity
- Moderate Aquifer Hydraulic Conductivity
- Hybrid UFM/CFR Method

**Well in Highlands Aquifer**
- Low Pumping Capacity
- High Gradient
- Low Aquifer Effective Porosity
- Low Aquifer Hydraulic Conductivity
- Hybrid UFM/CFR Method

This plot was made to overlay on the Pennington USGS Quadrangle
These WHPAs were produced using the Keyhole method developed by the NJGS
The parameters are typical values for each hydrogeologic setting
The values were derived using professional judgement

Figure 4-8. Interim wellhead protection areas in New Jersey using simplified variable shapes (New Jersey Department of Environmental Protection and Energy, 1991)

### Sidebar 4-1.
### Example Velocity and Time of Travel Calculations

Interstitial velocity can be estimated by the following equation

$\bar{v} = Ki/n$

where
K = hydraulic conductivity
i = hydraulic gradient
$\bar{v}$ = average velocity, in ft/d
n = effective porosity

Time of travel can be calculated from the velocity using the distance between the points for which the gradient is calculated

$t = d/v/365$
where
t = time of travel in years
d = distance in feet

The following example involves a spill of a conservative substance such as chloride The liquid waste infiltrates through the unsaturated zone and quickly reaches a water table aquifer that consists of sand and gravel with a hydraulic conductivity of 2,000 gpd/ft$^2$ and an effective porosity of 0 20 The water level in a well at the spill lies at an altitude of 1,525 feet and, at a well a mile directly downgradient, is at 1,515 feet The velocity of the water and the contaminant, and the time it will take for the chloride to contaminate the second well, can be determined by the following equations

$v = (2{,}000\ \text{gpd/ft}^2) \times (10\ \text{ft}/5{,}280\ \text{ft})/\ 20 =$
$18\ 9\ \text{gpd/f}^2 = 2\ 5\ \text{ft/d}^*$

$t = 5{,}280\ \text{ft}/2\ 5\ \text{ft/d} = 2{,}112$ days or 5 8 yr

Rearranging the time of travel equation allows calculation of a fixed radius for a wellhead protection area based on a time of travel threshold criterion

$d = 365tv$

In the above example, a threshold of 10 years would result in an upgradient distance of 9,125 feet

* 1 ft/d = 7 48 gpd/ft$^2$

is small compared to the aquifer or screened interval (<10 percent)

- To calculate time of travel of a contaminant from a point source to a downgradient point of interest, *if* the equipotential lines are approximately equally spaced between the two points (i e , the aquifer is homogeneous) Somewhat more complex methods are required for wells with steep gradients in the cone of depression and wells in areas where there is a sloping regional water table (Sections 4 4 2 and 4 4 3)

Equation 4 in Table 4-4 can be used to calculate velocity induced by a pumping well with a circular cone of depression

### *4.4.2 Cone of Depression/TOT (Flat Regional Hydraulic Gradient)*

Steep hydraulic gradients may exist in the vicinity of a pumping well If this is the case, the changes in gradient over relatively short distances must be considered when using Equation 4-5 In confined aquifers especially, the cone of depression may create a surface of continually steepening gradients for a distance of miles from the well In this situation, Kreitler and Senger (1991) recommend calculating the time of travel for various incremental distances from the well (e g , 0 to 10 ft, 10 to 100 ft, 100 to 1,000 ft, etc ) using the hydraulic gradient for each increment (values for n and K remain the same for each calculation) The total time of travel to a given point is the sum of the times of travel of each increment Intermediate times of travel can be estimated graphically by plotting log of time of travel versus the log of distance, which should be an approximately linear relationship Alternatively, the distance between increments can be adjusted until the sum of the incremental TOTs equals the target TOT

Equation 10 in Table 4-4 (which is essentially the same as Equation 4-5) can be used for these calculations This method requires reasonably accurate measurement or estimation of the geometry of the cone of depression

### *4.4.3 TOT With Sloping Regional Potentiometric Surface*

The cone of depression of a pumping well is asymmetric when there is a significant slope with drawdown extending farther upgradient than downgradient Equations 5 and 6 in Table 4-4 can be used to calculate pumping induced velocities in this situation Two similar time of travel equations are available for this situation Kreitler and Senger (1991) give the following equation, modified from Bear and Jacob (1965)

$$t_x = n/Ki\ [r_x - (Q/2\pi Kbi)\ln\{1 + (2\pi Kbi/Q)r_x\}] \quad (4\text{-}7)$$

where
$t_x$ = travel time from point x to a pumping well
n = porosity
$r_x$ = distance over which ground water travels in $T_x$, $r_x$ is positive (+) if the point is upgradient, and negative (–) is downgradient

**Table 4-4 Drawdown and Capture-Zone Geometry Equations (from Pekas, 1992)**

---

DRAWDOWN CALCULATIONS - CONFINED AQUIFER (Section 4 5 3)

| | | |
|---|---|---|
| (1a) Theoretical Drawdown | $dh_c = \frac{192\ 5\ Q}{4\ Pi\ K\ b}\ W(u)$ | Huntoon (1980) |
| (1b) | $u = \frac{Sc\ R}{4\ K\ b\ t}$ | Huntoon (1980) |
| (2) Pumping Well Drawdown | $dh_c = \frac{2\ 3\ Q}{4\ Pi\ K\ b}\ \log\ \frac{2\ 25\ K\ b\ t}{r_w^2\ Sc}$ | Javandel & Tsang (1986) |

DRAWDOWN CALCULATIONS - UNCONFINED AQUIFER

| | | |
|---|---|---|
| (3) Approximate Drawdown | $dh_u = \frac{(2\ b + [(2\ b)^2 - (4\ 1\ 2\ b\ dh_c)]^{1/2})}{2}$ | Walton (1962, 1967) |

GROUND-WATER FLOW VELOCITY CALCULATIONS (Sections 4 4 1 and 4 4 3)

| | | |
|---|---|---|
| (4) Velocity from Pumping | $V_p = \frac{Q}{2\ Pi\ R\ b\ n_e}$ | Keely & Tsang (1983) |
| NET VELOCITY<br>(5) Upgradient from PW | $V_{u\ pw} = V_p + \frac{K\ i}{n_e}$ | Keely & Tsang (1983) |
| (6) Downgradient from PW | $V_{d\ pw} = V_p - \frac{K\ i}{n_e}$ | Keely & Tsang (1983) |

GROUND-WATER DIVIDE CALCULATIONS (Section 4 5 1)

| | | |
|---|---|---|
| (7) Distance to Stagnation | $SP = \frac{Q}{2\ Pi\ K\ b\ i}$ | Javandel & Tsang (1986) |
| (8) Divide at Pumping Well | $Y_{d\ pw} = \frac{Q}{2\ K\ b\ i}$ | Javandel & Tsang (1986) |
| (9) Divide at Upgradient | $Y_{d\ ug} = \frac{Q}{K\ b\ i}$ | Javandel & Tsang (1986) |

GROUND-WATER CAPTURE/TRAVEL TIME CALCULATIONS (Section 4 4 2)

| | | |
|---|---|---|
| (10) Capture/Travel Time | $t_{ct} = \frac{R\ n_e}{K\ i_p}$ | McLane (1990) |

---

WHERE

$Q$ = Discharge or pumping rate (gpm)
$Pi$ = 3 14159
$K$ = Hydraulic Conductivity (ft/day)
$b$ = Saturated Thickness (ft)
$t$ = Duration of pumping (days)
$r_w$ = Radius of pumping well (ft)
$S_c$ = Storage Coefficient/Specific Yield (ND)
$R$ = Radial distance from pumping well (ft)
$n_e$ = Effective porosity (Decimal)
$i$ = Hydraulic gradient of static aquifer (ft/ft)

$dh_c$ = Drawdown - confined (ft)
$dh_u$ = Approximate Drawdown - unconfined (ft)
$V_p$ = Pumping induced velocity (ft/day)
$V_{u\ pw}$ = Net velocity upgradient of well (ft/day)
$V_{d\ pw}$ = Net velocity downgradient of well (ft/day)
$SP$ = Distance downgradient to stagnation point (ft)
$Y_{d\ pw}$ = GW divide at pumping well (ft)
$Y_{d\ ug}$ = GW divide upgradient from pumping well (ft)
$i_p$ = Pumping induced hydraulic gradient (ft/ft)
$t_{ct}$ = Capture/Travel time for pumping well (days)

Q = discharge
K = hydraulic conductivity
b = aquifer thickness
i = hydraulic gradient

In southern England the simplified variable shapes method is used (see Section 4 3 3) employing the uniform flow equation (Section 4 5 1) and the following time of travel equation (Southern Water Authority, 1985)

$$t_x = S/v[\pm(r_x - r_w) + Z\ln\{(Z \pm r_w)/(Z \pm r_x)\}] \qquad (4\text{-}8)$$

where: $Z = Q/2\pi Kbi$

and other factors not defined above are
v = velocity (see Eq 4-4)
S = specific yield or storativity
$r_w$ = well radius

The plus or minus sign indicates a point upgradient and downgradient, respectively

Calculation of distance for a specific travel time requires trial-and-error calculations using different values for distances until the equation yields the desired travel time This can easily be done using a spreadsheet on a microcomputer

The main weaknesses of these equations are (1) they only provide distance for travel times along a line through the pumping well that is parallel to the regional hydraulic gradient (i e , one point upgradient and one point downgradient), and (2) they do not take into account recharge from the surface in unconfined aquifers or vertical leakage into semiconfined aquifers Where equipotential lines on a potentiometric map are not straight lines, this would be the shortest flow line up- and downgradient. To define a wellhead protection *area,* these equations must be used in combination with the uniform flow equation (Section 4 5 1)

Kreitler and Senger (1991) recommend pathline tracing models such as WHPA and GWPATH (Section 6 4 3) as the best method for calculating time of travel for confined aquifers with regionally sloping potentiometric surfaces, because they are able to actually define TOT contours

### 4.4.4 Interaquifer Flow and Time of Travel

The presence of a second aquifer separated by confining strata above or below a pumping well requires consideration of whether to incorporate interaquifer leakage into calculations for delineating a wellhead protection area. Most of the simple methods for delineating wellhead protection areas assume that all of the water entering the well comes from the aquifer in which the well is completed. If there is significant leakage, this assumption results in a WHPA that is larger than required for any given time of travel threshold

Any equations that use discharge from a well (Section 4 5) can take into account interaquifer leakage, provided that the amount of the leakage can also be calculated A trial-and-error approach similar to that discussed in Section 4 4 3 is required to determine the area in which the volume of water from the aquifer and the volume of water from leakage equals the volume of water pumped from a well

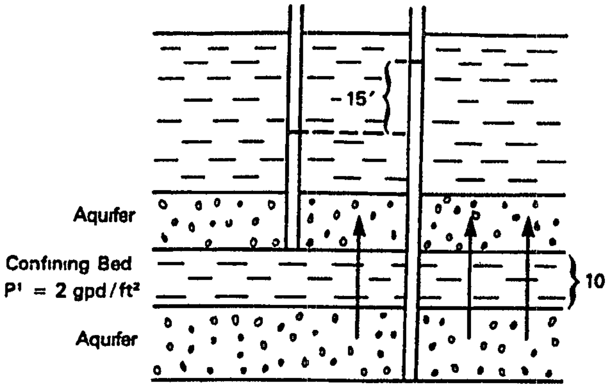
Determining flow from one aquifer to another via a confining unit uses a slightly modified form of Darcy's Law

$$Q_l = (K_v/m)AH \qquad (4\text{-}9)$$

where
$Q_l$ = quantity of leakage, in gpd
$K_v$ = vertical hydraulic conductivity of the confining unit, in gpd/ft$^2$
m = thickness of the confining unit, in ft
A = cross-sectional area, in ft$^2$
H = difference in head between the two wells

Figure 4-9 illustrates two aquifers separated by a layer of silt The silty confining unit is 10 feet thick and has a hydraulic conductivity of 2 gpd/ft$^2$ The difference in water level between wells tapping the upper and lower aquifers is 15 feet Assuming these hydrogeologic conditions exist in an area of 1 square mile, the daily quantity leaking from the shallower aquifer to the deeper one within the area is

$$Q_1 = (2\text{ gpd/ft}^2/10\text{ ft}) \times (5{,}280\text{ ft})^2 \times 15\text{ ft} = 83{,}635{,}200\text{ gpd}$$



Area of leakage = 1 mi$^2$
$P' = 2$ gpd/ft$^2$
$m' = 10$ ft
$\Delta h = 15$ ft
$Q = PIA = \frac{P'}{m'} A\Delta h$
$Q = \frac{2}{10} \times (5280 \times 5280) \times 15 = 83{,}635{,}200$ gpd

**Figure 4-9** Using Darcy's Law to calculate the quantity of leakage from one aquifer to another

This calculation clearly shows that the quantity of leakage, either upward or downward, can be highly significant even if the hydraulic conductivity of the confining unit is small

Kreitler and Senger (1991) propose using the time of travel across a confining layer as one of several criteria for differentiating semiconfined from highly confined aquifers Vertical time of travel across a confining layers is

$$t_v = nmx/K_vH \qquad (4\text{-}10)$$

where factors not defined above are

$t_v$ = vertical time of travel (years) across the confining layer

n = porosity

x = travel distance across confining strata (generally equal to the thickness, m)

The required information comes from well log interpretation and pumping tests of the well or well field

Kreitler and Senger (1991) recommend a 40-year time of travel to differentiate semiconfined (<years) from confined aquifers (>40 years) Rearranging the above equation allows determination of the vertical permeability required to separate a semiconfined from a confined aquifer

$$K_v = nmx/40H \qquad (4\text{-}11)$$

Any other TOT threshold can be substituted for 40 in the equation

## 4.5 WHPA Delineation Using Simple Analytical Methods: Drawdown

By definition, wellhead protection areas are delineated around pumping wells, which will create a cone of depression Gradients within the cone of depression are steeper than the local or regional hydraulic gradient, causing ground water to flow more rapidly there Any analytical method for analyzing the drawdown and flow of ground water in the vicinity of a pumping well has potential value for WHPA delineation *provided* that the well design and aquifer conditions do not violate the assumptions and boundary conditions upon which the equation is based Most analytical methods focusing on ground water flow to pumping wells have been developed to measure aquifer properties such as hydraulic conductivity, specific yield, and storativity The same equations, however, can be rearranged to solve for distance to a specific drawdown criterion using measured or estimated values for other aquifer parameters for WHPA delineation

Analytical solutions to ground water flow problems are most easily developed for confined aquifers, because the surface of the cone of depression does not represent an actual flow, as in an unconfined aquifer (i e , radial flow to the well is horizontal throughout the vertical section of the well, rather than having a vertical component when it reaches the cone of depression) Exact analytical solutions to radial flow to an unconfined aquifer are not possible, so simplifying assumptions that do not completely reflect unconfined flow conditions are required (Todd, 1980) The simplifying assumptions generally do not create problems for estimating discharge from a well, but become problematic in trying to define the radius of the cone of depression for purposes of WHPA delineation

Before selecting an analytical equation to characterize the zone of influence (cone of depression) of an aquifer, the characteristics of the aquifer and well must be known or approximately known in order to select an equation whose assumptions and boundary conditions are appropriate for the site Checklist 4-1 provides a checklist of key well and aquifer characteristics that may affect the appropriateness of a given analytical equation This section focuses only on analytical equations for radial flow to a pumping well Chapter 6 addresses considerations related to modeling of ground water flow in one, two, and three dimensions Only the most widely used analytical methods are described here

### *4.5.1 Uniform Flow Equation (Sloping Gradient)*

The uniform flow equation has been widely used for the delineation of wellhead protection areas where a sloping water table results in an asymmetrical cone of depression (U S EPA, 1987, Kreitler and Senger, 1991, New Hampshire Department of Environmental Services, 1991) The general equation for the boundary of the region producing inflow to a pumping well, developed by the German Forchheimer in 1930, is as follows (Todd, 1980)

$$-y/x = \tan[(2\pi Kbi/Q)y] \qquad (4\text{-}12)$$

where x and y are coordinates and other factors are as defined earlier The zone of contribution is defined using two equations derived from the above equation

$$x_l = -Q/2\pi Kbi \qquad (4\text{-}13)$$

and

$$y_l = \pm\, Q/2Kbi \qquad (4\text{-}14)$$

These define the downgradient flow boundary (null point) and the maximum width of the upgradient zone of contribution, respectively (Figure 4-10) Equation 9 in Table 4-4 can be used to calculate the distance to the edge of the cone of depression upgradient Upgradient

**Checklist 4-1 Aquifer Characteristics for the Selection of Analytical Solutions to Ground Water Flow in the Vicinity of Wells**

*Aquifer Type*
___ Water table/unconfined
___ Confined, leaky
___ Confined, non-leaky

*Regional Hydraulic Gradient*
___ <0 0005 (nearly flat)
___ 0 0005 to 0 001 (transitional)
___ >0 001 (sloping)

*Number of Aquifers*
___ One
___ Two
___ More than two

*Well Penetration*
___ Fully penetrating well
___ Partially penetrating well

*Aquifer Properties*
___ Porous media
___ Fracture flow*
___ Karst conduit flow
___ Isotropic
___ Anisotropic
___ Homogeneous hydraulic parameters
___ Heterogeneous hydraulic parameters*

*Flow Character/Dimension*
___ Steady-state
___ Transient
___ Radial
___ X
___ X-Y
___ X-Y-Z

* Analytical solutions are not able to handle fracture flow or heterogeneous aquifer properties In this situation, maximum measured or estimated aquifer parameters such as porosity and hydraulic conductivity should be used to account for reduced time of travel resulting from fracture

from the well one or more zones can be delimited for wellhead protection

1. Using the upgradient boundary of the cone of depression

2. Delineating the entire upgradient zone of contribution using ± $y_l$ as the width at the upgradient limit of the cone of depression and using a potentiometric map to extend the flow lines to a ground water divide or other aquifer boundary (see Figure 6-5a)

3. Alternatively, using either of the time of travel equations discussed in Section 4 4 to draw an approximate TOT contour

The uniform flow equation applies to highly confined aquifers It does not account for leakage, and so will define larger WHPAs than are necessary if TOT criteria are used As discussed in Section 4 4 4, it may be possible to account for leakage, although in this situation, the noncircular shape of the cone of depression would make this more difficult This equation can also be used for unconfined aquifers, using the saturated thickness of the aquifer, *provided* that drawdown is small (less than 10 percent) in relation to the saturated thickness

### 4.5.2 Thiem Equilibrium Equation

The radial distance to zero drawdown for a pumping well that has reached equilibrium (determined at the point at which pumping at a constant rate does not result in further declines in water levels in monitoring wells adjacent to the pumping well) can be estimated with the Thiem equation (Thiem, 1906) Kreitler and Senger (1991) present the equation in this form for calculating distance to a specified drawdown criterion

$$s = [Q/2\pi Kb]\log_e r_e/r \qquad (4\text{-}15)$$

where
s = drawdown from original potentiometric surface (threshold criterion)
Q = discharge
K = hydraulic conductivity
b = aquifer thickness
r = radial distance at point of drawdown observation
$r_e$ = radial distance of zero drawdown of cone of depression

Assumptions for this equation are fairly restrictive (1) the aquifer is homogeneous and isotropic,[1] (2) the aquifer has infinite areal extent (i e , there are no boundary conditions that affect flow within the cone of depression), (3) the well penetrates the entire aquifer, (4) the regional water table is nearly flat

### 4.5.3 Nonequilibrium Equations

A disadvantage of using the Thiem equation when conducting pumping tests is that a long period of pumping may be required to reach equilibrium A number of nonequilibrium equations have been developed to measure aquifer parameters based on changes in drawdown in the pumping and monitoring wells as a function of time For example, the Theis nonequilibrium equation (Theis, 1935) has been used by the Vermont Department of

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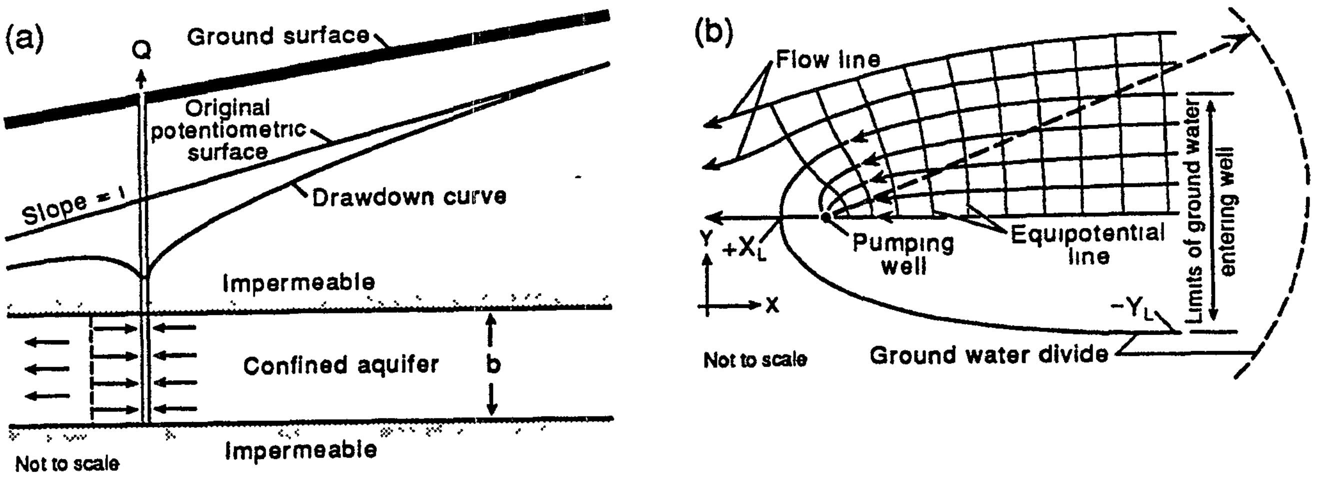
[1] Aquifers with secondary porosity, such as limestone and sandstone, may exhibit homogeneous characteristics if sufficiently large volumes are considered Consequently, pumping tests in rock aquifers may yield good results The measured aquifer properties, however, are only average values and tend to underestimate the potential for contaminant transport



Uniform-flow equation $-\frac{Y}{X} = \tan\left(\frac{2\pi Kbi}{Q}Y\right)$

Distance to down-gradient null point $X_L = -\frac{Q}{2\pi Kbi}$

Boundary limit $Y_L = \pm\frac{Q}{2Kbi}$

Where Q = Well-pumping rate
K = Hydraulic conductivity
b = Saturated thickness
i = Hydraulic gradient
$\pi$ = 3 1416

**Figure 4-10** **Flow to a well penetrating a confined aquifer having a sloping potentiometric surface (a) vertical section, (b) plan view (adapted from Todd, 1980)**

Water Resources (1985) to calculate the radius of the primary zone of protection

$$r = \mathrm{sqrt}(u4Tt/S) \qquad (4\text{-}16)$$

where
T = aquifer transmissivity (Kb)
t = time to reach steady state
S = storativity or specific yield of aquifer

and u is a dimensionless parameter related to the well function

$$W(u) = 4\pi Ts/Q \qquad (4\text{-}17)$$

where
s = drawdown at the maximum radius of influence
Q = pumping rate

To calculate the radius, the well function is calculated using Equation 4-17 and *u* is obtained from Table 4-5 Table 4-4 contains some other simple drawdown equations for a confined aquifer (Equations 1a, 1b and 3) and an approximate drawdown equation for an unconfined aquifer (Equation 3)

Any standard hydrogeology text provides examples and tables for use of nonequilibrium methods The assumptions underlying these equations are somewhat more restrictive than the Thiem equation (1) the aquifer is homogeneous and isotropic, (2) the aquifer is of infinite areal extent, (3) the well penetrates the entire aquifer, (4) the well diameter is infinitesimal, (5) the water removed for storage is discharged instantaneously with decline of head, (6) the regional water table is nearly flat Nonequilibrium equations were developed for confined aquifers

### *4.5.4 Vermont Leakage and Infiltration Methods for Bedrock Wells Receiving Recharge From Unconsolidated Overburden*

The Vermont Agency of Environmental Conservation (1983) has developed several simple equations for calculating the radius of primary concern for wellhead protection where fractures in bedrock wells receive recharge from unconsolidated overburden Where the bedrock well receives recharge from saturated overburden throughout the year, the leakage equation is used

$$r = \mathrm{sqrt}[(Q/K)\pi] \qquad (4\text{-}18)$$

where
r = radius in feet
Q = amount pumped in $ft^3$/day
K = hydraulic conductivity in ft/day

**Table 4-5. Values of the Function *W(u)* for Various Values of *u* for Theis Nonequilibrium Equation (adapted by Fetter, 1980, from Wenzel, 1942)**

| *u* | *W(u)* | *u* | *W(u)* | *u* | *W(u)* | *u* | *W(u)* |
|---|---|---|---|---|---|---|---|
| $1 \times 10^{-10}$ | 22 45 | $7 \times 10^{-8}$ | 15 90 | $4 \times 10^{-5}$ | 9 55 | $1 \times 10^{-2}$ | 4 04 |
| 2 | 21 76 | 8 | 15 76 | 5 | 9 33 | 2 | 3 35 |
| 3 | 21 35 | 9 | 15 65 | 6 | 9 14 | 3 | 2 96 |
| 4 | 21 06 | $1 \times 10^{-7}$ | 15 54 | 7 | 8 99 | 4 | 2 68 |
| 5 | 20 84 | 2 | 14 85 | 8 | 8 86 | 5 | 2 47 |
| 6 | 20 66 | 3 | 14 44 | 9 | 8 74 | 6 | 2 30 |
| 7 | 20 50 | 4 | 14 15 | $1 \times 10^{-4}$ | 8 63 | 7 | 2 15 |
| 8 | 20 37 | 5 | 13 93 | 2 | 7 94 | 8 | 2 03 |
| 9 | 20 25 | 6 | 13 75 | 3 | 7 53 | 9 | 1 92 |
| $1 \times 10^{-9}$ | 20 15 | 7 | 13 60 | 4 | 7 25 | $1 \times 10^{-1}$ | 1 823 |
| 2 | 19 45 | 8 | 13 46 | 5 | 7 02 | 2 | 1 223 |
| 3 | 19 05 | 9 | 13 34 | 6 | 6 84 | 3 | 0 906 |
| 4 | 18 76 | $1 \times 10^{-6}$ | 13 24 | 7 | 6 69 | 4 | 0 702 |
| 5 | 18 54 | 2 | 12 55 | 8 | 6 55 | 5 | 0 560 |
| 6 | 18 35 | 3 | 12 14 | 9 | 6 44 | 6 | 0 454 |
| 7 | 18 20 | 4 | 11 85 | $1 \times 10^{-3}$ | 6 33 | 7 | 0 374 |
| 8 | 18 07 | 5 | 11 63 | 2 | 5 64 | 8 | 0 311 |
| 9 | 17 95 | 6 | 11 45 | 3 | 5 23 | 9 | 0 260 |
| $1 \times 10^{-8}$ | 17 84 | 7 | 11 29 | 4 | 4 95 | $1 \times 10^{0}$ | 0 219 |
| 2 | 17 15 | 8 | 11 16 | 5 | 4 73 | 2 | 0 049 |
| 3 | 16 74 | 9 | 11 04 | 6 | 4 54 | 3 | 0 013 |
| 4 | 16 46 | $1 \times 10^{-5}$ | 10 94 | 7 | 4 39 | 4 | 0 004 |
| 5 | 16 23 | 2 | 10 24 | 8 | 4 26 | 5 | 0 001 |
| 6 | 16 05 | 3 | 9 84 | 9 | 4 14 | | |

This equation was derived by using Darcy's Law (Equation 3-2) to solve for area of vertical leakage by assuming a unit hydraulic gradient (i = 1 0) and solving for the radius of a circle with that area Suggested K values for use in Vermont are sand (100 ft/day), till (1 ft/day), basal till (0.01 ft/day) and silt and clay (0 001 ft/day)

The infiltration equation is used when the overburden is not saturated throughout the year and assumes that all infiltrating precipitation is available to the pumping well

$$r = \mathrm{sqrt}[(Q/I)/\pi] \qquad (3\text{-}19)$$

where
r = radius in feet
Q = annual pumpage ($ft^3/yr$)
I = infiltration (ft/yr)

Suggested infiltration rates till (0 58 ft/yr), more permeable tills shallow to bedrock (1 ft/yr), and sand and gravel (1.8 ft/yr) Primary WHPAs are delineated using the radius, significant fractures traces, structural trends, and topography. Secondary areas drain directly into primary areas and are outlined along upslope drainage divides. Figure 4-11 illustrates WHPA delineations using the leakage and infiltration methods

### *4.5.5 Equations for Special Situations*

A variety of solutions to the basic nonequilibrium equation have been derived for special aquifer and pumping conditions These special situations include

- Unconfined aquifers
- Semiconfined (leaky) aquifers
- Partially penetrating wells

Table 4-6 provides nonequilibrium analytical equations and associated well function tables for the following situations

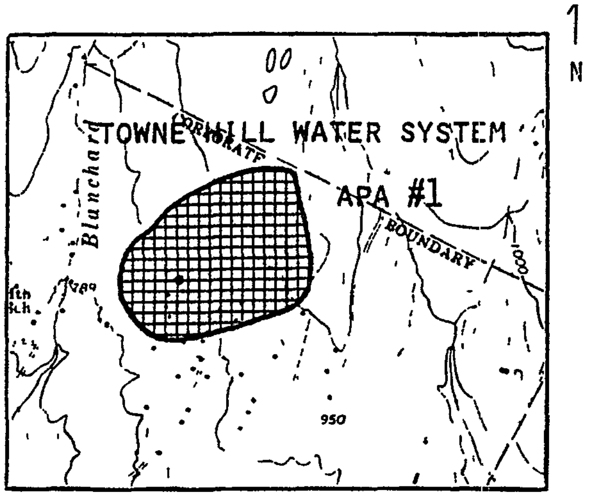
1 Isotropic, nonleaky confined aquifer with fully penetrating wells and constant-discharge conditions,

2 Isotropic nonleaky confined aquifer with *partially penetrating wells* and constant-discharge conditions,

3 Isotropic *leaky* confined aquifer with fully penetrating wells and constant-discharge conditions without water released from storage in the confining layer,

4 Isotropic *water table* aquifer with fully penetrating wells and constant-discharge conditions

Table 3-8 identifies additional references that address various combinations of these special situations Other complexities are added (1) when a well is located near an aquifer boundary, such as a perennial stream or water body, or near an impermeable boundary, (2) when the cone of depression of pumping wells interact, or (3) where a single well intersects more than one aquifer Table 3-8 also identifies references that may be useful for addressing these situations Often computer modeling is required, as discussed in Chapter 6



Leakage Model

$Q = KIA$

$Q$ = Discharge 72.5 gpm
$K$ = Hydraulic Conductivity .01 ft/day
$I$ = Vertical = 1
$A$ = Area

$$A = Q/K = \frac{72.5 \text{ gal/min } 1440 \text{ min/day}}{.01 \text{ ft/day } 7.48 \text{ gal/ft}^3}$$

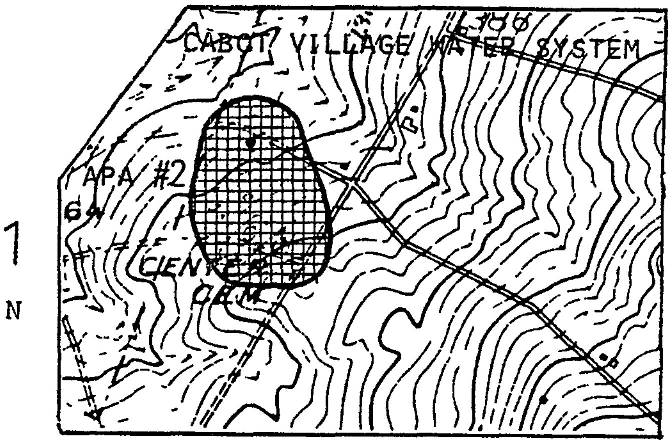
$$\text{Radius} = \sqrt{\frac{A}{\pi}} = \sqrt{\frac{1395721 \text{ ft}^2}{\pi}} = 666 \text{ ft.}$$

(a)

Infiltration Model

$$\text{Radius} = \sqrt{\frac{\frac{\text{Amount Pumped ft}^3\text{/yr}}{\text{Infiltration ft/yr}}}{\pi}}$$

Discharge = 8.3 GPM



$$R = \sqrt{\frac{\frac{575229 \text{ ft.}^3\text{/yr}}{.58 \text{ ft/yr}}}{\pi}} = 561 \text{ ft.}$$

(b)

**Figure 4-11** Delineation of wellhead protection areas for bedrock wells receiving recharge from overburden (a) leakage method, (b) infiltration method (Vermont Agency of Environmental Conservation, 1983)

## Table 4-6 Commonly Used Pump Test Analytical Equations (from Walton, 1970)

Isotropic nonleaky artesian aquifer with fully penetrating wells and constant-discharge conditions

$$s = \frac{114\ 6Q}{T} W(u) \qquad u = \frac{1\ 87r^2S}{Tt}$$

Isotropic nonleaky artesian aquifer with partially penetrating wells and constant-discharge conditions

$$s = \frac{114\ 6Q}{T} W\left(u, \frac{r}{m}, \gamma\right) \qquad u = \frac{1\ 87r^2S}{Tt}$$

$$\gamma = \frac{m - m_s}{m}$$

Isotropic leaky artesian aquifer with fully penetrating wells and constant-discharge conditions without water released from storage in aquitard

$$s = \frac{114\ 6Q}{T} W\left(u, \frac{r}{B}\right) \qquad u = \frac{1\ 87r^2S}{Tt}$$

$$\frac{r}{B} = \frac{r}{\sqrt{T/(P'/m')}} \qquad s = \frac{229Q}{T} K_0\left(\frac{r}{B}\right)$$

Isotropic water-table aquifer with fully penetrating wells and constant-discharge conditions

$$s = \frac{114\ 6Q}{T} W\left(u_{ay}, \frac{r}{D_t}\right) \qquad u_a = \frac{1\ 87r^2S}{Tt}$$

$$u_y = \frac{1\ 87r^2S_y}{Tt} \qquad \frac{r}{D_t} = \frac{2\ 73r}{\sqrt{T/D_tS_y}}$$

$$D_t = \frac{(r/D_t)^2(1/u_y)}{4t}$$

where $s$ = drawdown, in feet
$Q$ = discharge, in gpm
$T$ = coefficient of transmissibility of aquifer, in gpd/ft
$S$ = coefficient of storage of aquifer, fraction
$r$ = distance from production well to observation point, in feet
$t$ = time after pumping started, in days
$m$ = saturated thickness of aquifer, in feet
$m_s$ = distance from top of aquifer to top of screen, in feet
$P'$ = coefficient of permeability of aquitard, in gpd/sq ft
$m'$ = saturated thickness of aquitard, in feet
$S_y$ = specific yield of aquifer, in feet
$W(u)$—see Table 4-6 1
$W\left(u, \frac{r}{m}, \gamma\right)$—see Table 4-6 2
$W\left(u, \frac{r}{B}\right)$—see Table 4-6 3
$K_0\left(\frac{r}{B}\right)$—see Table 4-6 4
$W\left(u_{ay}, \frac{r}{D_t}\right)$—see Table 4-6 5

### Table 4-6 1. Values of *W(u)* or *W($u_{xy}$)* (after Wenzel, 1942)

| $N$ \ $u$ or $u_{xy}$ | $N \times 10^{-15}$ | $N \times 10^{-14}$ | $N \times 10^{-13}$ | $N \times 10^{-12}$ | $N \times 10^{-11}$ | $N \times 10^{-10}$ | $N \times 10^{-9}$ | $N \times 10^{-8}$ | $N \times 10^{-7}$ | $N \times 10^{-6}$ | $N \times 10^{-5}$ | $N \times 10^{-4}$ | $N \times 10^{-3}$ | $N \times 10^{-2}$ | $N \times 10^{-1}$ | $N$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 0 | 33 9616 | 31 6590 | 29 3564 | 27 0538 | 24 7512 | 22 4486 | 20 1460 | 17 8435 | 15 5409 | 13 2383 | 10 9357 | 8 6332 | 6 3315 | 4 0379 | 1 8229 | 0 2194 |
| 1.5 | 33 5561 | 31 2535 | 28 9509 | 26 6483 | 24 3458 | 22 0432 | 19 7406 | 17 4380 | 15 1354 | 12 8328 | 10 5303 | 8 2278 | 5 9266 | 3 6374 | 1 4645 | 0 1000 |
| 2 0 | 33 2684 | 30 9658 | 28 6632 | 26 3607 | 24 0581 | 21 7555 | 19 4529 | 17 1503 | 14 8477 | 12 5451 | 10 2426 | 7 9402 | 5 6394 | 3 3547 | 1 2227 | 0 04890 |
| 2.5 | 33 0453 | 30 7427 | 28 4401 | 26 1375 | 23 8349 | 21 5323 | 19 2298 | 16 9272 | 14 6246 | 12 3220 | 10 0194 | 7 7172 | 5 4167 | 3 1365 | 1 0443 | 0 02491 |
| 3.0 | 32.8629 | 30 5604 | 28 2578 | 25 9552 | 23 6526 | 21 3500 | 19 0474 | 16 7449 | 14 4423 | 12 1397 | 9 8371 | 7 5348 | 5 2349 | 2 9591 | 0 9057 | 0 01305 |
| 3.5 | 32.7088 | 30 4062 | 28 1036 | 25 8010 | 23 4985 | 21 1959 | 18 8933 | 16 5907 | 14 2881 | 11 9855 | 9 6830 | 7 3807 | 5 0813 | 2 8099 | 0 7942 | 0 006970 |
| 4 0 | 32.5753 | 30 2727 | 27 9701 | 25 6675 | 23 3649 | 21 0623 | 18 7598 | 16 4572 | 14 1546 | 11 8520 | 9 5495 | 7 2472 | 4 9482 | 2 6813 | 0 7024 | 0 003779 |
| 4.5 | 32.4575 | 30 1549 | 27 8523 | 25 5497 | 23 2471 | 20 9446 | 18 6420 | 16 3394 | 14 0368 | 11 7342 | 9 4317 | 7 1295 | 4 8310 | 2 5684 | 0 6253 | 0 002073 |
| 5.0 | 32.3521 | 30 0495 | 27 7470 | 25 4444 | 23 1418 | 20 8392 | 18 5366 | 16 2340 | 13 9314 | 11 6280 | 9 3263 | 7 0242 | 4 7261 | 2 4679 | 0 5598 | 0 001148 |
| 5.5 | 32.2568 | 29 9542 | 27 6516 | 25 3491 | 23 0465 | 20 7439 | 18 4413 | 16 1387 | 13 8361 | 11 5330 | 9 2310 | 6 9289 | 4 6313 | 2 3775 | 0 5034 | 0 0006409 |
| 6.0 | 32.1698 | 29 8672 | 27 5646 | 25 2620 | 22 9595 | 20 6569 | 18 3543 | 16 0517 | 13 7491 | 11 4465 | 9 1440 | 6 8420 | 4 5448 | 2 2953 | 0 4544 | 0 0003601 |
| 6.5 | 32.0898 | 29 7872 | 27 4846 | 25 1820 | 22 8794 | 20 5768 | 18 2742 | 15 9717 | 13 6691 | 11 3665 | 9 0640 | 6 7620 | 4 4652 | 2 2201 | 0 4115 | 0 0002034 |
| 7.0 | 32 0156 | 29 7131 | 27 4105 | 25 1079 | 22 8053 | 20 5027 | 18 2001 | 15 8976 | 13 5950 | 11 2924 | 8 9899 | 6 6879 | 4 3916 | 2,1508 | 0 3738 | 0 0001155 |
| 7 5 | 31 9467 | 29 6441 | 27 3415 | 25 0389 | 22 7363 | 20 4337 | 18 1311 | 15 8280 | 13 5260 | 11 2234 | 8 9209 | 6 6190 | 4 3231 | 2 0867 | 0 3403 | 0 0000658 |
| 8 0 | 31 8821 | 29 5795 | 27 2769 | 24 9744 | 22 6718 | 20 3692 | 18 0666 | 15 7640 | 13 4614 | 11 1589 | 8 8563 | 6 5545 | 4 2591 | 2 0269 | 0 3106 | 0 0000376 |
| 8 5 | 31 8215 | 29 5189 | 27 2163 | 24 9137 | 22 6112 | 20 3086 | 18 0060 | 15 7034 | 13 4008 | 11 0982 | 8 7957 | 6 4939 | 4 1990 | 1 9711 | 0 2840 | 0 0000216 |
| 9.0 | 31 7643 | 29 4618 | 27 1592 | 24 8566 | 22 5540 | 20 2514 | 17 9488 | 15 6462 | 13 3437 | 11 0411 | 8 7386 | 6 4368 | 4 1423 | 1 9187 | 0 2602 | 0 0000124 |
| 9 5 | 31 7103 | 29 4077 | 27 1051 | 24 8025 | 22 4999 | 20-1973 | 17 8948 | 15.5922 | 13-2896 | 10 9870 | 8 6845 | 6 3828 | 4 0887 | 1 8695 | 0 2387 | 0 0000071 |

Table 4-6 2 Values of $W(u, r/m, \gamma)$

$\gamma = 0\ 75$

| $u$ | $r/m = 0\ 1$ | $0\ 01$ | $0\ 001$ |
|---|---|---|---|
| $10^{-6}$ | 13 8767 | 15 2580 | 16 7637 |
| $10^{-5}$ | 11 5741 | 12 9554 | 14 2530 |
| $10^{-4}$ | 9 2716 | 10 6478 | 11 3995 |
| $10^{-3}$ | 6 9699 | 8 1392 | 8 3991 |
| $10^{-2}$ | 4 6712 | 5 2967 | 5 3635 |
| $10^{-1}$ | 2 2597 | 2 4103 | 2 4193 |
| 1 | 0 2823 | 0 2898 | 0 2898 |
| 2 | 0 0634 | 0 0643 | 0 0645 |
| 3 | 0 0167 | 0 0169 | 0 0169 |

$\gamma = 0.50$

| $u$ | $r/m = 0\ 5$ | $0\ 2$ | $0\ 1$ | $0\ 03$ | $0\ 01$ | $0\ 001$ |
|---|---|---|---|---|---|---|
| $10^{-6}$ | 13 5665 | 14 4689 | 15 4989 | 17 6358 | 19 7506 | 24.2954 |
| $10^{-5}$ | 11 2639 | 12 1663 | 13 1963 | 15 3332 | 17 4498 | 21 1506 |
| $10^{-4}$ | 8 9614 | 9 8638 | 10 8938 | 13 0307 | 15 1224 | 17 0340 |
| $10^{-3}$ | 6 6597 | 7 5621 | 8 5921 | 10 6994 | 11 9812 | 12 5845 |
| $10^{-2}$ | 4 3661 | 5 2685 | 6 2757 | 7 4555 | 7 8851 | 8 0462 |
| $10^{-1}$ | 2.1511 | 2 8822 | 3.2620 | 3 5305 | 3 6050 | 3.6304 |
| 1 | 0 3384 | 0 3986 | 0 4185 | 0.4319 | 0.4349 | 0 4353 |
| 2 | 0 0808 | 0 0910 | 0 0942 | 0 0964 | 0 0966 | 0 0968 |
| 3 | 0 0223 | 0 0247 | 0 0252 | 0 0254 | 0 0254 | 0 0255 |

$\gamma = 0\ 25$

| $u$ | $r/m = 1\ 00$ | $0\ 75$ | $0\ 20$ | $0\ 10$ | $0\ 03$ | $0\ 01$ | $0.001$ |
|---|---|---|---|---|---|---|---|
| $10^{-6}$ | 13 3385 | 13 9367 | 16 2123 | 18 9845 | 25 1707 | 31 4176 | 44 9718 |
| $10^{-5}$ | 11 0359 | 11 6341 | 13 9097 | 16 6837 | 22 8681 | 29.1150 | 40 7960 |
| $10^{-4}$ | 8 6334 | 9 3316 | 11 6072 | 14 3794 | 30 5656 | 26 7666 | 33 5338 |
| $10^{-3}$ | 6 4317 | 7 0299 | 0 3055 | 12.0777 | 18 2045 | 22 6026 | 24 9428 |
| $10^{-2}$ | 4 1381 | 4 7363 | 7 0119 | 9 7382 | 13 8971 | 15 3684 | 15.9702 |
| $10^{-1}$ | 1 9231 | 2 5213 | 4 4451 | 5 7545 | 6 8298 | 7.1101 | 7 1913 |
| 1 | 0 2981 | 0 4959 | 0 7160 | 0 7856 | 0 8493 | 0 8549 | 0 8531 |
| 2 | 0 0806 | 0 1271 | 0 1675 | 0 1794 | 0 1900 | 0.1875 | 0 1893 |
| 3 | 0 0245 | 0 0366 | 0 0454 | 0 0472 | 0 0501 | 0 0481 | 0 0481 |

Table 4-6 3 Values of $W(u, r/B)$ or $W(u'', r/B)$ (after Hantush, 1956)

| $r/B$<br>$u$ or $u''$ | 0 01 | 0 015 | 0 03 | 0.05 | 0.075 | 0 10 | 0 15 | 0.2 | 0 3 | 0 4 | 0.5 | 0 6 | 0 7 | 0.8 | 0 9 | 1.0 | 1.5 | 2 0 | 2 5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 000001 | | | | | | | | | | | | | | | | | | | |
| 0 000005 | 9 4413 | | | | | | | | | | | | | | | | | | |
| 0 00001 | 9 4176 | 8 6313 | | | | | | | | | | | | | | | | | |
| 0 00005 | 8 8827 | 8 4533 | 7 2450 | | | | | | | | | | | | | | | | |
| 0 0001 | 8 3983 | 8 1414 | 7 2122 | 6 2282 | 5 4228 | | | | | | | | | | | | | | |
| 0 0005 | 6 9750 | 6.9152 | 6 6219 | 6 0821 | 5 4062 | 4 8530 | | | | | | | | | | | | | |
| 0 001 | 6 3069 | 6 2765 | 6 1202 | 5 7965 | 5 3078 | 4 8292 | 4 0595 | 3 5054 | | | | | | | | | | | |
| 0 005 | 4 7212 | 4 7152 | 4 6829 | 4 6084 | 4 4713 | 4 2960 | 3 8821 | 3 4567 | 2 7428 | 2 2290 | | | | | | | | | |
| 0 01 | 4 0356 | 4.0326 | 4 0167 | 3 9795 | 3 9091 | 3 8150 | 3 5725 | 3 2875 | 2 7104 | 2 2253 | 1 8486 | 1 5550 | 1 3210 | 1 1307 | | | | | |
| 0 05 | 2 4675 | 2 4670 | 2 4642 | 2 4576 | 2 4448 | 2 4271 | 2 3776 | 2 3110 | 1 9283 | 1 7075 | 1 4927 | 1 2955 | 1.2955 | 1 1210 | 0 9700 | 0 8409 | | | |
| 0 1 | 1 8227 | 1 8225 | 1 8213 | 1 8184 | 1 8128 | 1 8050 | 1 7829 | 1 7527 | 1 6704 | 1 5644 | 1 4422 | 1 3115 | 1 1791 | 1 0505 | 0 9297 | 0 8190 | 0 4271 | 0 2278 | |
| 0 5 | 0 5598 | 0 5597 | 0 5596 | 0 5594 | 0 5588 | 0 5581 | 0 5561 | 0 5532 | 0 5453 | 0 5344 | 0 5206 | 0 5044 | 0 4860 | 0 4658 | 0 4440 | 0 4210 | 0 3007 | 0 1944 | 0 1174 |
| 1 0 | 0 2194 | 0 2194 | 0 2193 | 0 2193 | 0 2191 | 0 2190 | 0 2186 | 0 2179 | 0 2161 | 0 2135 | 0 2103 | 0 2065 | 0 2020 | 0 1970 | 0 1914 | 0 1855 | 0 1509 | 0 1139 | 0 0803 |
| 5 0 | 0 0011 | 0 0011 | 0 0011 | 0 0011 | 0 0011 | 0 0011 | 0 0011 | 0 0011 | 0 0011 | 0 0011 | 0 0011 | 0 0011 | 0 0011 | 0 0011 | 0 0011 | 0 0011 | 0 0010 | 0 0010 | 0 0009 |

Table 4-6 4 Values of $K_0(r/B)$ (after Hantush, 1956)

| $N$ | $r/B = N \times 10^{-3}$ | $N \times 10^{-2}$ | $N \times 10^{-1}$ | $N$ |
|---|---|---|---|---|
| 1 0 | 7 0237 | 4 7212 | 2 4271 | 0 4210 |
| 1 5 | 6 6182 | 4 3159 | 2 0300 | 0 2138 |
| 2 0 | 6 3305 | 4 0285 | 1 7527 | 0 1139 |
| 2 5 | 6 1074 | 3 8056 | 1 5415 | 0 0623 |
| 3 0 | 5 9251 | 3 6235 | 1 3725 | 0 0347 |
| 3 5 | 5 7709 | 3 4697 | 1 2327 | 0 0196 |
| 4 0 | 5 6374 | 3 3365 | 1 1145 | 0 0112 |
| 4 5 | 5 5196 | 3 2192 | 1 0129 | 0 0064 |
| 5 0 | 5 4143 | 3 1142 | 0 9244 | 0 0037 |
| 5 5 | 5 3190 | 3 0195 | 0 8466 | |
| 6 0 | 5 2320 | 2 9329 | 0 7775 | 0 0012 |
| 6 5 | 5 1520 | 2 8534 | 0 7159 | |
| 7 0 | 5 0779 | 2 7798 | 0 6605 | 0 0004 |
| 7 5 | 5 0089 | 2 7114 | 0 6106 | |
| 8 0 | 4 9443 | 2 6475 | 0 5653 | |
| 8 5 | 4 8837 | 2 5875 | 0 5242 | |
| 9 0 | 4 8266 | 2 5310 | 0 4867 | |
| 9 5 | 4 7725 | 2 4776 | 0 4524 | |

Table 4-6.5 Values of $W(u_{ay}, r/D_t)$ (from Boulton, 1963)

$1/u_a = N_n \times 10^n$

| $r/D_t$ = 0 01 | | | $r/D_t$ = 0 1 | | | $r/D_t$ = 0 2 | | | $r/D_t$ = 0 316 | | | $r/D_t$ = 0 4 | | | $r/D_t$ = 0 6 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $N$ | $n$ | $W(u_a, r/D_t)$ | $N$ | $n$ | $W(u_a, r/D_t)$ | $N$ | $n$ | $W(u_a, r/D_t)$ | $N$ | $n$ | $W(u_a, r/D_t)$ | $N$ | $n$ | $W(u_a, r/D_t)$ | $N$ | $n$ | $W(u_a, r/D_t)$ |
| 1 | 1 | 1 82 | 1 | 1 | 1 80 | 5 | 0 | 1 19 | 1 | 0 | 0 216 | 1 | 0 | 0 213 | 1 | 0 | 0 206 |
| 1 | 2 | 4 04 | 5 | 1 | 3 24 | 1 | 1 | 1 75 | 2 | 0 | 0 544 | 2 | 0 | 0 534 | 2 | 0 | 0 504 |
| 1 | 3 | 6 31 | 1 | 2 | 3 81 | 5 | 1 | 2 95 | 5 | 0 | 1 153 | 5 | 0 | 1 114 | 5 | 0 | 0 996 |
| 5 | 3 | 7 82 | 2 | 2 | 4 30 | 1 | 2 | 3 29 | 1 | 1 | 1 655 | 1 | 1 | 1 564 | 1 | 1 | 1 311 |
| 1 | 4 | 8 40 | 5 | 2 | 4 71 | 5 | 2 | 3 50 | 5 | 1 | 2 504 | 5 | 1 | 2 181 | 2 | 1 | 1 493 |
| 1 | 5 | 9 42 | 1 | 1 | 4 83 | 1 | 3 | 3 51 | 1 | 2 | 2 623 | 1 | 2 | 2 225 | 5 | 1 | 1 553 |
| 1 | 6 | 9 44 | 1 | 4 | 4 85 | | | | 1 | 3 | 2 648 | 1 | 3 | 2 229 | 1 | 2 | 1 555 |

| $r/D_t$ = 0 8 | | | $r/D_t$ = 1 0 | | | $r/D_t$ = 1 5 | | | $r/D_t$ = 2 0 | | | $r/D_t$ = 2 5 | | | $r/D_t$ = 3 0 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $N$ | $n$ | $W(u_a, r/D_t)$ | $N$ | $n$ | $W(u_a, r/D_t)$ | $N$ | $n$ | $W(u_a, r/D_t)$ | $N$ | $n$ | $W(u_a, r/D_t)$ | $N$ | $n$ | $W(u_a, r/D_t)$ | $N$ | $n$ | $W(u_a, r/D_t)$ |
| 5 | −1 | 0 046 | 5 | −1 | 0 0444 | 5 | −1 | 0 0394 | 3 33 | −1 | 0 0100 | 5 | −1 | 0 0271 | 5 | −1 | 0 0210 |
| 1 | 0 | 0 197 | 1 | 0 | 0 1855 | 1 | 0 | 0 1509 | 5 | −1 | 0 0335 | 1 | 0 | 0 0803 | 1 | 0 | 0 0534 |
| 2 | 0 | 0 466 | 2 | 0 | 0 421 | 1 25 | 0 | 0 199 | 1 | 0 | 0 114 | 1 25 | 0 | 0 0961 | 1 25 | 0 | 0 0607 |
| 5 | 0 | 0 857 | 5 | 0 | 0 715 | 2 | 0 | 0 301 | 1 25 | 0 | 0 144 | 2 | 0 | 0 1174 | 2 | 0 | 0 0681 |
| 1 | 1 | 1 050 | 1 | 1 | 0 819 | 5 | 0 | 0 413 | 2 | 0 | 0 194 | 5 | 0 | 0 1247 | 5 | 0 | 0 0695 |
| 2 | 1 | 1 121 | 2 | 1 | 0 841 | 1 | 1 | 0 427 | 5 | 0 | 0 227 | 1 | 1 | 0 1247 | 1 | 1 | 0 0695 |
| 5 | 1 | 1 131 | 5 | 1 | 0 842 | 2 | 1 | 0 428 | 1 | 1 | 0 228 | | | | | | |

$1/u_y = N_n \times 10^n$

| $r/D_t$ = 0 01 | | | $r/D_t$ = 0 1 | | | $r/D_t$ = 0 2 | | | $r/D_t$ = 0 316 | | | $r/Dt$ = 0 4 | | | $r/D_t$ = 0 6 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $N$ | $n$ | $W(u_y, r/D_t)$ | $N$ | $n$ | $W(u_y, r/D_t)$ | $N$ | $n$ | $W(u_y, r/D_t)$ | $N$ | $n$ | $W(u_y, r/D_t)$ | $N$ | $n$ | $W(u_y, r/D_t)$ | $N$ | $n$ | $W(u_y, r/D_t)$ |
| 4 | 2 | 9 45 | 4 | 0 | 4 86 | 4 | −1 | 3 51 | 4 | −1 | 2 66 | 1 | −1 | 2 23 | 4 44 | −1 | 1 586 |
| 4 | 3 | 9 54 | 4 | 1 | 4 95 | 4 | 0 | 3 54 | 4 | 0 | 2 74 | 1 | 0 | 2 26 | 2 22 | 0 | 1 707 |
| 4 | 4 | 10 23 | 4 | 2 | 5 64 | 2 | 1 | 3 69 | 4 | 1 | 3 38 | 5 | 0 | 2 40 | 4 44 | 0 | 1 844 |
| 4 | 5 | 12.31 | 4 | 3 | 7 72 | 4 | 1 | 3 85 | 4 | 2 | 5 42 | 1 | 1 | 2 55 | 1 67 | 1 | 2 448 |
| 4 | 6 | 14 61 | 4 | 4 | 10 01 | 1 5 | 2 | 4 55 | 4 | 3 | 7 72 | 3 75 | 1 | 3 20 | 4 44 | 1 | 3 255 |
| | | | | | | 4 | 2 | 5 42 | | | | 1 | 2 | 4 05 | | | |

| $r/D_t$ = 0 8 | | | $r/D_t$ = 1 0 | | | $r/D_t$ = 1 5 | | | $r/D_t$ = 2 0 | | | $r/D_t$ = 2 5 | | | $r/D_t$ = 3 0 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $N$ | $n$ | $W(u_y, r/D_t)$ | $N$ | $n$ | $W(u_y, r/D_t)$ | $N$ | $n$ | $W(u_y, r/D_t)$ | $N$ | $n$ | $W(u_y, r/D_t)$ | $N$ | $n$ | $W(u_y, r/D_t)$ | $N$ | $n$ | $W(u_y, r/D_t)$ |
| 2.5 | −2 | 1 133 | 4 | −2 | 0 844 | 7 11 | −2 | 0 444 | 4 | −2 | 0 239 | 2 56 | −2 | 0 1321 | 1 78 | −2 | 0 0743 |
| 2.5 | −1 | 1 158 | 4 | −1 | 0 901 | 3 55 | −1 | 0 509 | 2 | −1 | 0 283 | 1 28 | −1 | 0 1617 | 8 89 | −2 | 0 0939 |
| 1 25 | 0 | 1 264 | 4 | 0 | 1 356 | 7 11 | −1 | 0 587 | 4 | −1 | 0 337 | 2 56 | −1 | 0 1988 | 1 78 | −1 | 0 1189 |
| 2 5 | 0 | 1 387 | 4 | 1 | 3 140 | 2 67 | 0 | 0 963 | 1 5 | 0 | 0 614 | 9 6 | −1 | 0 3990 | 6 67 | −1 | 0 2618 |
| 9 37 | 0 | 1 938 | | | | 7 11 | 0 | 1 569 | 4 | 0 | 1 111 | 2 56 | 0 | 0 7977 | 1 78 | 0 | 0 5771 |
| 2.5 | 1 | 2.704 | | | | | | | | | | | | | | | |

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* See Introduction for information on how to obtain documents

# Chapter 5
# Hydrogeologic Mapping for Wellhead Protection

Hydrogeologic mapping provides a valuable complement to the simpler methods for wellhead protection area (WHPA) delineation covered in the previous chapter and is a necessary precursor to more complex numerical modeling of ground water flow using computers (Chapter 6) Figure 5-1 illustrates WHPA delineation using geologic contacts and ground water divides as the key elements of hydrogeologic mapping Potentiometric maps (Chapter 2) and methods for measuring aquifer parameters (Chapter 3) are essential parts of hydrogeologic mapping This chapter focuses on general approaches to hydrogeologic mapping (basic elements—Section 5 1, existing data collection and interpretation—Section 5 2, and field data collection—Section 5 3)

Section 5 4 covers four aspects of hydrogeologic mapping that require special consideration in relation to WHPA delineation (1) adjustments of WHPAs to account to aquifer boundaries (Section 5 4 1), (2) adjustments of WHPAs based on aquifer heterogeneity and/or anisotropy (Section 5 4 2), (3) assessing the presence and degree of confinement in aquifers (Section 5 4 3), and (4) mapping of fractured rock and karst aquifers (Section 5 4 4) Section 5 5 describes the approach of ground water vulnerability mapping based on hydrogeologic factors that affect the movement of contaminants in the subsurface Finally, Section 5 6 discusses use of geographic information systems (GIS) for WHPA delineation

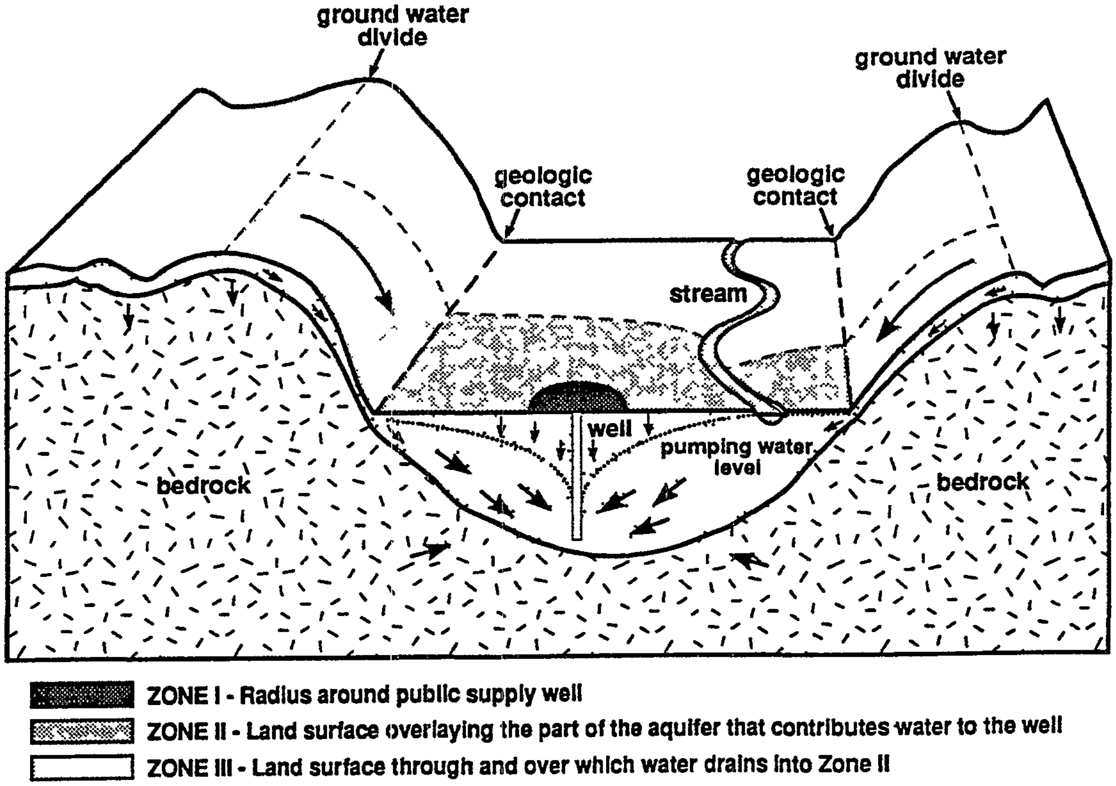


Figure 5-1 Wellhead protection delineation using hydrogeologic boundaries (U S EPA, 1993a)

## 5.1 Elements of Hydrogeologic Mapping

Hydrogeologic mapping requires the systematic and integrated appraisal of soils, geomorphology, geology, hydrology (including meteorologic aspects), geochemistry, and water chemistry as they affect the occurrence, flow, and quality of ground water A brief discussion of the significance of these elements follows Any standard hydrogeology textbook contains one or more chapters devoted to methods for hydrogeologic mapping (see Table 5-8). Section 5 3 identifies major references with a focus on field aspects of hydrogeologic mapping

### *5.1.1 Soils and Geomorphology*

The character and distribution of soils and landforms are major considerations in hydrogeologic mapping in humid areas where unconfined aquifers develop in unconsolidated materials and lie relatively near the land surface In this setting, the water table generally follows the land surface, although with more subdued relief (Section 2 1 2). Recharge areas are generally located in upland areas, and ground water divides tend to coincide with surface watershed boundaries Valley bottoms and floodplains with perennial streams represent discharge areas

For all areas, soils and topography are the primary features that determine how much precipitation infiltrates into the ground to recharge ground water, and how much runs off to surface streams Highly permeable soils and flat topography favor infiltration, less permeable soils and steep slopes promote surface runoff

### *5.1.2 Geology*

Geology forms the physical framework for the flow of ground water Porosity (primary and secondary—Section 2.1 4), storage properties (Section 3 1 1), and transmitting properties (hydraulic conductivity—Section 3.1.2) are largely a function of the geologic materials present. Stratigraphy (relationships of layered geologic materials) affects local and regional ground water flow by the distribution of strata of relatively higher and lower permeability Structural features (the folding and fracturing of rock by tectonic processes) may alter directions of ground water flow compared to horizontal sediments by changing the inclination of permeable sediments and confining units Displacement of sediments by faulting may either provide zones of increased permeability through fracturing or create aquifer boundaries when impermeable strata block the flow of water through permeable strata (see Figure 2-17) Secondary fracture porosity results primarily from tectonic stresses

### *5.1.3 Hydrology*

Although the focus of hydrogeologic mapping is ground water, the occurrence and flow of ground water must be understood in the context of the larger hydrologic cycle, which includes atmospheric water, water in the vadose (unsaturated) zone, and surface water This is especially true of unconfined aquifers, which are intimately connected to the hydrologic cycle Complete characterization of unconfined aquifers requires consideration of infiltration of precipitation, the effects of evapotranspiration, and the relationship between the ground water and surface water systems Potentiometric surface mapping (Chapter 2) is one of the most important aspects of hydrogeologic characterization Confined aquifers that are distant from areas of surface recharge can be considered effectively isolated from the hydrologic cycle, provided that they are highly confined (Section 5 4 3), which greatly simplifies analysis of the ground water flow system (Section 4 5)

### *5.1.4 Hydrochemistry*

Data on water quality can provide valuable insights into the hydrogeologic system As discussed in Section 5 4 3, a number of hydrochemical indicators are useful for assessing the presence and degree of confinement of an aquifer The geochemical characteristics of the aquifer matrix and factors such as pH and redox potential (Eh) and aquifer microbiology (Section 1 4) are especially important if the potential for attenuation of contaminants is being considered in the WHPA delineation process (Section 4 1 5)

## 5.2 Existing Data Collection and Interpretation

The first step in hydrogeologic mapping is to find out what information is already available for the area of interest This includes first reviewing published maps and reports about soils, geology, and hydrology of the area The next step is finding and analyzing any unpublished data, such as well drill logs, and hydrologic and water quality data on file at local, state, or federal government offices EPA's STORET database may have ground water quality data from the area (U S EPA, 1986c) Finally, examination of aerial photographs provides an opportunity to relate knowledge gained in reviewing published and unpublished information to the specific wellhead area, and helps focus field efforts to collect additional required information

The above steps do not have to be followed in strict sequential order, but an intensive initial effort to identify and review published and other existing information will generally pay off by (1) avoiding field effort spent in collecting data that is already available, and (2) targeting the location and type of field data collection to yield the greatest benefits Dury (1957) provides comprehensive coverage of general aspects of map interpretation, and Warman and Wiesnet (1966) discuss the design and use of hydrogeologic maps Pettyjohn and Randich

(1966) provide an example of hydrogeologic interpretations using lithofacies maps in glaciated areas Meyboom (1961) reviews terminology used in ground water maps

Getting to know one or more individuals in the various state and federal agencies that publish and maintain files of information on soils, geology, and water resources can facilitate the process of determining what is available for the area of interest The planning and utility departments of local government are also sources of potentially valuable information that may not be available from other sources Worksheet 5-1 provides a form for listing personal contacts and identifying available maps that can provide a starting point for compiling a hydrogeologic map of an area

### *5.2.1 Soil and Geomorphic Data*

Section 3 2 1 discusses the use of soil survey data in the estimation of aquifer parameters Soil surveys published by the Soil Conservation Service (SCS) of the U S Department of Agriculture are typically at a scale of 1 15,840 or 1 20,000 and mapped on a airphoto base Simplified geomorphic maps can be readily developed from a soil map by grouping soil map units into larger geomorphic units (floodplains, terraces, uplands, etc ) Nonfloodplain soils are differentiated on the basis of slope with letter designations in the map symbol This allows development of geomorphic units based on slope range Slope range, combined with the infiltration characteristics of the soil, allow interpretations of infiltration-runoff characteristics of an area Table 5-1 summarizes criteria for SCS runoff classes, and Table 5-2 includes criteria for SCS hydraulic conductivity and permeability classes This information can be used to develop a qualitative assessment of the ground water recharge potential in an area

### *5.2.2 Geologic and Hydrologic Data*

The Hydrologic Atlas (HA) and Water Resource Investigation (WRI) series of the U S Geological Survey are some of the best sources of hydrogeologic information In fact, a hydrologic atlas of aquifer areas and characteristics may provide much of the information required for WHPA delineation These maps are based on the interpretation of all available geologic information from soil profiles, test wells, rock outcrops, observation wells, seismic surveys, and other means of subsurface observation The location of aquifers on these maps is estimated by examining surficial geology, depth to bedrock, and depth to the water table A hydrologic atlas contains information about ground water availability, well locations, ground water quality, surficial deposits influencing transmissivity, basin boundaries, flow characteristics of surface water, and other hydrologic factors

**Table 5-1 SCS Index Surface Runoff Classes**

| | Runoff Classes* | | | | | |
|---|---|---|---|---|---|---|
| | Ksat Class** | | | | | |
| **Slope Gradient (%)** | **VH** | **H** | **MH** | **ML** | **L** | **VL** |
| Concave*** | N | N | N | N | N | N |
| <1 | N | N | N | L | M | H |
| 1-5 | N | VL | L | M | H | VH |
| 5-10 | VL | L | M | H | VH | VH |
| 10-20 | VL | L | M | H | VH | VH |
| >20 | L | M | H | VH | VH | VH |

* Abbreviations Negligible-N, very low-VL, low-L, medium-M, high-H, and very high-VH These classes are relative and not quantitative

** See Table 5-2 for definitions Assumes that the lowest value for the soil occurs at <0 5 m If the lowest value occurs at 0 5 to 1 m, reduce runoff by one class If it occurs at >1 m, then use the lowest saturated hydraulic conductivity < 1 m VL Ksat is assumed for soils with seasonal shallow or very shallow free water

*** Areas from which little or no water escapes by flow over the ground surface

Source U S EPA (1991b)

**Table 5-2 SCS Criteria for Hydraulic Conductivity and Permeability Classes**

| **Class** | **Units** | |
|---|---|---|
| *Saturated Hydraulic Conductivity* | µ/sec | in /hr |
| Very Low (VL) | <0 01 | <0 001 |
| Low (L) | 0 01-0 1 | 0 001-0 01 |
| Moderately Low (ML) | 0 1-1 | 0 01-0 14 |
| Moderately High (MH) | 1-10 | 0 14-1 4 |
| High (H) | 10-100 | 1 4-14 2 |
| Very High (VH) | >100 | >14 2 |
| *Permeability* | cm/hr | in/ hr |
| Very Slow | <0 15 | <0 06 |
| Slow | 0 15-0 5 | 0 06-0 2 |
| Moderately Slow | 0 5-1 5 | 0 2-0 6 |
| Moderate | 1 5-5 0 | 0 6-2 0 |
| Moderately Rapid | 5 0-15 2 | 2 0-6 0 |
| Rapid | 15 2-50 8 | 6 0-20 |
| Very Rapid | >50 8 | >20 |

Source U S EPA (1991b)

A water table or potentiometric surface map, if available, is the next most valuable source of hydrogeologic information (Chapter 2) Such maps may be available from the state water resource agency or geological survey SCS-published soil surveys usually give summary data on monthly distribution, averages, and ranges of temperature and precipitation The National Weather Service (1988) is the primary source for other climatological

## Worksheet 5-1
## Collection of Existing Data for Wellhead Protection

Contacts and Phone Numbers ______________________________

EPA Regional Ground-Water Representative ______________________________

USGS Water Resources Division State Office ______________________________

SCS District/State Office ______________________________

Federal Management Agency Local Office* ______________________________

State Wellhead Protection Program ______________________________

State Water Resource Agency** ______________________________

State Environmental Protection Agency** ______________________________

State Geological Survey ______________________________

Local College/University Geology Department ______________________________

Local College/University Library ______________________________

*Topographic Maps*

____ 7 1/2' Topographic
____ 15' Topographic
____ Regional
____ Other

*Geologic Maps*

____ State
____ Regional
____ Local

*Hydrologic Maps*

____ USGS Hydrologic Atlas
____ State-Published Hydrologic Maps
____ Water Table/Potentiometric Surface
____ Watershed
____ Wetlands
____ Flood Plain Maps (FEMA, FIRM)
____ Other

*Land Use Maps*

____ Ownership/Tax Assessment
____ Subsurface Ownership (if different from surface ownership)
____ Zoning/Planning
____ Utilities
____ Other

*Soils/Vegetation Maps*

____ Soil Map
____ Vegetation

*Aerial Photography*

____ Large scale
____ High altitude
____ Satellite

* Required only if wellhead protection area includes federal lands (most likely in western U S ) Possible agencies include the Bureau of Land Management, U S Forest Service, U S Fish and Wildlife Service, and U S Department of Defense

** If different from agency responsible for wellhead protection data, which may be required to evaluate recharge of unconfined aquifers Detailed precipitation data may be useful if available well-level measurements for developing a potentiometric surface map were taken at different times (Section 2 3)

Geologic information is available from many sources The U S Geological Survey and state geological surveys are the primary source for surficial and bedrock geologic maps Important surface hydrologic features include drainage basins (watersheds), surface water bodies, wetlands, and flood zones Wetlands can be identified on topographic maps, however, more detailed wetland maps may be available from the state wetlands regulatory agency or regional office of the U S Army Corps of Engineers Flood mapping for every state has been prepared by the Federal Emergency Management Agency (FEMA) Two types of flood mapping are available Flood Insurance Rate Maps (FIRM) and Flood Boundary and Floodway Maps These maps delineate the areas adjacent to surface waters that would be under water in 100-year and 500-year floods Historic flood data may also be available from community and state libraries

If published information sources are lacking or scarce, a review of well logs, both public and private, and test boring logs becomes the primary method for developing preliminary hydrogeologic interpretations for an area Well records provide geological data (although the quality of descriptions prepared by water well drillers may be problematic) Records of well discharge and water level fluctuations may provide a basis for evaluating an aquifer's hydraulic conductivity, transmissivity, and storativity

### *5.2.3 Airphoto Interpretation*

Aerial photographs provide an inexpensive way to directly observe natural and artificial features on the land surface Aerial photographs are basic to any geologic or hydrogeologic investigation Much information can be obtained from stereopairs of black-and-white air photos, which provide a three-dimensional image of the surface when viewed with a stereoscope Patterns of vegetation, variations in grey tones in soil and rock, drainage patterns, and linear features allow preliminary interpretations of geology, soils, and hydrogeology Table 5-3 describes the types of observations and the inferences about geologic and ground water conditions that can be made from aerial photographs Various standard texts are available for guidance in air photo interpretation methods (Avery, 1968, Lueder, 1959, Miller and Miller, 1961, Strandberg, 1967, Lillesand and Kiefer, 1979, Verstappen, 1977) All air photo interpretations should be field checked and revised where "ground truthing" indicates features that were missed or incorrectly delineated

Black-and-white air photos are available from various federal agencies for almost any location in the United States These are the cheapest type of air photo to obtain The nearest county office of the Soil Conservation Service or Agricultural Stabilization and Conservation Service (they will often be in the same building) is the best starting place to determine what is available Many of these offices have air photo coverage that extends back to the 1930s When photographs for multiple years are available, all should be examined, because significant features that are obscured in one set may be evident in another Also, sequential examination of air photos taken at different times provides valuable information on changes in land use

Air photos often reveal linear features, called fracture traces, that indicate zones of relatively higher permeability in the subsurface Fracture-trace analysis using air photos can provide preliminary information on possible preferential movement of contaminants Fetter (1980, pp 406-411) provides a good introduction to fracture-trace analysis Parizek (1976) provides a good review of the North American literature on fracture trace and lineament analysis

## 5.3 Field Data Collection

More often than not, existing information sources will not provide all the information required to delineate a WHPA Where financial resources are very limited, field data collection may be restricted to activities such as measurement of water levels in existing wells to develop a potentiometric map and very simple well tests (Section 3 2 3) Where a large population is served by a few wells, and options for alternative water supplies are limited if they should become contaminated, extensive hydrogeologic field investigations for computer modeling, costing tens of thousands of dollars or more, may be justified

A detailed discussion of field methods is beyond the scope of this manual Some standard texts on geologic mapping methods include Bishop (1960), Compton (1962), Lahee (1961), and Low (1952) Thomas (1978) reviews principles for field hydrogeological investigations, and Scheidegger (1973) reviews geomorphic aspects of hydrology Warman and Wiesnet (1966) provide guidance on the design of hydrogeologic maps LaMoreaux (1966) and UNESCO (1970) describe symbols and conventions for the preparation of hydrogeologic maps UNESCO (1975) provides the same for geohydrochemical maps Figure 5-2 provides an overview of symbols recommended for hydrogeologic mapping Moore (1991) provides guidance on planning and report preparation

As noted at the beginning of this chapter, any text on hydrogeology provides some coverage on field investi-

**Table 5-3 Representative Types of Observations and Inferences of Geologic and Ground-Water Conditions from the Study of Aerial Photographs (Heath and Trainer, 1981)**

| Type of Observation | Purpose of Observation |
|---|---|
| A. Water, or water features, at the land surface | Inference of ground-water conditions from surface-water conditions |
| 1. Drainage density, subdivision of area on basis of drainage density | Classification of terrain on basis of relative permeability, differentiation of tracts of rather different permeability |
| 2 Localized gain or loss of stream-flow (e g , springs and seeps along streams, sites or reaches of loss of water from channel) | Classification of streams as gaining or losing, and location of gaining and losing reaches, from this, inference of general nature of ground-water discharge, recharge, and circulation in near-surface rocks, together with geologic data, may permit inference of confined or unconfined aquifers, and of geologic controls on ground water |
| 3 Seepage at land surface (commonly shown by character and distribution of vegetation) | Location of sites of ground-water discharge, areal form and areal and topographic distribution of these sites, together with geologic data, may permit inference of type of aquifer and of geologic controls on ground water |
| 4 Presence and distribution of man-made water features (wells, improved springs, reservoirs, canals) | Show presence of water, with supplementary data, particularly relating to vegetation and land-surface drainage, may permit inference of effect of these water features on ground water in the area (Photographs made before and after construction of features are particularly valuable) |
| B Character and areal distribution of rocks | Inference of broad geologic controls on the occurrence of ground water |
| 1. Specific type(s) of rock(s) as inferred from such evidence as landforms, texture, color, or tone of land surface, vegetation | Broad classification of types of water-bearing material near the land surface, and hence inference of probable porosity and relative permeability of near-surface material, with data on climate, vegetation, and drainage, inference of chemical quality of ground water |
| 2. Spatial form and interrelations of rock units (stratigraphy and structure) | Inference of size, shape, and boundaries (lithologic and hydrologic) of probable aquifers and aquicludes, inference of conditions of recharge and discharge of ground water |
| 3 Spatial relation of rock units to surface-water bodies | Inference of hydrologic boundaries and recharge conditions |

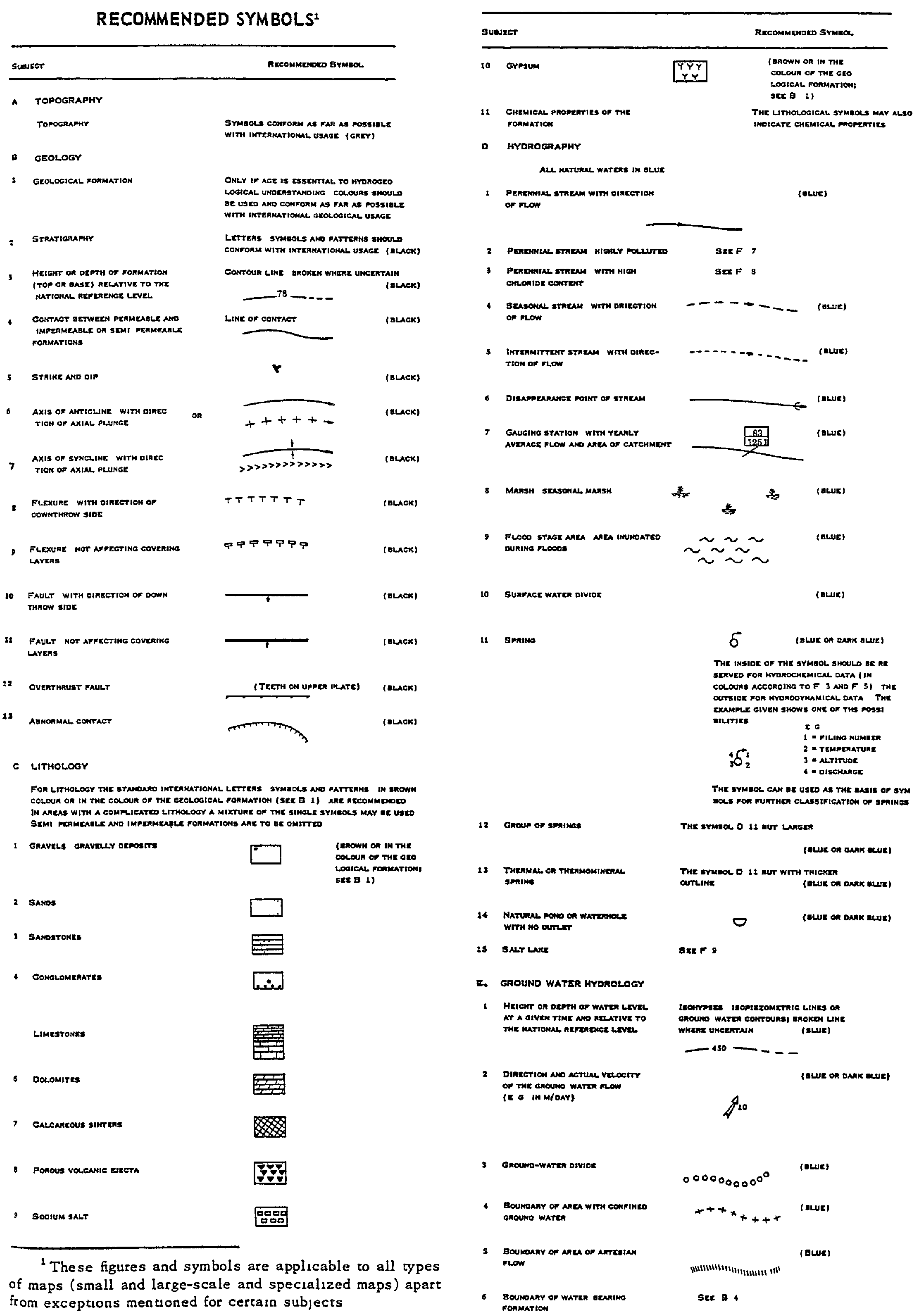
gation methods Ground water texts that give special emphasis to hydrogeologic mapping include Brassington (1988), Brown et al (1983), Erdélyi and Gálfi (1988), Mandel and Shifton (1981), UNESCO (1977), U S. Geological Survey (1980), and Walton (1970) U S EPA (1991a) provides an overview of ground water investigation methods The reports of EPA-sponsored workshops on minimum data requirements for ground water (U S EPA 1988a) and hydrogeologic mapping needs for ground water protection and management (U.S EPA 1990) may also serve as useful resources U.S. EPA (1993c) provides a comprehensive compilation of more than 250 methods for subsurface field characterization and monitoring techniques The rest of this section provides a brief overview of major field methods and their applicability to WHPA investigations

### 5.3.1 Soil Survey

If an SCS soil survey is not available for the county in which a WHPA is being investigated, SCS may be able to provide technical assistance by mapping the area of interest The nearest District SCS office should be contacted to find out about the possibility of, and procedures for, obtaining technical assistance If governmental assistance is not available, hiring a consulting soil scientist might be an option The cost of this option might be justified for a highly vulnerable unconfined aquifer serving a large population. Consulting soil scientists can be identified by contacting the National Society of Consulting Soil Scientists (325 Pennsylvania Ave , SE, Suite 700, Washington, DC, 20003), the Office of the American Registry of Certified Professionals in Agronomy, Crops, and Soils (ARCPACS, 677 S Segoe Rd , Madison, WI 53711-1086), or the state association of professional soil scientists, if one exists State associations may have their own certification programs, and are probably the best starting point to find a soil scientist familiar with soils in the area of interest Any contract signed with a consulting soil scientist should specify that the map conform to standards of the SCS National Cooperative Soil Survey program

### 5.3.2 Surface Geophysical Measurements

Surface geophysical methods, such as DC resistivity, electromagnetic induction, ground-penetrating radar, seismic refraction and reflection, and microgravity surveys, are beginning to be used more frequently in hydrogeologic investigations Table 5-4 provides summary information on applications of surface geophysical methods for ground water and contaminated site investigations The most commonly used methods are in boldface type Geophysical methods require specialized equipment and training and require verification by drilling of boreholes Consequently, they are relatively expensive Where detailed hydrogeologic investigations are required for numerical computer modeling, surface



# RECOMMENDED SYMBOLS[1]

| | Subject | Recommended Symbol |
|---|---|---|
| A | TOPOGRAPHY | |
| | Topography | Symbols conform as fai as possible with international usage (grey) |
| B | GEOLOGY | |
| 1 | Geological formation | Only if age is essential to hydrogeo logical understanding colours should be used and conform as far as possible with international geological usage |
| 2 | Stratigraphy | Letters symbols and patterns should conform with international usage (black) |
| 3 | Height or depth of formation (top or base) relative to the national reference level | Contour line broken where uncertain (black)<br>78 |
| 4 | Contact between permeable and impermeable or semi permeable formations | Line of contact (black) |
| 5 | Strike and dip | (black) |
| 6 | Axis of anticline with direc tion of axial plunge | or (black) |
| 7 | Axis of syncline with direc tion of axial plunge | (black) |
| 8 | Flexure with direction of downthrow side | (black) |
| 9 | Flexure not affecting covering layers | (black) |
| 10 | Fault with direction of down throw side | (black) |
| 11 | Fault not affecting covering layers | (black) |
| 12 | Overthrust fault | (Teeth on upper plate) (black) |
| 13 | Abnormal contact | (black) |
| C | LITHOLOGY | |
| | For lithology the standard international letters symbols and patterns in brown colour or in the colour of the geological formation (see B 1) are recommended In areas with a complicated lithology a mixture of the single symbols may be used Semi permeable and impermeable formations are to be omitted | |
| 1 | Gravels gravelly deposits | (brown or in the colour of the geo logical formation; see B 1) |
| 2 | Sands | |
| 3 | Sandstones | |
| 4 | Conglomerates | |
| | Limestones | |
| 6 | Dolomites | |
| 7 | Calcareous sinters | |
| 8 | Porous volcanic ejecta | |
| 9 | Sodium salt | |
| 10 | Gypsum | (brown or in the colour of the geo logical formation; see B 1) |
| 11 | Chemical properties of the formation | The lithological symbols may also indicate chemical properties |
| D | HYDROGRAPHY | |
| | All natural waters in blue | |
| 1 | Perennial stream with direction of flow | (blue) |
| 2 | Perennial stream highly polluted | See F 7 |
| 3 | Perennial stream with high chloride content | See F 8 |
| 4 | Seasonal stream with driection of flow | (blue) |
| 5 | Intermittent stream with direc-tion of flow | (blue) |
| 6 | Disappearance point of stream | (blue) |
| 7 | Gauging station with yearly average flow and area of catchment | 83<br>1261<br>(blue) |
| 8 | Marsh seasonal marsh | (blue) |
| 9 | Flood stage area area inundated during floods | (blue) |
| 10 | Surface water divide | (blue) |
| 11 | Spring | (blue or dark blue)<br>The inside of the symbol should be re served for hydrochemical data (in colours according to F 3 and F 5) the outside for hydrodynamical data The example given shows one of ths possi bilities<br>e g<br>1 = filing number<br>2 = temperature<br>3 = altitude<br>4 = discharge<br>The symbol can be used as the basis of sym bols for further classification of springs |
| 12 | Group of springs | The symbol D 11 but larger<br>(blue or dark blue) |
| 13 | Thermal or thermomineral spring | The symbol D 11 but with thicker outline (blue or dark blue) |
| 14 | Natural pond or waterhole with no outlet | (blue or dark blue) |
| 15 | Salt lake | See F 9 |
| E. | GROUND WATER HYDROLOGY | |
| 1 | Height or depth of water level at a given time and relative to the national reference level | Isohypses isopiezometric lines or ground water contours; broken line where uncertain (blue)<br>450 |
| 2 | Direction and actual velocity of the ground water flow (e g in m/day) | (blue or dark blue)<br>10 |
| 3 | Ground-water divide | (blue) |
| 4 | Boundary of area with confined ground water | (blue) |
| 5 | Boundary of area of artesian flow | (Blue) |
| 6 | Boundary of water bearing formation | See B 4 |

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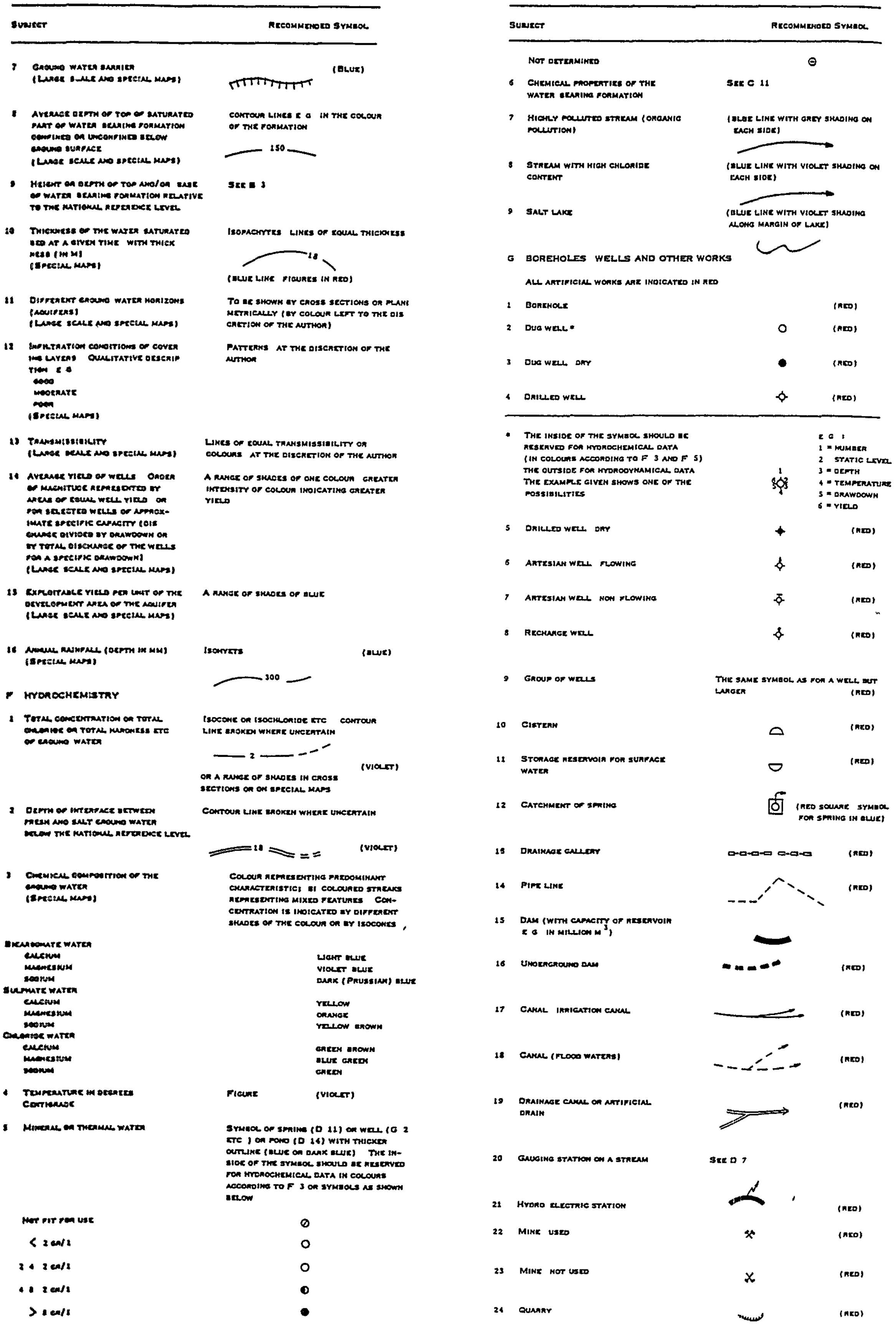
[1] These figures and symbols are applicable to all types of maps (small and large-scale and specialized maps) apart from exceptions mentioned for certain subjects

**Figure 5-2 Symbols and conventions for preparation of hydrogeologic maps (LaMoreaux, 1966)**



| Subject | Recommended Symbol |
|---|---|
| 7 Ground water barrier<br>(Large scale and special maps) | (Blue) |
| 8 Average depth of top of saturated part of water bearing formation confined or unconfined below ground surface<br>(Large scale and special maps) | Contour lines e g in the colour of the formation<br>150 |
| 9 Height or depth of top and/or base of water bearing formation relative to the national reference level | See E 3 |
| 10 Thickness of the water saturated bed at a given time with thickness (in m)<br>(Special maps) | Isopachytes lines of equal thickness<br>18<br>(Blue line figures in red) |
| 11 Different ground water horizons (aquifers)<br>(Large scale and special maps) | To be shown by cross sections or planimetrically (by colour left to the discretion of the author) |
| 12 Infiltration conditions of covering layers Qualitative description e g<br>good<br>moderate<br>poor<br>(Special maps) | Patterns at the discretion of the author |
| 13 Transmissibility<br>(Large scale and special maps) | Lines of equal transmissibility or colours at the discretion of the author |
| 14 Average yield of wells Order of magnitude represented by areas of equal well yield or for selected wells of approximate specific capacity (discharge divided by drawdown or by total discharge of the wells for a specific drawdown)<br>(Large scale and special maps) | A range of shades of one colour greater intensity of colour indicating greater yield |
| 15 Exploitable yield per unit of the development area of the aquifer<br>(Large scale and special maps) | A range of shades of blue |
| 16 Annual rainfall (depth in mm)<br>(Special maps) | Isohyets (blue)<br>300 |
| **F HYDROCHEMISTRY** | |
| 1 Total concentration or total chloride or total hardness etc of ground water | Isocone or isochloride etc contour line broken where uncertain<br>2<br>(Violet)<br>or a range of shades in cross sections or on special maps |
| 2 Depth of interface between fresh and salt ground water below the national reference level | Contour line broken where uncertain<br>18 (Violet) |
| 3 Chemical composition of the ground water<br>(Special maps) | Colour representing predominant characteristic; bi coloured streaks representing mixed features Concentration is indicated by different shades of the colour or by isocones , |
| Bicarbonate water | |
| Calcium | Light blue |
| Magnesium | Violet blue |
| Sodium | Dark (Prussian) blue |
| Sulphate water | |
| Calcium | Yellow |
| Magnesium | Orange |
| Sodium | Yellow brown |
| Chloride water | |
| Calcium | Green brown |
| Magnesium | Blue green |
| Sodium | Green |
| 4 Temperature in degrees Centigrade | Figure (Violet) |
| 5 Mineral or thermal water | Symbol of spring (D 11) or well (G 2 etc ) or pond (D 14) with thicker outline (blue or dark blue) The inside of the symbol should be reserved for hydrochemical data in colours according to F 3 or symbols as shown below |
| Not fit for use | ⊘ |
| < 2 gm/l | ○ |
| 2 4 2 gm/l | ○ |
| 4 8 2 gm/l | ◐ |
| > 8 gm/l | ● |

| Subject | Recommended Symbol |
|---|---|
| Not determined | ⊖ |
| 6 Chemical properties of the water bearing formation | See C 11 |
| 7 Highly polluted stream (organic pollution) | (Blue line with grey shading on each side) |
| 8 Stream with high chloride content | (Blue line with violet shading on each side) |
| 9 Salt lake | (Blue line with violet shading along margin of lake) |
| **G BOREHOLES WELLS AND OTHER WORKS** | |
| All artificial works are indicated in red | |
| 1 Borehole | (Red) |
| 2 Dug well * | ○ (Red) |
| 3 Dug well dry | ● (Red) |
| 4 Drilled well | (Red) |
| * The inside of the symbol should be reserved for hydrochemical data (in colours according to F 3 and F 5) the outside for hydrodynamical data The example given shows one of the possibilities | 1 2 3 4 5 6<br>e g :<br>1 = number<br>2 static level<br>3 = depth<br>4 = temperature<br>5 = drawdown<br>6 = yield |
| 5 Drilled well dry | (Red) |
| 6 Artesian well flowing | (Red) |
| 7 Artesian well non flowing | (Red) |
| 8 Recharge well | (Red) |
| 9 Group of wells | The same symbol as for a well but larger (Red) |
| 10 Cistern | (Red) |
| 11 Storage reservoir for surface water | (Red) |
| 12 Catchment of spring | (Red square symbol for spring in blue) |
| 13 Drainage gallery | (Red) |
| 14 Pipe line | (Red) |
| 15 Dam (with capacity of reservoir e g in million $m^3$) | |
| 16 Underground dam | (Red) |
| 17 Canal irrigation canal | (Red) |
| 18 Canal (flood waters) | (Red) |
| 19 Drainage canal or artificial drain | (Red) |
| 20 Gauging station on a stream | See D 7 |
| 21 Hydro electric station | (Red) |
| 22 Mine used | (Red) |
| 23 Mine not used | (Red) |
| 24 Quarry | (Red) |

Figure 5-2. Symbols and conventions for preparation of hydrogeologic maps (LaMoreaux, 1966) (continued)

**Table 5-4 Summary Information on Remote Sensing and Surface Geophysical Methods (All ratings are approximate and for general guidance only)**

| Technique | Soils/ Geology | Leachate | Buried Wastes | NAPLs | Penetration Depth[a] | Cost[b] | Section in U S EPA (1993b) |
|---|---|---|---|---|---|---|---|
| *Airborne Remote Sensing and Geophysics* | | | | | | | |
| **Visible Photography** | yes | yes[c] | possibly[d] | yes[c] | Surf only | L | 1 1 1 |
| Infrared Photography | yes | yes[c] | possibly[d] | yes[c] | Surf only | L-M | 1 1 1 |
| Multispectral Imaging | yes | yes[c] | no | yes[c] | Surf only | L | 1 1 1 |
| Ultraviolet Photography | yes | yes[c] | no | yes[c] | Surf only | L | 1 1 2 |
| Thermal Infrared Scanning | yes | yes (T) | possibly[d] | possibly | Surf only | M | 1 1 3 |
| Active Microwave (Radar) | yes | possibly | no | possibly | 0 1-2 | M | 1 1 4 |
| Airborne Electromagnetics | yes | yes (C) | yes | possibly | 0-100 | M | 1 1 5 |
| Aeromagnetics | yes | no | yes | no | ? | M | 1 1 6 |
| *Surface Electrical and Electromagnetic Methods* | | | | | | | |
| Self Potential | yes | yes (C) | yes | no | S ? | L | 1 2 1 |
| **Electrical Resistivity** | yes | yes (C) | yes (M) | possibly | S 60 (km) | L-M | 1 2 2, 9 1 1 |
| Induced Polarization | yes | yes (C) | yes | possibly | S km | L-M | 1 2 3 |
| Complex Resistivity | yes | yes (C) | yes | yes | S km | M-H | 1 2 3 |
| Time Domain Reflectometry | yes | yes (C) | no | yes | S 2[e] | M-H | 6 2 4 |
| Capacitance Sensors | yes | yes (C) | no | possibly | S 2[e] | L-M | 6 2 4 |
| **Electromagnetic Induction** | yes | yes (C) | yes | possibly | S 60(200)/C 15(50) | L-M | 1 3 1 |
| Transient Electromagnetics | yes | yes (C) | yes | no | S 150 (2000+) | M-H | 1 3 2 |
| **Metal Detectors** | no | no | yes | no | C/S 0-3 | L | 1 3 3 |
| VLF Resistivity | yes | yes (C) | yes | no | C/S 20-60 | M-H | 1 3 4 |
| Magnetotellurics | | | | | | | |
| *Surface Seismic and Acoustic Methods* | | | | | | | |
| **Seismic Refraction** | yes | yes | no | no | S 1-30(200+) | L-M | 1 4 1 |
| Shallow Seismic Reflection | yes | no | no | no | S 10-30(2000+) M-H | 1 4 2 | |
| Continuous Seismic Profiling | yes | no | no | no | C 1-100 | L-M | 1 4 3 |
| Seismic Shear/Surface Waves | yes | no | no | no | S ? | M-H | 1 4 4 |
| Acoustic Emission Monitoring | yes | no | no | no | S 2[e] | L | 1 4 5 |
| Sonar/Fathometer | yes | yes | no | no | C no limit | L-H | 1 4 6 |
| *Other Surface Geophysical Methods* | | | | | | | |
| **Ground-Penetrating Radar** | yes | yes (C) | yes | yes | C 1-25 (100s) | M | 1 5 1 |
| **Magnetometry** | no | no | yes (F) | no | C/S 0-20[f] | L-M | 1 5 2 |
| Gravity | yes | yes | no | no | S 100s+ | H | 1 5 3 |
| Radiation Detection | no | no | yes (nuclear) | no | C/S near surface | L | 1 5 4 |
| *Near Surface Geothermometry* | | | | | | | |
| Soil Temperature | yes | yes (T) | no | no | S 1-2[e] | L | 1 6 1 |
| Ground Water Detection | yes | yes (T) | no | no | S 2[e] | L | 1 6 2 |
| Other Thermal Properties | yes | no | no | no | S 1-2[e] | L-M | 1 6 3 |

**Boldface** = Most commonly used methods at contaminated sites

(C) = plume detected when contaminant(s) change conductivity of ground water, (F) = ferrous metals only, (T) = plume detected by temperature rather than conductivity

[a] S = station measurement; C = continuous measurement Depths are for typical shallow applications, ( ) = achievable depths

[b] Ratings are very approximate L = low, M = moderate, H = high

[c] If leachate or NAPLs are on the ground or water surface or indirectly affect surface properties, field confirmation required

[d] Disturbed areas which may contain buried waste can often be detected on aerial photographs

[e] Typical maximum depth, greater depths possible, but sensor placement is more difficult and cable lengths must be increased

[f] For ferrous metal detection, greater depths require larger masses of metal for detection, 100s of meters depth can be sensed when using magnetometry for mapping geologic structure

geophysical methods can reduce total costs by optimizing the location of drillholes for more detailed subsurface characterization For this situation, U S EPA (1987), U S EPA (1993b), and Chapter 1 of U S EPA (1993c) provide information that may be helpful in selecting appropriate methods Table 5-5 identifies the most commonly used surface geophysical methods for characterizing aquifer heterogeneity (Section 5 4 2)

**Table 5-5 Summary of Methods for Characterizing Aquifer Heterogeneity**

| Method | Properties | Comments |
|---|---|---|
| *Vertical Variations* | | |
| Drill logs | Changes in lithology<br>Aquifer thickness<br>Confining bed thickness<br>Layers of high/low hydraulic conductivity<br>Variations in primary porosity (based on material description) | Basic source for geologic cross sections<br>Descriptions prepared by geologist preferred over those by well drillers<br>Continuous core samples provided more accurate descriptions |
| Electric logs | Changes in lithology<br>Changes in water quality<br>Strike and dip (dipmeter) | Require uncased hole and fluid-filled borehole |
| Nuclear logs | Changes in lithology<br>Changes in porosity (gamma-gamma) | Suitable for all borehole condition (cased, uncased, dry, and fluid-filled) |
| Acoustic and seismic logs | Changes in lithology<br>Changes in porosity<br>Fracture characterization<br>Strike and dip (acoustic televiewer) | Requires uncased or steel cased hole, and fluid-filled hole |
| Other logs | Secondary porosity (caliper, television/photography)<br>Variations in permeability (fluid-temperature, flowmeters, single borehole tracing) | Require open, fluid-filled borehole<br>Relatively inexpensive and easy to use |
| Packer Tests | Hydraulic conductivity | Single packer tests used during drilling, double-packer tests after hole completed |
| Surface geophysics | Changes in lithology (resistivity, EMI, TDEM, seismic refraction) | Requires use of vertical sounding methods for electrical and electromagnetic methods |
| *Lateral Variations* | | |
| Potentiometric maps | Changes in hydraulic conductivity | Based on interpretation of the shape and spacing of equipotential contours |
| Hydrochemical maps | Changes in water chemistry | Requires careful sampling, preservation and analysis to make sure samples are representative |
| Tracer tests | Time of travel between points | Requires injection point and one or more downgradient collection points<br>Essential for mapping of flow in karst |
| Geologic maps and cross-sections | Changes in formation thickness<br>Structural features, faults | Result from correlation features observed at the surface and in boreholes |
| Isopach maps | Variations in aquifer and confining layer thickness | Distinctive strata with large areal extent required |
| Geologic structure maps | Stratigraphic and structural boundary conditions affecting aquifers | See Table 5-6 |
| Surface geophysics | Changes in lithology (seismic)<br>Structural features (seismic, GPR, gravity)<br>Changes in water quality/ contaminant plume detection (ER, EMI, GPR) | Interpretations require verification using subsurface borehole data |

### 5.3.3 *Geologic and Geophysical Well Logs*

Geologic and geophysical well logs are essential for developing a three-dimensional picture of the subsurface. Cliffs, road-cuts, river banks, and other areas where vertical sections of subsurface materials are exposed at the surface provide a good starting point for observing the character of bedrock and unconsolidated deposits below the ground surface As noted in Section 5.2.2, the examination of well logs and records of other subsurface borings provides information about the subsurface in areas where exposures are not available Often, additional drilling is required to confirm tentative interpretations made from existing data or to fill in gaps in coverage A hollow-stem auger with periodic or continuous core sampling with a thin-wall sampler is usually the best drilling method in unconsolidated material where accurate stratigraphic information is required In bedrock, continuous diamond coring provides samples that allow an accurate description of changes in lithology These samples are especially valuable for identifying the presence and observing the character of fractures Chapter 2 in U S EPA (1993a) provides more detailed information about the suitability, advantages, and disadvantages of different drilling and solids sampling methods

The collection of undisturbed or minimally disturbed subsurface samples adds to the cost of drilling Drill cuttings can be observed as they are brought to the surface, allowing the development of less precise descriptive logs of vertical changes in subsurface lithology The main difficulty in preparing logs from cuttings is that it is hard to know the exact depth from which they came In either situation, a trained geologist or hydrogeologist should prepare the actual descriptive logs

Borehole geophysical logs can provide valuable additional information about subsurface geology, especially when the drilling method does not recover intact cores Depending on the type or combination of logs that is used, a wide variety of subsurface properties can be characterized (1) identification of the type and thickness of strata within a borehole, (2) correlation of strata between boreholes, (3) measurement of moisture content in the vadose (unsaturated) zone, (4) measurement of porosity and specific yield, (5) characterization of fractures, (6) identification of zones of high permeability, (7) measurement of the direction of ground water flow, (8) characterization of water quality

Specific logging methods may be restricted to certain borehole conditions (e g , may require an uncased, fluid-filled hole or a certain minimum diameter) Chapter 3 in U S EPA (1993a) provides information on the applications, borehole requirements, advantages, and disadvantages of more than 40 geophysical logging techniques Perhaps a half dozen are commonly used in hydrogeological investigations, but many more have potential value for particular situations Section 5 4 2 identifies a number of methods that are particularly useful for characterizing aquifer heterogeneity

### *5.3.4 Measurement of Aquifer Parameters*

Section 3 3 discusses methods for field measurement of aquifer parameters for use in analytical equations and computer modeling for WHPA delineation Most of these methods can also be used as part of hydrogeologic mapping for locating aquifer boundaries and characterization of aquifer heterogeneity (Section 5 4 1 and 5 4 2)

### *5.3.5 Ground Water Chemistry*

Valuable complements to mapping physical characteristics of an aquifer include sampling ground water from existing wells and/or new boreholes drilled during hydrogeologic mapping, measuring such parameters as temperature, pH, and specific conductance, and analyzing for common dissolved constituents (nitrate, sulfate, calcium, sodium, and bicarbonate) Uses of hydrochemical data include

- Dating of ground water using tritium or carbon-14 allows estimation of how recently an aquifer has been recharged Wells that pump recently recharged water are more vulnerable to contamination than wells where the water has been below the surface for hundreds or thousands of years

- Other chemical characteristics, such as pH and dissolved constituent concentrations, tend to change the longer water is in the ground, providing another indicator of how close a well is to a recharge zone

- In karst areas, varying specific conductance of springs indicates that the springs are fed by different parts of the subsurface flow system

- Multiple aquifers in an area may have distinctive chemistries In this situation, analyses of ground water samples from wells can be used to determine which aquifer is being tapped Samples with intermediate chemical compositions may indicate mixing of water in a well that penetrates several aquifers

Ground water chemistry is a useful indicator of heterogeneity (Section 5 4 2) and is useful for assessing the presence and degree of confinement in a aquifer (Section 5 4 3) An important consideration in hydrochemical mapping is that the samples should be representative of conditions in the aquifer at the location sampled In addition, no chemical alterations of the sample should take place as a result of sampling, or between the time that the sample is taken and analyzed

## 5.4 Special Considerations for Wellhead Protection

Hydrogeologic mapping is especially valuable as a complement to other WHPA delineation methods in the following areas (1) adjustments of WHPAs to account for aquifer boundaries (Section 5 4 1), (2) adjustments of WHPAs based on aquifer heterogeneity and/or anisotropy (Section 5 4 2), and (3) assessing the presence and degree of confinement in aquifers (Section 5 4 3) Hydrogeologic mapping should be the primary method for delineating WHPAs in fractured rock and unconfined karst aquifers where a porous-medium approximation for ground water flow cannot be demonstrated Methods for characterization and hydrogeologic mapping in such settings are discussed in more detail in Section 5 4 4

## Checklist 5-1
## Possible Aquifer Boundaries

| | Distance to well | Within ZOC?* | |
|---|---|---|---|
| | | Yes | No |
| *Barrier Boundaries* | | | |
| ____ Vertical/Sloping | ____________ | ____ | ____ |
|     ____ Impermeable crystalline rocks | ____________ | ____ | ____ |
|     ____ Fault displacement | ____________ | ____ | ____ |
| ____ Horizontal** | ____________ | ____ | ____ |
| *Recharge Boundaries* | | | |
| ____ Natural ground-water divide (unconfined aquifer) | ____________ | ____ | ____ |
| ____ Areal recharge from precipitation | ____________ | ____ | ____ |
| ____ Loosing stream | ____________ | ____ | ____ |
| ____ Lake, other surface water body | ____________ | ____ | ____ |
|     ____ Above water table | ____________ | ____ | ____ |
|     ____ Surface expression of water table | ____________ | ____ | ____ |
| ____ Leaky confining layer (downward flow) | ____________ | ____ | ____ |
| ____ Injection well | ____________ | ____ | ____ |
| ____ Areal artificial recharge | ____________ | ____ | ____ |
| *Discharge Boundaries* | | | |
| ____ Gaining stream | ____________ | ____ | ____ |
| ____ Lake, other surface water body | ____________ | ____ | ____ |
|     ____ Surface expression of water table | ____________ | ____ | ____ |
|     ____ Interior drainage basin | ____________ | ____ | ____ |
| ____ Leaky confining layer (upward flow) | ____________ | ____ | ____ |
| ____ Drainage ditch/tile drain | ____________ | ____ | ____ |
| ____ Other pumping wells | ____________ | ____ | ____ |

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* As defined by one or more of the simple methods described in Chapter 4

** Impermeable geologic materials always form the base of an aquifer, see Table 5-6 for criteria for defining the extent to which impermeable confining layers represent boundaries to flow

### 5.4.1 Delineation of Aquifer Boundaries

Identification of aquifer boundaries is an essential part of identifying a well's zone of contribution[1] (ZOC) Ground water divides upgradient from a well can be readily identified using a potentiometric surface map (Chapter 2) Section 2 1 6 discusses other major types of aquifer boundaries Checklist 5-1 can be used to identify possible aquifer boundaries that may affect a well Figure 2-7 provides illustrations of most of these types of boundaries Determining the distance from the boundary to the well will help identify those boundaries that might be most significant for purposes of WHPA delineation

Additional analysis using simple analytical methods for calculating drawdown (Section 4 5) may be required to determine whether an aquifer boundary actually functions as a boundary to the well's zone of contribution For example, a stream downgradient from a well would represent a potential boundary, but if the distance to the null point using the uniform flow equation (Section 4 5 1) does not extend to the stream, then the null point, not the stream, would mark the downgradient limit of the zone of contribution[2] Similarly, an impermeable boundary that lies outside the upgradient ZOC indicated by the uniform flow equation would not be a boundary to the ZOC

If a barrier or discharge boundary lies *within* a WHPA defined by one or more of the simple methods covered in Chapter 4, a WHPA can be *reduced* based on the hydrogeological mapping of the boundary (provided that the boundary has been or can be defined with some precision) The presence of a recharge boundary within a well's zone of influence (ZOI) based on calculation of drawdown may require modification of the boundaries of the ZOC For example, if a losing stream lies within the ZOI, then the entire upstream drainage basin of the stream lies within the ZOC of the well On the other hand, as discussed in Section 4 4, any recharge in the ZOC of a well serves to *increase* the time of travel from more distant points in the ZOC While this means that travel of contaminants from more distant sources is slower, the presence of one or more recharge boundaries within a WHPA is an indicator of increased vulnerability to contamination in areas nearer the well

### 5.4.2 Characterization of Aquifer Heterogeneity and Anisotropy

As discussed in Section 2 1 3, aquifer heterogeneity and anisotropy are important considerations in delineation of wellhead protection areas Using an average value for hydraulic conductivity in any of the simple methods covered in Chapter 4 will underestimate the time of travel or zone of influence based on drawdown, because contaminants will travel faster in fractures or layers of higher permeability, if they are present Aquifer anisotropy or heterogeneity can result in incorrect delineation of WHPA boundaries based on potentiometric maps and flow net analysis (Section 2 2) Figure 2-12 illustrates this effect in an anisotropic aquifer, and Figure 2-19 shows how this can happen in a heterogeneous aquifer Consequently, a major purpose of hydrogeologic mapping for wellhead protection should be to assess the presence and degree of variability of hydrologic properties vertically and laterally Methods for measuring anisotropy (variations in vertical and horizontal hydraulic conductivity at a particular location) are discussed in Section 3 3 5

Any method that allows measurement or qualitative observation of the similarities and differences in a particular aquifer characteristic in a vertical or horizontal direction allows assessment of whether an aquifer is homogeneous or heterogeneous Table 5-5 summarizes a number of field methods that are commonly used or especially well suited for this purpose Drill logs and geophysical borehole logs allow assessment of vertical changes in lithology, porosity, and permeability Packer tests allow measurement of variations in hydraulic conductivity at different intervals Surface geophysical methods, such as seismic refraction, seismic reflection, and electrical resistivity soundings, also allow less precise mapping of vertical changes in lithology

An accurate potentiometric surface map (Chapter 2) is one of the most valuable ways to evaluate aquifer heterogeneity Hydrochemical maps also provide information that can be specifically related to the hydrogeology of an area Tracer tests (Section 3 3 3) may indicate whether fracture flow or zones of high permeability exist This is indicated when the time of travel of the tracer is faster than the time of travel calculated from estimated aquifer properties or values measured by well tests Geologic cross-sections, isopach maps, and structural maps, which are generally based on interpolations between borehole logs, allow assessment of lithologic variations Surface geophysical methods allow relatively rapid measurement of lateral variations in lithology, structure, and water quality where no better subsurface information is available However, some verification with subsurface borehole data is required

Geostatistical methods, originally developed for characterizing mineral ore bodies, have been found to be

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[1] Exceptions include (1) wells located in unconfined aquifers where the potentiometric surface is nearly flat and the zone of influence does not extend to a vertical impermeable aquifer boundary, and (2) wells in highly confined aquifers that are far from the recharge zone *and* in which faulting has not caused vertical displacement of sediments

[2] If the null point is within several hundred feet of the stream, some consideration should be given to the possibility of backwater effects during flooding on the ZOC (Section 2 3 2)

increasingly useful tools for characterizing the variability of aquifer parameters (Delhomme, 1979, Hoeksma and Kitandis, 1985) Poeter and Belcher (1991) recently described a method for characterizing porous medium heterogeneity by "inverse plume analysis," in which the spatial distribution of contaminant concentrations is used to evaluate variation in aquifer properties Both of these approaches, however, require a relatively high density of subsurface observations, which may not be available in potential wellhead protection areas Special approaches to aquifer characterization are typically required in fractured rock and karst limestone aquifers, as discussed in Section 5 4 4

### 5.4.3 Presence and Degree of Confinement

The presence and degree of confinement has a significant impact on the vulnerability of an aquifer to contamination and the size of the WHPA for a given time of travel or drawdown criterion (Sections 4 4 and 4 5) Figure 5-3 shows the location of major and significant minor confined aquifers in the contiguous United States Methods for evaluating these aquifer properties can be broadly classified as (1) geologic, (2) hydrologic, and (3) hydrochemical. Table 5-6 identifies 15 indicators of confinement and the characteristics that are associated with highly confined or semiconfined conditions Kreitler and Senger (1991) provide more detailed discussion of these methods.

### 5.4.4 Characterization of Fractured Rock and Karst Aquifers

Where fracture or conduit flow (Section 2 1 4) occurs in an aquifer, special care and techniques are required for delineating wellhead protection areas Figure 5-4 identifies major areas of the United States and associated territories where unconfined fracture flow is significant, and Figure 5-5 identifies major karst areas of the contiguous United States and other areas where carbonate rocks are at or near the surface The term "fractured rock" aquifer in this manual refers to areas where most of the water supplied to a pumping well comes from fractures with sufficiently narrow apertures that Darcian flow (Section 3 1 3) occurs Common geologic settings where fractured rock aquifers occur include crystalline intrusive igneous (i e , granites) and metamorphic rocks, basalts, and some carbonates

The term "karst" aquifer in this guide refers to carbonate aquifers where conduit flow is an important component of the ground water flow system As shown in Figure 5-5, not all carbonate rocks (limestone and dolomite) are karst aquifers However, whenever carbonate aquifers are present, either fracture or conduit flow should be assumed

The fundamental objective of hydrogeologic mapping in fractured rock and karst aquifers should be to identify (1) the *boundaries* of the flow system, and (2) the *structure* of the flow system The rest of this section provides

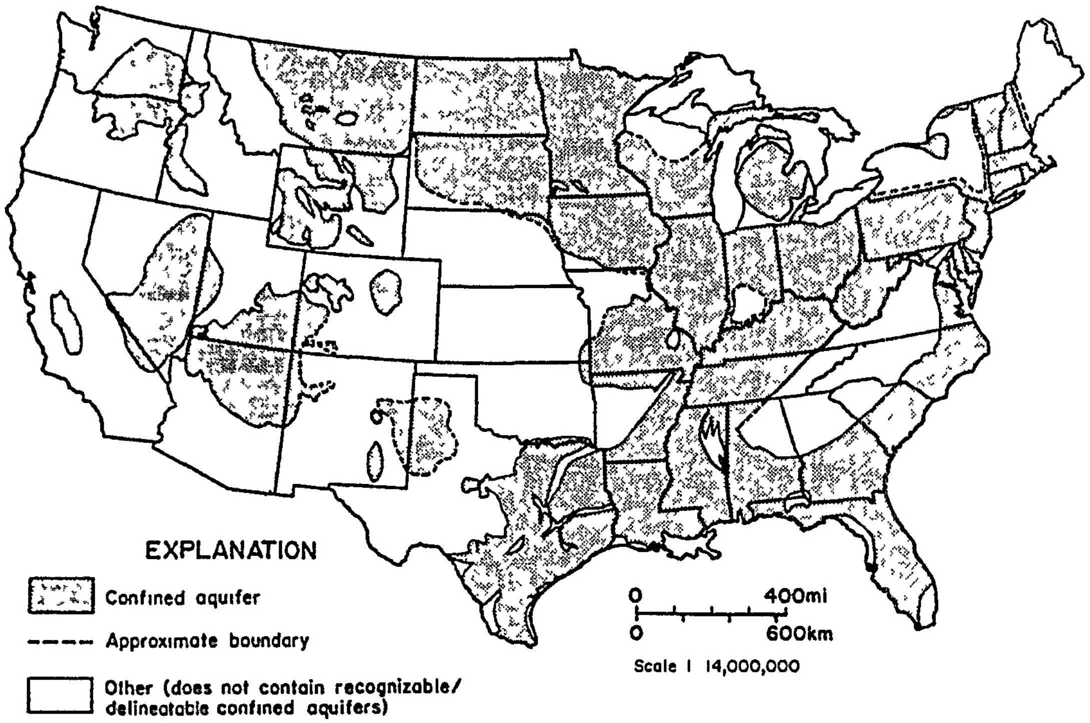

**Figure 5-3.** Major and significant minor confined aquifers of the United States (Kreitler and Senger, 1991)

**Table 5-6 Indicators of Presence and Degree of Confinement**

| Information Source | Highly Confined | Semiconfined (Leaky) |
|---|---|---|
| *Geologic* | | |
| Geologic maps and cross-sections | Presence of continuous, unfractured, confining strata (clays, glacial till, shale, siltstone) | Evidence of vertical permeability in confining strata (fracture traces, faults, mineralization or oxidation of fractures observed in cores) |
| Environmental geologic and hydrogeologic maps | See above | Presence of artificial penetrations (abandoned or producing oil and gas wells, water wells, exploration boreholes) |
| *Hydrologic* | | |
| Water level elevation (single well) of potentiometric surface | Above the top of the aquifer (not diagnostic for differentiation of highly and semi-confined aquifers) | Same |
| Hydraulic head differences between aquifers | Large head difference in water levels measured in wells cased in different aquifers (not diagnostic for differentiation of highly and semiconfined aquifers) | Same |
| Water level fluctuations (continuous measurement) | Short-lived and diurnal fluctuations in response to changes in barometric pressure, tidal effects, external loading (Table 2-1), no response to recharge events | Similar to highly confined aquifer, but may also exhibit relatively large and rapid response to recharge events because of leakage through discrete points |
| Hydrologic measurements in confining strata | No changes in water levels in response to pumping, diurnal but not seasonal water level fluctuations (see above) | Changes in water levels in response to pumping, seasonal water-level fluctuations in response to seasonal variations in precipitation |
| Pump test for storativity | Storativity less than 0 001 | Between 0 01 and 0 001 (not diagnostic) |
| Pump test for leakage | Pump drawdown vs time curve matches analytical solution(s) for highly confined aquifer Estimated or calculated leakage less than $10^{-3}$ gal/day/ft$^2$ | Pump drawdown vs time curve requires use of analytical solution for leaky aquifer Estimated or calculated leakage $10^{\ 2}$ to $10^{2}$ gal/day/ft$^2$ |
| Numerical modeling | Simulation of potentiometric surface possible without estimates of leakage, or required estimates are low (see above) | Simulation of potentiometric surface requires use of large leakage values |
| *Hydrochemistry* | | |
| General water chemistry | Chemical characteristics indicative of long distance from recharge area (region-specific) | Qualifies as confined using other criteria, but chemical characteristics more similar to ground water in recharge zones |
| Anthropogenic atmospheric tracers | No detectable tritium or fluorocarbons in ground water | Detectable concentrations of tritium or fluorocarbons (less than 40 years old) |
| Isotope chemistry | Carbon-14 dating of water samples indicates age > 500 years | See above |
| Contaminants | No detectable concentrations of potential contaminants identified by inventory of potential contaminant sources | Qualifies as confined using other criteria, and contaminants detected in aquifer |
| Changes in water chemistry over time | Head declines from long-term pumping have not resulted in changes in water chemistry indicators of vertical leakage | Head declines from long term pumping have resulted in changes in water chemistry indicators of vertical leakage (see above) |
| Time of travel through confining strata | Time of travel calculations based on measured or estimated values of difference in hydraulic head, porosity and hydraulic conductivity exceed 40 years | Time of travel through confining strata < 40 years based on calculations or presence of tritium or fluorocarbons |

Source Adapted from Kreitler and Senger (1991)

an overview of major methods for characterizing the boundaries and structure of fracture rock and karst systems Table A-2 provides an extensive list of major references on karst geology, geomorphology, and hydrology where more detailed information can be obtained

The primary method for mapping the boundaries of an unconfined fractured rock or karst aquifer is dye tracing (Section 3 3 3) In karst aquifers this is the *only* reliable method because conduit flow systems often do not follow surface water drainage systems For example, Bonacci and Zivaljevic (1993), using dye tracing and a water

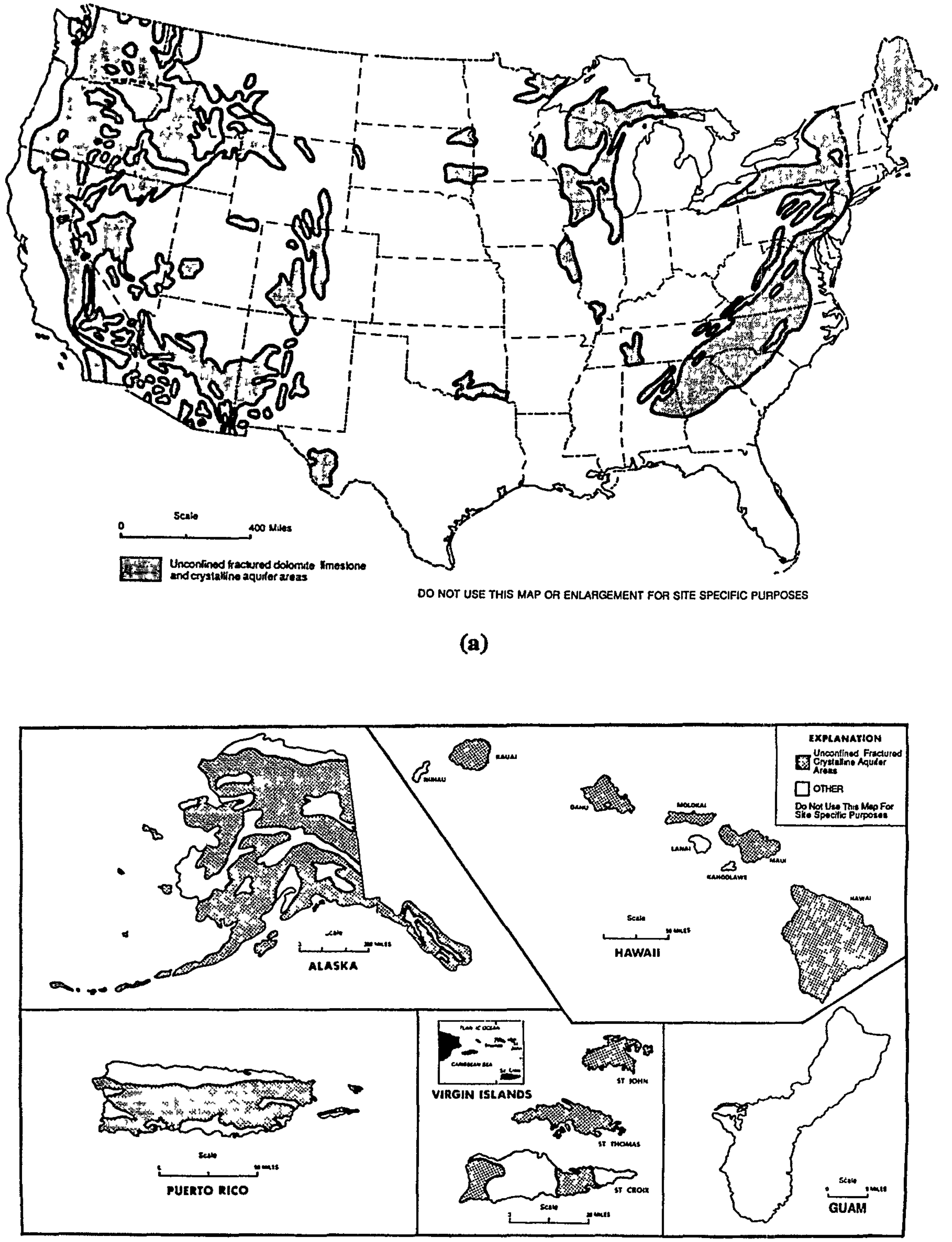

Figure 5-4. Areas of unconfined fractured rock aquifers (a) contiguous United States, (b) Alaska, Hawaii, Puerto Rico, Virgin Islands, and Guam (Bradbury et al , 1991)

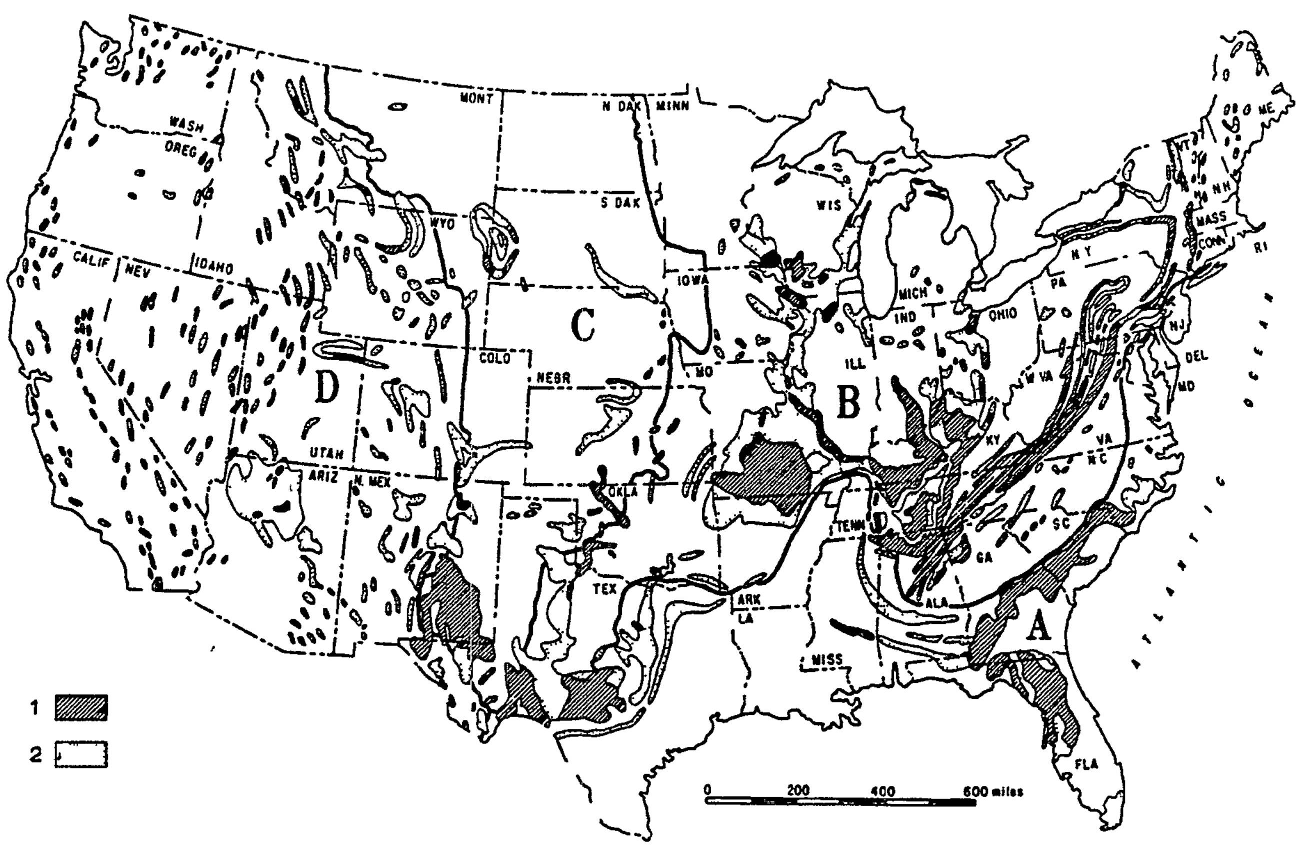

**Figure 5-5** **Distribution of karst areas in relation to carbonate and sulphate rocks in the United States A = Atlantic and Gulf Coastal Plain region, B = east-central region of Paleozoic and other old rock, C = Great Plains region, D = western mountain region, 1 = karst areas, 2 = carbonate and sulphate rocks at or near the surface (from Davies and LeGrand, 1972)**

budget of a large spring in the Dinaric karst of Montenegro, found the catchment area to be 76 to 79 km$^2$, while hydrogeologic mapping based on geology and topography indicated a catchment area of 120 to 170 km$^2$ [3] Significant differences in flow direction may occur in karst aquifers depending on whether low-flow or high-flow conditions exist Again, such changes can only be accurately determined using dye tracer tests For example, low-flow and high-flow tracer tests were conducted by injecting dye into several wells in the vicinity of Lemon Lane landfill, a Superfund site contaminated with PCBs The landfill is located on a topographic divide in a karst area where more than 30 springs have been identified within a mile-and-a-half radius of the landfill (Figure 5-6a) A low-flow tracer test conducted in 1987 found that most water infiltrating in the vicinity of the landfill flowed in a southeasterly direction, but some also flowed to the northeast (Figure 5-6a) A high-flow tracer test, conducted two years later, found that most flow was still in a southeasterly direction, but that some flow occurred in all directions, with dye being detected in essentially all of the springs in the area (Figure 5-6b)

A variety of methods are available for characterizing the structure of fractured rock and karst flow systems These can be broadly classified as (1) remote sensing, surface, and borehole geophysical methods, (2) monitoring of natural fluctuations of water levels in wells and their response to pumping, and (3) monitoring of discharge and chemistry of springs

### 5 4 4 1 Remote Sensing and Geophysical Methods

Fracture trace and lineament analysis using air photos (Section 5 2 3) is a useful starting point for identifying possible areas of concentration and preferential direction of ground water flow [4] Other remote sensing methods, such as near-infrared and thermal infrared scanners, which detect variations in near-surface moisture, may also be useful for mapping the location of sinkholes and fracture trace analysis (LaMoreaux, 1979) Such observations should be supplemented, where possible, with observation and analysis of the character and orientation of rock joint and fracture patterns at surface outcrops (LaPointe and Hudson, 1985)

A number of commonly used surface geophysical methods have potential applications for detection of subsur-

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[3] Note that the hydrogeology of karst terranes of the former Yugoslavia are generally very different from karst areas in North America In the United States, catchments in karst areas typically are *larger* than would be expected based on an analysis of surface topography

[4] Fracture trace analysis will not necessarily identify major conduits in karst aquifers, however, because these may follow bedding planes with no surface expression

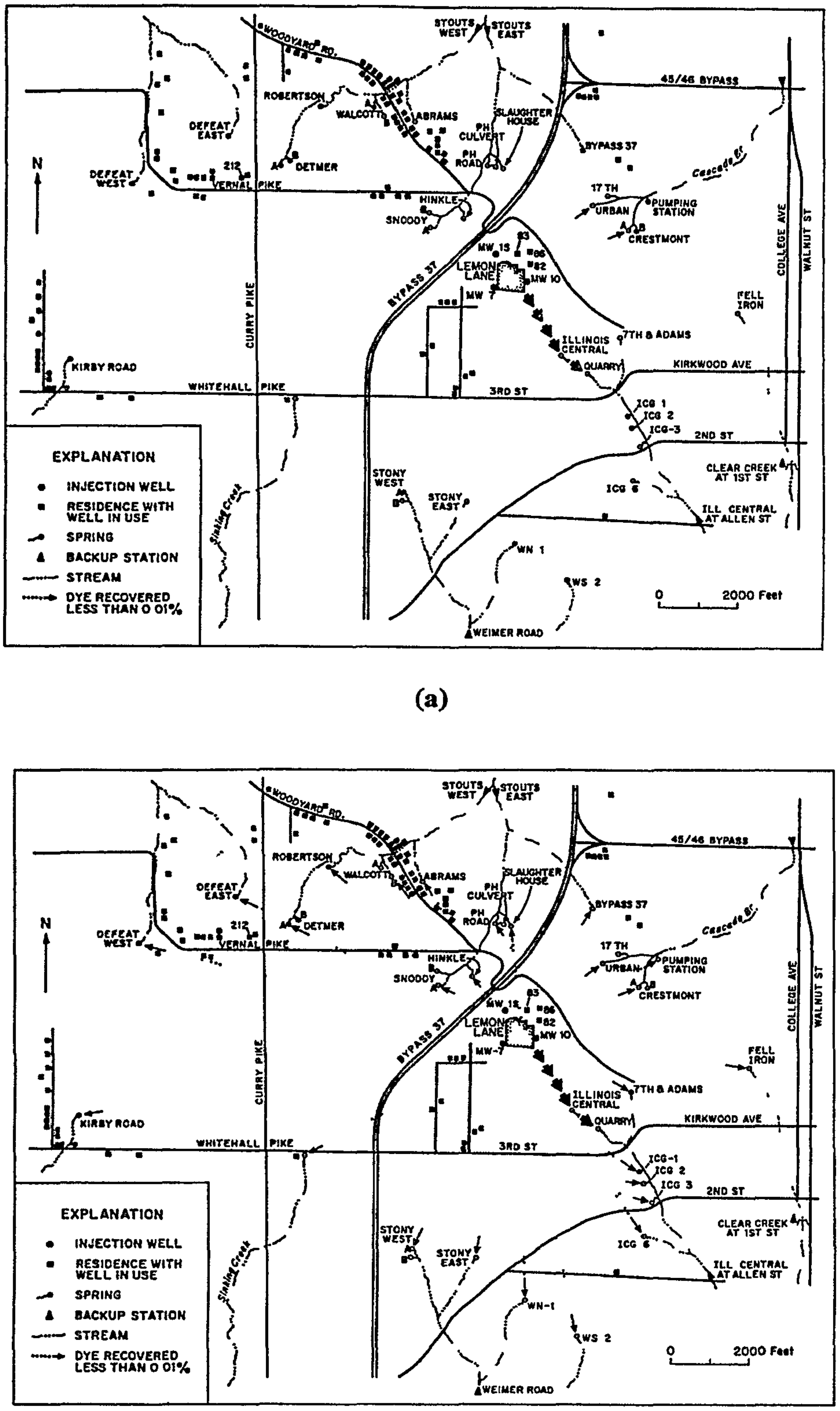

Figure 5-6 Directions of ground water flow in a karst aquifer, Monroe County, Indiana (a) 1987 low-flow tracer test, (b) 1989 high-flow tracer test (McCann and Krothe, 1992)

face cavities in karst areas, including gravity, electrical resistivity, seismic, and ground-penetrating radar (Greenfield, 1979) Karous and Mareš (1988) provide detailed treatment of use of geophysical methods for characterizing fractured-rock aquifers, including some methods that are less commonly known For example, Figure 5-7 illustrates how a conduit feeding a karst spring can be mapped using self-potential measurements In this example, the current electrode A was grounded at the spring orifice, and potentials measured along transects I through IV Figure 5-8 illustrates how repeated seismic velocity measurements at different orientations around a single point provide an indication of the orientation of major fractures In this example, velocities have been plotted on a polar diagram, with the inferred direction of major fractures based on the higher velocity measurements Azimuthal resistivity, in which a series of resistivity measurements are taken by shifting the position of the electrodes around a single point, is another possible method for detecting fracture orientation (Ritzi and Andolesk, 1992)

Borehole geophysical methods provide a necessary complement to surface geophysical and other characterization techniques Acoustic televiewer, borehole television, and dipmeter logs are especially useful for determining the location and orientation of subsurface fractures Fracture zones can also be detected using borehole flowmeters (mechanical, thermal and the recently developed electromagnetic flowmeter) with or without pumping Single borehole and multiple well tracer tests ar useful for characterizing the flow at a more local scale Additional information on the surface and borehole geophysical methods mentioned here can be found in U S EPA (1993) Table 3-10 identifies a number of additional references characterizing fractured rock aquifers

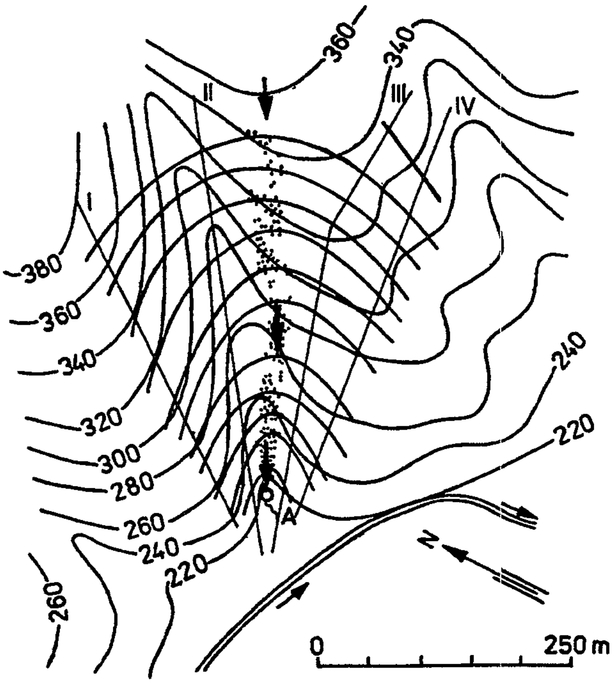

**Figure 5-7** **Mapping of subsurface conduit using self-potential method (from Karous and Mareš, 1988)**

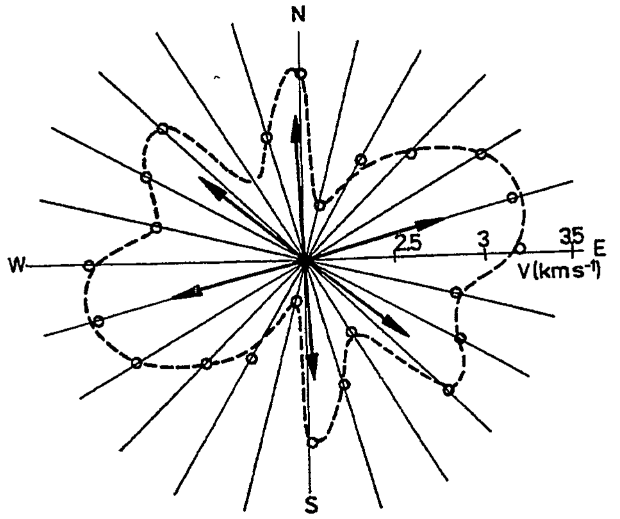

**Figure 5-8** **Azimuthal seismic survey to characterize direction of subsurface rock fractures (from Karous and Mareš, 1988)**

### 5 4 4 2 Water Level Monitoring

In unconfined fractured rock and karst aquifers, water levels in wells intercepting fractures or conduits commonly show relatively large fluctuations in response to precipitation events (see Figure 2-6) During times of low flow, large differences in water levels in nearby wells serve as an indicator of low matrix permeability (the well with higher water levels) and fracture or conduit flow in the well with the lower water levels

The response of water levels to pumping provides a basis for judging whether the flow system functions as a "porous medium equivalent" (i e , the aquifer can be modeled as if it were flowing in a porous medium, even though flow in fractures is occurring) [5] Figure 5-9 illustrates three types of aquifer responses to pumping that indicate a porous medium model should not be used for characterizing an aquifer Granular aquifers (and fractured-rock aquifers where fractures are relatively small and evenly spaced) will generally show a linear relation-

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[5] In the context of wellhead protection, even if a fractured rock or karst aquifer can be modeled using porous medium flow assumptions, results should be interpreted with great caution Values of hydraulic conductivity calculated from such aquifer tests will reflect average values, whereas actual ground water flow velocities will be much higher For example, Quinlan et al (1991) cite a tracer test in the Floridan aquifer using two wells 200 feet apart The theoretical arrival time of the injected dye, based on geophysical logging and aquifer testing, was about 40 days Actual breakthrough time was 5 hours

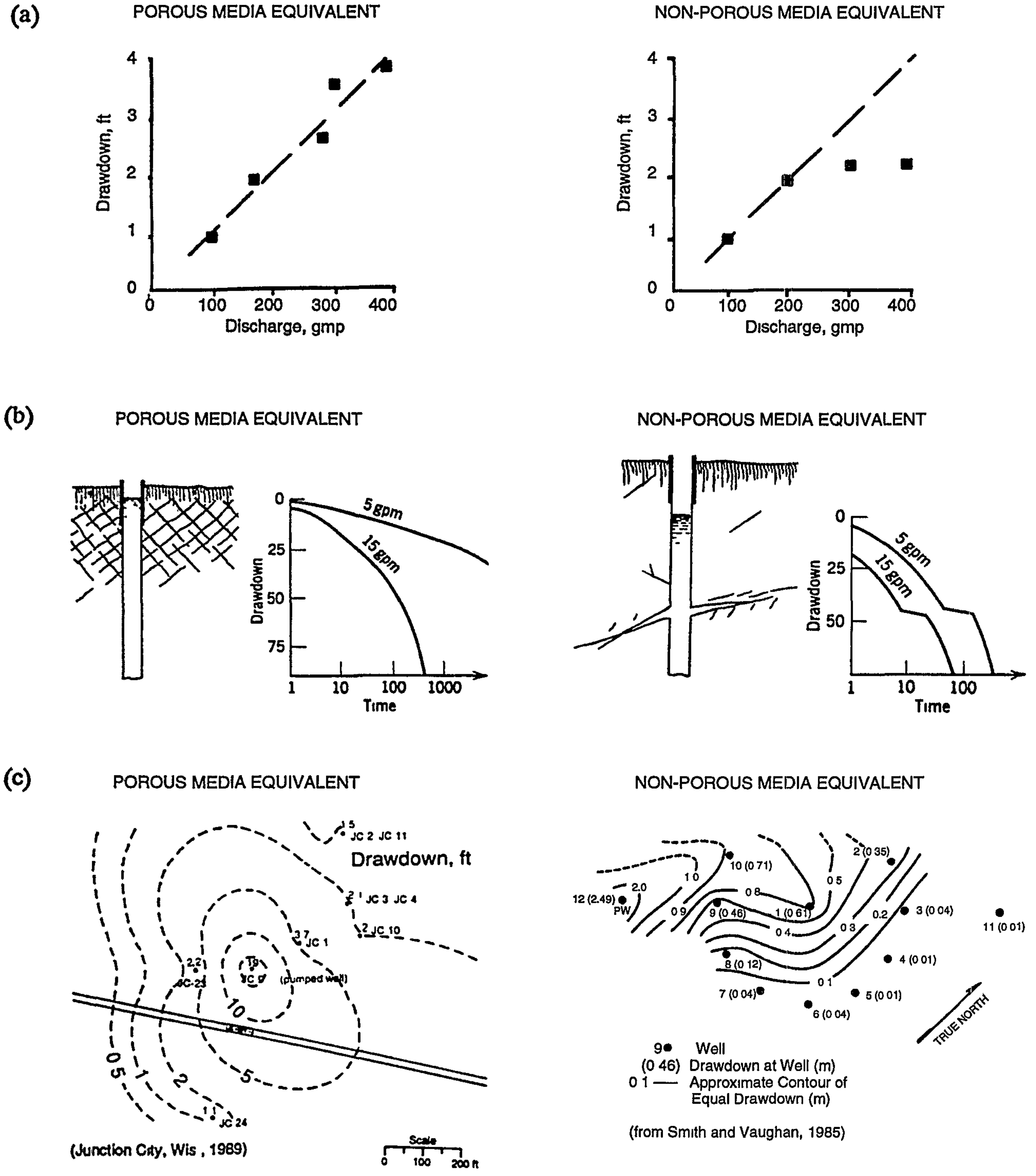

**Figure 5-9. Pumping-test response indicators of fracture/conduit flow (a) discharge drawdown plots (after Hickey, 1984), (b) time drawdown curves (from Davis and DeWiest, 1966), (c) areal drawdown distribution (Bradbury et al , 1991)**

ship between drawdown and pumping rate, whereas aquifers where fracture flow is significant may show a leveling off response in drawdown as pumping rates increase (Figure 5-9a) The presence of large water-bearing fractures is indicated by a temporary leveling off in a drawdown versus time plot (Figure 5-9b) Finally, if major fractures are feeding a well, the cone of depression may depart significantly from a circular or elliptical shape (Figure 5-9c) Non-porous medium equivalent responses in aquifer tests require use of the appropriate fracture-flow analytical solutions for analyzing pump test data (see Section 3 3 5 and references in Table 3-10) All of these responses can also be indicative of conduit flow in carbonate aquifers

### 5 4 4 3 Spring Monitoring

A distinctive characteristic of near-surface karst hydrologic systems is that springs serve as discharge points for subsurface flow Much useful information about a karst aquifer can be obtained by monitoring the amount and chemistry of flow from a spring Kresic (1993) provides a review of methods for spring hydrograph analysis and statistical analysis of time series measurements of flow from springs and water level measurements in wells With antecedent soil moisture conditions being equal, a rapid increase in discharge from a spring in response to a precipitation event indicates that point recharge is a major component of subsurface flow, whereas a relatively small flow response indicates that dispersed recharge contributes most of the flow to a spring Quantitative interpretations of spring hydrographs require continuous records of both spring discharge and precipitation in the catchment area

Specific conductance, an easily measured ground water parameter, is widely used for characterizing karst aquifers Where multiple springs are present in an area, springs with similar specific conductance can be considered to be closely interconnected, while large differences in specific conductance indicate that the flow systems feeding the springs are largely independent Monitoring of changes in water chemistry with changes in spring discharge is also a useful way to characterize karst aquifers Specific conductance is the parameter of choice because it is easy to measure and can be monitored continuously (Quinlan et al , 1992b) Other parameters such as hardness, degree of saturation with respect to calcite and dolomite, and the Ca/Mg ratio can also be used A high coefficient of variation of specific conductance (CVC) indicates that point recharge is a major contributor to flow, whereas a low CVC indicates that most recharge comes from dispersed sources Quinlan et al (1992b) suggest the following provisional guidelines using CVC as a measure of aquifer vulnerability as defined in Figure 5-6 moderately sensitive = <5 percent, very sensitive = 5 to 10 percent, hypersensitive = >10 percent

*A Cautionary Note* Footnote 5 discusses the possible risk of using porous-medium analytical models for delineating WHPAs in fractured rock or karst areas, even if aquifer test data suggest that flow behavior approximates that in a porous medium The results of any methods used to quantify storage properties or hydraulic conductivity in fractured rock and karst aquifers described above must be evaluated in the context of the volume of the aquifer that is being measured As noted in Section 3 3, values for hydraulic conductivity tend to increase as larger volumes of an aquifer are measured This effect is particularly dramatic in karst aquifers Figure 5-10a shows the effect of scale from laboratory core measurements (centimeters) to regional (thousands of meters) on the storage coefficient (S) and hydraulic conductivity (K) in the Swabian Alps of southwestern Germany Measurements of K range over six orders of magnitude Figure 5-10b, which summarizes data from many different studies in karst areas, shows an even wider range of eight orders of magnitude for the *predominant* ranges of major methods for estimating average velocity (laboratory core, double packer tests, slug tests, pumping tests, and dye tracer tests) These figures make it clear that time of travel estimates used for WHPA delineation in karst aquifers based on any methods other than dye tracer tests are unlikely to provide adequate protection

## 5.5 Vulnerability Mapping

Ground water vulnerability mapping involves the delineation of areas of varying susceptibility to ground water contamination based on the interaction of characteristics that promote or inhibit movement of contaminants in the subsurface Ground water vulnerability maps may be developed as specific units within a broader scheme of ground water classification, or may just delineate highly vulnerable areas without paying special attention to the characteristics of non-vulnerable areas

Figure 5-11 illustrates WHPAs based on an arbitrary radius and simplified shape marked on a vulnerability map of Door County, Wisconsin When vulnerability mapping is performed, efforts to inventory potential contaminant sources can be focused on areas where the hazard is greatest Vulnerability mapping also allows fine-tuning of management approaches within the WHPA Highly vulnerable areas require stricter management approaches than less vulnerable areas The rest of this section reviews a number of approaches that have been developed for vulnerability mapping

### *5.5.1 DRASTIC*

DRASTIC is a widely used method for evaluating the relative vulnerability of mappable hydrogeologic units to ground water contamination DRASTIC is an acronym

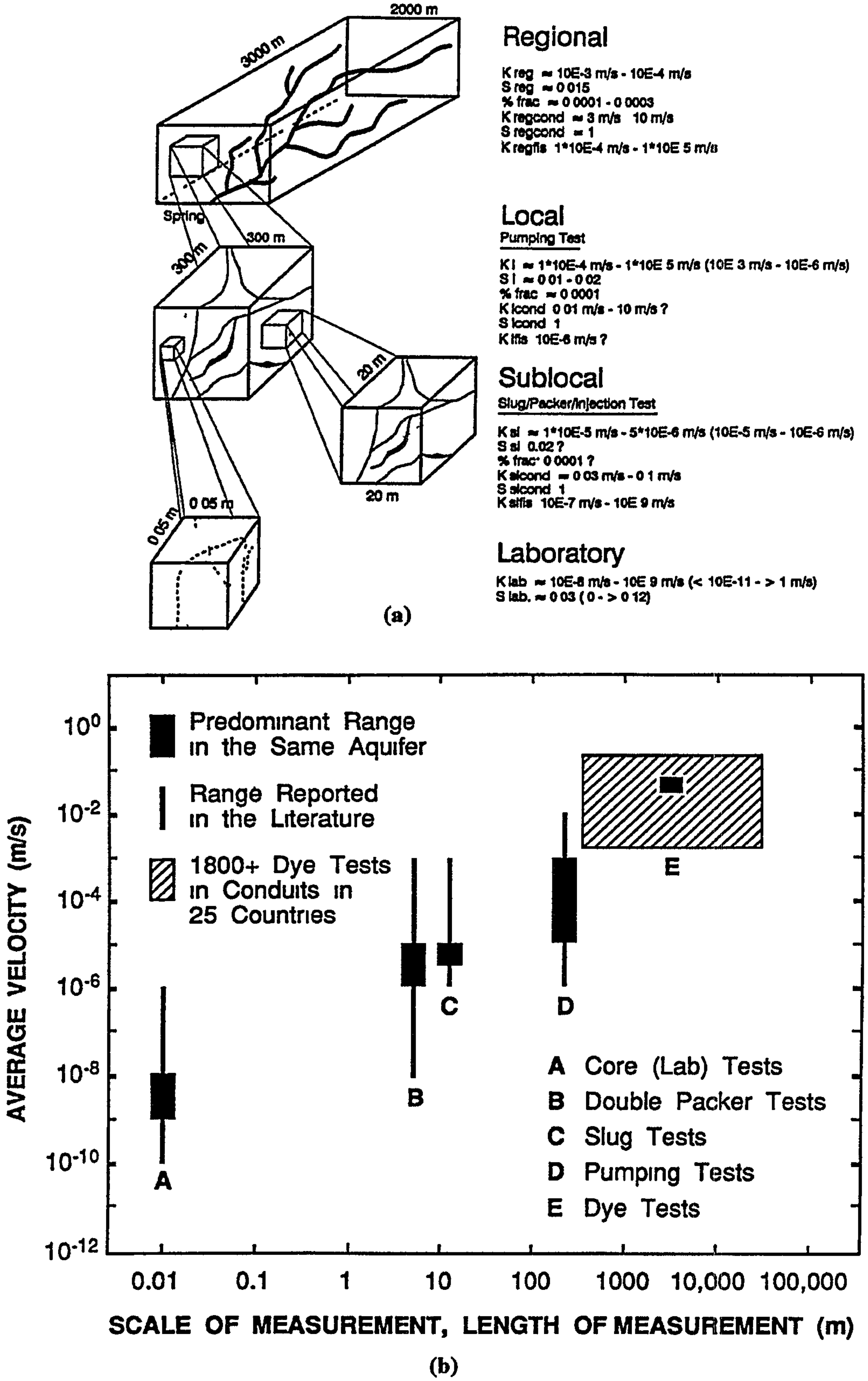

**Figure 5-10.** Scale dependence of ground water flow in karst systems (a) geometrical relationships and hydraulic conductivities at different scales (Sauter, 1992), (b) measurement scales and average velocities of different measurement methods (modified after Quinlan et al , 1992a, and Sauter 1992)

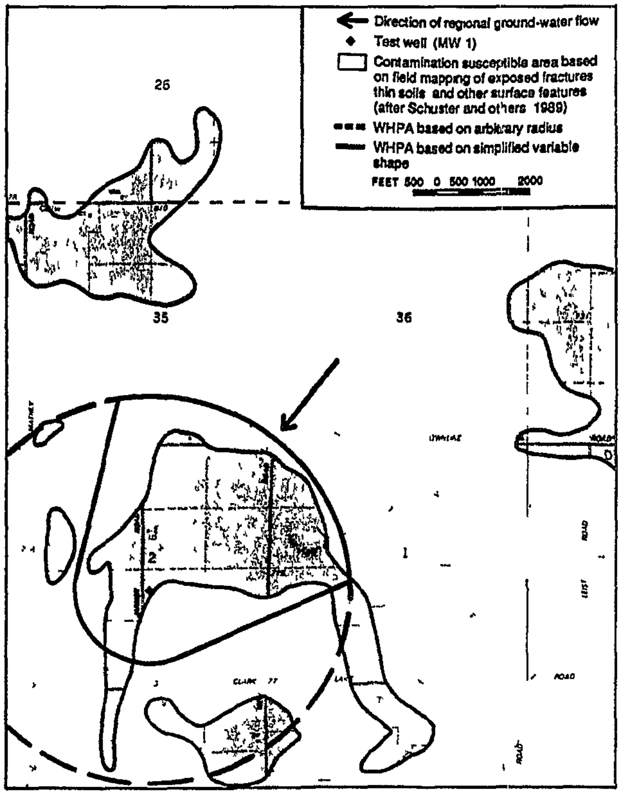

**Figure 5-11** **WHPAs at Sevastopol site, Door County, Wisconsin, based on fixed radius, simplified shape, and vulnerability mapping (from Bradbury et al , 1991)**

for the seven factors for which numerical ratings are made to develop an index of vulnerability to ground water contamination ***D***epth to water table, net ***R***echarge, ***A***quifer media, ***S***oil media, ***T***opography (slope), ***I***mpact to vadose zone, and hydraulic ***C***onductivity of the aquifer Conventional hydrogeologic mapping methods are first used to delineate areas with similar characteristics A numerical value is given to each of the seven factors, which are multiplied by a weighting factor and added to obtain the DRASTIC index for the map unit Worksheet 5-2 provides a form for calculating the DRASTIC index Appendix B provides a more detailed description of how to use this method with a SCS country soil survey to quickly develop a preliminary DRASTIC map of a county

The DRASTIC index does not have any absolute meaning, but provides a means to assess relative vulnerability A DRASTIC index of greater than 150 is one means of defining a highly vulnerable aquifer under EPA's ground water protection strategy (U S EPA, 1986a) The DRASTIC index has been found to give inconsistent results in karst areas where the water table is relatively deep (Sendlein, 1992), and in the arid Tucson basin, Arizona, for reasons that are not entirely clear (Pima Association of Governments, 1992) Both of these studies suggest that the relatively high weighting given to depth to water may understate the potential for contamination when preferential pathways allow relatively rapid vertical migration to deep water tables Another weakness in the DRASTIC index is that is that it does not readily allow differentiation of shallow perched water tables over deeper regional water tables

DRASTIC, like many other vulnerability assessment models, has technical limitations It must be remembered that it is a standardized classification system and only intended to provide qualitative guidelines Its focus is on criteria rather than specific or unique situations in an area According to Rosen (1994), DRASTIC was never intended to give any precise answers, and the system should be viewed and analyzed with this in mind Rosen (1994) found in his work, as an example, that the system tends to overestimate the vulnerability of porous media aquifers compared to aquifers in fractured media He recommended that the applicability of the results be enhanced and the risk of misuse be reduced by directing the analysis toward more scientifically defined factors, such as sorption capacity, travel time, and dilution

### *5.5.2 Other Vulnerability Mapping Methods*

Various other methods have been developed for vulnerability mapping They can be broadly classified as (1) systems using numerical ratings (as with DRASTIC) and (2) non-numerical systems in which map units may be numbered in order of increasing vulnerability, or classified as highly vulnerable and less vulnerable Table 5-7 describes a number of vulnerability mapping techniques and summarizes the type of criteria used Knox et al (1993) include tables summarizing criteria for the SAFE, WSSIM, HRS, SRM, and PI methods Perhaps the simplest application of vulnerability mapping for wellhead protection is to develop criteria based on local conditions for defining highly vulnerable hydrogeologic settings (Figures 5-6 and 5-12) The DRASTIC criteria in Worksheet 5-2, the information in Table 5-7, and the references indexed in Table 5-9 may be useful for developing locally appropriate vulnerability criteria

## 5.6 Use of Geographic Information Systems for Wellhead Protection

Geographic information systems (GIS) use a common spatial framework for data input, storage, manipulation, analysis, and display of geographic, cultural, political, environmental, and statistical data Computer processing of spatial data can range from the use of relatively simple graphics software that can plot contours or isopleths from data for which x and y coordinates are known using ASCII or other datafiles, through to complex systems that can process digitized map data, maintain and manipulate large spatial databases, and generate a wide variety of user-created tables, graphs, and maps (Figure 5-12) This handbook uses the term

# Worksheet 5-2.
# DRASTIC Worksheet (Circle appropriate range and rating).

**County·** ______________ **State** ______________

**General Soil Map Unit Number·** ____

**General Description**

**1 Depth to Water (ft)**

| Range | Rating |
|---|---|
| 0-5 | 10 |
| 5-15 | 9 |
| 15-30 | 7 |
| 30-50 | 5 |
| 50-75 | 3 |
| 75-100 | 2 |
| 100+ | 1 |

**2 Net Recharge (in)**

| Range | Rating |
|---|---|
| 0-2 | 1 |
| 2-4 | 3 |
| 4-7 | 6 |
| 7-10 | 8 |
| 10+ | 9 |

**3 Aquifer Media**

| | Rating | | |
|---|---|---|---|
| Type | Range | Typical | Actual |
| Massive Shale | 1-3 | 2 | ____ |
| Metamorphic/Igneous | 2-5 | 3 | ____ |
| Weathered M/I | 3-5 | 4 | ____ |
| Glacial Till | 4-6 | 5 | ____ |
| Bedded SS/LS/Shale | 5-9 | 6 | ____ |
| Massive Sandstone | 4-9 | 6 | ____ |
| Massive Limestone | 4-9 | 6 | ____ |
| Sand and Gravel | 4-9 | 8 | ____ |
| Basalt | 2-10 | 9 | ____ |
| Karst Limestone | 9-10 | 10 | ____ |

**4. Soil Media**

| Type | Rating |
|---|---|
| Thin/ Absent | 10 |
| Gravel | 10 |
| Sand | 9 |
| Peat | 8 |
| Structured Clay | 7 |
| Sandy Loam | 6 |
| Loam | 5 |
| Silty Loam | 4 |
| Clay Loam | 3 |
| Muck | 2 |
| Massive Clay | 1 |

**5 Topography (%)**

| Range | Rating |
|---|---|
| 0-2 | 10 |
| 2-6 | 9 |
| 6-12 | 5 |
| 12-18 | 3 |
| 18+ | 1 |

**6 Vadose Zone Media**

| | Rating | | |
|---|---|---|---|
| Type | Range | Typical | Actual |
| Confining Layer | 1 | 1 | ____ |
| Silt/Clay | 2-6 | 3 | ____ |
| Shale | 2-5 | 3 | ____ |
| Limestone | 2-7 | 6 | ____ |
| Sandstone | 4-8 | 6 | ____ |
| Bedded LS/SS/Shale | 4-8 | 6 | ____ |
| Sand and Gravel with Sig Silt and Clay | 4-8 | 6 | ____ |
| Metamorphic/Igneous | 2-8 | 4 | ____ |
| Sand and Gravel | 6-9 | 8 | ____ |
| Basalt | 2-10 | 9 | ____ |
| Karst Limestone | 8-10 | 10 | ____ |

**7. Hydraulic Conductivity (gpd/sq ft.)**

| Range | Rating |
|---|---|
| 1-100 | 1 |
| 100-300 | 2 |
| 300-700 | 4 |
| 700-1,000 | 6 |
| 1,000-2,000 | 8 |
| 2,000+ | 10 |

**DRASTIC Index**

| Rating x Weight = | Pesticide Rating x Weight = |
|---|---|
| 1 ____ x 5 = ____ | 1 ____ x 5 = ____ |
| 2 ____ x 4 = ____ | 2 ____ x 4 = ____ |
| 3 ____ x 3 = ____ | 3 ____ x 3 = ____ |
| 4 ____ x 2 = ____ | 4 ____ x 5 = ____ |
| 5 ____ x 1 = ____ | 5 ____ x 3 = ____ |
| 6 ____ x 5 = ____ | 6 ____ x 4 = ____ |
| 7 ____ x 3 = ____ | 7 ____ x 2 = ____ |
| Total ____* | Total ____ |

* Aquifers with DRASTIC ratings >150 are considered to be "highly vulnerable" by EPA

**Table 5-7 Summary of Major Ground-Water Vulnerability Mapping Methods**

| Description | Major Vulnerability Criteria | References |
|---|---|---|
| The DRASTIC method can be applied in any hydrogeologic setting Results in a numerical index based on the sum of weighted ratings for seven criteria Most widely used method | See Worksheet 5-2 Highly vulnerable = >150 (U S EPA, 1986a) | Aller et al (1987) *Case studies* See Table 5-9 |
| Illinois ground water aquifer vulnerability maps and geographic information system Subsurface geologic data to a depth of 50 feet has been digitized to develop a state-wide stack-unit map | Has been used for a variety of applications Uhlman and Smith (1990) defined 8 classes for LUST contamination potential based on depth to uppermost aquifer and presence or absence of major aquifer at depth Highly vulnerable aquifer material within 5 feet of land surface, variable underlying materials and major aquifer at depth | See Table 5-9 |
| Karst limestone areas are highly vulnerable by definition because conduit flow allows rapid travel of contaminants Several schemes provide more detailed criteria for assessing relative vulnerability | Quinlan et al (1992b) hypersensitive = high point recharge, high conduit flow, low soil storage (Figure 5-6) Schuster et al (1989), highly vulnerable = shallow or exposed fracture dolomite bedrock, permeable soils, open surface fractures, sinkholes (Figure 5-12) | Quinlan et al (1992b), Schuster et al (1989), Sendlein (1992) |
| Vulnerability to contamination by agricultural chemicals Various vulnerability indexes have been developed | DRASTIC pesticide index places greater weight on soil media and topography (Worksheet 5-2) RAVE index (DeLuca and Johnson (1990) uses a numerical index based on depth to ground water, soil texture, percent organic matter, topographic position, distance to surface waster, cropping practice, pesticide application frequency/method, and pesticide leaching index Scores >60 indicate high concern | Others include the Pesticide Index (PI)—Rao et al (1985), U S EPA (1986d), SAFE (Soil/Aquifer Field Evaluation)—Roux (1986), See Table 5-9 for additional case study references |
| Numerous schemes have been developed to assess site suitability for solid/hazardous waste land disposal siting or risk from currently contaminated sites Such suitability ranking systems can also be used to assess ground water vulnerability | LSR (landfill site rating) system uses (1) hydraulic conductivity, (2) sorption, (3) aquifer thickness, (4) depth and gradient of water table, (5) topography), (6) distance to wells or streams High suitability = low vulnerability to ground water contamination Low suitability = high vulnerability to ground water contamination Each method has slightly different criteria | LSR LeGrand (1964, 1983), LeGrand and Brown (1977), HRS (Hazard Ranking System) Caldwell et al (1981), SRM (Superfund Site Rating Methodology) Kufs et al (1980), U S EPA (1989, 1991c), SIA (Surface Impoundment Assessment method) Silka and Swearingen (1978), U S EPA (1983), WSSIM (Waste-Soil-Site Interaction Matrix) Phillips et al (1977) |
| General ground water classification schemes | Criteria varies depending on the objective of the classification scheme | General U S EPA (1985, 1986a), Sole aquifer program U S EPA (1988b) |

"full-scale GIS" to refer to the type of integrated system illustrated in Figure 5-12, and "mini-GIS" to refer to personal computer (PC)-based software that is able to perform most of the functions of full-scale GIS at the scale of a USGS 7 5 minute quadrangle (discussed further in Section 5 6 2) as an integrated package [6] The term "desktop" GIS applies to the use of independent pieces of PC-based software to achieve the same results that full-scale and mini-GIS systems perform This section provides a brief discussion of use of GIS for wellhead protection Tables A-3 (Index to Major References on Geographic Information Systems) and A-4 (Periodicals, Conferences, and Symposia With Paper Relevant to GIS) should be referred to for sources of more detailed information on GIS

Pickus (1992) identifies six major areas where GIS can support delineation of wellhead protection areas (1) conceptualization of the regional and local hydrogeologic flow system (this Chapter), (2) delineation of wellhead protection areas using geometric and simple analytical methods (Chapter 4), (3) development of maps to aid in development and management of wellhead protection areas (Chapter 7), (4) geological and geophysical mapping (this Chapter), (5) development of model parameters for numerical modeling of ground water flow and solute transport (Chapter 6), and (6) integration of simulation results (Chapter 6) Essentially all of these areas can be supported using either full-

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[6] The geographic area that would exceed the capabilities of a stand-alone PC depends on two main factors (1) the storage and memory capacity of the computer, and (2) the amount and number of layers of data that must be stored and processed Most stand-alone PCs can readily handle a digitized USGS 7 5 minute quadrangle map and the kind of data that would be required for WHPA delineation

**Table 5-8 Index to Major References on Hydrogeologic Mapping**

| Topic | References |
|---|---|
| AirPhoto/Map Interpretation | Avery (1968), Ciciarelli (1991), Denny et al (1968), Dury (1957), Lattman and Ray (1965), Lillesand and Kiefer (1979), Lueder (1959), Miller and Miller (1961), Ray (1960), SCS (1973), Strandberg (1967), Verstappen (1977) |
| Data Sources/Management | *Climatic:* Hatch (1988), *Ground Water Data* Orr (1984), Rowe and Dulaney (1991), U S EPA (1990b), *Minimum Data Requirements for Ground Water* U S EPA (1988a, 1992c), *STORET* Blake-Coleman and Dee (1987), U S EPA (1985b, 1986c), *Locational Data Policy* U S EPA (1992a, 1992b) |
| Hydrogeologic Mapping | *Texts:* Brasington (1988), Brown et al (1983), Erdélyi and Gálfi (1988), Fetter (1980), Kolm (1993), UNESCO (1970, 1975, 1977), U S EPA (1990a), U S EPA (1991a, 1993c), U S Geological Survey (1980), Walton (1970), see also references in Appendix A 1, *Papers:* Kempton and Cartwright (1984), LaMoreaux (1966), Meyboom (1961), Pettyjohn and Randich (1966), Scheidegger (1973), Thomas (1978a, 1978b), Warman and Wiesnet (1966), *Characterization of Heterogeneity:* Delhomme (1979), Gelher (1993), Gómez-Hernández and Gorelick (1989), Hoeksma and Kitandis (1985), Jury (1985), Philip (1980), Poeter and Belcher (1991) |
| Geologic Mapping | Bishop (1960), Compton (1962), Lahee (1961), Low (1957), Moore (1991), Tearing (1991), U S EPA (1991b), *Fractured Rock Characterization:* Bradbury et al (1991), Karous and Mareš (1988), LaPointe and Hudson (1985), Parizek (1976), UNESCO (1984) |
| Geophysical Methods | *General:* U S EPA (1987, 1993b), *Karst/Fractured Rock:* Karous and Mareš (1988), Dobecki (1990), Greenfield (1979), LaMoreaux (1979), Ritzi and Andolesk (1992) |
| Karst | Bonacci and Zivaljevic (1993), Kresic (1993), McCann and Krothe (1992), Quinlan et al (1992a, 1992b), Sauter (1992), see also Appendix A 2 |
| GIS Case Studies* | *EPA Projects:* Fenstermaker and Mynar (1986a, 1986b), *Wellhead Protection:* Baker et al (1993), Brandon et al (1992), Kerzner (1990a, 1990b), Rifai et al (1993), Steppacher (1988), Varljen and Wehrmann (1990), Zidar (1990), *Ground Water Vulnerability Mapping:* Barrocu and Biallo (1993), Sokol et al (1993) |

See Tables A-3 and A-4 for major general references on GIS

**Table 5-9 Index to Major References on Ground Water Vulnerability Mapping**

| Topic | References |
|---|---|
| Methods/Criteria | *General Reviews* Anderson and Gosk (1987), Bachmat and Collin (1987), Barrocu and Biallo (1993), Hoffer (1986), Kanivetsky et al (1991), Knox et al (1993), *DRASTIC* Aller et al (1987), *Illinois Stack Unit System* Berg and Kempton (1984), Berg et al (1984), Shafer (1985), *Waste Disposal Siting* Caldwell et al (1981—HRS), Gibb et al (1983), Halfon (1989), Kufs et al (1980—SRM), LeGrand (1964, 1983—LSR), LeGrand and Brown (1977—LSR), Phillips et al (1977—WSSIM), Silka and Swearingen (1978—SIA), U S EPA (1983—SIA, 1986b, 1989—HRS, 1991c—HRS), *Other Agricultural Chemical Systems* DeLuca and Johnson (1990—RAVE), Holman (1986a, 1986b), Rao et al (1985—PI), Roux et al (1986—SAFE), Sokol et al (1993), U S EPA (1986d—PI), *Karst:* Quinlan et al (1992a), Schuster et al (1989), *General Ground Water Classification Schemes:* Pettyjohn et al (1991), U S EPA (1985a, 1986a), *Sole Source Aquifers:* U S EPA (1988b) |
| Risk Assessment | McTernan and Kaplan (1990), Pfannkuch (1991), Reichard et al (1990), Trojan and Perry (1989—Hazard Index) |
| Applications | *Waste Disposal Siting:* Gibb et al (1983), *Agricultural Chemicals:* Alexander and Liddle (1986), Blanton and Villenueve (1989), Ehtemshemi et al (1991), Holman (1986a, 1986b), Sokol et al (1993), *Karst:* Schuster et al (1989), Quinlin et al (1992b), Sendlein (1992), *Leaking Underground Storage Tanks* Uhlman and Smith (1990) |
| Case Studies | *DRASTIC* Alexander and Liddle (1986), Blanton and Villeneuve (1989), Duda and Johnson (1987), Ehteshami et al (1991), FDER (undated), LeGrand and Rosen (1992), Pima Association of Governments (1992), Sendlein (1992), *Illinois Stack-Unit System* Kempton and Cartwright (1984), Uhlman and Smith (1990) |

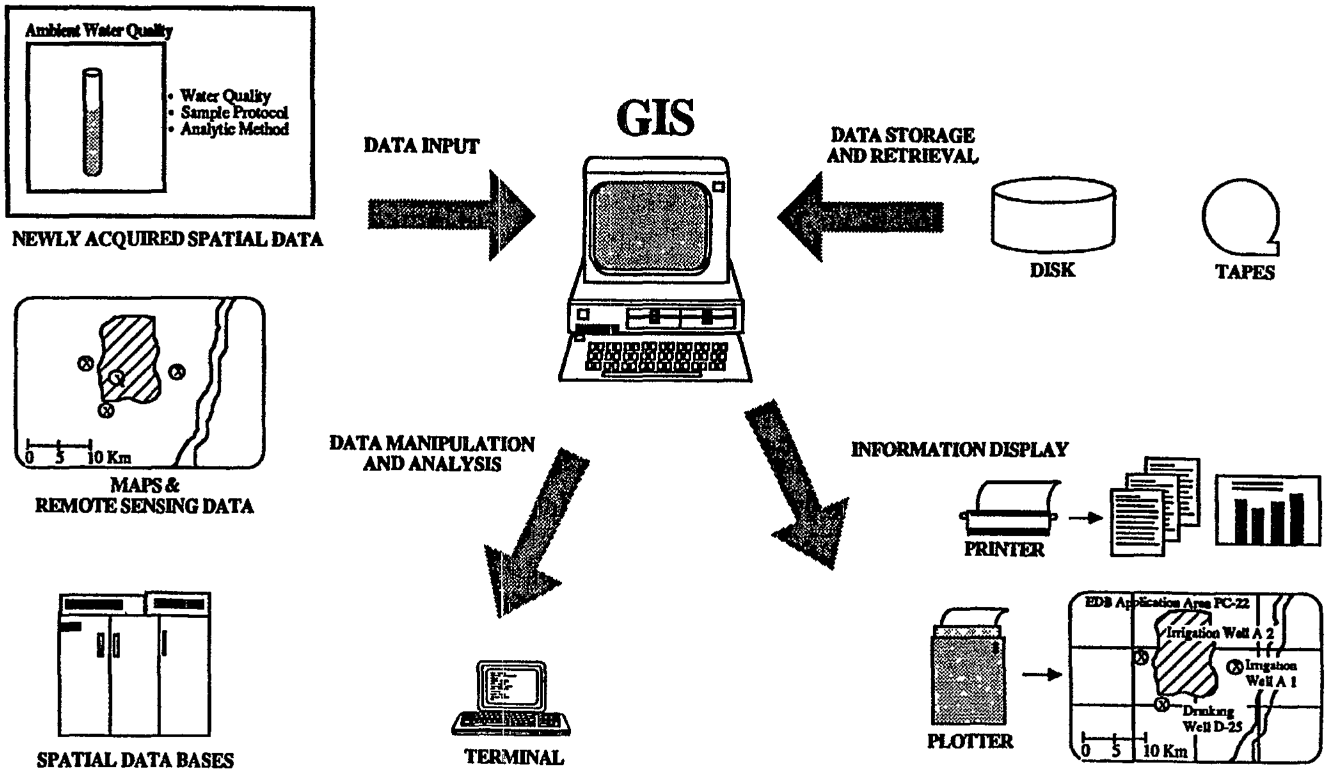

**Figure 5-12 Overview of major Geographic Information System functions (OIRM, 1992)**

scale GIS (Section 5 6 1) or PC-based GIS (Section 5 6 2)

### 5.6.1 Full-Scale GIS

The large amount of data that is stored and processed using full-scale GIS requires a workstation or mainframe computer environment with dedicated personnel for data entry and management The costs of a full-scale geographic information system are substantial, but the greatest cost is the required commitment of personnel for data entry and management[7] Consequently, the use of full-scale GIS for wellhead protection programs is limited primarily to areas where financial and personnel resources have been committed to developing GIS for purposes other than wellhead protection, or where a relatively large area is the focus for wellhead protection efforts, as in the Cape Cod Aquifer Management Project (Steppacher, 1988) Anyone considering acquisition of full-scale GIS for wellhead protection should read the lessons learned and recommendations for future GIS projects contained in Steppacher (1988) Pickus (1992) provides detailed guidance on using GIS and ARC/INFO, the full-scale geographic information system used by the U S Environmental Protection Agency for hydrogeologic analysis

Baker et al (1993) and Rifai et al (1993) have described use of the semianalytical WHPA code (Section 6 4 3) in conjunction with full-scale GIS in Rhode Island and Texas, respectively The Massachusetts Water Resources Authority, which supplies water to 46 communities in Metropolitan Boston, has used GIS to delineate critical recharge areas for local supplies and mapped thousands of point and nonpoint potential sources of contamination (Brandon et al , 1992)

### 5.6.2 Mini- and Desktop-GIS

Mini-GIS performs most of the functions of full-scale GIS as an integrated software package that can be used with a stand-alone PC[8] The specific capabilities of different commercial packages vary, but generally these systems include (1) a spatial database for geologic, hydrologic, and chemical data, (2) the ability to create base maps and special purpose maps using data in the database, and (3) the ability to create geologic cross-sections and graphs of time series data Often these systems can be used as preprocessors for numerical ground water models (i e , to create grids and input values into the grid)

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[7] The cost of most commercial, full-scale geographic information systems falls in the range of $10,000 to $100,000 (Rowe and Dulaney, 1991) The cost of mini-GIS and related PC-based software ranges from hundreds to thousands of dollars

[8] Examples of commercially available mini-GIS software packages include GEOBASE, SPASE, GIS\Key, StratiFact, and ROCKWORKS

and as postprocessors for graphic presentation of model output (see Chapter 6)

PC-based software that performs more specific functions, such as graphic presentation of borehole logs, cross sections, and contour maps, can also facilitate the analysis of geologic and hydrologic data for hydrogeologic mapping[9] Individual pieces of PC-based software that can handle spatial data can be used in combination to create a desktop GIS Varljen and Wehrmann (1990) describe using AutoCAD® as a desktop GIS for a hydrogeological investigation The base map contained digital data on terrain elevations, location of transportation and water features, and names of cities, towns, and major landmarks in a CAD (computer assisted drawing) DXF format [1 24000 scale (7 5 ft quadrangles)]. Additional layers containing hydrogeologic information were created using SURFER® and exported to AutoCAD® for overlay on the base map

The advantage of using mini-GIS software compared to using separate software to perform different functions is that import and export of data is minimized, reducing the time required for data processing The advantage of desktop GIS, especially if one or more of the individual software packages have been purchased and are in use, is possibly lower cost and greater flexibility in processing and presenting data for the particular needs of the user

### *5.6.3 Special Considerations in the Handling of Spatial Data*

Spatial data is inherent to hydrogeologic mapping For example, three coordinates are required to accurately locate borehole logging data x and y coordinates define the position with respect to the surface of the earth, and the z coordinate defines the elevation U S EPA and other federal agencies have adopted latitude and longitude as the standard system for x-y coordinates, new data collection should use that system U S EPA (1992a, 1992b, and 1992c) provides guidance for collection of spatial data Hydrogeologic data compiled from existing sources may be located using a variety of coordinate systems, such as Township-Range-and-Section, state planar coordinates, or Universal Transverse Mercator (UTM) If such data are to be processed electronically, conversion to a standard coordinate system is required Most mini-GIS software packages include conversion programs The General Coordinate Transformation Package (GCTP) developed by the U S Geological Survey can be used to convert data between any of the commonly used geodetic coordinate systems

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[9] Examples of commercially available software that can create borehole and well construction logs include GTLog, logWRITER, QUICKLOG, and LOGGER Software designed to create cross-sections (also able to construct individual borehole logs) include GTGS, gINT, LOGGCORRELATE, and QUICKCROSS/FENCE Available contouring software includes CONTUR, CoPlot, GRIDZO, LI-CONTOUR, PS-Plot, QUICKSURF, SURFER, TECKON, and TURBOCON

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* See Introduction for information on how to obtain documents

# Chapter 6
# Use of Computer Models for Wellhead Protection

Modeling with computers is a specialized field that requires considerable training and experience In the last few decades, hundreds of computer codes for simulating various aspects of ground water systems have been developed Refinements to existing codes and development of new codes proceed at a rapid pace The purpose of this chapter is to provide a basic understanding of modeling and data analysis with computers, and to present more detailed information on the use of computer models for wellhead protection area (WHPA) delineation

This chapter focuses on computer software designed specifically for modeling ground water flow and contaminant transport Computer spreadsheets, an attractive alternative to off-the-shelf software if relatively simple analytical methods are suitable, are discussed in Section 6 4 1 Table 6-1 provides definitions for some important terms used in connection with modeling of ground water The meaning of the term "model" varies depending on the context in which it is used For example, the analytical methods discussed in Chapter 4 are based on simplified mathematical models that do not require a computer Hydrogeologic mapping (Chapter 5) is performed to develop a conceptual model of a site, as such, it is an essential precursor to computer modeling The terms *code* and *program* have a precise meaning, referring to models designed for use on computers They may take the form of hard-paper documentation in the format of whatever programming language was used, or they may be on an electronic medium (disks or tapes) The term "computer model" is often used interchangeably with the term "computer code," but it may also have a broader meaning that includes the conceptual model of a site which forms the basis for entry of spatial and temporal data into a code

The first three sections in the chapter address basic mathematical approaches to modeling (Section 6 1), classification of computer codes (Section 6 2), and general considerations in selecting a computer code (Section 6 3) Section 6 4 focuses on the use of computer codes for WHPA delineation Finally, Section 6 5 provides guidance on where to find additional information on ground water modeling using computers

## 6.1 Mathematical Approaches to Modeling

Models and codes are usually described by the number of dimensions simulated (see the discussion of hetero-

**Table 6-1 Definitions of Terms Used in Ground Water Flow Modeling**

| Term | Definition |
|---|---|
| Model | (a) A representation of a real system or process, (b) an assembly of concepts in the form of mathematical equations that portrays understanding of a natural phenomenon |
| Conceptual model | An interpretation or working description of the characteristics and dynamics of the physical system |
| Mathematical model | (a) Mathematical equations expressing the physical system and including simplifying assumptions, (b) the representation of a physical system by mathematical expressions from which the behavior of the system can be deduced with known accuracy |
| Boundary condition | A mathematical expression of a state of the physical system which constrains the equations of a mathematical model |
| *Computer Models* | |
| Computer code/program | The assembly of numerical techniques, bookkeeping, and control languages that represents the model from acceptance of input data and instruction to delivery of output |
| Calibration (model application) | The process of refining the model representation of the hydrogeologic framework, hydraulic properties, and boundary conditions to achieve a desired degree of correspondence between the model simulation and observations of the ground water flow system |
| Sensitivity (model application) | The degree to which the model result is affected by changes in a selected model input representing the hydrogeologic framework, hydraulic properties, and boundary conditions |
| Verification (model application) | The use of the set of parameter values and boundary conditions from a calibrated model to approximate acceptably a second set of field data measured under similar hydrologic conditions This should be distinguished from code verification, which refers to software testing (comparisons with analytical solutions and other similar codes) |

Source Adapted from ASTM (1993)

geneity and isotropy in Section 5 4 2), and the mathematical approaches used At the core of any model or computer code are *governing equations* that represent the system being modeled Many different approaches to formulating and solving the governing equations are possible The specific numerical technique embodied in a computer code is called an *algorithm* The following discussion compares and contrasts some of the most important choices that must be made in mathematical modeling

### 6.1.1 Deterministic vs. Stochastic Models

A *deterministic* model presumes that a system or process operates such that the occurrence of a given set of events leads to a uniquely definable outcome The governing equations define precise cause-and-effect or input-response relationships In contrast, a *stochastic* model presumes that a system or process operates such that factors contributing to an outcome are uncertain Such models calculate the probability, within a desired level of confidence, of a specific value occurring at any point

Most available models are deterministic The heterogeneity of hydrogeologic environments, however, particularly the variability of parameters such as porosity and hydraulic conductivity, plays a key role in influencing the reliability of predictive ground water modeling (Smith, 1987) Beven (1989) argues that this heterogeneity creates fundamental problems in the application of physically based deterministic models

Stochastic approaches to characterizing variability with the use of geostatistical methods such as *kriging* are being used with increasing frequency to characterize hydrogeologic data (Delhomme, 1979, Hoeksma and Kitandis, 1985) The governing equations for both deterministic and stochastic models can be solved either analytically or numerically (van der Heijde et al , 1988) Vomvoris and Gelhar (1986) provide some simple analytical examples of stochastic prediction of dispersive contaminant transport Gómez-Hernández and Gorelick (1989) review the literature on approaches to stochastic simulation of ground water model parameters Dagan (1989) provides comprehensive treatment of stochastic modeling of subsurface flow and transport

### 6.1.2 System Spatial Characteristics

The spatial characteristics of a system can be modeled in two major ways *Lumped-parameter* systems are used when the total system is located at a single point *Distributed-parameter* systems define cause-and-effect relations for specific points or areas *Input-response* or black box models do not explicitly address spatial characteristics, but instead empirically relate observations of different variables, such as the response of water levels to recharge

The distributed-parameter approach is the one most frequently used in ground water modeling The rest of this chapter focuses on models of this type The mathematical framework for distributed-parameter models includes (1) one or more partial differential equations, called field equations, (2) initial and boundary conditions, and (3) solution procedures (Bear, 1979) Depending on the solution method used, such models are characterized as analytical, semianalytical, or numerical

### 6.1.3 Analytical vs. Numerical Models

A model's governing equation can be solved either analytically or numerically *Analytical* models use exact closed-form solutions of the appropriate differential equations The solution is continuous in space and time In contrast, *numerical* models apply approximate solutions to the same equations *Semianalytical* models use numerical techniques to approximate complex analytical solutions, allowing a discrete solution in either time or space Models using a closed-form solution for either the space or time domain and additional numerical approximations for the other domain are also considered semianalytical

Analytical models provide exact solutions, but employ many simplifying assumptions concerning the ground water system, its geometry, and external stresses to produce tractable solutions (Walton, 1984a) This places a burden on the user to test and justify the underlying assumptions and simplifications (Javendel et al , 1984)

Semianalytical models can provide streamline and traveltime information through numerical or analytical expression in space or time This information is especially useful for delineation of wellhead protection areas (Section 6 4 3) *Analytic element models* are a relatively recent development in semianalytical modeling of regional ground water flow These use approximate analytic solutions by superposing various exact or approximate analytic functions, each representing a particular feature of the aquifer (Haijtema, 1985, Strack, 1987) A major advantage of these models compared to analytic models is greater flexibility in incorporating varying hydrogeology and stresses without a significantly increased need for data (van der Heijde and Beljin, 1988)

Numerical models are much less burdened by the simplifying assumptions used in analytical models, and are therefore inherently capable of addressing more complicated problems They require significantly more input, however, and their solutions are inexact (numerical approximations) For example, the assumptions of homogeneity and isotropicity are unnecessary because the model can assign point (nodal) values of transmissivity and storage Likewise, the capacity to incorporate complex boundary conditions provides greater flexibility The user, however, faces difficult choices regarding time steps, spatial grid designs, and ways to avoid truncation errors and numerical oscillations (Remson et al , 1971, Javendel et al , 1984) Improper choices may result in errors unlikely to occur with analytical approaches (e g , mass imbalances, incorrect velocity distributions, and grid-orientation effects) Table 6-2 summarizes the advantages and disadvantages of analytical and numerical models

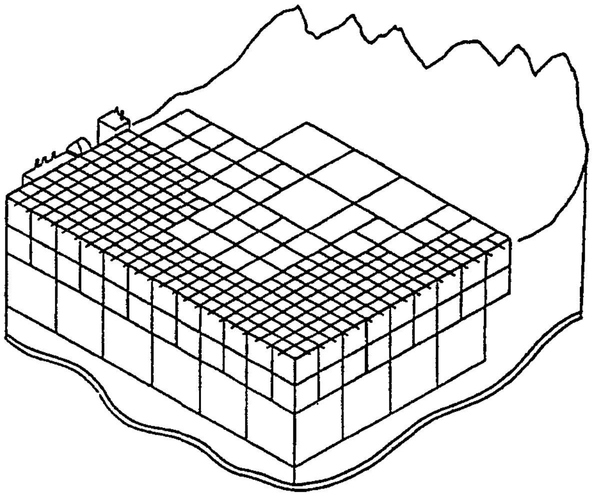
### *6.1.4 Grid Design*

A fundamental requirement of the numerical approach is the creation of a grid that represents the aquifer being simulated (see Figure 6-1) This grid consists of interconnected nodes at which process input parameters must be specified The grid forms the basis for a matrix of equations to be solved A new grid must be designed for each site-specific simulation based on the data collected during site characterization and the conceptual model developed for the physical system Grid design is one of the most critical elements in the accuracy of computational results (van der Heijde et al , 1988)

**Table 6-2 Advantages and Disadvantages of Analytical and Numerical Methods**

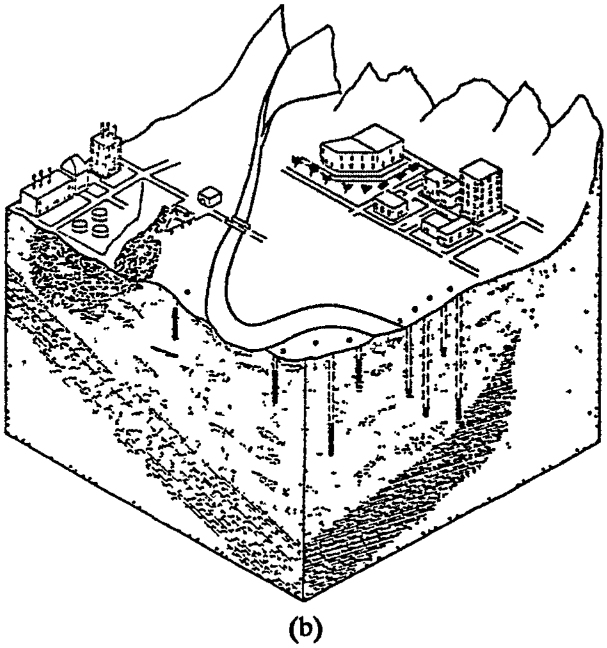
| **Advantages** | **Disadvantages** |
|---|---|
| *Analytical Models* | |
| 1 Efficient when data on the system are sparse or uncertain | 1 Limited to certain idealized conditions with simple geometry, may not be applicable to field problems with complex boundary conditions |
| 2 Economical | |
| 3 Good for initial estimation of magnitude of contamination | 2 Most cannot handle spatial or temporal variations in system |
| 4 Rough estimates often possible from existing data sources | |
| 5 Input data for computer codes usually simple | |
| *Numerical Models* | |
| 1 Easily handle spatial and temporal variations of system | 1 Achieving familiarity with complex numerical programs can be time-consuming and expensive |
| 2 Easily handle complex boundary conditions | 2 Errors due to numerical dispersion (artifacts of the computation process) may be substantial for transport models |
| 3 Three-dimensional transient problems can be treated without much difficulty | 3 More data input is usually required |
| | 4 Preparation of input data is usually time-consuming |

Source Adapted from Javandel et al (1984) and Prickett et al (1986)



**Values for natural process parameters would be specified at each node of the grid in performing simulations The grid density is greatest at the source and at potential impact locations**

(a)



**(b)**

**Figure 6-1 (a) Three-dimensional grid to model ground water flow in (b) complex geologic setting with pumping wells downgradient from potential contaminant source (from Keely, 1987)**

The grid design is influenced by the choice of numerical solution technique Numerical solution techniques include (1) finite-difference methods (FD), (2) integral finite-difference methods (IFDM), (3) Galerkin and variational finite element methods (FE), (4) collocation methods, (5) boundary (integral) element methods (BIEM or BEM), (6) particle mass tracking methods, such as random walk (RW), and (7) the method of characteristics (MOC) (Huyakorn and Pinder, 1983, Kinzelbach, 1986) Figure 6-2 illustrates grid designs involving FD and FE methods for the same well field

Finite-difference and finite-element methods are the most frequently used numerical solution techniques The finite-difference method approximates the solution of partial differential equations by using finite-difference equivalents, whereas the finite-element method approximates differential equations by an integral approach Figure 6-3 illustrates some of the mathematical and computational differences in the two approaches Table 6-3 compares the relative advantages and disadvantages of the two methods

## 6.2 Classification of Ground Water Computer Codes

The terminology for classifying computer codes according to the kind of ground water system they simulate is not uniformly established There are so many different ways to classify such models (i e , porous vs fractured-rock flow, saturated vs unsaturated flow, mass flow vs chemical transport, single phase vs multiphase, isothermal vs. variable temperature) that a systematic classification cannot be developed that would not require placing single codes in multiple categories

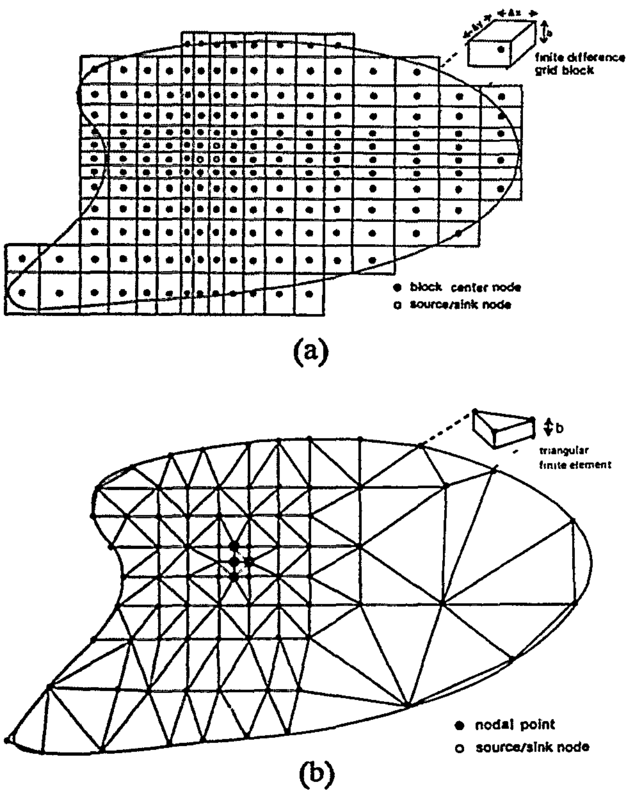


**Figure 6-2. Comparison of (a) finite-difference and (b) finite-element grid configurations for modeling the same well-field (from Mercer and Faust, 1981)**

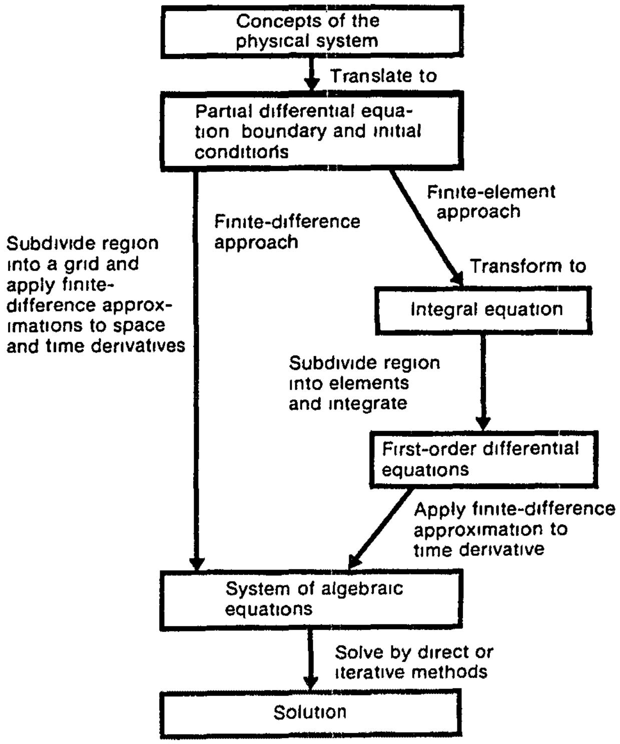


**Figure 6-3 Generalized model development by finite-difference and finite-element methods (from Mercer and Faust, 1981)**

**Table 6-3 Advantages and Disadvantages of FDM and FEM Numerical Methods**

| Advantages | Disadvantages |
|---|---|
| *Finite-Difference Method* | |
| Intuitive basis | Low accuracy for some problems (mainly solute transport) |
| Easy data entry | |
| Efficient matrix techniques | Rectangular grids required |
| Programming changes easy | |
| *Finite-Element Method* | |
| Flexible grid geometry | Complex mathematical basis |
| High accuracy possible | More complex programming |
| Evaluates cross-product terms better | |

Source Adapted from Mercer and Faust (1981)

Table 6-4 identifies 4 major categories of codes and 11 major subdivisions, discussed below This classification scheme differs from others (see, for example, Mangold and Tsang, 1987, van der Heijde et al , 1988), by distinguishing among solute transport models that simulate (1) only dispersion, (2) chemical reactions with a simple retardation or degradation factor, and (3) complex chemical reactions

**Table 6-4 Classification of Ground Water Flow and Transport Computer Codes**

| Type of Code | Description/Uses |
|---|---|
| *Flow (Porous Media)* | |
| Saturated | Simulates movement of water in saturated porous media Used primarily for analyzing ground water availability |
| Variable saturated | Simulates unsaturated flow of water in the vadose (unsaturated) zone Used in study of soil-plant relationships, hydrologic cycle budget analysis |
| *Solute Transport (Porous Media)* | |
| Dispersion | Simulates transport of conservative contaminants (not subject to retardation) by adding a dispersion factor into flow calculations Used for nonreactive contaminants such as chloride and for worst-case analysis of contaminant flow |
| Retardation/Degradation | Simulates transport contaminants that are subject to partitioning or transformation by the addition of relatively simple retardation or degradation factors to algorithms for advection-dispersion flow Used where retardation and degradation are linear with respect to time and do not vary with respect to concentration |
| Chemical-reaction | Combines an advection-dispersion code with a hydrogeochemical code (see below) to simulate chemical speciation and transport *Integrated* codes solve all mass momentum, energy-transfer, and chemical reaction equations simultaneously for each time interval *Two-step* codes first solve mass momentum and energy balances for each time step and then reequilibrate the chemistry using a distribution-of-species code Used primarily for modeling behavior of inorganic contaminants |
| *Hydrogeochemical Codes* | |
| Thermodynamic | Processes empirical data so that thermodynamic data at a standard reference state can be obtained for individual species Used to calculate reference state values for input into hydrogeochemical speciation calculations |
| Distribution-of-species (equilibrium) | Solves a simultaneous set of equations that describe equilibrium reactions and mass balances of the dissolved elements |
| Reaction progress (mass-ransfer) | Calculates both the equilibrium distribution of species (as with equilibrium codes) and the new composition of the water as selected minerals are precipitated or dissolved |
| *Specialized Codes* | |
| Fractured rock | Simulates flow of water in fractured rock Available codes cover the spectrum of advective flow, advection-dispersion, heat, and chemical transport |
| Heat transport | Simulates flow where density-induced and other flow variations resulting from fluid temperature differences invalidate conventional flow and chemical transport modeling Used primarily in modeling of radioactive waste and deep-well injection |
| Multiphase flow | Simulates movement of immiscible fluids (water and nonaqueous phase liquids) in either the vadose or saturated zones Used primarily where contamination involves liquid hydrocarbons or solvents |

Source U S EPA (1991)

The literature on ground water codes sometimes uses conflicting terminology For example, the term "hydrochemical" has been applied to completely different types of codes Rice (1986) and van der Heijde et al (1988) used the term hydrochemical for codes in the hydrogeochemical category in Table 6-4, while Mangold and Tsang (1987) used the term geochemical for such models and the term hydrochemical to describe coupled geochemical and flow models (chemical-reaction transport codes in Table 6-4) More recently, van der Heijde and Einawawy (1993) have used the term hydrogeochemical for codes that model aqueous chemical reactions without regard to transport, that term is used here The major types of models are discussed briefly below Section 6 4 5 provides further discussion of the selection of codes for WHPA delineation

### 6.2.1 Porous Media Flow Codes

Modeling of saturated flow in porous media is relatively straightforward, consequently, by far the largest number of codes are available in this category Modeling variably saturated flow in porous media (typically, soils and unconsolidated geologic material) is more difficult because hydraulic conductivity varies with changes in water content in unsaturated materials Such codes typically must model processes such as capillarity, evapotranspiration, diffusion, and plant water uptake

Van der Heijde et al (1988) summarized 97 saturated porous media codes and 29 variably saturated codes Further screening by van der Heijde and Beljin (1988) identified 27 flow models that are potentially suitable for delineating WHPAS, several of which also can simulate variably saturated flow These codes may result in smaller wellhead protection areas than required if hydrodynamic dispersion is a significant factor in contaminant transport (Section 6 2 2)

### 6.2.2 Porous Media Solute Transport Codes

The most important types of codes in the assessment of ground water contamination simulate the transport of contaminants in porous media This is the second largest category (73 codes) identified by van der Heijde et al. (1988) as being readily available Solute transport codes fall into three major categories (see Table 6-4 for descriptions)· (1) dispersion codes, (2) retardation/degradation codes, and (3) chemical-reaction transport codes

Dispersion codes differ from saturated flow codes only in having a dispersion factor These codes may be required if conservative contaminants such as nitrates are of potential concern Retardation/degradation codes are slightly more sophisticated because they add a retardation or degradation factor to the mass transport and diffusion equations Such codes can be used to delineate a zone of attenuation (Section 4 1 5) if flow transport modeling results in such a large WHPA that further targeting of management practices is required As discussed in Section 6 4 4, however, such codes must be used with caution Chemical reaction-transport codes are the most complex (but not necessarily the most accurate) because they couple geochemical codes with flow codes Chemical reaction-transport codes may be classified as *integrated* or *two-step* codes (see Table 6-4)

Two recent numerical models specifically incorporate biodegradation into contaminant transport models BIOPLUME II, developed for U S EPA, models oxygen-limited biodegradation for two-dimensional transport (Rifai et al., 1988). Celia et al. (1989) describe a new numerical solution procedure for simulation of reactive transport in porous media that incorporates both aerobic and anaerobic biodegradation, and Kindred and Celia (1989) present the result of test simulations

### 6.2.3 Hydrogeochemical Codes

Geochemical codes simulate chemical reactions in ground water systems without considering transport processes. These fall into three major categories (see Table 6-4). (1) thermodynamic codes, (2) distribution-of-species codes, and (3) reaction progress codes By themselves, geochemical codes can provide qualitative insights into the behavior of contaminants in the subsurface Chemical transport modeling of any sophistication requires coupling geochemical codes with flow codes (see previous section) More than 50 geochemical codes have been described in the literature (Nordstrom and Ball, 1984), but only 15 are cited by van der Heijde et al. (1988) as passing their screening criteria for reliability and usability Geochemical codes are unlikely to be used for WHPA delineation, except in specialized situations where qualitative interpretations of aquifer water quality are not adequate

### 6.2.4 Specialized Codes

This category contains special cases of flow codes and solute transport codes (see Table 6-4), including (1) fractured rock, (2) heat transport, and (3) multiphase flow Fractured rock creates special problems in the modeling of contaminant transport for several reasons First, mathematical representation is more complex due to the possibility of turbulent flow and the need to consider roughness effects Furthermore, precise field characterization of fracture properties that influence flow, such as orientation, length, and degree of connection between individual fractures, is extremely difficult In spite of these difficulties, much work is being done in this area (Schmelling and Ross, 1989), van der Heijde et al (1988) have identified 27 fractured rock models None of these models, however, meet screening criteria established by van der Heijde and Beljin (1988) for codes potentially suitable for delineation of WHPAs

Heat transport models have been developed primarily in connection with enhanced oil recovery operations (Kayser and Collins, 1986) and programs assessing disposal of radioactive wastes Van der Heijde et al (1988) summarized 36 codes of this type Early work in multiphase flow, centered in the petroleum industry, focused on oil-water-gas phases In the last decade, multiphase behavior of nonaqueous phase liquids in near-surface ground water systems has received increasing attention However, the number of codes capable of simulating multiphase flow is still limited Van der Heijde et al (1988) summarized 19 such codes This is a rapidly developing area of research (El-Kadi et al , 1991)

## 6.3 General Code Selection Considerations

All modeling involves simplifying assumptions concerning parameters of the physical system being simulated Furthermore, these parameters will influence the type and complexity of the equations used to represent the model mathematically Six major parameters of ground water systems must be considered when selecting a computer code for simulating ground water flow (Section 6 3 1) and six additional parameters for contaminant transport (Section 6 3 2) Section 6 4 5 describes a specific computer code selection process for WHPA delineation

### 6.3.1 Ground Water Flow Parameters

**Type of Aquifer** Confined aquifers with uniform thickness are easier to model than unconfined aquifers because the transmissivity (Section 3 1 2) remains constant The thickness of unconfined aquifers varies with fluctuations in the water table, thus complicating calculations Similarly, simulation of variable-thickness confined aquifers is complicated by the fact that velocities generally increase in response to reductions in the distance between confining beds, and decrease in response to increases in these distances

**Matrix Characteristics** Flow in porous media is much easier to model than in rocks with fractures or solution porosity This is because (1) equations governing laminar flow are simpler than those for turbulent flow, which may occur in fractures, and (2) porosity and hydraulic conductivity can be more easily estimated for porous media

**Homogeneity and Isotropy.** Homogeneous and isotropic aquifers are easiest to model because their properties do not vary in any direction (Section 2 1 3) If hydraulic properties and concentrations are uniform vertically and in one of two horizontal dimensions, a *one-dimensional* simulation is possible Horizontal variations in properties combined with uniform vertical characteristics can be modeled in *two dimensions* Most natural aquifers, however, show variation in all directions and consequently require *three-dimensional* simulation, which also necessitates more extensive site characterization data The spatial uniformity or variability of aquifer parameters such as recharge, hydraulic conductivity, porosity, transmissivity, and storativity (Section 3 1) will determine the number of dimensions to be modeled

**Phases** Multiple phases are more difficult to simulate than (1) flow of ground water, or (2) contaminated ground water in which the dissolved constituents do not create a plume that differs greatly from the unpolluted aquifer in density or viscosity (see Sections 1 2 3 and 6 3 2)

**Number of Aquifers** A single aquifer is easier to simulate than multiple aquifers

**Flow Conditions** *Steady-state* flow, where the magnitude and direction of flow velocity are constant with time at any point in the flow field, is much easier to simulate than transient flow *Transient,* or unsteady, flow occurs when the flow varies in the saturated zone in response to variations in recharge or discharge rates These terms may also be applied to unsaturated flow in the vadose zone In this manual, the term variably saturated flow is used to describe this type of unsteady flow

### 6.3.2 Contaminant Transport Parameters

**Concentration** The simplest way to model contaminant transport in the subsurface is to specify a starting concentration in the ground water, without considering the type of source

**Type of Source.** For more sophisticated simulation purposes, sources can be characterized as point, line, area, or volume A *point* source enters the ground water at a single point, such as a pipe outflow or injection well, and can be simulated with either a one-, two-, or three-dimensional model An example of a *line* source is a contaminant leaching from the bottom of a trench An *area* source enters the ground water through a horizontal or vertical plane The actual contaminant source may occupy three dimensions outside of the aquifer, but for modeling purposes contaminant entry into the aquifer can be represented as a plane Examples of area sources include leachate from a waste lagoon or an agricultural field A *volume* source occupies three dimensions within an aquifer An example of a volume source is a DNAPL that has sunk to the bottom of an aquifer (see Figure 1-9) Line and area sources may be simulated by either two- or three-dimensional models, while a volume source requires a three-dimensional model Figure 6-4 illustrates the type of contaminant plume that results from a landfill in the following cases Case 1, an areal source on top of the aquifer, Case 2, an areal source within the aquifer and perpendicular to the direction of flow, Case 3, a vertical line source in the aquifer, and Case 4, a point source on top of the aquifer

**Type of Source Release** The release of an instantaneous pulse, or *slug,* of contaminant is easier to model than a continuous release A continuous release may be either *constant* or *variable* Figures 1-7b and 1-8b show the different contaminant plume configurations resulting from continuous and slug releases, respectively Figure 1-14 illustrates some effects of variations in the rate of release on contaminant plume shape

**Dispersion** Accurate contaminant modeling requires incorporation of transport by dispersion (see Section 1 2 2) Unfortunately, the conventional convective-dispersion equation often does not accurately predict field-scale dispersion (U S EPA, 1988)

**Adsorption** It is easiest to simulate adsorption with a single distribution or partition coefficient (1 3 2) Nonlinear adsorption and temporal and spatial variation in adsorption are more difficult to model

**Degradation** As with adsorption, simulation of degradation is easiest when a simple first-order degradation coefficient is used Second-order degradation coefficients, which result from variations in various parameters such as pH, substrate concentration, and microbial population, are much more difficult to model Simulation of radioactive decay is complicated but easier to simulate with precision because decay chains are well known

**Density/Viscosity Effects** If the temperature or salinity of the contaminant plume is much different from that of the pristine aquifer, simulations must include the effects of density and viscosity variations (see Section 1 2 3)

### 6.3.3 Computer Hardware and Software

The type of computer hardware available (model, memory available for core storage, peripherals for printing code output, etc ) is a primary consideration in selecting a ground water computer code Earlier codes depended heavily on mainframe computers (such as CDC, IBM,

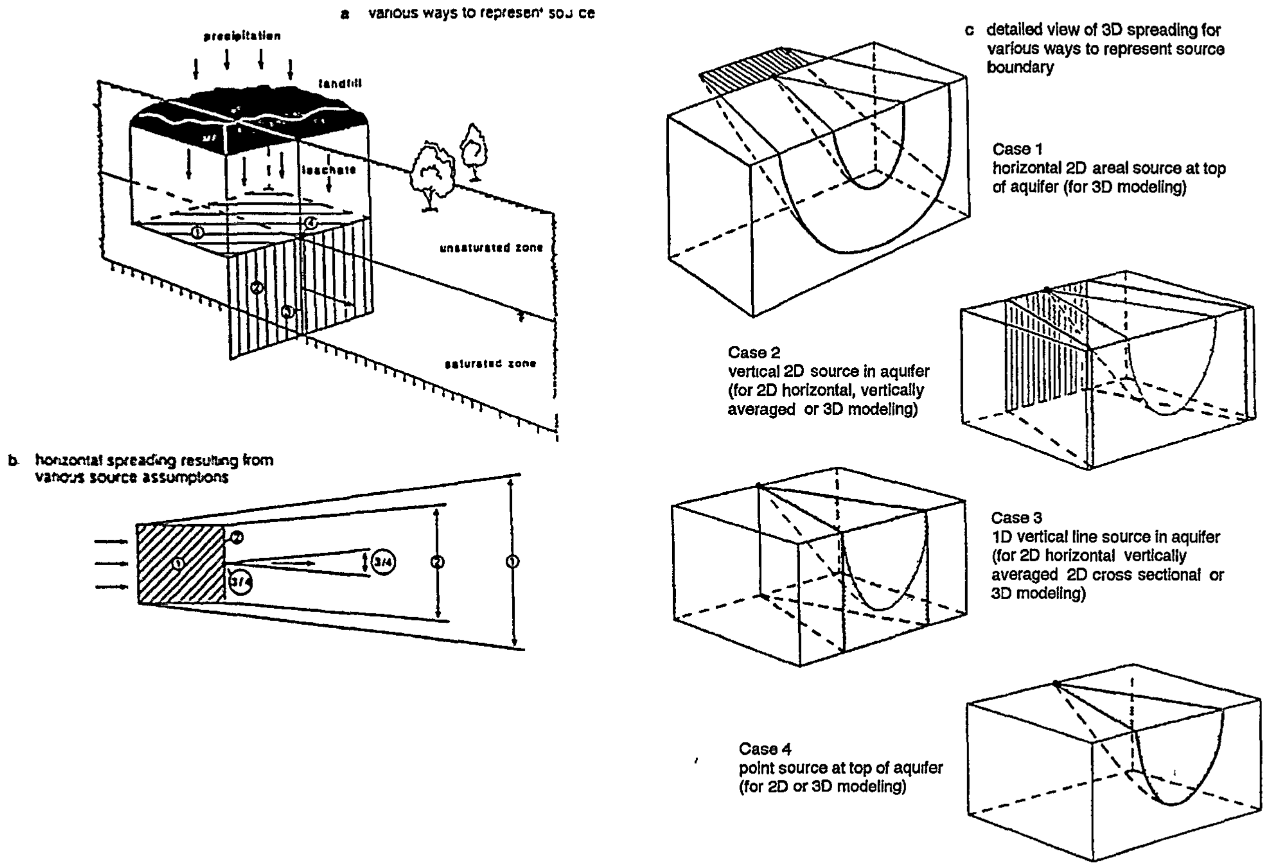


**Figure 6-4** Definition of the source boundary condition under a leaking landfill, numbers 1–4 refer to Cases 1–4 (from van der Heijde et al, 1988)

PRIME, UNIVAC, and VAX models) Rapid advances in microcomputer technology have resulted in increased availability of ground water modeling software for personal computers (PCs)[1] This trend stems from significant improvements in the computing power and quality of printed outputs obtainable from PCs It is also due to the improved telecommunications capabilities of PCs, which are now able to emulate the interactive terminals of large business computers so that vast computational power can be accessed and the results retrieved with no more than a phone call

Many of the mathematical models and data packages have been "down-sized" from mainframe computers to PCs. Many more are now being written directly for this market. A major advantage of PC-based codes is the relatively low cost of both hardware (the necessary computer and peripherals can probably be obtained for less than $5,000) and software Most codes can be obtained for less than $100

### 6.3.4 Usability and Reliability

An ongoing program at the International Ground Water Monitoring Center (IGWMC) evaluates codes using performance standards and acceptance criteria (van der Heijde, 1987b) The Center rates codes that are in its data base using six *usability* and four *reliability* criteria (van der Heijde and Beljin, 1988, van der Heijde et al, 1988) Favorable ratings for the usability criteria include

- *Pre- and Postprocessors* The code incorporates one or more of this type of software
- *Documentation* The code has an adequate description of user's instructions and sample problems using example datasets
- *Hardware Dependency* The code is designed to function on a variety of hardware configurations
- *Support* The code is supported and maintained by the developers or marketers

Favorable ratings for the reliability criteria include

- *Review* Both the theory behind the coding and the coding itself are peer-reviewed

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[1] Most first-generation software for microcomputers has been developed for IBM PC/AT/XT and compatibles that typically require 640 K (kilobyte) random access memory (RAM) Second-generation software typically requires a 386 or 486 CPU (central processing unit) with a math coprocessor and 2 megabytes (MB) RAM

- *Verification* The code has been verified (Table 6-1 and Section 6 3 5)
- *Field Testing/Validation* Code has been extensively field-tested for site-specific conditions for which extensive datasets are available (Section 6 3 5)
- *Extent of Use* Code has been used extensively by other modelers

### 6.3.5 Quality Assurance/Quality Control

Modeling and computer codes are increasingly used in regulatory settings where decisions may be contested in court Therefore, careful attention must be paid to quality assurance and quality control in both model development and application There are four major aspects to quality control for a site-specific application of a model, as in the case of WHPA delineation (1) sensitivity, (2) calibration, (3) verification, and (4) validation Table 6-1 provides summary definitions of these terms [2]

The accuracy of the input values is of less concern when model results are relatively insensitive to changes in values for input parameters, compared to when a small change in an input parameter causes a large change in the model output Sensitivity testing may be useful in guiding data collection for a site Less attention need be given to estimating or measuring parameters that do not greatly affect the outcome of the modeling, while additional effort may be required to ensure that sensitive input parameters are measured accurately

Whether the basic code has been verified and validated is an important criteria for selecting models Verification is also desirable for site-specific applications, if it is possible to obtain a second set of field data measured under similar hydrologic conditions to the site-calibrated code The code can be considered verified if it acceptably approximates the second data set This can be determined by defining an acceptable level of departure between simulated values and the actual data set and calculating the difference between actual and simulated values (residuals) If these residuals fall within the range that was defined as acceptable, the model can be considered verified for application to that particular field situation

Field validation of a numerical model consists of first calibrating the model using one set of historical records (e g , pumping rates and water levels from a certain year), and then attempting to predict the next set of historical records In the calibration phase, the aquifer coefficients and other model parameters are adjusted to achieve the best match between model outputs and known data, in the predictive phase, no adjustments are made (excepting actual changes in pumping rates, etc )

Presuming that the aquifer coefficients and other parameters were known with sufficient accuracy, a mismatch means that either the model is not correctly formulated or it does not treat all of the important phenomena affecting the situation being simulated (e g , it does not allow for leakage between two aquifers when this is actually occurring) Field validation is completed by conducting a *postaudit,* in which the predicted changes in responses to changes in the system are confirmed by field measurements

## 6.4 Computer Modeling for WHPA Delineation

The great advantage of the computer is that large amounts of data can be generated quickly and experimental modifications made with minimal effort, so that many possible situations for a given problem can be studied in great detail The danger is that without proper selection, data collection and input, and quality control procedures, the computer's usefulness can be quickly undermined, bringing to bear the adage "garbage in, garbage out "

A bewildering number of ground water flow and contaminant transport codes are available [3] The number of factors that must be considered in selecting a code (Section 6 3) can make the task of choosing a code for a particular wellhead area daunting Van der Heijde and Beljin (1988) identified 64 models in the International Ground Water Modeling Center's database that satisfied criteria for (1) outputs useful for WHPA delineation, and (2) usability and reliability (Section 6 3 4) Additional screening criteria were used to further reduce the number of codes covered in this manual

- Only codes identified in van der Heijde and Beljin (1988) that can be used on personal computers are considered Codes requiring mainframe computers are likely to be too expensive for most local governments concerned with wellhead protection, or will be used by consulting firms with personnel already familiar with how to use the code [4]

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[2] Note that the term "validation" is not defined in Table 6-1 because it has been the subject of some recent controversy Bredehoeft and Konikow (1993) suggested abandoning use of the term validation by the ground water modeling community because it implies a precision that is not achieved in reality In response, McCombie and McKinley (1993) argued that the term validation is appropriate for describing the process of ensuring that mathematical models "ensure an acceptable level of predictive accuracy" The term, which was included in early ASTM ballots for adoption of D5447-93, was dropped in the final standard Because the term is well established in the ground water modeling literature, it is used in this manual in the sense suggested by McCombie and McKinley (1993)

[3] As of March 1, 1987, the IGWMC had 632 code annotations in its MARS data base for mainframe computers and 104 annotations in its PLUTO database for personal computers These data bases have now been merged In late 1993, the data base contained more than 700 codes

[4] Anyone trying to select a mainframe model should refer to the following publications, which are recommended for comparative information van der Heijde and Beljin (1988), van der Heijde et al (1988), U S EPA (1988), and Thompson et al (1989)

- Any codes available for personal computers mentioned in the published literature on ground water and wellhead protection are included

### 6.4.1 Spreadsheet Models

PC computer spreadsheets are a very useful tool for analyzing ground water data and solving analytical equations for ground water flow Computer spreadsheets are well suited for use with the simple analytical methods described in Chapter 4 The major advantages of spreadsheets include the following

- They do not require knowledge of any particular computer programming language, although programming experience is certainly useful
- The logic of spreadsheet models is embedded in formulas contained within spreadsheet cells, which allows for easy modification and identification of errors
- Spreadsheet calculations are rapid, providing results within a fraction of a second (seconds for complex models) or after input values are entered
- Once a spreadsheet model has been set up, it is very easy to analyze the sensitivity of model output to changes in input parameters
- Many spreadsheet programs include data base and graphic capabilities

Spreadsheet models are primarily limited to analytical solutions Hence, they suffer from the disadvantages of analytical approaches compared to numerical modeling approaches (Table 6-2)

### 6.4.2 Overview of PC Models and WHPA Applications

About a dozen computer codes that meet the additional screening criteria mentioned above have been cited in the literature as having been used in actual WHPA delineation investigations These codes fall into three general categories and are discussed further in the next section.

1. Numerical codes developed for general ground water flow modeling (MODFLOW and USGS-2D FLOW) that are used to define the zone of influence (ZOI), the cone of depression (COD), and/or the zone of contribution (ZOC)
2. Simpler analytical and semianalytical "capture zone" codes for defining the zone of influence and/or zone of contribution of one or more pumping wells
3. Pathline tracing or reverse path codes (typically analytical or semianalytical) for calculating time of travel and/or velocity using the output from numerical modeling or capture zone codes

Solute transport (dispersion-only and retardation/degradation) models have received limited, if any, use in WHPA delineation This is primarily because the assimilative capacity of aquifers is not easily modeled or quantitatively determined Relatively simple solute transport models for personal computers, however, are increasingly available This provides opportunities for providing some assessment of the kind of safety factor that may be built into WHPA delineations based on the assumption that contaminants will not be attenuated Section 6 4 4 provides additional discussion of solute transport models

### 6.4.3 Numerical Flow, Capture Zone, and Pathline Tracing Models

Table 6-5 provides an index to documentation and case studies that describe the use of PC-based computer models for WHPA delineation At least four numerical codes have been used for delineation of WHPAs MODFLOW, FLOWPATH, PLASM, and USGS 2D-FLOW MODFLOW, developed by the U S Geological Survey, is a very versatile modular three-dimensional finite difference ground water model that simulates transient flow in anisotropic, heterogeneous, layered aquifer systems Very complex hydrogeologic systems can be modeled, provided that a porous media flow assumption can be justified This versatility is probably the reason that MODFLOW has been reported in the wellhead protection literature more frequently than any other method

The most commonly reported analytical capture zone models are the MWCAP module of the WHPA code, CAPZONE (a refinement of the THWELLS analytical model), and DREAM (Table 6-5) Pathline tracing models are especially useful for wellhead protection because of their relatively precise delineation of time of travel isochrons These may also be referred to as particle tracking or reverse flow path models (Kreitler and Senger, 1991) A two-set process is involved in pathline tracing First, the water level at the well and the potentiometric surface for the surrounding area is calculated, often using a numerical or analytical capture zone model Second, reverse flow paths are calculated using semianalytical or numerical methods These codes allow much more accurate determination of both flow paths and time of travel than do the TOT calculations in Section 4 4

The use of pathline tracing models in the context of wellhead protection is a relatively recent development, with all the models listed in Table 6-5 having become available since 1987 GWPATH, developed by the Illinois State Water Survey (Shafer, 1987a), has been most frequently mentioned in the published literature in this regard MODPATH, developed in 1989 for use with the popular USGS model MODFLOW, has gained rapid

**Table 6-5 Examples of Use of Computer Models for Wellhead Protection**

| Model | Documentation/Case Studies |
|---|---|
| *Numerical Flow Codes** | |
| FLOWPATH | *Documentation* Franz and Guiguer (1990), *Applications/Case Studies* Cleary and Cleary (1991), Swanson (1992) |
| MODFLOW | *Documentation* McDonald and Harbaugh (1988), *Case Studies* Bair and Roadcap (1992), Bradbury et al (1991), Heeley et al (1992), Kreitler and Senger (1991), Nelson and Witten (1990), OEPA (1992), Plomb and Arnett (1992), Springer and Bair (1992), Swanson (1992), Tolman et al. (1991), Trefry (1990), U.S EPA (1987, 1992) |
| PLASM | *Documentation* Hull (1983), Prickett and Associates (1984), Prickett and Lonnquist (1971), Walton (1989a); *Case Studies* Boring (1992), Wehrmann and Varljen (1990) |
| USGS-2D FLOW | *Documentation* Trescott et al (1976), *Case Studies* U S EPA (1987) |
| *Capture Zone Codes** | |
| CAPZONE/THWELLS | *Documentation* van der Heijde (1987a—THWELLS), Bair et al (1991a—CAPZONE), *CAPZONE Case Studies* Bair and Roadcap (1992), Bair et al (1991b, 1991c), OEPA (1992), Springer and Bair (1992), *THWELLS Case Studies* Roadcap and Bair (1990), Springer and Bair (1990) |
| DREAM | *Documentation* Bonn and Rounds (1990), *Case Studies* Bair and Roadcap (1992), Springer and Bair (1992), Swanson (1992) |
| WhAEM | *Documentation* Strack and Haitjema (in press) |
| WHPA (MWCAP) | *Documentation* Blandford and Huyakorn (1991), *Applications/Case Studies* See references for RESSQC/GPTRAC below |
| Spreadsheet Capture Zone | *Documentation* Pekas (1992), *Equations* Huntoon (1980), Javendel and Tsang (1986), Keely and Tsang (1983a, 1983b), McLane (1990) |
| Other Capture Zone Methods | *KGS Capture Zone* McElwee (1991), Woods et al (1987), *Analytic Element Method* Kraemer and Burden (1992), *Other* Ahlfield and Sawyer (1990), Grubb (1993), Lee and Wilson (1986), Linderfeldt et al (1989), Nelson (1978a,b), Newsom and Wilson (1988), Shafer-Perini and Wilson (1991), Tiedeman and Gorelick (1993), Wilson and Linderfeldt (1991) |
| Drainage Ditch Capture Zone | Chambers and Barr (1992), Zheng et al (1988a, 1988b) |
| *Reverse Path Codes** | |
| GWPATH | *Documentation* Shafer (1987a, 1990), *Applications/Case Studies* Bair and Roadcap (1992), Bair et al (1991b, 1991c), Kreitler and Senger (1991), OEPA (1992), Roadcap and Bair (1990), Shafer (1987b), Springer and Bair (1990, 1992), Varljen and Shafer (1991, 1993), Wehrmann and Varljen (1990) |
| PATH3D | *Documentation* Zheng (1992), Zheng et al (1992), *Case Studies* Bradbury et al (1991) |
| WHPA (RESSQC, GPTRAC) | *Documentation* Blanford and Huyakorn (1991), *Applications/Case Studies* Bair and Roadcap (1992), Baker et al (1993), Bhatt (1993), Boring (1992), Kreitler and Senger (1991), Oates et al (1990), Rifai et al (1993), Springer and Bair (1992), U S EPA (1992) |
| MODPATH | *Documentation* Pollock (1988, 1989, 1990), Srinivasan (1992), *Case Studies* Bair and Roadcap (1992), Buxton et al (1991), OEPA (1992), Springer and Bair (1992), Swanson (1992) |
| RESSQ | *Documentation* Javendel et al (1984), WellWare (1993), see also WHPA code above, *Case Studies* OEPA (1992) |
| ROSE | Lerner (1992a, 1992b) |
| *Unclassified* | Taylor (1989) |

* Numerical and analytical capture zone codes are typically coupled with reverse path (particle tracking) codes for wellhead protection area delineation Reported combinations include CAPZONE/GWPATH, DREAM/RESSQC, MWCAP/RESSQC (separate modules of the WHPA code), PLASM/GWPATH, MODFLOW/MODPATH

acceptance because no additional data, except possibly porosity, are required once a MODFLOW simulation has been completed

The WHPA (Wellhead Protection Area) code, developed for the U S Environmental Protection Agency, is designed specifically for WHPA delineation The pathline tracing module of the WHPA code, RESSQC, is based on the RESSQ code developed by Javendel et al (1984) A stand-alone version of RESSQ that is more user friendly has also recently become available (WellWare, 1993) The WHPA code also has a semianalytical/numerical particle-tracking module called GPTRAC The first version of WHPA (1 0) did not consider vertical leakage, resulting in unnecessarily large protection areas for semiconfined aquifers where leakage was significant The latest version (2 1) has been modified to allow vertical leakage, permitting time of travel calculations to leaky aquifer settings Additional modifications are under way to provide additional solutions and added boundary conditions (personal communication, Neil Blandford, HydroGeoLogic, Herndon, VA, September, 1993)

PATH3D is a pathline tracing model recently developed by the Wisconsin Geological and Natural History Survey (Zheng et al , 1992), and an enhanced version is commercially available (Zheng, 1992) ROSE, a semianalytical path line tracing model (Lerner, 1992a, 1992b), follows a family of semianalytical models using an approach first developed by Nelson (1978a,b) Keely and Tsang (1983) used Nelson's methods but presented results in terms of capture zones as well as fronts of pollution movement (RESSQ model) Javendel and Tsang (1986) extended this work to look at nondimensional expressions of capture zones Pekas (1992) adapted equations presented in Keely and Tsang (1983) and Javendel and Tsang (1986) to calculate capture zones using a spreadsheet

As noted earlier, numerical and analytical capture zone codes are typically coupled with reverse path (particle tracking) codes for wellhead protection area delineation Reported combinations include CAPZONE/GWPATH, DREAM/RESSQC, MWCAP/RESSQC (separate modules of the WHPA code), PLASM/GWPATH, MODFLOW/MODPATH Table 6-5 identifies case studies illustrating use of these various combinations

The Wellhead Analytic Element Method (WhAEM) model, currently under development for EPA's R S Kerr Environmental Research Laboratory (Ada, Oklahoma), will allow WHPA delineation in more complex hydrogeologic settings (multiple stream and other recharge boundary conditions) than can be handled by available capture zone/reverse path analytical codes It is likely to be an attractive alternative to more complex numerical codes, provided that the assumptions of homogeneity and isotropy apply

### 6.4.4 Solute Transport Models

Mechanisms for reducing the concentration of contaminants in an aquifer are generally too complex and difficult to predict for selection as criteria for wellhead protection (U S EPA, 1987) Accurate modeling of contaminant transport is limited by fundamental problems, including (1) inability to describe mathematically some processes, (2) complex mechanisms that are beyond the capability of available numerical techniques, and (3) difficulty in obtaining enough data of sufficient quality to calibrate models (van der Heijde and Beljin, 1988)

Hydrodynamic dispersion, the process by which contaminants may travel *faster* than would be expected from simple ground water flow calculations, must be considered during the WHPA delineation process As noted in Section 1 2 2, dispersion at the microscopic scale is such a minor component of ground water movement that it can generally be ignored Although dispersion at this scale results in a faster arrival time, it also reduces concentration levels, and consequently can be considered an attenuating process Contaminant transport by macroscopic dispersion, on the other hand, is best addressed using methods that account for the effect of aquifer heterogeneity on the speed of ground water flow (Sections 2 1 3 and 5 4 2) For simple methods, this involves using the upper range of estimated or measured hydraulic conductivity in ground water flow calculations Numerical computer codes allow design of the grid to account for more highly transmissive layers

Bradbury et al (1991) provide a good example of the difference that a single highly transmissive layer in an aquifer can make in travel times At the Sevastopol site in Door County, Wisconsin, where the aquifer is in fractured dolomite, time of travel to the upgradient ground water divide based on calculations using a potentiometric surface map was 100 years (Figure 6-5a) Ground water simulations using PATH3D that accounted for a fracture zone at a depth of 170 feet below the ground surface resulted in a travel time of *1* year from the ground water divide (Figure 6-5b)

Retardation processes (Section 1 3) provide an unstated safety factor to WHPA delineations based on advective flow to the extent that they diminish the concentration of a contaminant as it moves through an aquifer More than a dozen PC-based codes use relatively simple retardation and degradation factors to simulate concentrations of contaminants in ground water These codes are most commonly used in heavily contaminated settings to help develop remediation strategies Such codes may have value for wellhead protection, however, as a means of quantifying the safety factor contained in delineations based on other methods, or for further evaluations of the possible risks associated with potential contaminant sources within the WHPA (Chapter 8)

The main considerations in using methods that allow delineation of a zone of attenuation (Section 4 1 5) are that (1) aquifer anisotropy and heterogeneity must have been adequately incorporated into the WHPA to account for the zone of more rapid transport, and (2) reliance should not be placed on a single method for calculating contaminant transport

Arnold (1992) used eight numerical models and four analytical models to estimate attenuation of BTX (benzene, toluene, xylene) from a gasoline spill 4,000 feet from the Mississippi River Table 6-6 summarizes the processes included in each model and the predicted concentration (as a percentage of initial concentration) after traveling from the spill site to the river There is a

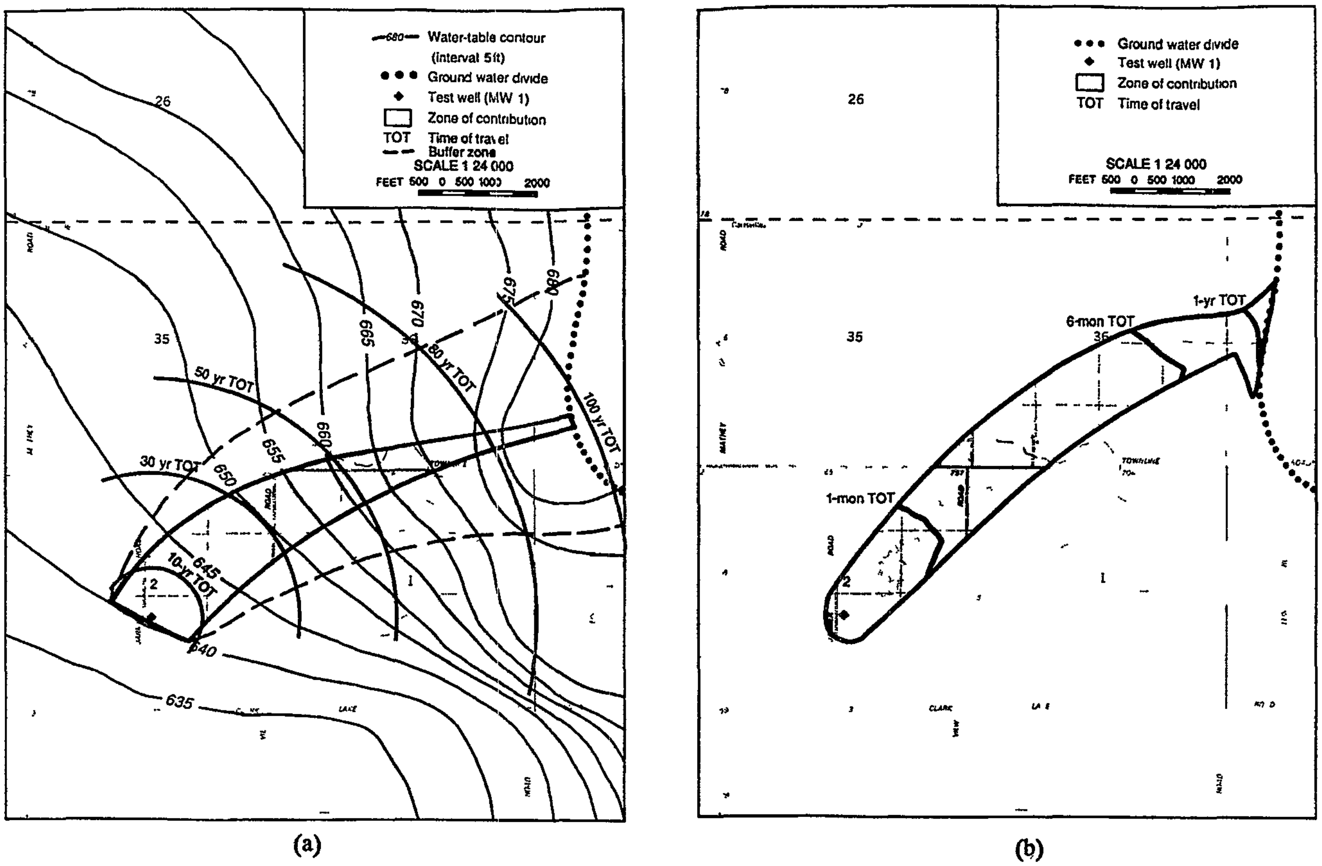

Figure 6-5 Time of travel contours in a dolomite aquifer based on (a) potentiometric surface map, (b) numerical modeling (from Bradbury et al 1991)

two-order-of-magnitude range in the predicted concentrations For the purposes of evaluating contaminant transport within a WHPA, the analytical models in Table 6-6 appear to be the most useful

### 6.4.5 Code Selection Process for Wellhead Delineation

As discussed in the introduction to this chapter, there is a continuous spectrum for increasing sophistication in computer modeling of ground water, ranging from use of simple analytical equations in spreadsheets on a PC (Section 6 4 1) to complex ground water flow and contaminant transport models that require a mainframe computer

If an IBM PC/AT/XT or compatible with at least 640K of RAM (random access memory) and personnel with some technical expertise in ground water are available, low-cost PC software can be considered for any wellhead area When an aquifer is anisotropic and heterogeneous, PC computer modeling is required, unless the limitations of simple analytical solutions can be overcome or very conservative assumptions are used in calculations for delineating a WHPA The following steps can help in selecting one or more codes for a site-specific application

1 Use Checklist 4-1 (Aquifer Characteristics for Selection of Analytical Solutions to Ground Water Flow in the Vicinity of Wells) to identify aquifer, matrix, and flow characteristics

2 For each candidate model selected, fill out Worksheet 6-1 to develop a detailed profile of the characteristics of the site and the model For all models with an IGWMC identification number, this detailed information can be obtained from Appendices B (Evaluation of Usability and Reliability) and C (Detailed Annotations) in van der Heijde and Beljin (1988), available from the National Technical Information Service Worksheet 6-1 also contains an area for defining the specifications for the computer and peripherals on which the software will be run

3 Compare the code suitability worksheets (Worksheet 6-1) for each model and eliminate any that do not seem appropriate based on a qualitative weighing of (1) model characteristics (including complexity of required input data and grid design), (2) model output, (3) usability and reliability, and (4) cost For the re-

## Worksheet 6-1.
## Worksheet for Developing Ground Water Computer Code Specifications or Evaluating Code Suitability for a Specific Site

Model Name: ______________________________ IGWMC No. ______

Contact ____________________________ Available from ____ IGWMC
Address ____________________________ ____ Other Location
____________________________ ________________________________
____________________________ ________________________________
Phone: ______________ ________________________________

**Site/Model Characteristics**

___ ___ Unconfined (water table)
___ ___ Semiconfined (leaky)
___ ___ Confined
___ ___ Single aquifer
___ ___ Multiple aquifers
___ ___ Isotropic
___ ___ Homogeneous
___ ___ Anisotropic
___ ___ Heterogeneous
___ ___ Radial
___ ___ One-dimensional
___ ___ Two-dimensional
___ ___ Three-dimensional
___ ___ Steady flow
___ ___ Transient flow
___ ___ Variably saturated flow
___ ___ Single-phase flow
___ ___ Multi-phase flow
___ ___ Hydrodyanmic dispersion
___ ___ Retardation
___ ___ Decay/degradation

**Model System Requirements** — **Available Computer Match System Requirements?** Yes No

____ IBM PC/AT/XT (circle) ___ ___
____ Other Computer ____________ ___ ___

Random Access Memory
____ 640 K ___ ___
____ 4 MB ___ ___
____ Other (________) ___ ___

Disk Drives
____ Single floppy (HD ___, DD ___) ___ ___
____ Two floppy (HD ____, DD ____) ___ ___
____ Hard drive ___ ___

Disk Operating System
____ DOS 2.1 ___ ___
____ > DOS 2.1 (_______) ___ ___

Math Coprocessor
____ Required ___ ___
____ Optional ___ ___

Graphics
____ CGA ___ ___
____ EGA ___ ___
____ VGA ___ ___

**Boundary Conditions** See Checklist 5-1

**Site/Model Output**

___ ___ Zone of Influence
___ ___ Cone of Depression
___ ___ Time of Travel
___ ___ Velocity
___ ___ Pathways
___ ___ Zone of Contribution
___ ___ Fluxes
___ ___ Concentration

**Usability**

Yes No ?

___ ___ ___ Preprocessor
___ ___ ___ Postprocessor
___ ___ ___ User's instructions
___ ___ ___ Sample problems
___ ___ ___ Hardware dependency
___ ___ ___ Support

**Reliability**

Yes No ?

___ ___ ___ Theory peer-reviewed
___ ___ ___ Coding peer-reviewed
___ ___ ___ Verified
___ ___ ___ Field validation

Model Users ___ many, ___ few, ___ unknown

**Table 6-6 Comparison of Predicted Concentrations of BTX Using the Same Inputs for Twelve Different Models (Arnold, 1992)**

| | Variables Included | | | | | |
|---|---|---|---|---|---|---|
| **Model Name** | **Dispersion** | **Retardation** | **Chemical Decay** | ***Biodegradation** | **Time to Run** | **Results % of Initial conc.** |
| *Numerical Models* | | | | | | |
| AT123D<br>(Yeh, 1981) | x | x | x | x | hrs-day | 0 1 |
| Bioplume II<br>(Bedient, 1989) | x | x | x | x | days-wk | 4 |
| Conmig<br>(Walton, 1989) | x | x | x | x | 1-2 hrs | 5 |
| Hydropal Slug<br>(Watershed, 1988) | x | | | | 1-2 hrs | 6 |
| MOC (Old)<br>(Konikow, 1978) | x | x | | | days-wk | 15 |
| MOC (New)<br>(Konikow, 1978) | x | x | x | x | days-wk | 4 |
| Random Walk<br>(Watershed, 1988) | x | | | | hrs | 13 |
| SLAEM<br>(Strack, 1989) | | x | x | x | days | 3 |
| *Analytical Models* | | | | | | |
| CDT Nomograph<br>(Dragun, 1989) | x | x | | | 1-2 hrs | 6 |
| HPS<br>(Galya, 1987) | x | | x | | hrs-day | 5 |
| Rapid Assessment Nomograph<br>(Guswa, 1987) | x | x | x | x | 2-4 hrs | 15 |
| Wilson-Miller Nomograph<br>(Kent, 1982) | x | x | x | | 1-2 hrs | 8 |

maining codes, contact the person or organization from which the code is available to (1) find out current price and availability information, and (2) determine whether it will work on the available hardware If cost is not a limitation, all codes that are left in this last screening step and will work on the available hardware should be obtained

The use of multiple methods (including those in Chapters 4 and 5) is always preferable to the use of a single method If different methods delineate similar areas, this increases the confidence that an appropriate area is being designated Large differences in areas using different delineation methods result in a better understanding of the hydrogeology of the site if the reasons for the differences can be discerned This understanding, in turn, allows selection of a WHPA that most accurately reflects site conditions

### *6.4.6 Potential Pitfalls*

Computers can easily give a false sense of security or cause unwarranted confidence in the results The adage "garbage in, garbage out" always applies The procedures outlined above are intended to reduce the chance that computer codes are used inappropriately, but it is useful to keep in mind pitfalls that can doom a ground water modeling effort to failure (OTA, 1982, van der Heijde et al , 1985)

1 Inadequate conceptualization of the physical system, such as flow in fractured bedrock

2 The use of insufficient or incorrect data

3 The incorrect use of available data

4 The use of invalid boundary conditions

5 Selection of an inadequate computer code

**Table 6-7. Index to Major References on Ground Water Flow and Contaminant Transport Modeling**

| Topic | References |
|---|---|
| General* | *Texts* Anderson and Woessner (1992), Bachmat et al (1980), Bear and Bachmat (1990), Bear and Verruijt (1987), Boonstra and de Ridder (1981), Cleary and Ungs (1978), Codell et al (1982), Dagan (1989), Domenico (1972), Fried (1975), Ghadiri and Rose (1992), Javendel et al (1984), Kinzelbach (1986), Mercer and Faust (1981), National Research Council (1990), Pinder and Gray (1977), Remson et al (1971), van der Heijde et al (1985), van Genuchten and Alves (1982), Walton (1988), Wang and Anderson (1982), Zienkiewicz (1977), *Computational/Mathematical Methods* Boas (1983), Burden et al (1981), Celia et al (1988), Cross and Moscardini (1985), Gerald and Wheatley (1984), Hunt (1983), Huyakorn and Pinder (1983), Istok (1989), James et al (1977), Press et al (1986), Rushton and Redshaw (1979), *Boundary Conditions* Franke and Reilly (1987), Franke et al (1987), *Review Papers* Anderson (1979, 1983, 1987), Bear et al (1992), Faust and Mercer (1980a, 1980b), Gorelick (1983), Konikow and Mercer (1988), Mercer and Faust (1980), Naymik (1987), Prickett (1979), Prickett et al (1986), Yeh and Tripathi (1989), *Bibliographies* Edwards and Smart (1988) |
| Conferences/Symposia | Arnold et al (1982), Buxton et al (1989), Celia et al (1988), Custodio et al (1988), Dickson et al (1982), Haimes and Bear (1987), Jousma (1989), Kovar (1990), Melli and Zennetti (1992), NWWA/IGWMC (1984, 1985, 1987, 1989), NGWA/IGWMC (1992), Wrobel and Brebbia (1991) |
| Reviews/Comparisons | Appel and Bredehoeft (1976), Appel and Reilly (1988), Bachmat et al (1978), Beven (1989), Beljin (1988), El-Kadi and Beljin (1987-vadose zone), El-Kadi et al (1991), IMS/OSWER (1990), Kayser and Collins (1986), Kincaid and Morrey (1984), Kincaid et al (1984), Mangold and Tsang (1987), Mercer et al (1982), Morrey et al (1986), van der Heijde and Beljin (1988), van der Heijde and Einawawy (1993), van der Heijde et al (1988), Simmons and Cole (1985), Thompson et al (1989), U S EPA (1988), Whelan and Brown (1988) |
| Applications | Anderson and Woessner (1992), Bachmat et al (1978), Boonstra and de Ridder (1981), Boutwell et al (1985), Bredehoeft et al (1982), Haimes and Bear (1987), Keely (1987), Moskowitz et al (1991), National Research Council (1990), OTA (1982), U S EPA (1988), van der Heijde (1991), van der Heijde et al (1985), Whelan and Brown (1988), *WHPA Delineation* Beljin and van der Heijde (1991), van der Heijde and Beljin (1988) |
| Quality Control | Adrion et al (1981), Bredehoeft and Konikow (1993), Buxton et al (1989), California Toxic Substance Control Program (1990), Huyakorn et al (1984), Kovar (1990), McCombie and McKinley (1993), Ross et al (1982), Siegel and Leigh (1985), U S EPA (1989), van der Heijde (1987b, 1989, 1990) |
| Other PC-Based Models** | *Ground Water Flow* Aral (1990a—SLAM, 1990b—ULAM), Walton (1984a, 1984b—WALTON35, 1989b—WELFLO, 1992), *Contaminant Transport/Biodegradation* Bedient et al (1989—BIOPLUME), Freeze et al (1992), Konikow and Bredehoeft (1978—MOC), Mueller and Crosby (1989—comparison), Mundell et al (1992—TDAST), Park et al (1992—VIRALT), Prickett and Associates (1984—Random Walk), Strack (1989—SLAEM), Rifai et al (1988—BIOPLUMEII), Walton (1989a—Random Walk, 1989b—CONMIG), Yeh (1981—AT123D), *Spreadsheets* Highland (1987) |
| Selected Topics | *Analytic Element Methods* Haitjema (1985), Strack (1987, 1989), *Capture Zones* see Table 6-6, *Stochastic Modeling* Ahlfield and Hyder (1990), Dagan (1989), Delhomme (1979), El-Kadi (1984), Gelhar (1986, 1993), Gómez-Hernández Gorelick (1989), McLane (1990), Smith (1987), van der Heijde (1985), Vomvoris and Gelhar (1986), Yen and Guymon (1990), *Modeling Contaminant Transport/Biodegradation* Beljin (1988), Celia et al (1989), Dragun (1989—CDT nomograph), Galya (1987), Guswa et al (1987—Rapid Assessment Nomograph), Kent et al (1982—Wilson-Miller Nomograph), Kindred and Celia (1989), *Hydrogeochemical Modeling* Nordstrom and Ball (1984), Rice (1986), Siegel and Leigh (1985), *Fracture Flow Modeling* Schmelling and Ross (1989), van der Heijde and El-Kadi (1989), *Multiphase Flow Modeling* Abriola (1988), El-Kadi et al (1991) |

* See Table A-1 for ground water and hydraulics tests that cover analytical equations

** See also models identified in Table 6-6

6. Incorrect interpretation of the computational results

7. Imprecise or wrongly posed management problems

Computer modeling requires expertise in both hydrogeology and computer technology The technology and software may be more readily available than the expertise When in doubt, consult an expert in government or academia or a consultant with special expertise in computer modeling of ground water

## 6.5 Sources of Additional Information on Ground Water Modeling

The trend toward development of relatively inexpensive and user-friendly codes for ground water modeling on PCs increases the risk that pitfalls identified in the last section will occur Users may lack the required breadth of knowledge about hydrogeology and computer modeling Short courses (usually focusing on a limited number of codes), such as those sponsored by the IGWMC, the National Ground Water Association, and various universities, are the best way to gain hands-on experience with the more sophisticated models Many good texts are available that address basic hydraulics and hydrogeology (Appendix A, Table A-1) and computer modeling Table 6-7 provides an index to major text references and review papers on principles and applications of ground water flow and contaminant modeling

The software catalog of the IGWMC (see address below) contains more than 70 PC-based ground water programs that can be purchased for prices ranging from fifty to several hundred dollars (IGWMC, 1992) Ground water flow and quality source codes developed by the U S Geological Survey can be obtained for IBM-compatible series 360 or 370 computers ($40 00 per program) from U S Geological Survey, WRD, National Water Information System, 437 National Center, 12201 Sunrise Valley Drive, Reston, VA, 22092 Appel and Reilly (1988) provide summary descriptions of these codes Many commercially developed codes, including enhanced versions of public domain codes such as MODFLOW, are available Two good sources of commercially available software are Scientific Software Group (1993), and Rockware Scientific Software (1993)

The continuing enhancement of existing software and the development of new codes makes keeping abreast with new developments a challenge The following newsletters (available at no cost) are useful for this purpose

- *IGWMC Ground Water Modeling Newsletter* is published by the International Ground Water Modeling Center, Colorado School of Mines, Golden, CO, 80401-1887 (303/273-3103)
- *Geraghty & Miller Software Newsletter* is a periodic publication of the Geraghty & Miller Modeling Group (10700 Parkridge Boulevard, Suite 600, Reston, VA 22091, 703/758-1200)
- *GeoTrans Newsletter* often contains information on applications and recent developments in ground water modeling (46050 Manekin Plaza, Suite 100, Sterling, VA 22170, 703/444-7000)

The scientific journals *Ground Water* and *Water Resources Research* are the best sources of peer-reviewed research on ground water modeling Periodic conferences sponsored jointly by the National Water Well Association and IGWMC are excellent sources of information on new developments and practical applications in ground water modeling (NWWA/IGWMC 1984, 1985, 1987, 1989, NGWA/IGWMC 1992) Table 6-7 lists other conferences and symposia addressing ground water modeling

EPA's Center for Subsurface Modeling Support (CSMoS) provides ground water and vadose zone modeling software and services to public agencies and private companies throughout the United States Its primary aim is to provide direct technical support to EPA and state decision makers and to coordinate the use of models for risk assessment, site characterization, remedial activities, wellhead protection, and geographic information systems (GIS) applications The Center's address is

Center for Subsurface Modeling Support
U S EPA
R S Kerr Environmental Research Laboratory
PO Box 1198
Ada, OK, 74820
(405) 332-8800

## 6.6 References*

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Adrion, W R , M A Branstad, and J C Cherniasky 1981 Validation, Verification and Testing of Computer Software NBS Special Publication 500-75 Institute for Computer Science and Technology, National Bureau of Standards, Washington DC

Ahlfield, D P and Z Hyder 1990 The Impact of Parameter Uncertainty on Delineation of Aquifer Protection Areas Variability in Hydraulic Conductivity Ground Water Management 3 23-30 (Proc Focus Conf on Eastern Regional Ground-Water Issues) [Farmington River Basin, CT, Monte Carlo method, unspecified numerical model]

Ahlfield, D P and C S Sawyer 1990 Well Location in Capture Zone Design Using Simulation and Optimization Techniques Ground Water 28(4) 507-512

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Appel, C A and J D Bredehoeft 1976 Status of Groundwater Modeling in the U S Geological Survey U S Geological Survey Circular 737 [Summarizes status of development and selected references on 42 ground water modeling projects supported by the U S Geological Survey]

Appel, C.A and T E Reilly 1988 Selected Reports that Include Computer Programs Produced by the U S Geological Survey for Simulation of Ground-Water Flow and Quality Water Resources Investigations Report 87-4271 [Provides summary information on about 40 models, March 6, 1991 update includes information on 16 more references]

Aral, M M 1990a Ground Water Modeling in Multilayered Aquifers Steady Flow Lewis Publishers, Chelsea, MI, 114 pp [Includes disks for SLAM—steady layered aquifer model]

Aral, M M 1990b Ground Water Modeling in Multilayered Aquifers Unsteady Flow Lewis Publishers, Chelsea, MI, 143 pp [Includes disks for ULAM—unsteady layered aquifer model]

Arnold, F 1992 A Performance Comparison of Different Analytical and Numerical Saturated Zone Contaminant Transport Models Ground Water Management 9 21-29 (Proc 5th Int Conf on Solving Ground Water Problems with Models)

Bachmat, Y, B Andrews, D Holtz, and S Sebastian 1978 Utilization of Numerical Groundwater Models for Water Resource Management. EPA 600/ 8-78/012 (NTIS PB285 782) [Appendix summarizes information on 250 models]

Bachmat et al (1980)—see van der Heijde et al (1985)

Bair, E S and G S Roadcap 1992 Comparison of Flow Models Used to Delineate Capture Zones of Wells 1 Leaky-Confined Fractured-Carbonate Aquifer Ground Water 30(2) 199-211 [CAPZONE/GWPATH, DREAM/RESSQC, MODFLOW/MODPATH, Ohio]

Bair, E S , C M Safreed, and B W Berdainier 1991a CAPZONE—An Analytical Flow Model for Simulation Confined, Leaky Confined, or Unconfined Flow to Wells with Superposition of Regional Water Levels, User's Manual Prepared for OHIO EPA by Dept of Geological Sciences, Ohio State University, Columbus, OH [Modification of THWELLS (van der Heijde, 1987a)]

Bair, E S , C M Safreed, and E A Stasny 1991b A Monte Carlo-Based Approach for Determining Traveltime-Related Capture Zones of Wells Using Convex Hulls as Confidence Regions Ground Water 29(6) 849-861 [CAPZONE/GWPATH, Sandstone aquifer, Ohio]

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Bear, J. and A Verruijt 1987 Modeling Groundwater Flow and Pollution. Reidel Publishing Co , Dordrecht, The Netherlands, 414 pp

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Bedient, P B et al 1989 Bioplume II Users Manual National Center for Ground Water Research, Rice University, Houston, TX

Beljin, M S 1988 Testing and Validation of Models for Simulating Solute Transport in Groundwater Code Intercomparison and Evaluation of Validation Methodology GWMI 88-11 International Ground Water Modeling Center, Butler University, Indianapolis, IN ** [$10 00]

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Bhatt, K 1993 Uncertainty in Wellhead Protection Area Delineation Due to Uncertainty in Aquifer Parameter Values J Hydrology 149 1-8 [WHPA/RESSQC model]

Blandford, T N and P S Huyakorn 1991 WHPA Modular Semi-Analytical Model for the Delineation of Wellhead Protection Areas, Version 2 0 Office of Ground Water Protection, Available from IGWMC Version 1 0 was released in 1990 [Four modules MWCAP, RESSQC, GPTRAC, MONTEC, available from IGWMC, most current disk version is 2 1]

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** The International Ground Water Modeling Center is now located in Golden, Colorado Prices subject to change

# Chapter 7
# Developing a Wellhead Protection Program

Delineation of a wellhead or aquifer protection area, covered in Part I of this handbook, is only one step in the multi-faceted process of developing a wellhead protection program Part II of this handbook focuses on implementation of wellhead protection areas (WHPAs) at a local or regional level This chapter provides an overview of the key steps in implementing a wellhead protection program, and the remaining chapters address the major steps in addition to WHPA delineation that involve technical issues contaminant identification and risk assessment (Chapter 8) and management of WHPAs (Chapter 9) Chapter 10 provides some case studies that illustrate how implementation may be affected by the natural hydrogeologic setting and social and political conditions in an area

## 7.1 Overview of the Process

EPA's seminar publication *Wellhead Protection A Guide for Small Communities* (U S EPA, 1993) defines five steps to developing a wellhead protection program

1 Form a community planning team

2 Define the land area to be protected

3 Identify and locate potential contaminants

4 Manage the wellhead protection area

5 Plan for the future [1]

Step 1 is the initial step in creating an evolving structure for developing and implementing a wellhead protection program It contains three essential elements

1 WHPA delineation (Section 7 2, and Part I)

2 Contaminant identification and risk assessment (Section 7 3, and Chapter 8)

3 WHPA management (Section 7 4, and Chapter 9)

The *planning* phase of developing a wellhead protection program addresses mainly the first two elements listed above WHPA delineation and contaminant identification/risk assessment The planning phase also includes identifying realistic options for WHPA management based on information concerning the type, location, and risk posed by chemicals in the delineated WHPA The *implementation* phase begins with selection of methods to be used to protect the area, contingency planning, and ongoing management and monitoring for as long as the program exists (Section 7 5)

Wellhead and ground water protection typically requires a cooperative effort at all governmental levels—local, state, and federal—and between units of local government Initiation at the local level will make the process more responsive to local needs Local initiation allows retention of local autonomy where autonomy is important, and negotiation of cooperative arrangements with other small communities or governmental units when the greater resources of a multi-jurisdictional approach are required

The actual structures used for planning and implementation should be compatible with any state-level wellhead protection program, and appropriate for the community or communities served by the wells or aquifers requiring protection The approach may vary somewhat, depending on the size of the community and whether multiple jurisdictions are likely to be affected by a wellhead protection program

### 7.1.1 Establishing a Community Planning Team

For a wellhead protection program to be responsive to local needs, the diverse perspectives and interests of the community must be involved from the very beginning This usually is best accomplished by establishing a planning team or committee with clear responsibility for carrying out the planning phase of a wellhead protection program Such a team serves several important functions (1) ensuring that the concerns of different segments of the community are addressed on an ongoing basis during the planning process, (2) serving as a focal point for public input during the process of evaluating alternative management options for wellhead protection, and (3) providing a core of leadership for educating the wider public and implementing the wellhead protection program

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[1] In this handbook, planning for the future is considered part of the ongoing process of managing the WHPA

The membership of the team should include local government officials who are in a position to set policy and make funding decisions, as well as respected community members who can explain and promote the program within their respective constituencies Types of individuals who might serve on a planning team include

- Representatives of agriculture, business, and labor
- Member of local chapter of environmental/conservation organization
- Mayor.
- City council member
- County board member or supervisor
- Personnel from drinking water/wastewater treatment/landfill facilities
- County sanitarian or health board member
- County emergency management representative
- Representative of home owners' or neighborhood association
- Academic or research person

The type of community served by a drinking water supply system will largely determine the types of government officials that would be involved in such a planning committee The proportions of the population in the planning area that are urban and rural and the activities that contribute to the area's economy will determine the community interests that should be represented on the committee Well-defined community interest groups—such as those representing business, agriculture, and the environment—are best represented by individuals in leadership positions (such as an official of the Chamber of Commerce or area development corporation, member of Soil and Water Conservation District Board, president of local chapter of an environmental organization)

Most members of the planning committee do not need to have special technical expertise By including personnel from drinking water and wastewater treatment facilities, the team will have members with technical expertise in the main areas of concern and also will have a ready resource for answering questions about the current situation with respect to drinking water and wastewater treatment

The planning committee should not do all the work, but rather should delegate, coordinate, and integrate the various activities required This can be accomplished through mechanisms such as work groups, task forces, and ad hoc or special committees established as needed to perform detailed work in the areas of WHPA delineation, contaminant inventory, identification of management options, and implementation of solutions

### *7.1.2 Obtaining Technical Assistance*

Early in the planning process, local expertise in addition to that already represented on the planning committee should be identified by compiling a list of the names, addresses, and phone numbers of individuals in the area who have expertise (or who supervise individuals with expertise) in the areas of soils, geology, environmental protection, drinking water and wastewater management, and hazardous/municipal waste management The list might include the following

- Person(s) responsible for water and wastewater treatment facilities (if not already part of the planning team)
- Person(s) responsible for municipal solid waste landfills
- County sanitarian
- Chief(s) of town and/or volunteer fire department(s)
- Representatives from federal or state service agencies in the area (Soil Conservation Service, Cooperative Extension)
- Representatives from federal or state resource management agency offices in the area (such as the Fish and Wildlife Service, Bureau of Land Management, Forest Service)
- Owners or managers of any major businesses that might employ scientists or engineers
- Presidents or presiding officers of any civic organizations (such as Rotary, Lion's Club) and local affiliates of state or national environmental organizations
- Science faculty (geology, chemistry, biology, etc ) and engineering faculty in any local educational institutions (high school, junior colleges, and 4-year colleges)
- Retired persons, especially those with technical backgrounds

Participation by individuals on this list can be solicited by sending a letter to each one that (1) describes the purposes of the planning committee, (2) asks for an indication of the willingness and availability of each identified individual to participate in the process, and (3) asks them to identify any other individuals with expertise who might be able to provide assistance The letter should make it clear that different levels of participation are possible, such as (1) being available to answer questions by phone, (2) providing technical review of documents, (3) participating on subcommittees or task groups, and (4) preparing written materials

## 7.2 Selection of Methods for Wellhead Protection Delineation

The state wellhead protection coordinator should be contacted to determine if there is any state guidance regarding the methods that can or should be used to delineate WHPAs For example, Table 7-1 presents proposed guidance from the state of Georgia identifying generic wellhead protection areas (1) a fixed radius "control zone" in the immediate vicinity of all wells, (2) a fixed radius "inner management zone" based on whether the aquifer is confined, unconfined, or karst, and (3) an "outer management zone" for which different delineation methods are specified, depending on the hydrogeologic setting Methods used for delineating the outer management zone include (1) graphical determination of radius based on pumping rate in crystalline rock aquifers (Figure 7-1), (2) hydrogeologic mapping in karst aquifers, and (3) 5-year time of travel or volumetric calculations in unconfined or partially confined porous media aquifers

The Idaho wellhead protection program, on the other hand, identifies four major zones within a wellhead protection area, with a fixed radius used to Zone IA (Table 7-2). Zones IB and Zone II are delineated based on time of travel using hydrogeologic mapping, semianalytical, analytical, or numerical modeling based on site-specific data Finally, Zone III includes known recharge areas and flow boundaries based on hydrogeologic mapping

**Table 7-1 Generic Wellhead Protection Areas Proposed for Georgia (Georgia Department of Natural Resources, 1992)**

| | |
|---|---|
| **CONTROL ZONE** | |
| *All Wells* | |
| Impervious surface (pavement) | 15 feet |
| Pervious surface (soil) | 25 feet |
| **INNER MANAGEMENT ZONE** | |
| *All Wells* | |
| Confined aquifer wells | 100 feet |
| Unconfined aquifer wells | 250 feet |
| Karst aquifer wells | 500 feet |
| **OUTER MANAGEMENT ZONE** | |
| *Piedmont and Blue Ridge (Crystalline Rocks)* | |
| Pumping rate | Radius of outer management zone determined by "Heath method" |
| *Karstic Valley and Ridge and Coastal Plain (Unconfined Aquifer)* | |
| Hydrogeologic mapping (by EPD) | |
| *Coastal Plain (Unconfined or Partially Confined Porous Media)* | |
| 5-year time of travel or volumetric calculations (by EPD) | |
| *Coastal Plain (Completely Confined Aquifer)* | |
| None | |

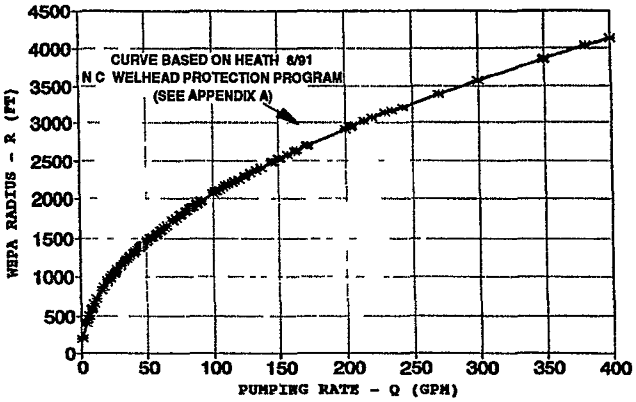

**Figure 7-1** **Radius of outer management zone based on pumping rate for crystalline rock aquifers, Piedmont and Blue Ridge (Georgia Department of Natural Resources, 1992)**

**Table 7-2 Zones for Wellhead Protection Areas in Idaho (Idaho Wellhead Protection Work Group, 1992)**

| Zone | Criteria and Thresholds | Methods |
|---|---|---|
| Zone IA | Minimum distance of 50 feet for wells<br>Minimum distance of 100 feet for springs | Fixed radius |
| Zone IB | Two-year time of travel | Hydrogeologic mapping, semianalytical, analytical, or numerical modeling using site specific data |
| Zone II | Five-year time of travel | Hydrogeologic mapping, semianalytical, analytical, or numerical modeling using site-specific data |
| Zone III | Known recharge areas and flow boundaries | Hydrogeologic mapping |

Table 4-1 (Chapter 4) summarizes the relative advantages and disadvantages of the major methods for delineating WHPAs Figure 7-2 provides a flow chart for delineating a WHPA This figure identifies the appropriate sections, tables, checklists, and worksheets in Part I of this handbook for obtaining the required information at each stage in the flow chart Figure 7-2 shows that some form of hydrogeologic mapping is required for any WHPA delineation effort At a minimum, this would involve collecting and compiling existing data and maps of the area (Worksheet 5-1) Collection of additional data, as needed, is an ongoing process at each step in the process State wellhead protection programs may specify or provide guidance in selecting criteria (i e , time of travel isochrons, drawdown limits) for delineating WHPAs using simple analytical methods or computer models

Use of multiple approaches to delineating a WHPA (i e , moving as far through the flow chart in Figure 7-2 as

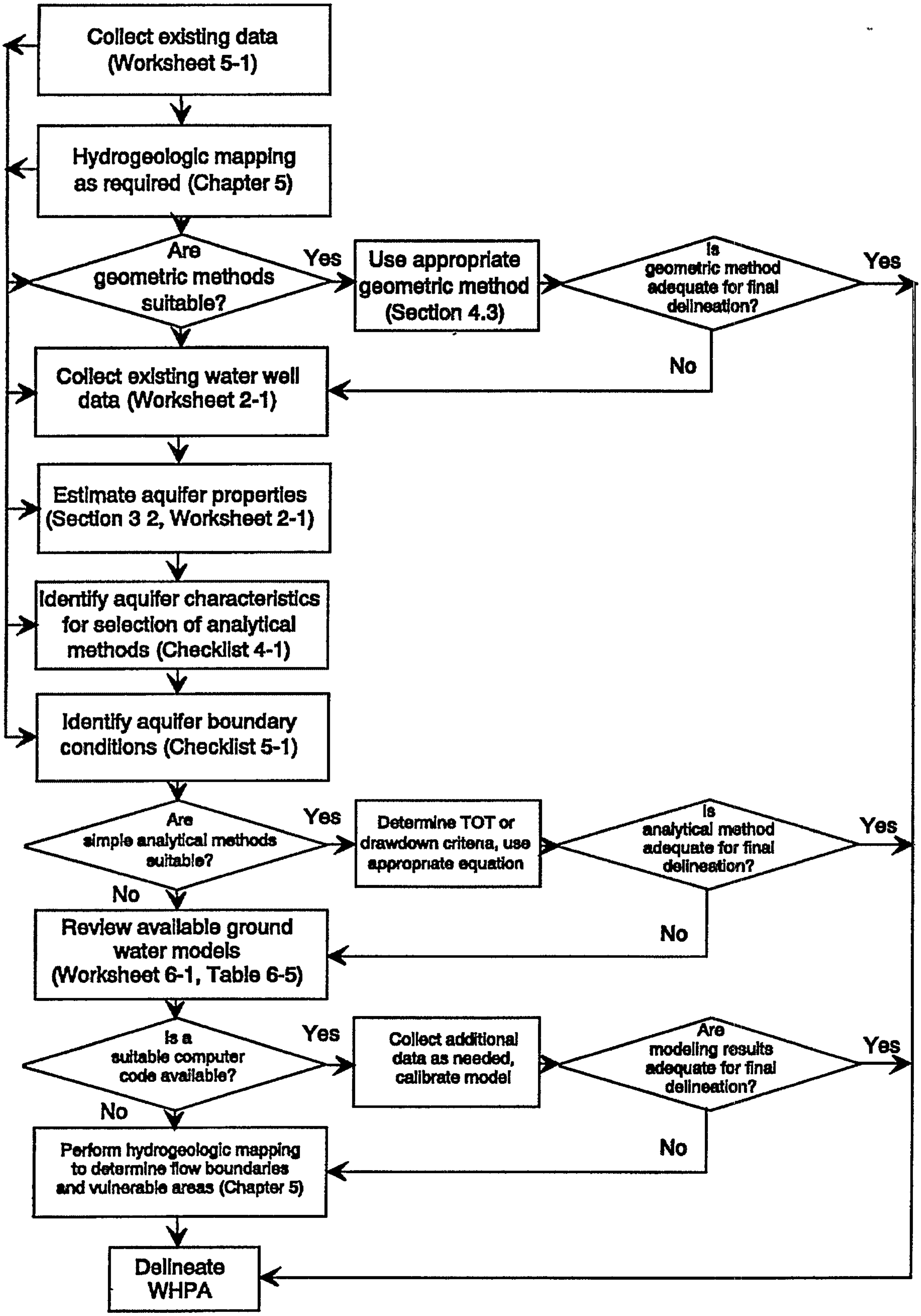

Figure 7-2. Flow chart for selection of wellhead protection area delineation methods

time and financial resources allow) increases the likelihood that the area delineated excludes areas that do not actually contribute ground water to the well Two situations that might require using more sophisticated delineation methods, such as computer modeling, include (1) the presence of a large number of potential sources of contamination, (2) the presence of strong opposition to regulatory controls for wellhead protection In the first situation, the use of more sophisticated methods may avoid unnecessary effort devoted to inventorying potential contaminant sources outside the zone of contribution In the second case, opposition may be partly defused by excluding areas from regulatory controls that might otherwise have been included More sophisticated methods are also easier to defend against legal challenge

Several authors have stressed the uncertainty in the outcomes of the various computational approaches to WHPA delineation (Varljen and Shafer, 1991, Bair et al , 1991, Linderfelt et al , 1989, McLane, 1990, and Tiedeman and Gorelick, 1993) They believe that due to the sometimes serious land use decisions to be made based on wellhead protection, the uncertainty in the boundaries of the WHPAs should be directly incorporated into establishment of the ground water protection policies

## 7.3 Contaminant Identification and Risk Assessment

Once a WHPA has been delineated, the next stage involves two distinct but interrelated activities (1) an inventory of the type, location, and amount of all sources within the WHPA that could potentially contaminate the well or well field, and (2) an assessment of the risk that contamination will actually occur Section 8 2 (Contaminant Identification Process for Wellhead Protection) and Section 8 3 (Inventory of Potential Sources of Contamination) provide detailed checklists for identifying the wide range of potential contaminant sources and tables that provide information on the characteristics of specific sources

The source inventory process can be carried out by volunteers who have received a modest amount of training Pilot projects sponsored by EPA and the American Association of Retired Persons (AARP) in 1990 in El Paso, Texas, and Elkhart, Indiana, trained retired volunteers to survey potential sources of ground water contamination in the vicinity of public water supply wells The success of these efforts has led to EPA/AARP Local Drinking Water Partnership projects in at least 14 states

The risk assessment process can range from something as simple as classifying sources within a WHPA as "high," "medium," or "low" risk to using computer modeling of contaminant transport to calculate potential exposure to specific contaminants Section 8 4 describes the various approaches that can be taken in assessing the risk posed by potential contaminant sources within a WHPA

## 7.4 Selection of Wellhead Protection Management Methods

The contaminant inventory and risk assessment provide the starting point for identifying options for managing a WHPA Full implementation of a wellhead protection management program begins with the selection of specific methods for protecting ground water in a WHPA Typical elements of a management program include

1 Public education to increase awareness of the need for protection of ground water supplies, and to encourage voluntary modifications of behavior and activities that may threaten ground water quality

2 Use of nonregulatory methods for increasing the area of a WHPA devoted to land uses that protect rather than degrade ground water quality

3 Where nonregulatory approaches are not adequate, regulation of land use and other human activities that could pose a significant threat to ground water quality

4 Contingency planning to provide for alternative water supplies in the event of unforseen or accidental contamination of a wellhead protection area

5 Monitoring of the effectiveness of the wellhead protection program and making appropriate modifications if objectives are not being met

High-risk sources, such as onsite septic-tank soil absorption systems, will generally require application of the most stringent regulatory controls, whereas low-risk sources can usually be addressed by nonregulatory approaches such as public education, training, and demonstration programs Sources that pose an intermediate risk can generally be controlled by a combination of regulatory and nonregulatory approaches Chapter 9 addresses regulatory and nonregulatory approaches to wellhead protection area management in more detail

## 7.5 Special Implementation Issues

Implementing a wellhead protection program presents special challenges for drinking water systems that serve small communities, which are faced with the task of addressing the requirements of multiple environmental programs with limited technical and financial resources (Section 7 5 1) Another common difficulty in managing a WHPA to protect ground water supplies occurs when the boundaries of a WHPA lie outside the jurisdiction of the governmental unit that serves the population that obtains its drinking water from a wellhead area (Section

7.5 2) Management of WHPAs in settings that are highly vulnerable to contamination also presents special challenges (Section 7 5 3)

### 7.5.1 *Small Community Drinking Water Systems*

About 90 percent of all drinking water systems serve a population less than 3,300 and 63 percent are "very small" systems serving populations less than 500 This population may be concentrated in a relatively small area under the jurisdiction of a town government, or may be scattered over an area as large as a county Half of all local governments, which typically have primary responsibility for implementing a wellhead protection program, serve populations of less than 1,000 About 75 percent of local governments have populations of less than 3,000, and 80 percent have populations of less than 5,000

A general characteristic of local governments that serve small communities is that they have few, if any, full-time paid employees and consequently limited resources for addressing environmental planning without outside volunteer or government assistance EPA's seminar publication *Wellhead Protection A Guide for Small Communities*, developed in cooperation with the National Rural Water Association (NRWA), is a useful starting point. NRWA has ground water technicians who are trained to assist small communities in developing wellhead protection management programs in fourteen states. Arkansas, Georgia, Idaho, Iowa, Kentucky, Louisiana, Michigan, Massachusetts, New Hampshire, Pennsylvania, Utah, Vermont, West Virginia, and Wisconsin The procedure suggested in Section 7 1 2 for identifying local resources with technical expertise would be especially useful for small communities

### 7.5.2 *Multiple Jurisdictions*

As noted above, local governments generally have primary responsibility for management of WHPAs Complications arise when a WHPA for one community extends into the jurisdiction of one or more governmental units This can occur when a WHPA for a town or city extends into a rural area administered by a separate county government. WHPAs also can cross county, state, and even national boundaries Land ownership patterns within a WHPA may also require coordination with multiple jurisdictions. For example, in the western United States, federally owned or state-owned land commonly will be located within a WHPA Jurisdictional questions may become especially complex for WHPAs where surface and subsurface ownership differ (common in the western United States), and for WHPAs that include Indian and non-Indian lands

The biggest problem that multiple jurisdictions pose for wellhead protection area management is that the local government serving the people most directly concerned with protection ground water quality is typically limited in its ability to impose regulatory controls outside of its jurisdiction This difficulty becomes most acute when the vulnerable and high-risk areas of a WHPA lie in another jurisdiction that has little direct incentive to impose regulatory controls to protect someone else's ground water supply

As soon as it becomes evident that a wellhead protection area will include more than one governmental jurisdiction, each jurisdiction should be asked to participate in the planning and implementation process Any jurisdictions choosing not to participate should be kept fully informed, and the door left open for more active participation In the absence of legal authority to impose controls in portions of a WHPA located outside the jurisdiction of the governmental unit with the highest stake in protecting ground water, the power of persuasion becomes the primary tool If the failure of another governmental unit to act seriously threatens the integrity of ground water quality in a WHPA, and all efforts at persuasion are unsuccessful, state and federal environmental agencies may have sources of leverage for convincing a recalcitrant governmental unit to take management actions within a WHPA

If all efforts at enlisting cooperation fail, a wellhead protection program must proceed within the constraints imposed by the noncooperating jurisdiction In this situation, the contingency plan for an alternative water source in the event of contamination assumes special importance The wellhead protection planning committee, which normally might consider its job completed once the implementation phase begins, might be given the additional task of developing a long-term plan that would phase out water supply wells where effective management of the entire WHPA is not possible, and replacing them with wells where jurisdictional issues do not serve as a major constraint on WHPA management

### 7.5.3 *Systems in Highly Vulnerable Areas*

Aquifers that are most vulnerable to ground water contamination include (1) near-surface alluvial aquifers, (2) unconfined fractured rock aquifers, and (3) karst terrains where flow is concentrated in conduits created by dissolution of limestone WHPAs in these areas tend to be larger than those for other hydrogeologic settings, because high hydraulic conductivity allows contaminants entering ground water to move long distances in a short period of time [2] This creates a double challenge More aggressive management is usually required to prevent contamination, and management practices have to be applied over a relatively large area A large WHPA also

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[2] WHPAs for confined aquifers based on the cone of depression also tend to be large, but the presence of the confining bed means that they are not highly vulnerable to contamination

increases the likelihood that multiple jurisdictions will be located within the WHPA (Section 7 5 2)

In vulnerable areas, accurate mapping of aquifer boundaries (Section 5 4 1) and characterization of fracture and conduit flow (Section 5 4 2) are especially important for defining the wellhead protection area Section 5 6 discusses special approaches to mapping karst areas An accurate inventory of the type and location of high-risk contaminant sources also takes on added importance The case studies in Sections 10 2 1 and 10 2 4 illustrate WHPA management in karst aquifers

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# Chapter 8
# Contaminant Identification and Risk Assessment

Delineation of a wellhead protection area (WHPA) is only the first step in protecting a ground water supply The next step requires the identification of potential contaminant sources within the WHPA and the evaluation of the risk posed by any identified sources This information, in turn, provides the basis for developing and implementing a wellhead area management plan (Chapter 9)

The chapter provides a national and regional perspective on the extent, character, and sources of ground water contamination (Section 8 1) Section 8 2 provides an overview of the contaminant identification process for wellhead protection Section 8 3 provides detailed checklists for identifying potential sources and information on major types of contaminants associated with specific sources Finally, Section 8 4 provides an overview of the process for assessing the relative risks posed by potential contaminant sources located within a WHPA

## 8.1 Overview of Ground Water Contamination in the United States

### *8.1.1 Extent of Contamination*

A small percentage of all ground water in the United States is estimated to be contaminated Lehr (1982), using simple assumptions of total ground water and the extent of ground water contamination, estimated that 0 2 percent of the ground water was contaminated The Office of Technology Assessment (OTA, 1984) cited a range of 1 to 2 percent, and concluded that the extent of contamination is likely to be greater because substances known to contaminate ground water are used throughout society, while efforts to detect contamination have focused primarily on public drinking water supplies and point sources of contamination, such as landfills and hazardous waste sites Furthermore, even if only a small percentage of potentially available ground water is contaminated, this percentage may be significant, because (1) contamination is often near heavily populated areas, and (2) ground water demand has increased for a variety of uses

### *8.1.2 Types of Contaminants*

EPA estimates that 52 percent of the community water wells and 57 percent of the domestic water wells in the United States contain nitrate (U S EPA, 1990c) Nitrate in ground water has few natural sources, at levels of greater than 10 mg/L (as nitrogen), it can be an acute health problem Fertilizer application, inadequate design and maintenance of septic systems, unlined wastewater holding ponds, leaking sewer lines, and improper sludge and manure application are major sources of ground water contamination by nitrates

At least 63,000 synthetic organic chemicals are in common industrial and commercial use in the United States This number continues to grow by approximately 500 to 1,000 new compounds every year (U S EPA, 1979) More than 200 chemical substances have been found in ground water, many of which could have potentially adverse impacts on human health (OTA, 1984) This number includes approximately 175 organic chemicals, over 50 inorganic chemicals (metals, nonmetals, and inorganic acids) and radionuclides Pettyjohn and Hounslow (1983) provide a good introductory review of the origin and significance of organic compounds in ground water pollution

Organic chemicals have become a pervasive contaminant in ground water supplies Page (1981) measured the concentrations of 56 toxic substances (9 heavy metals and 47 organic compounds) in more than 1,000 ground water samples and over 600 surface water samples selected to be representative of the entire state of New Jersey Each compound tested was detectable in one or more samples Five organic compounds were found in more than 50 percent of the ground water samples (1,1,1-trichloroethane—78 percent, chloroform and carbon tetrachloride—64 percent, 1,1,2-trichloroethylene—58 percent, and trans-dichloroethylene—50 percent) An additional 20 organic compounds were detected in 10 to 50 percent of the samples Page (1981) determined the maximum concentrations of most of the substances tested in ground water samples, and the statistical analysis indicated that overall ground water was as polluted as surface water in New Jersey

The Ground Water Supply Survey (GWSS) conducted by U S EPA provided information on the frequency with which volatile organic compounds (VOCs) were detected in 466 randomly selected public ground water supply systems (Westrick et al , 1984) The survey detected one or more VOCs in 16 8 percent of the small systems and 28 0 percent of the large systems sampled Two or more VOCs were found in 6 8 percent and 13 4 percent of the samples from small and large systems, respectively The two VOCs found most often were trichloroethylene (TCE) and tetrachloroethylene (PCE)

Palmer et al (1988) reviewed data on Superfund sites based on the primary hazardous substances detected (see Figure 8-1) Sites contaminated by organics made up the largest group, including 136 sites, 78 sites were contaminated by heavy metals Individual organic compounds frequently singled out as major contaminants include TCE, polychlorinated biphenyls (PCBs), toluene, and phenol Arsenic and chromium are the most frequently identified individual heavy metal contaminants

A reliable determination of the extent and severity of ground water degradation and associated health risks in the United States is probably not feasible because (1) tens of thousands of sites where a potential for contamination exists are not being monitored, and (2) comprehensive analyses of water quality at hundreds of thousands of wells would be required (Miller, 1985) The development of wellhead protection programs, however, provides a mechanism for focusing efforts to identify contaminants and assess risks in the areas of greatest need

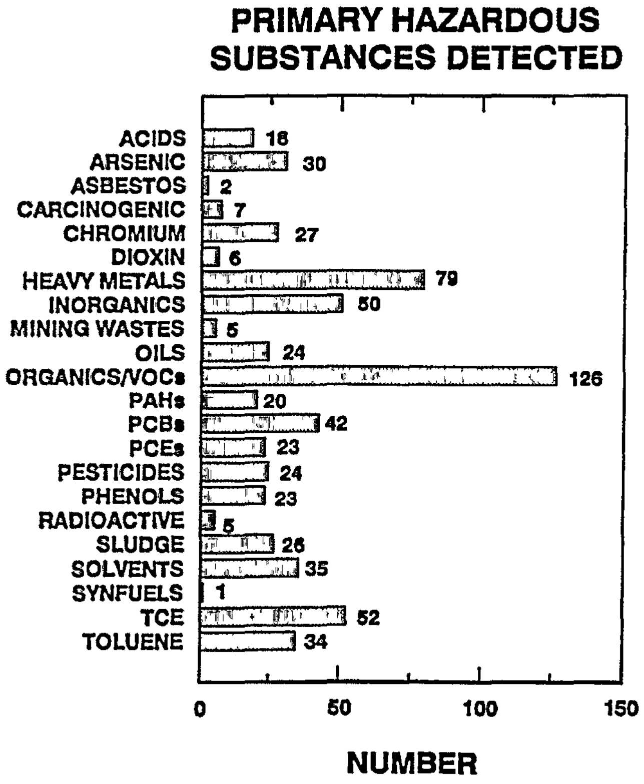

**Figure 8-1.** Major contaminants at Superfund sites (from Palmer et al , 1988)

### 8.1.3 Sources of Ground Water Contamination

Sources of ground water contamination can be categorized in a number of ways This section provides a general overview, using an analysis by the Office of Technology Assessment's grouping 33 types of ground water contamination sources into six major categories (Table 8-1) based on the general nature of the contaminating activity (OTA, 1984) Figure 8-2 depicts a number of these sources Section 8 3 provides a detailed identification of point and non-point sources of potential contamination

Category I includes sources that are intentionally designed to discharge substances Examples of these include subsurface percolation systems, such as septic tanks and cesspools, injection wells, and land application of wastewater or sludges Such systems are designed primarily to use the natural capacity of the soil materials to degrade wastewaters Septic tanks and cesspools have been estimated to discharge the largest volume of wastewater into the ground and are the most frequently reported sources of ground water contamination (U S EPA, 1977) More than 23 million homes in the United States rely on onsite wastewater disposal systems, the use of septic system cleaners that remove grease and kill roots may result in ground water contamination by halogenated hydrocarbons and heavy metals, respectively (Noss, 1989)

Injection wells are another potential source of contamination Injected wastewaters are often placed in unusable zones to be assimilated with poor quality ground water of natural origin Current regulations prohibit injection of wastes into an underground source of drinking water (USDW) or contamination of a USDW by deep-well injection Injection of hazardous wastes is regulated under EPA's Underground Injection Control Program

Land application, a popular and inexpensive method of disposing of wastewater and sludge, can pollute ground water in several ways (1) organic and inorganic contaminants in directly applied wastewater can move directly into ground water if the soil's filtration capacity is exceeded, and (2) precipitation infiltrating through land-applied sludges may leach contaminants in the ground water system EPA (1983) estimated that 40 to 50 percent of the municipal sludge generated every year is applied to the land

**Table 8-1 Sources of Ground Water Contamination**

**Category I—Sources Designed to Discharge Substances**

- Subsurface percolation (e g , septic tanks and cesspools)
- Injection wells
  - Hazardous waste
  - Nonhazardous waste (e g , brine disposal and drainage)
  - Nonwaste (e g , enhanced recovery, artificial recharge, solution mining, and in situ mining)
- Land application
  - Wastewater (e g , spray irrigation)
  - Wastewater by-products (e g , sludge)
  - Hazardous waste
  - Nonhazardous waste

**Category II—Sources Designed to Store, Treat, and/or Dispose of Substances, Discharge through Unplanned Release**

- Landfills
  - Industrial hazardous waste
  - Industrial nonhazardous waste
  - Municipal sanitary
- Open dumps, including illegal dumping (waste)
- Residential (or local) disposal (waste)
- Surface impoundments
  - Hazardous waste
  - Nonhazardous waste
- Waste tailings
- Waste piles
  - Hazardous waste
  - Nonhazardous waste
- Materials stockpiles (nonwaste)
- Graveyards
- Animal burial
- Aboveground storage tanks
  - Hazardous waste
  - Nonhazardous waste
  - Nonwaste
- Underground storage tanks
  - Hazardous waste
  - Nonhazardous waste
  - Nonwaste
- Containers
  - Hazardous waste
  - Nonhazardous waste
  - Nonwaste
- Open burning and detonation sites
- Radioactive disposal sites

**Category III—Sources Designed to Retain Substances during Transport or Transmission**

- Pipelines
  - Hazardous waste
  - Nonhazardous waste
  - Nonwaste
- Materials transport and transfer operations
  - Hazardous waste
  - Nonhazardous waste
  - Nonwaste

**Category IV—Sources Discharging Substances as Consequence of Other Planned Activities**

- Irrigation practices (e g , return flow)
- Pesticide applications
- Fertilizer applications
- Animal feeding operations
- De-icing salts applications
- Urban runoff
- Percolation of atmospheric pollutants
- Mining and mine drainage
  - Surface mine-related
  - Underground mine-related

**Category V—Sources Providing Conduit or Inducing Discharge through Altered Flow Patterns**

- Production wells
  - Oil (and gas) wells
  - Geothermal and heat recovery wells
  - Water supply wells
- Other wells (nonwaste)
  - Monitoring wells
  - Exploration wells
- Construction excavation

**Category VI—Naturally Occurring Sources Whose Discharge Is Created and/or Exacerbated by Human Activity**

- Ground water-surface water interactions
- Natural leaching
- Saltwater intrusion/brackish water upcoming (or intrusion and other poor quality natural water)

Source OTA (1984)

Category II includes sources designed to store, treat, or dispose of substances but not to release contaminants to the subsurface Examples include landfills, open dumps, local residential disposal, surface impoundments, waste tailings and piles, materials stockpiles, graveyards, aboveground and underground storage tanks, containers, open burning sites, and radioactive disposal sites It is important to note that while a number of sources in this category are considered "waste" sources (e g , landfills, dumps, impoundments, etc ), many others are "nonwaste" sources Storage tanks, stockpiles, and a variety of containers with residues of commercial products have been found to contribute contaminants to ground water

Category III consists of sources designed to retain substances during transport or transmission Such sources consist primarily of pipelines and materials transport or transfer operations Contaminant releases generally occur by accident or neglect—for example, as a result of pipeline breakage or a traffic accident Again, most substances subject to release from sources within this category are not wastes but raw materials or products to be used for some beneficial purpose

Category IV includes those sources discharging substances as a consequence of other planned activities This category contains a number of agriculturally related sources such as irrigation return flows, feedlot operations, and pesticide and fertilizer applications A number

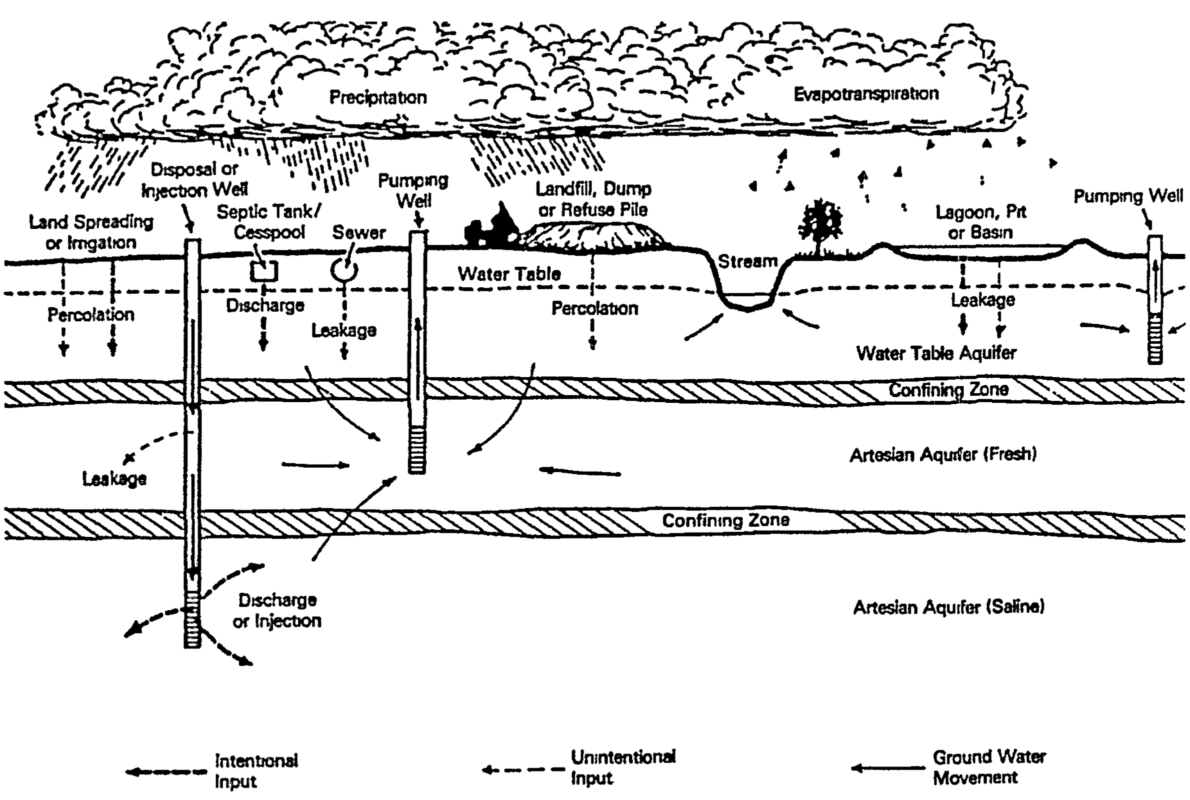

**Figure 8-2 Sources of ground water contamination (from Geraghty and Miller, 1985)**

of sources related to urban activities, such as highway desalting, urban runoff, and atmospheric deposition, are included Surface and underground mine-related drainage also fall within this category

Category V comprises sources providing conduits or inducing discharge through altered flow patterns Such sources include water, oil, and gas production wells, monitoring wells, exploration holes, and construction excavations Ground water contamination from production wells stems from poor installation and operation methods and incorrect plugging or abandonment procedures Such practices create opportunities for cross-contamination by vertical migration of contaminants

Finally, Category VI includes naturally occurring sources whose discharge is induced or intensified by human activity Ground water/surface water interactions, described in the previous section, and saltwater intrusion or upcoming (ground water movement upward as a result of pumpage) provide the basis for this category Withdrawals that are significantly more than recharge can affect ground-water quality Saltwater intrusion in coastal areas and brine-water upconing from deeper formations in inland areas both can occur when pumpage exceeds an aquifer's natural recharge rate

Contaminants can be released from both point or nonpoint sources *Point sources* are those that release contaminants from a discrete geographic location, including leaking underground storage tanks, septic systems, and injection wells *Nonpoint* sources of contamination are more extensive in area and diffuse in nature It is therefore difficult to trace contaminants from nonpoint sources back to their origin Agricultural activities (i e , application of pesticides and fertilizers), urban runoff, and atmospheric deposition are potential nonpoint contaminant sources

In the 1970s, U S EPA conducted a series of regional ground water contamination assessments (Table 8-6 identifies the individual reports) The four most commonly reported pollutants were (1) chlorides, (2) nitrates, (3) hydrocarbons, and (4) heavy metals Table 8-2 identifies the major sources for these four contaminants Table 8-3 provides an overview of the relative importance of principal sources of ground water contamination by region Septic tanks and cesspools received the highest ranking as a contamination source in all four regions

## 8.2 Contaminant Identification Process for Wellhead Protection

The WHPA delineated using one or more methods described in the preceding chapters provides the focus for efforts to identify potential sources of contamination

**Table 8-2 Source of Contamination for Four Commonly Reported Pollutants (Miller and Scalf, 1974)**

| Source | Chlorides | Nitrates | Hydrocarbons | Heavy Metals |
|---|---|---|---|---|
| Septic Tanks and Cesspools | x | x | | |
| Petroleum Exploration and Development | x | | x | |
| Landfills | x | | | x |
| Irrigation Return Flows | x | x | | |
| Surface Dischargers | x | x | x | x |
| Surface Impoundments | x | x | x | x |
| Spills | x | | x | x |
| Buried Pipelines and Storage Tanks | | x | x | x |
| Mining Activities | | | | x |
| Salt-Water Intrusion | x | | | |
| Water Wells | x | x | | |
| Agricultural Activities | | x | | x |
| Disposal Wells | x | x | | x |
| Highway Deicing Salts | x | | | |
| Artificial Recharge | x | x | | |
| River Infiltration | x | | | x |
| Spray Irrigation by Waste Water | x | x | | |

**Table 8-3 Principal Sources of Ground-Water Contamination and Their Relative Regional Importance (Miller and Scalf, 1974)**

| Source | Northeast | Northwest | South Central | Southwest |
|---|---|---|---|---|
| Septic Tanks and Cesspools | I | I | I | I |
| Petroleum Exploration and Development | II | II | I | I |
| Landfills | I | II | II | II |
| Irrigation Return Flows | IV | I | I | I |
| Surface Dischargers | II | I | III | I |
| Surface Impoundments | I | I | II | III |
| Spills | I | II | II | II |
| Buried Pipelines and Storage Tanks | I | II | II | III |
| Mining Activities | II | I | III | II |
| Salt-Water Intrusion | | | | |
| Coastal Areas | III | III | II | I |
| Inland Areas | I | II | II | II |
| Water Wells | II | III | I | III |
| Agricultural Activities | | | | |
| Fertilizers | III | II | III | II |
| Feedlot and Barnyard Wastes | III | III | II | III |
| Pesticides | III | III | III | III |
| Disposal Wells | | | | |
| Deep Wells | IV | III | III | III |
| Shallow Wells | II | I | III | III |
| Highway Deicing Salts | I | III | IV | IV |
| Artificial Recharge | III | IV | III | II |
| River Infiltration | II | II | IV | IV |
| Spray Irrigation by Waste Water | III | IV | III | III |

I — High, II — Moderate, III — Low, IV — Not significant

The inventory should be comprehensive and should include.

- Potential points sources (underground storage tanks, wells, small commercial and industrial facilities, etc )
- Potential line sources (sewer lines, gas/petroleum pipelines, highways with traffic that may haul hazardous chemicals, etc )
- Potential area sources (waste disposal areas, agricultural lands receiving fertilizer and pesticide treatments, etc )

The inventory should identify the type of source, location, and types of potential contaminants at each source The next section provides detailed checklists for identifying potential sources Identification of *active* potential sources is relatively straightforward Location of *inactive* sources, such as abandoned wells and old waste disposal sites, might require some detective work All existing maps and sources of information on past human activity in the area should be gathered and reviewed Interviews with long-time residents in the area could yield valuable information that cannot be obtained in any other way In areas with a long history of oil and gas exploration and production, or where the exact boundaries of old waste disposal sites are not known, surface geophysical methods and other field investigation techniques might be required to locate and map abandoned features Table 5-4 provides summary information on potential surface geophysical methods Table 8-6 identifies references that provide more detailed information on methods for locating abandoned wells

A convenient way to compile the results of the inventory is to assign each source an identification number and plot the identification number on a map of the WHPA The boundaries of the areal sources should be clearly marked on the map Repetition of the identifying number along a line source provides a means for distinguishing different types of sources This map provides the focus for subsequent protective strategy development and land management activities

Where a large number of commercial and industrial sites with potential contaminants are located within a WHPA, a phased approach may be desirable The first phase would focus on identifying all potential sources, but would not necessarily involve collection of detailed information of all sites This information would then be screened to identify sites where contaminants represent a significant potential risk based on the preliminary inventory. In the second phase, these sites would then be revisited to collect more detailed information The final step in this stage of the wellhead protection process would be to evaluate the degree of threat posed by each source. This is discussed further in Section 8 4

## 8.3 Inventory of Potential Sources of Contamination

Hundreds of nonindustrial, commercial, and industrial activities that produce or use organic and inorganic substances pose a potential threat to ground water quality The number of potential contaminants of concern for a given activity may be restricted to a few or many substances A single comprehensive list of these activities for inventory purposes would be so large as to be unmanageable This guide offers a four-step approach to developing an inventory of potential sources of contamination within a WHPA

1 Checklist 8-1 provides a "short list" of four major categories of potential contamination sources A "yes" or "uncertain" answer to any of the questions within a major category on this checklist means that use of the detailed checklist for that category should be used (see next step)

2 Checklists 8-2 through 8-5 provide comprehensive lists of activities that may result in ground water contamination The first two (cross-cutting sources and non-industrial sources) will probably be required for most WHPAs In rural areas, the use of the remaining checklists may not be required Sections 8 3 1 through 8 3 2 provide additional discussion of these checklists

3 More detailed information should be compiled for each item that is identified within the WHPA The following worksheets in Appendix C may provide assistance in gathering information on specific sources (1) Worksheet C-1 (Residential Source Inventory), (2) Worksheet C-2 (Farm Source Inventory), (3) Worksheet C-3 (Agricultural Chemical Usage Survey), (4) Worksheet C-4 (Transportation Hazard Inventory), (5) Worksheets C-5 and C-6 (Municipal/Commercial/Industrial Source Inventory) Worksheet 2-1 can be used to compile information on active and abandoned wells

4 A separate inventory worksheet should be filled out for each household or business by contacting the resident, owner, or other responsible party The information obtained from interviews can be cross-checked and supplemented using Tables 8-4 and 8-5 This table contains a comprehensive list of the potential sources contained in the checklist (in alphabetical order) It provides the following information (1) common contaminants associated with the activity, and (2) references where more detailed information about the contaminants associated with the activity can be found Files maintained by the Local Emergency Planning Committee (LEPC), established under Title III of SARA (the Emergency Planning and Community Right-to-Know Act—EPCRA), should also be consulted These files identify loca-

# Checklist 8-1
# Potential Contaminant Source Shortlist for Wellhead Protection

## Cross-Cutting Sources (Checklist 8-2)

___ Does the WHPA include natural geologic or hydrogeologic conditions that impair ground-water quality for drinking water? ___ yes ___ no If yes, evaluate the following options, if this has not already been done

- ___ Look for alternative, higher quality water supply
- ___ Evaluate effectiveness of existing drinking water treatment system in treating water quality problems
- ___ If there are problems with the existing system evaluate additional or alternative treatment technologies

___ Are any active/abandoned wells or boreholes located within the WHPA? ___ yes ___ no ___ uncertain? If yes, or uncertain, conduct inventory using Checklist 8-2.

___ Are any above- or underground storage tanks in the WHPA? ___ yes ___ no ___ uncertain? If yes, or uncertain, conduct inventory using Checklist 8-2.

___ Are there any areas of controlled or uncontrolled disposal of wastes in the WHPA? ___ yes ___ no ___ uncertain? If yes, or uncertain, conduct inventory using Checklist 8-2.

## Nonindustrial Sources (Checklist 8-3)

___ Are there any areas within the WHPA used for agricultural, livestock or forest production? ___ yes ___ no ___ uncertain If yes, or uncertain, conduct inventory using the Agricultural section of Checklist 8-3

___ Are there any private homes, apartments or condominiums within the WHPA? ___ yes ___ no ___ uncertain If yes, or uncertain, conduct inventory using the residential section of Checklist 8-3

___ Are there any nonagricultural, nonresidential areas within the WHPA that receive treatment with fertilizers or pesticides? ___ yes ___ no ___ uncertain If yes, or uncertain, conduct inventory using the nonresidential green areas section of Checklist 8-3

___ Are any areas within the WHPA dedicate for municipal and other public service facilities? ___ yes ___ no ___ uncertain If yes, or uncertain, conduct inventory using the municipal/public services section of Checklist 8-3

___ Are any highways, roads, airports, railroads, pipelines, or associated transportation service and support facilities located within the WHPA? ___ yes ___ no ___ uncertain If yes, or uncertain, conduct inventory using the transportation section of Checklist 8-3

## Sources From Commercial, Natural Products Processing/Storage, and Resource Extraction Activities (Checklist 8-4)

___ Are there nonindustrial commercial activities within the WHPA? ___ yes ___ no ___ uncertain If yes, or uncertain, conduct inventory using the commercial section of Checklist 8-4

___ Are there any food, animal, or wood products processing or storage activities located within the WHPA? ___ yes ___ no ___ uncertain If yes, or uncertain, conduct inventory using the natural products section of Checklist 8-4

___ Are there any areas within the WHPA affected by current or past mining, oil and gas production or other resource extraction activities? ___ yes ___ no ___ uncertain If yes, or uncertain, conduct inventory using the resource extraction section of Checklist 8-4.

## Industrial Sources (Checklist 8-5)

___ Are there any chemical processing or manufacturing facilities within the WHPA? ___ yes ___ no ___ uncertain If yes, or uncertain, conduct inventory using the chemical section of Checklist 8-5

___ Are there any metal manufacturing, fabrication, or finishing facilities within the WHPA? ___ yes ___ no ___ uncertain If yes, or uncertain, conduct inventory using the metals section of Checklist 8-5

___ Are there any other manufacturing facilities not included in the two previous categories within the WHPA? ___ yes ___ no ___ uncertain If yes, or uncertain, conduct inventory using the last section of Checklist 8-5

## Checklist 8-2
## Cross-cutting Potential Contaminant Sources
## (Check all categories found within the WHPA)

Wells and Related Features

| Active | Abandoned | |
|---|---|---|
| ___ | ___ | Water supply wells |
| ___ | ___ | Monitoring wells |
| ___ | ___ | Sumps and dry wells for drainage |
| ___ | ___ | Geotechnical boreholes |
| ___ | ___ | Oil and gas production wells |
| ___ | ___ | Mineral, oil and gas exploration boreholes |

For each identified feature obtain the following information, if possible

___ Location
___ Depth
___ Borehole Condition (cased, uncased, sealed, leaky)
___ Depth to ground water
___ Ground water quality

Storage tanks (see Worksheets C-2, C-5, and C-6)

| Above- | Underground | |
|---|---|---|
| ___ | ___ | Agricultural |
| ___ | ___ | Residential |
| ___ | ___ | Nonresidential green areas |
| ___ | ___ | Municipal and other public services |
| ___ | ___ | Commercial |
| ___ | ___ | Industrial |
| ___ | ___ | Resource Extraction |

For each identified tank obtain the following information, if possible

___ Location
___ Size
___ Contents
___ Age and condition

Waste Disposal Sites

Residential/Municipal Wastewater Treatment

___ Septic-tank soil absorption systems
___ Cesspools
___ Storage, treatment, and disposal ponds and lagoons
___ Municipal sewage treatment plant
___ Municipal sewer lines/lift stations
___ Wastewater irrigation/artificial ground-water recharge areas
___ Septage/sewage sludge land spreading areas

## Checklist 8-2
## Cross-cutting Potential Contaminant Sources (Continued)

Controlled Waste Disposal/Handling Sites

___ Municipal solid waste landfill (active)
___ Recycling and waste reduction facility
___ RCRA Hazardous Waste TSD Facility
___ Waste surface impoundments/lagoons
___ Waste injection well
___ Incinerator ___ municipal waste, ___ medical waste, ___hazardous waste
___ Demolition/detonation sites
___ Radioactive waste storage sites
___ Fire training facilities
___ Geothermal discharge

Uncontrolled Waste Disposal Sites

___ Accidental spill sites
___ Inactive/abandoned hazardous waste site (Superfund)
___ Other uncontrolled/clandestine waste disposal sites, open dumps
___ Abandoned mine spoils, mine tailings pile/pond
___ Radioactive (uranium mill tailings, laboratory wastes)

For each identified waste disposal obtain the following information, if possible

___ Location
___ Amount and type of waste
___ Age
___ Inplace or planned measures to control contamination

## Checklist 8-3
## Nonindustrial Potential Contaminant Sources
## (Mark location of each identified feature on the WHPA map)

Residential (Single-family, apartments and condominiums) — see Worksheet C-1

___ Common Household products
___ Wall and Furniture treatments
___ Car maintenance
___ Other mechanical repair and maintenance products
___ Lawns and Gardens (EPA/530/SW-90-027i)
___ Swimming Pools
___ Home-based business (beauty shop, welding, etc.—see appropriate category in Checklist 8-4

Agricultural* (EPA/530/SW-90-027i) — see Worksheet C-2

___ Livestock*

    ___ Animal feedlots, stables, kennels
    ___ Manure spreading areas and storage pits (line/unlined)
    ___ Livestock waste disposal areas
    ___ Animal burial

___ Chemical storage areas and containers*
___ Farm machinery areas
___ Irrigated cropland*
___ Irrigation canals
___ Non-irrigated cropland*
___ Pasture*
___ Orchard/nursery*
___ Rangeland*
___ Forestland*

Other Green Areas* (EPA/530/SW-90-027i)

Building grounds

    ___ Educational/vocational institutions
    ___ Government offices
    ___ Other offices
    ___ Stores
    ___ Processing/manufacturing facilities

___ Camp grounds
___ Cemeteries
___ Country clubs
___ Golf courses
___ Nurseries
___ Parklands
___ Pest-infested areas (specify type of land use)

Municipal and Other Public Services (see also Checklist 7-2, controlled waste disposal sites)

___ Educational/Vocational facilities (EPA/530/SW-90-027i)
___ Public swimming pools
___ Sewer/stormwater drainage overflows
___ Storm water drains and basins
___ Government service offices
___ Military base/depot

## Checklist 8-3
## Nonindustrial Potential Contaminant Sources (Continued)

Municipal and Other Public Services (cont.)

Public Utilities

___ Electric power and steam generation (coal storage areas, coal ash/FGD disposal areas)
___ Natural gas
___ Telephone/communications

Medical/care facilities (EPA/530/SW-90-027m)

___ Doctor/Dentist Offices
___ Hospital
___ Nursing and rest homes
___ Veterinary Services

Transportation — see Worksheet C-4

Airports
___ Active
___ Abandoned air fields

Automobile/Truck (EPA/530/SW-90-027a & 027n)

___ Gasoline Service stations
___ Truck stops (gasoline plus diesel)
___ Dealers without service departments
___ Dealers with service departments
___ Car rental facilities
___ Government vehicle maintenance facilities
___ Taxi cab maintenance facilities
___ School bus maintenance facilities
___ Quick lube shops
___ Repair shops
___ Muffler repair shops
___ Body/paint shops
___ Undercoaters/rust proofing
___ Car washes

Other point/areal sources

___ Boat yards and marinas
___ Road/highway maintenance depots/road salt storage
___ Passenger transit facilities (local and interurban)
___ Railroad yards (EPA/530/SW-90-027k)
___ Trucking terminals (EPA/530/SW-90-027k)

Linear sources

___ Highways and roads*
___ Railroad tracks*
___ Oil and gas pipelines*
___ Other industrial pipelines*
___ Powerline corridors*

* Conduct agricultural chemical usage survey (Worksheet C-3)

# Checklist 8-4

## Potential Contaminant Sources: Commercial, Natural Products Processing/Storage, and Resource Extraction (see Worksheet C-5)

Commercial

___ Agricultural chemicals sales/storage (pesticides, herbicides, fertilizers)
___ Barber and beauty shops/salons (EPA/530/SW-90-027q)
___ Bowling alleys

Cleaning services (EPA/530/SW-90-027b)

___ dry cleaners
___ commercial laundry
___ laundromats
___ carpet and upholstery cleaners

Construction service/materials (EPA/530/SW-90-027j)

___ plumbing
___ heating and air conditioning
___ paper hanging/decorating
___ drywall and plastering
___ carpentry
___ carpet flooring
___ roofing and sheet metal
___ wrecking and demolition
___ hardware/lumber/parts stores

___ Equipment/appliance repair (EPA/530/SW-90-027d)
___ Florists
___ Furniture/wood manufacturing repair and finishing shops (EPA/530/SW-90-027c & 027n)
___ Funeral services and crematories
___ Heating oil companies
___ Jewelry/metal plating shops (EPA/530/SW-90-027n)
___ Leather/leather products (EPA/530/SW-90-027r)
___ Lawn and garden care services (EPA/530/SW-90-027i)
___ Office buildings and office complexes
___ Paint stores (EPA/530/SW-90-027p)
___ Pest extermination services/pesticide application services (EPA/530/SW-90-027i)
___ Pharmacies
___ Photography shops, photo processing laboratories
___ Printers, publishers and allied industries (EPA/530/SW-90-027g & 027p)
___ Laboratories (research/testing) (EPA/530/SW-90-027m)
___ Scrap, salvage, and junk yards
___ Sports and hobby shops
___ Taxidermists
___ Welders (EPA/530/SW-90-027n)

Food/Animal/Timber Products Processing and Storage

___ Canned and preserved fruits and vegetables
___ Canned and preserved seafood processing
___ Soft drink bottlers
___ Grain mills (___ grain storage/processing, ___ animal feed, breakfast cereal, and wheat)
___ Sugar processing (___ beet sugar, ___ cane sugar refining)
___ Dairy products processing (creameries and dairies)
___ Leather products (EPA/530/SW-90-027r)
___ Meat products and rendering (slaughterhouses)
___ Poultry and eggs processing

## Checklist 8-4

## Potential Contaminant Sources: Commercial, Natural Products Processing/Storage, and Resource Extraction (Continued)

Food/Animal/Timber Products Processing and Storage (cont.)

___ Timber products processing

___ Pulp, paper and paperboard (EPA/530/SW-90-027o)

  ___ Builders' paper and board mills
  ___ Unbleached kraft and semichemical pulp
  ___ Pulp, paper and paperboard
  ___ Paper coating and glazing

___ Wood preserving facilities (EPA/530/SW-90-027f)

Resource Extraction

___ Abandoned exploration/production wells
___ Construction materials (sand, gravel)
___ Coal mining (___ active, ___ inactive)
___ Uranium mining (___ active, ___ inactive)
___ Metals mining (___ active, ___ inactive)
___ Phosphate mining (___ active, ___ inactive)
___ Natural gas production
___ Petroleum production/secondary recovery operations
___ Synthetic fuels (coal gasification, oil shale)
___ Waste tailings ___ heap leaching, ___ non-heap leaching

## Checklist 8-5
## Potential Contaminant Sources (See Worksheets C-5 and C-6)

<u>Chemical Processing/Manufacturing</u>

Chemical manufacturers
___ Explosives (EPA/530/SW-90-027h)
___ Inorganic chemical manufacturing (EPA/530/SW-90-027h)
___ Fertilizer manufacturing (___ basic fertilizer chemicals, ___ formulated fertilizer) (EPA/530/SW-90-027p)
___ Organic chemical manufacturing and plastics and synthetic fibers (EPA/530/SW-90-027h)
___ Paint manufacturing (EPA/530/SW-90-027p)
___ Pesticide formulation (EPA/530/SW-90-027h & 027p)
___ Petroleum refining/storage
___ Pharmaceutical manufacturing (EPA/530/SW-90-027p)
___ Phosphate manufacturing (___ phosphorus-derived chemical, ___ other non-fertilizer chemicals
___ Porcelain enameling
___ Rubber processing (___ tire and synthetic, ___ fabricated and reclaimed rubber) (EPA/530/SW-90-027h)
___ Soaps and Detergents (EPA/530/SW-90-027q)

<u>Metals Manufacturing/Fabrication/Finishing</u>

Aluminum Manufacturing and forming
    ___ Aluminum forming
    ___ Bauxite refining
    ___ Primary aluminum smelting
    ___ Secondary aluminum smelting

___ Coil coating
___ Copper forming

Electroplating (EPA/530/SW-90-027n)
    ___ Copper, nickel, chrome and zinc
    ___ Electroplating pretreatment

Metal manufacturing and fabrication (EPA/530/SW-90-027n)
    ___ Ferroalloy (smelt and slag processing)
    ___ Iron and steel manufacturing
    ___ Metal molding and casting (foundries)

___ Metal finishing (EPA/530/SW-90-027n)
___ Machine and metalworking shops (EPA/530/SW-90-027n)
___ Nonferrous metals forming

<u>Other Manufacturing</u>

___ Asbestos manufacturing
___ Asphalt/tar plants
___ Battery manufacturing (EPA/530/SW-90-027n)
___ Cement manufacturing
___ Electric/electronic/communications equipment manufacturers (EPA/530/SW-90-027n)
___ Furniture and fixtures manufacturers (EPA/530/SW-90-027c)

___ Glass manufacturing
    ___ Pressed and blown glass
    ___ Insulation fiberglass
    ___ Flat glass

___ Stone, and clay manufacturers
___ Textile manufacturing (EPA/530/SW-90-027e)

**Table 8-4 Contaminants Associated With Specific Contaminant Sources**

| Source/Checklist No | Contaminants[1,2,3] | Information Sources |
|---|---|---|
| Airports, abandoned airfields (8-3) | Jet fuels, deicers (urea), batteries, diesel fuel, chlorinated solvents, automotive wastes,[7] heating oil, building wastes[13] | BMPs Noake (1988) |
| Aluminum forming (8-5) | | Table 8-5 |
| Asbestos manufacturing (8-5) | Asbestos | Table 8-5 |
| Asphalt plants (8-5) | Petroleum derivatives | BMPs Noake (1988) |
| Automobile/Truck service (8-3) | *Auto repair* Waste oils, solvents, acids, paints, automotive wastes,[7] miscellaneous cutting oils, *Dealers* Automotive wastes,[7] waste oils, solvents, miscellaneous wastes, *Car washes* Soaps, detergents, waxes, miscellaneous chemicals, *Gasoline service stations* Gasoline, oils, solvents, miscellaneous wastes | U S EPA (1991a), BMPs Inglese (1992), NJDEPE (1992), Noake (1988), U S EPA (1991-1993—repair and refinishing) |
| Battery manufacturing (8-5) | | Table 8-5, Dotson (1991) |
| Barber and beauty shops (8-4) | Perm solutions, dyes, miscellaneous chemicals contained in hair rinses | BMPs Inglese (1992) |
| Boat yards and marinas (8-3) | Diesel fuels, batteries, oil, septage from boat waste disposal areas, wood preservative and treatment chemicals, paints, waxes, varnishes, automotive wastes[7] | BMPs Noake (1988), U S EPA (1991-1993) |
| Bowling alleys | Epoxy, urethane-based floor finish | |
| Camp grounds (8-3) | Septage, gasoline, diesel fuel from boats, pesticides for controlling mosquitoes, ants, ticks, gypsy moths, and other pests,[5,9] household hazardous wastes from recreational vehicles (RVs)[8] | |
| Canned and preserved fruits and vegetables (8-4) | | Table 8-5 |
| Canned and preserved seafood processing (8-4) | | Table 8-5 |
| Cement manufacturing (8-5) | | Table 8-5 |
| Cemeteries | Leachate (formaldehyde), lawn and garden maintenance chemicals[10] | BMPs Noake (1988) |
| Chemical process/Manufacturing (8-5) | See entries for individual categories in Checklist 8-5 | BMPs Noake (1988) |
| Chemical storage areas and containers (8-3) | Pesticide[5] and fertilizer[6] residues | U S EPA (1990a) |
| Clandestine dumping areas | Potentially almost anything | BMPs Noake (1988) |
| Cleaning services—dry cleaners, commercial laundry, laundromats (8-4) | *Dry cleaners* Solvents (perchloroethylene, petroleum solvents, Freon), spotting chemicals (trichloroethane, methylchloroform, ammonia, peroxides, hydrochloric acid, rust removers, amyl acetate), *Laundromats* Detergents, bleaches, fabric dyes | U S EPA (1991a), BMPs Inglese (1988—dry cleaning), Noake (1988—dry cleaning, laundromats) |
| Coil coating (8-5) | | Table 8-5 |
| Construction service/materials (8-4) | Solvents, asbestos, paints, glues and other adhesives, waste insulation, lacquers, tars, sealants, epoxy waste, miscellaneous chemical wastes | |
| Copper forming (8-5) | | Table 8-5 |
| Country clubs/golf courses (8-3) | Fertilizers,[6] herbicides,[5,10] pesticides for controlling mosquitoes, ticks, ants, gypsy moths, and other pests,[9] swimming pool chemicals,[11] automotive wastes | BMPs Noake (1988) |
| Cropland—irrigated and nonirrigated (8-2) | Pesticides,[5] fertilizers,[6] gasoline and motor oils from chemical applicators | Worksheet 8-3, U S EPA (1990a), BMPs Noake (1988) |
| Dry cleaning (see cleaning services) | | |
| Dairy products processing (8-4) | | Table 8-5 |
| Educational institutions (8-3) | | BMPs U S EPA (1991-1993) |

**Table 8-4. Contaminants Associated With Specific Contaminant Sources (Continued)**

| Source/Checklist No | Contaminants[1,2,3] | Information Sources |
|---|---|---|
| Electric/electronic/ communications equipment manufacturers (8-5) | *Communications equipment* Nitric, hydrochloric, and sulfuric acid wastes, heavy metal sludges, copper-contaminated etchant (e g , ammonium persulfate), cutting oil and degreasing solvent (trichloroethane, Freon, or trichloroethylene), waste oils, corrosive soldering flux, paint sludge, waste plating solution, *Electric/electronic* Cyanides, metal sludges, caustics (chromic acid), solvents, oils, alkalis, acids, paints and paint sludges, calcium fluoride sludges, methylene chloride, perchloroethylene, trichloroethane, acetone, methanol, toluene, PCBs | U S EPA (1988b), BMPs Noake (1988), U S EPA (1991-1993—printed circuit boards) |
| Electroplating and metal finishing (8-5) | Boric, hydrochloric, hydrofluoric, and sulfuric acids, sodium and potassium hydroxide, chromic acid, sodium and hydrogen cyanide, metallic salts, spent solvents | Table 8-5, Dotson (1991), U S EPA (1988b, 1990a, 1991a), BMPs U S EPA (1991-1993—finishing) |
| Equipment/appliance repair (8-4) | Solvents, lubricants, solder (lead, tin), paint thinner | BMPs Inglese (1992), U S EPA (1991-1993) |
| Farm machinery areas<br>(8-3) | Automotive wastes,[7] welding wastes | U S EPA (1990a) |
| Ferroalloy (8-5) | | Table 8-5 |
| Fertilizer manufacturing (8-5) | | Table 8-5 |
| Fiberglass-reinforced and composite plastics | | BMPs U S EPA (1991-1993) |
| Food processing (8-4) | Chlorine, ammonia, ethylene glycol, nickel, formaldehyde, bromomethane, pesticides and herbicides[5,10] | PEI Associates (1990) |
| Funeral services and crematories (8-4) | Formaldehyde, wetting agents, fumigants, solvents | BMPs Inglese (1992) |
| Furniture and fixtures manufacturers (8-4) | Paints, solvents, degreasing sludges, solvent recovery sludges | U S EPA (1988b) |
| Furniture/wood manufacturing, repair, and finishing shops (8-4) | Paints, solvents (methylene chloride, toluene), degreasing and solvent recovery sludges | U S EPA (1991a), BMPs Inglese (1992), Noake (1988) |
| Glass manufacturing (8-5) | Solvents, oils and grease, alkalis, acetic wastes, asbestos, heavy metal sludges, phenolic solids or sludges, metal-finishing sludge | Table 8-5 |
| Grain mills (8-4) | | Table 8-5 |
| Hazardous materials TSDs (8-2) | Potentially any regulated hazardous waste | BMPs Noake (1988) |
| Hospitals—see medical institutions | | |
| Industrial lagoons and pits | See industry-specific waste listings | BMPs Noake (1988) |
| Inorganic chemical manufacturing (8-5) | | Table 8-5 |
| Iron and steel manufacturing—blast furnaces, steel works, rolling mills (8-5) | Heavy metal wastewater treatment sludge, pickling liquor, waste oil, ammonia scrubber liquor, acid tar sludge, alkaline cleaners, degreasing solvents, slag, metal dust | Table 8-5 |
| Jewelry/metal plating shops (8-4) | Sodium and hydrogen cyanide, metallic salts, alkaline solutions (KOH, NaOH), acids (chromic, hydrochloric, hydrofluoric, nitric, phosphoric, sulfuric), spent solvents, heavy-metal contaminated wastewater/sludge | BMPs Noake (1988) |
| Junkyards—see scrap and salvage yards | | |
| Landfills (8-2) | Leachate (composition depends on type of waste disposed) | BMPs Noake (1988) |
| Lawns and gardens (8-3) | Fertilizers,[5] herbicides and other pesticides used for lawn and garden maintenance[10] | Worksheet 8-3, U S EPA (1990a), BMPs NJDEPE (1992) |

**Table 8-4 Contaminants Associated With Specific Contaminant Sources (Continued)**

| Source/Checklist No | Contaminants[1,2 3] | Information Sources |
|---|---|---|
| Leather tanning (8-4) | | Table 8-5, U S EPA (1988b) |
| Livestock (8-3) | Livestock sewage wastes, nitrates, phosphates, chloride, chemical sprays and dips for controlling insect, bacterial, viral, and fungal pests on livestock, coliform[4] and noncoliform bacteria, viruses | U S EPA (1990a), BMPs Naoke (1988) |
| Machine and metalworking shops (8-5) | Solvents, metals, miscellaneous organics, sludges, oily metal shavings, lubricant and cutting oils, degreasers (TCE), metal marking fluids, mold-release agents | BMPs Inglese (1992), Noake (1988) |
| Meat products and rendering (8-4) | | Table 8-5 |
| Medical institutions/services (8-3) | X-ray developers and fixers,[17] infectious wastes, radiological wastes, biological wastes, disinfectants, asbestos, beryllium, dental acids, formaldehyde, miscellaneous chemicals | BMPs Inglese (1992), U S EPA (1991-1993) |
| Metal fabrication (8-5) | | BMPs U S EPA (1991-1993) |
| Metal finishing (8-5) | Paint wastes, acids, heavy metals, metal sludges, plating wastes, oils, solvents, explosive wastes | Table 8-5, U S EPA (1988b) |
| Metal molding and casting/foundries (8-5) | Paint wastes, acids, heavy metals, metal sludges, plating wastes, oils, solvents, explosive wastes | Table 8-5, U S EPA (1988b), BMPs U S EPA (1991-1993) |
| Metals mining (8-4) | Cyanide, sulfides, metals, acid drainage | |
| Nonferrous metals forming (8-5) | | Table 8-5 |
| Nonferrous metal manufacturing (8-5) | | Table 8-5 |
| Organic chemical manufacturing, plastics, and synthetic fibers (8-5) | Solvents, oils, miscellaneous organics and inorganics (phenols, resins), paint wastes, cyanides, acids, alkalis, wastewater treatment sludges, cellulose esters, surfactant, glycols, phenols, formaldehyde, peroxides, etc | Table 8-5 |
| Paint manufacturing (8-4) | | |
| | Dotson (1991), BMPs U S EPA (1991-1993) | |
| Pesticide application services (8-4) | Pesticides, herbicides[5 10] | BMPs Inglese (1992), U S EPA (1991-1993) |
| Pesticide formulators (8-5) | | BMPs U S EPA (1991-1993) |
| Petroleum refining (8-5) | | Table 8-5, Dotson (1991) |
| Pharmaceutical industry (8-5) | | U S EPA (1991-1993) |
| Phosphate manufacturing (8-5) | | Table 8-5 |
| Photography shops, photo processing laboratories (8-4) | Cyanides, biosludges, silver sludges, miscellaneous sludges | BMPs Inglese (1992), Noake (1988), U S EPA (1991-1993) |
| Porcelain enameling (8-5) | | Table 8-5 |
| Printers, publishers, and allied industries (8-4) | Solvents, inks, dyes, oils, miscellaneous organics, photographic chemicals | U S EPA (1988b), BMPs Ingleses (1992), U S EPA (1991-1993) |
| Pulp, paper, and paperboard (8-4) | Metals, acids, minerals, sulfides, other hazardous and nonhazardous chemicals[16], organic sludges, sodium hydroxide, chlorine, hypochlorite, chlorine dioxide, hydrogen peroxide | Table 8-5, U S EPA (1988b) |
| Railroad tracks and yards (8-3) | | BMPs Noake (1988) |
| Research laboratories (8-4) | X-ray developers and fixers,[17] infectious wastes, radiological wastes, biological wastes, disinfectants, asbestos, beryllium, solvents, infectious materials, drugs, disinfectants (quaternary ammonia, hexachlorophene, peroxides, chlornexade, bleach), miscellaneous chemicals | BMPs Noake (1988), U S EPA (1991-1993) |
| Road deicing/maintenance (8-3) | Sodium chloride, calcium chloride, waste oil | U S EPA (1991a), BMPs NJDEPE (1992), Noake (1988) |
| Rubber processing (8-5) | | Table 8-5, U S EPA (1988b) |

**Table 8-4. Contaminants Associated With Specific Contaminant Sources (Continued)**

| Source/Checklist No. | Contaminants[1,2,3] | Information Sources |
|---|---|---|
| Sand and gravel mining (8-4) | Diesel fuel, motor oil, hydraulic fluids | BMPs Noake (1988) |
| Scrap, salvage, and junkyards (8-4) | Used oil, gasoline, antifreeze, PCB contaminated oils, lead acid batteries | U S EPA (1991a), BMPs NJDEPE (1992), Noake (1988) |
| Septic systems, cesspools, and sewer lines (8-3) | Septage, coliform and noncoliform bacteria,[4] viruses, nitrates, heavy metals, synthetic detergents, cooking and motor oils, bleach, pesticides,[9 10] paints, paint thinner, photographic chemicals, swimming pool chemicals,[11] septic tank/cesspool cleaner chemicals,[12] elevated levels of chloride, sulfate, calcium, magnesium, potassium, and phosphate | |
| Soaps and detergents (8-5) | | Table 8-5 |
| Stormwater drains and basins (8-3) | Sodium chloride, pathogens, petroleum products, soluble pesticides | BMPs Noake (1988) |
| Sugar processing (8-4) | | Table 8-5 |
| Stone and clay manufacturers (8-5) | Solvents, oils and grease, alkalis, acetic wastes, asbestos, heavy metal sludges, phenolic solids or sludges, metal-finishing sludge | |
| Swimming pools (8-3) | Swimming pool maintenance chemicals[11] | |
| Textile mills manufacturing (8-5) | | Table 8-5, U S EPA (1988b) |
| Timber products processing—sawmills and planers (8-4) | Treated wood residue (copper quinolate, mercury, sodium bazide), tanner gas, paint sludges, solvents, creosote, coating and gluing wastes | Table 8-5 |
| Underground storage tanks (8-2) | Gasoline, diesel fuel, other liquid petroleum products | BMPs NJDEPE (1992), Noake (1992) |
| Veterinary services (8-3) | Solvents, infectious materials, vaccines, drugs, disinfectants (quaternary ammonia, hexachlorophene, peroxides, chlornexade, bleach), x-ray developers and fixers[17], formaldehyde, pesticides | BMPs Inglese (1992) |
| Welders (8-4) | Oxygen, acetylene, solvents and oils | U S EPA (1990a), BMPs Inglese (1992) |
| Wood preserving facilities (8-4) | Wood preservatives (pentachlorophenol, chromated copper arsenate, ammoniacal copper arsenate), creosote | U S EPA (1988b,1990a, 1991a), BMPs Noake (1988) |

Source Adapted from U S EPA (1992)

[1] In general, ground water contamination stems from the *misuse and improper disposal* of liquid and solid wastes, the *illegal dumping or abandonment* of household, commercial, or industrial chemicals, the *accidental spilling* of chemicals from trucks, railways, aircraft, handling facilities, and storage tanks, or the *improper siting, design, construction, operation, or maintenance* of agricultural, residential, municipal, commercial, and industrial drinking water wells and liquid and solid waste disposal facilities Contaminants also can stem from *atmospheric pollutants*, such as airborne sulfur and nitrogen compounds, which are created by smoke, flue dust, aerosols, and automobile emissions, fall as acid rain, and percolate through the soil When the sources listed in this table are used and managed properly, ground-water contamination is not likely to occur

[2] Contaminants can reach ground water from activities occurring on the land surface, such as industrial waste storage, from sources below the land surface but above the water table, such as septic systems, from structures beneath the water table, such as wells, or from contaminated recharge water

[3] This table lists the most common wastes, but not all potential wastes For example, it is not possible to list all potential contaminants contained in storm water runoff or research laboratory wastes

[4] Coliform bacteria can indicate the presence of pathogenic (disease-causing) microorganisms that may be transmitted in human feces Diseases such as typhoid fever, hepatitis, diarrhea, and dysentery can result from sewage contamination of water supplies

[5] Pesticides include herbicides, insecticides, rodenticides, fungicides, and avicides EPA has registered approximately 50,000 different pesticide products for use in the United States Many are highly toxic and quite mobile in the subsurface An EPA survey found that the most common pesticides found in drinking water wells were DCPA (dacthal) and atrazine (EPA, 1990b), which EPA classifies as *moderately toxic* (class 3) and *slightly toxic* (class 4) materials, respectively

[6] The EPA National Pesticides Survey (EPA, 1991) found that the use of fertilizers correlates to nitrate contamination of ground water supplies

[7] Automotive wastes can include gasoline, antifreeze, automatic transmission fluid, battery acid, engine and radiator flushes, engine and metal degreasers, hydraulic (brake) fluid, and motor oils

[8] Toxic or hazardous components of common household products are noted in Table 3-2

[9] Common household pesticides for controlling pests such as ants, termites, bees, wasps, flies, cockroaches, silverfish, mites, ticks, fleas, worms, rats, and mice can contain active ingredients including napthalene, phosphorus, xylene, chloroform, heavy metals, chlorinated hydrocarbons, arsenic, strychnine, kerosene, nitrosamines, and dioxin

[10] Common pesticides used for lawn and garden maintenance (i e , weed killers, and mite, grub, and aphid controls) include such chemicals as 2,4-D, chlorpyrifos, diazinon, benomyl, captan, dicofol, and methoxychlor

[11] Swimming pool chemicals can contain free and combined chlorine, bromine, iodine, mercury-based, copper-based, and quaternary algicides, cyanuric acid, calcium or sodium hypochlorite, muriatic acid, sodium carbonate

**Table 8-4 Contaminants Associated With Specific Contaminant Sources (Continued)**

[12] Septic tank/cesspool cleaners include synthetic organic chemicals such as 1,1,1 trichloroethane, tetrachloroethylene, carbon tetrachloride, and methylene chloride

[13] Common wastes from public and commercial buildings include automotive wastes, rock salt, and residues from cleaning products that may contain chemicals such as xylenols, glycol esters, isopropanol, 1,1,1-trichloroethane, sulfonates, chlorinated phenolys, and cresols

[14] Municipal wastewater treatment sludge can contain organic matter, nitrates, inorganic salts, heavy metals, coliform and noncoliform bacteria, and viruses

[15] Municipal wastewater treatment chemicals include calcium oxide, alum, activated alum, carbon, and silica, polymers, ion exchange resins, sodium hydroxide, chlorine, ozone, and corrosion inhibitors

[16] The Resource Conservation and Recovery Act (RCRA) defines a hazardous waste as a solid waste that may cause an increase in mortality or serious illness or pose a substantial threat to human health and the environment when improperly treated, stored, transported, disposed of, or otherwise managed A waste is hazardous if it exhibits characteristics of ignitability, corrosivity, reactivity, and/or toxicity Not covered by RCRA regulations are domestic sewage, irrigation waters or industrial discharges allowed by the Clean Water Act, certain nuclear and mining wastes, household wastes, agricultural wastes (excluding some pesticides), and small quantity hazardous wastes (i e , less than 220 pounds per month) generated by businesses

[17] X-ray developers and fixers may contain reclaimable silver, glutaldehyde, hydroquinone, phenedone, potassium bromide, sodium sulfite, sodium carbonate, thiosulfates, and potassium alum

**Table 8-5 Index to Development Documents for Effluent Limitations Guidelines for Selected Categories[a] (U S EPA, 1987b)**

| Industrial Point Source Category | Subcategory | EPA Publication Document No | NTIS Accession No | GPO Stock No |
|---|---|---|---|---|
| Aluminum forming | Aluminum forming | EPA 440/1-84/073<br>Vol I<br>Vol II | PB84-244425<br>PB84-244433 | -<br>- |
| Asbestos manufacturing | Building, construction, and paper | EPA 440/1-74/017a | PB238320/6 | 5501-00827 |
| | Textile, friction materials, and sealing devices | EPA 440/1-74/035a | PB240860/7 | - |
| Battery manufacturing | Battery manufacturing | EPA 440/1-84/067<br>Vol I<br>Vol II | PB85-121507<br>PB85-121515 | -<br>- |
| Builder's paper and board mills | Pulp, paper and paperboard, and builder's paper and board mills | EPA 440/1-82/025 | PB83-163949 | - |
| Canned and preserved fruits and vegetables | Apple, citrus, and potato processing | EPA 440/1-74/027a | PB238649/8 | 5501-00790 |
| Canned and preserved seafood processing | Catfish, crab, and shrimp | EPA 440/1-74/020a | PB238614/2 | 5501-00920 |
| | Fishmeal, salmon, bottom fish, sardinge, herring, clam, oyster, scallop, and abalone | EPA 440/1-75/041a | PB256840/0 | - |
| Cement manufacturing | Cement manufacturing | EPA 440/1-74/005a | PB238610/0 | 5501-00866 |
| Coil coating | Coil coating, Phase I | EPA 440/1-82/071 | PB83-205542 | - |
| | Coil coating, Phase II - can-making | EPA 440/1-83/071 | PB84-198647 | - |
| Copper forming | Copper | EPA 440/1-84/074 | PB84-192459 | - |
| Dairy products processing | Dairy products processing | EPA 440/1-74/021a | PB238835/3 | 5501-00898 |
| Electroplating and metal finishing | Copper, nickel, chrome, and zinc | EPA 440/1-74/003a | PB238834/AS | 5501-00816 |
| | Electroplating - pretreatment | EPA 440/1-79/003 | PB80-196488 | - |
| | Metal finishing | EPA 440/1-83/091 | PB84-115989 | - |
| Ferroalloy | Smelting and slag processing | EPA 440/1-74/008a | PB238650/AS | 5501-00780 |
| Fertilizer manufacturing | Basic fertilizer chemicals | EPA 440/1-74/011a | PB238652/AS | 5501-00868 |
| | Formulated fertilizer | EPA 440/1-75/042a | PB240863/AS | 5501-01006 |
| Glass manufacturing | Pressed and blown glass | EPA 440/1-75/034a | PB256854/1 | 5501-01036 |
| | Insulation fiberglass | EPA 440/1-74/001b | PB238078/0 | 5501-00781 |
| | Flat glass | EPA 440/1-77/001c | PB238-907/0 | 5501-00814 |
| Grain mills | Grain processing | EPA 440/1-74/039a | PB238316/4 | 5501-00844 |
| | Animal feed, breakfast cereal, and wheat | EPA 440/1-74/028a | PB240861/5 | 5501-01007 |

**Table 8-5. Index to Development Documents for Effluent Limitations Guidelines for Selected Categories[a] (Continued)**

| Industrial Point Source Category | Subcategory | EPA Publication Document No | NTIS Accession No | GPO Stock No |
|---|---|---|---|---|
| Inorganic chemicals manufacturing | Inorganic chemicals Phase I | EPA 440/1-82/007 | PB82-265612 | - |
| | Inorganic chemicals Phase II | EPA 440/1-84/007 | PB85-156446/XAB | - |
| Iron and steel manufacturing | Iron and steel | EPA 440/1-82/024 | | - |
| | Volume I | EPA 440/1-82/024 | PB82-240425a | |
| | Volume II | EPA 440/1-82/024 | PB82-240433b | |
| | Volume III | EPA 440/1-82/024 | PB82-240441c | |
| | Volume IV | EPA 440/1-82/024 | PB82-240458d | |
| | Volume V | EPA 440/1-82/024 | PB82-240466e | |
| | Volume VI | EPA 440/1-82/024 | PB82-240474f | |
| Leather tanning | Leather tanning | EPA 440/1-82/016 | PB83-172593 | - |
| Meat products and rendering | Red meat processing | EPA 440/1-74/012a | PB238836/AS | 5501-00843 |
| | Renderer | EPA 440/1-74/031d | PB253572/2 | - |
| Metal finishing | Metal finishing | EPA 440/1-83/091 | PB84-115989 | - |
| Metal molding and casting (foundries) | Metal molding and casting | EPA 440/1-85/070 | PB86-161452/XAB | - |
| Nonferrous metals forming | Nonferrous metals forming | EPA 440/1-84/019b | - | - |
| | | Vol I | PB83/228296 | |
| | | Vol II | PB83/228304 | |
| | | Vol III | PB83/228312 | |
| Nonferrous metals manufacturing | Bauxite refining - aluminum segment | EPA 440/1-74/019c | PB238463/4 | 5501-00116 |
| | Primary aluminum smelting - aluminum segment | EPA 440/1-74/019d | PB240859/9 | 5501-00817 |
| | Secondary aluminum smelting - aluminum segment | EPA 440/1-74/019e | PB238464/2 | 5501-00819 |
| Organic chemical manufacturing and plastics and synthetic fibers | Organic chemicals manufacturing and plastics and synthetic fibers | EPA 440/1-87/009 | Available from NTIS after publication (1/87) | |
| Petroleum refining | Petroleum refining | EPA 440/1-82/014 | PB83-172569 | - |
| Pharmaceuticals | Pharmaceutical | EPA 440/1-83/084 | PB84-180066 | - |
| Phosphate manufacturing | Phosphorus-derived chemicals | EPA 440/1-74/006a | PB241018/1 | 5503-00078 |
| | Other non-fertilizer chemicals | EPA 440/1-75/043 | - | - |
| Porcelain enameling | Porcelain enameling | EPA 440/1-82/072 | - | - |
| Pulp, paper, and paperboard | Unbleached kraft and semi-chemical pulp | EPA 440/1-74/025a | PB238833/AS | - |
| | Pulp, paper and paperboard, and builder's paper and board mills | EPA 440/1-82/025 | PB83-163949 | - |
| Rubber processing | Tire and synthetic | EPA 440/1-74/013a | PB238609/2 | 5501-00885 |
| | Fabricated and reclaimed rubber | EPA 440/1-74/030a | PB241916/6 | 5501-01016 |
| Soaps and detergents | Soaps and detergents | EPA 440/1-74/018a | PB238613/4 | 5501-00867 |
| Sugar processing | Beet sugar | EPA 440/1-74/002b | PB238462/6 | 5501-00117 |
| | Cane sugar refining | EPA 440/1-74/002c | PB238147/3 | 5501-00826 |
| Textile mills manufacturing | Textile mills | EPA 440/1-82/022 | PB83-116871 | - |
| Timber products processing | Wood furniture and fixtures | EPA 440/1-74/033a | - | - |
| | Timber products processing | EPA 440/1-81/023 | PB81-227282 | - |

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[a] This list includes only "final" development documents for effluent limitations guidelines For many industries, these documents are in the draft or proposal stage

**Table 8-6 Index to Major References on Types and Sources of Contamination in Ground Water**

| **Topic** | **References** |
|---|---|
| General | Canter et al (1987), Cole (1972-Europe), Guswa et al (1984), Haimes and Snyder (1986), Meyer (1973), Miller (1980, 1985), Pettyjohn (1972), U S Public Health Service (1961), van Duijvenbooden and van Waegeningen (1987), van Duijvenbooden et al (1981), Ward et al (1985), *Bibliographies/Literature Reviews* Atlantic Research Corporation (1980), Bader (1973), Congressional Research Service (1984), Geyer (1972), Lindorff and Cartwright (1977), Rima et al (1971), Summers and Spiegel (1974), Todd and McNulty (1974), U S EPA (1972), van der Leeden (1991), Zanoni (1971) |
| Baseline Chemistry | Durfor and Becker (1964), *Soil* Connor and Shacklette (1975), Ebens and Shacklette (1982), Shacklette et al (1971a,b, 1973, 1974), *Ground/Surface Water·* Clarke (1924), Durum and Haffty (1961), Durum et al (1971), Ebens and Shacklette (1982), Feth (1981), Fishman and Hem (1976), Hem (1972), Kopp and Kroner (1968), Ledin et al (1989), Leenheer et al (1974), Skougstad and Horr (1963), Thurman (1985), White et al (1963, 1970) |
| Types of Contaminants | Page (1981), Palmer et al (1988), Pettyjohn and Hounslow (1983), Zoeteman (1985), *National Water Quality Assessments* Francis et al 1981), U S EPA (1985a), Westrick et al (1984) |
| Contaminant Chemical Behavior | See Table 1-2 |
| GW Contamination Assessments | *U S* Ballentine et al (1972), Lehr (1982), Patrick et al (1987), Pye and Kelley (1984), U S EPA (1984), *Regional Assessment* Fuhriman and Barton (1971-AZ, CA, NV, UT), Miller and Scalf (1974), Miller et al (1974-northeast), Miller et al (1977-southeast), Scalf et al (1973-southcentral), van der Leeden et al (1975-northwest), *Source Assessments* U S EPA (1977—waste disposal), U S EPA (1978, 1983-surface impoundments), U S EPA (1985b-injection of hazardous waste), U S EPA (1986a, 1986b-underground storage tanks), U S EPA (1986d, 1990c-pesticides) |
| *Contamination Sources* | |
| General | Cape Cod Aquifer Management Project (1988), LaSpina and Palmquist (1992), Meyer (1973), Miller (1982), Noake (1988), Shineldecker (1992), U S EPA (1977, 1987a, 1988a, 1990b, 1991b), U S Fish and Wildlife Service (1986), U S OTA (1984), *State WHPA Contaminant Inventory Guidance* Nebraska Department of Environmental Quality (1992), New Hampshire Office of State Planning (1991), North Dakota State Department of Health (1993), Ohio Environmental Protection Agency (1991), Oregon Department of Environmental Quality (1992), RIDEM (1992), Washington State Department of Health (1993) |
| Commercial/Industrial* | Dotson (1991), U S EPA (1987b, 1988b, 1990a, 1991a, 1992), Ward et al (1990) |
| Rural/Non Point | Ashton and Underwood (1975), Delfino (1977), D'Itri and Wolfson (1987), Nielsen and Lee (1987), Novotny and Chesters (1981), Overcash and Davidson (1980), U S EPA (1984, 1991b) |
| Agricultural Chemicals | Bloom and Degler (1969), Fairchild (1987), Hallberg (1986) Irvine and Knights (1974), Jenkins (1979), U S EPA (1986c) |
| Abandoned Wells | Aller (1984), Frischknecht et al (1983), Gass et al (1977), Texas Water Commission (1989b) |
| Surface Impoundments | Silka and Swearingen (1978), U S EPA (1978, 1983) |
| Landfills | Geyer (1972), Zanoni (1971) |
| Accidental Spills | Guswa et al (1984) |
| Waste Injection Wells | Rima et al (1971), U S EPA (1985b, 1990) |
| USTs | U S EPA (1986a, 1986b) |
| Septic Systems | California Assembly Office of Research (1985), Canter and Knox (1984, 1985), Cartwright and Sherman (1974), Noss (1989), Scalf et al (1977, Thomson (1984) |
| Energy Production/Use | Boulding (1992), Dotson (1991), U S Army Engineers Waterways Experiment Station (1979), U S EPA (1988c) |

* See also references for estimating releases of hazardous chemicals in Table A-5

tions where hazardous chemicals are stored and used Table A-5 identifies references that provide more information on collection and analysis of information collected pursuant to EPCRA

Users of this manual should be aware that many state wellhead protection programs have developed their own checklists, worksheets, and inventory forms for identifying potential contaminant sources The materials in this chapter represent a synthesis based on a review of materials developed by state programs as of late 1993 Any of these state materials, as well as any subsequently developed, can be used as an alternative to or in combination with the materials in this chapter This is a complex topic in which improvements are always possible The best approach is probably to compare the latest materials available for the state's wellhead protection program with the material in this chapter and select the materials that seem most appropriate for the WHPA of interest Alternatively, materials should be modified if comparisons show that no single checklist, worksheet, or inventory form addresses all the information needs for the WHPA

*A few words about natural contamination sources* The checklists in this chapter do not address contamination sources that result from natural processes In some areas, particularly in arid and semi-arid areas of the western United States, ground water is of marginal quality, or exceeds drinking water standards for elements such as arsenic, chloride, fluoride, heavy metals, and radionuclides. Little can be done to prevent such contamination, so the options are essentially limited to finding an alternative, higher quality source of drinking water, or treatment to remove contaminants Human activity may cause degradation of ground water from natural sources Examples include mobilization of heavy metals and radionuclides by mining activities and saltwater intrusion into fresh-water aquifers by pumping Such activities are included in the checklists in this chapter.

### *8.3.1 Cross-Cutting Sources: Wells, Storage Tanks and Waste Disposal*

Checklist 8-2 identifies three major sources of potential contamination. (1) wells and related features, (2) storage tanks, and (3) waste disposal sites These are called cross-cutting sources because they may be associated with any of the activities identified in the detailed checklists for nonindustrial, commercial, and industrial sources The high risk of ground water contamination from storage tanks, especially underground storage tanks, and waste disposal sites is another reason for placing them in a separate checklist

### *8.3.2 Nonindustrial Sources*

Checklist 8-3 identifies five major categories of potential contamination sources that can be broadly classified as nonindustrial· (1) agricultural, (2) residential, (3) other green areas, (4) municipal and other public services, and (5) transportation The category of "other green areas" includes any nonagricultural and nonresidential area where grass and other vegetation may receive regular applications of agricultural chemicals In the residential category, each individuals in each residence or living unit should be interviewed, if possible, and a household hazardous waste inventory prepared Such interviews should increase awareness by individuals and families living within a WHPA of ground water concerns, and should lay the groundwork for any future public education efforts

### *8.3.3 Commercial and Industrial Sources*

Checklists 8-4 and 8-5 identify more than 90 commercial and industrial activities that present potential for ground water contamination Commercial activities are generally service- and sales-oriented, while industrial activities involve primarily processing and manufacturing In practice, the dividing line is not always clear, so both checklists should be examined if the classification of an identified source is uncertain Commercial activities associated with transportation are included in Checklist 8-3

Checklist 8-4 identifies three major categories of activities (1) commercial services and sales, (2) activities related to processing and storage of natural products (food, other animal products, and wood), and (3) resource extraction activities Checklist 8-5 identifies three major categories of industrial activities (1) chemical processing and manufacturing, (2) metal manufacturing, fabrication, and finishing, and (3) other manufacturing

A wide array of potential contaminants are associated with commercial and industrial activities U S EPA has developed a series of information sheets, available from the RCRA Hotline, on 17 business activities that may generate hazardous wastes (U S EPA, 1990a) Checklists 8-4 and 8-5 indicate activities covered by these summary sheets with the EPA document order number Tables 8-4 and 8-5 identify reference sources where more detailed information can be obtained on industrial processes and potential contaminants

## 8.4 Evaluating the Risk From Potential Contaminants

Methods for evaluating the risk posed by potential contaminant sources within a WHPA can range from a relatively simple process—classifying sources as high, moderate, and low risk—to a comprehensive risk assessment process in which fate and transport of chemicals of concerns are modeled to quantify exposure and risk to people or ecosystems This section focuses on relatively simple ranking methods for evaluating risk (Section 8 4 1) and briefly discusses situations in which more complex methods may be required

### *8.4.1 Risk Ranking Methods*

Classifying potential contaminant sources into risk categories (high, medium, low) is the simplest way to identify the sources within a WHPA that pose a threat to ground water quality Figure 8-3 illustrates a matrix developed by the Cape Cod Aquifer Management Project to evaluate pollution potential from 32 land use categories The top of the matrix contains ratings for 16 groups of chemicals according to (1) overall threat to public health, (2) mobility, (3) and whether they may occur naturally in significant concentrations The overall threat to public water supply for each land use category in Figure 8-3 is rated as low (L) to high (H) in the right hand column, based on the number of potential contaminants associated with the category and the potential threat posed by each contaminant

| Land Use Considerations | Acids | Bases | Chloride | Fluoride | Iron/Manganese (Fe/Mn) | Metals (except Fe & Mn) | Nitrate[1] | Pathogens (Virus/Bacteria) | Pesticides/Herbicides | Petroleum Products | Phenols | Radioactivity | Sodium | Solvents | Sulfate | Surfactants (Detergents) | Overall Threat to Public Water Supply[3] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Overall Threat to Public Health | L M | L M | L | L | L | H | M | L | H | H | H | H | L | H | L | L | |
| Mobility | M | L | H | H | M | L H | H | L | L H | M | M | L H | H | H | H | H | |
| Natural Background | ▨ | | ▨ | ▨ | ▨ | ▨ | | | | | | ▨ | ▨ | | ▨ | | |
| **Land Use Categories** | | | | | | | | | | | | | | | | | |
| Agriculture/Golf Courses | | | | | | | ▨ | | ▨ | | | | | | | | M |
| Airports | | | | | | ▨ | | | ▨ | ▨ | | | | ▨ | | ▨ | M H |
| Asphalt Plants | | | | | | | | | | ▨ | | | | | | | L M |
| Beauty Parlors | | ▨ | | | | ▨ | | | | | | | | ▨ | | ▨ | L[2] |
| Boat Yards/Builders | | | | | | ▨ | | | | ▨ | ▨ | | | ▨ | | | L |
| Car Washes | | | ▨ | | | ▨ | | | | ▨ | | | ▨ | ▨ | | ▨ | L |
| Cemeteries | | | | | | | | | ▨ | | | | | | | | L |
| Chemical Manufacture | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | H |
| Clandestine Dumping | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | | H |
| Dry Cleaning | | | | | | | | | | | | | | ▨ | | | H |
| Furniture Stripping and Painting | ▨ | ▨ | | | | ▨ | | | | | | | | ▨ | | | M |
| Hazardous Materials Storage and Transfer | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | H |
| Industrial Lagoons and Pits | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | H |
| Jewelry and Metal Plating | ▨ | ▨ | | ▨ | ▨ | ▨ | | | | ▨ | | | ▨ | ▨ | | ▨ | M |
| Junkyards | ▨ | | | | ▨ | ▨ | | | | ▨ | | | | ▨ | ▨ | | L |
| Landfills | ▨ | | ▨ | | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | | H |
| Laundromats | | | | | | | | ▨ | | | | | | ▨ | | ▨ | L M |
| Machine Shops/Metal Working | ▨ | ▨ | | | | ▨ | | | | ▨ | | | | ▨ | | ▨ | H |
| Municipal Wastewater/Sewer Lines | | | | | ▨ | ▨ | ▨ | ▨ | | | | | ▨ | ▨ | | ▨ | H |
| Photography Labs/Printers | ▨ | ▨ | | | | ▨ | | | | | | | | ▨ | | ▨ | L M |
| Railroad Tracks and Yards Maintenance Stations | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | M |
| Research Labs/Universities/Hospitals | ▨ | ▨ | | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | | ▨ | | ▨ | L M |
| Road and Maintenance Depots | | | ▨ | | | | | | ▨ | ▨ | | | ▨ | ▨ | | | M |
| Sand and Gravel Mining/Washing | | | | | | | | | | ▨ | | | | ▨ | | | L |
| Septage Lagoons and Sludge | | | ▨ | | ▨ | ▨ | ▨ | ▨ | | | | | ▨ | ▨ | | ▨ | H |
| Septic Systems Cesspools and Water Softeners | | | ▨ | | ▨ | ▨ | ▨ | ▨ | ▨ | | | | ▨ | ▨ | | ▨ | H |
| Stables Feedlots Kennels Piggeries Manure Pits | | | | | | | ▨ | ▨ | | | | | ▨ | | | | M H |
| Stormwater Drains/Retention Basins | | | ▨ | | | ▨ | | ▨ | ▨ | ▨ | | | ▨ | ▨ | | | L M |
| Stump Dumps | | | | | ▨ | ▨ | ▨ | | | | ▨ | | ▨ | | | | L |
| Underground Storage Tanks | | | | | | | | | ▨ | ▨ | | | | ▨ | | | H |
| Vehicular Services | | | | | | ▨ | | | | ▨ | | | | ▨ | | ▨ | H |
| Wood Preserving | | | | | | ▨ | | | | ▨ | ▨ | | | ▨ | ▨ | ▨ | L |

**Figure 8-3 Land use/public-supply well pollution potential matrix (Noake, 1988)**

**Key to Figure 8-3**

▨ The contaminant(s) released from this land-use category *may render* groundwater at a public-supply well undrinkable in accordance with federal and state maximum contaminant levels

☐ This land use category is not generally associated with the release of the particular contaminant in quantities that would render the groundwater at a public-supply well undrinkable However, the contaminant may be associated with a particular activity

L = Low Threat

M = Medium Threat

H = High Threat

This Matrix is based on a literature review and the combined field experience of the Cape Cod Aquifer Management Project (CCAMP) **THIS MATRIX SHOULD BE USED AS A GUIDE AND HANDY REFERENCE** It is not a substitute for looking at a particular land use in detail There will always be the potential for a business to use an unusual process using chemicals not normally associated with that business The land-use categories included in the Matrix and *Guide to Contamination Sources for Wellhead Protection* are those that might be found in the primary recharge area of a public-supply well in Massachusetts This Matrix may be misleading or erroneous if applied to low-yield private wells

1 Nitrate has a cumulative impact on groundwater quality No one category is responsible for the release of nitrate A variety of land use categories release nitrate These include animal feedlots, landfills septic systems septage lagoons municipal wastewater and agricultural activities including turf maintenance

2. There are no known instances of beauty parlors contaminating well water in Massachusetts More research is needed to determine the severity of a threat to groundwater from this land use category

3 Refer to *Guide to Contamination Sources for Wellhead Protection* pp 1 2

**Figure 8-3. Land use/public-supply well pollution potential matrix (Noake, 1988) (continued)**

Following the approach in Figure 8-3, once the potential contaminant source inventory has been completed, each land use category or individual source is placed in a risk category Figure 8-3 has five categories (low, low-medium, medium, medium-high, and high), but fewer categories (low, medium, and high) can also be used Figure 8-3 and Checklist 8-6, which identifies high and moderate risk land use activities based on ratings from a variety of sources, can provide some guidance in how to classify potential contaminant sources within a wellhead protection area Not all sources agree in their classification of specific land use categories, and classification decisions should consider all factors particular to the wellhead protection area in question Aquifer vulnerability mapping, as described in Section 5 5, is a valuable complement to the risk ranking approach to evaluating potential contaminant sources For example, any given potential contaminant source represents a less significant threat to a highly confined aquifer than to an unconfined aquifer (see Section 5 4 3) [1] Table 5-9 identifies a number of references that discuss vulnerability mapping in the context of risk assessment

Whether a land use is classified as high or moderate risk becomes a significant consideration when developing options for managing the WHPA High-risk land uses are frequently prohibited in high priority wellhead protection areas, and moderate-risk are commonly restricted in such areas Table 10-1 illustrates how particular high- and moderate-risk land uses have been either prohibited or restricted (i e , special permit required) in four water resource protection zones on Nantucket Island

Figure 8-4 illustrates the results of a two-phased evaluation of potential hazards for a public water supply well in Illinois The first phase (Figure 8-4a) involved a summary tabulation of the information obtained from the individual source surveys (see Worksheet C-6) The numbers in the first column refer to map locations, and the second and third columns refer to Illinois environmental permits Note that the last two columns indicate whether the source is a potential hazard, and if so, whether the hazard might be significant The Phase II evaluation (Figure 8-4b) incorporates the potential source characteristics tabulated in the first phase and also takes into consideration geologic susceptibility, attenuative soil properties and depth to water table In this example, a geographic information system was used to relate all of the variables identified in Figure 8-4 and to evaluate the potential hazardous to the ground water in the wellhead study area

### 8.4.2 Other Risk Evaluation Methods

Risk ranking and aquifer vulnerability mapping methods are probably adequate for many WHPAs Where many high risk potential contaminant sources exist within a WHPA, more sophisticated risk assessment approaches

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[1] An exception to this would be where the source is near an improperly abandoned well that provides a pathway from the surface to the confined aquifer

## Checklist 8-6

## Risk Categories of Land Uses and Activities Affecting Ground Water Quality

<u>High Risk</u> (Frequently Prohibited in High Priority Water Supply Protection Areas)

___ Airport maintenance areas
___ Animal feedlots
___ Appliance/small engine repair shops
___ Asphalt/concrete/coal tar plants
___ Auto repair and body shops*
___ Boat service, repair and washing establishments
___ Beauty parlors/hairdressers
___ Business and industrial uses (excluding agriculture) which involve the onsite disposal of process wastes from operations
___ Car washes
___ Chemical/biological laboratory
___ Chemical manufacturing/industrial areas
___ Cleaning service (dry cleaning, laundromat, commercial laundry)*
___ Disposal of liquid or leachable waste except for properly designed commercial and residential onsite wastewater disposal systems and normal agricultural operations
___ Electroplaters (metal plating and finishing) and metal fabricators*
___ Fuel oil distributors
___ Furniture and wood stripping and refinishing*
___ Gasoline stations
___ Golf courses/parks/nurseries
___ Graveyards
___ Improperly constructed or abandoned wells (perched, confined aquifers)
___ Junkyards and salvage yards*
___ Landfills and dumps
___ Making the surface of more than 10% of any lot impervious
___ Mining operations
___ Medical services (including dental/vet)
___ Military installations
___ Motels/hotels
___ Municipal sewage treatment facilities with onsite disposal of primary or secondary effluent
___ Oil and gas drilling and production
___ Outdoor storage of road salt, or other de-icing materials, the application of road salt and the dumping of salt-laden snow*
___ Outdoor storage of pesticides or herbicides
___ Parking areas of over 50 spaces
___ Pesticide/herbicide stores
___ Petroleum product refining and manufacturing
___ Photo processors/printing establishments
___ RCRA hazardous materials TSDs
___ Sand and gravel extraction
___ Trucking or bus terminals
___ Underground storage and/or transmission of oil, gasoline or other petroleum products
___ Use of septic system cleaners which contain toxic chemicals (such as methylene chloride, and 1,1,1 trichloroethane)
___ Wood preserving and treating*

## Checklist 8-6
## Risk Categories of Land Uses and Activities Affecting Ground Water Quality (Continued)

Moderate Risk (Frequently restricted in high priority water supply protection areas)

___ Aboveground storage tanks without secondary containment structures
___ Artificial groundwater recharge facilities
___ Excavation for the removal of earth, sand, gravel and other soils
___ Drainage from impermeable surfaces without installation and maintenance of oil, grease and sediment traps
___ Drywells and unlined stormwater drainage channels and impoundments
___ Irrigation in areas with coarse, permeable soils
___ Residential lot size in areas not served by municipal sewers (larger lot sizes reduce the amount of contamination from septic systems and household chemicals)
___ Unlined irrigation canals and tailwater sumps (arid areas)
___ Use of road salt (NaCl)
___ Use of commercial fertilizers, pesticides and herbicides

Sources: Lowrence (1992), Noake (1988), Michigan Departments of Natural Resources and Public Health (1993)**

* Highest risk light industrial uses identified in U.S EPA (1991a)

** Incomplete; several other sources the provide this kind of risk ranking have been identified and will be incorporated into this table for the final report

Phase I Evaluation of Potential Hazards

| SITE NAME | ESDA 302/303 | ESDA 311/312 | NON-SEWERED | ONSITE UST | ONSITE SOLVENTS | ONSITE RELEASE | SOIL/GW CONTAM. | CLEANUP | MONITOR WELLS | POTEN HAZARD | SIGNIFICANT HAZARD |
|---|---|---|---|---|---|---|---|---|---|---|---|
| MISSISSIPPI RIVER GRAIN (3) | NO | NO | NO | NO | NO | NO | NO | NO | NO | NO | NO |
| LOUIS DREYFUS CORP (4) | NO | NO | NO | YES | YES | NO | NO | NO | NO | YES | NO |
| PEKIN WASTE-WATER PLANT #1 (7) | YES | NO | NO | NO | NO | NO | NO | NO | NO | YES | NO |
| SOURS GRAIN CO (8) | NO | YES | NO | NO | NO | NO | NO | NO | NO | NO | NO |
| PEKIN ENERGY CO (9) | NO | YES | NO | YES | NO | YES | NO | NO | NO | YES | YES |
| MIDWEST GRAIN (10) | YES | YES | NO | YES | YES | NO | NO | NO | NO | YES | YES |
| ELECTRIC BOOSTER STATION (11) | NO | NO | N/A | NO | NO | NO | NO | NO | NO | NO | NO |
| QUAKER OATS CO (12) | YES | NO | NO | YES | NO | NO | NO | NO | NO | YES | NO |
| TRUCK CLEANING (14) | NO | NO | N/A | NO | ? | NO | NO | NO | NO | YES | NO |
| GOLF GREEN LAWN CARE (15) | NO | NO | NO | NO | ? | NO | NO | NO | NO | YES | NO |
| KMI (16) | NO | YES | NO | YES | ? | NO | NO | NO | NO | YES | NO |
| SHALLENBERGER EXCAVATING (17) | NO | NO | NO | NO | ? | NO | NO | NO | NO | YES | NO |
| HOHIMER'S AUTOMOTIVE (18) | NO | NO | NO | NO | ? | NO | NO | NO | NO | YES | NO |

(a)

Phase II Evaluation of Potential Hazards

| SITE NAME | PROBLEM SITE | SUSC GEOLOGY | ATTENUATIVE SOIL PROP. H | M | L | IN 1-YEAR CAP ZONE | IN 2-YEAR CAP ZONE | IN 3-YEAR CAP ZONE | DEPTH TO WATER | HAZARD POTENTIAL |
|---|---|---|---|---|---|---|---|---|---|---|
| MISSISSIPPI RIVER GRAIN (3) | 1. | X |  | X | X |  |  |  | X | 4 |
|  | 2. X |  | X |  |  | X | X | X |  | 5 |
| LOUIS DREYFUS CORP. (4) | 1. X |  |  | X | X |  |  |  | X | 4 |
|  | 2 | X | X |  |  | X | X | X |  | 5 |
| PEKIN WASTE WATER PLANT #1 (7) | 1. X |  |  | X | X |  |  |  | X | 4 |
|  | 2 | X | X |  |  | X | X | X |  | 5 |
| SOURS GRAIN (8) | 1. |  |  | X | X |  |  |  | X | 3 |
|  | 2 X | X | X |  |  | X | X | X |  | 6 |
| PEKIN ENERGY COMPANY (9) | 1 X | X |  | X | X |  |  |  | X | 5 |
|  | 2. |  | X |  |  | X | X | X |  | 4 |
| MIDWEST GRAIN PRODUCTS (10) | 1 X | X |  | X | X |  |  |  | X | 5 |
|  | 2 |  | X |  |  | X | X | X |  | 4 |
| ELECTRIC BOOSTER STATION (11) | 1 | X |  | X | X |  |  |  | X | 4 |
|  | 2. X |  | X |  |  | X | X | X |  | 5 |

1 = YES (e g., yes facility is problemat ic, geology is susc., soils have low attenuation capability, in 1 yr ZOC, in 3 yr ZOC, and depth of water less than 50 ft of LSE.)

2 = NO (means the opposite)

(b)

**Figure 8-4** Illustration of wellhead protection contaminant source evaluation of potential hazards, Pekin, Illinois (a) Phase I, (b) Phase II (Adams et al , 1992) may be required to help identify the most efficacious and cost-effective options for reducing risk Factors that need to be considered for a comprehensive risk assessment include (1) chemical toxicity, (2) pathways that can lead to exposure, (3) the characteristics of the population being exposed (density, age, etc ), (4) the probability that health-threatening exposures will actually occur, (5) the cost of options for reducing risk from exposure, and (6) the perception of risk by the exposed population

EPA has developed a relatively sophisticated procedure to assess and screen relative threats to ground water supplies posed by potential contaminant sources (U S EPA, 1991c) This procedure results in an overall risk rating for each contaminant source based on (1) the likelihood of well contamination and (2) the severity of well contamination Figure 8-5 shows three potential contaminant sources in Pekin, Illinois, plotted on the EPA risk matrix Source 6 represents a high risk, even though the likelihood of well contamination is low, because the contamination would be severe if it did occur

A variety of methods have been developed for evaluating risks addressed by other EPA programs For example, several methods have been developed to help communities evaluate the risk posed by chemicals that must be reported under EPA's Toxic Release Inventory (TRI) program (FEMA/DOT/EPA, 1989, U S EPA, 1989) These methods focus more on the risks posed by airborne accidental releases of chemicals Elements of these methods, however, could be adapted for use in evaluating the risks of ground water contamination by chemicals reported under the TRI program Similarly, methods used to assess risk at Superfund sites and for other EPA programs may be useful, under certain circumstances, for evaluating risk in WHPAs Table A-5 provides an index to major references on risk assessment in relation to ground water contamination and other methods for exposure and risk assessment

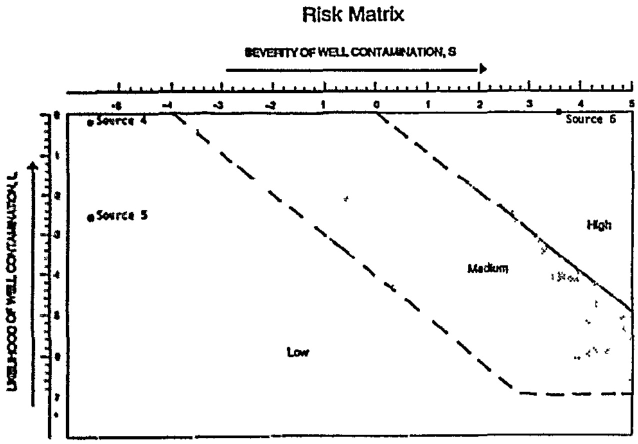

**Figure 8-5** **Risk matrix for selected contaminant sources within wellhead protection area for well numbers 1, 2, and 3, Pekin, Illinois (Adams et al, 1992)**

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* See Introduction for information on how to obtain documents

# Chapter 9
# Wellhead Protection Area Management

Management of wellhead protection areas (WHPAs) to prevent ground water contamination involves several steps

- Identification of protection options appropriate for the types of potential contaminants present
- Selection of those that are technically and politically feasible for the area
- Implementation of the options
- Monitoring of the effectiveness of management and application of additional management practices, if required
- Development of contingency plans to address threats to a water supply as a result of accident or failure of the management practices that have been implemented

This chapter includes a checklist and tables that provide a comprehensive overview of available options, but does not discuss specific approaches in detail Table 9-4 at the end of the chapter provides an index to major references sources where more detailed information can be obtained about specific options for management of wellhead protection areas

## 9.1 General Regulatory and Nonregulatory Approaches

Wellhead protection management options or tools can be broadly classified as *regulatory* and *nonregulatory* At the local level, regulatory approaches generally involve the use of some form of (1) zoning ordinances, (2) subdivision or individual lot controls, or (3) promulgation of local health and environmental regulations designed to directly or indirectly protect ground water in a WHPA State-level legislation or regulations may also address wellhead protection Nonregulatory controls, as the name implies, involve voluntary actions on the part of the public and private sector to enhance ground water protection

Wellhead protection management options can also be classified as *technical* and *nontechnical* Although the dividing line may not always be clear, technical options generally involve controls based on some understanding of the relationship between contaminant characteristics and the hydrogeology of a WHPA Nontechnical options are generally not directly related to scientific considerations, although indirect relationships exist to the extent that WHPA delineation and contaminant risk assessment processes are scientifically based

Checklist 9-1 identifies 45 specific wellhead protection tools in three major categories (1) nontechnical regulatory options, (2) nontechnical nonregulatory options, and (3) technical regulatory and nonregulatory options Nontechnical options are not discussed further here However, Checklist 9-1 indicates where Tables 9-1 and 9-2 provide summary information on specific options The rest of this chapter focuses on general technical approaches to WHPA management (Section 9 2), specific approaches for different types of land use (Section 9 3), and contingency planning (Section 9 4)

## 9.2 General Technical Approaches

### 9.2.1 Design Standards and Best Management Practices

Design standards define specifications for how a building or onsite wastewater disposal system should be constructed Best management practices (BMPs) define how repeated activities, such as construction and farming, should be carried out so as to minimize adverse environmental impacts The great advantage of these approaches is their simplicity They establish an objective standard for monitoring compliance Design standards usually require inspection for compliance at the time of inspection, although some ongoing monitoring may also be required BMPs may require ongoing monitoring for compliance Design standards and BMPs will only provide adequate protection, however, if the assumptions used in establishing the standard or practice apply within a WHPA Design standards and BMPs tend to be less flexible than performance standards (next section) because they cannot be readily modified to reflect local conditions

## Checklist 9-1
## Wellhead Protection Tools

Regulatory Options (Nontechnical)

Zoning Ordinances (Table 9-2)

___ Overlay ground water protection districts (Table 9-1)
___ Land use prohibitions (Table 9-1)
___ Special permitting (Table 9-1)
___ Large-lot zoning (Table 9-1)
___ Transfer of development rights (Table 9-1)
___ Cluster/PUD Design (Table 9-1)
___ Growth controls/timing (Table 9-1)

Subdivision and Individual Lot Controls

___ Subdivision ordinances (Table 9-2, see also Technical Options below)
___ Site plan review (Table 9-2)

Health and Environmental Regulations

___ Prohibit or additional regulation of underground storage tanks (Table 9-1)
___ Other source prohibitions (Table 9-2)
___ Inspection and testing (Table 9-2)
___ Prohibition/regulation of small sewage treatment plants (Table 9-1)
___ Phosphorus buffer zone
___ Septic cleaner ban (Table 9-1)
___ Septic system maintenance/upgrades (Table 9-1)
___ Registration and inspection of businesses using toxic/hazardous materials (Table 9-1)
___ Regulation of household hazardous waste
___ Regulation of agricultural chemicals
___ Regulation of private wells. permits, pump and water quality testing (Table 9-1)

Legislative (State-level)

___ Establishment of regional WHPAs (Table 9-1)
___ Passage of laws authorizing regulation where regulatory powers are limited

Nonregulatory Options (Nontechnical)

___ Land acquisition by purchase or donation (Tables 9-1, 9-2)
___ Purchase of development rights (Table 9-2)
___ Taxation deferments for nondevelopment
___ Conservation easements (Table 9-1)
___ Voluntary limits to development (Table 9-1)
___ Land banking/transfer taxes (Table 9-1)
___ Contingency planning (Tables 9-1, 9-2)
___ Hazardous waste collection program (Table 9-1)
___ Public education (Tables 9-1, 9-2)
___ Training and demonstration (Table 9-2)
___ Waste reduction (Table 9-2)
___ Water conservation

# Checklist 9-1
# Wellhead Protection Tools (Continued)

Technical Regulatory and Nonregulatory Options

General

___ Wellhead protection zones
___ Ground water monitoring (Tables 9-1, 9-2)
___ Performance standards (Table 9-1)
___ Operating standards (Table 9-2)
___ Design standards (Table 9-2)
___ Best management practices — BMPs (Table 9-2)
___ Capture zone management

Subdivision Controls

___ Nitrogen/phosphorus loading standards
___ Drainage Requirements (Table 9-1)

Nonpoint Source Pollution Controls

___ Agriculture BMPs
___ Construction Site BMPs

**Table 9-1. Summary of Wellhead Protection Tools**

| | Applicability to Wellhead Protection | Land Use Practice | Legal Considerations | Administrative Considerations |
|---|---|---|---|---|
| **Regulatory: Zoning** | | | | |
| Overlay GW Protection Districts | Used to map wellhead protection areas (WHPAs)<br>Provides for identification of sensitive areas for protection<br>Used in conjunction with other tools that follow | Community identifies WHPAs on practical base/zoning map | Well-accepted method of identifying sensitive areas<br>May face legal challenges if WHPA boundaries are based solely on arbitrary delineation | Requires staff to develop overlay map<br>Inherent nature of zoning provides "grandfather" protection to pre-existing uses and structures |
| Prohibition of Various Land Uses | Used within mapped WHPAs to prohibit ground-water contaminants and uses that generate contaminants | Community adopts prohibited uses list within their zoning ordinance | Well-organized function of zoning<br>Appropriate techniques to protect natural resources from contamination | Requires amendment to zoning ordinance<br>Requires enforcement by both visual inspection and onsite investigations |
| Special Permitting | Used to restrict uses within WHPAs that may cause ground water contamination if left unregulated | Community adopts special permit "thresholds" for various uses and structures within WHPAs<br>Community grants special permits for "threshold" uses only if ground water quality will not be compromised | Well-organized method of segregating land uses within critical resource areas such as WHPAs<br>Requires case-by-case analysis to ensure equal treatment of applicants | Requires detailed understanding of WHPA sensitivity by local permit granting authority<br>Requires enforcement of special permit requirements and onsite investigations |
| Large-Lot Zoning | Used to reduce impacts of residential development by limiting numbers of units within WHPAs | Community "down zones" to increase minimum acreage needed for residential development | Well-recognized prerogative of local government<br>Requires rational connection between minimum lot size selected and resource protection goals<br>Arbitrary large lot zones have been struck down without logical connection to Master Plan or WHPA program | Requires amendment to zoning ordinance |
| Transfer of Development Rights | Used to transfer development from WHPAs to locations outside WHPAs | Community offers transfer option within zoning ordinance<br>Community identifies areas where development is to be transferred "from" and "to " | Accepted land use planning tool | Cumbersome administrative requirements<br>Not well suited for small communities without significant administrative resources |
| Cluster/PUD Design | Used to guide residential development outside of WHPAs<br>Allows for "point source" discharges that are more easily monitored | Community offers cluster/PUD as development option within zoning ordinance<br>Community identifies areas where cluster/PUD is allowed (i e , within WHPAs) | Well-accepted option for residential land development | Slightly more complicated to administer than traditional "grid" subdivision<br>Enforcement/inspection requirements are similar to "grid" subdivision |
| Growth Controls/ Timing | Used to time the occurrence of development within WHPAs<br>Allows communities the opportunity to plan for wellhead delineation and protection | Community imposes growth controls in the form of building caps, subdivision phasing, or other limitation tied to planning concerns | Well-accepted option for communities facing development pressures within sensitive resource areas<br>Growth controls may be challenged if they are imposed without a rational connection to the resource being protected | Generally complicated administrative process<br>Requires administrative staff to issue permits and enforcement growth control ordinances |

**Table 9-1 Summary of Wellhead Protection Tools (Continued)**

| | Applicability to Wellhead Protection | Land Use Practice | Legal Considerations | Administrative Considerations |
|---|---|---|---|---|
| Performance Standards | Used to regulate development within WHPAs by enforcing predetermined standards for water quality<br>Allows for aggressive protection of WHPAs by limiting development within WHPAs to an accepted level | Community identifies WHPAs and established "thresholds" for water quality | Adoption of specific WHPA performance standards requires sound technical support<br>Performance standards must be enforced on a case-by-case basis | Complex administrative requirements to evaluate impacts of land development within WHPAs |
| **Regulatory** | **Subdivision Control** | | | |
| Drainage Requirements | Used to ensure that subdivision road drainage is directed outside of WHPAs<br>Used to employ advanced engineering designs of subdivision roads within WHPAs | Community adopts stringent subdivision rules and regulations to regulate road drainage/runoff in subdivisions within WHPAs | Well-accepted purpose of subdivision control | Requires moderate level of inspection and enforcement by administrative staff |
| **Regulatory** | **Health Regulations** | | | |
| Underground Fuel Storage Systems | Used to prohibit underground fuel storage systems (USTs) within WHPAs<br>Used to regulate USTs within WHPAs | Community adopts health/zoning ordinance prohibiting USTs within WHPAs<br>Community adopts special permit or performance standards for use of USTs within WHPAs | Well-accepted regulatory option for local government | Prohibition of USTs require little administrative support<br>Regulating USTs requires moderate amounts of administrative support for inspection followup and enforcement |
| Privately Owned Wastewater Treatment Plants (Small Sewage Treatment Plants) | Used to prohibit small sewage treatment plants (SSTP) within WHPAs | Community adopts health/zoning ordinance within WHPAs<br>Community adopts special permit or performance standards for use of SSTPs within WHPAs | Well-accepted regulatory option for local government | Prohibition of SSTPs require little administrative support<br>Regulating SSTPs requires moderate amount of administrative support of inspection followup and enforcement. |
| Septic Cleaner Ban | Used to prohibit the application of certain solvent septic cleaners, a known ground water contaminant, within WHPAs | Community adopts health/zoning ordinance prohibiting the use of septic cleaners containing 1,1,1-trichloroethane or other solvent compounds within WHPAs | Well-accepted method of protecting ground water quality | Difficult to enforce even with sufficient administrative support |
| Septic System Upgrades | Used to require periodic inspection and upgrading of septic systems | Community adopts health/zoning ordinance requiring inspection and, if necessary, upgrading of septic systems on a time basis (e g , every 2 years) or upon title/property transfer | Well-accepted purview of government to ensure protection of ground water | Significant administrative resources required for this option |

**Table 9-1. Summary of Wellhead Protection Tools (Continued)**

| | Applicability to Wellhead Protection | Land Use Practice | Legal Considerations | Administrative Considerations |
|---|---|---|---|---|
| Toxic and Hazardous Materials Handling Regulations | Used to ensure proper handling and disposal of toxic materials/waste | Community adopts health/zoning ordinance requiring registration and inspection of all businesses within WHPA using toxic/hazardous materials above certain quantities | Well accepted as within purview of government to ensure protection of ground water | Requires administrative support and onsite inspections |
| Private Well Protection | Used to protect private onsite water supply wells | Community adopts health/zoning ordinance to require permits for new private wells and to ensure appropriate well-to-septic-system setbacks Also requires pump and water quality testing | Well accepted as within purview of government to ensure protection of ground water | Requires administrative support and review of applications |
| **Non-regulatory. Land Transfer and Voluntary Restrictions** | | | | |
| Sale/Donation | Land acquired by a community with WHPAs, either by purchase or donation Provides broad protection to the ground-water supply | As non-regulatory technique, communities generally work in partnership with non-profit land conservation organizations | There are many legal consequences of accepting land for donation or sale from the private sector, mostly involving liability | There are few administrative requirements involved in accepting donations or sales of land from the private sector Administrative requirements for maintenance of land accepted or purchased may be substantial, particularly if the community does not have a program for open space management |
| Conservation Easements | Can be used to limit development within WHPAs | Similar to sales/donations, conservation easements are generally obtained with the assistance of non-profit land conservation organization | Same as above | Same as above |
| Limited Development | As the title implies, this technique limits development to portions of a land parcel outside of WHPAs | Land developers work with community as part of a cluster/PUD to develop limited portions of a site and restrict other portions, particularly those within WHPAs | Similar to those noted in cluster/PUD under zoning | Similar to those noted in cluster/PUD under zoning |
| **Non-regulatory: Other** | | | | |
| Monitoring | Used to monitor ground water quality within WHPAs | Communities establish ground water monitoring program within WHPA Communities require developers within WHPAs to monitor ground water quality downgradient from their development | Accepted method of ensuring ground water quality | Requires moderate administra-tive staffing to ensure routine sampling and response if sampling indicates contamination |
| Contingency Plans | Used to ensure appropriate response in cases of contaminant release or other emergencies within WHPA | Community prepares a contingency plan involving wide range of municipal/county officials | None | Requires significant up-front planning to anticipate and be prepared for emergencies |

**Table 9-1 Summary of Wellhead Protection Tools (Continued)**

| | Applicability to Wellhead Protection | Land Use Practice | Legal Considerations | Administrative Considerations |
|---|---|---|---|---|
| Hazardous Waste Collection | Used to reduce accumulation of hazardous materials within WHPAs and the community at large | Communities, in cooperation with the state, regional planning commission, or other entity, sponsor a "hazardous waste collection day" several times per year | There are several legal issues raised by the collection, transport, and disposal of hazardous waste | Hazardous waste collection programs are generally sponsored by government agencies, but administered by a private contractor |
| Public Education | Used to inform community residents of the connection between land use within WHPAs and drinking water quality | Communities can employ a variety of public education techniques ranging from brochures detailing their WHPA program, to seminars, to involvement in events such as hazardous waste collection days | No outstanding legal considerations | Requires some degree of administrative support for programs such as brochure mailing to more intensive support for seminars and hazardous waste collection days |
| **Legislative** | | | | |
| Regional WHPA Districts | Used to protect regional aquifer systems by establishing new legislative districts that often transcend existing corporate boundaries | Requires state legislative action to create a new legislative authority | Well-accepted method of protecting regional ground water resources | Administrative requirements will vary depending on the goal of the regional district<br>Mapping of the regional WHPAs requires moderate administrative support, while creating land use controls within the WHPA will require significant administrative personnel and support |
| Land Banking | Used to acquire and protect land within WHPAs | Land banks are usually accomplished with a transfer tax established by state government empowering local government to impose a tax on the transfer of land from one party to another | Land banks can be subject to legal challenge as an unjust tax, but have been accepted as a legitimate method of raising revenue for resource protection | Land banks require significant administrative support if they are to function effectively |

Source Horsley and Witten, 1989

### 9.2.2 Performance and Operating Standards

Performance and operating standards focus on establishing measurable environmental standards that protect human health or the environment Performance and operating standards alone do not specify how performance should be achieved Determining compliance for environmental standards, such as minimum acceptable concentrations of a chemical in ground water, is relatively simple, requiring sampling and chemical analysis Noncompliance, however, will require additional actions to find the reason for noncompliance and the implementation of methods to bring the system back into compliance This approach generally provides more flexibility than design standards and BMPs, since almost any method can be used as long as the performance standard is achieved To be effective, performance and operation standards must be implemented far enough from the wellhead area that noncompliance can be rectified without posing a threat to the well

### 9.2.3 Ground Water Monitoring

Ground water monitoring is an essential component of wellhead protection All WHPA delineation methods involve irreducible uncertainties due to the inherent physical and chemical complexity of hydrogeologic systems Previous chapters have made suggestions for ways to address uncertainties, but no delineation method or ground water management practice is fail-safe For early detection of contamination, monitoring wells should be installed between significant point sources of potential contamination and the wellhead ahead in the most direct ground water flow path line (Chapter 2) One or more monitoring wells should be installed upgradient of the wellhead along a specified time of travel contour (say 2- to 5-year isochron) to provide an early warning of the presence of contaminants traveling toward the well

Installation of ground water monitoring wells and ground water sampling require special procedures to ensure

Table 9-2. Potential Management Tools for Wellhead Protection (Born et al , 1987, U S EPA, 1989)

| Regulatory | Nonregulatory |
|---|---|
| **Zoning Ordinances.** Zoning ordinances typically are comprehensive land-use requirements designed to direct the development of an area Many local governments have used zoning to restrict or regulate certain land uses within wellhead protection areas | **Purchase of Property or Development Rights** The purchase of property or development rights is a tool used by some localities to ensure complete control of land uses in or surrounding a wellhead area This tool may be preferable if regulatory restrictions on land use are not politically feasible and the land purchase is affordable |
| **Subdivision Ordinances.** Subdivision ordinances are applied to land that is divided into two or more subunits for sale or development. Local governments use this tool to protect wellhead areas in which ongoing development is causing contamination | **Public Education** Public education often consists of brochures, pamphlets, or seminars designed to present wellhead area problems and protection efforts to the public in an understandable fashion This tool promotes the use of voluntary protection efforts and builds public support for a community protection program |
| **Site Plan Review.** Site plan reviews are regulations requiring developers to submit for approval plans for development occurring within a given area This tool ensures compliance with regulations or other requirements made within a wellhead protection area | **Waste Reduction** Residential hazardous waste management programs can be designed to reduce the quantity of household hazardous waste being disposed of improperly This program has been used un localities where municipal landfills potentially threaten ground water due to improper household waste disposal in the wellhead area |
| **Design Standards** Design standards typically are regulations that apply to the design and construction of buildings or structures This tool can be used to ensure that new buildings or structures placed within a wellhead protection area are designed so as not to pose a threat to the water supply | **Best Management Practices** BMPs are voluntary actions that have a long tradition of being used, especially un agriculture Technical assistance for farmers wishing to apply them is available from local Extension and SCS offices |
| **Operating Standards** Operating standards are regulations that apply to ongoing land-use activities to promote safety or environmental protection Such standards can minimize the threat to the wellhead area from ongoing activities such as the application of agricultural chemicals or the storage and use of hazardous substances | **Training and Demonstration** These programs can complement many regulations, for example, training underground storage tank inspectors and local emergency response teams or demonstration of agricultural BMPs |
| **Source Prohibitions.** Source prohibitions are regulations that prohibit the presence or use of chemicals or hazardous activities within a given area Local governments can use restrictions on the storage or handling of large quantities of hazardous materials within a wellhead protection area | **Ground-Water Monitoring** Ground-water monitoring generally consists of sinking a series of test wells and developing an ongoing water quality testing program This tool provides for monitoring the quality of the ground-water supply or the movement of a contaminant plume |
| **Inspection and Testing** Local governments can use their statutory home rule power to require more stringent control of contamination sources within wellhead protection areas than given in federal or state rules | **Contingency Planning** Local governments can develop their own contingency plans for emergency response to spills and for alternative water supply in case of contamination of the existing supply |

that samples are representative Major EPA documents that provide guidance in this area include Aller et al (1991), Barcelona et al (1985), U S EPA (1986d), U S EPA (1986e), and U S EPA (1993b)

## 9.3 Specific Regulatory and Technical Approaches

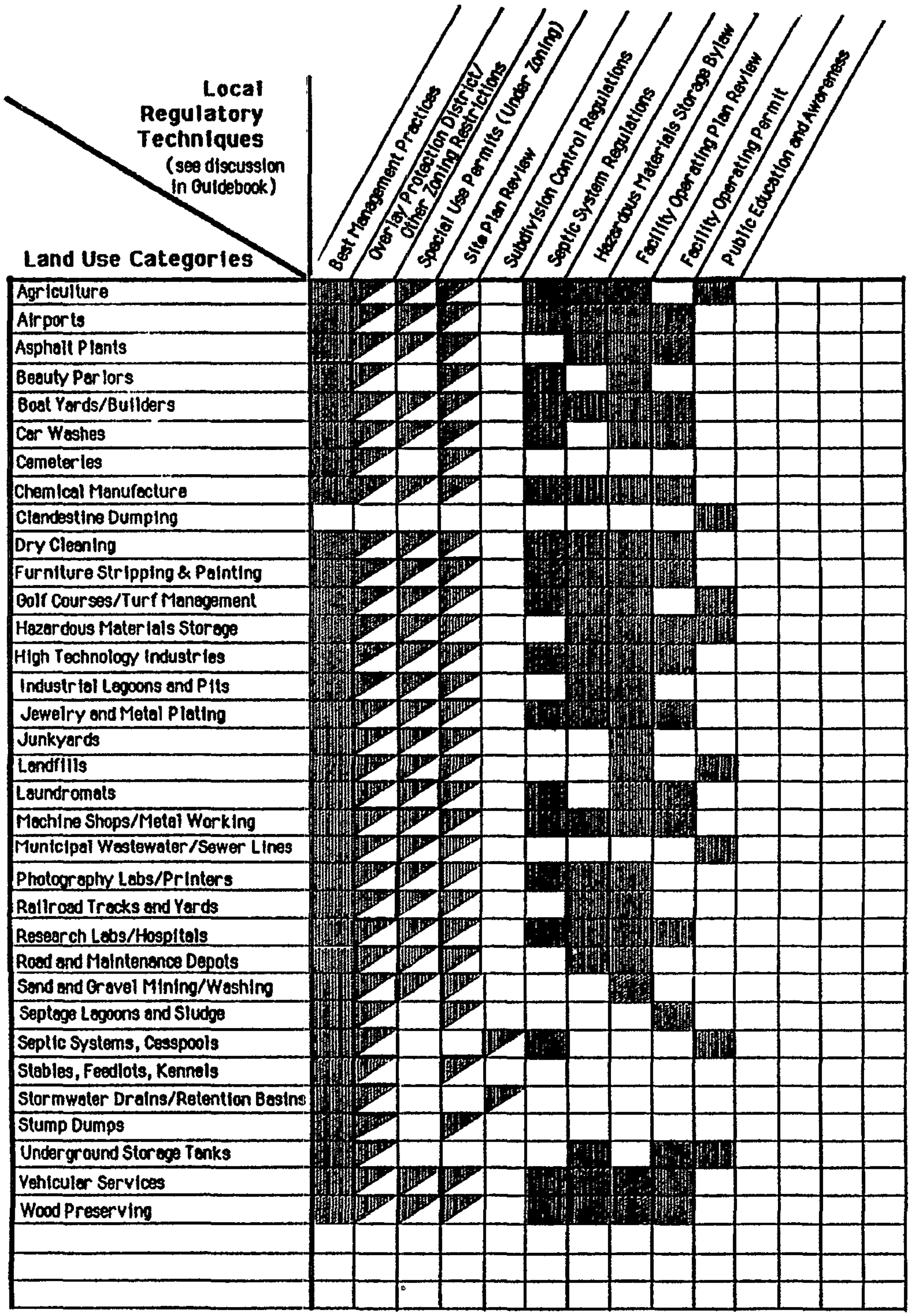
In addition to Checklist 9-1 and Tables 9-1 and 9-2 discussed earlier, the following may be helpful in developing specific regulatory and technical approaches for managing a WHPA

- Worksheet C-7 includes (1) a summary form for identifying existing bylaws available to regulate land use activities within a WHPA and areas where regulations might be needed, and (2) a questionnaire to identify key concerns and existing control mechanisms
- Figure 9-1 provides ratings for the applicability of 10 local regulatory techniques to 34 land use categories
- Table 9-3 identifies general BMPs for commercial and industrial facilities
- Table 8-4 identifies references containing recommended detailed BMPs for specific land uses

Chapter 10 includes six case studies that provide examples of different approaches to management of WHPAs in different hydrogeologic settings

## 9.4 Contingency Planning

Developing a contingency plan to deal with emergency threats to ground water quality in the WHPA, such as accidental chemical spills, is an essential part of managing a wellhead protection area The plan should include information that allows a rapid response to minimize damage from accidental spills or other releases of chemicals, such as during efforts to control a fire at a known chemical storage site The plan should also include short- and long-term solutions to the



**Local Regulatory Techniques** (see discussion in Guidebook)

| Land Use Categories | Best Management Practices | Overlay Protection District/Other Zoning Restrictions | Special Use Permits (Under Zoning) | Site Plan Review | Subdivision Control Regulations | Septic System Regulations | Hazardous Materials Storage Bylaw | Facility Operating Plan Review | Facility Operating Permit | Public Education and Awareness | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Agriculture | ▨ | ◩ | ◩ | ◩ | | ▨ | ▨ | ▨ | | ▨ | | | | |
| Airports | ▨ | ◩ | ◩ | ◩ | | ▨ | ▨ | ▨ | ▨ | | | | | |
| Asphalt Plants | ▨ | ◩ | ◩ | ◩ | | | ▨ | ▨ | ▨ | | | | | |
| Beauty Parlors | ▨ | ◩ | | ◩ | | ▨ | | ▨ | | | | | | |
| Boat Yards/Builders | ▨ | ◩ | ◩ | ◩ | | ▨ | ▨ | ▨ | ▨ | | | | | |
| Car Washes | ▨ | ◩ | ◩ | ◩ | | ▨ | | ▨ | ▨ | | | | | |
| Cemeteries | ▨ | ◩ | | ◩ | | | | | | | | | | |
| Chemical Manufacture | ▨ | ◩ | ◩ | ◩ | | ▨ | ▨ | ▨ | ▨ | | | | | |
| Clandestine Dumping | | | | | | | | | | ▨ | | | | |
| Dry Cleaning | ▨ | ◩ | ◩ | ◩ | | ▨ | ▨ | ▨ | ▨ | | | | | |
| Furniture Stripping & Painting | ▨ | ◩ | ◩ | ◩ | | ▨ | ▨ | ▨ | ▨ | | | | | |
| Golf Courses/Turf Management | ▨ | ◩ | ◩ | ◩ | | ▨ | ▨ | ▨ | | ▨ | | | | |
| Hazardous Materials Storage | ▨ | ◩ | ◩ | ◩ | | | ▨ | ▨ | ▨ | ▨ | | | | |
| High Technology Industries | ▨ | ◩ | ◩ | ◩ | | ▨ | ▨ | ▨ | ▨ | | | | | |
| Industrial Lagoons and Pits | ▨ | ◩ | ◩ | ◩ | | | ▨ | ▨ | | | | | | |
| Jewelry and Metal Plating | ▨ | ◩ | ◩ | ◩ | | ▨ | ▨ | ▨ | ▨ | | | | | |
| Junkyards | ▨ | ◩ | ◩ | ◩ | | | | ▨ | | | | | | |
| Landfills | ▨ | ◩ | ◩ | ◩ | | | | ▨ | | ▨ | | | | |
| Laundromats | ▨ | ◩ | ◩ | ◩ | | ▨ | | ▨ | ▨ | | | | | |
| Machine Shops/Metal Working | ▨ | ◩ | ◩ | ◩ | | ▨ | ▨ | ▨ | ▨ | | | | | |
| Municipal Wastewater/Sewer Lines | ▨ | ◩ | ◩ | ◩ | | | | | | ▨ | | | | |
| Photography Labs/Printers | ▨ | ◩ | ◩ | ◩ | | ▨ | ▨ | ▨ | | | | | | |
| Railroad Tracks and Yards | ▨ | ◩ | ◩ | ◩ | | | ▨ | ▨ | | | | | | |
| Research Labs/Hospitals | ▨ | ◩ | ◩ | ◩ | | ▨ | ▨ | ▨ | ▨ | | | | | |
| Road and Maintenance Depots | ▨ | ◩ | ◩ | ◩ | | | ▨ | ▨ | | | | | | |
| Sand and Gravel Mining/Washing | ▨ | ◩ | ◩ | ◩ | | | | ▨ | | | | | | |
| Septage Lagoons and Sludge | ▨ | ◩ | | ◩ | | | | | ▨ | | | | | |
| Septic Systems, Cesspools | ▨ | ◩ | | | ◩ | ▨ | | | | ▨ | | | | |
| Stables, Feedlots, Kennels | ▨ | ◩ | | ◩ | | | | | | | | | | |
| Stormwater Drains/Retention Basins | ▨ | ◩ | | | ◩ | | | | | | | | | |
| Stump Dumps | ▨ | ◩ | | ◩ | | | | | | | | | | |
| Underground Storage Tanks | ▨ | ◩ | | | | | ▨ | | ▨ | ▨ | | | | |
| Vehicular Services | ▨ | ◩ | ◩ | ◩ | | ▨ | ▨ | ▨ | ▨ | | | | | |
| Wood Preserving | ▨ | ◩ | ◩ | ◩ | | ▨ | ▨ | ▨ | ▨ | | | | | |
| | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |

**Explanation of the Matrix**

- ☐ Not Applicable
- ◩ Applicable to Proposed Uses
- ▨ Applicable to Existing and Proposed Land Uses

This Matrix relates local regulatory techniques to various land use categories The local authority has options for controlling potential contaminant sources Each technique can incorporate provisions for existing uses, proposed uses, and other situations, such as a changed use or an abandoned use Because techniques to control existing uses automatically cover future uses, a box showing applicability to existing uses only does not appear

Figure 9-1 Land use/local regulatory techniques matrix (Noake, 1988)

**Table 9-3. General Best Management Practices (Inglese, 1992)**

| | |
|---|---|
| **DESIGN BMPs** | |
| Subsurface Disposal Systems | Minimum setback distances should be established between limits of leach fields and wellheads Distances should be based on information such as percolation tests, zone of influence of leachate mounding, wellhead protection areas, and time of travel |
| | Leach fields must be sized according to soil characteristics and hydraulic and pollutant loadings Excessively sized septic system leach fields may cause reduced effectiveness if normal flows are inadequate to maintain a biologically active clogging layer throughout the leach field |
| | Septic systems are not recommended in areas with karst, fractured, cavernous, volcanic, or any other highly permeable subsurface formation |
| | Additional detention times for septic tanks, and larger buffer zones around leachfields should be considered in septic system design |
| | All septic tank installations should be designed or retrofitted with provisions for sampling at the outlet baffle Gas baffles should be installed at the outlet |
| | Maximum contaminant levels must be met for pollutants prior to discharge to leachfield distribution system |
| | Any facility on a septic system must have its septic tanks effluent monitored for Ph, BOD, nitrites, nitrates, and ammonia Monitoring should be done annually and increased to a quarterly schedule if detectable levels are recorded After three successive non-detectable readings, the monitoring can be reduced to an annual schedule |
| | Verify that the septic system is serviced by a waste hauler |
| Floor Drains | Eliminate floor drain discharges to the ground, septic systems (except in sanitary facilities), storm sewers, or to any surface water body from any location in the facility |
| | If no floor drains are installed, all discharges to the floor should be collected, contained, and disposed of by an appropriate waste hauler in accordance with federal and state requirements |
| | Floor drains in sanitary facilities must either discharge to a septic system, a municipal sanitary sewer, or a holding tank which is periodically pumped out |
| | Floor drains in work areas can either be connected to a holding tank with a gravity discharge pipe, or to a collection sump which discharges to a holding tank |
| Dry Wells | Dry wells must be eliminated in ALL cases unless they receive ONLY CLEAN WATER DISCHARGES which meets all established Maximum Contaminant Levels (MCLs) promulgated under the Safe Drinking Water Act and other state and local standards for drinking water, and is in compliance with any other state and local requirements |
| Floors | Floor surfaces in work areas and chemical storage areas should be sealed with an impermeable material resistant to acids, caustics, solvents, oils, or any other substance which may be used or generated at the facility Sealed floors are easier to clean without the use of solvents |
| | Work area floors should be pitched to appropriate floor drains If floor drains are not used, or if they are located close to entrance ways, then berms should be constructed along the full width of entrances to prevent stormwater runoff from entering the building |
| | Berms should also be used to isolate floor drains from spill-prone areas |
| Storage Facilities | Loading and unloading of materials and wastes should be done within an enclosed or roofed area with secondary containment and isolated from floor drains to prevent potential spills from contaminating stormwater or discharging to the ground |
| | Underground storage tanks should not be used, unless explicitly required by fire codes or other federal, state or local regulations |
| | Where underground tanks are required, they should have double-walled construction or secondary containment such as a concrete vault lined or sealed with an impermeable material and filled with sand Both types of tanks should have appropriate secondary containment monitoring, high level and leak sensing audio/visual alarms, level indicators, and overfill protection If a dip stick is used for level measurements, there should be a protective plate or basket where the stick may strike the tank bottom |
| | Above-ground tanks should have 110% secondary containment or double-walled construction, alarms, and overfill protection, and should be installed in an enclosed area isolated from floor drains, stormwater sewers, or other conduits which may cause a release into the environment. |
| | Fill-pipe inlets should be above the elevation of the top of the storage tank |
| | Tanks and associated appurtenances should be tested periodically for structural integrity |
| | Storage areas for new and waste materials should be permanently roofed, completely confined within secondary confinement berms, isolated from floor drains, have sealed surfaces, and should not be accessible to unauthorized personnel |
| | Drum and container storage areas should be consolidated into one location for better control of material and waste inventory |

**Table 9-3 General Best Management Practices (Continued)**

| | |
|---|---|
| Cooling Water | Closed-loop cooling systems should be considered to eliminate cooling water discharges |
| | Any cooling water from solvent recovery systems should be free of combination from solvent, metals or other pollutants, and should not discharge to the ground Cooling water may be discharged to a storm sewer, sanitary sewer, or stream, provided all federal, state, and local requirements are met |
| Utilities | Floor drains should be eliminated in rooms where boilers or emergency generators are housed |
| Water Conservation | Flow restrictors and low-flow faucets for sinks and spray nozzles should be installed to minimize hydraulic loading to subsurface disposal systems |
| Foundation Drainage & Dewatering | If water from foundation drainage and dewatering is not contaminated, it may be discharged to a storm sewer or stream in accordance with any applicable federal, state, or local requirements |
| | Contaminated water from foundation drainage and dewatering indicates a likely ground water combination problem, which should be investigated and remediated as necessary |
| Stormwater Management | Stormwater contact with materials and wastes must be avoided to the greatest extent possible Storage of materials and wastes should be isolated in roofed or enclosed areas to prevent contact with precipitation |
| | Uncovered storage areas should have a separate stormwater collection system which discharges to a holding tank |
| | Stormwater from building roofs may discharge to the ground However, if solvent distillation equipment or vapor degreasing is used, with a vent that exhausts to the roof, then roof leaders may become cross contaminated with solvent These potential sources of cross contamination must be investigated and eliminated |
| Cross-connections | Cross-connections, such as sanitary discharges to storm sewers, stormwater discharges to sanitary sewers, or floor drain discharges to storm sewer systems, should be identified and eliminated |
| Work Areas | Consolidate waste-generating operations and physically segregate them from other operations They should preferably be located within a confinement area with sealed floors and with no direct access to outside the facility This reduces the total work area exposed to solvents, facilitates waste stream segregation and efficient material and waste handling, and minimizes cross combination with other operations and potential pathways for release into the environment |
| | Waste collection stations should be provided throughout work areas for the accumulation of spent chemicals, soiled rags, etc Each station should have labeled containers for each type of waste fluid This provides safe interim storage of wastes, reduces frequent handling of small quantities of wastes to storage areas, and minimizes the overall risk of a release into the environment |
| | New solvent can be supplied by dedicated feed lines or dispensers to minimize handling of materials These feed lines must default to a closed setting to prevent unmonitored release of material |
| Connection to Municipal Sanitary Sewers | Existing and future facilities should connect their sanitary facilities to municipal sanitary sewer systems where they are available |
| Holding Tanks | Facilities should discharge to holding tanks if they are located where municipal sanitary sewers are not available, subsurface disposal systems are not feasible, existing subsurface disposal systems are failing, or if they are high risk facilities located in wellhead protection areas |
| **PROCEDURAL BMPs** | |
| Material & Waste Inventory Control | Conduct monthly monitoring of inventory and waste generation |
| | Order raw materials on an as-needed basis and in appropriate unit sizes to avoid waste and reduce inventory |
| | Observe expiration dates on products in inventory |
| | Eliminate obsolete or excess materials from inventory |
| | Return unused or obsolete products to the vendor |
| | Consider waste management costs when buying new materials and equipment |
| | Ensure material and waste containers are properly labeled Not labeling or mislabeling is a common problem |
| | Mark purchase date and use older materials first |
| | Maintain product Material Safety Data Sheets to monitor materials in inventory and the chemical ingredients of wastes Make MSDS sheets available to employees |
| | Observe maximum on-site storage times for wastes |
| | Control access to materials that are hazardous when spent, encourage material substitution |
| Preventative & Corrective Maintenance | A regularly scheduled internal inspection and maintenance program should be implemented to service equipment, to identify potential leaks and spills from storage and equipment failure, and to take corrective action as necessary to avoid a release to the environment At a minimum, the schedule should address the following areas |

**Table 9-3 General Best Management Practices (Continued)**

| | |
|---|---|
| Preventative & Corrective Maintenance (continued) | Tanks, drums, containers, pumps, equipment, and plumbing, |
| | Work stations & waste disposal stations, |
| | Outside and inside storage areas, and stormwater catch basins & detention ponds, |
| | Evidence of leaks or spills within the facility and on the site, |
| | Areas prone to heavy traffic from loading and off loading of materials and wastes, |
| | Properly secured containers when not in use, |
| | Proper handling of all containers, |
| | Drippage from exhaust vents, |
| | Proper operation of equipment, solvent recovery, and emission control systems |
| Spill Control | Use emergency spill kits and equipment Locate them at storage areas, loading and unloading areas, dispensing areas, work areas |
| | Clean spills promptly |
| | Use recyclable rags or absorbent spill pads to clean up minor spills, and dispose of these materials properly |
| | Clean large spills with a wet vacuum, squeegee and dust pan, absorbent pads, or brooms Dispose of all clean up materials properly |
| | Minimize the use of disposable granular- or powder-absorbents |
| | Spilled material should be neutralized as prescribed in Material Safety Data Sheets (MSDS), collected, handled, and disposed of in accordance with federal, state, and local regulations |
| | Use shake-proof and earthquake proof containers and storage facilities to reduce spill potential |
| Materials & Waste Management | Use spigots, pumps, or funnels for controlled dispensation and transfer of materials to reduce spillage, use different spigots, etc , for different products to maintain segregation and minimize spillage |
| | Store materials in a controlled, enclosed environment (minimal temperature and humidity variations) to prolong shelf life, minimize evaporative releases, and prevent moisture from accumulating |
| | Keep containers closed to prevent evaporation, oxidation, and spillage |
| | Place drip pans under containers and storage racks to collect spillage |
| | Segregate wastes that are generated, such as hazardous from non-hazardous, acids from bases, chlorinated from nonchlorinated solvents, and oils from solvents, to minimize disposal costs and facilitate recycling and reuse |
| | Empty drums and containers may be reused, after being properly rinsed, for storing the same or compatible materials |
| | Recycle cleaning rags and have them cleaned by an appropriate industrial launderer |
| | Use dry cleanup methods and mopping rather than flooding with water |
| | Floors may be roughly cleaned with absorbent prior to mopping, select absorbents which can be reused or recycled |
| | Recycle cardboard and paper, and reuse or recycle containers and drums |
| | Wastes accumulated in holding tanks and containers must be disposed of through an appropriately licensed waste transporter in accordance with federal, state, and local regulations |
| Management | Management involvement in the waste reduction and pollution prevention initiatives is essential to its successful implementation in the work place By setting the example and encouraging staff participation through incentives or awards, management can increases employee awareness about environmentally sound practice A first step is to involve management in conducting a waste stream analysis to determine the potential for waste reduction and pollution prevention This analysis should include the following steps |
| | Identify plant processes where chemicals are used and waste is generated, |
| | Evaluate existing waste management and reduction methods, |
| | Research alternative technologies, |
| | Evaluate feasibility of waste reduction options, |
| | Implement measures to reduce wastes, and |
| | Periodically evaluate your waste reduction program |
| | Develop an energy and materials conservation plan to promote the use of efficient technologies, well-maintained inventories, and reduced water and energy consumption |

**Table 9-3 General Best Management Practices (Continued)**

| | |
|---|---|
| Management (continued) | Sound environmental management should include the currency and completeness of site and facility plans, facility records and inventory management, discharge permits, manifests for disposal of wastes, contracts with haulers for wastes, and contracts with service agents to handle recycling of solvents or to regularly service equipment |
| Employee Training | Training programs should be developed which include the following<br>Proper operation of process equipment,<br>Loading and unloading of materials,<br>Purchasing, labeling, storing, transferring, and disposal of materials,<br>Leak detection, spill control, and emergency procedures, and<br>Reuse/recycling/material substitution<br>Employees should be trained prior to working with equipment or handling of materials, and should be periodically refreshed when new regulations or procedures are developed<br>Employees should be made aware of MSDS sheets and should understand their information<br>Employee awareness of the environmental and economic benefits of waste reduction and pollution prevention, and the adverse consequences of ignoring them, can also facilitate employee participation |
| Communication | Posting of signs, communication with staff, education and training, and posting of manuals for spill control, health and safety (OSHA), operation and maintenance of facility and equipment, and emergency response are essential Storage areas for chemicals and equipment, employee bathrooms, manager's office, and waste handling stations are suggested areas for posting communication A bulletin board solely for environmental concerns should be considered<br>Regular inspection and maintenance schedules should be posted and understood by staff |
| Record Keeping | Facility plans, plumbing plans, and subsurface disposal system plans and specifications must be updated to reflect current facility configuration Copies of associated approvals and permits should be maintained on file<br>OSHA requirements, health and environmental emergency procedures, materials management plans, inventory records, servicing/repair/inspections logs, medical waste tracking and hazardous waste disposal records must be maintained up to date and made available for inspection by regulatory officials |

temporary or permanent loss of all or a portion of the water system source A contingency plan should include the following elements

1 Basic information about the water supply system, such as population, number of service connections, location of fire hydrants, average daily usage, and the names and telephone numbers of the water system operator, the fire chief, police chief, and other emergency planning officials

2 A list of potential contaminant sources and their locations (see Chapter 8)

3 A map identifying the WHPA boundaries, how they were delineated, and significant aspects of local hydrogeology, geography, and geology that affect movement of contaminants in the subsurface

4. Fire-fighting plans for specific sites, especially sites within the WHPA that store or handle toxic chemicals Such plans should be developed in coordination with the Local Emergency Planning Committee (see Section 8 3)

5 Surface spill emergency response procedures, including the names and phone numbers of agencies and other individuals outside the community who should be informed These procedures should be developed in coordination with the Local Emergency Planning Committee (see Section 8 3) Information on the type, location, and amount of spill should be recorded

6 Short-term emergency water supply options, including a brief description of the type and location of water supply and the names and telephone numbers of people who should be contacted in the event that the source must be used

7 Long-term alternative water supply options

U S EPA (1990c) provides general guidance on contingency planning Many state wellhead protection programs have developed additional guidance Worksheet C-8 can be used to develop a contingency plan, and Worksheet C-9 can be used for chemical emergency spill and documentation If these worksheets are used, any state guidance documents should be reviewed and the worksheet modified, if necessary

**Table 9-4. Index to Major References on Ground Water Protection Management***

| Topic | References |
|---|---|
| General Land Use Planning | Ellickson and Tarlock (1981), Freund and Goodman (1968), Getzels and Thurow (1979), Global Cities Project (1993), Hendler (1977), Miller and Wood (1983), Mossa (1987), Robinson (1988), Rusmone (1982), Wilson et al (1979) |
| GW Protection | Amsden and Mullen (1990), Cantor and Knox (1986), Cantor et al (1987), Clark and Cherry (1992), Conservation Foundation (1987a, 1987b, 1987c), Cross (1993), Flanagan et al (1991), Greeley-Polhemus Group (1985), Horsley Witten Hegemann, Inc (1992), Kerns (1977), LeGrand and Rosen (1992), Matthess et al (1985), Milde et al (1983), Montana Environmental Quality Council (1990), Page (1987), Pojacek (1977), Southern Water Authority (1985), Stroman (1987), U S EPA (1984a, 1984b, 1985a, 1987b, 1987g, 1991a, 1991b, 1992c), U S OTA (1984), Western Michigan University (1988), Worden (1988), Zaporozec (1991), *Best Management Practices* Noake (1988), Inglese (1992), *Emergency Planning* New York State Department of Health (1984), U S EPA (1985e), *Nonpoint Source Pollution Control* Holmes (1979), ICPRB (1981), Novotny and Chesters (1981), *Erosion/Sediment Control* APA (1984), Association of Bay Area Governments (1981), Goldman et al (1986), *Agriculture* Baker (1990-pesticides), Freshwater Foundation (1988-1990), Kemp and Erickson (1989), Massey (1984), Stewart (1976), U S EPA (1987e, 1988d), *Road Salt* Curtis et al (1986), Greeley-Polhemus Group (1985), NJDEPE (1992), *Septic Systems* Lukin (1992), NJDEPE (1992), U S EPA (1986b, 1986c, 1987c), *Industrial Source Control* API (1988), Inglese (1992), Licis et al (1991), NJDEPE (1992), vanZyl et al (1987), Ward et al (1990), *Karst* Davis and Quinlin (1991), Fischer et al (1991), Quinlin et al (1991), Rubin (1991), *Accidental Spills* Yang and Bye (1979a, 1979b), *Sole Source Aquifers* U S EPA (1987d, 1988c), *Monitoring* Aller et al (1991), Barcelona et al (1985), Meyer (1990), Nielsen and Schalla (1991), U S EPA (1986d, 1986e, 1989e, 1993b) |
| Institutional Framework | Henderson (1987), Hodge and Brown (1990), Holmes (1979), Kerns (1977), LeGrand and Rosen (1992), Lehr (1987), Pisanelli and Dutram (1990), Redlich (1988), Tolman et al (1991), Western Michigan University (1988), Yanggen and Amrhein (1989), *Ordinances* Minnesota Project (1984), Trefry (1990), *Data Management* U S EPA (1987h, 1988f, 1990b), *EPA Program Analyses* U S EPA (1985b, 1990d, 1992c), *State Programs* Booth and Bronson (1983-New York), Born et al (1988-Wisconsin), Environmental Law Institute (1990), Henderson et al (1985), Leavall (1990-Ohio), Meccozi (1989-Wisconsin), National Research Council (1987), NHDES (1991—NH), Pisanelli and Dutram (1990-Maine), Raymond (1981), Roy (1988), Stroman (1987-MA), U S EPA (1985c, 1987b, 1987f, 1988a, 1988e, 1989a, 1992b), Walden (1988), Weatherington-Rice and Hottman (1990-Ohio), *Financing* Allee (1986), U S EPA (1987i, 1987f, 1988b, 1989a, 1989b, 1992b) |
| Local Planning/Approaches | Allee (1986), APA (1975), Blatt (1986), Boody (1990), Born et al (1988), Cross (1991), Dean (1988), DiNovo and Jaffe (1984a, 1984b), Group for the South Fork (1982), Jaffe (1987), Jaffe and DiNovo (1987), MDEP (1991), Michigan Departments of Natural Resources and Public Health (1993), National Research Council (1987), National Rural Water Association (1991), New Hampshire Office of State Planning (1991), Oates et al (1990), Pettyjohn (1989), Potter (1984), Redlich (1988), Rusmone (1982), Tripp and Jaffe (1979), University of Oklahoma (1986), U S EPA (1989c, 1989d, 1990c), Yanggen and Weberdorfer (1991), *Decision-Maker/Citizen Guides* Baize and Gilkerson (1992), Born et al (1987), Central Connecticut Regional Planning Agency (1981), Community Resource Group (1992), Concern (1989), Dean and Wyckoff (1991), Gordon (1984), Hall Associates and Dight (1986), Harrison and Dickinson (1984), Hrezo and Nickinson (1986), Madarchik (1992), Masschusetts Department of Environmental Quality Engineering (1985), Mullikin (1984), Murphy (undated), North Dakota State Department of Health (1993), Paly and Steppacher (undated), Pierce (1992), Raymond (1986), U S EPA (1987a, 1990a, 1992a, 1993a) |
| Public Education Materials | Maine Association of Conservation Commissions 1985), Massachusetts Audubon Society (1984-1987), New England Interstate Water Pollution Control Commission (1989), North Dakota State Department of Health (1992), Paly and Steppacher (undated), Sponenberg and Kahn (1984), Texas Water Commission (1989), University of Rhode Island (1988), U S EPA (1984b, 1985d, 1990a, 1991c, 1991d, 1992d), Waller (1988) |

* See also case study references in Chapter 10

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* See Introduction for information on how to obtain documents

# *Chapter 10*
# *Wellhead Protection Case Studies*

## 10.1 Overview of Case Studies

This chapter contains six case studies that illustrate the range of approaches that are possible for planning and implementing wellhead protection programs Each case study is presented in a uniform format that includes (1) a brief description of the community and hydrogeologic setting of the wellhead area, (2) wellhead protection area (WHPA) delineation methods used, (3) contaminants of concern, and (4) management methods used to protect ground water The case studies emphasize two hydrogeologic settings that are especially vulnerable to contamination (1) alluvial aquifers (Sections 10 2 2, 10 2 5, and 10 2 6), and (2) carbonate aquifers (Sections 10 2 1, 10 2 3 and 10 2 4) The first three case studies illustrate well-based protection approaches ranging from a single well in southeastern Pennsylvania (Section 10 2 1) to multiple wells in Rockford, Illinois (Section 10 2 2), to multiple wellfields in Palm Beach County, Florida (Section 10 2 3)

The remaining case studies illustrate different approaches to ground water protection that emphasize land use controls without special reference to location of wells Clinton Township in Hunterdon County, New Jersey, focuses on land use controls in highly vulnerable carbonate areas (Section 10 2 4) Nantucket, Massachusetts, applies land use controls of varying stringency to four aquifer protection zones that cover the island's entire 40 square miles (Section 10 2 5) The Pima Association of Governments, in Pima County, Arizona, has developed a regional approach to ground water protection that emphasizes land use controls based on hydrogeologic vulnerability mapping (Section 10 2 6)

Section 10 3 provides information on additional reference sources that contain case studies in WHPA delineation and management

## 10.2 Case Studies

### *10.2.1 Cabot Well, Pennsylvania: The Cost of Not Protecting Ground Water Supplies*

The Cabot well illustrates the possible costs associated with failing to develop a wellhead protection program (Emrich and Luitweiler, 1990)

**Community and Hydrogeologic Setting** The Philadelphia Suburban Water Company (PSWC) serves a population of about 8,000,000 people in a 333 square mile service area north and west of Philadelphia, Pennsylvania About 25 percent of the utility's production capacity comes from one well and one major ground water reservoir In 1965, PSWC drilled a water supply well near King of Prussia, Pennsylvania The well was completed in the Cambrian-age Ledger dolomite, a fairly pure, often massive, coarsely crystalline formation known to yield large amounts of water The well was drilled to a depth of 275 feet, cased to 140 feet, and yields almost 2,000 gallons per minute

**Wellhead Protection Area Delineation Methods** The Cabot well was drilled before existing programs for wellhead protection were established

**Contaminant Sources** When the Cabot well first began operation, there were occasional incidents of elevated turbidity which were attributed to sinkhole activity in the carbonate rock terrain These incidents were successfully controlled (see below) Rapid urbanization occurred around the well in the 1970s and 1980s, nearby land was developed for a business campus and an office/hotel/convention center complex (Figure 10-1) Construction activities resulted in turbidity problems in the well Relocation of a stream in the area, fill of the floodplain, and inadequate sizing of culverts resulted in occasional floods that inundated the well The periodic flooding resulted in erratic turbidity spikes and high bacteria counts

**Wellhead Protection Area Management Methods** Turbidity from sinkhole development was successfully controlled by locating sinkholes as soon as they developed and promptly filling them with compacted gravel and clay to prevent infiltration of surface waters Recasing of the well failed to solve the problems of turbidity and bacterial contamination stemming from uncontrolled urban development in the vicinity of the well Eventually, investigation of bacterial records, dye studies of the stream and nearby sewer, review of a sewer inflow and infiltration study, and placement of monitoring wells around the central well provided evidence that the sewer was the source of the bacteria At the time the case

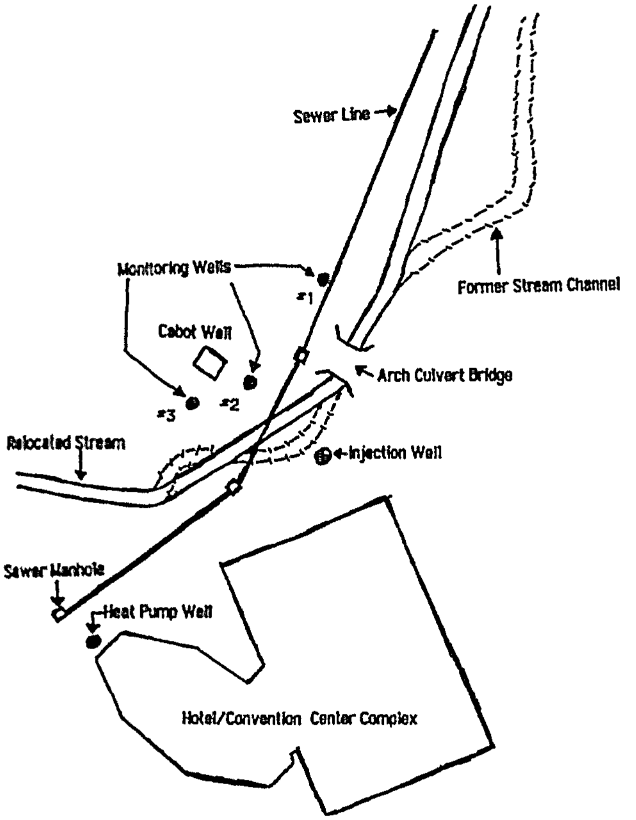

**Figure 10-1.** Development around Cabot well (Emrich and Luitweiler, 1990)

study was written, remediation of the sewer was in progress, and PSWC was conducting pilot tests of advanced filtration technology in case problems were not entirely corrected The authors of the case study concluded that hundreds of thousands of dollars in investigation and remediation costs were the legacy of the absence of an effective wellhead protection program

### *10.2.2 Rockford, Illinois: Wellhead Management in a Contaminated Aquifer*

Rockford, Illinois, illustrates the importance of considering possible variations in well pumping rates, and interactions between multiple pumping wells when delineating a wellhead protection area (Wehrmann and Varljen, 1990).

**Community and Hydrogeologic Setting** Rockford, in northcentral Illinois, has a population of about 140,000 The main source of water supply is a sand and gravel glacial outwash aquifer associated with the Rock River that fills a bedrock valley to depths exceeding 250 feet Depth to ground water is approximately 30 to 40 feet, and municipal wells are capable of producing in excess of 1,000 gallons per minute The study area, which has been placed on EPA's National Priority List for cleanup of contamination (see below), includes over 300 private domestic wells and 3 municipal wells

**Wellhead Protection Area Delineation Methods** Numerical ground water flow modeling (PLASM and GWPATH) was used to delineate zones of contribution of wells and evaluate the interactions of well operations on capture zones

**Contaminant Sources** A large number of industrial facilities, many of which have operated in the area for decades, have created a high potential for contamination of ground water Sampling of ground water wells has documented extensive contamination by volatile organic compounds (VOCs) of the public and private wells in southeast Rockford Maximum VOC levels in several private wells exceeded 0 4 mg/L, and the 3 municipal wells contained VOC concentrations from 0 035 to more than 1 4 mg/L These findings resulted in southeast Rockford being placed on EPA's National Priority List of Superfund Sites, with emergency response and remedial investigations currently under way

**Wellhead Protection Area Management Methods** The discovery that three municipal wells were contaminated with VOCs resulted in their abandonment and an increase in pumping rates from two wells to the northeast Figure 10-2 shows 5-, 10-, and 20-year capture zones under pre-VOC discovery pumping conditions (Wells 7A, 35, and 38 are the ones that were found to be contaminated with VOCs ) The small circle around each well marks the 400-foot minimum setback zone specified in the Illinois Groundwater Protection Act of

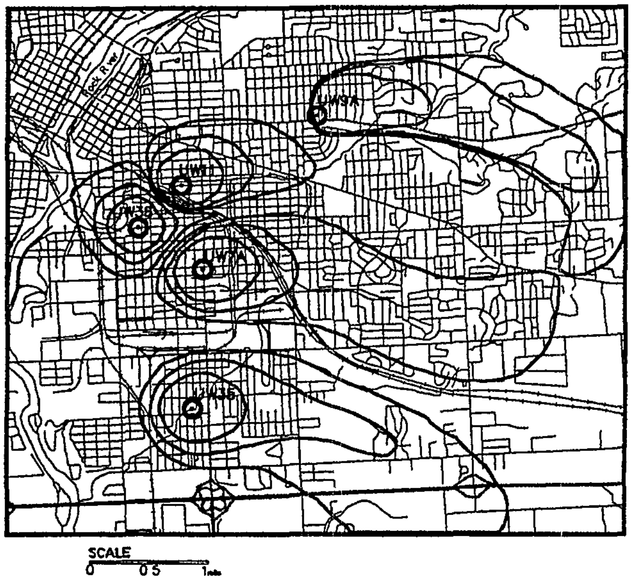

**Figure 10-2** Five-, 10-, and 20-year time-related captures zones under pre-VOC discovery pumping conditions, Rockford, Illinois, the small circle denotes the 400′ minimum setback zone (Wehrmann and Varljen, 1990)

1987 (IGPA) The IGPA also allows a maximum setback zone of 1,000 feet from the wellhead, and a regulated recharge area that extends up to 2,500 feet from a well or group of wells It is clear from Figure 10-2 that even the maximum setback is not adequate if more than a 5-year time of travel criterion is used for delineating a wellhead protection area Figure 10-3 illustrates 20-year capture zones for pre-VOC discovery pumping conditions (dark line), post-VOC pumping conditions (lighter line around wells 9A and 11), and the locations of potential hazardous waste sources This figure illustrates the importance of considering the effect of pumping rates and interactions between wells in well fields when delineating wellhead protection areas For example, the effect of increasing pumping rates in Well 11 and shutting down contaminated wells 7A and 38 resulted in a shift of the 20-year capture zone to the south The total number of potential contaminant sources for Well 11 remained about the same About half the potential contaminant sources for pre-VOC discovery pumping lie outside the post-VOC discovery capture zone, however, while an equal number of potential contaminant sources that were previously located within the capture zone of the contaminated wells fall within the post-VOC discovery capture zone of Well 11 The lesson from this case study is that "capture zone management" may be an option for protection of ground water supplies in addition to land use management

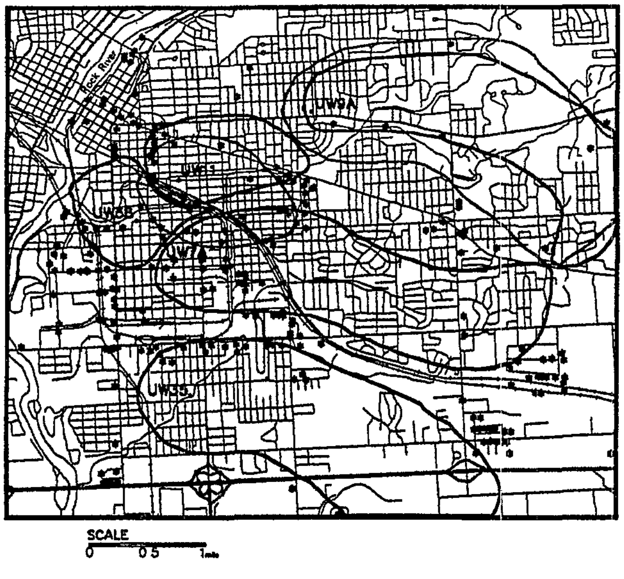

**Figure 10-3** Twenty-year capture zones overlain on locations of potential hazardous waste sources Asterisks denote potential sources of contamination, the darker outline constitutes the capture zone for pre-VOC discovery pumping conditions and the light outline, post-VOC discovery conditions (Wehrmann and Varljen, 1990)

### *10.2.3 Palm Beach County, Florida: Wellfield Protection Ordinance*

Palm Beach County illustrates a zoned approach to protection of multiple wellfields (Trefry, 1990)

**Community and Hydrogeologic Setting** Palm Beach County, in southeastern Florida, includes 25 county and municipal governments and 30 water utilities Approximately 80 percent of the potable water supply comes from ground water Withdrawals of ground water are regulated by the multi-county South Florida Water Management District Most ground water in the county comes from a shallow unconfined aquifer system Forty-two wellfields, each permitted for withdrawals of 100,000 gallons per day or more, serve incorporated and unincorporated portions of the county These wellfields include a total of 445 existing and proposed wells

**Wellhead Protection Area Delineation Methods** The U S Geological Survey's MODFLOW numerical model was used to delineate four zones around each wellfield (1) the land area around the wellhead/field bounded by the 30-day time of travel isochron, (2) the area included within the 30-day and 210-day time of travel isochron, (3) the area between the 210-day and 500-day isochron, and (4) the area within the 1-foot drawdown contour line Zones for each wellfield are periodically reviewed and revised, if necessary

**Contaminant Sources** The use, handling, production, and storage of hazardous and toxic materials associated with commercial and industrial activities are the main contaminant sources of concern in the county

**Wellhead Protection Area Management Methods** In April 1985, the South Florida Water Management District informed Palm Beach County that a request for an increase in its water consumption permit would not be granted until a wellhead protection ordinance was developed That same month a Water Resources Management Advisory Board was created by the Board of County Commissioners, which in turn created a Wellfield Protection Ordinance Subcommittee to draft an ordinance The ordinance was passed in early 1988 The ordinance requires a permit for the use, handling, production, and storage of regulated toxic substances Different requirements apply depending on the wellhead protection zone (see above for definitions of the limits of the four zones) In general, Zone 1 is an area of prohibition, Zones 2 and 3 require secondary containment to obtain a permit, and daily monitoring of chemicals is required in Zone 4

Initial implementation of the ordinance resulted in identification of a total of 3,550,000 gallons of regulated substances, and 118 pollutant storage tanks that require secondary containment and monitoring or removal from Zones 1, 2, and 3 Difficulties in implementing the ordinance include (1) activities and information must be coordinated with the large number of utilities (30) and local governmental units (25), (2) wellfield mapping has been hampered by constantly changing locations of existing, proposed, and previously unidentified wells, (3) staff is overloaded in dealing with permit review and enforcement; and (4) facilities have had difficulty obtaining bonding for their operations

### *10.2.4 Clinton Township, New Jersey: A Limestone Aquifer Protection Ordinance*

Clinton Township illustrates the use of technically based land use controls to protect areas of the township underlain by vulnerable carbonate aquifers Emphasis is on controlling development in all vulnerable areas, not just wellhead areas (Fischer et al , 1991a&b)

**Community and Hydrogeologic Setting** The Township of Clinton, Hunterdon County, in northwestern New Jersey, was primarily an agricultural area in the 1970s but in recent years has been targeted by state planning agencies and development interests as a prime growth area for urban development. The township relies upon ground water as the source of all its drinking, agricultural, and industrial water The township is located upon a Paleozoic outlier within the New Jersey Highlands physiographic province, and about 15 percent of the township is underlain by solution-prone, folded and faulted Cambro-Ordovician carbonates In addition to being highly vulnerable to contamination, the potential for foundation failure or sinkhole formation below potential contaminants must be considered

**Wellhead Protection Area Delineation Methods** Existing detailed geologic maps delineated areas of carbonate rock in the township where the "limestone" ordinance discussed below applied

**Contaminant Sources** Specific contaminant sources were not identified in the source case study, although the potential for sinkhole formation under hazardous material storage or use areas were identified as a special concern with the carbonate rocks

**Wellhead Protection Area Management Methods** Officials in Clinton Township had the foresight to initiate a process that would protect ground water supplies without eliminating the inevitable urban development that was occurring in the Township In the fall of 1987, the Township ordered a 150-day moratorium on development in carbonate rock areas Geologists with the state provided the necessary information for delineating the moratorium areas A committee of lay and technical people was immediately convened to draft an ordinance that would protect ground water supplies in the carbonate areas The "limestone" committee include representatives from the local watershed association, the Township Engineers office, the Township Sanitary Engineers office, the New Jersey Geological Survey, the New Jersey Department of Environmental Protection, The County Health Department, the Town Councils, and a geological engineer with experience in investigation and construction in karst terrane An attorney who was experienced in state land laws reviewed the final committee drafts of an ordinance and converted what was primarily a technical document into a defendable legal document

In May 1988 two ordinances were passed (1) an enabling ordinance setting forth the reasons regulatory controls were required in the carbonate areas of the township to protect public health, welfare, and safety, and (2) a "limestone" ordinance that established procedures for ensuring that any proposed construction project would only be approved if protection of ground water quality could be ensured The ordinance established a phased investigation process that provides the applicant for a construction permit to cancel a project if the problems seem insurmountable at an early stage For each phase of investigation and design, the ordinance provides specific requirements or suggested methods of investigation, as well as indicating preferred and alternate procedures As of 1991, the ordinance had withstood legal challenge by a developer, and resulted in several developments being either canceled or significantly altered in order to protect ground water quality in the carbonate areas of the township

### *10.2.5 Nantucket Island, Massachusetts: Implementation of a Comprehensive Water Resources Management Plan*

Nantucket Island illustrates how a zoned approach to ground water protection combined with regulatory controls targeted at major contaminants of concern can protect both public wellhead areas and more dispersed privately owned water wells (Horsley, 1990)

**Community and Hydrogeologic Setting** The Island of Nantucket, south of Cape Cod, Massachusetts, covers an area of 40 square miles A shallow glacial sand and gravel aquifer serves as the only source of drinking water for its 7,400 year-round residents and 32,000 summer visitors Two major public supply wellfields and about 3,500 private wells tap the aquifer The water table is at or near the surface in the vicinity of ponds and streams and is as much as 100 feet below the surface in central portions of the island Typically ground water is within 10 to 20 feet of the surface Hydraulic conductivities as high as 970 feet/day have been measured

**Wellhead Protection Area Delineation Methods** The Theis nonequilibrium equation (Section 4 5 3) and flow net analysis were used to delineate the zone of contribution to the Siasconset wellfield (Figure 10-4) and a simplified fixed radius approach was used for the Wan-

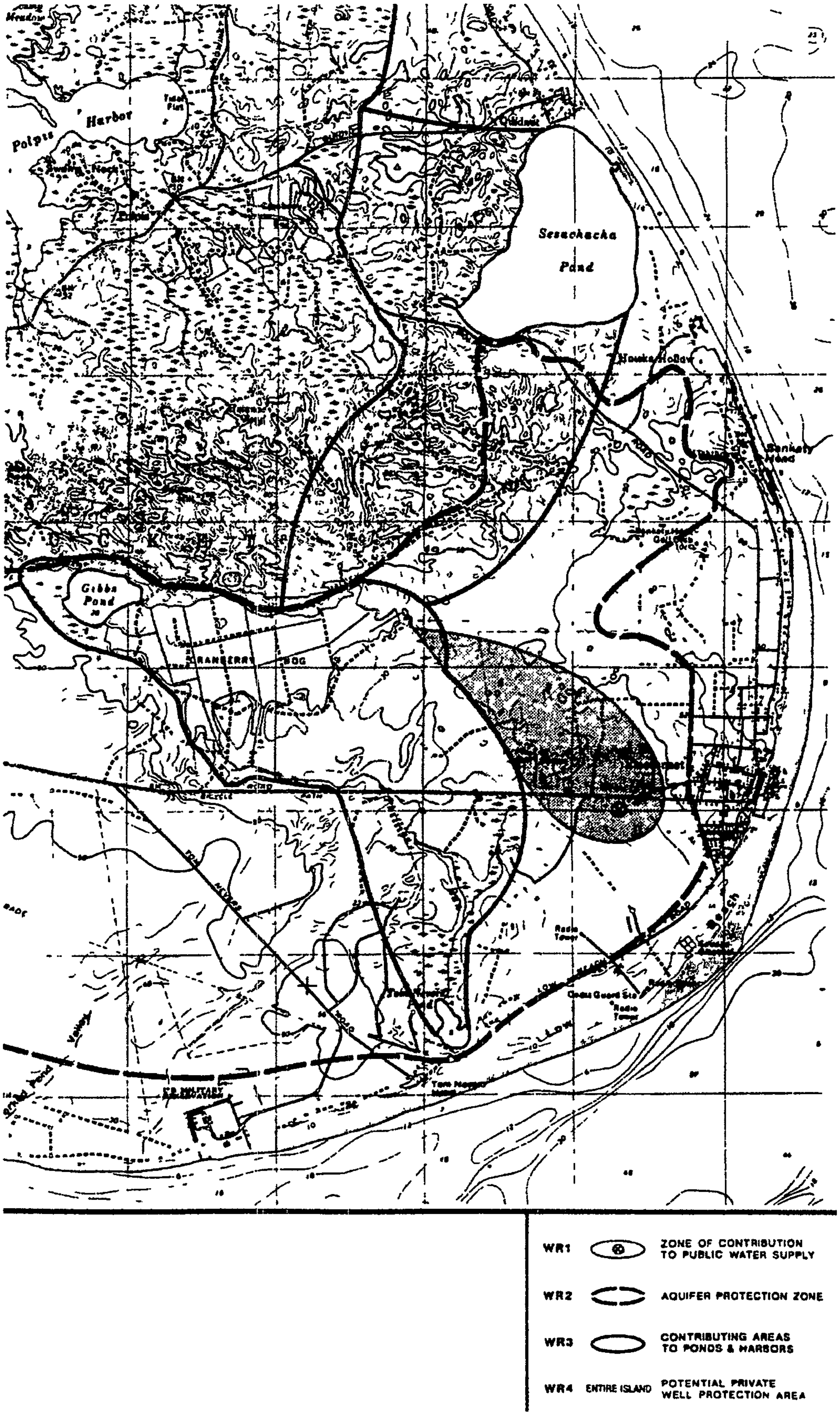

**Figure 10-4** Water resource protection districts, southeastern Nantucket Island, Massachusetts (Horsley, 1990)

nacomet wellfield Water table maps were used to delineate identify aquifer recharge areas on the island

**Contaminant Sources** Septic systems, used by 60 percent of Nantucket's residents for wastewater disposal, are the most common contamination source Potential sources of contamination include two landfills, four active farms, extensive cranberry bogs, three golf courses, eight hazardous waste sites, 400 underground fuel storage systems, two sewage treatment plants, and numerous businesses that use toxic and hazardous materials. Salt water intrusion is a problem in many private wells located near the island's shoreline

**Wellhead Protection Area Management Methods** The water resource management plan for Nantucket involved the delineation of four critical water resources protection zones Recommended land use controls included (1) a four-tiered water resources overlay zoning bylaw, (2) health regulations limiting sewage flow per lot size based on nitrogen loading, (3) a 300-lot separation between private wells and septic systems, (4) a regulation requiring registration and inspection of businesses using toxic and hazardous materials, (5) an effluent limitation of 5 mg/L for new projects proposing sewage discharges exceeding 2,000 gallons/day, and (6) a wetlands bylaw addressing the predicted hydrologic impacts of sea level rise Figure 10-4 illustrates the four water resource protection districts delineated in the Siasconset area, and Table 10-1 identifies regulated land uses within each district

**Table 10-1 Regulated Land Uses, Water Resource Protection Zones, Nantucket Island, Massachusetts (Horsley, 1990)**

| | WR1 | WR2 | WR3 | WR4 |
|---|---|---|---|---|
| Sanitary landfills | P | P | P | SP |
| Junk yards, salvage yards | P | P | P | SP |
| Municipal sewage treatment facilities with on-site disposal of primary or secondary treated effluent | P | P | P | SP |
| Car and truck washes | P | P | SP | SP |
| Road salt stockpiles | P | P | SP | SP |
| Dry cleaning establishments, coin or commercial laundries | P | P | SP | SP |
| Motor vehicle and boat service and repair facilities including body shops | P | P | P | SP |
| Metal plating establishments | P | P | SP | SP |
| Chemical and bacteriological laboratories | P | P | P | SP |
| Trucking or bus terminals | P | P | P | SP |
| Any use which involves as a principal activity the manufacture, storage, use, transporation, or disposal of toxic or hazardous materials | P | P | SP | SP |
| Any use which involves the use of toxic and hazardous materials in quantities greater than those associated with normal household use | P | P | SP | SP |
| Residential development at densities exceeding those stated in Section E of this bylaw | P | P | P | SP |
| Golf courses | P | SP | SP | SP |

P = Prohibited, SP = Special permit required

### *10.2.6 Tucson Basin, Arizona: Regional Wellhead Protection in an Urbanized Arid Environment*

The Tucson Basin illustrates how an association of local governments within a single county used a study of already contaminated wells to develop a regional approach of ground water protection (Pima Association of Governments, 1992)

**Community and Hydrogeologic Setting** Pima County in southern Arizona is located in the Basin and Range physiographic province, which is characterized by northwest-trending mountain ranges separated by alluvial basins. The climate is arid to semi-arid Most of the population in the county in concentrated in the Tucson basin, which has no significant sources of natural, perennial surface water in its urbanized areas The Tucson metropolitan area relies entirely on ground water for agricultural, industrial, and drinking water, which is drawn from three major Pleistocene- to Tertiary-age alluvial units In 1980, ground water pumpage was about 200,000 acre-feet/year, divided equally between industrial, agricultural, and public supply In 1989, depths to water in the Tucson basin generally ranged between 50 and 300 feet below land surface and averaged around 200 feet Current water levels in some wells have dropped more than 100 feet compared to levels in 1940

**Wellhead Protection Area Delineation Methods** The Pima Association of Governments (PAG) is developing a system for ground water vulnerability mapping based on the hydrogeologic factors that are most closely correlated with contamination of existing wells (see below)

**Contaminant Sources** Forty-four contaminated public-supply wells were identified in Pima County, the major contaminants were volatile organic compounds (VOCs), petroleum products and additives, and nitrate Landfills and unrestricted discharges of liquid waste from industrial areas were the most significant known sources of the VOC contamination Petroleum contamination was traced to a leaking underground pipeline and leaking underground storage tanks Irrigated agriculture, sewage treatment plants, and septic systems were identified as the likely sources of nitrate contamination In general, the wells were not adjacent to the pollution sources

**Wellhead Protection Area Management Methods** PAG evaluated various wellhead protection strategies based on hydrogeologic and land use information related to the contaminated wells PAG concluded that strategies that focused on establishing WHPAs around individual wells, whether they were based on an arbitrary fixed radius or a time of travel criterion, were ineffective and impractical This conclusion was based primarily on the finding that the pollution sources for most of the contaminated wells were more than a mile away The high density of wells in the Tucson area also makes a well-by-well delineation strategy difficult The most significant factors in evaluating a well's susceptibility to contamination were (1) proximity to a major recharge source, (2) shallow or perched ground water, and (3) the presence of upgradient land uses that might contribute contaminants PAG has developed a strategy of delineating regional WHPAs to protect the areas in Pima County that are most susceptible to ground water contamination (i e , recharge zones and areas with shallow or perched ground water) High-risk land uses would be excluded from undeveloped, sensitive areas through planning and zoning ordinances and land acquisition programs No new regulatory programs were recommended, but existing regulatory programs would be modified to provide additional protection and increased monitoring in the regional WHPAs

## 10.3 Sources of Additional Information on Case Studies

Table 10-2 summarizes information on case studies addressing ground water or wellhead protection in other publications that contain multiple case studies Table 10-3 provides an index of individual case studies by state, and also identifies case studies in karst areas

**Table 10-2 Summary Information on Case Studies in Other Sources on Ground Water and Wellhead Protection***

| Reference | Description of Case Studies |
|---|---|
| Born et al (1988) | Case studies on the development of wellhead protection districts for six communities in Wisconsin (Whiting, Seymour, Rib Mountain, Eagle River, Tomah, and Mazomanie) Hydrogeologic settings included unconfined sand-and-gravel aquifers, and unconfined and semiconfined sandstone aquifers Wellhead delineation methods included hydrogeologic mapping, analytical models (cone of depression), and time of travel calculations |
| Bradbury et al (1991) | Two detailed case studies on WHPA delineation in fractured rock aquifers (1) Junction City, Wisconsin (wells in clayey residuum over metavolcanic rock, and (2) Sevastopol test site, Door County, Wisconsin (well in residual soils over fractured dolomite aquifer) Delineation methods included water table mapping, aquifer tests, isotope analysis, and numerical computer modeling |
| Kreitler and Senger (1991) | Detailed case studies on WHPA delineation in confined sandstone aquifers in the Gulf Coast Sedimentary Basin for the towns of Bastrop and Wharton, Texas Delineation methods included hydrogeologic and hydrochemical mapping, the cylinder method, simple analytical methods, and semianalytical and numerical computer modeling |
| Maryland Department of the Environment (1991) | Chapter 6 contains case studies of wellhead protection area delineation for six communities in Maryland including the following hydrogeologic units coastal plain semi-confined aquifer, coastal plain unconfined aquifer, central Maryland sedimentary rock aquifer, Piedmont crystalline rock aquifer, and carbonate rock aquifer |
| U S EPA (1987) | Appendix A provides examples of application of WHPA delineation methods for Florida and Dade County, Florida, Massachusetts, Vermont, The Netherlands, and Germany Appendix B contains four detailed case studies comparing different delineation methods (1) Cape Cod, Massachusetts, (2) southern Florida, (3) central Colorado, and (4) southwestern Connecticut |
| U S EPA (1993) | Four case studies (1) Hill, New Hampshire (WHPA delineated in sandy glacial till aquifer over crystalline rocks using uniform flow equation), (2) Cottage Grove, Wisconsin (WHPA delineated for sandstone aquifer using the WHPA code), (3) Enid, Oklahoma (WHPA delineated for wellhead in an alluvial aquifer using hydrogeologic mapping, semianalytical methods, and computer modeling), (4) Descanso Community Water District, California (WHPA delineated in weathered regolith over metamorphic and granitic bedrock using water table map, analytical methods, flow net analysis, and time of travel calculations) |

**Table 10-3 Index to Case Study References on Ground Water and Wellhead Protection***

| Topic | References |
|---|---|
| States | *Arizona* Pima Association of Governments (1992), *California* Horsely Witten Hegemann, Inc (1991), Lewcock (1987), Zidar (1990), *Connecticut* Miller et al (1992), *Delaware* Kerzner (1990a, 1990b), Yancheski (1992), Yancheski et al (1990), *Illinois* Adams et al (1992), Wehrmann and Varljen (1990)**, *Indiana* Parrett (1986), *Florida* Trefry (1990)**, Walters (1987), *Kentucky* Sendlein (1991), *Maine* Marler (1991), Tolman et al (1991), *Maryland* Maryland Department of the Environment (1991), *Massachusetts* Brandon et al (1992), Heeley et al (1992), Horsley (1990)**, Moore et al (1990a), Nelson and Witten (1990), Nickerson (1986), Paly and Steppacher (undated), Ram and Scwharz (1987), Steppacher (1988), *Michigan* Dean (1988), *Missouri* Moore et al (1990b), *New Jersey* Fischer et al (1991a, 1991b)**, Heeley et al (1992), Page (1987b, 1987c), *New York* Koppelman (1987), *Ohio* Bair and Roadcap (1992), Bair et al (1991a, 1991b), Roadcap and Bair (1990), Springer and Bair (1990, 1992), Weatherington-Rice and Hottman (1990), *Pennsylvania* Emrich and Luitweiler (1990)**, *Texas* Butler (1987), Cross (1990), Cross and Schulze (1988), Rifai et al (1993), *Vermont* Toch (1991), *Washington* Randall and Brown (1987), *Wisconsin* Born et al (1988), Osborne and Sorenson (1990), Osborne et al (1989), Page (1987a), Potter (1984), Zaporzec (1985), *Unspecified* Caswell (1993—New England), *Other Countries* Roeper (1990-Canada) |
| Karst | Emrich and Luitweiler (1990)**, Fischer et al (1991a, 1991b)**, Moore et al (1990b), Sendlein (1991) |
| GIS | See Table 5-8 |
| Computer Models | See Table 6-6 |

* See also Table 6-6 for case studies indexed according to computer model use

** Case study written up in this chapter

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* See Introduction for information on how to obtain documents

# Appendix A
# Additional Reference Sources

This appendix identifies major reference sources for the following four areas

1 Hydrology, hydrogeology, and hydraulics (Table A-1)

2 Karst geology, geomorphology, and hydrology (Table A-2)

3 Geographic information systems (Tables A-3 and A-4)

4 Chemical hazard exposure and risk assessment (Table A-5)

The references for each subject area follow the table(s) that identify the major subject areas covered by the references

**Table A-1. Index to Major References on Hydrology, Hydrogeology, and Hydraulics***

| Topic | References |
|---|---|
| Water Resources/Hydrology | Bras (1990), Bowen (1982), Branson et al (1981), Chow (1964), Chow et al (1988), Downing and Wilkinson (1992), Dunne and Leopold (1978), Gray (1973), Grigg (1985), Kazmann (1988), Leopold and Langbein (1960), Linsley et al (1949), Maidment (1993), Meinzer (1942), Shaw (1988), Tebutt (1973), Todd (1970), van der Leeden et al (1990), Viessman et al (1977), Wisler and Brater (1959), *Engineering* ASCE (1952), Butler (1957), Linsley et al (1958), Linsley and Franzini (1972), Skeat (1969) |
| Hydrogeology | *Bibliography/Glossary* Lohman et al (1972), Pfannkuch (1969), van der Leeden et al (1991), *Introductory* AWWA (1989), Baldwin and McGuiness (1963), Barton et al (1985), Heath (1980, 1983), Heath and Trainer (1981), Mills et al (1985), Rau (1970), Redwine et al 1991), U S EPA (1985, 1990), *Intermediate-Advanced* Bouwer (1978), Bowen (1980), Cooley et al (1972), Custodio and Llama (1975), Davis and DeWiest (1966), Driscoll (1986), Fetter (1980), Freeze and Cherry (1979), Gelher (1993), Johnson (1966), Klimentov (1983), Kovács et al (1981), Matthess (1982), McWhorter and Sunada (1981), Raghunath (1982), Todd (1980), Tolman (1937), *Investigations* Brassington (1988), Brown et al (1983), Erdélyi and Gálfi (1988), Mandel and Shifton (1981), U S Geological Survey (1980), Walton (1970), *Ground Water Engineering* De Marsily (1986), Hunt (1983), Kashef (1986), Rethati (1984), Walton (1991), *Edited Volumes* Back and Stephenson (1979), IAH (1985), IAHS (1967), Jones and Laenen (1992), Moore et al (1989, 1991), Saleem (1976), Zaporozec (1990) |
| Chemical/Contaminant Hydrogeology | See Table 1-2 |
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| Hydraulics** | *Ground Water Flow* Bear (1979), Bennett (1976), Bureau of Reclamation (1960, 1981), Campbell and Lehr (1973), Chapman (1981), Daly (1984-flow lines), DeWiest (1965), Edelman (1983), Freeze and Witherspoon (1967), Glover (1964, 1974), Halek and Svec (1979), Hantush (1964), Hubbert (1940, 1969), Hunt (1983), Jacob (1950), Lohman (1972), De Marsily (1986), McWhorter and Sunada (1981), Peterson et al (1952), Randkivi and Callender (1976), Rosenshein and Bennett (1984), Strack (1989), U S EPA (1986-flow lines), Verruijt (1970), Zijl and Nawalany (1993), *Porous Media Flow* Bear (1972), Bear and Corapcioglu (1987), Brooks and Corey (1964), Collins (1961), Corey (1977-heterogenous fluids), Cushman and Hall (1991), Dagan (1989), DeWiest (1966), Dullien (1979), Greenkorn (1983), IAHR (1972), Milne-Thompson (1968), Muskat (1937), Scheidegger (1960), White (1974), *Engineering Hydraulics* Colt Industries (1974), Dodge and Thompson (1937), Hauser (1991), Lencastre (1987), Rouse (1950), Simon (1976), *Drainage/Seepage* Bear et al (1968), Bureau of Reclamation (1968), Cedergren (1989), Harr (1977), Luthin (1973), Marino and Luthin (1982), Powers (1992), Rushton and Redshaw (1979) |

* See Table A-2 for index of major references on karst geology, geomorphology, and hydrology

** References listed under hydrogeology will also cover hydraulics and pumping tests

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* See Introduction for information on how to obtain documents

**Table A-2 Index to Major References on Karst Geology, Geomorphology and Hydrology**

| Topic | References |
|---|---|
| Glossary | Monroe (1970) |
| Hydrology/Ground Water | *Bibliographies* LaMoreaux (1986), LaMoreaux et al (1970, 1989, 1993), Warren and Moore (1975), *Texts* Bögli (1980), Bonacci (1987), Burger and Dubertret (1975), Ford and Williams (1988), LaMoreaux (1986), LaMoreaux et al (1975, 1984), Milanovic (1981), Stringfield et al (1974), White (1988), *Review Papers* Kresic (1993), LeGrand and Stringfield (1973), *Case Histories* Burger and Dubertret (1984), White and White (1989), *Proceedings* AGWSE (1991), Beck and Wilson (1987), Doaxin (1988), Gunay and Johnson (1986), IASH (1967), Rauch and Werner (1974), Tolson and Doyle (1977), Yevjevich (1976) |
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| Geomorphology/Geology | Dreybodt (1988), Ford and Williams (1988), Herak and Stringfield (1972), Jakucs (1977), Jennings (1985), Rauch and Werner (1974), Sweeting (1973), Trudgill (1985), White (1988) |
| Geochemistry | Dreybodt (1988) |
| Engineering Aspects | Davies et al (1976), James (1992), *Proceedings* Beck (1984, 1989), Beck and Wilson (1987) |
| Environmental Aspects | AGWSE (1991), Beck (1984, 1990), Beck and Wilson (1987), Doaxin (1988), NWWA (1986, 1988) |
| Conference Proceedings | AGWSE (1991), Beck (1984, 1990), Beck and Wilson (1987), Doaxin (1988), Gunay and Johnson (1986), IASH (1967), NWWA (1986, 1988), Rauch and Werner (1974), Tolson and Doyle (1977), Yevjevich (1976) |

## *Table A-2 References*

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International Association of Scientific Hydrology (IASH) 1967 Hydrology of Fractured Rocks (Proc of 1965 Dubrovnik Symposium), 2 Vols IASH Publ No 73

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LaMoreaux, P E , D Raymond, and T J Joiner 1970 Hydrology of Limestone Terranes Annotated Bibliography of Carbonate Rocks Geological Survey of Alabama Bulletin 94A

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Symposium on Underground Water Tracing (SUWT) 1966 1st SUWT (Graz, Austria) Published in Steirisches Beitraege zur Hydrogeologie Jg 1966/67

Symposium on Underground Water Tracing (SUWT) 1970 2nd SUWT (Freiburg/Br , West Germany) Published in Steirisches Beitraege zur Hydrogeologie 22(1970) 5-165, and Geologisches Jahrbuch, Reihe C 2(1972) 1-382

Symposium on Underground Water Tracing (SUWT) 1976 3rd SUWT (Ljubljana-Bled, Yugoslavia) Published by Ljubljana Institute for Karst Research Volume 1 (1976), 213 pp , Volume 2 (1977) 182 pp See also Gospodaric and Habic (1976)

Symposium on Underground Water Tracing (SUWT) 1981 4th SUWT (Bern, Switzerland) Published in Steirisches Beitraege zur Hydrogeologie 32(1980) 5-100, 33(1981) 1-264, and Beitraege zur Geologie der Schweiz—Hydrologie 28 pt 1(1982) 1-236, 28 pt 2(1982) 1-213

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Tolson, J S and F L Doyle (eds ) 1977 Karst Hydrogeology Memoirs of the 12th Int Congress, Int Assoc Hydrogeologists University of Alabama, Huntsville, AL [60 papers]

Trudgill, S T 1985 Limestone Geomorphology Longman, New York

Warren, W M and J D Moore 1975 Hydrology of Limestone Terranes Annotated Bibliography of Carbonate Rocks Geological Survey of Alabama Bulletin 94E, pp 31-163

White, W B 1988 Geomorphology and Hydrology of Karst Terrains Oxford University Press, New York, 454 pp

White, W B and E L White (eds ) 1989 Karst Hydrology Concepts from the Mammoth Cave Area Van Nostrand Reinhold, New York, 343 pp [12 contributed papers]

Yevjevich, V (ed ) 1976 Karst Hydrology and Water Resources, Vol 1 Karst Hydrology, Vol 2 Karst Water Resources Water Resources Publications, Fort Collins, CO [Symposium proceedings with 38 papers]

**Table A-3 Index to Major References on Geographic Information Systems (GIS)**

| Topic | References |
|---|---|
| Texts | *Introductory* Arnoff (1989), Cadoux-Hudson and Heywood (1992), Pequet and Marble (1990), Ripple (1989), Star and Estes (1990), *Cartography* ACSM (1992d), Clarke (1990), Johnson et al (1992), Tomlin (1990), *Technology* ACSM (1992b), Antenucci et al (1991), Maguire et al (1992), *Land Resource Assessment* Burrough (1986), Gokee and Joyce (1992), Ripple (1987), Young and Cousins (1993), *Urban Applications* Huxhold (1991), *Geoscience/Geotechnical Applications* Johnson et al (1992), Thomas (1988), *Ground-Water and Environmental Applications* Johnson et al (1992), Kovar and Nachtnebel (1993), Pickus (1992), Scepan et al (1993) *General Applications* Johnson et al (1992), Maguire et al (1991), Ripple (1987) |
| GIS Systems | *Arc/Info* ESRI (1990), Pickus (1992), *AutoCAD®* Jones and Martin (1988), *TIGER* Carbaugh and Marx (1990), *Comparison/Evaluation* FICC (1988), Rowe and Dulaney (1991) |
| Government Use | *U S EPA* Fenstermaker (1987), OIRM (1992), U S EPA (1992a, 1992b, 1992c), *U S Geological Survey* USGS (1991a), *Soil Conservation Service* SCS (1991), *Other Federal* FICC (1990), FGDC (1991a, 1991b, 1993), *States* ACSM (1992a), August and McCann (1990), PlanGraphics (1991), Warnecke (1988), *Local* ACSM (1992c) |
| Spatial Data | *Analysis* Cressie (1991), Goodchild and Gopal (1989), Raper (1989), Samet (1990), Tomlin (1990), *Data Management/Processing* Date (1985, 1990), Fergino (1986), Fleming and von Halle (1986), International Geographical Union Commission on GIS (1992), Samet (1989, 1990), *Standards/Format* Elissal and Caruso (1983), Johnson et al (1992), National Committee for Cartographic Data Standards (1987), USFWS (1984), USGS (1990a, 1990b, 1991b), *Information Exchange* ANSI (1986a, 1986b), ASTM (1993), Bureau of Census (1992—TIGER), Lockheed Engineering and Sciences Company (1991), Morrison and Wortman (1992), NIST (1992), USGS (1992), *Data Coding* NBS (1987, 1988), U S EPA (1992c), USGS (1983), *Locational Methods/Surveying* Onsrud and Cook (1990), U S EPA (1992a, 1992b) |
| Temporal GIS | Langran (1992) |
| Data Sources | *Soils* SCS (1991), *Topography* Bauer (1989—AutoCad) |

**Table A-4 Periodicals, Conferences, and Symposia with Papers Relevant to GIS**

| Sponsor | Year | Title |
|---|---|---|
| **ACSM/ASPRS Annual Convention Proceedings** | | |
| | 1986 | Firm Foundations, New Horizons (Vol 3, Geographic Information Systems, 286 pp ) |
| | 1987 | Technology for the Future, Applications for Today (7 Volumes, Vol 5, GIS/LIS, 222 pp ) |
| | 1988 | The World in Space (6 Volumes, Vol 5, GIS, 248 pp ) |
| | 1989 | Agenda for the Nineties (Vol 4, GIS/LIS) |
| | 1991 | Annual Convention (6 Volumes, Vol 2 Cartography and GIS/LIS, Vol 4, GIS) |
| | 1992 | Annual Convention (Vol 1 ASPRS, Vol 2 ACSM) |
| | 1992 | Global Change (5 Volumes, Vol 3, GIS and Cartography) |
| **Annual GIS Workshops/Conferences** | | |
| ASPRS/USFS | 1986 | Geographic Information Systems Workshop, 220 pp |
| ACSM/ASPRS | 1987 | GIS'87—Into the Hands of the Decision Maker (2 Volumes, 760 pp , Vol III—post conference proceedings, 234 pp ) |
| ACSM/ASPRS | | |
| AAG/URISA | 1988 | GIS/LIS'88—Accessing the World (2 Volumes, 980 pp ) |
| | 1989 | |
| | 1990 | |
| | 1991 | GIS/LIS'91 Proceedings |
| | 1992 | GIS/LIS'92 Proceedings |
| **Biannual International Automated Cartography Proceedings** | | |
| | 1987 | AutoCarto 8 (775 pp ) |
| | 1989 | AutoCarto 9 (879 pp ) |
| | 1991 | AutoCarto 10 (Vol 6 of ACSM/ASPRS Annual Convention Proceedings) |
| **Photogrammetric Engineering and Remote Sensing Special GIS Issues** | | |
| | 1987 | October, 184 pp |
| | 1988 | November, 170 pp |
| | 1989 | November, 144 pp |
| **Other Conferences/Symposia** | | |
| ASTM | 1990 | Geographic Information Systems (GIS) and Mapping Practices and Standards |
| AWRA | 1993 | Geographic Information Systems and Water Resources |

**Periodicals/Newsletters**

*Technical Journals* Cartography and Geographic Information Systems (ACMS), GIS/GIMS News (ASPRS*), International Journal of GIS, Photogrammetric Engineering and Remote Sensing (ASPRS)

*Vendor Newsletters* ARC News (Environmental Systems Research Institute, Redlands CA*), Grass Clippings (Geographic Resource Analysis Support System, Stennie Space Center, MS*), Monitor (Erdas, Inc , Atlanta, GA*), Remote Sensing and Database Development (James W Sewall Company, Old Town ME*), TYDAC News (TYDAC Technologies Corporation, Arlington, VA*)

*Government Agency Newsletters* Federal Geographic Data Committee (FDC) Newsletter (USGS, Reston, VA*), GIS News Layers (Division of Equalization and Assessment, Albany, NY*), GIS Update (Vermont Geographic Information System, Montpelier, VT*), MASS GIS Newsletter (Massachusetts GIS Project, Boston, MA*), New Jersey GIS Update (Department of Environmental Protection, Trenton, NJ*), NRGIS News (Minnesota Natural Resources Geographic Information Systems, St Paul, MN*), RIGIS News (University of Rhode Island, Kingston, RI*)

*Other* CAGIS Journal, Environmental Resources Research Institute Newsletter (Pennsylvania State University, University Park, PA*), Geo Info Systems, GIS Review (Greenland, NH*), GIS World (Fort Collins, CO*), Kansas Applied Remote Sensing (KARS) Newsletter (University of Kansas, Lawrence, KS*), The GIS Forum (Spring, TX*), SALIS Journal, URISA News (URISA, Washington, DC*), Wisconsin Land Information Newsletter (Center for Land Information Studies, University of Wisconsin, Madison, WI*)

Abbreviations
AAG Association of American Geographers
ACMS American Congress on Surveying and Mapping
ASPRS American Society for Photogrammetry and Remote Sensing
ASTM American Society for Testing and Materials
AWRA American Water Resources Association
UIRSA Urban and Regional Information Systems Association

* Addresses listed in August and McCann (1990)

## *Table A-3 References**

Adams, S et al 1992 Illinois Groundwater Protection Program Pilot Groundwater Protection Needs Assessment for Pekin Public Water Supply Facility Number 1795040 Division of Public Water Supplies, Illinois Environmental Protection Agency, Springfield, IL [GIS]

American Congress on Surveying and Mapping (ACSM) 1992a State Geographic Information Activities Compendium ACSM, Bethesda, MD

American Congress on Surveying and Mapping (ACSM) 1992b GIS A Guide to the Technology ACSM, Bethesda, MD

American Congress on Surveying and Mapping (ACSM) 1992c The Local Government Guide to GIS ACSM, Bethesda, MD

American Congress on Surveying and Mapping (ACSM) 1992d GIS Microcomputer and Modern Cartography ACSM, Bethesda, MD

American National Standards Institute (ANSI) 1986a Specification for a Data Descriptive File for Information Interchange ANSI/ISO 8211-1985, FIPS PUB 123

American National Standards Institute (ANSI) 1986b Computer Graphics Metafile for the Storage and Transfer of Picture Descriptive Information ANSI X3 122-1986, FIPS PUB 128

American Society for Testing and Materials (ASTM) 1993 Metadata Support for Geographic Information Systems and Spatial Data Exchange Draft Specification D18 01 Subcommittee ballot, January

Antenucci, J C , K Brown, P L Croswell, M J Kevany, and H N Archer 1991 Geographic Information Systems A Guide to the Technology Van Nostrand Reinhold, New York, 301 pp

Aronoff, S 1989 Geographic Information Systems A Management Perspective WDL Publications, Ottawa, Canada, 294 pp [Introduction for users and managers]

August, P V and A McCann 1990 Geographic Information Systems (GIS) in Rhode Island Department of Natural Resources Science Fact Sheet No 90-23, University of Rhode Island, Kingston, RI, 11 pp [Included as Appendix to RIDEM (1992)]

Bauer, M F 1989 Digital Map Users Guide American Digital Cartography, Inc , Appleton, WI [USGS topographic maps for AutoCad]

Bureau of Census 1992 TIGER/SDTS$^{TM}$ Prototype Files, 1990 Preliminary Description Available from Census Bureau, Geography Division, Geographic Base Development Branch, Washington, DC 20233

Burrough, P A 1986 Principles of Geographical Information Systems for Land Resources Assessment Clarendon/Oxford University Press, New York, 193 pp [Advanced text]

Cadoux-Hudson, J and D I Heywood (eds ) 1992 Geographic Information 1992/3 Yearbook of the Association for Geographic Information Taylor & Francis, Bristol, PA, 632 pp

Carbaugh, L and R W Marx 1990 The TIGER System A Census Bureau Innovation Serving Data Analysts Government Information Quarterly 7(3) 285-306

Clarke, K 1990 Analytical and Computer Cartography Prentice Hall, Englewood Cliffs, NJ

Cressie, N 1991 Statistics for Spatial Data John Wiley & Sons, New York. [Comprehensive and readable text on the analysis of spatial data through statistical models, unifies a previously disparate subject under a common approach and notation]

Date, C J 1985 Introduction to Database Systems, Vol II Addison-Wesley, Reading, MA

Date, C J 1990 Introduction to Database Systems, Vol I , 5th ed Addison-Wesley, Reading, MA

Elissal, A A and V M Caruso 1983 Digital Elevation Models U S Geological Survey Circular 895-B

ESRI, Inc 1990 PC Arc/Info User's Manual Environmental Research Institute, Inc , Redlands, CA

Federal Interagency Coordinating Committee on Digital Cartography (FICC) 1988 A Process for Evaluating Geographic Information Systems Available from U S Geological Survey Publications, Reston, VA

Federal Interagency Coordinating Committee on Digital Cartography (FICC) 1990 A Summary of GIS Use in the Federal Government Available from U S Geological Survey Publications, Reston, VA

Federal Geographic Data Committee (FGDC) 1991a A National Geographic Information Resource The Spatial Foundation of the Information-Based Society U S Government Printing Office, Washington, DC, 10 pp + 4 Appendices

Federal Geographic Data Committee (FGDC) 1991b First Annual Report to the Director, Office of Management and Budget Available from U S Geological Survey Publications, Reston, VA

Federal Geographic Data Committee (FGDC) 1993 Manual of Federal Geographic Data Products Available from U S Geological Survey Publications, Reston, VA

Fenstermaker, L K 1987 Geographic Information System Briefing for the Administrator and Deputy Administrator TS-AMD-87650, U S EPA Environmental Monitoring Systems Laboratory, Las Vegas, NV

Ferigno, C F 1986 A Data-Management System for Detailed Areal Interpretive Data U S Geological Survey Water Resource Investigations Report 86-4091, 103 pp

Fleming, C and B von Halle 1989 Handbook of Relational Database Design Addison-Wesley, Reading, MA

Gokee, T L and L A Joyce 1992 Analysis of Standards and Guidelines in a Geographic Information System Using Existing Resource Data Research Paper RM-304, Rocky Mountain Forest and Experiment Station, Fort Collins, CO, 12 pp

Goodchild, M and S Gopal (ed ) 1989 Accuracy of Spatial Databases Taylor & Francis, Bristol, PA, 308 pp

Huxhold, W 1991 Introduction to Urban GIS Oxford University Press, New York

International Geographical Union Commission on GIS 1992 Proceedings 5th International Symposium on Spatial Data Handling, 2 Vols [More than 70 papers, held August 3-7, 1992 in Charleston, SC]

Johnson, A I , C B Pettersson, and J L Fulton 1992 Geographic Information Systems (GIS) and Mapping Practices and Standards ASTM STP 1126, American Society for Testing and Materials, Philadelphia, PA

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Kovar, K. and H P Nachtnebel (eds ) 1993 Application of Geographic Information Systems in Hydrology and Water Resources Management Int Assoc Sci Hydrology Pub No 211, 693 pp [Proc IAHS/UNESCO conference held in Vienna, Austria, April, 1993, 68 papers]

Langran, G 1992 Time in Geographic Information Systems Taylor & Francis, Bristol, PA, 200 pp [Covers conceptual, logical, and physical design of temporal GISs]

Lockheed Engineering & Sciences Company 1991 Information Exchange Format for Environmental Expert Systems, Preliminary Analysis (Draft) EPA/600/X-91/119 U S EPA Environmental Monitoring System Laboratory, Las Vegas

Maguire, D J, M F Goodchild, and D W Rhind 1991 Geographical Information Systems Principles and Applications John Wiley & Sons, New York. [2 volume set with 60 papers]

Morrison, J L and K. Wortman (eds ) 1992 Implementing the Spatial Data Transfer Standard Cartography and Geographic Information Systems 19(5):277-334 [Special issue with 12 papers on the federal STDS]

National Bureau of Standards (NBS) 1987 Codes for the Identification of the State, The District of Columbia and the Outlying Areas of the United States, and Associated Areas Federal Information Processing Standards (FIPS) Publication 5-2, NBS, U S Department of Commerce, Washington, DC

National Bureau of Standards (NBS) 1988 Representation for Calendar Date and Ordinal Date for Information Interchange Federal Information Processing Standards (FIPS) Publication 4-1, NBS, U S Department of Commerce, Washington, DC

National Committee for Digital Cartographic Data Standards 1987 Issues in Digital Cartographic Data Standards Report 9

National Institute of Standards and Technology (NIST) 1992 Spatial Data Transfer Standard Federal Information Processing Standard Publication 173 (FIPS Pub 173) [Available from NTIS or Internet lsdres er usgs gov(130 11 48 2), user name anonymous, after connecting cd usgs sdts]

Office of Information Resource Management (OIRM) 1992 Geographic Information Systems (GIS) Guidelines Document OIRM 88-01. U S Environmental Protection Agency, Washington, DC

Onsrud, H J and D W Cook (eds ) 1990 Geographic and Land Information Systems for Practicing Surveyors A Compendium American Congress on Surveying and Mapping, Bethesda, MD, 219 pp [Collection of 22 articles from the recent GIS/LIS literature]

Pequet, D and D Marble (eds ) 1990 Introductory Readings in Geographic Information Systems Taylor & Francis, Bristol, PA, 387 pp

Pickus, J 1992 Data Automation Using GIS and ARC/INFO GIS Support for Hydrogeologic Analysis Contract No 68-CO-0050, U S EPA Environmental Monitoring Systems Laboratory, Las Vegas, NV, 87 pp

PlanGraphics 1991 Summary of State GIS Coordination, Legislation and Funding Sources PlanGraphics, Frankfort, KY, 9 pp

Raper, J (ed ) 1989 Three Dimensional Applications in Geographic Information Systems Taylor & Francis, Bristol, PA, 189 pp [Survey of approaches and problems in modeling real geophysical data]

Rhode Island Department of Environmental Management (RIDEM) 1992 Inventory of Potential Sources of Groundwater Contamination in Wellhead Protection Areas RIDEM Guidance Document. RIDEM, Providence, RI, 38 pp + appendices

Ripple, W (ed ) 1987 Geographic Information Systems for Resource Management. A Compendium ASPRS, Falls Church, VA/American Congress on Surveying and Mapping, Bethesda, MD, 288 pp [Papers on land suitability; water, soil, and vegetation resource management, and urban and global GIS applications]

Ripple, W. (ed.) 1989 Fundamentals of Geographic Information Systems. A Compendium ASPRS, Falls Church, VA/American Congress on Surveying and Mapping, Bethesda, MD, 248 pp

Rowe, G W and S J Dulaney 1991 Building and Using a Groundwater Database Lewis Publishers, Chelsea, MI, 218 pp [Appendix includes summary information on more than 80 GIS-related software]

Samet, H 1989 Applications of Spatial Data Structures Addison-Wesley, Reading, MA [Applications in computer graphics, image processing, and GIS]

Samet, H 1990 Design and Analysis of Spatial Data Structures Addison-Wesley, Reading, MA [Hierarchical (quad-tree and octree) state structures]

Scepan, J, R C Frohn, D Heath, J Pickus, M Finkbeiner, and B Moore 1993 The Use of Geographic Information Systems in Wellhead Protection Programs (February Draft) Cooperative Agreement CR-816196, U S EPA Environmental Monitoring Systems Laboratory, Las Vegas, NV

Soil Conservation Service (SCS) 1991 State Soil Geographic Data Base (STATSGO) Data Users Guide SCS Miscellaneous Publication No 1492, U S Department of Agriculture, Washington, DC, 88 pp

Star, J and J Estes 1990 Geographic Information Systems An Introduction Prentice Hall, Englewood Cliffs, NJ, 303 pp [Introductory text for students and professionals]

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Tomlin, D 1990 Geographic Information Systems and Cartographic Modeling Prentice Hall, Englewood Cliffs, NJ

U S Environmental Protection Agency (EPA) 1992a Locational Data Policy Implementation Guidance Guide to the Policy EPA/220/B-92-008, Office of Administration and Resources Management, Washington DC

U S Environmental Protection Agency (EPA) 1992b Locational Data Policy Implementation Guidance—Global Positioning System Technology and Its Application In Environmental Programs—GPS Primer EPA/600/R-92/036

U S Environmental Protection Agency (EPA) 1992c Definitions for the Minimum Set of Data Elements for Ground Water Quality Policy Order 7500 1A, Guidance document EPA/813/B-92/002 Available from ODW *

U S Fish and Wildlife Service (USFWS) 1984 Map Projections for Use with the Geographic Information System FWS/OBS-84/17, USFWS, Washington, DC

U S Geological Survey (USGS) 1983 Specifications for Representation of Geographic Point Locations for Information Interchange U S Geological Survey Circular 878-B, 23 pp

U S Geological Survey (USGS) 1990a Digital Elevation Models—Data Users Guide 5 USGS National Mapping Division, Reston, VA, 51 pp

U S Geological Survey (USGS) 1990b Digital Line Graphs from 1 24,000-Scale Maps—Data Users Guide National Mapping Program Technical Instructions USGS National Mapping Division, Reston, VA, 107 pp

U S Geological Survey (USGS) 1991a National Mapping Program Technical Instructions, FIPS Pub 123 Function Library Software Documentation (Draft) USGS National Mapping Division, Reston, VA

U S Geological Survey (USGS) 1991b General Cartographic Transformation Package USGS National Mapping Division, Reston, VA, 87 pp

U S Geological Survey (USGS) 1992 A Prototype SDTS Federal Profile for Geographic Vector Data with Topology (Draft) USGS National Mapping Division, Reston, VA, 17 pp

Warnecke, L. 1988 Geographic Information Coordination in the States Past Efforts, Lessons Learned, and Future Opportunities Information Management Review 3(4) 27-38

Young, R H and S Cousins (eds ) 1993 Landscape Ecology and Geographic Information Systems Taylor & Francis, Bristol, PA, 300 pp

* See Introduction for information on how to obtain documents

**Table A-5 Index to Major References on Chemical Hazard and Risk Assessment**

| Topic | References |
|---|---|
| **General** | |
| Risk Communication | Sandman (1986), U S EPA (1987-1989, 1988j, 1988a, 1989a, 1989c, 1990a) |
| SARA Title III* | *General* U S EPA (1988b, 1988e, 1989f, 1989g, 1989h, 1989i, 1990b, 1992b), *Emergency Planning* U S EPA (1987b, 1988g, 1988h, 1988i, 1990j) |
| **Chemical Fate Assessment** | (See also Table 1-2) |
| Models/Methods | Calabrese and Kostecki (1992) |
| Exposure Assessment | |
| General | U S EPA (1986-1988, 1988c, 1990i), *Exposure Factors* Schaum (1990), U S EPA (1985b), *Food Contamination Pathways* U S EPA (1986c) |
| Models/Methods | Bird et al (1991—TEEAM) |
| **Risk Assessment** | |
| General | National Research Council (1983), U S EPA (1986-1988, 1987a), *Information Sources* U S EPA (1986b), *Biological Values* U S EPA (1988d), *Data Useability* U S EPA (1990g), *Model/Methods Reviews* Calabrese and Kostecki (1992), U S EPA (1990e, 1990f) |
| Chemical Hazards | Conway (1982), FEMA/DOT/EPA (1989), U S Department of Agriculture Extension Service (1989), U S EPA (1987d, 1988b, 1988f, 1989b, 1990f, 1992b), *Estimating Chemical Releases* PEI Associates (1990), U S EPA (1987c, 1989b, 1990d) |
| Ground Water** | *Texts/Reports* McTernan and Kaplan (1990), Reichard et al (1990), Trojan and Perry (1989), U S EPA (1991), *Papers* Flanagan et al (1991), Pfannkuch (1991) |
| Drinking Water | Lowrence (1992), U S EPA (1985a, 1990e) |
| Ecological | Eastern Research Group (1991), Norton et al (1988), Suter (1993), U S EPA (1989e, 1990h) |
| Public Health | U S EPA (1986-1988, 1986a, 1989d, 1990c, 1990i) |

* Commonly referred to as the Emergency Planning and Community Right-To-Know Act (EPCRA)

** See also references on vulnerability mapping identified in Table 5-9

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* See Introduction for information on how to obtain documents

# *Appendix B*
# *DRASTIC Mapping Using an SCS Soil Survey*

This appendix describes a relatively simple method for developing a preliminary countywide ground water vulnerability map when a soil survey prepared by the Soil Conservation Service (SCS) of the U S Department of Agriculture is available SCS has published soil surveys for most counties in the eastern and midwestern U S and many counties in western states These soil maps delineate *map units* containing similar soil characteristics based on such characteristics as landscape position, slope, soil wetness, depth to bedrock, and type of bedrock Map units are then grouped into soil associations based on geomorphology, surface, and/or bedrock geology Figure B-1 illustrates a general soil association map for Monroe County, Indiana, which has seven major soil associations

The procedure for developing a DRASTIC index for each soil association is as follows

1 Review the text descriptions of the major soil series in the soil association Most of the information needed to make ratings on Worksheet 5-2 can be obtained from these descriptions, including depth to water, aquifer media, soil media, topography, and vadose zone media Where soils in the association have contrasting properties, make ratings for the dominant soil or some sort of weighting based on relative acreages in the soil association (The soil report will have a table indicating the total acreages of different map units )

2 Use the table and figures identified in Section 3 2 2 to estimate hydraulic conductivity for each soil association

3 Where the water table is generally deeper than five feet, someone familiar with the hydrogeology of the area should be contacted (U S Geological Survey, state Water Resources Division office, state water resources agency, high school earth science teacher, etc ) to estimate typical water-table depths in each map unit Where perched water tables are present near the surface but the regional water table is significantly deeper, the depth to the water table used for water supply should be used If both are used for water supply, separate DRASTIC indexes should be calculated for the two aquifers in the soil association

4 Estimate net recharge for each soil association, as described in more detail below

5 Calculate the DRASTIC index for each soil association

Figure B-2 illustrates a filled-out DRASTIC Worksheet for a soil association over karst limestone in southern Indiana The rating of 172 is well above the EPA index value of 150 for highly vulnerable aquifers The legend for Figure B-1 shows the DRASTIC indexes for all seven soil associations in the county The DRASTIC indexes range from 74 for map unit 1 (relatively unsusceptible to ground-water contamination) to 172 for map unit 2 These ratings, made by someone familiar with the soils and geology of the county, took only a couple of minutes for each map unit Someone with no special familiarity with the soils and geology of the county might need a couple of hours to come up with ratings, based on a review of the contents of the soil survey

The precise numerical ratings for individual elements of the DRASTIC index is less important than the *relative* differences in the index for different map units If numerical index ratings for several units are very close together or very high, expert advice from a geologist or hydrogeologist to refine the accuracy of ratings may be required

## *Estimation of Net Recharge*

Net recharge is the most difficult parameter to estimate for the DRASTIC index, because accurate estimation of net recharge requires extensive collection of data on precipitation and surface and ground water flow for a watershed Aller et al (1987), the developers of the DRASTIC index, do not provide much guidance for estimation of net recharge The following procedure is suggested as a relatively simple method to develop a first approximation of net recharge

1 Identify the ground water region within which the county is located, using Figure B-3 [1] Chapter 2 in U S EPA (1990), available from the Center for Envi-

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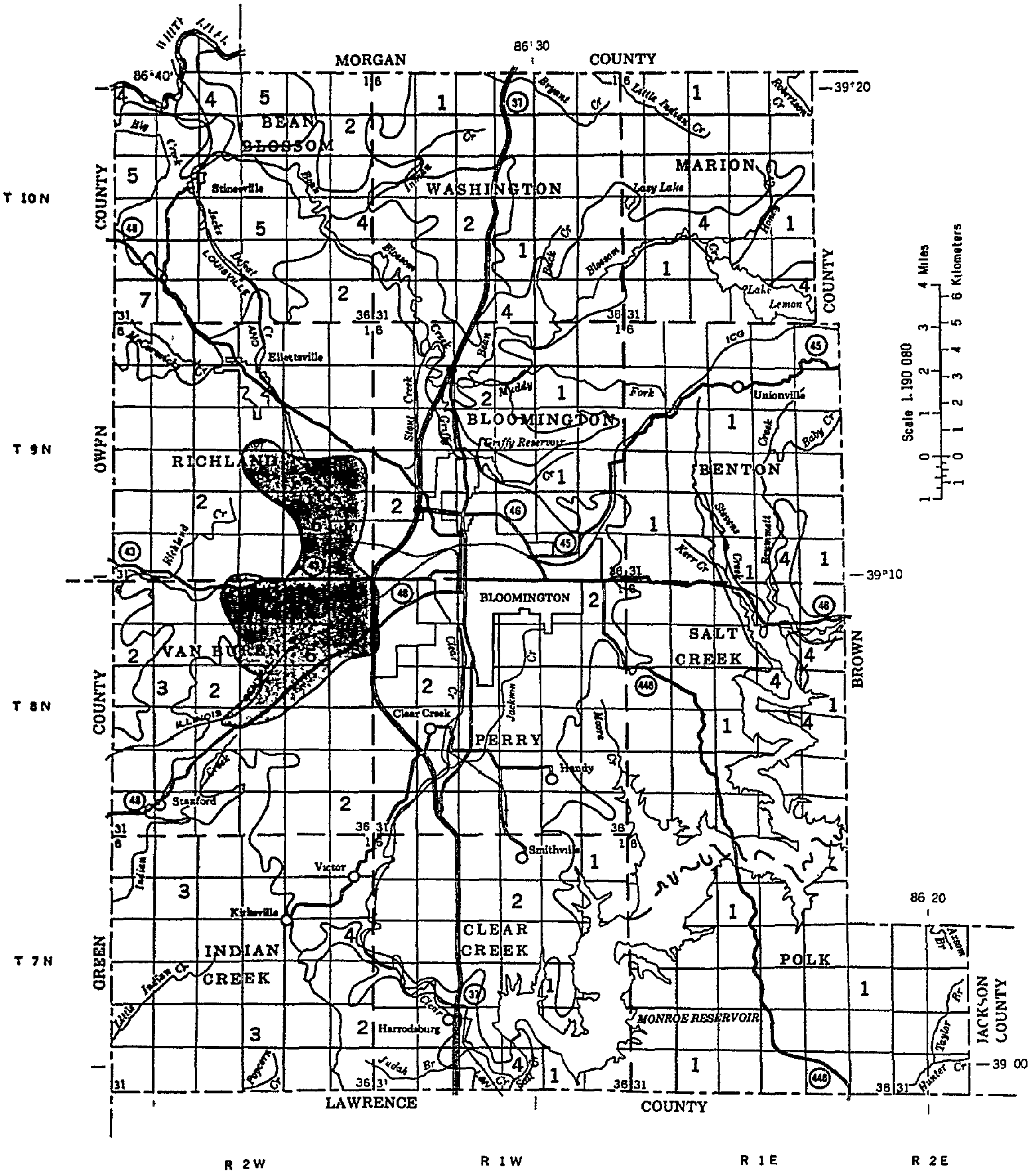
[1] The alluvial valleys regions include the floodplains of major U S rivers The range of recharge can be applied to any soil association consisting of alluvial soils



| Drastic Rating | | SOIL LEGEND |
|---|---|---|
| 74 | 1 | Berks-Weikert: Moderately deep and shallow steep and very steep well drained soils formed in residuum from sandstone siltstone and shale on uplands |
| 172 | 2 | Crider-Caneyville Deep and moderately deep gently sloping to strongly sloping well drained soils formed in loess and residuum from limestone on uplands |
| 74 | 3 | Ebal-Gilpin Tilsit: Deep and moderately deep nearly level to moderately steep moderately well drained and well drained soils formed in loess colluvium and residuum from shale sandstone and siltstone on uplands |
| 131 | 4 | Haymond-Stendal Deep nearly level well drained and somewhat poorly drained soil formed in alluvium on flood plains |
| 100 | 5 | Ryker Hickory Deep gently sloping to very steep well drained soils formed in loess glacial till and residuum from limestone on uplands |
| 133 | 6 | Hosmer-Crider Deep nearly level to moderately sloping well drained and moderately well drained soils formed in loess and residuum from limestone sandstone siltstone and shale: on uplands |
| 130 | 7 | Peoga-Bartle Deep nearly level poorly drained and somewhat poorly drained soils formed in loess and lakebed sediments or in old alluvium on uplands |

**Figure B-1. SCS soil association map for Monroe County, Indiana, with DRASTIC ratings (modified from Thomas, 1981)**

**Worksheet 5-2 DRASTIC WORKSHEET** (Circle appropriate range and rating).

**County:** Monroe **State:** IN

**General Soil Map Unit Number:** 2

**General Description:** Well-drained loess and terra rossa over karst limestone
Crider - Caneyville

**1. Depth to Water (feet)**

| Range | Rating |
|---|---|
| 0-5 | 10 |
| 5-15 | 9 |
| 15-30 | 7 |
| 30-50 | 5 |
| [✓ 50-75] | [✓ 3] |
| 75-100 | 2 |
| 100+ | 1 |

**2. Net Recharge (inches)**

| Range | Rating |
|---|---|
| 0-2 | 1 |
| 2-4 | 3 |
| 4-7 | 6 |
| [✓ 7-10] | [✓ 8] |
| 10+ | 9 |

**3. Aquifer Media**

| Type | Range | Rating Typical | Rating Actual |
|---|---|---|---|
| Massive Shale | 1-3 | 2 | |
| Metamorphic/Igneous | 2-5 | 3 | |
| Weathered M/I | 3-5 | 4 | |
| Glacial Till | 4-6 | 5 | |
| Bedded SS/LS/Shale | 5-9 | 6 | |
| Massive Sandstone | 4-9 | 6 | |
| Massive Limestone | 4-9 | 6 | |
| Sand and Gravel | 4-9 | 8 | |
| Basalt | 2-10 | 9 | |
| [✓ Karst Limestone] | [✓ 9-10] | 10 | 10 |

**4. Soil Media**

| Type | Rating |
|---|---|
| Thin/ Absent | 10 |
| Gravel | 10 |
| Sand | 9 |
| Peat | 8 |
| [✓ Structured Clay] | [✓ 7] |
| Sandy Loam | 6 |
| Loam | 5 |
| Silty Loam | 4 |
| Clay Loam | 3 |
| Muck | 2 |
| Massive Clay | 1 |

**5. Topography (Percent Slope)**

| Range | Rating |
|---|---|
| 0-2 | 10 |
| 2-6 | 9 |
| [✓ 6-12] | [✓ 5] |
| 12-18 | 3 |
| 18+ | 1 |

**6. Vadose Zone Media**

| Type | Range | Rating Typical | Rating Actual |
|---|---|---|---|
| Confining Layer | 1 | 1 | |
| Silt/Clay | 2-6 | 3 | |
| Shale | 2-5 | 3 | |
| Limestone | 2-7 | 6 | |
| Sandstone | 4-8 | 6 | |
| Bedded LS/SS/Shale | 4-8 | 6 | |
| Sand and Gravel with Sig. Silt and Clay | 4-8 | 6 | |
| Metamorphic/Igneous | 2-8 | 4 | |
| Sand and Gravel | 6-9 | 8 | |
| Basalt | 2-10 | 9 | |
| [✓ Karst Limestone] | [✓ 8-10] | 10 | 10 |

**7. Hydraulic Conductivity (gpd/sq. ft.)**

| Range | Rating |
|---|---|
| 1-100 | 1 |
| 100-300 | 2 |
| 300-700 | 4 |
| 700-1,000 | 6 |
| [✓ 1,000-2,000] | [✓ 8] |
| 2,000+ | 10 |

**DRASTIC Index**

Rating x Weight =

1. 3 x 5 = 15
2. 8 x 4 = 32
3. 10 x 3 = 30
4. 7 x 2 = 14
5. 5 x 1 = 5
6. 10 x 5 = 50
7. 8 x 3 = 24

Total 172*

* Aquifers with DRASTIC ratings >150 are considered to be "highly vulnerable" by EPA.

Figure B-2 Sample Drastic Worksheet for soil association overlying karst limestone in Monroe County, Indiana

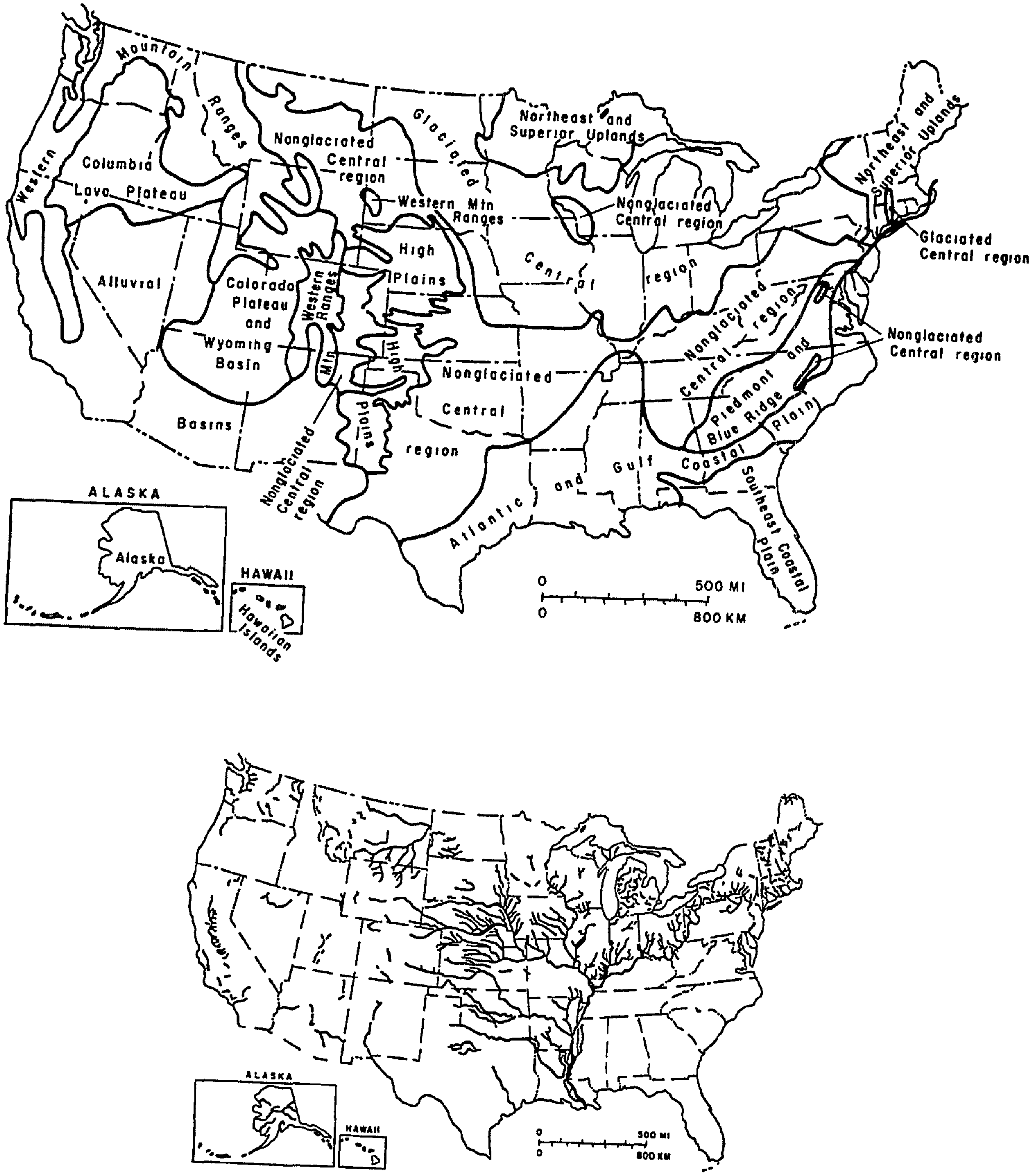


Figure B-3. Major ground water regions in the United States (Heath, 1982) ronmental Research Information (see Introduction for information on how to obtain documents) provides more detailed descriptions of these ground water regions

2 Determine the typical range for net annual recharge (inches) for the appropriate region using the following information from Heath (1982) western mountain ranges (0 1-2), western alluvial basins (0 0001-1), Columbia lava plateau (0 2-10), Colorado plateau and Wyoming basin (0 01-2), high plains (0 2-3), nonglaciated central region (0 2-20), glaciated central region 0 2-10), Piedmont and Blue Ridge (1-10), Northeast and Superior uplands (1-10), Atlantic and Gulf coastal plain (2-20), Southeast coastal plain (1-20), alluvial valleys (2-20), Hawaiian Islands (1-40), and Alaska (0 1-10)

3 Use Figures B-4 (mean annual precipitation) and B-5 (average annual potential evapotranspiration) to estimate the approximate maximum and minimum difference between average precipitation and evapotranspiration in the ground water region of interest This involves, first, comparing the boundaries of the ground water region (Figure B-3) and marking or noting the location of maximum and minimum average precipitation (Figure B-4) and maximum and minimum evapotranspiration (Figure B-5) within the region Calculating the difference between precipitation and evapotranspiration at the max/min points in Figure B-4 (precipitation) and the max/min points in Figure B-5 (evapotranspiration) will allow identification of the two points in the region where precipitation minus evapotranspiration is the greatest and where it is the least Negative values should not be a matter of concern (in fact, they should be expected west of 95° longitude) What is important is the range between the maximum and the minimum

4 Estimate the approximate average precipitation and evapotranspiration for the area of the SCS soil survey, using Figures B-4 and B-5 [2]

5 Estimate average net recharge in the soil survey area in relation to the net recharge range identified in step 2 by interpolation For example, in the nonglaciated central region, if the county value for precipitation minus evapotranspiration lies halfway between the range calculated for the region as a whole, the average net recharge would be around 10 inches per year (halfway between 0 2 and 20 inches) This is a county average that must be adjusted to account for differences in runoff between soil associations

6 Use Tables 5-1 (SCS Index Runoff Classes) and 5-2 (SCS Criteria for Hydraulic Conductivity and Permeability Classes) to assign a runoff class for each soil association map unit

7 Net recharge ratings for the DRASTIC index (Worksheet 5-2) for each soil association should be assigned as follows based on surface runoff class index (see Table 5-1 for abbreviations) M = use value calculated in Step 5, N, VL, and L = circle the next higher net recharge category in Worksheet 5-2, H and VH = next lower net recharge category Note the inverse relationship between runoff and recharge For example, in the example cited in step 5, where average net recharge was estimated to be 10 inches, soil associations in the medium (M) runoff class would have a DRASTIC rating of 8, soil associations low runoff classes would have a DRASTIC index rating of 9, and soil associations with high runoff classes would have a DRASTIC index of 6

At best, the above procedure will provide a rough estimate of net recharge that can be used in the absence of better data More accurate estimates may require assistance from the individuals who are familiar with the soils, geology, surface and subsurface hydrology of the area

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* See Introduction for information on how to obtain documents

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[2] The SCS soil survey report contains precipitation data for comparison with Figure 5-15

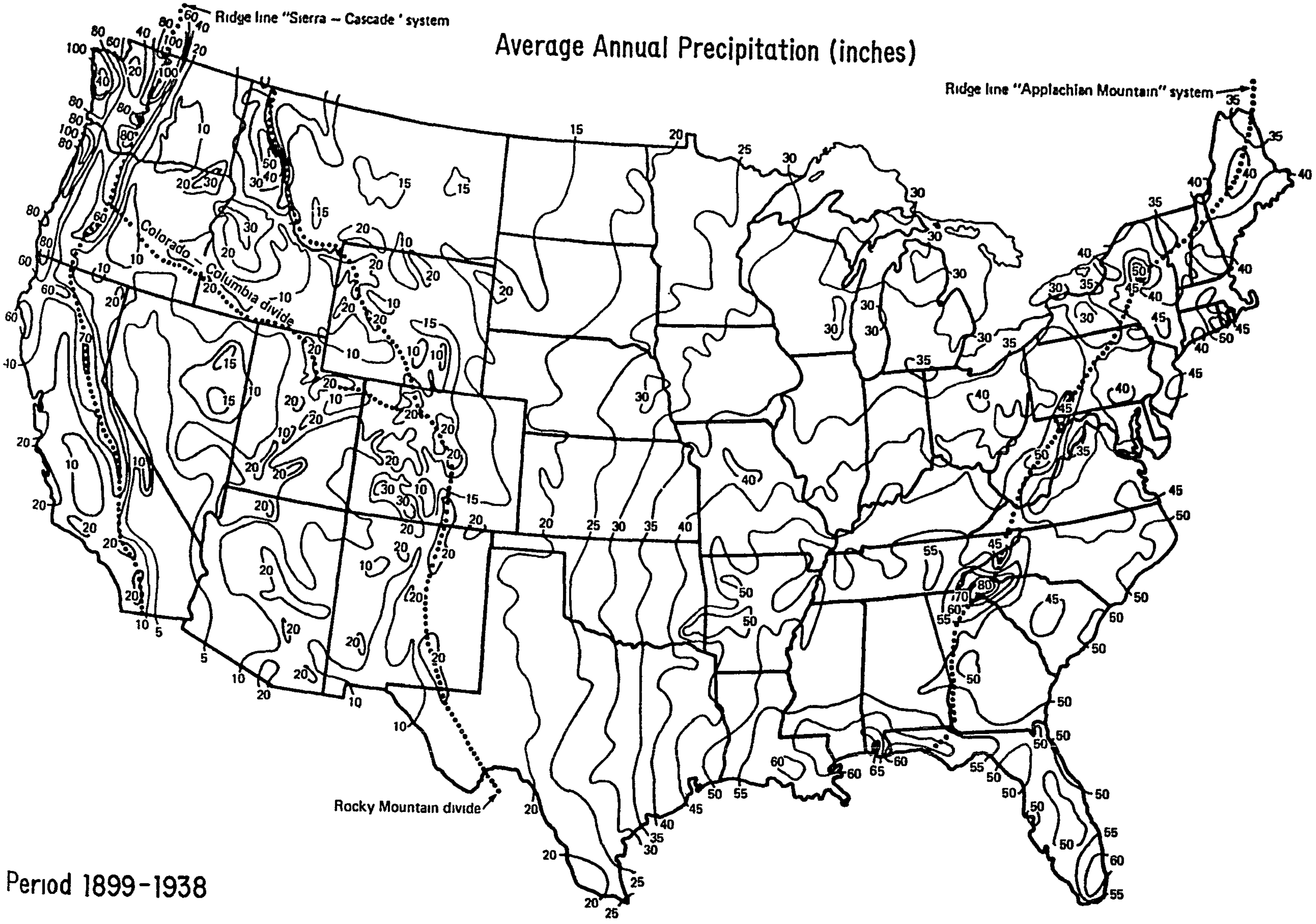


Figure B-4 Mean annual precipitation, 1899-1938 (Viessman et al 1972, after U S Department of Agriculture Soil Conservation Service)

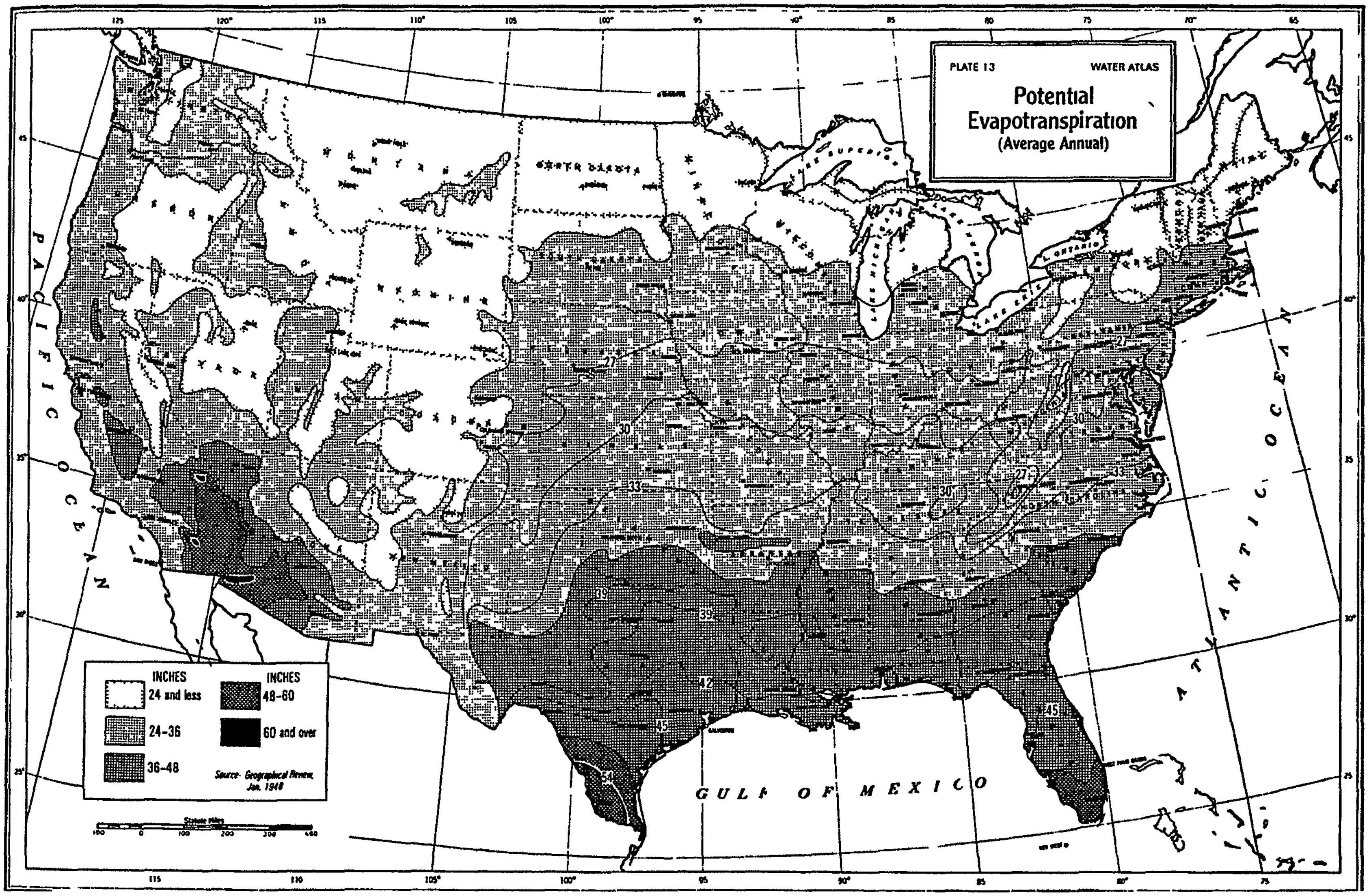


Figure B-5 Average annual potential evapotranspiration (after Thornthwaite, 1948)

# Appendix C
# Worksheets for Potential Contaminant Source Inventories and Wellhead Protection Area Management

This appendix includes examples of worksheets that may be useful for conducting contaminant source inventories within wellhead protection areas and developing management plans for ground water protection Many state wellhead protection programs have developed worksheets for similar purposes If such worksheets are available, they can be compared with similar worksheet(s) in this Appendix and the worksheet that is most comprehensive and easiest to use should be selected If neither worksheet includes all relevant information, the worksheet that is selected can be modified to include the desired additional information

The following worksheets are intended for use with the inventory of potential contaminants within wellhead protection areas (Chapter 8)

- Residential Potential Contaminant Source Inventory (Worksheet C-1)
- Farm Potential Contaminant Source Inventory (Worksheet C-2)
- Agricultural Chemical Usage Inventory (Worksheet C-3)
- Transportation Hazard Inventory (Worksheet C-4)
- Municipal/Commercial/Industrial Potential Contaminant Source Inventory Short Form (Worksheet C-5)
- Municipal/Commercial/Industrial Potential Contaminant Source Inventory Long Form (Worksheet C-6)

The "short form" for municipal, commercial, and industrial contaminant sources (Worksheet C-5) can be used when the presence of storage tanks and/or use of solvents are the primary sources of potential concern If other hazardous chemicals are present, the "long form" (Checklist C-6) can be used

The following worksheets are intended for use in developing a management plan for wellhead protection

- Bylaw Summary Form and Wellhead Protection Worksheet (Worksheet C-7)
- Drinking Water Supply Contingency Plan (Worksheet C-8)
- Chemical Spill Emergency Notification and Documentation (Worksheet C-9)

## References (Sources of Worksheets)

Adams, S et al 1992 Pilot Groundwater Protection Needs Assessment for Illinois American Water Company's Pekin Public Water Supply Facility Number 1795040 Division of Public Water Supplies, Illinois Environmental Protection Agency, Springfield, IL

Massachusetts Department of Environmental Protection (MDEP) 1991 Guidelines and Policies for Public Water Systems (Revised, October 1991) MDEP, Division of Water Supply, Boston, MA, 182 pp + appendices

New York State Department of Health 1984 Emergency Planning and Response—A Water Supply Guide for the Supplier of Water New York State Department of Health, Albany, NY

North Dakota State Department of Health 1993 North Dakota Wellhead Protection User's Guide Division of Water Quality, Bismarck, ND

Ohio Environmental Protection Agency 1991 Guidance for Conducting Pollution Source Inventories in Wellhead Protection Areas (Draft) OEPA, Division of Ground Water, Columbus, OH, 17 pp

Ohio Environmental Protection Agency 1992 Ohio Wellhead Protection Program OEPA, Division of Drinking and Ground Water, Columbus, OH

# Worksheet C-1
# Residential Potential Contaminant Source Inventory
# (North Dakota State Department of Health, 1993)

NORTH DAKOTA
WELLHEAD PROTECTION

DATE: ____________________
PWS : ____________________

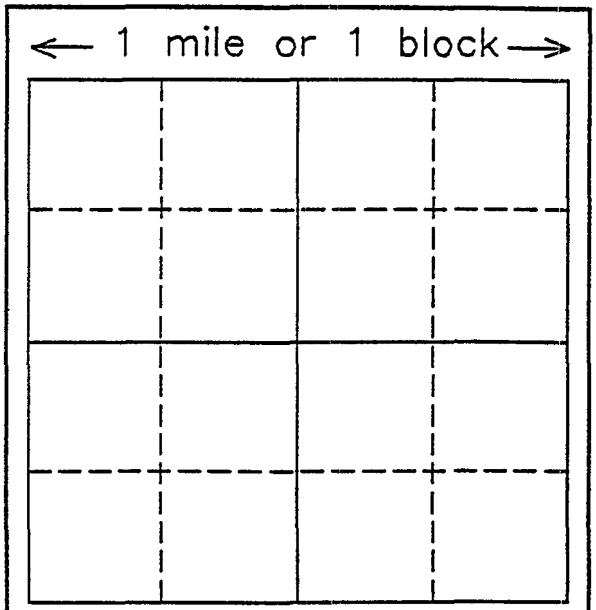
WELLHEAD PROTECTION AREA SURVEY FORM
RESIDENTIAL

This survey form is designed to inventory activities that may impact groundwater quality within the public water supply wellhead protection area (WHPA).

Name: ____________________
Address: ____________________
City: ____________________
Phone: ____________________

Please describe all water wells on the property:

First well:
Use/Name: ____________________
(e.g., stock, house, irrigation)
Depth: ________ Diameter: ________
Depth to water: ________
Pumping rate (gallons per minute): _____
What year was the well installed? _____
Location: Township _____ Range _____
Section _____ Quarters _____
(Please locate on the section/block map provided.)



SECTION MAP
This map represents an entire section of land. Please take care to plot the location of the source to the nearest 10 acres (see instructions). This map may also be used to represent a one-block area.

Second Well:
Use/Name: ____________________
(e.g., stock, house, irrigation)
Depth: ________ Diameter: ________
Depth to water: ________ Pumping rate (gallons per minute): ________
What year was the well installed? ________
Location: Township _____ Range _____ Section _____ Quarters _____
(Please locate on the section/block map provided.)

Third Well:
Use/Name: ____________________
(e.g., stock, house, irrigation)
Depth: ________ Diameter: ________
Depth to water: ________ Pumping rate (gallons per minute): ________
What year was the well installed? ________
Location: Township _____ Range _____ Section _____ Quarters _____
(Please locate on the section/block map provided.)

## Worksheet C-1 (Continued)

Are there any abandoned wells on the property?____________________
If yes, were they plugged and how?____________________
________________________________________

If there is a septic tank/drain field on the property, please describe:
Septic tank:
Location: ____________________________________
(township, range, section, quarters, or other description; also locate on map)
Size: ________ Depth: ________ Year: ______ Last pumped out: ________

Drain field size and location: ______________________________
________________________________________

Is there any heating/fuel oil storage on the property? Describe: __________
________________________________________

Are there any livestock on the property? Describe (if farm, please use Farm form): ______________________________

Please describe any chemicals used or stored on the property.
Storage: __________________________________
________________________________________
Usage: (fertilizers or pesticides on lawns or gardens? what type? quantity? frequency?) ____________________________
________________________________________
Disposal: __________________________________
________________________________________

Are there any floor drains in your home or building that do not connect to the city sewer system? ____________________________
If so, what is disposed of there? ____________________________

Other problems or comments: ____________________________
________________________________________
________________________________________

## Worksheet C-2
## Farm Potential Contaminant Source Inventory
## (North Dakota State Department of Health, 1993)

NORTH DAKOTA
WELLHEAD PROTECTION

DATE: ____________________
PWS : ____________________

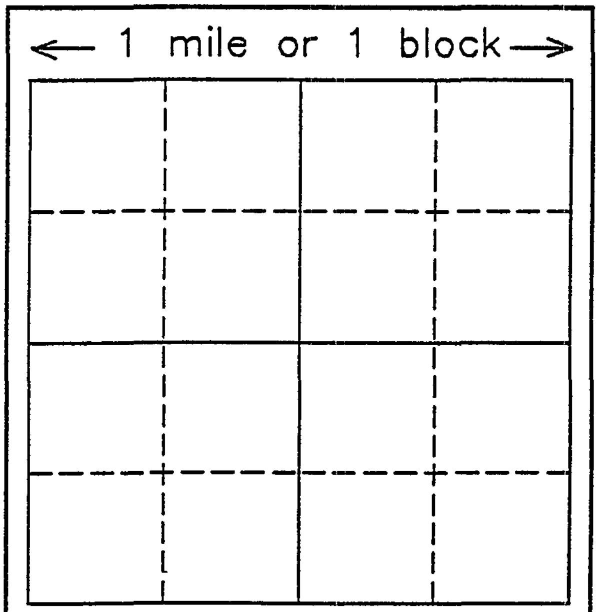
WELLHEAD PROTECTION AREA SURVEY FORM
FARM

This survey form is designed to inventory activities that may impact groundwater quality within the wellhead protection area (WHPA).

Name: ____________________
Address: ____________________
City: ____________________
Phone: ____________________

Please describe all water wells on the property:

First well:
Use/Name: ____________________
(e.g., stock, house, irrigation)
Depth: __________ Diameter: __________
Depth to water: __________
Pumping rate (gallons per minute): ______
What year was the well installed? ______
Location: Township _____ Range _______
Section _____ Quarters _____
(Please locate on the section/block map provided.)



SECTION MAP
This map represents an entire section of land. Please take care to plot the location of the source to the nearest 10 acres (see instructions). This map may also be used to represent a one-block area.

Second Well:
Use/Name: ____________________
(e.g., stock, house, irrigation)
Depth: __________ Diameter: __________
Depth to water: ________ Pumping rate
(gallons per minute): ________
What year was the well installed? ________
Location: Township _____ Range _____ Section _____ Quarters _____
(Please locate on the section map provided.)

Third Well:
Use/Name: ____________________
(e.g., stock, house, irrigation)
Depth: __________ Diameter: __________
Depth to water: ________ Pumping rate (gallons per minute): ________
What year was the well installed? ________
Location: Township _____ Range _____ Section _____ Quarters _____
(Please locate on the section map provided.)

## Worksheet C-2 (Continued)

Are there any abandoned wells on the property? ____________________
If yes, were they plugged and how? ____________________
____________________

If there is a septic tank/drain field on the property, please describe:
Septic tank:
Location: ____________________
(township, range, section, quarters, or other description; also locate on map)
Size: ________ Depth: ________ Year: ______ Last pumped out: ______
Drain field size and location: ____________________
____________________

Is there any heating/fuel oil storage on the property? Describe: __________
____________________

Please list the crops that you typically plant. ____________________
____________________

What is the total acreage that you farm? ____________________

Please list each crop separately followed by the number of acres that are generally in that crop or the percentage of the total in that crop.

Crop #1 ______________ acres or % ______________
Crop #2 ______________ acres or % ______________
Crop #3 ______________ acres or % ______________
Crop #4 ______________ acres or % ______________

Chemicals (pesticides or fertilizers):

Please list the chemicals that you applied to each crop in the last two years.

| Crop # | Chemicals applied | # of Years | Volume Kg/hectare/yr |
|---|---|---|---|
| ____ | ______________ | ______ | ______ |
| ____ | ______________ | ______ | ______ |
| ____ | ______________ | ______ | ______ |
| ____ | ______________ | ______ | ______ |

Please describe any chemical storage procedures and the name of the chemicals which you currently store. ____________________
____________________
____________________

Please describe any irrigation or chemigation practices. ____________________
____________________
____________________

Please describe any chemical mixing practices. ____________________
____________________
____________________

Please describe your container disposal practices. ____________________
____________________
____________________

## Worksheet C-2 (Continued)

Are there any livestock on the property? _______

Please list the types of livestock, how many, and their location. ____________
________________________________________
________________________________________
________________________________________
________________________________________

Please describe the location, age, and design of any feedlots. ____________
________________________________________
________________________________________

Please describe any manure storage on the property. ____________
________________________________________
________________________________________

Do you have any underground storage tanks? If so, describe their size, location, and contents. ____________
________________________________________
________________________________________

Do you have any above ground storage tanks? If so, describe their size, location, and contents. ____________
________________________________________
________________________________________

Other problems or comments: ____________
________________________________________
________________________________________
________________________________________

# Worksheet C-3
## Agricultural Chemical Usage Inventory (State of Oklahoma)

## AGRICULTURAL CHEMICAL USAGE SURVEY

ID ____________ SYSTEM ____________________

SOURCE NAME OR WELL NUMBER ____________________

If any of the following crops or activities have been in use or cultivation within the last 25 years please obtain information on any of the following chemicals which may have been used in proximity to your water source Please check which chemicals may have been used

### INFORMATION SOURCE

Landowner _____ County Extension Agent _____ Okla Dept of Ag _____ County Sanitarian _____
Other (Specify) ____________________

### HORTICULTURAL

### ALFALFA

- ☐ **Carbaryl** (Sevin Carbamine Denapon Dicarbam Hexavin Karbaspray Nac Ravyon Septene Tercyl Tricarnum Arilate Bercema NMC50 Caprolin)
- ☐ **Carbofuran, 3 hydroxycarbofuran** (Furadan)
- ☐ **Dinoseb** (Basanite Dinitro Dynamyte Premerge Vertac Weed Killer)
- ☐ **Endothall** (Endothall Aquatrol K Hydrothol 191 Herbicide 273 Des-i-cate Accelerate)
- ☐ **Methomyl** (Lannnate LV Methomex Nudrin Mesomile Acetimidic Acid)
- ☐ **Methoxyclor** (Marlate Chemform DMDT)
- ☐ **Metribuzin** (Lexone 4L Lexone DF Sencor 4 Sencoral Sencorex Sencor DF Salute Turbo)
- ☐ **Simazine** (Aquazine Princep Princep Caliber 90 Primatol S Simadex Simanex)

### ASPARAGUS

- ☐ **Dicamba** (Banvel Banes Banex Banlen Brush Buster Dianat Dinate Dicambe Mediben Mondak MDBA)
- ☐ **Metribuzin** (Lexone 4L Lexone DF Sencor 4 Sencoral Sencorex Sencor DF Salute Turbo)
- ☐ **2 4-D** (Weedone Esteron Dacamine Weed B Gone Weed Rhap Amine 4 Butyl Ester 4 LV 4 LV 6 Aqua Kleen)

### BARLEY

- ☐ **Metribuzin** (Lexone 4L Lexone DF Sencor 4 Sencoral Sencorex Sencor DF Salute Turbo)
- ☐ **Ethylene dibromide EDB** (Bromofume E D Bee Kopfume Nephis Dowfume Soilbrome)

### CLOVER

- ☐ **Dinoseb** (Basanite Dinitro Dynamyte Premerge Vertac Weed Killer
- ☐ **Endothall** (Endothall Aquatrol K Hydrothol 191 Herbicide 273, Des i-cate Accelerate)

### CORN

- ☐ **Carbofuran 3 hydroxycarbofuran** (Furadan)
- ☐ **Metribuzin** (Lexone 4L Lexone DF Sencor 4 Sencoral Sencorex Sencor DF Salute Turbo)
- ☐ **Simazine** (Aquazine Princep Princep Caliber 90 Primatol S Simadex Simanex)
- ☐ **Endrin** (Endrin Nendrin Hexadrin)

## AGRICULTURAL CHEMICAL USAGE SURVEY

- ☐ **Lindane** (Lindane Isotox Gamma HCH BHC)
- ☐ **Metolachlor** (Bicep Dual Ontrack Pennant Pimagram, Turbo)
- ☐ **Methomyl** (Lannate LV Methomex Nudrin Mesomile Acetimidic Acid)
- ☐ **Picloram** (Tordon Amdon ACTP Borolin K Pin Acces Grazon)
- ☐ **Toxaphene** (Toxaphene Camphochlor Motox Phenacide Phenatox Toxakil Toxon 63)
- ☐ **2,4-D** (Weedone Esteron Dacamine Weed B Gone Weed Rhap Amine 4 Butyl Ester 4 LV 4 LV 5 Aqua Kleen)
- ☐ **Dicamba** (Banvel Banes Banex Banlen Brush Buster Dianat Dinate Dicambe Mediben Mondak MDBA)
- ☐ **Alachlor** (Lasso Lazo Pillarzo Alazine Bullet Lariat Freedom Nudor Extra Rasdor)
- ☐ **Atrazine** (Aatrex Alazine Bullet Rhino Tomahawk Bicep Primextra Rastra)
- ☐ **Heptachlor, heptachlor epoxide** (Heptachlor Drinox Heptox Termide)
- ☐ **Glyphosate** (Roundup Rodeo Roundup L&G Landmaster)

### COTTON

- ☐ **Carbofuran 3-hydroxycarbofuran** (Furadan)
- ☐ **Endothall** (Endothall Aquatrol K Hydrothol 191 Herbicide 273 Des i-cate Accelerate)
- ☐ **Methomyl** (Lannate LV Methomex Nudrin Mesomile Acetimidic Acid)
- ☐ **Endrin** (Endrin Nendrin Hexadrin)
- ☐ **Metolachlor** (Bicep Dual Ontrack Pennant Pimagram Turbo)
- ☐ **Toxaphene** (Toxaphene Camphochlor Motox Phenacide Phenatox Toxakil Toxon 63)
- ☐ **Alachlor** (Lasso Lazo Pillarzo Alazine Bullet Lariat Freedom Nudor Extra Rasdor)
- ☐ **Aldicarb, aldicarb sulfoxide aldicarb sulfone** (Temik)
- ☐ **Dibromochloropropane, DBCP** (Nemafume Nemanax Nemaset Nemagon Fumazone Nematocide)
- ☐ **Oxamyl** (Vydate DPX 1410 Oxamidic Acid Thioxamyl)
- ☐ **Glyphosate** (Roundup Rodeo Roundup R&G Landmaster)

### FOREST

- ☐ **Carbaryl** (Sevin Carbamine Denapon Dicarbam Hexavin Karbaspray Nac Ravyon Septene Tercyl Tricarnum Arilate Bercema NMC50 Caprolin)
- ☐ **Endrin** (Endrin Nendrin Hexadrin)
- ☐ **Lindane** (Lindane Isotox Gamma HCH BHC)
- ☐ **2,4-D** (Weedone Esteron Dacamine Weed B-Gone Weed Rhap Amine 4 Butyl Ester 4 LV 4 LV 6 Aqua Kleen)
- ☐ **2 4 5-TP Silvex** (Silvex AquaVex Kurosal Ded Weed Kuron Silvi Rhap, Dacamine T Nox Fencerider)

### FRUIT TREES/BERRIES

- ☐ **Methomyl** (Lannate LV Methomex Nudrin Mesomile Acetimidic Acid)
- ☐ **Endrin** (Endrin Nendrin Hexadrin)
- ☐ **Metolachlor** (Bicep Dual Ontrack Pennant Pimagram Turbo)
- ☐ **Dibromochloropropane DBCP** (Nemafume Nemanax Nemaset Nemagon Fumazone Nematocide)
- ☐ **Oxamyl** (Vydate DPX 1410 Oxamidic Acid Thioxamyl)

## AGRICULTURAL CHEMICAL USAGE SURVEY

☐ **Lindane** (Lindane, Isotox Gamma HCH, BHC)
☐ **Methoxychlor** (Marlate Chemform, DMDT)
☐ **Simazine** (Aquazine Princep Princep Caliber 90 Primatol S Simadex, Simanex)
☐ **Dinoseb** (Basanite Dinitro, Dynamyte, Premerge, Vertac Weed Killer)
☐ **Glyphosate** (Roundup Rodeo Roundup R&G Landmaster)
☐ **Carbaryl** (Sevin, Carbamine Denapon Dicarbam, Hexavin, Karbaspray Nac, Ravyon Septene Tercyl Tricarnum Arilate Bercema NMC50 Caprolin)

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### GRAIN SORGHUM

☐ **Carbofuran, 3 hydroxycarbofuran** (Furadan)
☐ **Lindane** (Lindane Isotox Gamma HCH, BHC)
☐ **Metolachlor** (Bicep, Dual, Ontrack Pennant Primagram, Turbo)
☐ **2,4-D** (Weedone Esteron Dacamine Weed B Gone Weed Rhap Amine 4 Butyl Ester 4 LV 4 LV 6, Aqua Kleen)
☐ **Dicamba** (Banvel Banes Banex Banlen, Brush Buster Dianat, Dinate Dicambe, Mediben Mondak, MDBA)
☐ **Atrazine** (Aatrex Alazine Bullet Rhino, Tomahawk Bicep Primextra, Rastra)
☐ **Dinoseb** (Basanite Dinitro Dynamyte Premerge Vertac Weed Killer)
☐ **Heptachlor, heptachlor epoxide** (Heptachlor Drinox, Heptox Termide)
☐ **Methomyl** (Lannate LV Methomex Nudrin Mesomile Acetimidic Acid)
☐ **Aldicarb, aldicarb sulfoxide aldicarb sulfone** (Temik)
☐ **Carbaryl** (Sevin, Carbamine Denapon Dicarbam Hexavin Karbaspray Nac Ravyon Septene Tercyl Tricarnum Arilate Bercema NMC50 Caprolin)
☐ **Glyphosate** (Roundup Rodeo Roundup R&G Landmaster)
☐ **Alachlor** (Lasso Lazo, Pillarzo Alazine Bullet Lariat Freedom, Nudor Extra Rasdor)

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### GREENHOUSES

☐ **Carbaryl** (Sevin Carbamine Denapon Dicarbam. Hexavin Karbaspray Nac Ravyon Septene Tercyl Tricarnum Arilate Bercema NMC50 Caprolin)
☐ **Oxamyl** (Vydate DPX 1410 Oxamidic Acid Thioxamyl)
☐ **Lindane** (Lindane Isotox Gamma HCH BHC)

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### LAWN/TURFGRASS

☐ **Carbaryl** (Sevin Carbamine Denapon Dicarbam Hexavin Karbaspray Nac Ravyon Septene Tercyl, Tricarnum, Arilate Bercema NMC50 Caprolin)
☐ **Glyphosate** (Roundup Rodeo Roundup R&G Landmaster)
☐ **2,4-D** (Weedone Esteron, Dacamine Weed-B-Gone Weed Rhap Amine 4 Butyl Ester 4 LV 4 LV 6 Aqua Kleen)
☐ **Dicamba** (Banvel Banes Banex Banlen Brush Buster Dianat Dinate Dicambe, Mediben, Mondak, MDBA)
☐ **Dibromochloropropane, DBCP** (Nemafume Nemanax Nemaset Nemagon Fumazone Nematocide)
☐ **Simazine** (Aquazine Princep Princep Caliber 90 Primatol S Simadex Simanex)
☐ **Endothall** (Endothall Aquatrol K. Hydrothol 191 Herbicide 273 Des-i-cate Accelerate)

## AGRICULTURAL CHEMICAL USAGE SURVEY

☐ **Dalapon** (Dalapon, Dowpon Basinex P Gramevin, Kenapon, Liropon, Unipon Revenge Alatex Ded-Weed, Devipon)
☐ **Metribuzin** (Lexone 4L, Lexone DF Sencor 4 Sencoral, Sencorex, Sencor DF Salute, Turbo)
☐ **Methomyl** (Lannate LV Methomex, Nudrin Mesomile Acetimidic Acid)
☐ **Atrazine** (Aatrex Alazine Bullet, Rhino, Tomahawk Bicep Primextra, Rastra)
☐ **Diquat** (Aquacide Dextrone Weedtrin-D, Aquakill)

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### MELONS

☐ **Dibromochloropropane, DBCP** (Nemafume, Nemanax Nemaset, Nemagon Fumazone Nematocide)
☐ **Methomyl** (Lannate LV Methomex Nudrin Mesomile Acetimidic Acid)
☐ **Oxamyl** (Vydate, DPX 1410 Oxamidic Acid Thioxamyl)
☐ **Metribuzin** (Lexone 4L, Lexone DF Sencor 4 Sencoral Sencorex Sencor DF Salute Turbo)
☐ **Dinoseb** (Basanite Dinitro Dynamyte, Premerge Vertac Weed Killer)
☐ **Lindane** (Lindane Isotox, Gamma HCH BHC)
☐ **Methoxychlor** (Marlate Chemform DMDT)
☐ **Atrazine** (Aatrex Alazine, Bullet Rhino Tomahawk Bicep Primextra Rastra)
☐ **Chlordane** (ChlorKill Gold Crest C 100 Octa Klor, Chlorotox)
☐ **Ethylene dibromide, EDB** (Bromofume E D Bee Kopfume Nephis Dowfume Soilbrome)
☐ **Glyphosate** (Roundup Rodeo Roundup R&G Landmaster)
☐ **Carbaryl** (Sevin Carbamine Denapon Dicarbam Hexavin Karbaspray Nac, Ravyon Septene Tercyl Tricarnum Arilate Bercema NMC50 Caprolin)
☐ **Alachlor** (Lasso Lazo Pillarzo Alazine Bullet Lariat Freedom Nudor Extra Rasdor)
☐ **Simazine** (Aquazine Princep Princep Caliber 90 Primatol S Simadex Simanex)
☐ **Metolachlor** (Bicep, Dual Ontrack Pennant, Primagram Turbo)
☐ **2 4-D** (Weedone Esteron, Dacamine Weed-B-Gone Weed Rhap Amine 4 Butyl Ester 4 LV 4 LV 6 Aqua Kleen)
☐ **Dalapon** (Dalapon Dowpon Basinex P Gramevin Kenapon Liropon Unipon Revenge Alatex Ded Weed Devipon)

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### ORNAMENTALS/NURSERY STOCK

☐ **Methomyl** (Lannate LV Methomex Nudrin Mesomile Acetimidic Acid)
☐ **Endrin** (Endrin Nendrin Hexadrin)
☐ **Metolachlor** (Bicep, Dual, Ontrack Pennant Primagram Turbo)
☐ **Dibromochloropropane DBCP** (Nemafume, Nemanax Nemaset Nemagon Fumazone Nematocide)
☐ **Oxamyl** (Vydate DPX 1410 Oxamidic Acid Thioxamyl)
☐ **Lindane** (Lindane Isotox Gamma HCH BHC)
☐ **Methoxychlor** (Marlate Chemform DMDT)
☐ **Aldicarb, aldicarb sulfoxide, aldicarb sulfone** (Temik)
☐ **Carbaryl** (Sevin, Carbamine Denapon Dicarbam Hexavin Karbaspray Nac Ravyon Septene Tercyl, Tricarnum Arilate Bercema NMC50 Caprolin)
☐ **Atrazine** (Aatrex Alazine Bullet Rhino Tomahawk Bicep Primextra Rastra)

## AGRICULTURAL CHEMICAL USAGE SURVEY

☐ **Chlordane** (ChlorKill Gold Crest C 100 Octa Klor Chlorotox)
☐ **Simazine** (Aquazine Princep Princep Caliber 90 Primatol S Simadex Simanex)
☐ **Glyphosate** (Roundup Rodeo Roundup R&G Landmaster)

### PASTURE/RANGELAND

☐ **Carbaryl** (Sevin Carbamine Denapon Dicarbam Hexavin Karbaspray Nac Ravyon Septene Tercyl Tricarnum Arilate Bercema NMC50 Caprolin)
☐ **Atrazine** (Aatrex Alazine Bullet Rhino Tomahawk Bicep Primextra Rastra)
☐ **2 4-D** (Weedone Esteron Dacamine Weed B Gone Weed Rhap Amine 4 Butyl Ester 4 LV 4 LV 6 Aqua Kleen)
☐ **Metribuzin** (Lexone 4L, Lexone DF Sencor 4 Sencoral Sencorex Sencor DF Salute Turbo)
☐ **Picloram** (Tordon Amdon ACTP Borolin K Pin Acces Grazon)
☐ **Dicamba** (Banvel Banes Banex Banlen Brush Buster Dianat Dinate Dicambe Mediben Mondak MDBA)

### PEANUTS

☐ **Carbofuran, 3 hydroxycarbofuran** (Furadan)
☐ **Methomyl** (Lannate LV Methomex Nudrin Mesomile Acetimidic Acid)
☐ **Metolachlor** (Bicep Dual Ontrack Pennant Pimagram Turbo)
☐ **Alachlor** (Lasso Lazo Pillarzo Alazine Bullet Lariat Freedom, Nudor Extra Rasdor)
☐ **Oxamyl** (Vydate DPX 1410 Oxamidic Acid Thioxamyl)
☐ **Dibromochloropropane DBCP** (Nemafume Nemanax Nemaset Nemagon Fumazone Nematocide)
☐ **Carbaryl** (Sevin Carbamine Denapon Dicarbam Hexavin Karbaspray Nac Ravyon Septene Tercyl Tricarnum Arilate Bercema NMC50 Caprolin)

### PECAN/NUTS

☐ **Dinoseb** (Basanite Dinitro Dynamyte Premerge Vertac Weed Killer)
☐ **Metolachlor** (Bicep Dual Ontrack Pennant Pimagram Turbo)
☐ **Dibromochloropropane DBCP** (Nemafume Nemanax Nemaset Nemagon Fumazone Nematocide)
☐ **Lindane** (Lindane Isotox Gamma HCH BHC)
☐ **Aldicarb aldicarb sulfoxide aldicarb sulfone** (Temik)
☐ **Simazine** (Aquazine Princep Princep Caliber 90 Primatol S Simadex Simanex)
☐ **Glyphosate** (Roundup Rodeo Roundup R&G Landmaster)

### POTATOES

☐ **Dinoseb** (Basanite Dinitro Dynamyte Premerge Vertac Weed Killer)
☐ **Carbofuran 3-hydroxycarbofuran** (Furadan)
☐ **Metolachlor** (Bicep Dual Ontrack Pennant Pimagram Turbo)
☐ **Alachlor** (Lasso Lazo Pillarzo Alazine Bullet Lariat Freedom Nudor Extra Rasdor)
☐ **Metribuzin** (Lexone 4L Lexone DF Sencor 4 Sencoral Sencorex Sencor DF Salute Turbo)
☐ **Endothall** (Endothall Aquatrol K Hydrothol 191 Herbicide 273 Des-i-cate Accelerate)
☐ **Diquat** (Aquacide Dextrone Weedtrin D Aquakill)

## AGRICULTURAL CHEMICAL USAGE SURVEY

### RICE

☐ **Butachlor** (Butachlor Lambast Aimchlor)

### SMALL GRAINS

☐ **Picloram** (Tordon Amdon ACTP Borolin K Pin Acces Grazon)
☐ **Dicamba** (Banvel Banes Banex Banlen Brush Buster Dianat Dinate Dicambe Mediben Mondak MDBA)
☐ **Carbofuran 3-hydroxycarbofuran** (Furadan)
☐ **Endrin** (Endrin Nendrin Hexadrin)
☐ **Toxaphene** (Toxaphene Camphochlor Motox Phenacide Phenatox Toxakil Toxon 63)
☐ **Heptachlor heptachlor epoxide** (Heptachlor Drinox Heptox Termide)
☐ **2 4-D** (Weedone Esteron Dacamine Weed B-Gone Weed Rhap Amine 4 Butyl Ester 4 LV 4 LV 6 Aqua Kleen)
☐ **Ethylene dibromide EDB** (Bromofume E D Bee Kopfume Nephis Dowfume Soilbrome)
☐ **Glyphosate** (Roundup Rodeo Roundup R&G Landmaster)
☐ **Methomyl** (Lannate LV Methomex Nudrin Mesomile Acetimidic Acid)
☐ **Lindane** (Lindane Isotox Gamma HCH BHC)

### SOYBEANS/POD CROPS

☐ **Carbofuran 3-hydroxycarbofuran** (Furadan)
☐ **Methomyl** (Lannate LV Methomex Nudrin Mesomile Acetimidic Acid)
☐ **Metolachlor** (Bicep Dual Ontrack Pennant Pimagram Turbo)
☐ **Alachlor** (Lasso Lazo Pillarzo Alazine Bullet Lariat Freedom Nudor Extra Rasdor)
☐ **Aldicarb aldicarb sulfoxide aldicarb sulfone** (Temik)
☐ **Dibromochloropropane, DBCP** (Nemafume Nemanax Nemaset Nemagon Fumazone Nematocide)
☐ **Oxamyl** (Vydate DPX 1410 Oxamidic Acid Thioxamyl)
☐ **Metribuzin** (Lexone 4L, Lexone DF Sencor 4 Sencoral Sencorex Sencor DF Salute Turbo)
☐ **Dinoseb** (Basanite Dinitro Dynamyte Premerge Vertac Weed Killer)
☐ **Glyphosate** (Roundup Rodeo Roundup R&G Landmaster)
☐ **Carbaryl** (Sevin Carbamine Denapon Dicarbam Hexavin Karbaspray Nac Ravyon Septene Tercyl Tricarnum Arilate Bercema NMC50 Caprolin)

### SWEET POTATOES

☐ **Aldicarb aldicarb sulfoxide, aldicarb sulfone** (Temik)
☐ **Glyphosate** (Roundup Rodeo Roundup R&G Landmaster)

### VEGETABLES

☐ **Methomyl** (Lannate LV Methomex Nudrin Mesomile Acetimidic Acid)
☐ **Dibromochloropropane DBCP** (Nemafume Nemanax Nemaset Nemagon Fumazone Nematocide)
☐ **Oxamyl** (Vydate DPX 1410 Oxamidic Acid Thioxamyl)

## AGRICULTURAL CHEMICAL USAGE SURVEY

☐ **Metribuzin** (Lexone 4L, Lexone DF Sencor 4 Sencoral, Sencorex, Sencor DF Salute Turbo)
☐ **Dinoseb** (Basanite Dinitro, Dynamyte Premerge Vertac Weed Killer)
☐ **Lindane** (Lindane Isotox Gamma HCH BHC)
☐ **Methoxychlor** (Marlate Chemform, DMDT)
☐ **Atrazine** (Aatrex Alazine Bullet Rhino Tomahawk Bicep Primextra Rastra)
☐ **Chlordane** (ChlorKill Gold Crest C 100 Octa Klor Chlorotox)
☐ **Ethylene dibromide, EDB** (Bromofume, E D Bee Kopfume Nephis Dowfume Soilbrome)
☐ **Glyphosate** (Roundup Rodeo Roundup R&G Landmaster)
☐ **Carbaryl** (Sevin, Carbamine Denapon Dicarbam, Hexavin Karbaspray Nac, Ravyon Septene Tercyl Tricarnum Arilate Bercema NMC50 Caprolin)
☐ **Alachlor** (Lasso Lazo Pillarzo Alazine Bullet Lariat Freedom Nudor Extra Rasdor)
☐ **Simazine** (Aquazine Princep Princep Caliber 90 Primatol S Simadex Simanex)
☐ **Metolachlor** (Bicep Dual Ontrack, Pennant Pimagram Turbo)
☐ **2,4-D** (Weedone Esteron, Dacamine Weed B Gone Weed Rhap Amine 4 Butyl Ester 4 LV 4 LV 6, Aqua Kleen)
☐ **Dalapon** (Dalapon Dowpon, Basinex P Gramevin Kenapon Liropon Unipon Revenge Alatex Ded Weed Devipon)

### WHEAT

☐ **Metribuzin** (Lexone 4L Lexone DF Sencor 4 Sencoral Sencorex Sencor DF Salute Turbo)
☐ **Lindane** (Lindane Isotox Gamma HCH BHC)
☐ **Ethylene dibromide EDB** (Bromofume E D Bee Kopfume Nephis Dowfume Soilbrome)
☐ **Hexachlorobenzene** (HCB Anticane Ceku D B No Bunt)
☐ **Methomyl** (Lannate LV Methomex, Nudrin, Mesomile Acetimidic Acid)
☐ **Glyphosate** (Roundup Rodeo Roundup R&G Landmaster)
☐ **Carbaryl** (Sevin Carbamine Denapon Dicarbam Hexavin Karbaspray Nac, Ravyon Septene Tercyl Tricarnum Arilate Bercema NMC50 Caprolin)
☐ **Carbofuran 3 hydroxycarbofuran** (Furadan)

### LIVESTOCK

### DAIRY/BEEF CATTLE

☐ **Lindane** (Lindane Isotox Gamma HCH BHC)
☐ **Methoxychlor** (Marlate Chemform DMDT)
☐ **Toxaphene** (Toxaphene Camphochlor Motox Phenacide Phenatox Toxakil Toxon 63)
☐ **Methomyl** (Lannate LV Methomex Nudrin Mesomile Acetimidic Acid)

### HORSES

☐ **Lindane** (Lindane Isotox Gamma HCH BHC)

## AGRICULTURAL CHEMICAL USAGE SURVEY

### HOUSEHOLD PETS/KENNELS

☐ **Lindane** (Lindane Isotox Gamma HCH, BHC)
☐ **Carbaryl** (Sevin, Carbamine Denapon, Dicarbam Hexavin Karbaspray Nac Ravyon, Septene Tercyl, Tricarnum Arilate Bercema NMC50 Caprolin)
☐ **Heptachlor heptachlor epoxide** (Heptachlor Drinox Heptox Termide)

### POULTRY

☐ **Carbaryl** (Sevin Carbamine Denapon, Dicarbam Hexavin, Karbaspray Nac, Ravyon Septene Tercyl Tricarnum, Arilate Bercema NMC50 Caprolin)
☐ **Methomyl** (Lannate LV Methomex, Nudrin, Mesomile Acetimidic Acid)

### SHEEP/GOATS

☐ **Lindane** (Lindane Isotox Gamma HCH BHC)
☐ **Methoxychlor** (Marlate Chemform DMDT)

### SWINE

☐ **Lindane** (Lindane Isotox Gamma HCH BHC)
☐ **Methoxychlor** (Marlate Chemform DMDT)

### ENVIRONMENTAL

### AQUATIC WEEDS

☐ **Diquat** (Aquacide Dextrone, Weedtrin D Aquakill)
☐ **Endothall** (Endothall Aquatrol K. Hydrothol 191 Herbicide 273, Des-i-cate Accelerate)
☐ **Simazine** (Aquazine Princep Princep Caliber 90 Primatol S Simadex Simanex)
☐ **2,4-D** (Weedone Esteron Dacamine Weed B-Gone Weed Rhap Amine 4 Butyl Ester 4 LV 4 LV 6 Aqua Kleen)
☐ **Glyphosate** (Roundup Rodeo Roundup R&G Landmaster)

### DRAINAGE DITCHES

☐ **Dalapon** (Dalapon Dowpon Basinex P Gramevin Kenapon, Liropon Unipon Revenge Alatex Ded Weed Devipon)
☐ **Diquat** (Aquacide Dextrone Weedtrin-D Aquakill)
☐ **Endothall** (Endothall Aquatrol K. Hydrothol 191 Herbicide 273 Des i-cate Accelerate)
☐ **Simazine** (Aquazine Princep Princep Caliber 90 Primatol S Simadex Simanex)
☐ **2 4 D** (Weedone Esteron Dacamine Weed-B-Gone Weed Rhap Amine 4, Butyl Ester 4 LV 4 LV 6 Aqua Kleen)
☐ **Glyphosate** (Roundup Rodeo Roundup R&G Landmaster)

### MOSQUITO/GRASSHOPPER CONTROL

☐ **Dieldrin** (HEODD Alvit Quintox Octalox)

## AGRICULTURAL CHEMICAL USAGE SURVEY

### RIGHTS OF WAY

☐ **Dalapon** (Dalapon Dowpon Basinex P Gramevin Kenapon Liropon Unipon Revenge Alatex Ded Weed Devipon)
☐ **Dicamba** (Banvel Banes Banex Banlen Brush Buster Dianat Dinate Dicambe Mediben Mondak MDBA)
☐ **Glyphosate** (Roundup Rodeo Roundup R&G Landmaster)
☐ **Metolachlor** (Bicep Dual Ontrack Pennant Pimagram Turbo)
☐ **Picloram** (Tordon Amdon ACTP Borolin K Pin Acces Grazon)
☐ **Atrazine** (Aatrex Alazine Bullet Rhino Tomahawk Bicep Pnmextra Rastra)

### STORAGE, WAREHOUSE, HOUSEHOLD FUMIGANTS

☐ **Methoxychlor** (Marlate Chemform DMDT)
☐ **Ethylene dibromide, EDB** (Bromofume E D Bee Kopfume Nephis Dowfume Soilbrome)
☐ **Pentachlorophenol PCP** (Dowcide EC 7 Penchloral Penta Pentacon Penwar Weedone)

### STRUCTURAL/HOUSEHOLD PEST CONTROL

☐ **Aldrin** (Aldnn Aldrex Aldnte Seednn)
☐ **Dieldrin** (HEODD Alvit Quintox Octalox)
☐ **Lindane** (Lindane Isotox Gamma HCH BHC)
☐ **Methoxychlor** (Marlate Chemform DMDT)
☐ **Chlordane** (ChlorKill Gold Crest C 100 Octa Klor Chlorotox)
☐ **Heptachlor heptachlor epoxide** (Heptachlor Drinox Heptox Termide)
☐ **Pentachlorophenol PCP** (Dowcide EC 7 Penchloral Penta Pentacon Penwar Weedone)
☐ **Carbaryl** (Sevin Carbamine Denapon Dicarbam Hexavin Karbaspray Nac Ravyon Septene Tercyl Tricarnum Anlate Bercema NMC50 Caprolin)

## Worksheet C-4
## Transportation Hazard Inventory (Ohio Environmental Protection Agency)

**FORM C. TRANSPORTATION TRANSMISSION FACILITY**
**(railroads, highways, sewers, fuel/chemical pipelines, terminals, service areas)**

1. Facility Name________________________________________

2. Describe facility type________________________________________

________________________________________

3. Describe Location________________________________________

________________________________________

4 Map No.________________ 5. Minimum Distance from nearest public well ________________

6. List potential pollution sources (operation and construction information)________________

________________________________________

________________________________________

7. Describe any past pollution incidents________________________________________

________________________________________

________________________________________

8. Date of installation (pipelines)________________________________________

9. Additional Information (protection measures, handling practices, etc.)

## Worksheet C-5
## Municipal/Commerical/Industrial Potential Contaminant Source Inventory Short Form
(Adams et al., 1992)

1. FACILITY NAME:

2. FACILITY ADDRESS:

3. OWNER/OPERATOR/OTHER:

4. TYPE OF BUSINESS:

5. TYPE OF HAZARD OBSERVED:

6. ARE STORAGE TANKS PRESENT? Yes ___ NO ___
(IF NO, SKIP TO QUESTION 7)
A. IF YES, ARE THE TANKS ABOVE GROUND (AG) ___
BELOW GROUND (BG) ___

a.) IS SECONDARY CONTAINMENT PRESENT? YES ___ NO ___
INTEGRITY?

| | AGE | SIZE | ITEMIZE TANK MATERIAL | MATERIAL STORED | AG/BG |
|---|---|---|---|---|---|
| TANK 1 | | | | | |
| TANK 2 | | | | | |
| TANK 3 | | | | | |
| TANK 4 | | | | | |
| TANK 5 | | | | | |
| TANK 6 | | | | | |
| TANK 7 | | | | | |
| TANK 8 | | | | | |
| TANK 9 | | | | | |
| TANK 10 | | | | | |

B. COMMENTS: Owner Darrell Becker
Tank Pressure Tested Annually

7. ARE SOLVENTS PRESENT? YES ___ NO ___
(IF NO, SKIP TO QUESTION 8)

| | TYPE | STORAGE METHOD | ITEMIZE QUANTITY | DISPOSAL METHOD | USE |
|---|---|---|---|---|---|
| SOLV. 1 | | | | | |
| SOLV. 2 | | | | | |
| SOLV. 3 | | | | | |
| SOLV. 4 | | | | | |
| SOLV. 5 | | | | | |

A. COMMENTS:

## Worksheet C-5 (Continued)

PAGE 2

8. IS THE FACILITY SEWERED? YES ___ NO ___

A. ARE THE FLOOR DRAINS CONNECTED TO THE SEWER? YES ___ NO ___

B. COMMENTS: No floor drains present.

9. IS THE FACILITY SUBJECT TO AN ENVIRONMENTAL REMEDIATION? YES ___ NO ___ (IF NO, SKIP TO QUESTION 10)

A. IF YES, WHAT TYPE OF REMEDIATION?

B. IS THIS REMEDIATION CURRENTLY UNDER AGENCY LITIGATION, VOLUNTARY CLEAN-UP, OTHER?

C. COMMENTS:

10. ARE THERE ANY PHYSICAL OBSERVATIONS WHICH MAY INDICATE A POTENTIAL HAZARD TO THE GROUNDWATER? YES ___ NO ___
(IF NO, SKIP TO QUESTION 11)

A. IF YES, DESCRIBE:

B. COMMENTS:

11. SUMMARIZE THE RESULTS OF THE FINDINGS ENUMERATED ABOVE, AND INDICATE THE DEGREE OF POTENTIAL HAZARD THIS FACILITY MAY POSE TO THE GROUNDWATER.

This facility stores petroleum below ground, is within the capture zone of the wells. Therefore, Beck Oil Co. appears to pose a significant hazard to the future security of the public water supply.

INSPECTOR: ________________________________

# Worksheet C-6
# Municipal/Commerical/Industrial Potential Contaminant Source Inventory Long Form
# (Adams et al., 1992)

HAZARD REVIEW WORKSHEET

1 Unique I D Number _ _ _ _ _ _ _ - _ _ Distance and Direction from the Wellhead __________

2 Nature of Business __________

3 DLPC Permit Number(s) and Description (e g RCRA Generic Solid Waste, UIC, etc ) __________

4 DAPC Permit Number(s) and Description __________

5 DWPC Permit Numbers and Description (e g , NPDES Industrial Pre-Treatment, Sewer Plans, etc ) __________

6 ERU Incidents and Description __________

7 ERU 313 Reports and Description __________

8 ESDA 302/303 Reports and Description __________

9 ESDA 311/312 Reports and Description __________

10 PWS compliance monitoring conducted and describe the results (e g , VOC/VOA sample detects etc ) __________

11 ISFM list the underground storage tanks registered, provide the owner name and address

| Owner Name | Address |
|---|---|
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |

12 Is the site sewered or non-sewered? __________

If the site is not sewered, describe __________

# Worksheet C-6 (Continued)

13 Has on-site past or present landfilling, land treating, or surface impoundment of waste, other than landscape waste or construction and demolition debris occurred?

[ ] Yes. If yes, describe ____________________

[ ] No.

14 Are there currently any on-site piles of special or hazardous waste?

[ ] Yes. If yes, describe. ____________________

[ ] No.

15. Are on-site piles of waste (other than special or hazardous wastes) managed according to Agency guidelines?

[ ] Yes.

[ ] No If no, describe ____________________

16. Are there currently any underground storage tanks present on-site, and will any underground tanks be installed in the future?

[ ] Yes If yes, describe ____________________

[ ] No

17a) Has any situation(s) occurred at this site which resulted in a "release" of any hazardous substance or petroleum?

[ ] Yes (continue to next question)
[ ] No (stop here)

(b). Have any hazardous substances or petroleum, which were released come into contact with the ground surface at this site? (Note--do not automatically exclude paved or otherwise covered areas that may still have allowed chemical substances to penetrate into the ground.)

[ ] Yes (continue to next question)
[ ] No (stop here)

(c). Have any of the following actions/events been associated with the release(s) referred to in question 17(b)?

[ ] Hiring of a cleanup contractor to remove obviously contaminated materials including subsoils

[ ] Replacement or major repair of damaged facilities

[ ] Assignment of in-house maintenance staff to remove obviously contaminated materials including subsoils

[ ] Designation, by IEPA or the ESDA, of a release as "significant" under the Illinois Chemical Safety Act

[ ] Reordering or other replenishment of inventory due to the amount of substance lost

[ ] Temporary or more long-term monitoring of groundwater at or near the site

[ ] Stop usage of an on-site or nearby water well because of offensive characteristics of the water

[ ] Coping with fumes from subsurface storm drains or inside basements

[ ] Signs of substances leaching out of the ground along the base of slopes or at other low points on or adjacent to the site

## Worksheet C-6 (Continued)

(d) The on-site release(s) may have been of sufficient magnitude to contaminate groundwaters Summarize the problem

18 Are there more than 100 gallons of either pesticides or organic solvents, or 10,000 gallons of any hazardous substance or 30 000 gallons of petroleum present at any time?

[ ] Yes If yes describe

[ ] No

19 Do any of the regulated entities have groundwater monitoring systems, and have any exceeded compliance requirements?

[ ] Yes If yes, describe

[ ] No

20 After considering all of the above criteria does this site potentially pose a hazard to groundwater?

[ ] Yes If yes describe

[ ] No

RC jmm/sp0867K/1-5

## Worksheet C-7
## Bylaw Summary Form and Wellhead Protection Worksheet
## (Massachusetts Department of Environmental Protection, 1991)

### <u>Bylaw Summary Form</u>

Please note with an (X) if controls exist to regulate the following land uses/activities If controls are currently under consideration, indicate with an (X) in the "To Be Addressed" column. For all existing controls, cite the authority for regulating land use and the appropriate bylaw or regulation

| | <u>Existing Controls</u> | | To be | Regulatory | |
|---|---|---|---|---|---|
| | Prohibit/Restrict | | Addressed | Authority | Section |
| 1. Landfills and open dumps | | | | | |
| 2. Landfilling of sludge or septage | | | | | |
| 3. Automobile graveyards/junkyards | | | | | |
| 4 Stockpiling/disposal of snow/ice containing de-icing materials | | | | | |
| 5. Individual sewage disposal systems exceeding 110 gals/quarter acre or 440 gals/acre | | | | | |
| 6. Wastewater treatment plants except for replacement, repair, or systems treating contaminated ground or surface water | | | | | |
| 7. Facilities that generate, treat, store or dispose of hazardous waste other than very small quantity generators, household hazardous waste collection, waste oil retention, treatment works associated with groundwater cleanups | | | | | |
| 8. Storage of sludge and septage | | | | | |
| 9. Storage of deicers unless in proper building | | | | | |
| 10. Storage of commercial fertilizers unless in proper structure | | | | | |
| 11. Storage of manure unless in proper structure | | | | | |
| 12. Storage of liquid hazardous materials unless in proper container | | | | | |
| 13. Soil removal/replacement within four feet of the water table | | | | | |
| 14. Storage of liquid petroleum products other than household use, waste oil retention, emergency generators or treatment works | | | | | |
| 15. Making impervious >15% or 2500 ft$^2$ of any lot without artificial recharge | | | | | |

PLEASE ATTACH COPIES OF REFERENCED BYLAWS AND REGULATIONS

## Worksheet C-7 (Continued)

Guidelines and Policies for Public Water Systems - 1991 Edition
**Appendix E** - Bylaw Summary Form and Wellhead Protection Questionnaire Page 2

### Wellhead Protection Questionnaire

### I. Name of Applicant

Municipal contact person

Address.

Phone number·

Community in which the proposed new source is located

If this wellhead protection questionnaire accompanies a request for the approval of a Zone II for an existing source(s), please check here ____

Please respond to the following questions. If the applicant is not a municipality, it may be necessary to obtain information from appropriate local officials

### II. Wellhead Protection Priorities

Rank in order of importance (1 high - 6 low) the following municipal management priorities for the town in which the Zone I for the proposed well is located Please indicate with an (X) if some initiative is underway in a given area.

____ Set up representative water protection committee
____ Coordinate with adjacent towns, watershed associations or other groups to enhance multi-town protection efforts
____ Improve bylaws, regulations and/or zoning
____ Improve enforcement and local review
____ Financing for wellhead protection
____ Other (describe). ____________________________________________

### III. Intermunicipal Relations

1. Is any of the estimated recharge area of the proposed new source located in an adjoining community(ies)? YES NO

   If so, please list the Recharge Area (Zone I, II, III) and community(ies).

2. List the communities that have estimated or delineated aquifer recharge areas in the community in which the proposed well is located.

## Worksheet C-7 (Continued)

Guidelines and Policies for Public Water Systems - 1991 Edition
Appendix E - Bylaw Summary Form and Wellhead Protection Questionnaire Page 3

3. Do you anticipate that any of the estimated Zone II for the proposed well is threatened by actions or activities in an adjacent community? YES NO

4. Is the community in which the new source is located involved in any intermunicipal activities related to wellhead protection with the communities listed in 1 and 2 (above)? YES NO

   Briefly describe. ______________________________

   ______________________________

   ______________________________

   ______________________________

IV. Existing and Potential Public Supply Well Concerns

1. Possible ground water problems may be associated with existing land use in the estimated Zone II of the proposed well.

   Does the estimated Zone II contain.

   ____ Industry
   ____ Commercial businesses
   ____ Vacant land zoned for industry or commerce
   ____ Non-sewered residences
   ____ Landfills

   What are the residential lot size requirements in the estimated Zone II (i.e., one acre zoning, etc.)?

   ______________________________

   What percent of the estimated Zone II is sewered? ______________________________

2. Have any water supplies in the municipality been contaminated? If yes, please describe briefly.

   ______________________________

   ______________________________

   ______________________________

   ______________________________

## Worksheet C-7 (Continued)

Guidelines and Policies for Public Water Systems - 1991 Edition
**Appendix E** - Bylaw Summary Form and Wellhead Protection Questionnaire Page 4

3 Water supply concerns for the overall supply system to which the new source will contribute After you have noted specific concerns, please indicate if you feel they are being adequately addressed

| | **Is this concern being addressed?** | |
|---|---|---|
| ____ inadequate water supply (difficulty meeting peak seasonal demands) | Yes | No |
| ____ inadequate supply (long-term) | Yes | No |
| ____ decreasing yields | Yes | No |
| possible need to add treatment (such as filtration, etc ) | Yes | No |
| ____ lack of drought/emergency planning | Yes | No |

### V. Existing Control Mechanisms

Resource Management Activities

Please use the following code in your response

Yes = currently in place
N/A = not applicable
UD = under development
NAD = not addressed
? = unfamiliar with activity

_______ Aquifer protection district or water supply protection district
_______ Inventory of potentially threatening land uses
_______ Cluster zoning
_______ Nutrient loading limits or other performance standards
_______ Open space zoning

_______ Septic system design, placement and management
_______ Prohibition or limited use of septic system cleaners
_______ Private well construction regulations and/or periodic inspections
_______ Herbicide/pesticide control or Integrated Pest Management program
_______ Site plan review

_______ Temporary building moratoria (purpose_______________________)
_______ Subdivision development (*i.e.*, controls for drainage)
_______ Stormwater management
_______ Land Acquisition Program
_______ Household hazardous waste collection

_______ Used motor oil collection
_______ Early warning monitoring system for groundwater protection
_______ Modified road salt application in water supply areas
_______ Water conservation program

## Worksheet C-7 (Continued)

Guidelines and Policies for Public Water Systems - 1991 Edition
Appendix E - Bylaw Summary Form and Wellhead Protection Questionnaire Page 5

_______ Representative water protection committee
_______ Inter-governmental coordination (with adjacent or other towns)
_______ Intra-governmental coordination (within your community)
_______ Conservation Commission, Board of Health, Water Dept. and Water Commissioners input on development proposals
_______ Designation of a "Water Resources Management Official" to be in charge of the planning process and manage the Water Management Act permit applications
_______ Public Education Program

Economic Related Activities

_______ True cost pricing
_______ Rate structure to promote conservation
_______ Rate structure to promote water conservation; seasonal pricing, flat rate or increasing block rate
_______ Transferrable development rights

Implementation/Enforcement

Y=Yes N=No D=Don't know

1. Zoning and non-zoning controls that protect groundwater and recharge areas are in place but all provisions are not fully implemented Y N D

2. Enforcement provisions are written into existing and proposed controls Y N D

3. Enforcement provisions under zoning and non-zoning bylaws are adequate to address violations. Y N D

4. Use of MGL Ch. 40, Section 21D, Noncriminal disposition (environmental ticketing), is authorized for the town in which the primary recharge area is located. Y N D

Prepared by: ____________________

Title/Affiliation: ____________________

____________________

Date: ____________________

# Worksheet C-8
# Drinking Water Supply Contingency Plan
# (Ohio Environmental Protection Agency, 1992)

WATER SUPPLY CONTINGENCY PLAN FOR ______________________________ MOBILE HOME PARK

LOCATED AT ______________________________, OHIO AS OF ____________
Date

COPIES OF THIS PLAN ARE AT THE FOLLOWING LOCATIONS

PARK OFFICE - LIST EXACT LOCATION - ______________________________
(Desk, Bulletin Board, etc.)

PARK OPERATORS RESIDENCE ______________________________

PARK MAINTENANCE BUILDING ______________________________

______________________________

REVISIONS (All copies of this plan must be revised as the names, addresses and telephone numbers of personnel, suppliers, contractors and governmental agencies are are changed, as well as changes in the water supply system but at least annually )

| PAGE | NAME | DATE REVISED |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

IN ABSENCE OF PARK OWNER OR OPERATOR

The following person(s) are thoroughly familiar with the emergency plan and are authorized to make necessary repairs to the water system in absence of the owner.

| NAME | ADDRESS | PHONE DURING OFFICE HOURS | IF NO ANSWER CALL |
|---|---|---|---|
| | | | |
| | | | |
| | | | |

The following person(s) are thoroughly familiar with the plan and are available under emergency circumstances.

| | | | |
|---|---|---|---|
| | | | |
| | | | |
| | | | |

## Worksheet C-8 (Continued)

POTENTIAL EMERGENCY CONDITIONS

Power Outage

Park manager shall take all necessary steps as to shut down the water treatment plant such as turning off the chemical feed equipment, disconnecting well pump and high service pumps, to prevent electrical damage to equipment or over feed of chemicals under certain conditions.

1. Determine the expected length of the electrical outage.
2. Determine the amount of water on hand in the distribution system storage tank.
3. Notify the park residents if necessary.

Short Term Power Failure (Less than 2 Hours)

(a) If necessary, ask for water conservation during power outage.
(b) If system pressure should drop below 20 lbs., all water for drinking and cooking shall be disinfected before use by boiling or chlorination as indicated under Emergency Disinfection.
(c) Advise the park residents when conditions are back to normal.

EXTENDED POWER FAILURE (Two Hours or More)

(a) Restrict water use for drinking and cooking.
(b) Notify all necessary parties (see call list).
(c) Notify water users (see Emergency Notification).
(d) Provide water hauling if necessary (see Alternate Sources).
(e) Request state aid if necessary (see call list).
(f) Emergency power generating equipment.

WELLS OUT OF SERVICE - CONTAMINATION, LOSS OF WATER TABLE, PUMP FAILURE, ETC.

1. Should any one of the wells become contaminated or deteriorated to a condition that is unable to furnish water of a satisfactory quantity and quality it shall then be taken out of service until the cause can be determined. The other well should then be placed into service.
2. If one well is out of service, depending on severity of situation, users should be notified to conserve water during well repairs if necessary.
3. If both wells are contaminated or unable to pump water due to the water table level, shut-down the wells, treatment plant and close the main line finished water valve.
4. Notify Ohio E.P.A. and Park Owner.

## Worksheet C-8 (Continued)

5. Obtain and analyze water samples at ______________________________
6 Make necessary repairs and disinfect per Ohio E P A. instructions.

______________________________

______________________________

______________________________

TREATMENT PLANT FAILURE (Filters, Softeners, etc.)

In the event of filters or softeners, bypass the plant from the raw water main into the distribution system.

1 Immediately bypass the plant.
2. Notify Ohio E.P.A. and Park Owner.
3. Make necessary repairs and disinfect if necessary

______________________________

______________________________

______________________________

WATER LINE BREAK - RAW

1. Raw water line breaks from well field.

    (a) Shut-down wells and plant. See Power Outages Section.
    (b) Isolate area of break.
    (c) Notify users of situation if necessary.
    (d) Make necessary repairs and disinfect.

______________________________

______________________________

______________________________

DISTRIBUTION BREAKS

1. Break in distribution main.

    (a) Immediately isolate area of break.
    (b) Check for depressurization of system.
    (c) Notify users of situation.
    (d) Make necessary repairs and disinfect.

______________________________

______________________________

______________________________

LOSS OF STORAGE CAPABILITY

If the storage tank is out of service due to contamination or repair, pressure relief valves shall be installed in distribution system. The well pumps can be used to maintain pressure in the system. A pressure gauge shall be installed in the system in order to monitor the system's pressure.

## Worksheet C-8 (Continued)

WATER USERS HAVING A NEED FOR CONTINUOUS WATER SUPPLY

| NAME | ADDRESS | PHONE |
|---|---|---|
| | | |
| | | |

(Suggestion) (It would be helpful to identify these persons for health or other reasons who require a continuous water supply. (i e. medical equipment, etc.) If this does not apply enter "NONE.")

TWENTY FOUR HOUR PHONE NUMBERS

| NAME | ADDRESS | PHONE DURING OFFICE HOURS | IF NO ANSWER, CALL |
|---|---|---|---|
| OHIO EPA DISTRICT OFFICE | | | 1-800-282-9378 |
| SHERIFF'S OFFICE | | | |
| FIRE DEPARTMENT | | | |
| COUNTY DISASTER AGENCY | | | |
| ELECTRIC CO. | | | |
| PHONE CO. | | | |
| LOCAL RADIO STATION | | | |
| HOSPITAL | | | |
| EMERGENCY SQUAD | | | |
| OHIO UTILITIES PROTECTION SERVICE | | | 1-800-362-2764 |
| OTHER PHONE NUMBERS | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| MATERIALS (Repair Clamps, Valves, Pipe and Fittings, Feeders, etc.) | | | |
| | | | |
| | | | |
| | | | |
| CHEMICALS (Chlorine, Calcium Hypochlorite, etc.) | | | |
| | | | |
| | | | |
| | | | |
| ELECTRICIANS (Local Contractors for Equipment & Support) | | | |
| | | | |
| | | | |
| | | | |

## Worksheet C-8 (Continued)

### BACKHOE

| NAME | ADDRESS | PHONE DURING OFFICE HOURS | IF NO ANSWER, CALL |
|---|---|---|---|
| | | | |
| | | | |
| | | | |

### WELL DRILLERS AND PUMP SERVICE

| | | | |
|---|---|---|---|
| | | | |
| | | | |
| | | | |

### WATER SYSTEM MAP (Attach Copies of Maps to the Plan)

(Suggestion) (This map may be hand drawn and should show location of valves, lines, etc. with sufficient accuracy to allow others to locate the valve.)

### EMERGENCY NOTIFICATION OF WATER USERS

(Suggestion) (Door-to-Door, Written Notification, etc.)

In the event of a water related emergency, public information will be provided to the residents door-to-door by the employees and on the bulletin board in the park office.

1 Notify users if emergency disinfection of drinking water is required.
2. Advise the public as to the expected duration of the emergency.
3. If necessary, ask for conservation.
4. Advise if necessary that potable water is available at the park office with limits for drinking and cooking.
5. Advise the public when water is available for sanitation.
6. Advise the public when conditions are near normal.

### EMERGENCY SUPPLY OF DRINKING WATER

| NAME OF SUPPLY | LOCATION TO OBTAIN WATER | CONTACT PERSON | PHONE |
|---|---|---|---|
| | | | |
| | | | |
| | | | |

### TRANSPORTING DRINKING WATER

(Suggestions) (Water Haulers, Milk Haulers, Fire Department, etc.)

| NAME | ADDRESS | PHONE DURING OFFICE HOURS | IF NO ANSWER, CALL |
|---|---|---|---|
| | | | |
| | | | |
| | | | |

## Worksheet C-8 (Continued)

1. Notify users of situation.
2. Make necessary repairs and disinfect per Ohio E.P.A District Office instruction.

PROCEDURES TO RETURN THE SYSTEM TO SERVICE

Emergency situations could result in depressurization or contamination of the water system at a single point in the distribution system or over a larger area of the system. If depressurization occurs within a small, defined area, the system can be isolated by immediately closing valves to keep the spread of possible contamination. The following steps should be taken:

1. Determine area to be isolated and isolate area.
2. Repair damages to distribution system and disinfect if necessary
3. If repairs are lengthy, make provisions for temporary water supply
4. Notify users to boil all water for drinking purposes in affected area.
5. Obtain and test water samples for possible contamination.
6. Disinfect affected mains with calcium hypochlorite or other approved method, from the Ohio E.P.A. District Office.
7. If contaminated, thoroughly flush mains and services; obtain and test additional samples.
8. Notify users that problems have been corrected; open valves.

REPAIR PARTS & LOCATION (Inventory of Equipment, Spare Parts and Chemicals Required or Repair of the Water System Which are Carried in Inventory by Local Suppliers or Contractors)

PARTS AND SIZE (Valves, Pipe, Repair Clamps, Extra Pump, Motors, Chemicals, etc.)

LOCATION

EMERGENCY DISINFECTION OF DRINKING WATER

See Attached OEPA Form PWS-3

# Worksheet C-9
# Chemical Spill Emergency Notification and Documentation
# (Adapted from New York State Department of Health, 1984)

This notification report represents a typical form that might be adapted for use in a water supply contingency plan

PART 1 - FACTS RELATED TO EMERGENCY

1 Person or department calling in emergency ______________________

Phone No /Radio frequency ____________ Date/Time call received ____________

.2 Location of emergency

Street and Home/Building number ______________________

Other (approximate location, distance from landmark, etc.) ______________________

______________________

3. Nature of the emergency (e g, broken water main, chemical spill, lost pressure in home, etc ) ____

______________________

4 Condition at scene ______________________

______________________

5 Actual/Potential damage (briefly describe the situation) ______________________

______________________

______________________

6 Access restrictions, if any ______________________

______________________

7 Assistance already on the scene (who, what are they doing, etc.) ______________________

______________________

______________________

PART 2 - EMERGENCY INVESTIGATION

1 Personnel investigating emergency ______________________

______________________

2. Reported results of investigation ______________________

______________________

3 Time Assessed ______________________

---

[1] Adapted from Emergency Planning and Response - A Water Supply Guide for the Supplier of Water New York State Department of Health, January 1984

## Worksheet C-9 (Continued)

### EXAMPLE OF EMERGENCY NOTIFICATION REPORT*

### PART 3 - EMERGENCY ACTION TAKEN

1 Immediate action taken ____________________________________________

____________________________________________

____________________________________________

2. Is immediate action· Permanent ____________ Temporary ____________

3. Was an emergency crew dispatched: Yes ___ No ___ Time arrived on scene ________

4. Note all other actions that will be necessary to bring the water supply system back into operation

____________________________________________

____________________________________________

____________________________________________

### PART 4 - PERSONS/DEPARTMENTS NOTIFIED OF EMERGENCY

| Positions | Name | Work Phone | Home Phone | Time of Call |
|---|---|---|---|---|
| __ Chief Operator | | | | |
| __ General Manager | | | | |
| __ Local Health Department | | | | |
| __ Engineer | | | | |
| __ Operations Supervisor | | | | |
| __ Plant Manager | | | | |
| __ Shift Operator | | | | |
| __ Fire Department | | | | |
| __ Police Department | | | | |
| __ Highway Department | | | | |
| __ Local Elected Official (Mayor, Commissioner etc.) | | | | |
| __ Department of Health | | | | |
| __ Department of Transportation | | | | |
| __ Department of Environmental Conservation | | | | |
| __ County Civil Defense | | | | |
| __ Other (refer to system personnel and support call up lists) | | | | |
| __ Priority water users | | | | |
| __ News Media | | | | |

Signature of Person Who Filled Out Form

____________________________________________

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* To be completed and used by water supply system personnel

## Worksheet C-9 (Continued)

### EXAMPLE OF REPORTING FORM FOR CHEMICAL INCIDENTS

- Identity of contaminant material ____________________
  - Manifest/shipping invoice/billing label ____________________
  - Shipper/manufacturer identification ____________________
  - Container type ____________________
  - Placard/label information ____________________
  - Railcar/truck 4-digit identification number ____________________
  - Nearest railroad track intersection/line intersection ____________________
- Characteristics of material, if readily detectable (for example, odor, flammable, volatile, corrosive) ____________________
- Present physical state of material (gas, liquid, solid) ____________________
- Amount already released ____________________
- Amount that may be released ____________________
- Other hazardous materials in proximity ____________________
- Whether significant amounts of the material appear to be entering the atmosphere, nearby surface water, storm drains, or soil ____________________
- Direction, height, color, odor of any vapor clouds or plumes ____________________
- Weather conditions (including wind direction and speed) ____________________
- Local terrain conditions ____________________
- Personnel at the scene ____________________

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